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Advanced digital methods for analysing and optimising accessibility and visibility of water for designing sustainable healthy urban environments

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ABSTRACT

Water, a vital element of human existence, shapes cities and benefits human health through daily exposure. This study delves into advanced digital methods to describe blue space exposure effectively, aiming to optimise spatial accessibility and visibility of water for designing sustainable healthy urban environments. Rotterdam is utilised as a test case, demonstrating the role of these methods in evaluating the performance of blue space exposure in urban environments, specifically in terms of spatial morphology and physical characteristics. Eight distinct methods are discussed, addressing exposure type, scale levels, and design interactions, subsequently offering a novel flowchart for their integration into cross-scale spatial design and policymaking. The findings underscore the need to select appropriate methods to analyse and optimise blue exposure in spatial planning or design assignments. The selection should be based on design intentions and data availability. The biggest potential is found in combining these methods to handle the complexity of urban issues. The research reveals the importance of blue space accessibility and visibility in promoting sustainable healthy urban environments while also emphasising the need to go beyond them, factoring in the quality, function, and usage of blue spaces.

1. Introduction

With the prevalence of chronic lifestyle-related diseases, global attention to urban health issues has risen, making the sustainable healthy urban environment a major concern (Adlakha & John, 2022; Hua et al., 2022). Derived from the Healthy Cities movement and the importance of health in the Sustainable Development Goals (SDGs), the sustainable healthy urban environment is widely mentioned in research and policy documents (Crane et al., 2021; de Sa et al., 2022). It requires cities to provide supportive environments for human health and enable people to mutually support each other in performing all the functions of life and developing to their maximum potential (Nieuwenhuijsen & Khreis, 2019; Watts et al., 2017; WHO, 2021b). Natural environments or nature-based solutions could be regarded as practical solutions to cope with non-communicable diseases and offer multiple ecosystem services on social and environmental dimensions, effectively contributing to sustainable healthy urban environments (Kondo et al., 2015; Mapar et al., 2020; Megahed & Ghoneim, 2020; Ramaswami et al., 2016; WHO, 2017).

With the continuous development of nature-health research in the urban context, health benefits of blue spaces have gradually been pointed out and attracted wide attention amongst researchers in recent years, such as the 'BlueHealth' project, a recent global research initiative, combined interdisciplinary approaches to comprehensively understand of the health benefits of blue space (Bell et al., 2021; Grellier et al., 2017; McDougall et al., 2020; Smith et al., 2021; Völker & Kistemann, 2011; Zhang et al., 2022). Therefore, fulfilling the health benefits of blue space becomes an effective way to build sustainable healthy urban environments. On the other hand, exposure to or contact with blue space could be regarded as the first and fundamental step for people to gain health benefits from it (Hartig et al., 2014; White et al., 2020). Blue space exposure means the amount of contact an individual or population has with blue spaces and is critical in planning and designing sustainable healthy urban environments (WHO, 2021a; Zhang et al., 2022). However, the growing accumulation of evidence has paid limited attention to incorporating blue space exposure in the action phase and has led to calls for the integration of knowledge into spatial design and policymaking, especially in driving the design process, which recent studies have recognised as a significant research gap (WHO, 2021a; Zhang et al., 2022).

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1.1. Conceptual frameworks and pathways linking blue spaces and human health

Multiple studies have identified and proposed conceptual frameworks and pathways linking blue spaces and human health. Specifically, Markevych et al.'s (2017) and Hartig et al.'s (2014) research summarised the pathways between exposure to broad nature environments and human health benefits. Grellier et al.'s (2017) and White et al.'s (2020) research hypothesise that health benefits from blue space exposure will follow the pathways similar to other nature environments and further extend the pathways into the blue space by introducing a feedback loop from health outcomes to exposure and two effect modifiers. Additionally, Zhang et al. (2022) reflected on existing pathways and proposed a conceptual framework for translating the health evidence into design practice. Fig. 1 presents a tailored conceptual framework linking blue spaces and human health based on the above studies (Grellier et al., 2017; Hartig et al., 2014; Markevych et al., 2017; White et al., 2020; Zhang et al., 2022). Blue space exposure is the basic step for gaining health benefits, and then four main pathways are identified linking blue spaces and human health, including (1) the presence of blue spaces could improve the ambient environment and reduce harm in several ways, such as regulating urban temperature (Ampatzidis & Kershaw, 2020; Burkart et al., 2016), alleviating air pollution (Ren et al., 2018), preventing environmental noise (Thoma et al., 2018; White et al., 2020), and enhancing immune functions (Frumkin et al., 2017; Grafetstätter et al., 2017); (2) exposure to blue spaces could reduce the risk of illness caused by stress and promote restoration ability, which is mainly guided by two influential theories: Attention Restoration Theory (Kaplan & Kaplan, 1989) and Stress Reduction Theory (Ulrich et al., 1991); (3) promoting individuals' social interactions is closely related to the health benefits of blue spaces through visits and usage of blue spaces (Pitt, 2018; Völker & Kistemann, 2015; Wyles et al., 2019); and (4) blue space could be regarded as an ideal place for a variety of physical activities that may be unique compared to green spaces, such as swimming, surfing, boating, etc (Perchoux et al., 2015; Vert et al., 2019; White et al., 2014). Next, the empirical evidence supporting these pathways could be further translated into concepts for actions that contribute to policymaking and design practices for the construction of sustainable healthy urban environments. Meanwhile, the creative practices could expand the exposure types and provide input for refining health evidence.

1.2. Two dominate aspects of blue space exposure

As outlined in several frameworks, exposure to or contact with blue space is the starting point for fulfilling its health benefits (Hartig et al., 2014; Markevych et al., 2017; White et al., 2020). Exposure is a broad term defined as 'the process of estimating or measuring the magnitude, frequency, and duration of exposure to an agent, along with the number and characteristics of the population exposed' (Zartarian et al., 2005). In blue-health research, exposure could be conceptualised into several intertwined concepts, including accessibility, visibility, availability, quality, etc. (Labib et al., 2020; Nieuwenhuijsen & Khreis, 2019; Pasanen et al., 2019; Thornhill et al., 2022; White et al., 2020). In contrast to spatial quality, which emphasises subjective perceptions, spatial accessibility and visibility rely primarily on objective measures, dominating the current analysis of blue space exposure. Specifically, accessibility refers to the relative ease by which populations can reach the location of blue spaces from their positions (Wang et al., 2021). It could be measured mainly through two ways: a) setting the distance buffer and identifying the presence of blue spaces within the buffer; and b) directly calculating the lowest distance to the nearest blue space from a specific location (residence or working place). Although the studies on spatial accessibility were relatively substantial, there are still some limitations in measuring the blue space accessibility due to the distinctiveness of blue space, including the difficulty of clearly defining blue space's destinations which led to using Euclidean distance of nearest water boundaries in accessibility calculation rather than network-based distance representing the actual condition, inadequate application of advanced and emerging methods or techniques for analysing accessibility, and the insufficient explorations of application possibilities for incorporating the methodologies into action and design (Chen & Yuan, 2020; Huang et al., 2022; Pasanen et al., 2019).

On the other hand, many studies suggest the health benefits of blue spaces could derive from viewing the water without physically visiting, which is more related to psychological outcomes (Coleman & Kearns, 2015; Helbich et al., 2019; Völker et al., 2018; White et al., 2010; Wyles et al., 2019). Hongkong, Guangzhou, and Irish studies suggested that the blue view is crucial for older adults and populations with poor mobility (Chen & Yuan, 2020; Dempsey et al., 2018; Garrett et al., 2019). Blue space visibility assesses what water bodies are likely to be visible from a specific location by considering the features of the topographic and built environments (Qiang et al., 2019). However, measuring and describing blue visibility are often challenging, especially for freshwater bodies in urban environments, such as small lakes, canals, rivers, etc. (McDougall et al., 2020). The GIS-based method is commonly used to analyse the visibility of large-scale water bodies (oceans) (Dempsey et al., 2018; Nutsford et al., 2016). However, the limitations of the input data and the interwoven features of water and vegetation (green space) make it difficult to apply in the visibility calculation of inland water bodies relying more on individual's self-report or other alternative indicators.

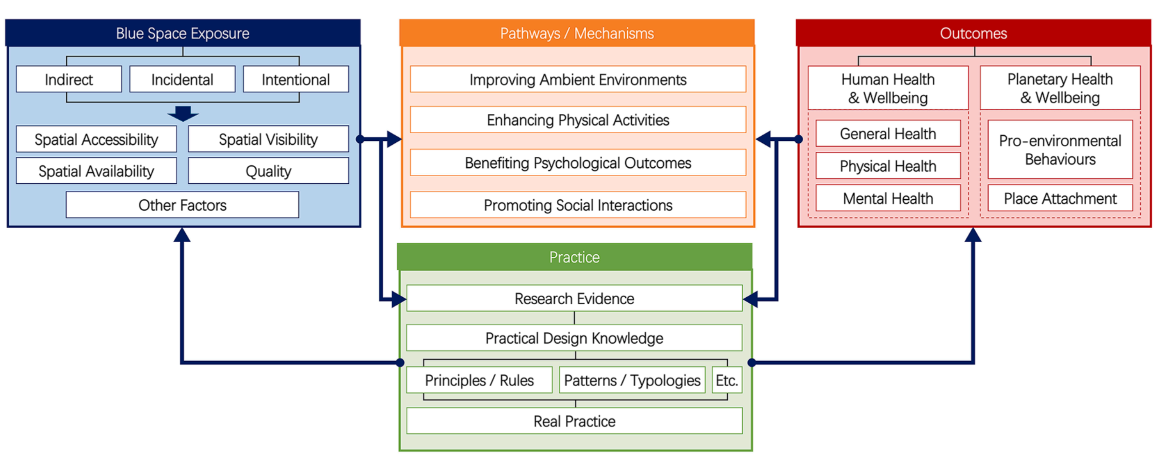

Fig. 1. A tailored conceptual framework of the relationships amongst blue spaces, human health, and practice based on the existing studies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1.3. Existing methods for describing blue space exposure

Given the two dominant aspects of blue space exposure, multiple approaches quantitatively measure spatial accessibility and visibility of blue spaces. Existing studies on the accessibility of green/blue spaces or public facilities systematically categorised the methods of measuring spatial accessibility into three types (McDougall et al., 2020; Wang et al., 2021; Zhang et al., 2011): a) statistical index approaches, also known as area-based or container approaches, which describe spatial accessibility by measuring the existence or density of green/blue spaces in a defined geographic area. Specific indicators include quantity, total area, land use ratio, cumulative kernel density estimation, etc. (Pasanen et al., 2019; Wu & Kim, 2021); b) spatial proximity approaches or travel cost approaches emphasise the travel costs between green/blue spaces and individual's location, with specific indicators including linear/network distance, estimated travel duration, self-reported distance/time, etc. (Hooyberg et al., 2020; McDougall et al., 2022); c) spatial interaction approaches, the extension of the gravity model, consider the supply-demand relationship of green/blue spaces and population to describe accessibility, and specific methods include gravity model analysis, 2SFCA, E2SFCA, 3SFCA, etc. (Liang et al., 2023; Sharifi et al., 2021). Generally, these methods primarily rely on GIS for calculation, and some recent advanced techniques have shown great potential in integrating existing methods (Costa et al., 2021; Rothfeld et al., 2019; Wolff, 2021). For spatial visibility, the viewshed method conducted in GIS is commonly adopted in current blue-health research to quantify visibility. Isovist analysis originates from architectural and urban analysis, which share similar computational logic of viewshed. Some studies have demonstrated its potential to introduce 3D models of urban environments to describe visibility more accurately (KIM et al., 2019; Krukar et al., 2021; Morello & Ratti, 2009). In addition, segmentation analysis from computer vision is being widely used in measuring green exposure, while eye-tracking analysis is being accepted in many studies to describe visibility subjectively for exploring visual preference.

1.4. Knowledge gap and research objective

Currently, only limited studies mentioned and analysed the methods for measuring spatial accessibility and visibility, and even fewer explored their application potential. Specifically, McDougall et al. (2020) identified four types of methods for measuring blue space quantitatively and critically compared these methods to inspire subsequent research. Labib et al.'s (2020) research analysed the methods for describing spatial exposure used in nature-health studies from a broader perspective and appealed to the multi-scale methods to comprehensively understand nature exposure. These two studies primarily reviewed existing methods and evidence rather than providing case applications to demonstrate the potential of each method. On the other hand, Liu and Nijhuis (2020) and Wang et al. (2021) adopted specific cases to compare and analyse the application of different methods. Derived from the study of green spaces, Wang et al. (2021) compared the methods for spatial accessibility and explored the inter-relationship amongst them. Liu and Nijhuis (2020) took a similar view of this research by emphasising the method's potential in spatial design, while it explored the methods for understanding spatial-visual characteristics from the larger landscape design perspective.

Although these studies provide valuable support for this research, there remains a knowledge gap in applying the methods for measuring blue space exposure for usage in design and planning (WHO, 2021a; Zhang et al., 2022). Specifically, this gap lies three-fold. First, some practical methods for analysing blue space exposure have been inspired and provided by existing studies, while the contents and indicators described by these methods are not systematically summarised and explored. Wang et al. (2021) study compared the methods for the accessibility of green space, but there are limited articles focusing on visibility. Second, due to the spatial nature of the methods used to describe blue space exposure, it is worth exploring the potential of incorporating and applying them in spatial design and interpreting their application from the design perspective through real cases. Spatial design is a core activity in urban design, landscape architecture, and related disciplines, providing spatial solutions for fulfilling the health benefits of blue space exposure (Nijhuis & de Vries, 2019). Third, there are challenges in method selection and application guidance in combining the methods in multi-scale spatial design as urban environments' complexity and dynamic nature (Nijhuis & de Vries, 2019). Only limited studies have explored the application of some of these methods in design practice (Bell et al., 2021; Mishra et al., 2020). Based on the analysis–synthesis–evaluation (ASE) paradigm (Braha & Maimon, 1997; Jones, 1992), evidence/knowledge-based design approaches are being widely adopted, and designers require these methods to translate evidence into practice (Brown & Corry, 2011; Klaasen, 2017; Nijhuis & Bobbink, 2012). Therefore, all of the above provide the necessary prerequisites for incorporating methods of describing blue space exposure into spatial design.

This study aims to explore advanced digital methods for analysing and optimising spatial accessibility and visibility of water for designing sustainable healthy urban environments. Several cases in Rotterdam are used as examples to test and demonstrate their application to reveal the performance of blue space exposure in urban environments regarding spatial morphology and physical characteristics. Specifically, eight methods for describing blue space exposure, classified by two key concepts and three scale levels, are presented in this paper, including a) regional level: statistical index approach, spatial interaction approach, and spatial orientated approach; b) district level: spatial proximity approach and object-based approach; c) local level: 3D landscape analysis, spatial configurational approach, and segmentation analysis. Subsequently, these methods are applied to cases in Rotterdam based on three scale levels to demonstrate and explore their potential in assisting spatial design to achieve the blue space's health benefits for sustainable healthy urban environments.

The paper is organised into the following sections (Fig. 2). Section 2 provides the specification of methods for describing blue space exposure, the clarification of spatial scales, and the contents or indicators described by the methods at each spatial scale. Section 3 introduces the

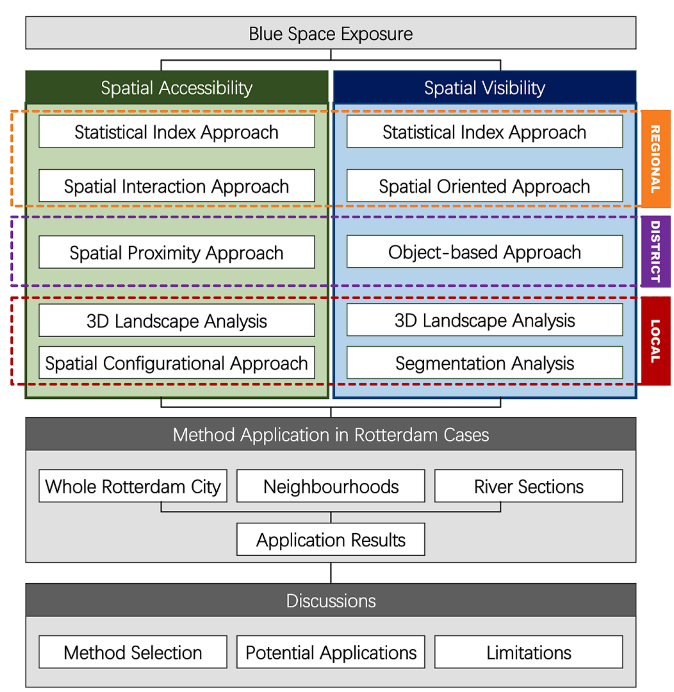

Fig. 2. A brief framework of the research.

study context, data, analysis methods or tools in the research. Section 4 presents the application results of eight methods for describing blue space exposure, consisting of the mapping visualisations and their interpretation from the standpoint of spatial design. Next, the applicability of these methods, the framework for integrating them into design processes, and the limitations of this research are discussed in section 5. In the end, a concluding remark is proposed.

2. Methods for measuring exposure

2.1. The potential of incorporating methods of describing blue exposure in spatial design

As mentioned above, blue space exposure could be mainly conceptualised into accessibility and visibility, and several methods are emerging and available to describe or measure them. Since the evaluative nature of these methods, they show great potential to assist the design of blue spaces, which could parallel current research to better understand the relationship between blue space exposure and health benefits. According to the analysis–synthesis–evaluation (ASE) paradigm, design is an iterative process and can be divided into three interconnected phases (Braha & Maimon, 1997; Jones, 1992; Nijhuis & de Vries, 2019). Specifically, the analysis phase allows designers to collect knowledge or information from the existing context and identify the limitations or potential for subsequent steps. The synthesis phase refers to the process in which designers creatively propose solutions based on analysis results and communications with different stakeholders. Finally, the evaluation phase simulates and assesses the integral solutions (Nijhuis & de Vries, 2019). A well-known example is the Geodesign framework developed by Steinitz (2012), which combines GIS-based impact simulation methods with the creation of policies and design proposals. Methods for describing the accessibility and visibility of blue space could play the same role by supporting policymakers and designers in analysis, assessment/simulation, and communication during the practice.

2.2. Understanding the role of scale in integrating the methods of describing blue exposure into the design process

Scale is an inevitable critical concept when incorporating methods of describing blue space exposure into the design process, as is the case with current research on the relationship between blue space exposure and human health. For example, the area-based approach for measuring blue accessibility can help answer the health effects amongst different levels of blue exposure and assess the spatial equity of blue spaces at the regional level. They are often analysed in conjunction with health data based on regional statistics (McDougall et al., 2020). On the other hand, scale is one of the core concepts in spatial design, distinguishing spatial design into many sub-categories, ranging from regional design to detailed building technology. Spatial design at different scales responds to specific questions, influences stakeholders' interests operating at that scale, and impacts other scale levels (de Jong, 2006).

To help integrate the methods of describing blue exposure into the design process, it is necessary to distinguish scales. Otherwise, the paradox of scale can arise, in which conclusions made at one scale cannot be applied to another without concern (Gell-Mann & Mermin, 1994). To properly classify scales for incorporating methods into the design process, two existing spatial scale classification approaches, derived from the spatial design and behavioural/cognitive geography, respectively, are mainly introduced to provide the basis. Specifically, the first approach is developed from de Jong (2006) . From the spatial design perspective, his research divided physical space into six categories: regional design, urbanism, urban design, architecture, interior design, and building technology, which correspond to the different physical sizes and in line with the recent '3–30–300 rule' for spatial planning aimed at fulfilling health benefits of green spaces (Konijnendijk, 2023; Nieuwenhuijsen et al., 2022). On the other hand, the classification of space proposed by Montello (1993), centring on people's psychological spatial perception, is included as the second source for distinguishing scales. By considering the human body's locomotion in space, Montello's classification focused on the functional properties amongst different scales and distinguished four main types of psychological spaces, including figural, vista, environmental, and geographical spaces (Montello, 1993).

Due to the continuous nature of physical space, different scales serve different objectives and are not entirely isolated but partially overlapping. By incorporating these two classification approaches, an analytical diagram is proposed to develop a new simplified spatial classification, which helps explore the application of the blue exposure methods in the design process (Fig. 3). Thus, a connection from the scale between psychological and physical space is established by setting psychological space scales as the horizontal axis and physical space scales as the vertical axis. For the sake of clarity, three new scales are defined, including local, district, and regional levels, each corresponding to physical and psychological space, respectively. Specifically, the regional level mainly refers to the sub-national, regional design and urbanisation scale in physical space. While in psychological space, it relates to the environmental and geographical space that cannot be perceived through people's movement. On the other side, the local level spans multiple scales of physical space, from building technology to architecture/landscape design, and can be perceived directly or through limited locomotion, which refers to figural and vista space according to the psychological space. The district level lies in the middle of the classification, which ranges from architecture/landscape design to urbanism scale from physical space and corresponds to vista and environmental space in psychological space. At this level, space can be perceived by people through considerable movement. The simplified classification aligns with the existing '3–30–300 rule' in planning, which supports subsequent applications and interpretations of methods from spatial planning and design.

Similar to the existing classification approaches, which have fuzzy boundaries between scales, the boundaries of the new three levels are not distinct and contain some overlapping areas in order to improve the method's applicability potential and avoid the limitations caused by explicit categorisation. Specifically, the advantages are three-fold: (1) strengthening the continuous and dynamic nature of space, whose importance has been pointed out in the existing space classifications; (2) providing flexibility in the choice of methods to describe visibility and accessibility of blue spaces based on target audiences and participating stakeholders for some cross-scale projects; (3) supporting practitioners to make integrated decisions based on the evidence provided by different methods in some projects located in the overlapping areas.

2.3. Methods and their meanings for describing blue exposure at different scales

Reviewing the existing research outcomes on the blue/green spaces exposure shows eight representative methods for describing it, including the statistical index approach, spatial interaction approaches, spatial orientated approach, spatial proximity approach, object-based approach, 3D landscape analysis, spatial configurational approach, segmentation analysis (Dempsey et al., 2018; Helbich et al., 2019; Liu & Nijhuis, 2020; Ma et al., 2022; Nijhuis, 2015; Nutsford et al., 2016; Qiang et al., 2019; Ruzickova et al., 2021; Tannous et al., 2021; Wang et al., 2021; Yu et al., 2016; Zhou et al., 2019). The details, meanings, and application potentials of the methods are briefly discussed below in accordance with the three scale levels just presented.

2.3.1. Regional level

Space at the regional level cannot be perceived by people even through massive movements. It is mainly connected to regional or urbanism design projects, the outcomes of which are often abstract, such

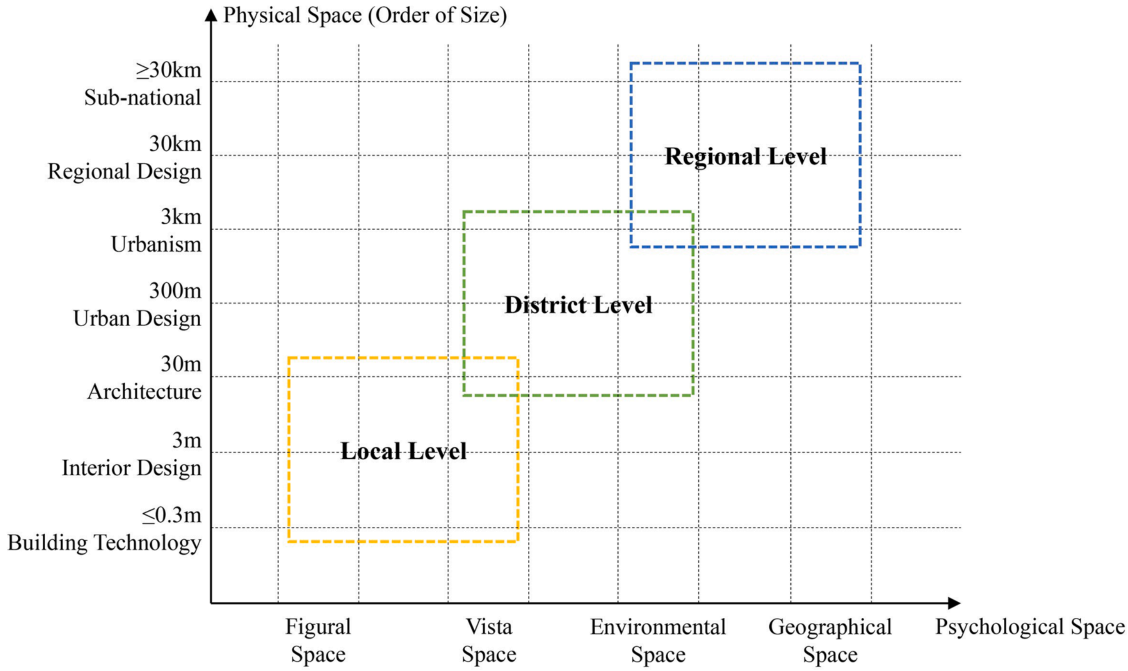

Fig. 3. Space classification based on the existing two approaches (Developed based on de Jong's (2006) and Montello's (1993) research).

as policy recommendations and visions for future development. Accordingly, the statistical index approach, spatial interaction approach, and spatial orientated approach could be suitable and applicable to spatial design projects at the regional level for describing exposure (Table 1). Specifically, the statistical index approach measures the number, total area, or density of blue spaces within selected units (Chen & Yuan, 2020; Pearson et al., 2019; Wang et al., 2021). These indicators can be regarded as alternative indicators of accessibility or visibility and show good reliability when analyses in conjunction with health data at the regional level (Boers et al., 2018; Crouse et al., 2018; White et al., 2021), as the greater the proximity to blue spaces, the higher the likelihood of contact with them (White et al., 2020). Its advantage lies in the simplicity and convenience of data acquisition, calculation, and explanations, allowing for evaluation under limited time or data and communication of results with others easily. Its shortcomings consist of the difficulty in accurately describing blue space exposure and the modifiable areal unit problem (MAUP) when measuring accessibility (Wong, 2004). On the other hand, spatial interaction and spatial-orientated approach could provide more precise and direct measures of accessibility and visibility, respectively, with

Table 1
Specification of 8 methods for describing blue exposure based on three scale levels.

Application scale	Methods	Type of exposure	Description	Main tools & platforms	Input data	Interactions with planning and design processes
Regional level	Statistical index approach	Accessibility Visibility	Using some indicators (e.g., total or mean area) within selected units to describe the accessibility or visibility of blue spaces	GIS[a]; Excel	Land use map; Satellite images	Pre/post-planning/ design analysis
	Spatial interaction approach	Accessibility	Measuring accessibility by considering the supply-demand relationship	GIS; Excel	Land use data; Population data	Pre/post-planning/ design analysis
	Spatial orientated approach	Visibility	Delineating the surfaces or areas which are visible to a set of observer features	GIS	GIS data (raster)	Pre/post-planning/ design analysis
District level	Spatial proximity approach	Accessibility	Measuring the minimum travel time or distance, or the amount of blue spaces that can be reached within a certain time or distance threshold	Python; GIS; Online map platform	Road data (vector)	Pre/post-planning/ design analysis
	Object-based approach	Visibility	Similar to the spatial-orientated approach, but with more focus on the polygon of visibility	Rhino & Grasshopper; Depthmap X	Rhino 3D models; CAD maps[b]	Scenario-based analysing tool
Local level	3D landscape analysis	Accessibility Visibility	Using photos or digital models to describe the exposure qualitatively	Camera; Rhino; SketchUp	Field survey; Photographs; 3D models	Scenario-based analysing tool
	Spatial configurational approach	Accessibility	Exploring the characteristics of spatial configuration to analyse whether the specific locations are easy to reach or pass through	Depthmap X; GIS; Pen & Sketchbook	Field survey; CAD map (Road networks)	Pre/post-planning/ design analysis
	Segmentation analysis	Visibility	Describing the types and proportions of landscape elements in the FOV quantitatively	Python; Excel	Photographs	Scenario-based analysing tool

[a] GIS (Geographic Information System) refers to software applications used for capturing, storing, analyzing, managing, and presenting geographic or spatial data, such as ArcGIS, QGIS, etc.
[b] CAD (Computer-Aided Design) maps represents the digital documentations and drawings of specific areas that produced by 2D or 3D CAD programs such as AutoCAD, Rhino 3D, etc.

high-quality data availability and computing power. Spatial interaction approaches could avoid MAUP and generate accessibility measurements by incorporating population data and distance decay models (Tao et al., 2020; Wang et al., 2021). However, the distance decay model selection may influence the calculation results. Moreover, the spatial orientated approach could be used to measure blue visibility at the regional level using cumulative viewshed analysis to calculate the total area of visible blue space in specific areas. Although it provides more accurate descriptions of visibility, the requirements of computing power and model quality (such as high-resolution Digital Surface Model) are much higher than the statistical index approach. For practitioners, all three methods allow comparison between different areas and pre-/post-interventions of sites to support the development of policies and design interventions.

2.3.2. District level

The district-level space can be gradually perceived through locomotion, connecting the physical scales from urbanism to architecture/landscape design. Describing blue space exposure at this level should consider people's movements which are affected mainly by spatial morphological attributes and elements arrangement. Therefore, the spatial proximity approach measuring accessibility and the object-based approach describing visibility could be adopted at this level. Specifically, the spatial proximity approach describes accessibility by measuring the travel cost of the nearest blue space or the amount of blue space that can be reached within a certain threshold (Wang, 2012). However, it could be influenced by destination selection and travel preferences, which assume people prefer to use the nearest blue spaces (Wang et al., 2021). Moreover, with the development of geo-big data approaches incorporating real-time traffic information and point-to-point distance calculations, it has become possible to analyse space-time accessibility through travel time estimations, which is more representative of individual behaviour and movement than accessibility on Euclidean/network-based distance (Costa et al., 2021; Su et al., 2017). The object-based approach, a three-dimensional (3D) visibility calculation, could represent the proportion of visible blue spaces to the observer's views during the specific movements. Compared with the viewshed analysis in GIS relying on 2.5D geometry, its advantage lies in using 3D models to describe blue visibility, which has a more accurate representation of vegetation and other elements (Ruzickova et al., 2021). Moreover, the analysis results of these two methods could be clearly demonstrated in visualizations to assist designers in the analysis and evaluation phases. Especially, the object-based approach could be used as a scenario-based tool, allowing instant changes to represent and test new ideas by designers.

2.3.3. Local level

The local-level space emphasises the people's direct perception without movement. It is closely related to projects of architecture/landscape design, interior design, and even building technology. Accordingly, the projects at this level emphasise specific spatial forms and their meanings, and the outcomes mainly include the spatial organisation of various landscape elements based on physics, function and aesthetics (Nijhuis, 2015; Polat & Akay, 2015). Describing blue exposure at this level mainly considers the influence of physical environments' specific configurational and compositional properties on people's direct contact with or view of blue spaces. Therefore, the blue exposure at this level can be described and analysed by 3D landscape analysis, spatial configurational approach, and segmentation analysis. To be specific, 3D landscape analysis is widely used by designers in daily practice to identify the characteristics of specific spatial arrangements using 2/3D visualisations (Liu & Nijhuis, 2020). It provides qualitative descriptions of accessibility and visibility based on spatial characteristics, which may be influenced by the designer's subjective interpretation. The spatial configurational approach could offer quantitative measurements of accessibility compared to 3D landscape analysis. It relies significantly on the interrelationship between human behaviour and urban surroundings, such as the notion of natural mobility, which argues roadway layout affects city movement patterns (Hillier et al., 1993; Koohsari et al., 2019). Through exploring the spatial configurations, accessibility could be described as whether it is easy to reach or pass through. On the other hand, the segmentation analysis mainly uses techniques and algorithms in computer vision to provide an objective description of blue space visibility, which calculates the amount of different landscape elements and their proportion in fixed viewpoints. It is noted that 3D landscape and segmentation analysis are also scenario-based tools allowing designers to test ideas quickly.

In brief, the eight methods are classified into three categories based on three scales and two aspects of blue exposure (Table 1). The statistical index approach is appropriate for describing visibility and accessibility at the regional level. Meanwhile, the spatial interaction method is suitable for blue accessibility, and the spatial orientated approach emphasises blue visibility. At the district level, the spatial proximity approach can be utilised to describe blue accessibility, whereas the object-based approach can be employed for blue visibility. Additionally, at the local level, the 3D landscape analysis can be considered a robust tool to describe both aspects of exposure, similar to the statistical index approach. The spatial configurational approach is particularly suitable for evaluating accessibility, while the segmentation analysis focuses on blue visibility.

3. Case study and data sources

3.1. Case study context

To showcase the applications of blue exposure describing methods at different scales and how their results can be interpreted from the design perspective, several cases in Rotterdam are used as examples. Rotterdam, the second largest city of the Netherlands and Europe's major port, is located in Western Europe with a temperate oceanic climate (Fig. 4). The city covers 326 km^2 and contains a population of over 600,000. It is a commercial and industrial hub at the Nieuwe Maas River, and its economy is heavily dependant on careful water control. The city is located on river banks, polders, and reclaimed land, and much of the city is below sea level (up to -6 m). Therefore, the city has wealthy blue space resources, including different types of natural and artificial waters, which account for 34.9% of the city's surface. The local government has implemented various plans to enhance the quality of green/blue spaces, underscoring their importance in the urban environment (Frantzeskaki & Tilie, 2014). On the other hand, existing studies have reported the positive relationships between blue space exposure and health in Rotterdam, providing concrete evidence for selecting cases (de Vries et al., 2003, 2016; Jansen et al., 2018; Luttik, 2000; White et al., 2021). Moreover, data availability and physical accessibility (i.e., fieldwork) contribute to evaluating the analysis results and allow for reflection on their potential integration into design phases. As a result, Rotterdam is an important and representative learning case for exploring the potential of different blue exposure-describing methods.

3.2. Data sources and analysis tools

Data used in the study areas are from multiple sources (see supplementary materials for detailed information). Most vector data of spatial features was extracted from the BGT (Basisregistratie Grootschalige Topografie) database via the PDOK platform. The raster data of Rotterdam for visibility analysis at the regional level mainly adopted the digital surface model (DSM) with 0.5 m resolution, which developed on laser altimetry from AHN (Actueel Hoogtebestand Nederland) and captured height information of city surface, including non-ground level objects (such trees, buildings, etc.). The raw road network data were sourced from the OSM dataset (OpenStreetMap 2022), and then the BGT data were used for manual inspection to meet the requirements of space syntax analysis. Population and neighbourhood data were obtained from

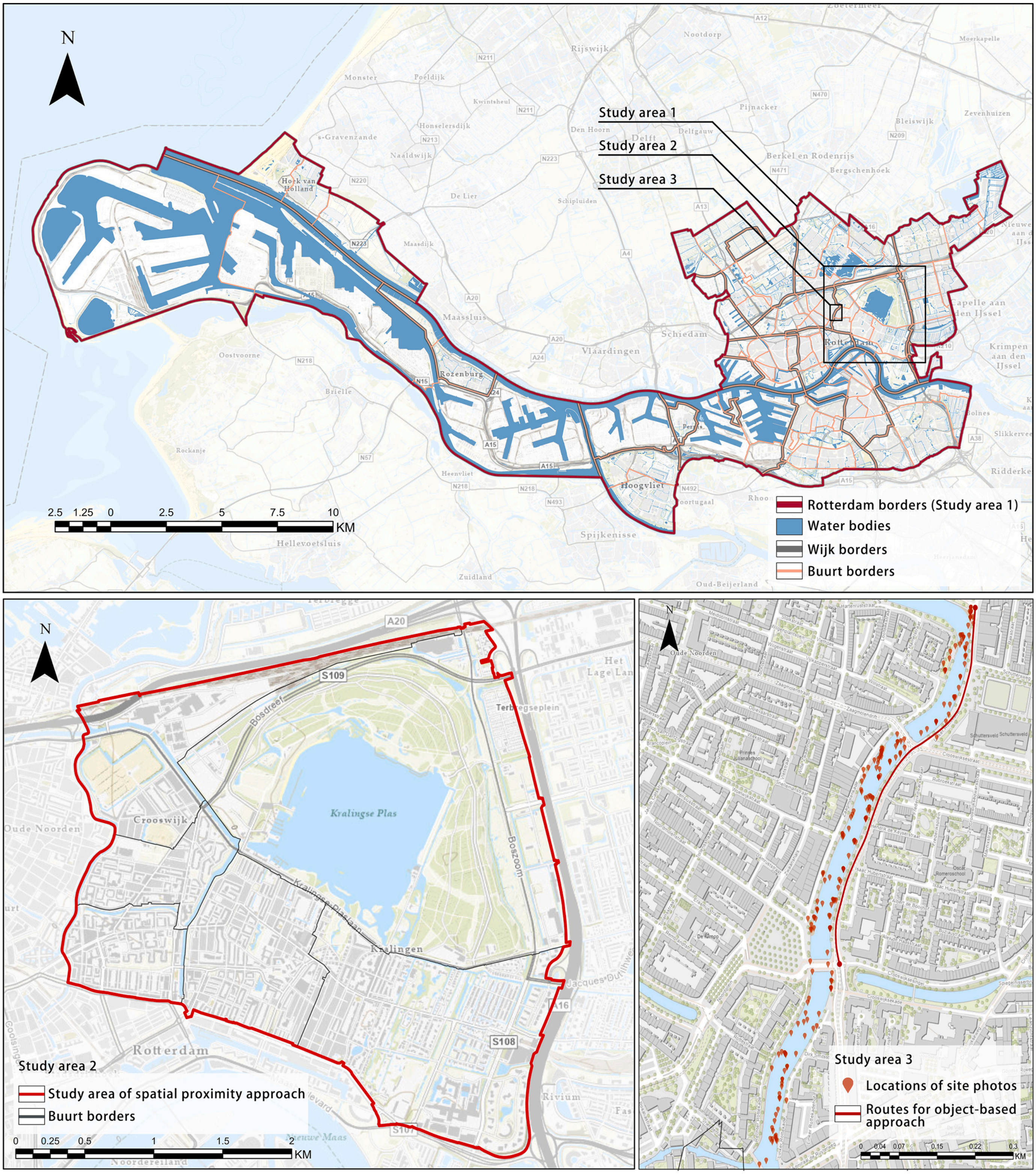

Fig. 4. Study areas in Rotterdam.

CBS (Dutch Central Bureau of Statistics). The data for digital models and photographs used in 3D landscape analysis were collected during the fieldwork in August and September 2022.

As mentioned above, eight methods for describing blue exposure were introduced to explore their application potential in multi-scale design processes. Each technique has its own features, so the next section and supplemental materials give extensive method descriptions, application outcomes, and interpretations of results from the design perspective.

4. Applications of methods for describing blue space exposure

Eight methods were applied at different scales to describe blue exposure, addressing space from quantitative and qualitative perspectives and evaluating the study results from the design perspective.

4.1. Describing blue exposure at the regional level

Describing blue space exposure at the regional level adopted two neighbourhood units for analysis and summarising results, including Wijk and Buurt (in Dutch). They are developed by the CBS based on the characteristics of urban history, development and design, making them suitable for describing blue space exposure at the regional level. Normally, Wijk is larger in scale and contains several Buurts that dominate by a single main function. Fig. 5 [1–4] shows the spatial patterns of the blue exposure in Rotterdam, produced by the statistical index approach based on Wijk and Buurt, respectively. The statistical index approach counted the total blue space area (see supplementary materials), the percentage area of blue spaces over the total area ([1], [3]), and the per capita area ([2], [4]) of blue spaces within different Wijk or Buurt as indicators to describe both accessibility and visibility, with darker colours indicating higher blue exposure. The results of the three indicators presented a similar pattern, high exposure areas (red areas) appear in the western part of the city, away from the city centre, and mainly serve as the port area. Within the city centre, the spatial distribution of high blue exposure areas is scattered, primarily appearing in the neighbourhoods located in the central and southern parts of the city.

Fig. 5 [5–6] presents the analysis results through the spatial interaction approach considering the supply-demand relationship between resources and the population. The results are also summarised based on Wijk and Buurt borders, where darker colours indicate better accessibility. The Gaussian-based two-step floating catchment area (G2SFCA) method is adopted in this research since its simplicity in implementation and data availability (Dai, 2011; Li et al., 2019; Wang, 2012). A detailed description of the G2SFCA method is presented in the supplementary

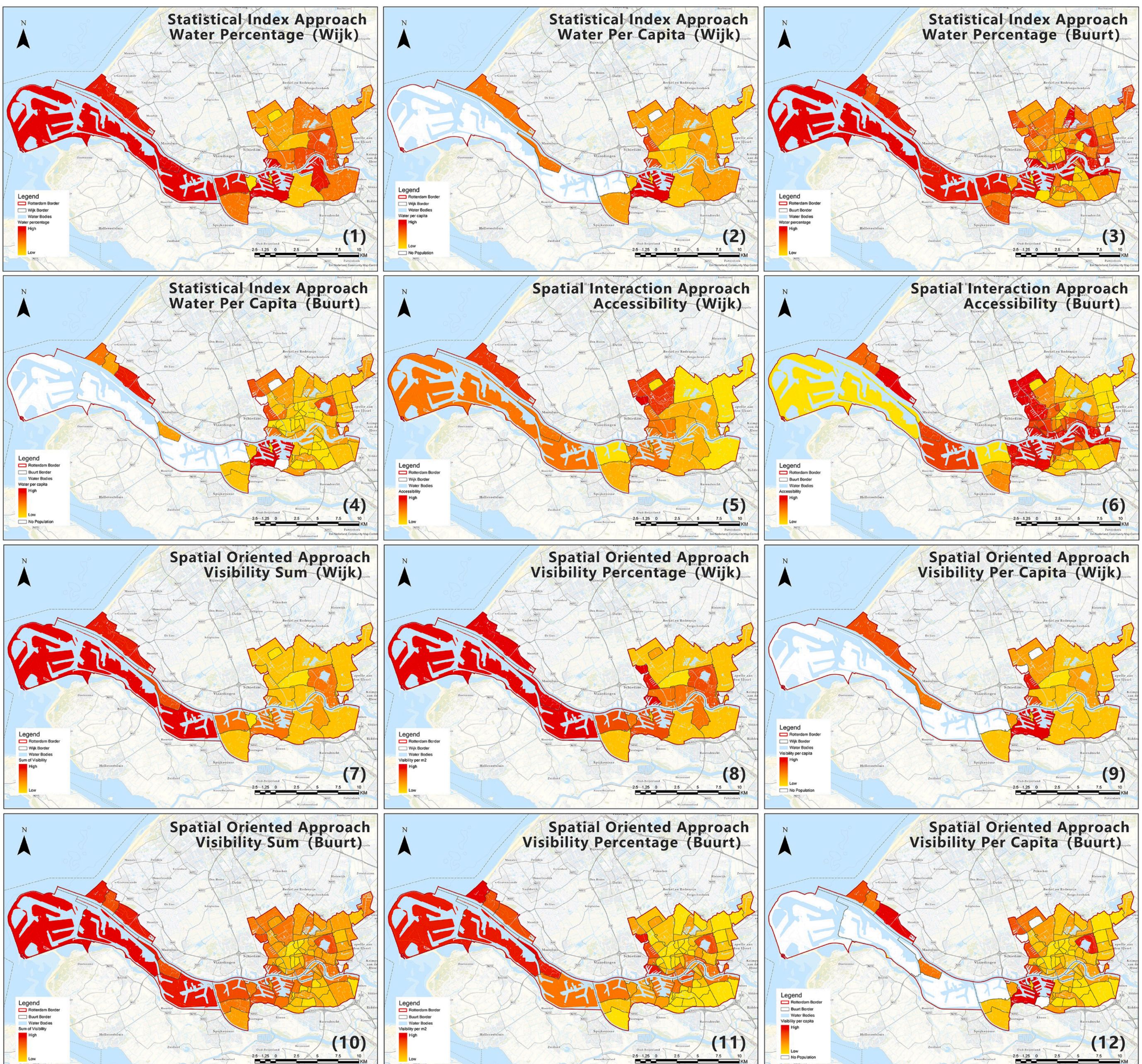

Fig. 5. Analysis results at the regional level based on the Wijk and Buurt boundaries.

materials. The average accessibility index of all population grids in Rotterdam was 121.33, indicating the great overall accessibility of blue spaces. According to the spatial distribution of areas with high accessibility, the Nieuwe Maas River is the most important provider of blue spaces. On the other hand, the standard deviation of the accessibility index was 239.48, showing apparent spatial differentiation amongst population grids. From the mapping of the result based on the Wijk border, it can be found that the northeast and southeast neighbourhoods, including Prins Alexander and IJsselmonde, have relatively poor blue space accessibility. In addition, the smaller border (Buurt) mapping results indicate that the detailed areas with weak blue space accessibility are mainly located in the city's northeast, central and southern neighbourhoods. However, some of these smaller neighbourhoods (Buurt) have good accessibility, while they are classified as those areas with low accessibility in the larger neighbourhood (Wijk) border mapping, including Oude Noorden and Agniesebuurt.

The spatial orientated approach is conducted for analysing blue visibility at the regional level through the cumulative viewshed analysis method. Its results are presented in Fig. 5 [7–12] and also summarised based on the Wijk and Buurt borders. Cumulative viewshed analysis is widely used in research on visual impact assessment (VIA) of specific projects (Palmer, 2022). This study extends its application from projects to the visibility of water bodies by setting the point matrix with multiple grids. Detailed descriptions of the analysis method and the sensitivity analysis for selection modelling grids are presented in the supplementary materials. In general, locations with strong blue visibility captured by the spatial orientated method are found on both banks of the Nieuwe Maas river and near major lakes, demonstrating that large-scale water bodies have a greater impact on visibility. Besides, dense and high-rise buildings along the Nieuwe Maas River may impede visibility from distant neighbourhoods, except those in the west port region with low-density and low-height structures. Incorporating population data into cumulative blue visibility study results (Fig. 5 [9] and [12]) demonstrates that city centre blue visibility declines, especially for the results on the Buurt border. When the total area of each neighbourhood is considered (Fig. 5 [8] and [11]), the changes in overall patterns are limited, while the visibility of some neighbourhoods is amplified.

Comparing the three approaches' spatial patterns reveals multiple similarities and some variations. In general, existing studies have shown that the spatial interaction approach considering the supply-demand relationship and the spatial orientated approach describing cumulative blue visibility provide more accurate analysis results than the statistical index approach (McDougall et al., 2020; Wang et al., 2021). These analysis results can provide the basis and evidence for spatial planning and design at the regional level from four aspects. First, identifying the areas with high and low blue exposure could support proposing regional spatial development strategies and policies, such as increasing blue space provision in low-exposure areas, enhancing the development of high-exposure areas, controlling building height or reserving visual corridors to increase blue visibility from distant areas, etc. Second, different types of blue spaces can significantly influence blue exposure, whereby linear water bodies significantly affect blue accessibility and large-scale water bodies greatly impact blue visibility. Therefore, Rotterdam's overall blue space exposure could be improved by adjusting the regional traffic structure or visual corridors related to linear and large water bodies. Thirdly, more specific spatial interventions at the district/local level can be supported by the results of regional-level blue exposure analysis based on different neighbourhood borders (Buurt and Wijk). It can help enhance the pertinence of the spatial strategies, as some neighbourhoods (Buurt) with better blue exposure are classified as less blue exposed in the larger-scale neighbourhood borders (Wijk). Lastly, considering the results of the accessibility and visibility analysis together can lead to targeted recommendations for improving blue exposure. For instance, improving the blue exposure of Noord Wijk with relatively good blue accessibility and limited visibility should focus on design strategies emphasising blue visibility. On the other hand, the identification of areas with poor blue exposure can provide support for policymaking. For example, Oude Noorden, Agniesebuurt and Provenierswijk Buurt in Noord Wijk could be considered critical for subsequent spatial interventions as they have both poor blue accessibility and visibility.

4.2. Describing blue exposure at the district level

The spatial proximity and object-based approaches were applied to describe the blue exposure at the district level. As mentioned above, the minimum costs for visiting blue spaces are selected as the indicators to describe blue accessibility at this level. Existing studies suggest multiple means to measure such travel costs. Euclidean distance between individual locations and blue spaces could be the most commonly used way to measure travel distance, which is convenient to conduct in GIS. However, the simplicity of Euclidean distance calculation leads to the inaccuracy of measuring. It is widely recognised that network-based analysis could provide more accurate measures of travel costs to capture actual travel behaviour (Wang et al., 2021). On the other hand, the network-based analysis method largely relies on the modelling quality of the road network, which poses challenges to data availability. With advanced technology and novel geo-big data approaches, the API function of the online map platform could provide a promising measurement of space-time accessibility by estimating travel time costs (Rothfeld et al., 2019). Compared to the Euclidean/network-based analysis, its advantages lie threefold: (1) the higher precision of the results on space-time accessibility by considering the combination of real-time traffic flow and door-to-door distance; (2) describing individual movements and reflecting behavioural preferences directly through estimating travel time costs; (3) no need for advance preparation with updated road network data available. Inspired by Rothfeld et al.'s (2019) research, the travel time and distance between blue space entrances and individual locations are obtained from the Google Maps Distance Matrix API. Several neighbourhoods (Buurt) located in the city centre were carefully selected as case studies (Fig. 3). These neighbourhoods encompass various blue spaces and exhibit a population density that exceeds the city average. Collectively, the selected area covers an approximate area of 9 km^2, corresponding to the district level in our study. Subsequently, the walking travel time mapping was generated with the resolution of 50*50 m through the assistance of the Distance Matrix API and QGIS. Next, the number of blue space entrances that can be reached is mapped according to different time thresholds, including 5, 10, and 15 minutes. The selection procedures of the blue space entrances, the application of Distance Matrix API, and the mapping processes are explained in the supplementary materials.

Fig. 6 shows the analysis results of the spatial proximity approach. In general, areas with high accessibility captured by travel time calculation are located in the southern part of the study region with denser coverage of road networks. And the less accessible areas exist mainly in a small part in the north and northeast, as the adjacent highway blocks the walking routes. Only a few areas can reach multiple blue space entrances within 5 minutes of walking. As the time threshold increases, more blue space entrances are accessible. However, areas in the north and northeast and some scattered areas still retain poor accessibility, where even the number of blue space entrances reachable within 15 min walking is limited. The measurements and visualisations of travel costs or related indicators calculated by the spatial proximity approach allow designers to better identify areas that require design interventions and are closely related to spatial design projects at the district level. In addition, the different indicators calculated by the spatial proximity approach can provide mutual support for identifying areas with limited accessibility.

While describing accessibility via travel costs of movement, the object-based approach analyses the visibility of blue spaces at the district level, emphasising the blue visibility during movements and requiring a more precise representation of physical environments. Viewshed analysis used in the spatial orientated approach could also be

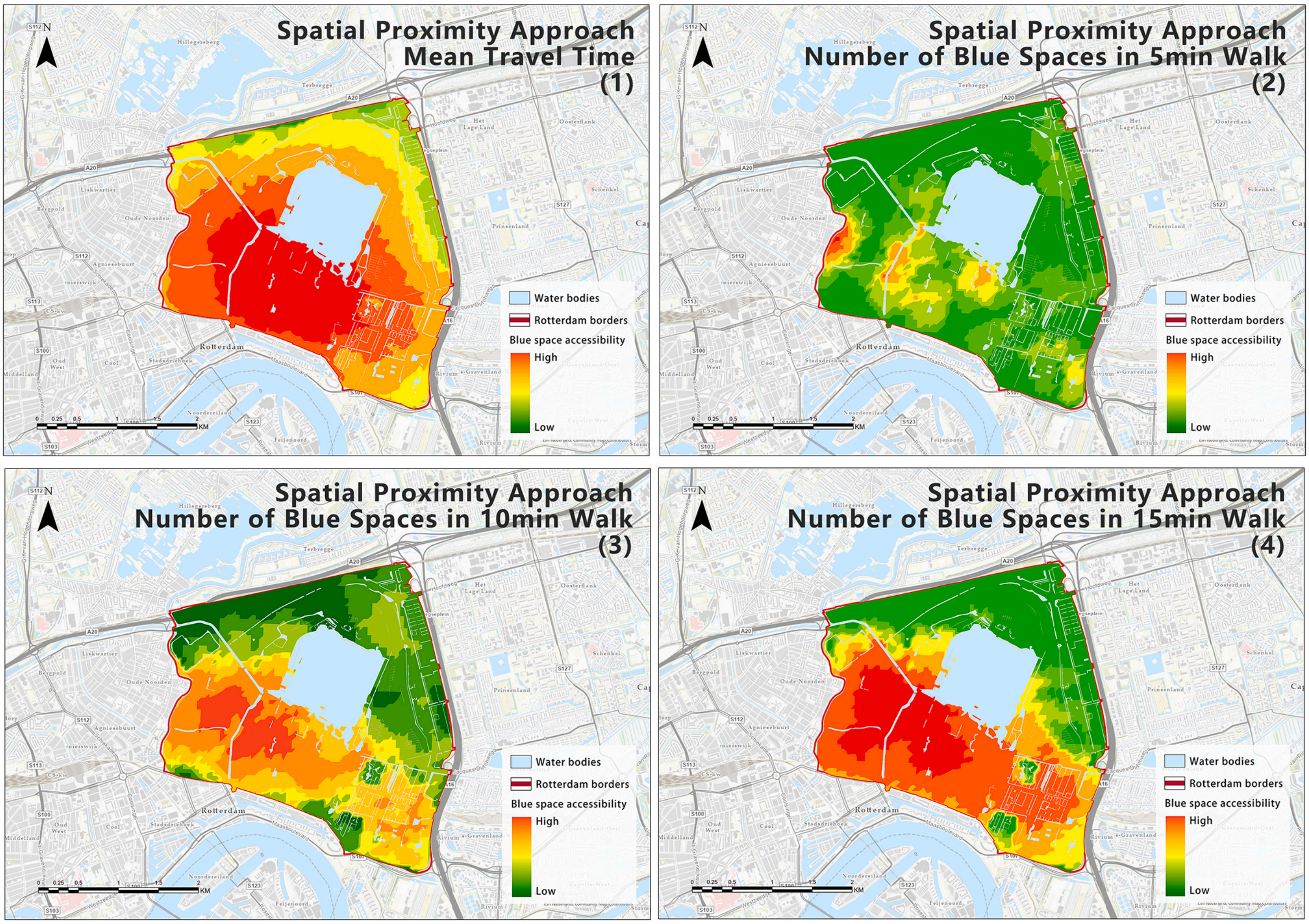

Fig. 6. Accessibility analysis results at the district level.

adapted to measure blue visibility in this situation to some extent. However, it is mostly conducted in GIS environments relying heavily on 2.5D geometry, and the accuracy of modelling physical environments may not be guaranteed (Ruzickova et al., 2021). Therefore, a novel method, called the object-based approach, is developed in this study to describe visibility at the district level. Relying on the Isovist analysis, it is conducted in the Rhino-Grasshopper environment by considering transportation modes, directions, and characteristics of viewing during movements, providing interactive results directly (Fig. 7). Compared with viewshed analysis, it introduces 3D geometry for analysis, which greatly improves the accuracy of modelling and calculation. On the other hand, the object-based approach presents the advantage of usability and real-time interactivity, allowing practitioners to quickly understand the blue space visibility under movements and simulate various potentials to support decision-making, even though the precision may be lower than the segmentation analysis using in-site photos.

Fig. 7 shows the analysis results of two directions and three transportation modes, which can directly identify the changes in the blue-visible range in movements. The blue visibility analysis results of the two directions present a similar pattern. The northern section of the selected route shows lower visibility of blue spaces compared to the southern section, with relatively higher blue visibility. The differences within the route could be that the northern section has more vegetation, leading to a minor proportion of the visible blue spaces. In addition, blue visibility while jogging alongside the route is the highest amongst transportation modes in both directions, while blue visibility is the lowest during walking. There was inconsistency in the blue visibility of the three transportation modes, which varied greatly in blue visibility change but showed a similar trend amongst the jogging and cycling. In contrast, the blue visibility of walking had a unique trend with limited fluctuations. This may be caused by the differences in the field of view (FOV) amongst different traffic modes. Specifically, walking has a large FOV, while the FOV of jogging and cycling mainly concentrates on the front to avoid dangers in movements. On the other hand, some sections with abnormally high or low blue visibility can be identified, such as viewpoints 1, 2, and 24, showing the lowest blue visibility while cycling along path B, significant blue visibility changes happening at viewpoints 18–19 while cycling and jogging along path A, and a similar pattern also appears in viewpoints 32–33 along path B.

The above results of the object-based approach could be used to assist spatial design in multiple ways. First, this analysis can support vegetation planning and design by comparing the differences in blue visibility caused by vegetation locations through simulations. Second, the analysis results of different transportation modes can support route planning and design. The above results are partially similar across three transportation modes, as there is no clear lane classification and design amongst different transportation modes. Lastly, the detailed analysis of specific route sections can help designers better implement and test their design intentions, such as the blue visibility of cycling routes at intersections could be lower to prevent distraction.

4.3. Describing blue exposure at the local level

Describing blue exposure at the local level mainly concerns people's direct perception without movements. As mentioned above, 3D landscape analysis could qualitatively describe both accessibility and

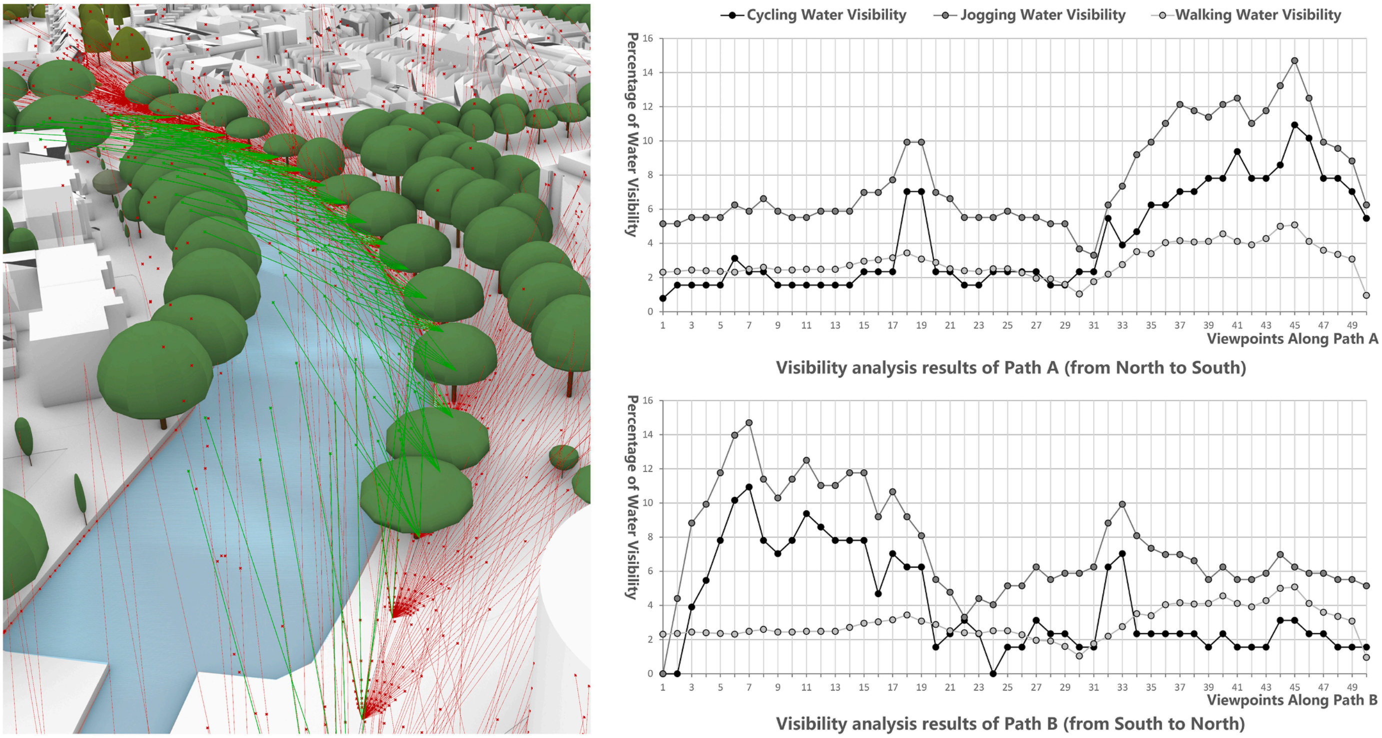

Fig. 7. Object-based approach in Rhino-Grasshopper environment and results on blue visibility of two paths based on three transportation modes.

visibility. Moreover, the spatial configurational approach and segmentation analysis could be used to describe accessibility and visibility, respectively. Derived from visual landscape research, 3D landscape analysis understands landscape spaces from the user's perspective through 3D visualisations. Critical techniques for 3D landscape analysis are sketches, photographs, photomontages, and some emerging digital or virtual tools, including digital modelling, virtual reality interactions, etc. They can provide comprehensive insights about several static landscapes and reveal the dynamic landscape changes via serial analysis, especially for describing blue visibility (Cullen, 2012). To keep the method simple and designers-friendly, 3D models and site photographs are used to illustrate the application of 3D landscape analysis in this research.

Fig. 8 presents the 3D digital models of typical water edges alongside the Rotte River in Rotterdam. Accessibility at the local level is understood as the difficulty of physically contacting the water bodies, which

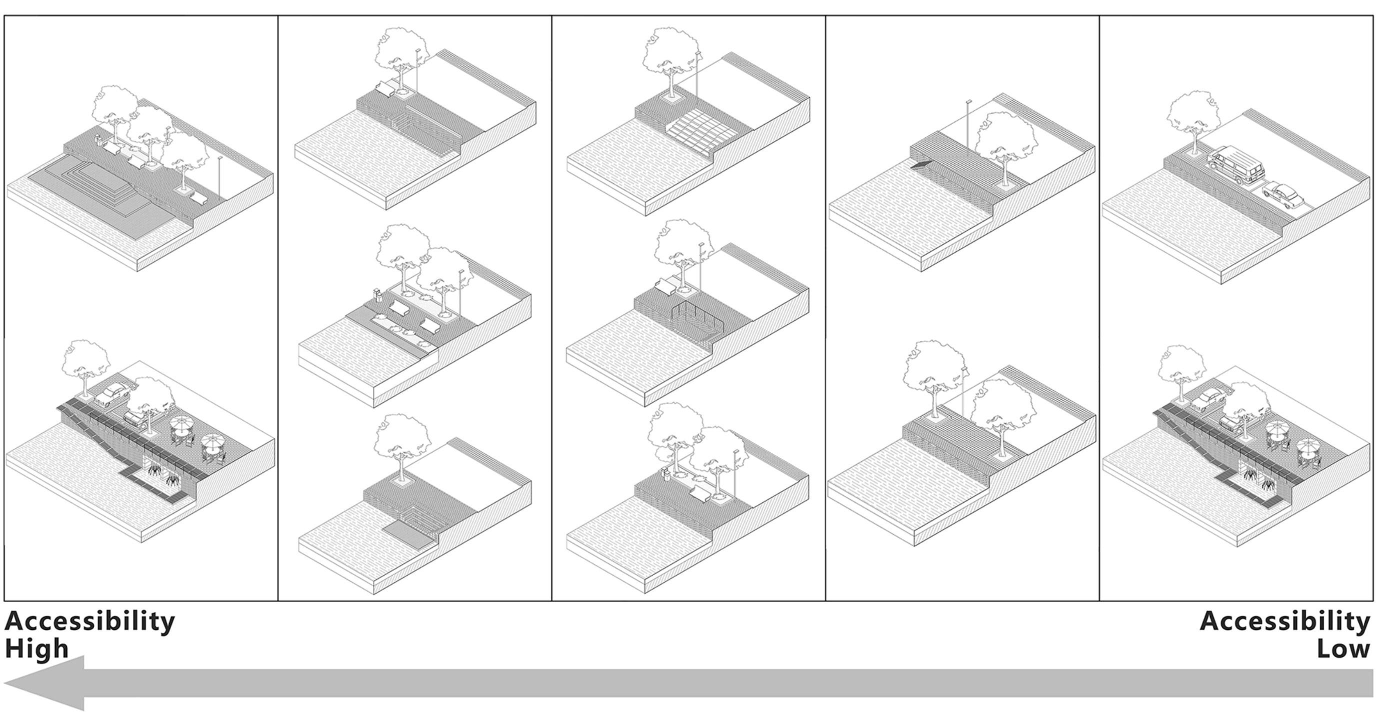

Fig. 8. 3D models of different water edges in the Rotte River.

can be qualitatively and directly perceived by designers from 3D models. Guided by the understanding of accessibility, the digital models of Rotte River's edge can be divided into five groups from high to low accessibility. Specifically, the water edges with the highest accessibility mean that it provides extensive on-water facilities allowing people to interact with the water body easily. Conversely, the water edge with the lowest accessibility is one where access to water is hindered, as shown in the last column of models, where parking areas impede the way to the water. The accessibility of the three middle groups in descending order refers to the provision of limited on-water facilities, the provision of on-land facilities for interacting with the water body, and the provision of on-land open spaces adjacent to water. Due to the method's subjectivity, the benchmark for evaluating accessibility can vary between projects and contexts.

3D landscape analysis has widely been adopted to grasp spatial-visual attributes, including describing visibility (Cullen, 2012; Liu & Nijhuis, 2020). For instance, a set of photographs alongside the Rotte River in Fig. 9 are shown to demonstrate the differences in blue visibility during the walking route. Fig. 9 [1–3] show how the facilities (on-water building, parking cars, and facilities) may largely interfere public's attention to water during walking and reduce the quality of the blue view, while the water body occupies a large proportion of the view. Fig. 9 [4–6], where water also occupies a significant proportion of the view, show that the public has better blue visibility during walking. The blue area of Fig. 9 [5–6] shows that some facilities could enhance the quality of blue visibility. The fountains and colourful vegetation in a different direction from the movement may attract more visual attention and cause the observers to stop and enjoy the scenes. On the other hand, the platforms in Fig. 9 [6], consistent with movement direction, could also attract visual attention and serve as the activity destination. 3D landscape analysis thus helps the designer to make fast implementations and extract subjective connotations from its results, which can help design decisions in practice. However, relying too much on the designer's judgement could lead to difficulties, limiting the result's reuse ability.

Unlike 3D landscape analysis emphasises the subjective understanding of accessibility, the spatial configurational approach explores the specific 3D spatial characteristics and human behaviour patterns to describe accessibility quantitatively. Specifically, this study uses space syntax for analysis, which is the most widely used typical representative of spatial configuration approaches. Space syntax originated as an exploration of the interaction between space layout and human mobility in a single building and expanded to urban contexts. This study adopts the latest angular model of space syntax for calculations, and the most representative indicators, including integration and choice, are used to describe the possibility of people reaching the destinations and the potential of moving through linear spaces, respectively (Turner, 2007; Yamu et al., 2021).

Fig. 10 presents the partial results of the spatial configurational approach by using space syntax. To comprehensively understand the result and improve its reliability, several distance thresholds representing different travel durations are included in the analysis (full results are shown in the supplementary materials). The results show similar spatial patterns across different distance thresholds: the roads with higher integration or choice value are located in the central part of the city centre. Meanwhile, the main road networks with critical higher values are identified as the threshold increases. According to the detailed observation of the integration value, Kralingen lake may not be an accessible destination for people to visit from the spatial configurational perspective due to the low integration value of its surrounding roads, while it makes significant contributions to the blue visibility at the regional level. Some linear blue spaces along higher choice routes are noted in Fig. 10 [4–6], suggesting that they are more likely to be used in people's everyday life, including the Rotte river, Westersingel, and the middle portion of the Boezem river. For practitioners, the spatial configuration approach could provide insights into multiple characteristics of accessibility at different scales. Specifically, the analysis results can identify areas with overall poor road accessibility and offer evidence for design interventions on traffic structures at the regional/district level. Moreover, through extensive interpretations of analysis results, the effects of the surrounding spatial layout of the targeted blue spaces on accessibility may be revealed to undertake spatial interventions at the local level.

Segmentation analysis is a machine learning-based visibility analysis method which corresponds to the local level and is widely used to understand the spatial characteristics of landscape elements within fixed scenes or images. It provides accurate encoding and decoding for multi-class scenes and conducts the composition analysis by identifying different landscape elements with colours. Followed by the analysis procedures in Helbich et al.'s (2019) research, the fully convolutional neural network for semantic segmentation (FCN-8s) model is trained by the ADE20K scene parsing and segmentation databases. More than 210

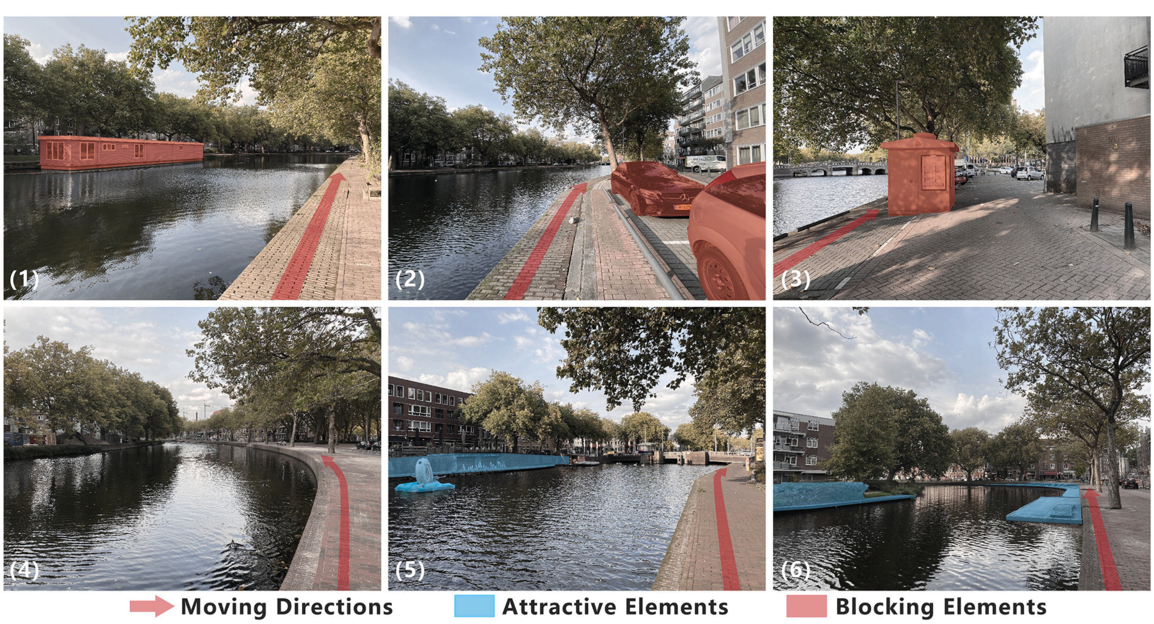

Fig. 9. Blue visibility analysis results and illustrations of a set of Rotte River photographs.

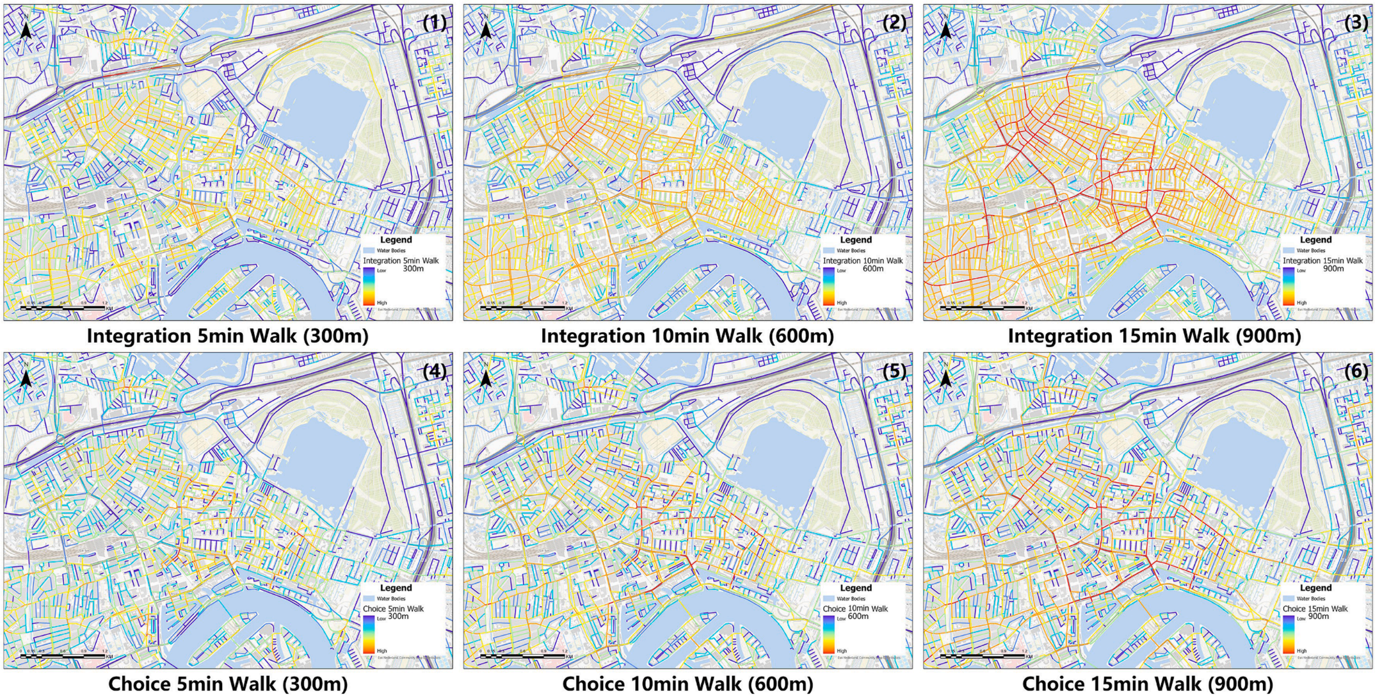

Fig. 10. Analysis results of the spatial configurational approach by using space syntax.

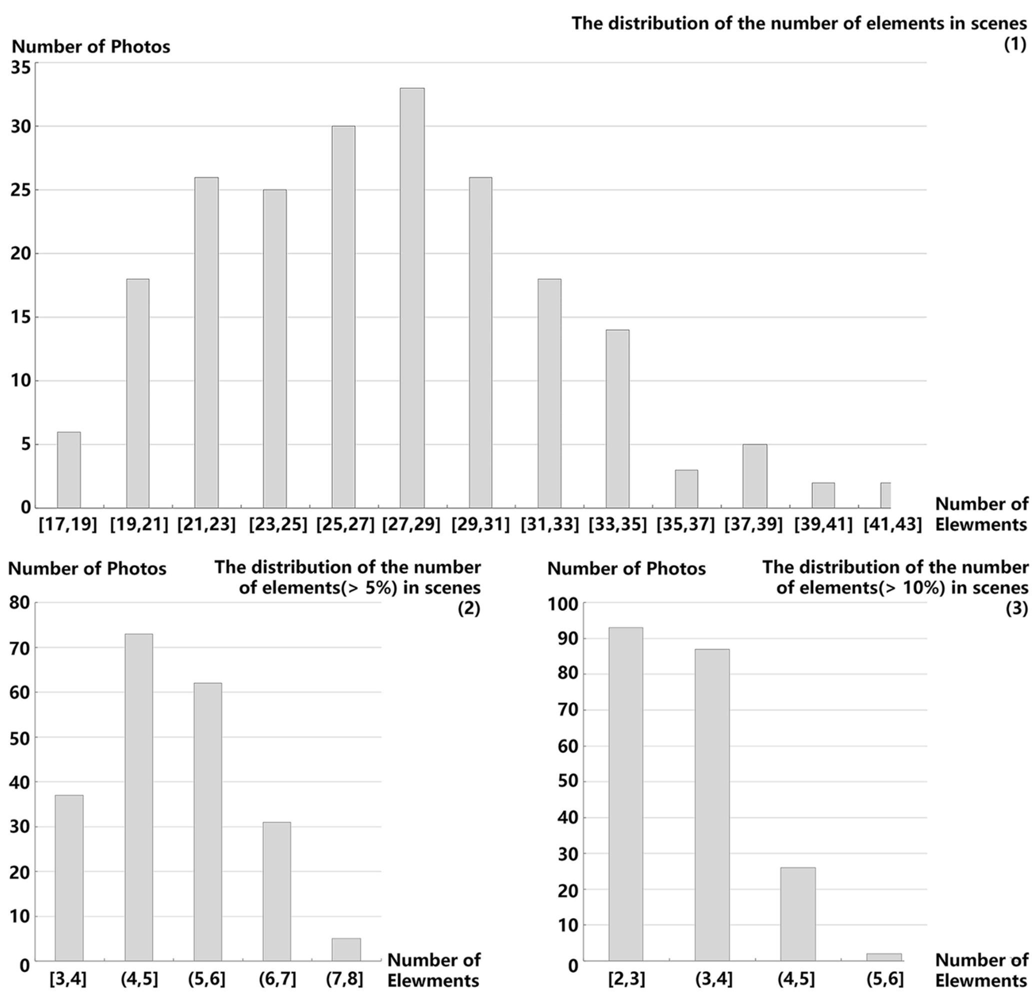

Fig. 11. Number of different elements in scenes.

images from the on-site research are used as input images for segmentation. The number of elements in each scene and the ratio of different elements to total pixels are calculated as indicators for describing blue visibility.

Supplementary materials show examples of segmentation analysis results on typical scenes alongside a section of Rotte River where different coloured areas represent various landscape elements. These graphs directly visualise the component analysis results, which designers could adopt to compare the differences of landscape elements in specific scenes pre-/post-design interventions. On the other hand, Fig. 11 shows the number of elements in the scene analysed using the segmentation results. The number of elements in current scenes is concentrated in 20–35, and the number of elements whose FOV accounts for more than 5% and 10% are concentrated in 3–7 and under 5, respectively. Designers can use this method to measure spatial-visual complexity in selected routes and areas, which has been widely adopted in several studies (Ode et al., 2010). Existing studies reveal that people prefer moderately complex coherent environments, and scenes with relatively high complexity are more likely to stimulate people's interest in exploration (Forsythe et al., 2011; Nadal et al., 2010). Moreover, the average proportion of area occupied by the main landscape element groups in scenes is shown in Fig. 12. Detailed information on group re-classification is presented in supplementary materials. The result reflects that vegetation, water, and sky are the main landscape element groups in scenes, while multi-facilities (on-water, on-land, and traffic facilities) only occupy a limited proportion. Furthermore, the results can be used to calculate the degree of openness and naturalness of scenes. They are two critical indicators for designers to describe the visual space, while traditional methods rely heavily on photo-based qualitative descriptions. Here, designers can use segmentation analysis to analyse and simulate different design intentions by incorporating photomontages or digital modelling.

5. Discussion

5.1. Choosing the appropriate methods to measure blue exposure

The analysis of the eight blue exposure methods' applications in multi-scale Rotterdam cases demonstrates that different methods produce distinct types of blue exposure descriptions that may be suitable in various contexts. Therefore, it is necessary to identify and select appropriate methods when encountering spatial planning or design assignments aiming to improve blue exposure. As mentioned above, the eight methods are first classified according to the two aspects of exposure (accessibility and visibility), which led to the designer's choice of methods that should correspond to the design intentions of spatial interventions. For instance, the spatial proximity approach focuses on proposing spatial interventions to reduce travel costs, while the object-based approach emphasises the visual experiences during movements. On the other hand, even describing the same type of exposure, the method could be varied. The scale applicability of the various methods (regional, district, and local levels) leads to the demands of input data type and precision. Therefore, data availability and situations for method applications become critical factors in designers' method selection. For example, the statistical index approach is easy to calculate and better applied to uniformed spatial units, which provides the potential for rapid analysis and communications (Wang et al., 2021; Zhang et al., 2011). However, spatial interaction and spatial-orientated approaches with rich data input could better represent blue exposure and provide solid evidence for design decisions than just implementing statistical index approaches.

Instead, the scale can offer clues for designers to select suitable blue exposure description methods in practice and explore the possibilities of collaborative analysis via crossing-scale methods. For instance, the methods at the regional level could identify the areas with limited blue exposure, which could be regarded as sources for specific spatial design interventions at the district/local levels. On the other hand, the analysis of two exposure aspects can comprehensively evaluate the degree of blue exposure and assist in developing specific interventions. For the areas with inconsistent analysis results on blue accessibility and visibility, designers can propose targeted strategies combining the considerations of their contexts rather than over-emphasising one aspect without supporting evidence. Moreover, the multiple indicators in the analysis of the same blue exposure aspect could support designers in identifying site limitations and proposing targeted interventions, as the results of the spatial proximity approach demonstrated in section 4.2.

Lastly, as shown in the last column of Table 1, the different interactions between methods and spatial design processes play critical roles in method selection and application. Two groups of methods are pointed out, including pre/post-planning or design analysis methods and scenario-based analysis methods. Specifically, the two groups all emphasise the nature of evaluation and analysis, allowing designers to compare the differences between multiple prospective design proposals and the original situations to make decisions. However, compared to pre/post-planning or design analysis methods, scenario-based analysis methods pay more attention to the characteristics of rapid simulations,

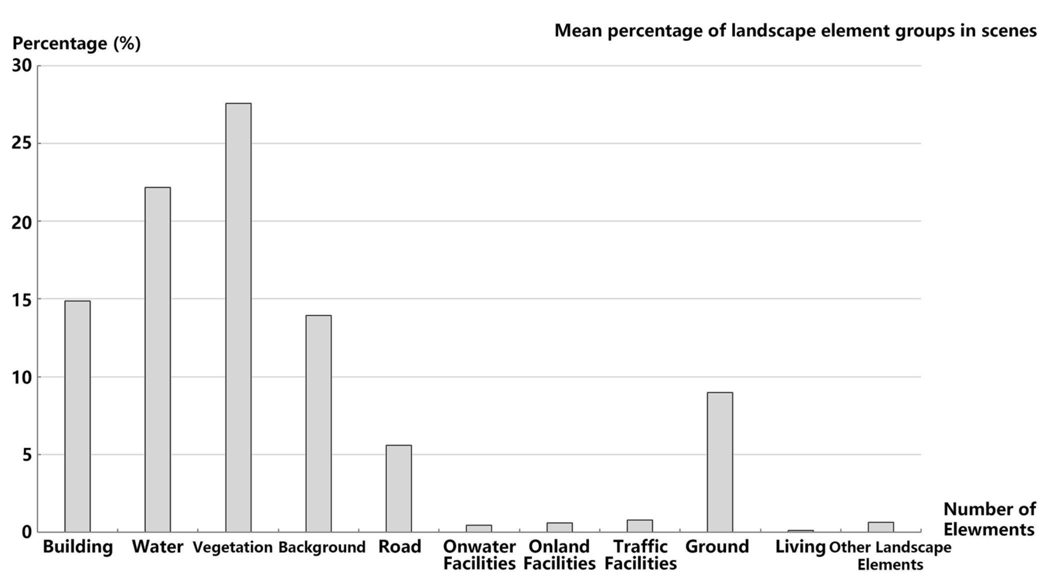

Fig. 12. Mean percentage of landscape element groups in scenes.

which allow designers to test and change the ideas or intentions through visualisations quickly, and often link to projects at the district/local level.

5.2. Potential applications

Spatial planning or design, a fundamental activity in urban design and related disciplines, encompasses creativity, rationality, and interdisciplinary collaboration (Nijhuis & de Vries, 2019). The methods shown in this study enable designers to understand and visualise blue space exposure at multi-scales and explore the potential for improving it. The results section presents potential applications of these methods in spatial planning/design processes, highlighting their relevance to practitioners. Beyond their integration into planning processes, these methods hold valuable implications for policies of urban planning and public health. This part will concisely summarise these possibilities and propose a conceptual flowchart for integrating these multi-scale methods into spatial planning/design and policymaking processes, recognising the interconnectedness of spatial projects and interventions across different scales.

5.2.1. Spatial planning and policymaking processes

The statistical index approach describes blue exposure by measuring quantitative characteristics of blue spaces in geographic areas. However, the spatial interaction and spatial orientated approaches represent blue exposure by directly measuring accessibility and visibility, which are unattainable information in the statistical index approach. These three methods demonstrate the spatial distribution and inter-region relationships of blue spaces, enabling designers to propose regional spatial strategies and future visions that maximise the health benefits of blue space exposure. In addition, these methods possess the potential to be combined with additional contextual data for analysing the spatial distribution inequities of blue space, thereby supporting more comprehensive policy development.

The spatial proximity approach can precisely visualise the accessibility of blue spaces within neighbourhoods, which allows for the immediate identification of areas with inadequate access to support developing targeted spatial strategies. The object-based approach captures the variations of blue space within the FOV during movement, making it useful for site analysis and simulating the impacts of different design proposals. Furthermore, specific spatial strategies and proposals derived from these approaches can be integrated into policies to guide future urban development.

At the local level, 3D landscape analysis is easily generated through field surveys to understand the site situations with limited data availability. Instant sketches, photographs, and digital modelling are practical tools in 3D landscape analysis, which support designers in exploring the relationship between characteristics of spatial forms and blue space exposure. On the other hand, the spatial configuration approach and segmentation analysis enable designers to quantitatively describe blue exposure and provide more solid and objective evidence for decisions on design assignments. All these three methods could be applied in the analysis and evaluation phases to allow multiple stakeholders' communications regarding potential design proposals, resulting in a dynamic and interactive design process. Additionally, these methods could be served as a platform for policymakers to engage with stakeholders and the public, facilitating the identification of trade-offs and synergies amongst various factors and enabling the proposal of more inclusive policies. For instance, the findings from the spatial configurational approach highlight the importance of spatial morphological features, which could be influenced by factors such as road networks and building layouts. Addressing these considerations necessitates collaborative efforts in policymaking.

It is noted that the methods at the three scales are independent at their level and closely connected to the results of the methods on the other levels. Fig. 13 illustrates the method application in spatial planning/design and policymaking processes with a simplified conceptual flowchart to facilitate the practitioner's understanding, as the analysis–application–evaluation loop and communication amongst stakeholders may perform several rounds to make design decisions in real practice. Specifically, the regional-level methods could first be used to understand the limitations of existing situations to provide evidence support for spatial interventions of regional planning/design projects. Next, these methods could also be adopted to evaluate the consequences of different interventions to help designers communicate and make final decisions, as the complexity of urban issues leads to no unique solution.

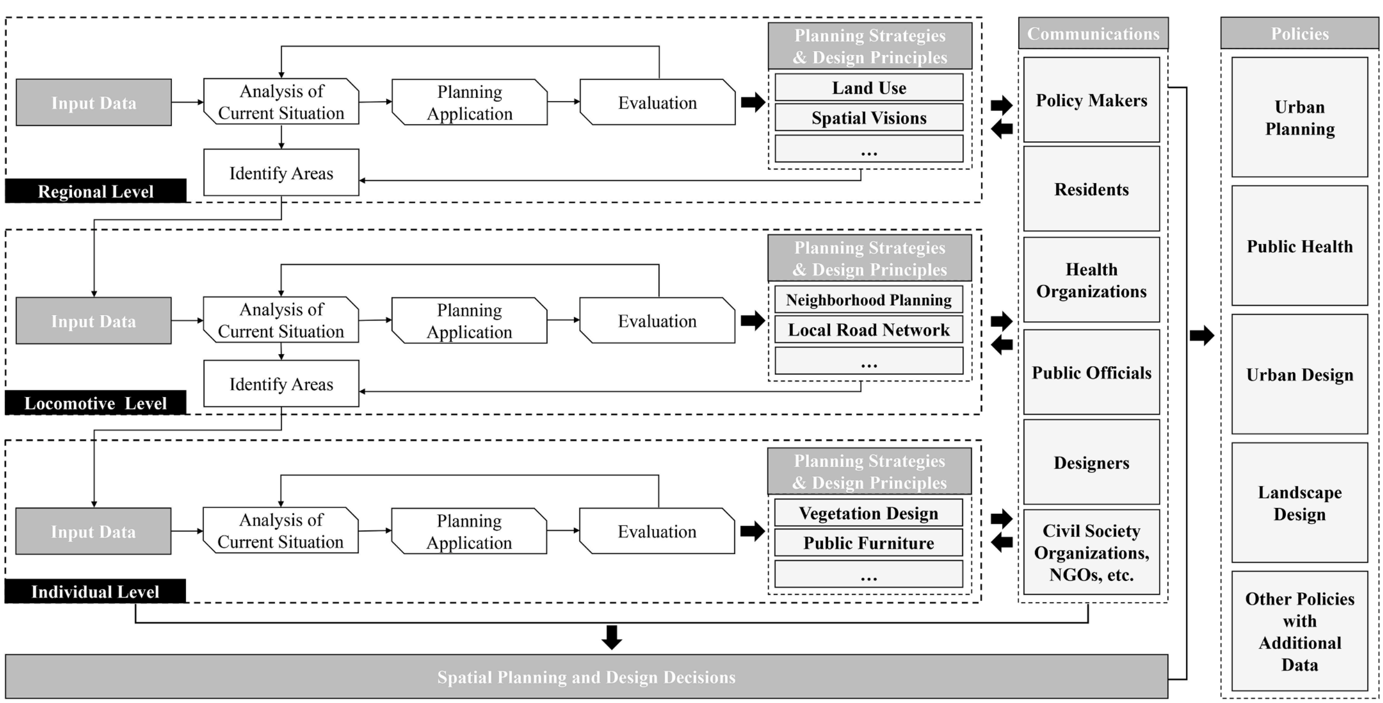

Fig. 13. A conceptual flowchart for incorporating multi-scale methods in spatial planning/design and policymaking processes.

In addition, the analysis results of current situations could inform the design of future spatial interventions. For instance, areas with limited accessibility identified using regional-level methods may serve as potential input sources for projects at the district/local level (Fig. 13). On the other hand, the results obtained from these methods can be used as a powerful communication tool amongst stakeholders, facilitating the identification of trade-offs and synergies between spatial visions. This enables the development of diverse policies for sustainable healthy urban environments, spanning urban planning, public health, and urban design. Furthermore, the strategies for enhancing blue space exposure derived from spatial planning and design, informed by the methods' results, can contribute to the refinement and development of public policies.

5.2.2. Policy implications

Integrating methods to analyse blue exposure in urban planning is paramount for promoting public health and well-being. Accordingly, policy-makers, urban designers, and landscape architects could forge collaborative partnerships to streamline these methods into planning processes. For instance, improving access to and enhancing the visibility of blue spaces within urban contexts can be a shared objective, necessitating the city's proactive evaluation of the accessibility of these spaces. Following these analyses, policy interventions could encompass devising pedestrian-friendly routes to nearby water bodies and augmenting public transportation options for more distant blue spaces. Simultaneously, strategic measures can be undertaken to enhance the visibility of blue spaces, such as developing guidelines for developers to integrate blue spaces into city-wide strategic plans or when redesigning built environments to expand sightlines towards water bodies and create view corridors in city planning.

Alongside accessibility and visibility, achieving equitable blue exposure across various regions and for diverse population groups is critical, especially when considering the quality of blue spaces. As such, policies should advocate for the comprehensive evaluation of blue spaces' regional distribution, providing a foundation for devising spatial strategies and future visions for equitable blue exposure (Song et al., 2021). Moreover, policies could extend beyond mere exposure quantification to encompass the quality, functionality, and usage of these spaces, which may include regulations or guidelines for maintaining and improving urban blue spaces (Knight et al., 2022). In the case of Rotterdam, a concentrated effort to examine the regional distribution of blue spaces could be made to offer equitable access to all residents, irrespective of their geographical location within the city. Furthermore, it is important to acknowledge the crucial role of data availability in effectively implementing these methods. Thus, there is a need to advocate for open data policies to ensure the method applications for constructing sustainable healthy urban environments.

5.3. Limitations

Existing evidence suggests that exposure to blue spaces, such as spatial accessibility and visibility, can benefit human health and well-being in multiple ways. Therefore, considering blue exposure in spatial design is crucial in realising blue space's health benefits and constructing sustainable healthy urban environments. To comprehensively understand and describe the blue space exposure in practice, the available methods and tools addressing the visibility and accessibility from a spatial-related standpoint are of fundamental importance for multi-scale spatial design and supporting practitioners' decisions. However, several factors that may affect blue space exposure were not included in this study, such as spatial quality, meaning, functions, etc. The methods presented in this study mainly support practitioners in analysing the accessibility and visibility of blue spaces, two of the most critical factors, and partially consider availability and visual quality. Future studies could encourage the exploration of more methods to aid design decisions and policymaking by considering the remaining factors influencing blue space exposure, such as eye-tracking and spatial perception experiments through virtual reality.

In this study, the cases for method applications in one city may raise concerns about the inadequate applicability of the method in other areas, such as water-scarce areas. From the perspective of method application, the reason for selecting Rotterdam lies in the abundance and diversity of water bodies within urban environments, which allows the study to present relatively complex situations to promote applicability in other areas. Moreover, the study didn't provide benchmarks as criteria to assess the accessibility and visibility of blue space since the existing situations vary amongst different areas. The presented methods aim to assist designers and policymakers in understanding the situation and supporting decision-making through simulations of different scenarios. However, the potential difficulties of methods applications in other areas may not be fully identified without on-site tests. Therefore, future studies or practices could actively extend and apply the method to other areas to maximise their potential, as well as develop benchmarks as evidence accumulates to support the decision-making.

On the other hand, the methods presented in the paper remain limitations in the selection, data processing, and analysis results. First, due to the advancement of technology and the availability of methods or data, this study cannot include all potential methods in each category but only shows practical ones which could be incorporated into the design process efficiently. Second, the quality and precision of data adopted in the study could impact the analysis results. For instance, visibility analysis through the Rhino-Grasshopper environment can partially address the limitations of the Digital Terrain Model (DTM) in the GIS environment. However, current data quality is insufficient to fully solve the issue of vegetation modelling. In this respect, the 3D point cloud provides promising clues to achieve more accurate results, while the high processing capacity requirement still makes it challenging to apply in practice. Last, some emerging algorithms are not all included in this research (such as deep-learning models for segmentation and distance decay models for 2SFCA), as the study objective aims to illustrate the methods' current usability for designers and potential for design processes. Instead, new algorithms could provide the basis for future research and allow designers to explore their design applications.

6. Conclusions

This study provides an overview of practical methods for describing blue space exposure and their applications through Rotterdam cases, and then explores their potential in spatial planning/design and policymaking processes. These methods show great possibilities to become part of the toolset of urban designers, landscape architects, policymakers, etc., and offer a new horizon to designerly interpret blue space exposure that brings multiple benefits to human beings. On the other hand, it is well to be noted that most of these methods come from interdisciplinary fields rather than directly from planning/design-related disciplines. They need to be combined when dealing with practical planning/design assignments due to the complexity of urban issues. In other words, each method has its own strengths and weaknesses, and using them in combination can address the multi-scale issues of spatial planning/design in an effective way. In general, the summary and applications of the methods contribute specific clues for future research and applications from the following three aspects:

(1) Expanding the understanding of blue space exposure from the spatial planning/design perspective. Existing studies mainly explore evidence of relationships between blue space exposure and behavioural and health effects, while investigations of how to apply the evidence in the design process are limited (Zhang et al., 2022). The methods in this study can help designers apply the health evidence, gain insights on multi-scale spatial elements influencing blue space exposure, and implement interventions in

design practice, which contribute to building sustainable healthy urban environments.

(2) Supplementing the body of the designer's toolset. The study showcases several methods that address the blue space exposure from multi-scales and provides a wide range of possibilities for exploring integrating these methods into spatial design in combination with case applications. In addition, these methods are applicable to other practical projects and studies with different geographic contexts, features and data availability. Especially some of the methods can be extended to describe the exposure of other objects, including green spaces, critical public facilities, etc.

(3) Exploring new perspectives for practice. As mentioned above, the methods presented in this study are mainly derived from various disciplines. The multidisciplinary nature allows for knowledge exchange and inspires the innovative application of knowledge from different disciplines in planning/design and policymaking processes.

Future studies could expand the methods of describing blue space exposure by incorporating more interdisciplinary knowledge and emerging techniques while considering the convenience of practitioners' usage. At the same time, it is necessary to encourage the utilisation of existing methods in practical cases to verify their effectiveness and explore their novel application potential. On the other hand, future empirical studies could employ current methods to standardise measures of blue space exposure, which could help infer causality between blue space exposure and health and provide more detailed support for the policy. Last but not least, the logic of integrating emerging techniques into spatial design processes demonstrated in this study can be generalised to achieve broader objectives for the development of knowledge/evidence-based design approaches.

Declaration of Competing Interest

The authors 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.

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Supplementary materials

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