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Jichang Garden as a case study

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DOI
10.1016/j.ufug.2023.128159

Publication date
2024

Document Version
Final published version

Published in
Urban Forestry and Urban Greening

Urban Forestry & Urban Greening 91 (2024) 128159

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Towards a framework for point-cloud-based visual analysis of historic gardens: Jichang Garden as a case study

Yuyang Peng [a,*,1], Guanting Zhang [b,1], Steffen Nijhuis [a], Giorgio Agugiaro [a], Jantien E. Stoter [a]

[a] School of Architecture and Built Environment, Delft University of Technology, the Netherlands
[b] School of Architecture, Nanjing Tech University, China

ARTICLE INFO

Keywords:
Spatial analysis
Jichang Garden
Heritage gardens
LiDAR
GIS

ABSTRACT

Historic gardens, regarded as a significant genre of cultural heritage, encapsulate the enduring essence of bygone eras while concurrently transcending temporal boundaries to resonate with the present and future. These gardens provide us vitality and inspiration, holding a collective repository of human memory and serving as a testament to our shared heritage. However, like landscapes, gardens constantly change through natural processes and human interventions. How can we preserve these gardens, though changes are unavoidable? Spatial and visual characteristics are the gardens' essential characteristics, and point-cloud (LiDAR) technologies are powerful tools to reveal and analyze gardens' spatial-visual relationships and characteristics. Therefore, this paper aims to present a point-cloud-based approach to identifying spatial-visual design principles and making them operational to protect and develop historic gardens. Additionally, several methods have been proposed in this research, including (a) a voxel-based method to transfer points into a solid model for GIS-based computation, (b) a novel method to analyze the field of view (FOV), and (c) a systemic framework to reveal historic gardens' spatial-visual characteristics based on the voxelized model. Jichang Garden, a historic garden in Wuxi, China, known for its visual design and spatial arrangement, has been selected as a case study to showcase how to apply the methods proposed by this paper. The findings include the design principles for the water body, the arrangement for a route, and the planting strategies of the garden. The conservational strategies have been formed based on the findings, and the appliable potentials and limitations of the methods have also been discussed.

1. Introduction

International Council on Monuments and Sites defines a historic garden as "an architectural and horticultural composition of interest to the public from the historical or artistic point of view" (The Florance Charter, 1981). According to the definition, historic gardens are an essential category of heritage landscapes (Scazzosi, 2004), which encompass the legacy of the past, the present, and the future, representing invaluable sources of life and inspiration (UNESCO, 2021). Preserving and studying historic gardens can offer excellent "prototypes" for the design of current built environments and landscapes (Hunt, 1992; Rinaldi, 2012). These gardens also play a crucial role in fostering cultural identity among the local population (Araoz, 2013) and contribute significantly to the tourism revenue of the garden's location (Benfield, 2020). Despite these gardens' cultural and inspirable significance, they face challenges associated with climate change and urbanization, threatening their authenticity (Bisgrove and Hadley, 2002; Carrari et al., 2022). Nevertheless, it is crucial to understand the origins of cultural landscapes before their preservation and utilization. Because, like other cultural landscapes, historic gardens are also dynamic (Amici et al., 2015; Antrop, 2005) and subject to the influence of vegetation growth (Ciaffi et al., 2018; Kuśmierski, 2022; Tomao et al., 2015)(blinded for review), other human activities like tourism (Collins-Kreiner and Gatrell, 2006), and environmental factors such as climate and water movements (Aktürk and Dastgerdi, 2021; Pérez-Urrestarazu et al., 2018). Therefore, the perspective of this paper is that the protection of historic gardens is more important to protect their essential characteristics rather than to preserve their appearance.

What are the essential characteristics of historic gardens? The European Landscape Convention defines landscape as "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (ELC, 2000: 3). This

* Corresponding author.
E-mail address: Y.Peng-1@tudelft.nl (Y. Peng).
[1] co-first author

https://doi.org/10.1016/j.ufug.2023.128159
Received 4 July 2023; Received in revised form 27 October 2023; Accepted 24 November 2023
Available online 29 November 2023

definition emphasizes the importance of human perception in experiencing landscapes (Jones et al., 2007). Although perceptual processes are not limited to visual perception, visual perception is the primary way humans collect information from the outside world (Bell, 2012). Therefore, understanding a garden's visual and spatial characteristics is essential to reveal its essence. Besides traditional analysis like sketching and drawing, many powerful digital methods, including GIS-based mapping methods, point-cloud-based technologies, and virtual reality, have been introduced to understand the landscapes' spatial-visual characteristics, providing quantitative and novel visions for this field. Focusing on point-cloud-based (LiDAR-based) research for historic gardens, numerous studies have been completed, covering various disciplines and utilizing different research methods, including:

(a) *Studies focusing on developing digital technologies:* the emphasis is on innovation in Geo-technology and exploring algorithms, routines, applications, and methods to acquire and process point cloud data for historic gardens. Examples include the photogrammetry method, using photos to construct 3D models (Chiabrando et al., 2017; Malinverni et al., 2019; Martínez-Carricondo et al., 2020); 3D scanning systems, data acquisition techniques (Ahmed Shalaby, 2022; Del Duca and Machado, 2022, 2023; Liang et al., 2018; Zhang et al., 2018), 3D modeling, digital realities (Antón et al., 2018; Augustine et al., 2019; Liang et al., 2020; Pirotti et al., 2022), information display (Kumazaki and Kunii, 2015; Zhang et al., 2012), virtual reality (Chiabrando et al., 2017; Jia et al., 2022b; Martínez-Carricondo et al., 2020; Rodríguez Sáchez et al., 2023), digital mapping (Pirotti et al., 2022), semantic segmentation, classification of point-cloud (Liang et al., 2019).
(b) *Studies focusing on developing methods for historic gardens' conservation:* these studies elaborate approaches for heritage gardens' preservation, monitoring, and management. Examples include reconstruction methods (Dong et al., 2020), strategies for future development and evolution (Jia et al., 2022a; Malinverni et al., 2019), a daily monitoring method for tourism, climate challenges, and deformation (Fu et al., 2023; Guo et al., 2023; Guo et al., 2020), establishing digital models to maintain heritages in a digital environment (Ahmed Shalaby, 2022; Chiabrando et al., 2017; Hess and Ferreyra, 2021; Liang et al., 2018; Liang et al., 2019; Martínez-Carricondo et al., 2020; Pérez-Martín et al., 2021; Rodríguez Sáchez et al., 2023).
(c) *Studies focusing on spatial features analysis:* revealing the design methods, visibility of historic gardens, and distribution of heritage landscapes, are primarily conducted using airborne point-cloud to indicate the spatial characteristics of the historic garden complex's distribution among areas, as well as to develop the managing strategies (Dudzińska and Szpakowska, 2018). Additionally, applications for exploring the characterization of historic gardens also exist (Hess and Ferreyra, 2021; Nijhuis, 2015; Yang et al., 2023).

While there are many examples of using point-cloud-based/LiDAR-related technologies for historic gardens, mainly for surveying, visualizing, and modeling historical remains and the gardens (e.g., modeling the rockeries), there are only a few examples where point-cloud-based methods have been applied to analyze historic gardens' design intentions or spatial-visual characteristic that are closer to the essence of the gardens. Although point-cloud-based methods are a powerful means to explore the spatial-visual attributes of landscapes. In addition, the majority of the algorithms are set for mapping the spatial-visual characteristics with "overlooking" graphs, but the methods to analyze "eye-level" views, such as field of view (FOV), are even rarer. Due to the lack of understanding of spatial-visual features, most point-cloud-based strategies focus on maintaining the current appearance rather than proposing management and design strategies based on spatial-visual characteristics. Last but not least, point-cloud-based 3D modeling methods often lead to difficulties for designers or excessive processing time in GIS-based analysis due to the high precision of the points (Hinks et al., 2013; Wang et al., 2020).

Therefore, this article aims to propose a systematic visual landscape research method/framework for analyzing the historic gardens' spatial-visual characteristics (utilizing high-precision point-cloud data) and manage to demonstrate their potential applications with a case study. This objective can be further broken into the following sub-aims: (a) developing a time-saving and easy-taking method to generate a solid model from the point cloud, and the digital model can be used to conduct GIS-based analysis for historic gardens; (b) developing a new and accurate method to do the spatial-visual analysis for historic gardens, in which both the "overviewing" method and "eye-level" views analysis are combined; (c) exploring the potential applications of the method in landscape design and spatial-visual analysis for historic gardens; (d) proposing management and design strategies for historic garden based on the visual-spatial analysis. Jichang Garden is a historic Chinese garden located in Wuxi, China. It is widely recognized for its exceptional spatial arrangement and visual design, including the utilization of borrowed scenery and the creation of spatial sequences (Eunyeong, 2017; Shu et al., 2018). Therefore, the Jichang Garden is a proper case study for point-cloud-based spatial-visual analysis. In addition, the most acclaimed area within the Jichang Garden is the region centered around the picturesque "Jinhuiyi" pond. To reveal the spatial-visual characteristics that make this region well-known and picturesque, the following explorations will focus on the water surfaces of the garden, including the ponds, surrounding buildings, and adjacent ground, as the designated study region.

2. Methodology

The method proposed in this article focuses on GIS-based methods and technologies for visual landscape research with point cloud data. Three different approaches can be used to conduct the GIS-based visual analysis (e.g., visibility) with point cloud: voxel-based, ray-tracing, and surfaced-based approaches (Alsadik et al., 2014; Zhao et al., 2020). Voxel-based techniques are mainly applied for volumetric data applications. Though computing the visibility with voxels is less accurate, it is an efficient method to automatically generate a solid model for GIS-based visual analysis (Hinks et al., 2013). Especially when the research focuses on understanding the spatial-visual organization and design principles of landscape architecture compositions, there is a strong need to develop easy-taking LiDAR-based approaches to enable landscape researchers/designers to exploit the powerful computational possibilities of standard GIS software like ArcGIS. Therefore, the workflow consists of three parts: (a) scanning the real environment to obtain point data, (b) transferring the points to voxels, and (c) revealing spatial-visual characteristics of the garden with GIS-based tools, including both the "overviewing" mapping method and "eye-level" views analysis (Fig. 1**a**).

2.1. Collecting the point cloud data

Two categories of tools can be used to capture point cloud data, laser scanners and photogrammetry (Wang et al., 2020). A laser scanner is a survey-grade system that includes a number of different sensors and technologies. These tools for acquiring point cloud data include mobile scanning, like car-mounted laser scanning (Kukko et al., 2012), stationary scanning (Alhasan et al., 2017), and drone laser scanning (Resop et al., 2019). While the photogrammetry method is more a methodology than a specific type of tool (Eisenbeiss and Sauerbier, 2011; Valença et al., 2012). Point cloud data can contain various types of information. For instance, some point clouds may only include spatial position information. The others may include RGB values to indicate color and segmentation information for different points. However, to successfully

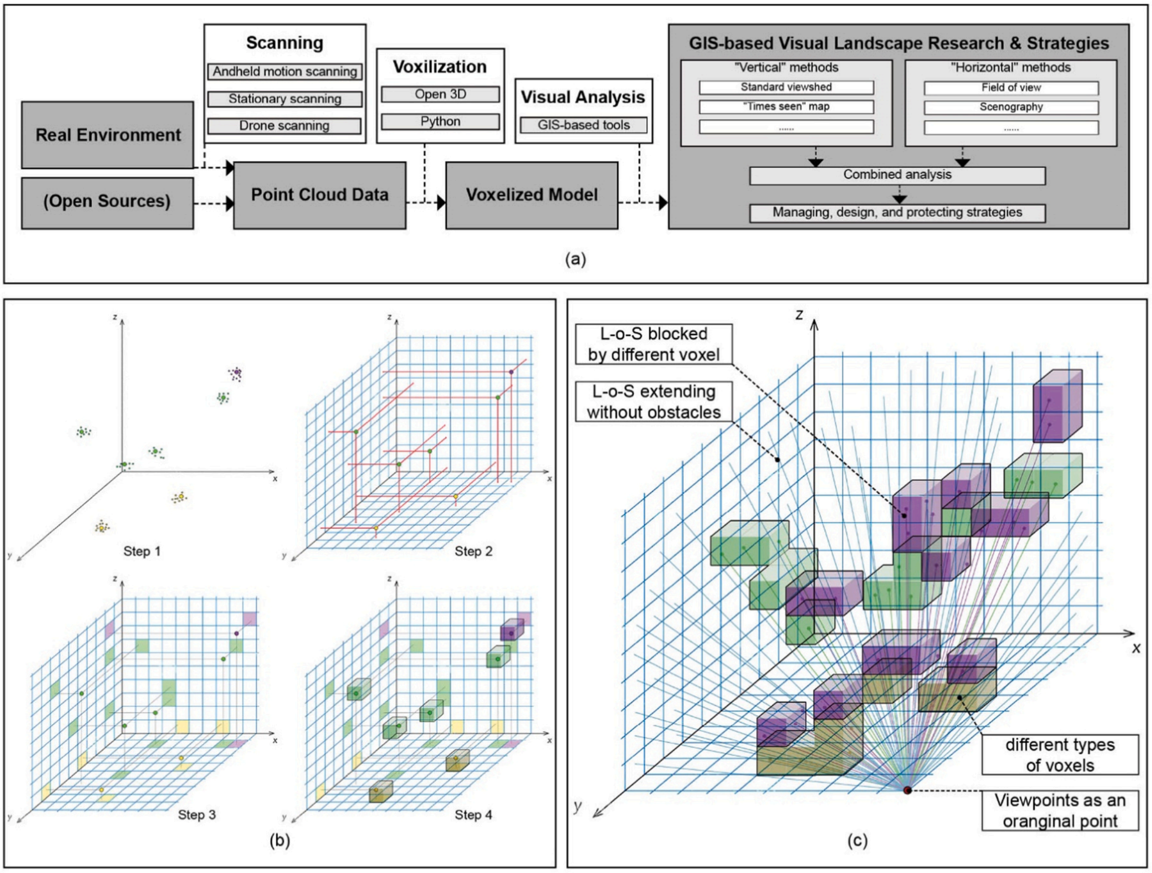


Fig. 1. Graphs for the methodology and algorithms: (a) workflow for the proposed methodology; (b) processes for voxelization; (c) how voxels block the L-o-S in a 3D virtual space.

conduct subsequent FOV analysis, this paper strongly recommends segmenting the point data based on the characteristics of the studied landscape elements. These categories can include but are not limited to vegetation, buildings and structures, rocks and artificial hills, roads, and bare ground.

2.2. Voxelization for point cloud

After acquiring the point cloud data, the next step is to perform voxelization. Open3D and ArcGIS have been applied in the process: Step-1 downsampling the points; Step-2 gridding the virtual space; Step-3 extracting the central point for each voxel containing point information; Step-4 forming each voxel with the point information (Fig. 1**b**). The voxelized model provides the solid surfaces for GIS-based computation, including generating viewsheds and FOV graphs.

2.3. Framework for GIS-based visual landscape research for historic gardens

After completing the voxelization of a historic garden or garden complex, GIS-based mapping analysis can be conducted on the digital model. The methods and algorithms for these mappings can be customized according to research needs. The resulting graphs' can be categorized into "vertical" (overlooking maps, like viewshed maps) and "horizontal" (perspective graphs, like Field of View) (Nijhuis, 2015; Nijhuis et al., 2011). The formation presents the graph, showcasing the central concern of the analysis. Overlooking maps tend to focus more on the spatial patterns, structure and process, and relationships (coherence) of the environment. Meanwhile, perspective graphs (e.g., scenography) emphasize the face of the composition of landscape elements or physiognomy of landscapes, applying to measure the depth of field, colors within a view, and other factors that directly impact human perception. Therefore, this study combines the "vertical" and "horizontal" methods.

2.3.1. Generating vertical (overviewing) visual maps

Many of overviewing mapping analysis methods, such as visibility, viewsheds, isovist, and openness, can be implemented in standard software platforms. They will not be further elaborated on in this paper. The choice of specific methods depends on the research objectives. It is important to note that GIS-based methods and algorithms are constantly evolving and advancing, including the iterative updates of software like ArcGIS. Therefore, new application scenarios and technical approaches have many potentials to be realized based on the voxelization method proposed in this paper.

2.3.2. Generating horizontal (eye-level) FOV graphs

LiDAR-based "eye-level" visual research is relatively rare, existing but focusing mainly on the visualization of point clouds. One of the current obstacles is translating point clouds into recognizable perspective views (e.g., FOV, scenography) with quantifiable information such as distance and composition categories. Therefore, a novel approach using the voxels to visualize and analyze the fields of view (FOV) has been developed in this research, comprising four steps (Fig. 1**c**):

(a) Viewpoints are selected based on the research demand, and the height from the ground, position, and amount of them can be set accordingly.
(b) Line-of-Sights (L-o-S) are constructed for each viewpoint using these "viewpoints" as a basis. The L-o-S are established every 5°

horizontally, with an angle range of 0–355°, and every 5° vertically, with an angle range of 30–180°, resulting in a total of 2232 L-o-S for each viewpoint. Finally, the length of each L-o-S is set according to the garden's scale.

(c) After constructing the L-o-S for each viewpoint, the information table for each viewpoint is obtained in this study. As the L-o-S mostly encounter blockages from the voxels before reaching the designated distance, these voxels contain information about different landscape elements, which includes data on the landscape elements and the distance information from these voxels. When the L-o-S is not blocked, there are no obstacles in the direction, and it is the area of the sky. The recorded information for each viewpoint is consolidated in a single table.

(d) Based on the information in the table, a visualization is created in a rasterized graph with 31 * 72, which amounts to 2332 cells. Different landscape elements are displayed in various hues, with the lightness of the color used to distinguish distance. Specifically, green represents vegetation, brown represents the ground, blue represents the water surface, red represents buildings, gray represents rockery, and black represents the sky. Moreover, a cell with relatively low lightness indicates that the voxels it represents are closer to the viewpoint.

2.3.3. Combined visual landscape analysis

It can be affirmed that when the "overlooking" (vertical) and "eye-level"(horizontal) methods complement each other, a more comprehensive range of research goals can be achieved, which has the potential to identify and explain more spatial-visual characteristics. This is because these two methods provide different perspectives on the cognitive visual space. Therefore, by integrating the "vertical" and "horizontal" methods and employing cross-validation between the two analytical perspectives, the analysis's reliability can also be enhanced. In conclusion, combining the two approaches as mentioned above is necessary. The following case study showcases several applications by combining the two types of visual landscape research methods.

2.4. Case study: Jichang Garden, Wuxi, China

2.4.1. Scanning and voxelizing the Jichang Garden

The point cloud data of Jichang Garden was collected in two types: true-color 3D point cloud data by the Trimble X7 Scanner (stational scanning) and data collected by the ZEB-Horizon Scanner (walking scanning). Within an area of less than 1.5 ha, there are over 80 million points, with the majority concentrated around the pond. Furthermore, these data include spatial positioning information, RGB values representing real colors, and preliminary segmentation based on landscape elements. Before further processing, point cloud downsampling is required, followed by voxelization using the earlier method. In this case study, the voxels are set with a size of 0.1 m and categorized into three types: plants, buildings, and rockeries, while the ground is represented by a digital elevation model (DEM) generated from the point data.

2.4.2. "Vertically" mapping the Jichang Garden

Waterscapes constitute a vital component of the Jichang Garden environment. Regarding visual landscape research for waterscapes, visibility is crucial as a visual-spatial characteristic. Among various algorithms employed in vertical mapping, visibility algorithms are commonly used and proven effective. Therefore, a "times seen" map and accumulated viewsheds map were generated to assess the visibility of the pond's surface. Then, interpolation was applied, and color gradients would be used for both the two maps.

2.4.3. "Horizontally" depicting the Jichang Garden

The route on the west side of the pond was selected as the research site, given its proximity to the pond and its significance in connecting the primary buildings from north to south. Viewpoints were established along the route by placing "points" at equidistant intervals of 10 m on the road and elevating these "points" by 1.6 m to simulate the human eye's position. These elevated "points" were designated as "viewpoints" for the study. The length of the Line-of-Sight was set to 100 m (determined by the scale of Jichang Garden). Then, the FOV graphs were generated with the method introduced in 2.3.2. The combined analysis results are presented in the next section. .

3. Results

3.1. "Overlooking" maps: visibility maps of the "Jinhuiyi" pond

The computation generated two graphical outputs: the accumulated viewshed map, in which the red represents the highest visibility while the green represents the lowest (Fig. 4**a**), and the "times seen" map for the pond, in which the red represents the most visible potions while the blue represents the least visible potions (Fig. 4**e**).

3.2. "Eye-level" perspective graphs: FOV of viewpoints besides the pond

After the computation with the method mentioned, a table filled with information, including different types of landscapes and distances to corresponding voxels, was generated for each viewpoint (Fig. 3). Subsequently, the tables were visualized as perspective graphs, composed of six color schemes, each comprising the same hue with varying lightness.

3.3. Combined spatial-visual analysis for Jichang Garden

3.3.1. How does the "Jinhuiyi" pond organize the garden's space?

Many literature sources indicate that the landscape elements surrounding the "Jinhuiyi" pond, such as buildings, rockeries, and plants, are organized about its water surface (DONG, 2014; Eunyeong, 2017; Shu et al., 2018). Moreover, the "Jinhuiyi" pond serves as the visual centerpiece of the garden and even creates an illusion of a larger space than its actual scale. How do we explain this phenomenon within our framework?

(a) "Overlooking" mapping analysis methods

The visibility map showcases the comprehensive coverage of the pond's viewsheds over essential sites, pathways, and significant buildings within the garden, highlighting its centrality in the sightseeing experience. This indicates that the garden designers deliberately arranged these leisure objects around the pond (Fig. 4**b,** Fig. 4**c**). Furthermore, evidence supports this notion by observing the axial lines of several main buildings in a bird's-eye view (Fig. 4**d**). Due to such spatial arrangement, the water surface naturally becomes the visual core. The "times seen" map also indicates a higher likelihood of the central regions (rather than central points) of the pond being visible, further emphasizing the pond's significance as the organizing element for the garden's views. Moreover, other noteworthy phenomena are still on the "times seen" map:

- Two core areas on the water surface can be noticed (Fig. 4**e**). This can be explained as the garden's designer employed an ingenious strategy by shaping the pond as an "8-like" shape, completing with a peninsula ("Hebutan") and a building ("Zhiyujian"), which create two open central spaces with the pond.
- The southern core region is more concentrated, while the northern core region tends to split into two. By examining the bare earth model, it is apparent that there are two other corresponding peninsulas on both banks of the northern water area (Fig. 4**g**). The difference lies in the influence of vertical elements such as plants and buildings. From an "overlooking" perspective, it is also noticeable that the water surfaces are divided into two parts by a large tree located on "Hebutan" (Fig. 4**h**).

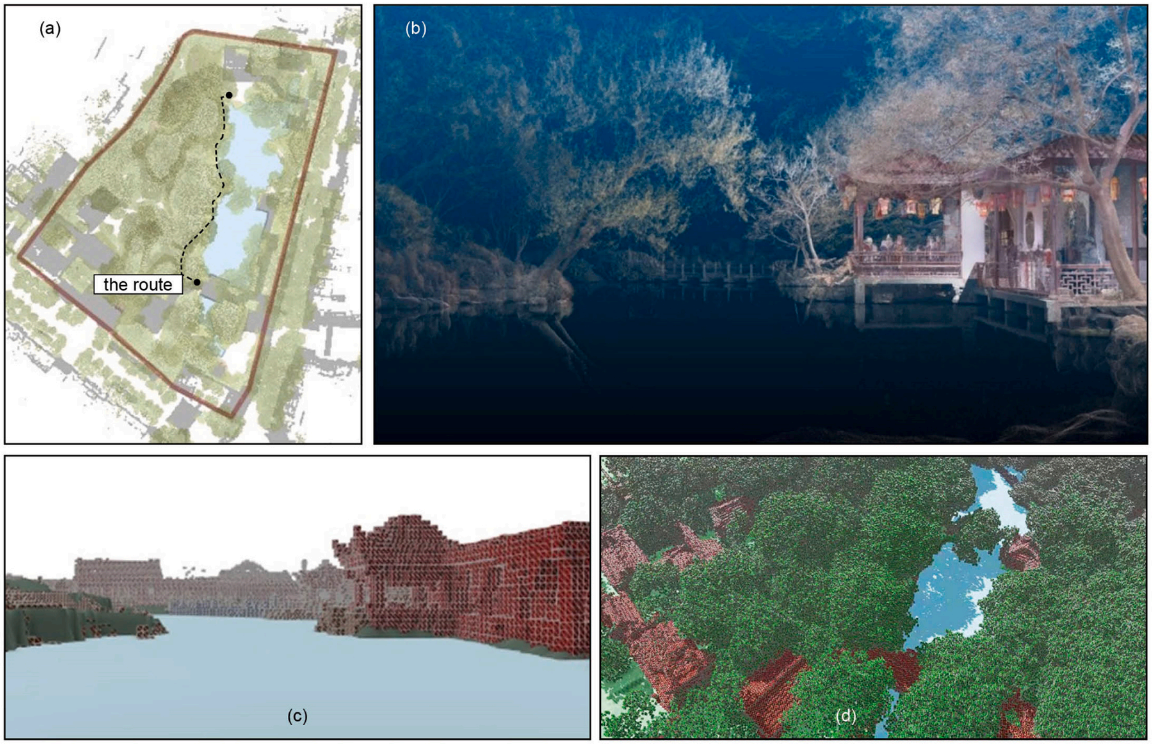
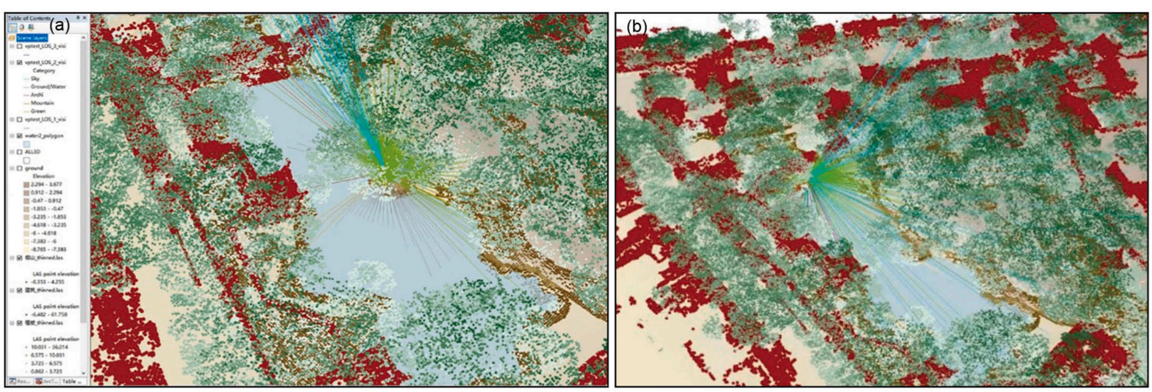


Fig. 2. A case study of Jichang Garden: (a) Master plan of the garden; (b) a typical scenery visualized with points data; (c) the voxels for buildings; (d) the voxels for vegetation.



	A	B	C	D	E	F	G	H	I
1	SourceOID	VisCode	TarIsVis	OBSTR_MPID	Shape_Leng	Azimuth	Vert_Angle	Area	Category
2	1	1	0	393864	5.25469819002	0.00000000000	30.00000000000	84.77787749530	4
3	2	1	0	393843	5.25470652717	5.00000000000	30.00000000000	84.77787749530	4
4	3	1	0	399166	5.25470173718	10.00000000000	30.00000000000	84.77787749530	4
5	4	1	0	399166	5.25471645845	15.00000000000	30.00000000000	84.77787749530	4
6	5	1	0	399201	5.25471531419	20.00000000000	30.00000000000	84.77787749530	4
7	6	1	0	375085	5.23512366210	25.00000000000	30.00000000000	84.77787749530	4
8	7	1	0	399150	5.54336753582	30.00000000000	30.00000000000	84.77787749530	4
9	8	1	0	398844	5.01698715777	35.00000000000	30.00000000000	84.77787749530	4
10	9	1	0	244646	4.67735079897	40.00000000000	30.00000000000	84.77787749530	4
11	10	1	0	398829	4.06957561189	45.00000000000	30.00000000000	84.77787749530	4

(c)

Fig. 3. Eye-level" outcomes: (a), (b) L-o-S in the digital space; (c) screenshot for computation outcomes of FOV. "Shape-Length" represents the distance from a viewpoint to the voxel; "Azimuth" and "vert_angle" represent the angle for the L-o-S contacting the voxel; "Category" means the type of the voxel contacted with the L-o-S, and 1 refers to ground, 2 refers to water surfaces, 3 to rocks and stones, 4 to vegetation, 5 to buildings, and 0 means no voxels have been contacted, which is referred to the sky.

- The northeastern boundary of the northern core area did not continue to extend. The reason for this phenomenon is that the "Qixingqiao", a bridge spanning the water surface at this location, divides the water surface (Fig. 4**h**).

(b) "Eye-level" perspective analysis methods

Through the "overlooking" analysis, it becomes evident that the garden designers have implemented a series of spatial arrangements to

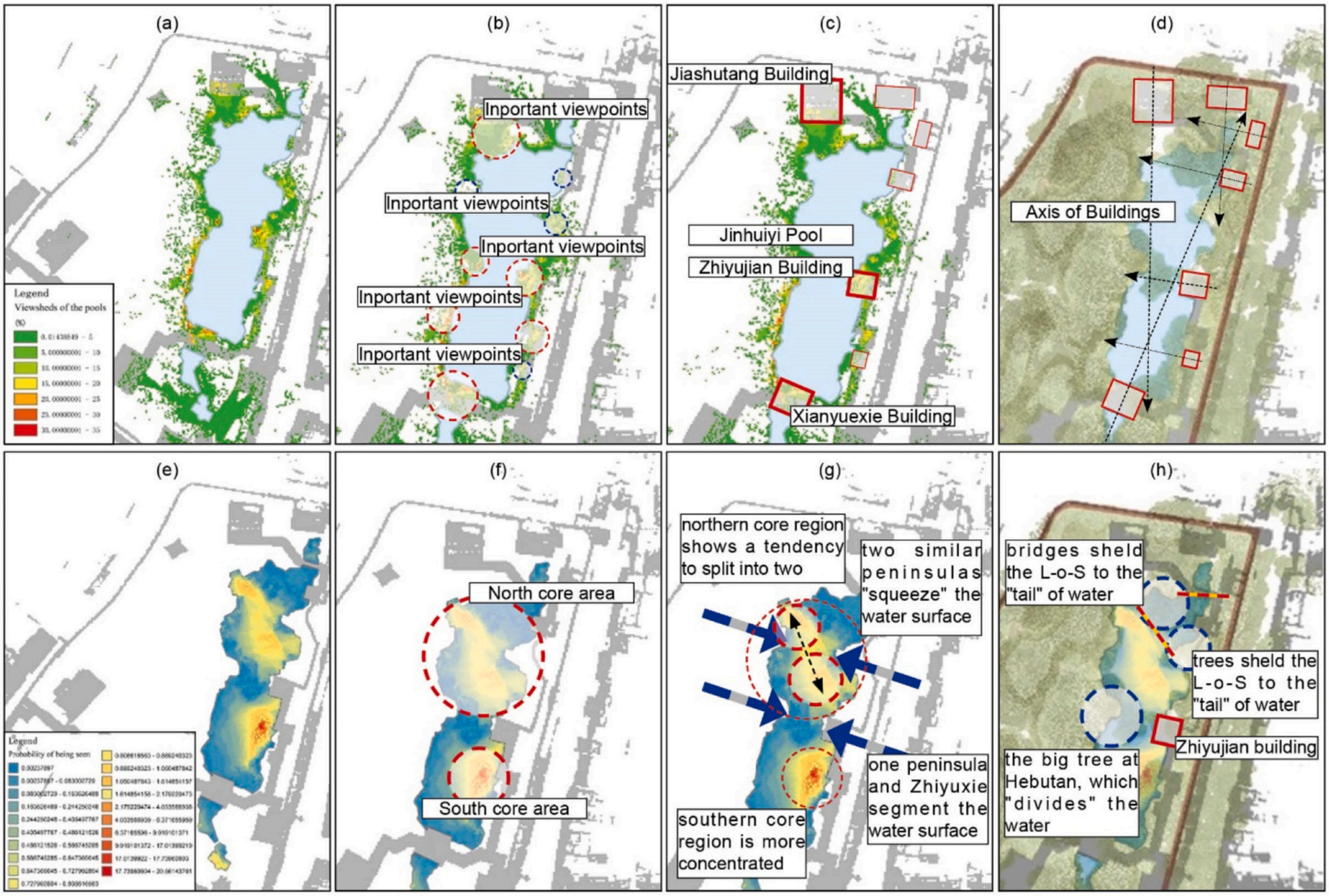


Fig. 4. "Overlooking" analysis: (a)Viewsheds map; (b) important viewpoints around the pond and their spatial relationship with the viewsheds map; (c) the same for the main buildings around the pond; (d) main buildings' axes are set to point to the pond; (e) "times seen" map; (f) two central areas accessible to be viewed; (g) the shape of the pond is composed with three adjacent spaces rather than two ("8" shaped); (h) The explanation for the central areas' formation.

enrich the perceptual environment of the garden. As a result, the viewpoints surrounding the pond offer various framed views, presenting diverse perspectives on the pond, vegetation, and built structures. However, what influences do these designs have on the FOV, and how are these design arrangements accomplished to create the visual illusion of expanded space? Answering these questions requires an analysis from an "eye-level" perspective.

In Jichang Garden, one of the most famous viewpoints is from the terrace near the "Xianyuexie" building. This viewpoint and its vision of the pond will be utilized for a detailed analysis. By capturing images from the viewpoint, a perspective view close to human vision can be obtained (Fig. 5**b**). Building upon the overlooking analysis, we will focus on the plants, buildings, and the bridge spanning the water's surface. The large tree at "Hebutan" is observed to be farther from this viewpoint than several trees on the eastern bank. The "Zhiyujian" building is relatively closed, and a few trees are visible behind it, but at a greater distance (detail of the distance can be seen in Fig. 5**b**). Consequently, the arrangement of plants and buildings (both are semi-transparent) forms a spatial composition of overlapping and occlusion, creating a powerful sense of depth in the visual perception of space. The placement of "Qixingqiao" bridge is located at the far end of this vision, whose presence prevents a clear view of where the water flows (Fig. 5**c**). The vegetation on both sides stimulates the imagination of a larger space beyond the visual boundaries. This further expands the perceived space.

It is noted that many studies analyzing Jichang Garden point out that the "trick" of the perceived extension of space was constructed by creating the shape of an "8" on the water's surface with "Zhiyujian" and "Hebutan" (Shu et al., 2018; Zhou et al., 2018). However, the contour of the "Jinhuiyi" pond's water surface resembles three interconnected spaces stretching from north to south. What causes people, including professional researchers, to have such a misled impression? The author believes this is also a visual-spatial design "trick" involved. The FOV from the viewpoint of "Hebutan" showcases that the aforementioned large tree, due to its eastward growth orientation, gradually blends with the vegetation on the opposite bank in the depth map (Fig. 6). Through this "trick", visitors are led to perceive a false impression of the two banks being very close to each other.

3.3.2. How do the routes make visitors' perceptual experiences interesting?

The garden path is one of the central locations for visitors to engage in recreational activities and is a physical manifestation of the designer's concept of the garden space. Therefore, studying route-based visual space is also essential for understanding and revealing the essence of historic gardens. Hence, this article selects a route adjacent to the "Jinhuiyi" pond as the research site.

(a) "Overlooking" mapping analysis for the route

The "overlooking" viewshed map is applied to reveal the relationship between the route and the "Jinhuiyi" pond. The spatial relationship between the route and the pond is of interest: (a) the route covers terrain with different ranges of visibility for the pond, and (b) the distance between them also varies. Consequently, the designer deliberately crafted this visual-spatial arrangement to generate distinct perceptual experiences for visitors, enhancing the overall sightseeing entertainment.

(b) "Eye-level" perspective analysis for the route

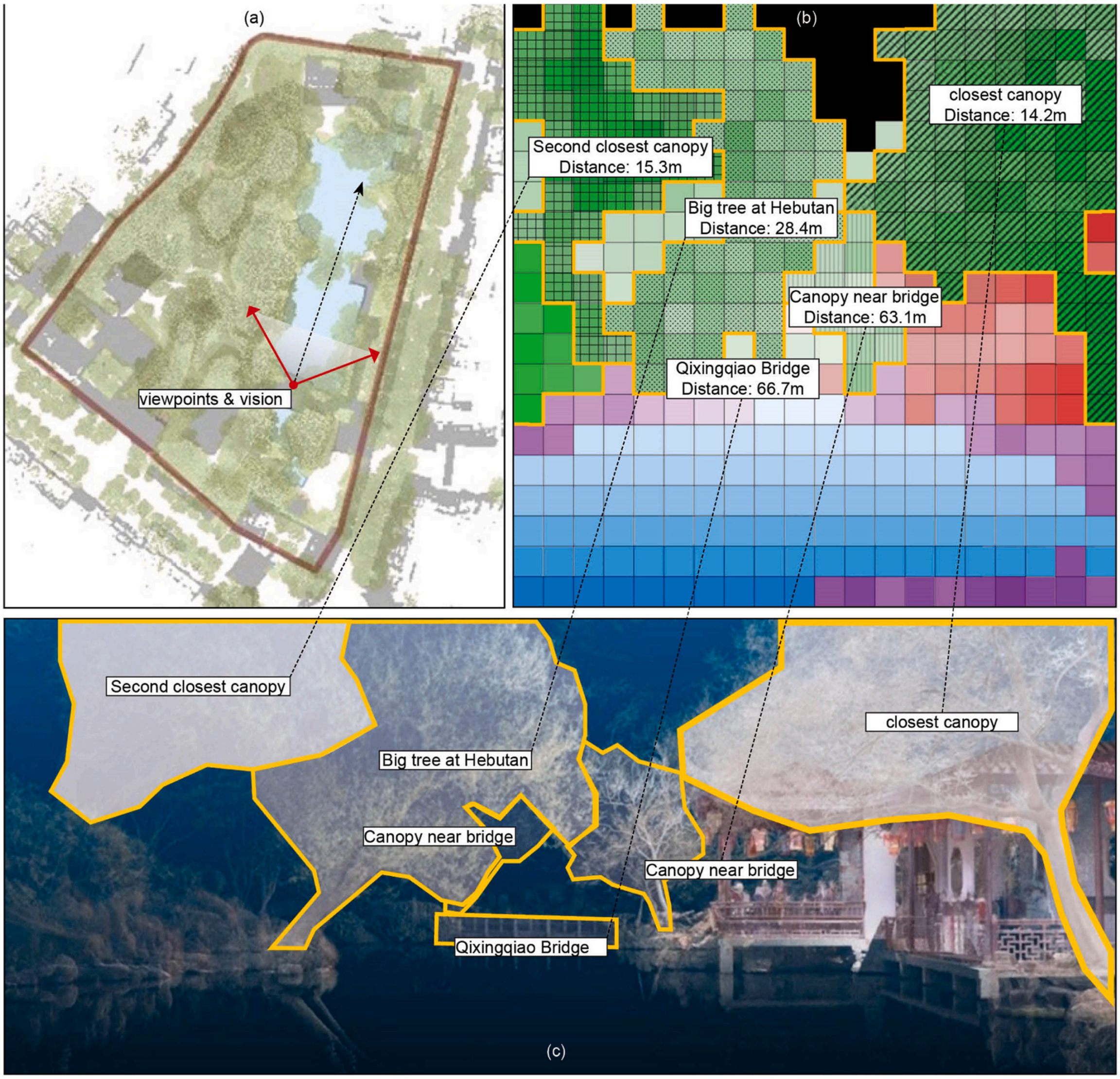


Fig. 5. "Eye-level" analysis for the viewpoint: (a) Location of the viewpoint; (b) Segment of the vision (horizontally ranges 100° and vertically ranges 100°, and the accurate distances (in average for the voxels) among the objects to the viewpoint; (c) the same vision visualized with 3D true-color point cloud.

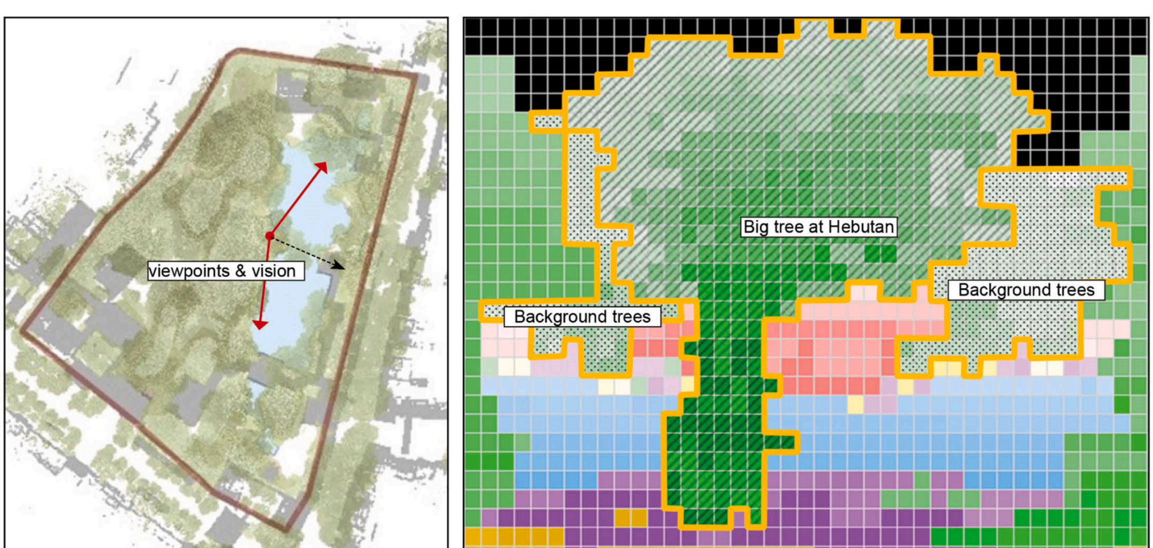


Fig. 6. "Eye-level" analysis for the viewpoint around the "Hebutan": The big tree has extended into the east and blended with the vegetation on the opposite bank.

The analysis of selected viewpoints on this route reveals that the buildings occupy a significant portion of the visual field when people look at the water, indicating that they play a crucial role in the landscape design. Specifically, the “Xianyuexie” building is located on the south side of the pond, the “Jiashatang” building on the north, and the “Zhiyujian” building in the center. The relationship between the building and the landscape can be illustrated using FOV below:

*In the first stage of the journey from “Xianyuexie” to “Hebutan”:*The FOV maps reveal a noticeable trend in which the “Zhiyuejian” building gradually approaches the observer’s viewpoint and becomes increasingly dominant in the FOV. The building of “Jiashutang” also slowly appears in the direction of walking. Conversely, the “xianyuexie” building diminishes in size and prominence in the observer’s FOV (Fig. 7).

*In the second stage of the journey from “Hebutan” to “Jiashutang”:*The FOV map indicates a reduction in the proportion of the “Zhiyuejian” building visible in the observer’s FOV. The presence of the “Qixingqiao” bridge assumes greater prominence in the observer’s view of the water surface and serves as a directional guide towards the “Jiashutang” building (Fig. 7).

Throughout the entire process, it is evident that the “Zhiyujian” building has played a crucial transitional role in linking the preceding and subsequent spaces. The designers have strategically utilized various techniques to visually accentuate the “Zhiyujian” building, such as elevating the building vertically, protruding it towards the water on the plane, and employing color contrasts to enhance its prominence.

3.4. *Conservative managing strategies for Jichang Garden*

The analysis above identifies many core spatial-visual characteristics within the Jichang Garden and the landscape elements involved in achieving them. Conversely, we can better maintain the spatial-visual features of the Garden. As the architecture, topography, rockery, and embankments of the garden cannot be easily adjusted, the suggested protective management focuses on plants and replaceable elements:

(a) The health of the big tree on "Hebutan" must be prioritized for maintenance (Fig. 8**b**). This tree serves as an essential object that

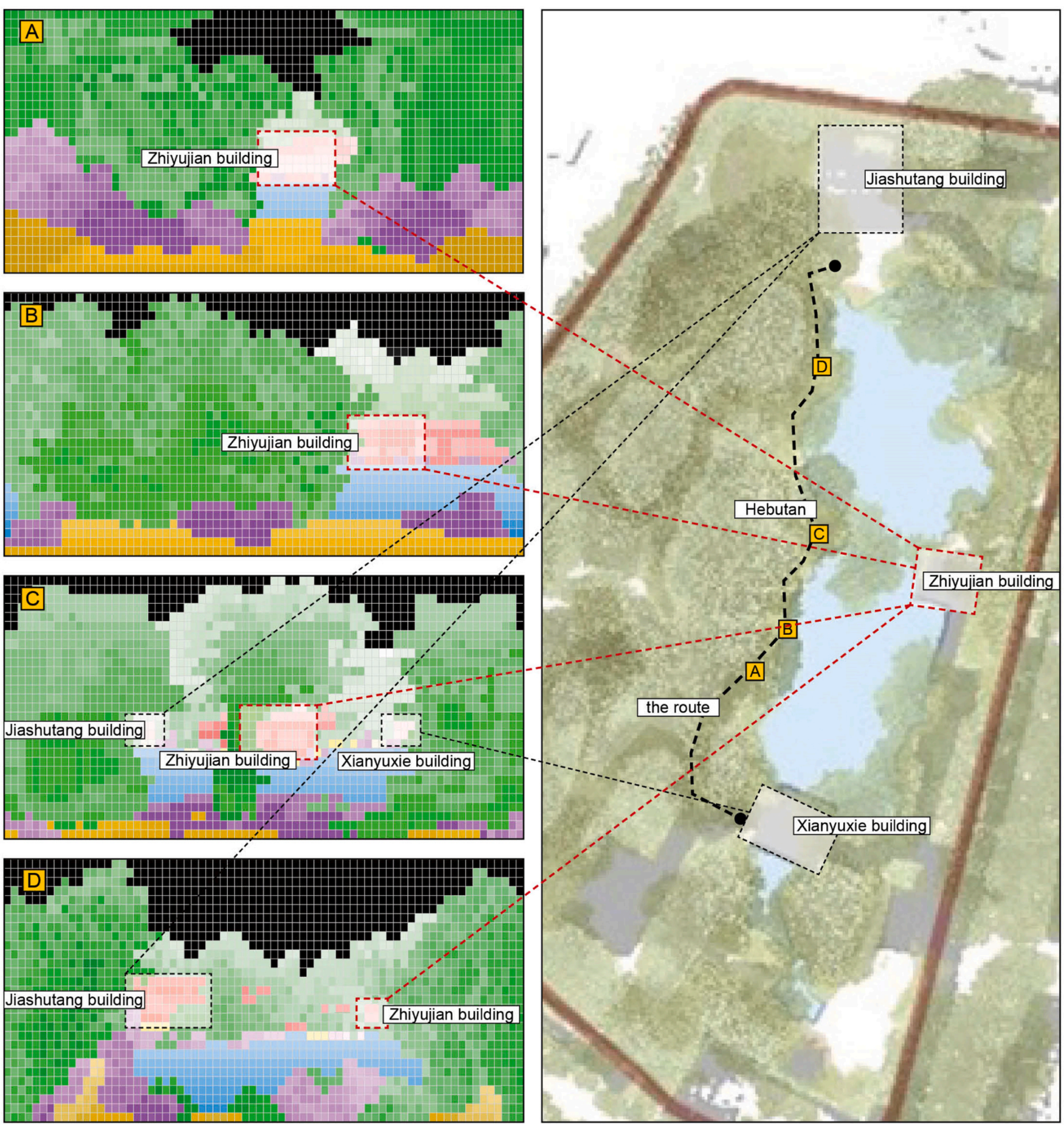


Fig. 7. How does the “Zhiyujian” building play a crucial transitional role in linking the preceding and subsequent spaces?.

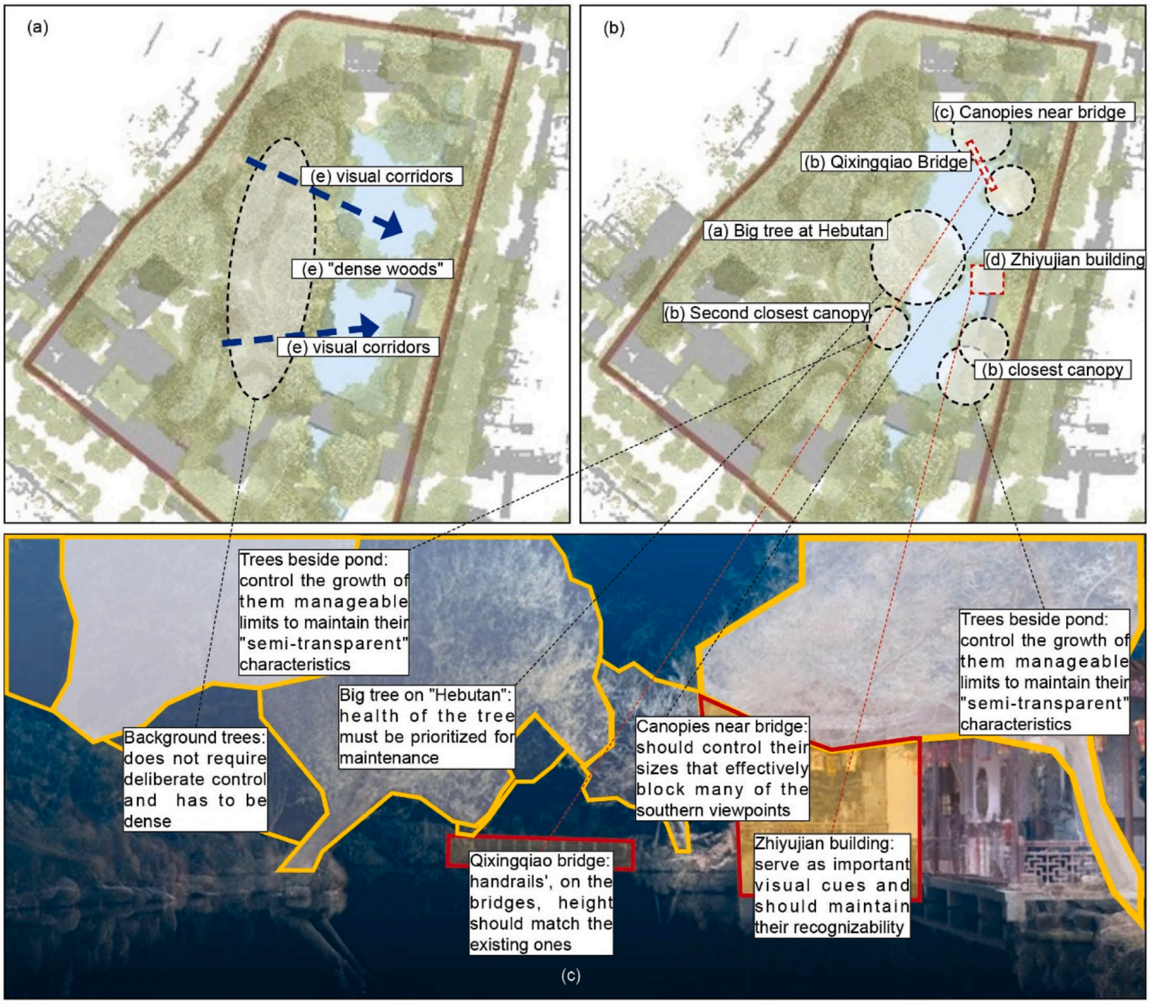


Fig. 8. Conservative managing strategies: (a) region of the trees' growth does not need stringent control and the visual corridors; (b) the distribution of the management strategies on a "vertical" map; (c) the visualization of the management strategies in a "horizontal" perspective view.

facilitates the formation of multiple visual centers on the water surface. It also contributes to shortening the east-west distance and increasing the north-south depth perception. If the tree disappears, it will significantly diminish the core visual-spatial characteristics of Jichang Garden. Even with salvage replanting, restoring the visual and spatial environment would still require considerable time.

(b) To ensure relatively unobstructed north-south visibility within the site while still providing some plant coverage, it is important to control the growth of the plants shown in the diagram within manageable limits to maintain their "semi-transparent" characteristics. Additionally, if any of these plants die, they should be replaced.

(c) The deciduous trees around the "Qixingqiao" bridge should have canopy sizes that effectively block many of the southern viewpoints, creating a visual barrier towards the water surface on the northernmost side (Fig. 8**b**). Furthermore, if the handrails on bridges like the "Qixingqiao" bridge need replacement, their height should match the existing ones, while maintaining a relatively airy to stay semi-transparent. This ensures that visitors perceive the presence of the water surface but without actually seeing its size, thus creating an illusion of expanded garden space through the viewer's imagination.

(d) The "Zhiyujian" building should capture visitors' attention in the middle section of the path along the west of the pond (Fig. 8**b**). Methods to ensure this building is visually captivating are needed, including protecting the background plants create contrasting colors that make the "Zhiyujian" building stand out and controlling the scale of surrounding plants or newly added rockery stones.

(e) The growth of woods on the pond's west does not require deliberate control, and the canopies must be dense. However, it is essential to ensure that in the critical visual "corridor" areas (Fig. 8**a**). This ensures the variability of spatial-visual characteristics during the stroll, providing a rich and interesting visitor experience.

4. Discussion

4.1. Insights

The above analysis serves as a proper example to demonstrate that, in the context of spatial-visual analysis and preservation of historic gardens, the application of a combined approach based on high-precision point cloud technology offers insights in the following areas:

4.1.1. Higher accuracy and quantifiability

The advantage of using point clouds lies in their ability to quantify the elements being analyzed precisely. For example, in the earlier analysis of the vegetation surrounding the Jinhuiyi (Fig. 5), precise measurements of the average distance between the visible portion of plants and the viewpoint were calculated. Traditional methods often rely on measuring the distance between the viewpoint and the target planting points, making it challenging to quantify elements like branches and tree canopies in reality. However, in a voxelized virtual space, the visible parts of each tree from the viewpoint and the distances between them can be accurately quantified. This eliminates the vagueness in spatial-visual analysis, where observations rely on observers' perception of the environment and their descriptive feedback. Furthermore, compared to methods that primarily use DEM or DLM models for analysis, which struggle with non-standardized and non-regular landscape elements like plants and rockeries, this approach provides precise quantification, enhancing the accuracy of calculations.

4.1.2. Why apply the combined method

In the analysis, an overviewing map can first identify macro-level "phenomena," while eye-level analysis can further explore the causes of these phenomena. For example, in the route-based analysis section, analysis with a visibility map provides the clue that the route covers different visibility areas to the pond, while FOV can provide specific insights into the perceptual changes from different viewpoints along the route. Due to the quantifiable voxelized point cloud model, changes in the FOV from different views can be analyzed concretely and quantitatively (Fig. 7). Therefore, the role of the Zhiyujian building as a pivotal element in the spatial design of the garden was discovered.

4.1.3. Revealing visual tricks

Many visual tricks in historic gardens do not have more documentation or explanations from the designers, leading researchers to overlook many ingenious spatial arrangements and visual tricks. For example, in the former pieces of literature, researchers often emphasized the "8-like" shape of the pond, while in reality, the water surface consists of three adjacent spaces. What caused this misinterpretation? It was the presence of giant trees growing within the garden (Fig. 6). This paper, aided by the combined analysis method based on point cloud technology, unveiled this long-overlooked truth.

4.1.4. Forming conservation strategies

With the support of point cloud technology, conservation strategies can be tailored to individual plants and their canopies. Additionally, by identifying core visual-spatial features in historical gardens and their influencing elements, the combined analysis framework offers advantages in devising more precise and efficient conservation strategies for these core elements (Fig. 8).

4.2. Limitations

This paper's analysis methods and conclusions are conducted in a virtual and digital space. However, real-world visual experiences and perceptions cannot be entirely replaced by digital analysis. For example, color was not included in the analysis, despite being an essential factor influencing human visual perception and the visual-spatial characteristics of the environment. Therefore, the reliability of the methods still needs to be supported by extensive field investigations within the research scope. Techniques such as eye-tracking can be employed to validate human visual perception experiences further.

Moreover, historic gardens, as a category of cultural landscapes, possess solid regional cultural characteristics. Each culture has its own visual-spatial features and gardening design language. Therefore, many design concepts and spatial meanings/metaphors could hardly be directly derived from simplified GIS-based analyses of the virtual 3D environment. Instead, this method only provides a quantifiable perspective for research with a digital technology-based methodology.

Although 3D point cloud technology provides highly detailed data, especially in stationary scanning, the data is more refined, and a significant amount of data loss often occurs during the process of converting point data into computable and solid digital models. Segmentation and downsampling of points can compromise the authenticity of the data. Compared to the formers, voxelization involves even more irreversible loss of data details, including but not limited to (a) expanding plant boundaries and concretizing the porous canopies (not solid masses but translucent elements). Consequently, the initially "semi-transparent" tree canopy becomes an "opaque" state that the L-o-S cannot penetrate. (b) Structural and architectural details are lost, requiring a reexamination in the 3D point cloud space. Furthermore, since scanning is conducted at a specific period, the variations in the appearance of plants across different seasons can also impact the conclusions.

Though flaw exists regarding computing efficiency and accessibility, the presented method is relatively accurate, and easy-taking to acquire the spatial-visual characteristics. Thus, it enables researchers/designers to utilize this framework in design analysis and visual-spatial research for historic gardens.

5. Conclusions

Historic gardens, as important human heritage, require the recognition of their spatial-visual characteristics, interpretation of design ideas, and protection of their spatial-visual environments. Point cloud technology provides a tool for rapidly scanning high-precision data of historic gardens from the real environment. GIS-based techniques and algorithms offer convenient and time-saving methods for visual landscape analysis. Both can be applied to facilitate the study, protection, and management of historic gardens. These GIS-based visual analysis methods can still be divided into "vertical" and "horizontal" approaches, which, due to their different perspectives and the spatial-visual features they reflect, can complement each other and cross-validate the accuracy and reliability of calculations. Therefore, this article proposes a comprehensive method, or a framework, that encompasses the following:

(a) It demonstrates technical application by utilizing the scanning of point clouds to obtain high-precision data and the voxelization algorithm to simplify the point cloud to generate a voxel-based, solid model for GIS-based visual landscape research.
(b) This article has developed a new algorithm that reflects the distance and type of voxels in various colors, enabling us to understand the FOV precisely from any viewpoint within the model.
(c) A spatial-visual analysis framework integrating "horizontal" and "vertical" approaches has been proposed and developed for historic gardens. Though some studies combine these two approaches, few have explored the positive impact of their combined application on analysis results. Furthermore, the application of this method in historic garden research is even less common.

In the case study for Jichang Garden, several scenarios have been presented to demonstrate the application of this framework. The following has been achieved: (a) Visual research combining "overlooking" visibility maps with key viewpoints' "eye-level" perspective views was conducted to identify the causes and crucial factors shaping spatial forms. (b) By integrating viewshed maps and FOV analysis, route-based research has been conducted to thoroughly explore visitors' visual perception processes through the path and the visual-spatial characteristics of the route. (c) Complementary protective management strategies were proposed. Moreover, as this framework is not a fixed method but a flexible approach/framework, its application prospects are more open-ended. It can be further developed to explore new application scenarios and possibilities, and many other directions await exploration and development.

CRediT authorship contribution statement

Yuyang PENG (co-first author & Corresponding author): Writing (original draft and revision) and editing, Visualization; Works of "Introduction, Methods: the way to Visualize the FOV, Results, Discussion, and Conclusions." **Guanting ZHANG (co-first author):** Methods for voxelization and visibility computation. **Steffen NIJHUIS:** Supervision, Suggestions on framing the research and paper, and writing the revision. **Giorgio AGUGIARO:** Supervision and Suggestions on methodology. **Jantien E. STOTER:** Supervision.

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.

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