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A GIS-based Algorithm for Visual Exposure Computation: The West Lake in Hangzhou (China) as Example

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Abstract: Visual perception is crucial in landscape experience. Therefore, visual landscape research is an important field of inquiry that needs further development and applications (NIJHUIS 2011), and visibility analysis is the basis for further research. There are many methods and applications of landscape visibility analysis that have been developed and applied in the past decades. The pioneering work of Llobera explores the concept of "visual exposure". He defined the visual exposure (V-E) as a measure of the visible portion of whatever is the focus of the investigation, which is about the surface area covered on the retina (LLOBERA 2003). In this research, a newly developed V-E computation algorithm for complex environments has been developed, which enables the analysis of views from multiple viewpoints. The West-Lake, a UNESCO world heritage site in Hangzhou (China), is used as a case study to compute the V-Es' value for viewpoints on routes beside and around the lake. Finally, the method's accuracy and the algorithm's adoption potential have been evaluated.

Keywords: GIS-based visibility analysis, Visual exposure, the West Lake Hangzhou, V-E computation algorithm

1 Introduction

Visual perception is crucial in landscape experience. Therefore, visual landscape research is an important field of inquiry that needs further development and applications. Visual landscape research entails an interdisciplinary approach that combines (a) landscape planning, design and management concepts, (b) landscape perception approaches, and (c) Geo-information technology. When psychological knowledge of landscape perception, the technical considerations of geomatics, and landscape architecture and urban planning methodology are integrated, a solid basis is provided for visual landscape assessment in cities, parks, and rural areas. It offers great potential for acquiring design knowledge by exploring landscape architectonic compositions from the "inside out" and possibilities to enrich landscape character assessment with visual landscape indicators (NIJHUIS et al. 2011). Visibility analysis is an important and primary element in visual landscape research. Referring to the methods for visibility evaluation, a line-of-sight algorithm was invented by Ford in 1959 to compute the visibility of the terrain surfaces and was first applied in military fields (FORD et al. 1959). Later, visibility computation has been utilised in many other fields and disciplines, such as architecture and urban planning (WILSON et al. 2008), geographic study (GOODCHILD et al. 1990) and archaeology (LLOBERA 2003). Within the discipline of architecture and built environment, two major categories of methods have been developed, including the concept "isovist", initially put forward by TANDY (1967), and various algorithms for viewshed computation based on different GIS platforms. Though the purpose of visibility computation is to provide ways to research the relation between landscape and human beings' perception,

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the traditional visibility analysis methods, neither viewsheds nor isovist, could provide effective means to depict the composition of views from specific viewpoints at eye-level, because these visual mapping methods are focussed on the "overlooking" views instead of "perspective" views (DOMINGO-SANTOS et al. 2011).

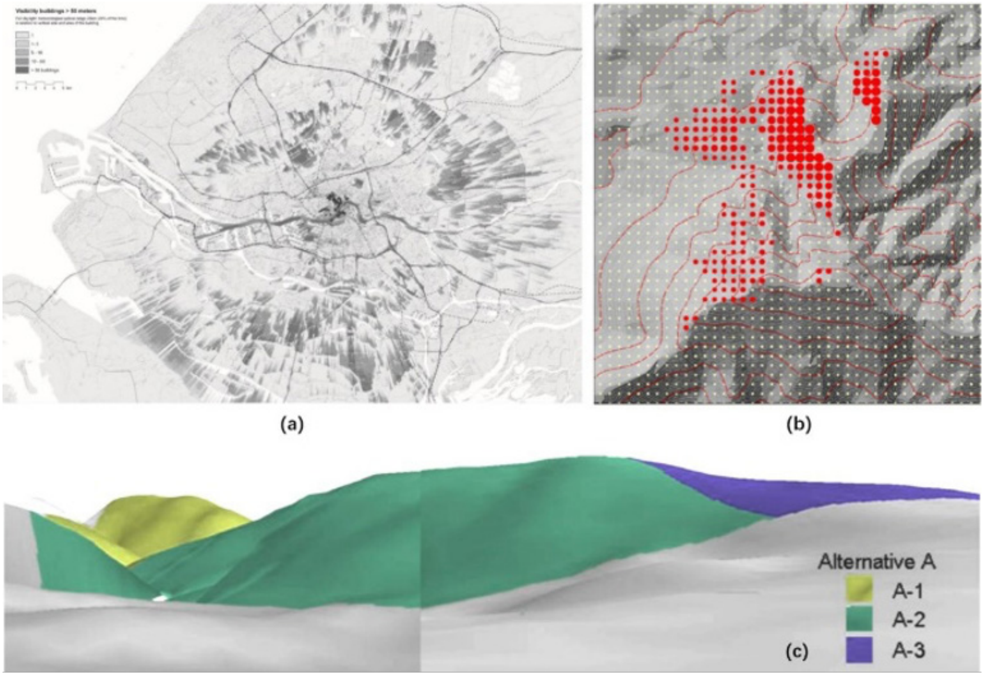

Fig. 1: (a), (b) Typical viewsheds computation and visual landscape mapping, which relates the visible portions to the observed objects in an "overlooking" plan (source: NIJHUIS & VAN DER HOEVEN 2018, ZHANG 2014); (c) a graphic presentation for V-E analysis, and the computing outcomes are the measurements of the occupied areas within perspective views (source: DOMINGO-SANTOS et al. 2011)

1.1 Visual Exposure (V-E) Computation

Common visibility methods often result in maps and numerical tables, but these are complicated means to delineate the view's composition from a horizontal perspective. To address this problem, lots of efforts have been made. The pioneering work of Llobera defines and explores the concept of "visual exposure". He defined visual exposure (V-E) as a measure of the visible portion of whatever is the focus of the investigation, which is about the surface area covered on the retina (LLOBERA 2003). Since the concept of "visual exposure" has not been widely accepted, many other similar definitions, such as visual magnitude (CHAMBERLAIN et al. 2015), visual perception sensitivity in VIEWIT program (TRAVIS et al. 1975), are also employed to conduct similar research. In general, two types of algorithms can be distinguished: (a) Indirect-computing methods, in which the distance and aspect relative to the observer are considered, are usually applied to estimate the one specific region's V-E for single or multiple viewpoints. The indirect-computing methods can be adopted in huge, complex environments with many viewpoints, but the accuracy of the calculation would be relatively low; (b) Direct-computing methods, such as the GIS-based algorithms developed by Domingo-Santos, which calculates the visual exposure of the terrain surfaces for several viewpoints (DOMINGO-SANTOS et al. 2011). The visual quality computation methods developed by the Lin's enable accurate calculations for different objects in the observers' fields of view using the parameters like distance, solid angle, and visual fields (LIN & LIN 2017). The accuracy of direct-computing methods has been scrutinised. However, these methods are ineffective and time-consuming in complex and extensive digital environments with many viewpoints to analyse. Many studies based on photography are employed, digitally analysing and quantifying the composition of views based on photographs. For example, this type of analysis is recently used to monitor park structures' changes by calculating the percentages of the landscape elements in multiple photographs from the same view (NIEDŹWIECKA-FILIPIAK et al. 2020). This method is practical and easy to implement, but difficult to apply in forecasting the visual impacts of proposed spatial developments. It is also not flexible as the analysis relies on the taken photographs, making it difficult to change the views under investigation. However, GIS-based V-E computation methods are based on accurate digital landscape models and allow rapid and flexible analytical procedures from a multitude of viewpoints.

1.2 Using West Lake as a Case Study

This paper takes the West Lake, Hangzhou, as an example. The West Lake is famous for its intricate and articulate relationship between the lake and its surroundings, consisting of an aesthetically pleasing hilly natural landscape with green forests, villa and garden complexes, pagodas and a vast urban landscape. From the 1980s, rapid urbanisation started to change the West Lake's scenery dramatically and urged the government to develop policy regulations to protect the scenery. Two policy documents for protecting the scenery and aesthetics of the West Lake and surroundings have been adopted. The first one focuses on the landscape planning and design for the West-side of the West Lake (2003) and especially elaborated on the importance of the eco-environments in the western parts of the lake. The second document focused on an urban planning and landscape design strategy for the West Lake's East bank (2009) and elaborated on the urban area's visual management on the Eastern bank. This document includes guidelines for the city's skyline development, restrictions on high-building development, the visual protection of critical views, etcetera. Several analytical methods were proposed and applied, such as sections, picturing from selected viewpoints, and sketching the skyline. This policy exerted a significant favourable influence on the protection of the lake's visual-aesthetic qualities, which led to UNESCO's recognition.

From a more technological perspective, the employed methods are time-consuming and imprecise. To advance digital methods for understanding and planning the visual-spatial characteristics of the lake is of crucial importance.

1.3 Research Objective

The objective of this paper is twofold: (a) to showcase a novel, time-saving and easy-taking algorithm, which is useful and accurate in a large and complex digital environment with many viewpoints to analyse, and compute the V-Es of the lakes; (b) to explore the possible application of the method in urban planning or visual management for the West Lake. The paper is organised in three parts. The first part addresses a novel algorithm for V-E computation. The second part focuses on the application of the method using the West Lake as a case. Finally, the outcomes are discussed, and some potential applications identified.

1.4 Limitations

Concerning recent visibility research and studies, one of the critical promotions is the possibility to use high-precision geodata, such as the LiDAR or so-called point cloud technology (VUKOMANOVICA et al. 2018). However, gaining high-resolution data and developing DEMs is time-consuming with high cost, and sometimes not possible because of security reasons or technical limitations. Therefore, it is vital to develop methods for situations without such data, like West Lake. Consequently, the proposed methods and their outcomes will have limitations, as the quality of any analysis depends on the data quality. For instance, the lack of detailed data on vegetation has a significant influence on the analysis outcomes presented in this paper (VUKOMANOVICA et al. 2018). Additionally, the scope of the site under investigation is also restricted by the availability of geodata. For example, the mountains and hills around the lake are not fully covered. Finally, the geometric distortion caused by the perspective projecting process is unavoidable, which might be not accurate in presenting the observer's views. Though these flaws exist, with regards to the computing efficiency, the presented method is relatively accurate in acquiring the visual characteristics within the eye-level perceptual views.

2 Methodology

2.1 Data and Modelling

In the West Lake data model, the lake's water surface plays a significant role, as well as the green spaces and hills around the lake, the eastern part of the wetland, and the western section of the urban area. The study region's data, being surveyed and mapped in 2008, was provided by the local government. A few types of data are available, including data on elevation (elevation points and contour lines), data of buildings and other structures (master plan and the number of stories for each building), data for roads (bolder and central lines for each road), data for land use (border and properties). GISs consider two main classes of digital elevation models (DEM): triangulated irregular networks (TINs) and regular square grids (RSGs) (KUMLER 1994). In this study, we employed RSG. The modelling process included four steps: (a) to establish a model for the bare earth with elevation data (the raster resolution of the model is 0.5m); (b) to model the buildings and structures, the floor height has set as 3.5m; (c) to fit the two models and merge them; (d) to classify the surface of the combined model with five different properties, including West Lake, the other water bodies, green space, buildings and structures, and paved grounds or undefined terrain areas.

2.2 V-Es Computation Algorithm

As the V-Es could be measured with the occupied areas of the objects' projections on the retina, the essential process is to depict the coverages of the target on the projected plane. In the previous studies, the viewed objects are mostly regarded as a surface. Therefore, the researchers were trying to obtain the "shape" of these objects on observers' retina, which cause obstacles to abstract the exact borders and distinguishing the blank areas to covered areas. In this study, we used the "point-to-point" method, instead of the previous "point-to-surface" method, to obtain the visual-spatial relationship between surroundings and eye points, since the relationship between two points could be more straight-forward and easier to be formulated than the relationship between one point and several surfaces. Additionally, the usage of perspective projecting is the key to this new method, which solves the problem of transferring the dots in a 3-dimensional (3D) modelling space to a 2-dimensional (2D) plane. The final V-E assessment algorithm follows several steps as below: (a) preparation works; (b) viewsheds computation and outputting the results with GIS software; (c) measuring the V-Es.

2.3 Preparation Works

This step could be done within the GIS-based software, including five sections: (a) Setting the viewpoints. Three different types of roads, including five segments (L_1, L_2, L_3, L_4, L_5) of the main roads surrounding the lake (most important traffic streamlines around the lake), two segments (L_1', L_2') of the causeways (historical and distinctive routines in the lake) surrounded by the lake, and three segments (L_1'', L_2'', L_3'') of the walkways beside the lake (the popular footpaths for the tourists and local citizens), have been selected as research sites. To ensure that there would be one for every 50 meters, and 1.6 meters higher than the surface of the ground, viewpoints have been set on the central lines of these roads: 233 viewpoints (V_1, $V_2 \ldots V_{233}$) on the main roads, 72 viewpoints (V_1', $V_2' \ldots V_{72}'$) on the causeways, and 126 viewpoints (V_1'', $V_2'' \ldots V_{126}''$) on the walkways. The sights' directions for all the viewpoints have been defined as the vectors normal to the roads and pointing to West Lake. (b) Setting the D-Ms for the DEM. The D-M density would influence the results' accuracy, while too many dots might cause a massive challenge for the computation procedure. Therefore, we set three D-Ms with different grid density: 5*5m, 10*10m, and 50*50m. Then, all the dots have adhered to the surface of the DEM. After a few attempts, we decided to use the D-M with a grid of 10*10m to complete the computation, and the other two would be used as comparative samples. (c) Setting the fixed dots for buildings and structures. Since the master plans of the buildings and structures have been collected, we set the dots on the plans' edges. Then, the dots were duplicated as the stories increased in the DEM. The buildings and structures could be classified as two types: the buildings located close to the eye points (distance shorter than 30m) and the others. For the first type, the dots were set more intensive, and there is one for every 2m on the edge of each story. For the second type, the dots were set sparser, and there is one point for every 5m. (d) Setting the D-Ms for the roads and the surface around them. According to the perspective principle, there would be denser dots reflecting the adjacent areas to the viewpoints; thus, we set three D-Ms belts with more elaborate resolutions besides the researching roads. 4m-belt with 1.5*1.5m D-M, 10m-belt with 2.5*2.5m D-M and 30m-belt with 5*5m D-M are included. (e) Classification for the dots. We classified the dots into five different types according to the property of the surface they are adhered to.

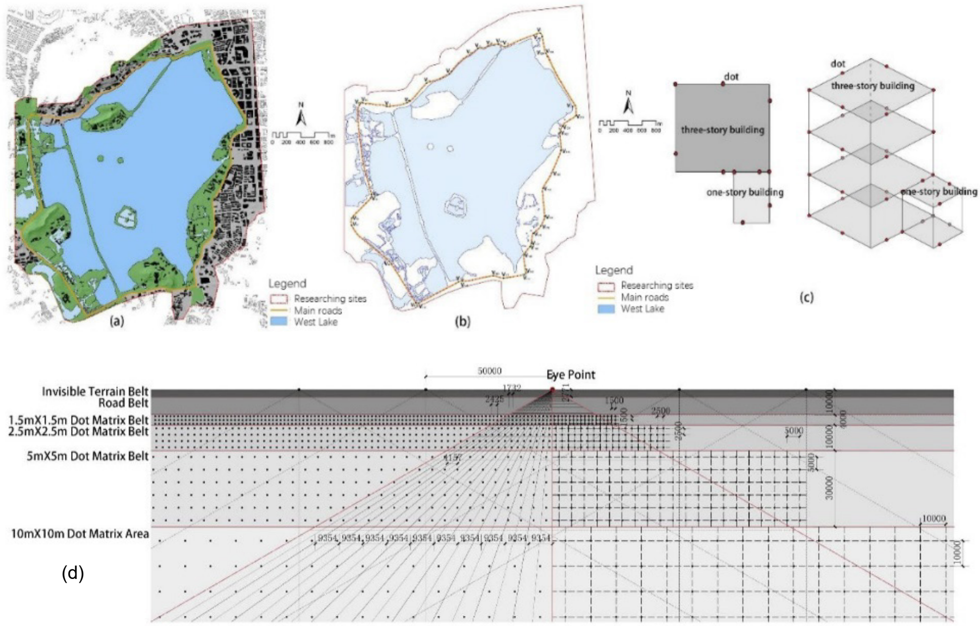

Fig. 2: (a) Classification of the land use; (b) the selected roads and set viewpoints on them; (c) setting the dots on buildings; (d) setting D-Ms for roads

2.4 Measuring the V-Es for the Viewpoints

The initial procedures are performed with ArcGIS 10.2 with a few standard algorithms. While, in a later process, the newly developed methods programmed in Python were applied. Measuring V-Es consists of two major stages, (a) transaction of the coordinates data and (b) computation of the V-Es.

In step (a), the perspective projection has been chosen to deal with this issue, which was recognised as one of the foundational visualisation technologies (TANKUS, SOCHEN & YESHURUN 2005).

Firstly, we had to translate the visible dots' spatial data in the 3D world coordinates (X_w, Y_w, Z_w) to the 3D coordinates (X_e, Y_e, Z_e) with the viewpoint as a new origin point and the vector of sight as a new X-axis. This process could be realised by moving the origin of the world coordinates to the viewpoint and rotating the coordinates with the angle, defined as θ, which is between the axis (X_w) and the sight vector. As for the dots within the coordinates space, their new coordinate value (x', y', z') could be gained with the following group of equations and the usage of the former coordinates value (x, y, z).

A plane, which is 1m away from the viewpoint and normal to the axis (X_e), has been defined as the projecting plane, also used as the replacement of the retina's surface. Those points behind the observer can be easily eliminated because their x-values are below 0. Either one of the remaining points Q (x_1, y_1, z_1) could be projected onto the plane, and a projected point Q' (x_1', y_1', z_1') would be obtained. The new coordinates values of Q' could also be gained by using the equations below. Only the "Y" values and "Z" values are kept; thus, the dots in a 3D coordinates space are projected onto a 2D coordinates plane.

Table 1: Equations for coordinates transactions and projecting transactions

Equation Set 1:	Equation Set 2:	Equation Set 3:	Equation Set 4:
$\text{Cos}(\theta)=(x_m-x_n)/d$ $\text{Sin}(\theta)=(y_m-y_n)/d$ $d^2=[(x_m-x_n)^2*(y_m-y_n)^2]$ $(d>0)$	$x'=x-x_n$ $y'=y-y_n$ $z'=z-z_n$	$x''=x'\cos(\theta)-y'\sin(\theta)$ $y''=x'\sin(\theta)+y'\cos(\theta)$ $z''=z'$	$x_1'=1$ $y_1'=y_1*x_1'/x_1$ $z_1'=z_1*x_1'/x_1$

Finally, to simulate the visual range of an observer, a view-frustum is created as an ideal rectangular pyramid, and the apex of the hypothetical geometry is set at the observer's eye point. To be in accord with the sight of an observer, the vertical angle (β) of the pyramid is set at 60°, the horizontal angle (α) is set as 120°. Therefore, the projection plane and the frustum would have an intersection face, which could be regarded as the approximate model of the retina surface and defined as face SOR (surface of retina). As Table 2 shows, the points out of SOR could be eliminated by comparing coordinate values.

Table 2: Equations for coordinates transactions and projecting transactions

horizontal edges	vertical edges	the range of Y-values	the range of Z-values
$Y_{rmax}=\tan(\beta\alpha/2)$ $Y_{rmin}=-\tan(\alpha/2)$	$Z_{rmax}=\tan(\beta/2)$ $Z_{rmin}=-\tan(\beta/2)$	$Y_{rmin}\leq y_r\leq Y_{rmax}$	$Z_{rmin}\leq z_r\leq Z_{rmax}$

In step (b), measuring the V-Es on the SOR is hardly available by counting directly, because points, mathematically, could be on a surface but cannot occupy any areas of the plane. Therefore, the SOR needs to be put into rasterization, so that we are accessible to count the cells which contain different classes of dots. Moreover, the number of cells containing one property dots could measure the V-E value of this kind of surfaces. For instance, if the number of the cells with the property of West Lake's surfaces is 80 out of 800 divisions, which means the lake would occupy the 80/800, equal to 10.0%, of the field of view for this viewpoint, and the V-E value of this class is 10.0%. Two things were carefully considered: the number of the divisions (for cells) and the method to count them. A proper dividing method needs to ensure that at least one point is located in any cell under the skyline. Therefore, the procedure to divide the SOR has a close relationship with the density of the points. In this study, we divided the SOR into 800 cells: 20 divisions horizontally multiply 40 divisions vertically, which is sufficiently accurate and easily operated for computers. Though it is easy to accomplish the counting, a problem still challenges the program. There may be more than one type of points belonging to one cell. We divide the cells into several equal "shares" according to the number of types to solve this. For instance, a cell might include three types of points, and we would "divide" the cell into three equal shares. As a result, each type of points occupied one-third of the cell. Finally, we could measure the areas for each type of points by adding up the numbers of entire cells and dividing cells. In this way, the V-Es, not only of West Lake, but also other four types of surfaces, could be gained, and the results would be visualised with different histograms in six different colours.

3 Results

All the V-Es of different surfaces have been measured for all the viewpoints. As the graphs indicate, six types of columns in different colours are applied to present V-Es' proportions for each viewpoint. The yellow columns are applied to present the V-Es of the West Lake's surface. They are outlined with red edges to emphasise the significance. A higher yellow column also equals a better vision for the lake. The lighter grey columns are used to show the empty cells on the SORs, the green spaces are shown in green, the buildings and structures are in black, the other water surfaces are in blue, and the paved or other undefined terrains are in darker grey.

(a) V-Es for the viewpoints on the main roads. As the result shows, the north shore roads are better viewpoints for observers to appreciate the West Lake. 51 of 59 viewpoints could view the lake, and 22 viewpoints (the V-Es for the lake is higher than 10%) of them have prominently sweeping sights of the lake. The viewpoints on the west shore mostly have greener sights. Only 5 of 67 viewpoints own the sights, where the coverage of green spaces is lower than 10 per cent, and there are 15 viewpoints with the V-E for green spaces higher than 20%. The V-Es of other water surfaces also play an essential role: the water surfaces of the wetland, as only 14 viewpoints could not see them. The western section of the north shore could view the lake, while green spaces or hills cover the eastern sections' sights. The east shore results are more complicated than the other sections; the V-E values for empty cells and buildings change dramatically. As for the northern segments, 17 of 26 viewpoints could have a relatively expansive view of the West Lake.

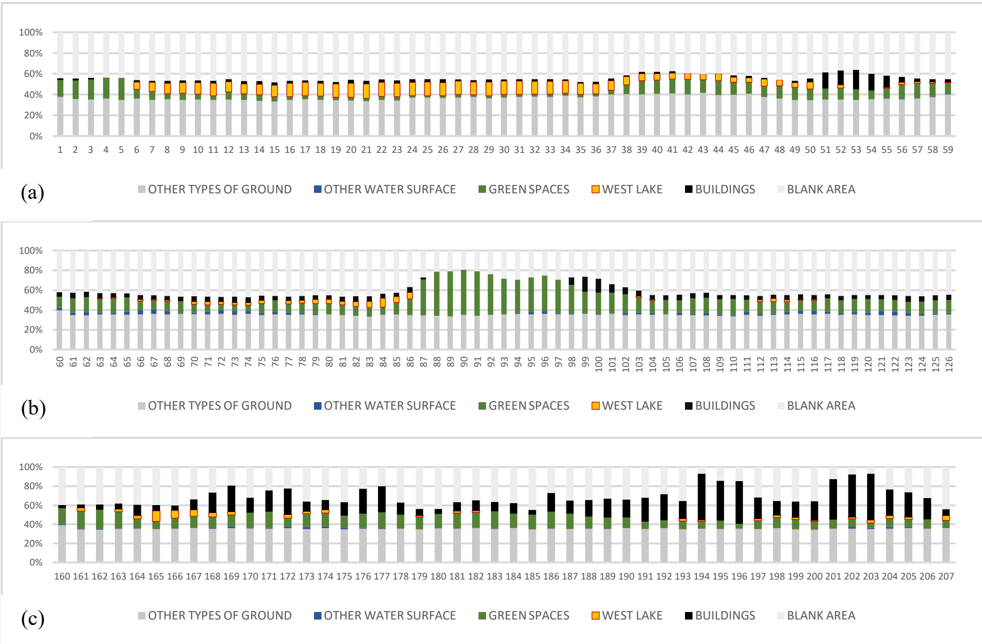

Fig. 3: (a) V-E value for viewpoints on L_1; (b) V-E value for viewpoints on L_2; (c) V-E value for viewpoints on L_4

(b) V-Es for the viewpoints on the causeways. Since the causeways' viewpoints have double views of the lake, the V-Es would be calculated twice to match with the two views. In general, the value of V-Es of the lake is relatively high for these viewpoints, ranging from 6% to 8%, while the V-Es for the lake is too high, like over 30% when the viewpoints are on the bridges.

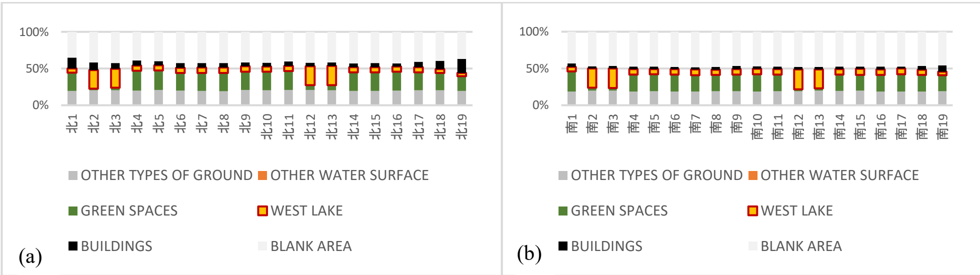

Fig. 4: (a) V-E value for viewpoints on L_{N1}'; (b) V-E value for viewpoints on L_{S1}'

(c) V-Es for the viewpoints on the walkways. The V-Es for the lake fluctuate dramatically, ranging from 0 to over 30%. The viewpoints on L_1'' own the best views to the lake, and the average value of the V-Es for the lake is over 29%. While the viewpoints from L_3'' could hardly view the lake, the V-Es' average value for the lake is merely around 3%.

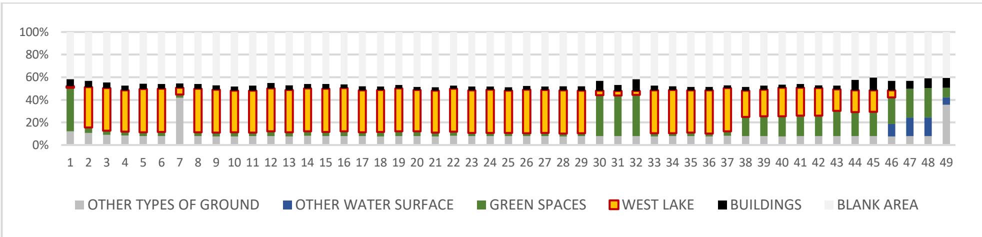

Fig. 5: V-E value for viewpoints on L_1''

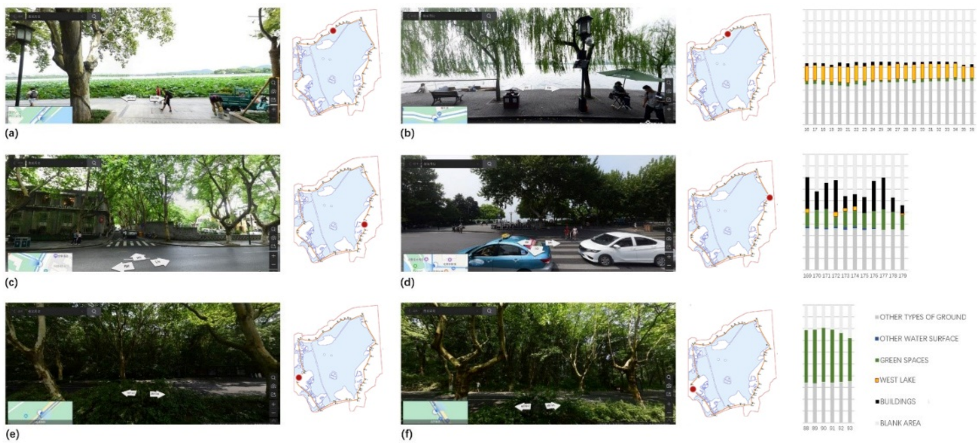

Fig. 6: (a) (b) the viewpoints where the V-E value for the lake is relatively high, around the V10-V36; (c) (d) the viewpoints where the V-E value for the buildings and structures is relatively high, around the V168-V174; (e) (f) the viewpoints where the V-E value for the green spaces is relatively high, around the V87-V93

4 Discussion

4.1 About the Algorithm

One effective way to verify the new V-E algorithm's computation results is to visualise views and compare them with the real situation. We used the Matplotlib toolkits for Python, which provides a pack of tools to translate the digital data into a 2D raster or vector graphs. One of the tools named seaborn could produce "heatmaps". We assigned values for the cells according to the type(s) of D-M they include so that these values could be adopted to create a raster graph to visualise the perspective FOV (field of view) for each viewpoint. There are 30 different classes for all the cells with permutations of the five properties, and their given values and colours are shown in the table. Five viewpoints were selected, and the visualised graphs for views are similar to reality; thus, the algorithm for V-E is reliable and accessible.

Table 3: The values for different classified cells. L=the surfaces of the West Lake; W= the other water surfaces; G= green spaces; O=paver or other undefined grounds; B=buildings and structures

class	L	LW	LG	LO	LB	LWG	LWO	LWB
value	1	2	3	4	5	6	7	8
class	LGO	LGB	LOB	LWGO	LWGB	LWOB	LGOB	
value	9	10	11	12	13	14	15	
class	W	WG	WO	WB	WGO	WGB	WOB	
value	16	17	18	19	20	21	22	
class	G	GO	GB	GOB	O	OB	B	EMPTY
value	23	24	25	26	27	28	29	0

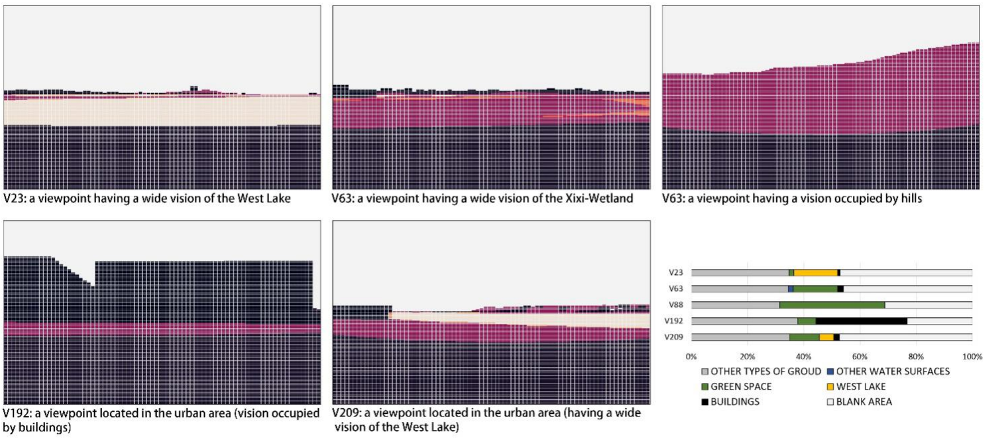

Fig. 7: Visualisation for the sights and V-Es for those viewpoints

The histogram of the V-Es for all possible pairs was juxtaposed to explore the impacts of the parameters' resolution. It could be seen that both the division of cells and the D-M metrics have significant influences on the accuracy of the computation. Besides, the impact is not a single functional factor. We could notice that the two conditions are mutually dependent, which means that for each resolution of D-M, there should be relatively suitable SOR divisions matching with it.

4.2 Possible Applications

Nowadays, many researching or planning projects are merely based on the outcomes produced by GIS-based viewshed analysis, which sometimes might have blind points on design for the perceptual visual environment. Therefore, one of the method's potentials is obvious. By combining the viewsheds analysis with V-E analysis, both the "overlooking" visual-spatial relationships and the "perspective" perceptual visual connections could be considered in the design and planning process.

Firstly, V-E computation could be an effective way to reveal the visual characteristics from a perceptual perspective. For example, by merely comparing V-Es' average value for viewpoints from different roads, we could find that the L_1' causeway has "greener" views. The green spaces make up considerable proportions in the views (Fig 4). We could also find that the L_1" walkway has the best views to the lake in these 10 segments (Fig. 5). In addition, with a few statistical processes, more visual characteristics could be analysed. For example, by adding the V-Es value together, all the occupied areas of the retina are counted, thus the rest empty areas must be the coverage of the sky. Besides, the variation in amounts of empty cells of different viewpoints could be applied to explore the changes of the skyline. The computation results also support this idea. Seeing the top of the columns in the L_2, the "curve" is near to the shape of the hill in front of the observers (Fig. 3). What's more, the variations of the V-Es' value from one viewpoint to another could be a possible way to evaluate the variation of visual environments among different viewpoints. The hill's shape V-Es reflect the sights viewed. Therefore, we employed the Standard Deviation method to calculate the variations among the viewed sights for different roads. Finally, the L_4 was identified to be the road with the most variable sights (Fig. 3). This fits the fact that the L_4 locates in a semi-urban situation where the views on buildings and green spaces shift dramatically.

Secondly, the V-E computing method has the potential to be useful in many aspects. For example, planners or designers could apply this visual impact assessment method to new constructional projects. By using the visibility analysis with viewsheds, the range of impacted areas could be quickly gained. Then the viewpoints could be set in the influenced areas, and the V-E data could be collected with this algorithm, which would indicate the possible visual impacts on those viewpoints. The evaluation results could be more reliable and more reasonable than merely using the viewshed analysis since the perceptual environments' effects are also presented. Finally, looking back to the mentioned urban design project for Hangzhou in 2009, the improvements could also be easily reached. The high-rises' possible visual impacts were not merely gained by sketching the sections for several so-called essential viewpoints. However, by evaluating their visibility, the impacts on the V-E values for numerous viewpoints within the influenced viewshed portions could be analysed. The visualisation of V-Es' computation could also help analyse the skyline. The so-called "rhythmical architectural variations" of the skyline could mathematically be discussed instead of empirical and fuzzy description by sketching.

5 Conclusion

Visual perception is essential for landscape experience. Before planning and managing visual elements for the built environments and natural landscapes, it is core to evaluate their visibility. Previous methods are usually stressing viewshed computation, while this research proposed a V-E computation method to assess the visibility of a scenic landscape with a "perspective" perceptual angle. Empowering the planners and city managers to consider the visual environment at different scale levels is of crucial importance and the presented method offers great potential for that.

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