Measuring the Integrated Development Degree of Urban Waterfront: A Quantitative Index Based on Multi-sourced Urban Data and Geodesign

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The urban waterside area is an important component of the urban spatial structure. However, current research on this topic cannot comprehensively and accurately measure the integrated development of the urban waterside area because of its comprehensive value and the coordination topic of watersides' equilibrium resulting from various elements in the physical space and the social system. Therefore, with an emphasis on urban synergy and balance, it is indispensable to establish a comprehensive quantitative index system to evaluate the integrated development of urban waterside areas. This research takes Shanghai, Guangzhou, Wuhan, and Ningbo as cases and evaluates urban waterside areas on aspects of socio-economic and physical spaces to construct an integrated development evaluation system. First, the distance that can be reached by public transit within 30 minutes from each city river's shoreline is considered as the research scope. The socioeconomic indicators include the number of points of interest (PoIs) and population density based on location-based services (LBS) data, while physical space indicators include walking and vehicle traveling potential. Moreover, the analytic hierarchy process (AHP) is employed to calculate the weights of the above indicators. Finally, a qualitative evaluation model based on multi-source data for evaluating the integrated development of urban waterside areas is proposed. The results show that Ningbo and Guangzhou have maintained relatively high integrated grades, and the balance has developed more evenly. Among the four cities, the waterside's integrated level of Wuhan is the lowest in each range, leading to its relatively large spatial diversity, weak accessibility, and low development intensity. This research not only contributes a more scientific way of defining isochrones based on Gaode API but also solves the long-lasting problems of limited labor costs, few research samples, and a short-covered timeline in urban evaluation, which support future refined urban design practices in the waterside area.

1. INTRODUCTION

1.1. THE RISING DEMAND FOR INTEGRATED DEVELOPMENT

The reconstruction and redevelopment of the waterfront are important means for many cities to cope with the transformation of their socio-economic structures.[1] As an important carrier of urban vitality and a characteristic expression of the urban context, the waterfront has gradually become an important object of urban renewal and an important way to improve the city's image.[2] Recently, the development of waterfront areas in many megacities around the world has integrated such characteristics.[3] In addition, waterfront research has developed a wealth of qualitative and quantitative refined indicators to improve the spatial quality of the waterfront and achieve the economic benefits of urban land use.[4]

However, most of the research on urban waterfronts discusses specific issues of material space or socio-economic dimensions from a single perspective, such as urban planning, urban transportation, public space, industrial development, and natural ecology. Nevertheless, the comprehensive value of the waterfront and the integration of the two sides of the river are the results of the interactions between multiple elements in the physical space and the social system. With the emphasis on urban synergy and integration, a comprehensive quantitative index has more exploratory significance for waterfront evaluation.

1.2. NEW POTENTIALS FOR MEASURING THE INTEGRATED DEVELOPMENT OF AN URBAN WATERFRONT

As discussed above, establishing analysis methods and a comprehensive quantitative index to accurately evaluate the integration of urban waterfronts is inevitable. The emergence of new data and technologies has provided new opportunities for measuring traditional unmeasurable space and quality.[5] Previous research provides new perspectives for studying the waterfront public space and functions via PoIs data,[6] mobile phone data,[7] space syntax,[8] and multi-agent behavior simulation.[9] However, the existing studies are often limited to a specific population or a spatial characteristic, with rare insights in the multi-dimensional data for integration analysis. Thus, this research attempts to reveal
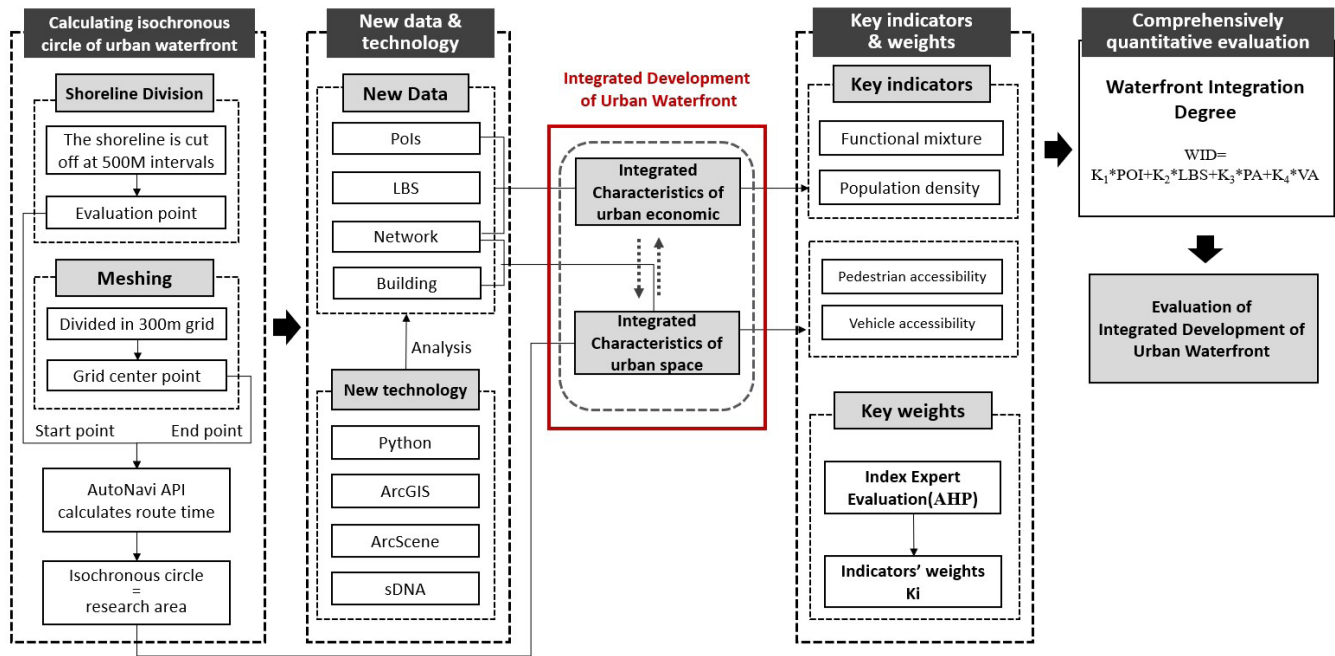
Figure 1. Research framework.

both physical and social dimensions through multi-sourced data, aiming to construct a quantitative evaluation index for the integrated development of the two sides of the urban waterfront.

2. METHODOLOGY AND DATA

2.1. METHODOLOGY
The evaluation of the waterfront mainly involves two main aspects: physical space elements and socio-economic elements. Accordingly, this research consists of five steps: calculating the isochronous circle, collecting data and using new technologies to analyze them, determining four indicators and their weights, calculating the waterfront integration degree (WID), and evaluating the integrated development of urban waterfronts (Figure 1).

First, Python was used to determine the study area, which is fully described in the next section. Second, we collected POI, LBS, road network, 3D built environment, and other multi-source data of the corresponding waterfront area. Third, four indicators were extracted, including functional mixture, population density, pedestrian, and vehicle accessibility, using an analytic hierarchy process (AHP) to determine their weights. Finally, a comprehensive evaluation index of the integrated degree of the urban waterfront was developed after calculating the WIDs.

2.2. STUDY AREA
In this study, Shanghai, Guangzhou, Wuhan, and Ningbo, the core waterfront areas of the four cities were selected as the research samples. All four have a waterfront space as their core, and the balance between the two sides of the waterfront hinterland is significantly affected by the water body (Figure 2(a)). To obtain

a precise research scope, this study uses the navigation route calculation via the AutoNavi API to calculate the transit time of the bus navigation route from the waterfront shoreline to each point in the research area and takes the minimum navigation time to the shoreline as the travel time from the grid to the waterfront shoreline. We cut off the coastline at 500m intervals and set the limit distance that can be reached within 30 minutes of the urban waterfront coastline. Finally, the inverse distance weighting method (IDW) is used for spatial interpolation, 30 min contours are extracted as the isochronous circle of each shoreline, and the online map is loaded using the Mapbox platform for visualization (Figure 2(b)).

2.3. DATA

2.3.1. FUNCTIONAL MIXTURE BASED ON THE NUMBER AND DIVERSITY OF POIS
POIs are the spatial reflections of various functional facilities in the city. This research uses Python and AutoNavi Map API to extract the POIs of various functional facilities (commercial, business, catering, public services, etc.). It is measured from three aspects: the total density of POIs, their Shannon index, and their median of the density in a 300m*300m grid.

2.3.2. POPULATION DENSITY BASED ON LBS DATA
The research uses Tencent's heat map LBS data on May 19 and 22, 2019. The sum of the weekend value multiplied by two and the midweek value multiplied by five is used as an indicator to measure population density. The kernel density tool in ArcGIS was used to calculate the population density, obtain the

Central district of Huangpu River in Shanghai

Central district of Zhujiang River in Guangzhou

Central district of Yangtse River in Wuhan

Central district of Yongjiang River in Ningbo

(a) Center of 4 cities

Isochronous circle in 15\30 mins of Shanghai eastern shore

Isochronous circle in 15\30 mins of Shanghai western shore

Isochronous circle in 15\30 mins of Ningbo eastern shore

Isochronous circle in 15\30 mins of Ningbo western shore

Isochronous circle in 15\30 mins of Guangzhou Northern shore

Isochronous circle in 15\30 mins of Guangzhou southern shore

Isochronous circle in 15\30 mins of Wuhan eastern shore

Isochronous circle in 15\30 mins of Wuhan western shore
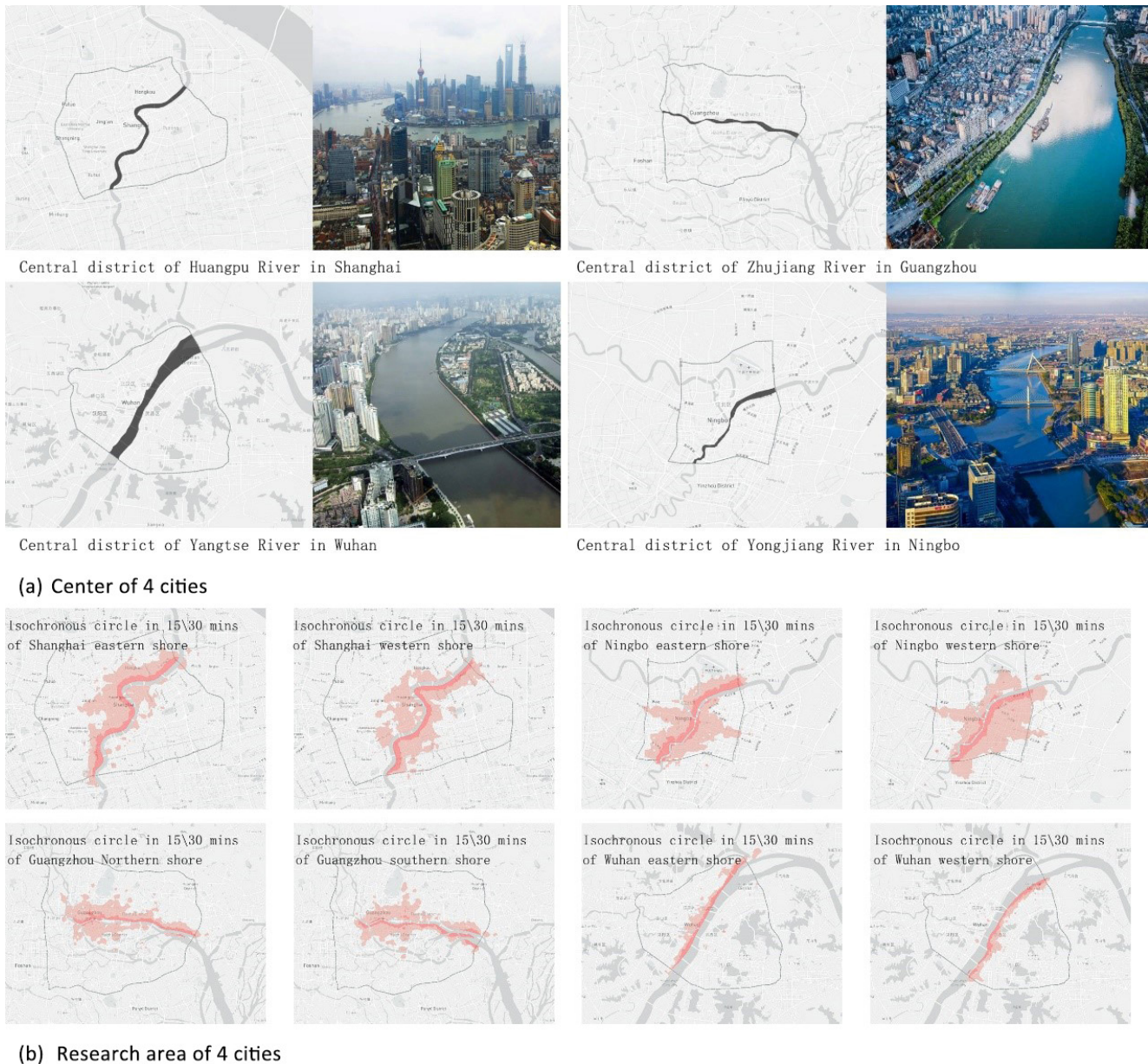
(b) Research area of 4 cities

Figure 2. Research area.

population density within 30 min isochrones of the shoreline on both sides, and import ArcScene to visualize the 3D heat map.

2.3.3. ACCESSIBILITY OF PEDESTRIAN AND VEHICLE NETWORKS

The study uses the spatial design network analysis (sDNA) to calculate the "Betweenness" index based on the angular distance to measure the accessibility of the road network.[10] In the specific analysis, the road centerline extracted from the Baidu map is used as the basic network data to analyze the "Betweenness" of the road network; a small-scale analysis radius of 800m is used to reflect the pedestrian accessibility, and a large-scale analysis radius of 8km is used to reflect the vehicle accessibility.

3. RESULTS

3.1. FUNCTIONAL MIXTURE

As seen from Figure 3, PoIs in Shanghai, Guangzhou, and Wuhan all have obvious concentration centers: the highest PoI density on the east coast of Shanghai is near Lujiazui, and the PoI density on the west side is significantly higher than that on the east side. The PoI density on the north side of the Pearl River in Guangzhou is higher than that in the south, the PoI density on the west of the Wuhan Yangtze River is greater than that on the east, and the PoI on the east is densely located in Wuchang District near the Yellow Crane Tower and Qingshan University. However, Ningbo has multiple cores of PoI-dense areas, which are relatively scattered.
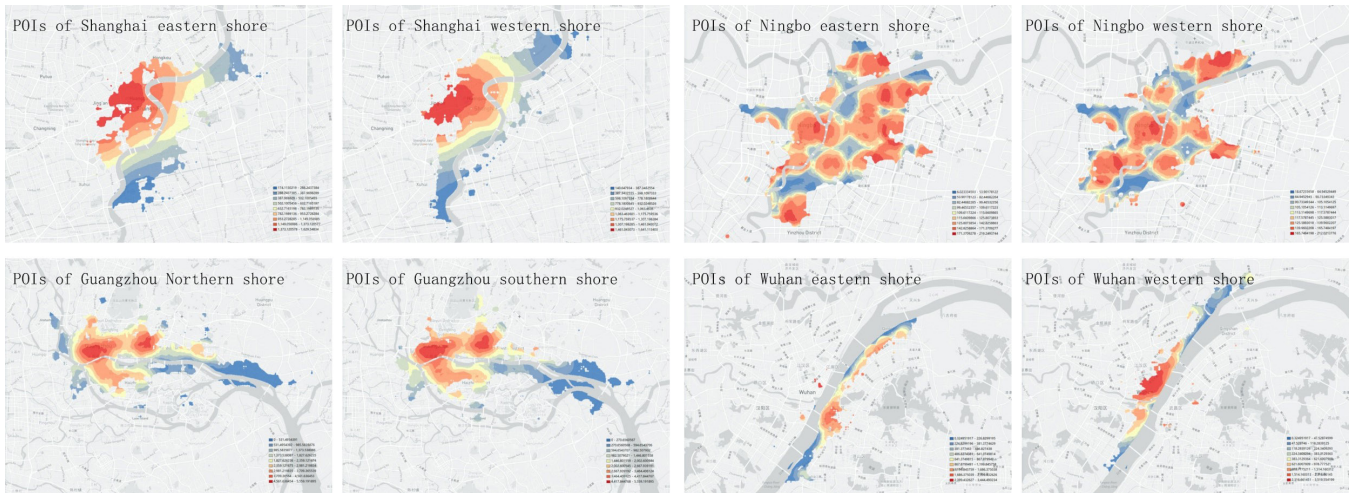
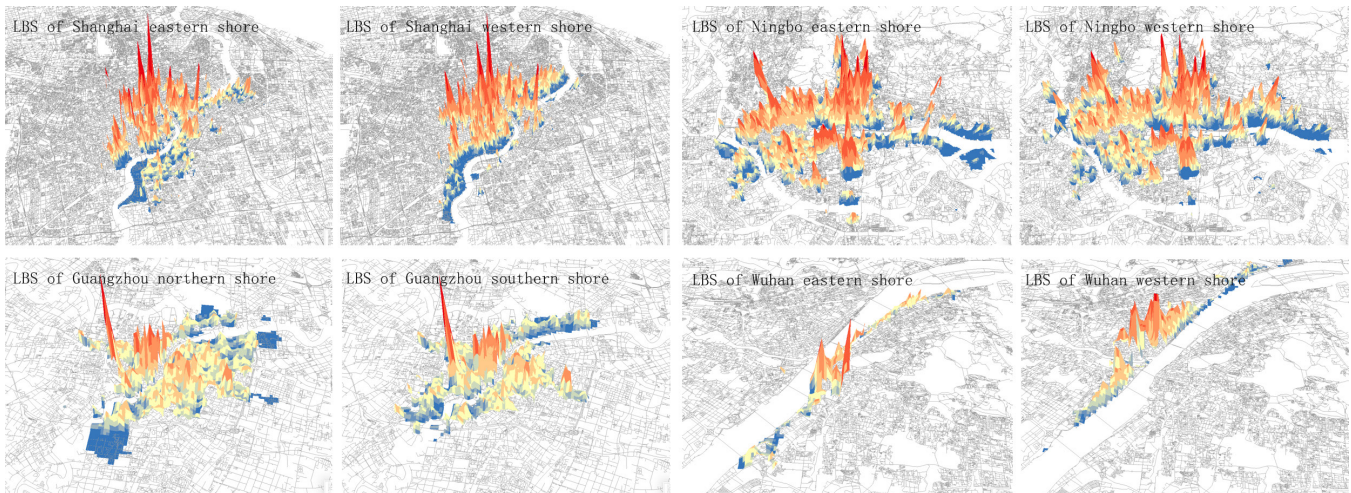Figure 3. Functional mixture of four cities.

Figure 4. Population density of four cities.

The median score in Ningbo is the smallest, and the difference between the median values of the east and west coasts is extremely small. In contrast, the median score in Guangzhou is the largest, and the median difference between the north and south sides of Guangzhou, Shanghai, and Wuhan are relatively large. From the perspective of the number and diversity of PoIs, Ningbo has the highest integrated degree, while Wuhan and Shanghai have the lowest.

3.2. POPULATION DENSITY
According to the LBS data (Figure 4), except for Guangzhou, the population density in the waterfront areas of the other three cities shows obvious agglomeration. Specifically, the area near the Ningbo Railway Station has the highest population density. The

high population density center in Shanghai is located near the Nanjing East Road and Bund. The high population density area on the east side of the Han Yangtze River is near Wuhan Avenue and the Wuhan Yangtze River Bridge. It can be seen that Wuhan has the lowest integrated score, and the population difference between the two sides is relatively large. Ningbo has the highest score, and the population distribution is the most balanced, followed by Guangzhou and Shanghai.

3.3. ACCESSIBILITY OF PEDESTRIAN AND VEHICLE NETWORK
As shown in Figure 5(a), in terms of walking, there are more roads with higher accessibility in Guangzhou, and the south bank and the north bank are more similar. The internal roads of

(a) Accessibility of pedestrian network

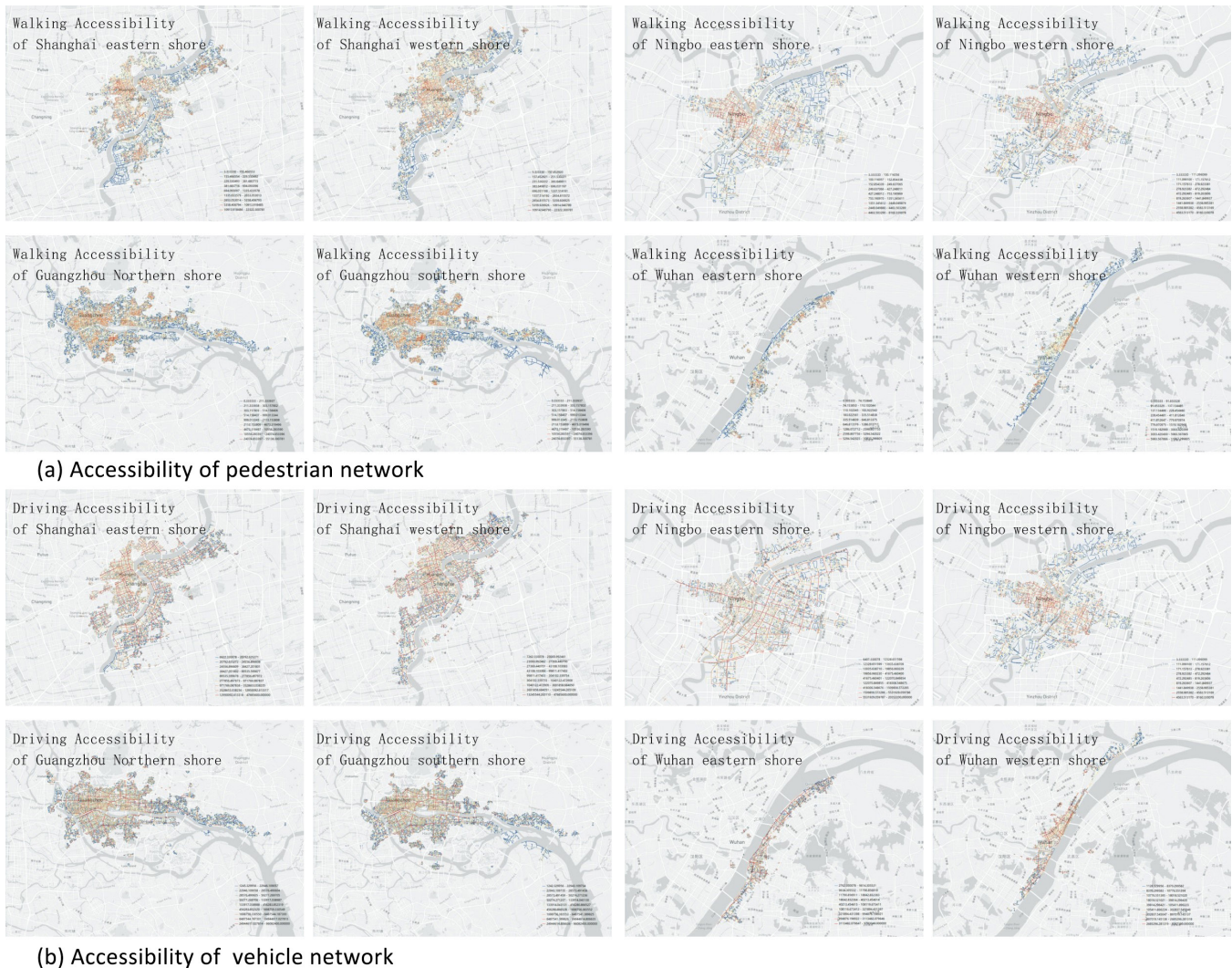(b) Accessibility of vehicle network

Figure 5. Accessibility of pedestrian and vehicle network.

the Hankou River Beach on the west coast of Wuhan have the highest pedestrian accessibility, and the roads closest to the water on the east coastline are not highly accessible on foot. In terms of vehicle networks, there are no obvious congregation areas on roads with higher travel accessibility in the four cities (Figure 5(b)). From the perspective of both walking and driving accessibilities, Wuhan's integrated index is the lowest, and there is a big difference between the two sides; those of Guangzhou and Shanghai are higher, but the differences are relatively large. Ningbo has the highest score, indicating that the difference in accessibility between the two sides of the Yongjiang River is very small.

3.4. WEIGHTS OF INDICATORS BASED ON AHP
We invited 30 experts from the fields of architecture, planning, and landscape to use the AHP for calculating the weights of the above-mentioned integrated development evaluation indices. The numerical weighted arithmetic average of each expert's

judgment matrix is used for group decision-making. The assembled judgment matrix is listed in Table 1.

3.5. WID OF FOUR CITIES
On this basis, the final results of the WID development in each case can be obtained (Table 2). Shanghai is the most unbalanced, while Wuhan is the worst overall. The integrated development index from the east coastline of Shanghai is as high as 0.6413, which is mainly due to the dense road network and super-high development intensity in this area. The average score of Wuhan is only 0.1296, which is geographically far from those of other cities. In addition, the cross-strait integration of Guangzhou and Ningbo is relatively good, with average indices of 0.5653 and 0.6107, respectively, and the development of the two sides of the river is relatively balanced.

Table 1 Weights for the integrated development in AHP

Indicator(x)	Socioeconomic characteristics		Physical space characteristics	
	Functional mixture	Population density	Accessibility of pedestrian network	Accessibility of vehicle network
Weight(k_x)	0.4033	0.3520	0.1660	0.0787

Table 2 Results of WID

City	Wuhan		Shanghai		Ningbo		Guangzhou	
Waterfront side	East waterfront	West waterfront	East waterfront	West waterfront	East waterfront	West waterfront	East waterfront	West waterfront
Integrated development	0.1467	0.1126	0.6413	0.2657	0.6089	0.6124	0.6297	0.5008
Average score	0.1296		0.4535		0.6107		0.5653	

4. CONCLUSION AND DISCUSSION

4.1 COMBINING TRAFFIC REACHABILITY TO DELIMIT THE WATERFRONT AREA AFFECTING THE HINTERLAND

The traditional isochronous circle division does not calculate the actual travel route; thus, the actual travel time considering walking and bus transfer cannot be obtained. This study uses Python and AutoNavi API navigation routes to calculate the shortest traffic time and interpolates the 30 min isochrones using the IDW method, which can more accurately measure the accessibility of an urban waterfront. This method provides a paradigm for delimiting the impact area of a waterfront. Similar methods can be used in the quantitative study of planning and urban design, such as living circles, pedestrian circles, vehicle ranges, and urban impact areas.

4.2. USING NEW DATA AND NEW TECHNOLOGY TO MEASURE THE "UNMEASURABLE" DATA-INFORMED URBAN DESIGN

Traditional urban design evaluation systems, limited by labor and time costs, often face difficulty in forming quantifiable implementation standards. The evaluation and analysis of urban space design in the traditional data environment are mostly qualitative descriptions, with fewer research samples and shorter coverage periods. This study uses new analysis tools such as Python, Mapbox, ArcGIS, and sDNA to integrate POI, LBS, refined road network, and 3D built environment data into the evaluation index. This study is a successful attempt using multi-source data to carry out a quantitative analysis of the WID development, providing a reference for future urban studies that need to measure the "unmeasurable."

4.3. DEVELOPING AN INTEGRATED DEVELOPMENT EVALUATION INDEX FOR URBAN WATERFRONT

Based on the two main aspects of waterfront evaluation, the material and spatial elements and the socio-economic elements, with the help of new data and technologies, a quantitative evaluation system supported by more comprehensive indicators has been established. PoIs data are used to measure the number of facilities and diversification of functions, LBS data are used to evaluate the spatial vitality, and sDNA is used to calculate the walkability and motor vehicle accessibility of the road network. On this basis, the AHP method is used to obtain the weight of each indicator, and the development of the urban WID is measured based on multi-sourced data.

The WID can effectively reflect the differences in the development progress of a certain waterfront area. At the application level, this analytical framework can not only provide strong support for refined waterfront urban design but can also be used in the fields of urban function mixture, urban vitality assessment, urban spatial accessibility, and spatial quality assessment.

4.4. SHORTCOMINGS AND FUTURE WORKS

The research method used in this study still has certain limi¬tations. First, the key indicators of urban socio-economic and physical spaces are not sufficiently comprehensive. The socio-economic indicators can also include housing prices, GDP, Weibo sign-in data, street view people, and so on, and physical space can still be included in street green viewing rate, sky visibility, and aggregation degree. Second, the credibility of multi-source Internet data needs to be improved. For example, there is room for improvement in the reliability and validity of LBS data. In addition, the AHP method to determine the weight is based on expert experience, and there are some deviations

from the pub¬lic experience and actual conditions. In a future analysis, we will pair this analysis with human-scale experiential data to verify that the WID is reflective of positive human activity in a well-integrated city. In addition, further research of effectively tracking improved experience and comparing these cities' before and after waterfront environment will be conducted in the next step.

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