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Research Article

Extraction and Digital Translation of Urban Spatial Elements Based on a Series of Historical Maps

Nan Zhang,[1,2] **Fang Liu**,[1] **PengFei Zhao**,[3] **Su Sun**,[1,2] **Lifeng Tan**,[1] **Yangqinxue Zeng**,[1] **Suqian Duan**,[1] **and Xue Fang**[1]

[1]*School of Architecture, Tianjin Chengjian University, Tianjin 300384, China*
[2]*School of Architecture, Tianjin University, Tianjin 300072, China*
[3]*School of Architecture and Urban Planning, Shandong Jianzhu University, Jinan 250101, China*

Correspondence should be addressed to PengFei Zhao; jnzpf123@126.com

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It was an important step to understand the evolution of urban forms by clarifying the development process of spatial forms over time. In this step, the application of historical maps with rich spatial and temporal information provided an opportunity to increase the objectivity, accuracy, and repeatability of the research. On the other hand, efficient extraction of spatiotemporal information from historical maps as a basis for subsequent analysis remained a common bottleneck in the current time. What could be done to effectively extract urban spatial elements from historical maps? How could spatial elements be translated to obtain quantified data that could be used for spatiotemporal analysis? In this study, we selected historical maps and archival illustrations of the former British Concession area of Tianjin, China, as research materials to explore the extraction and digital translation methods of urban spatial elements for analyzing the evolution of urban spatial form based on historical maps. This method consisted of loading the map, selecting the registration and calibration point, correcting residual, and saving the path of calibration. The study discussed the specific operation of these steps. In addition, based on this method, this paper analyzed the road network, water area, bridges, and gardens in the former British Concession area of Tianjin, China, to verify the feasibility and accuracy of this method. This method was expected to advance the study of urban spatial morphological evolution and its mechanism with rich data of historical maps.

1. Introduction

The elements of the urban environment were the key content of urban morphological changes, and the changes themselves were the complex relationships and events that unfolded in the interweaving of time and space, making the process almost impossible to describe with words alone. "Analyze the reasoning with rhetoric, deconstruct the body with diagrams" [1], historical maps provided relatively reliable and intuitive records of urban environmental elements, which could be a powerful basis for analyzing urban morphological changes.

Historical maps were used for analysis by various researchers, including Camillo Sitte in 1889 and contemporary researchers [2] such as Kevin Lynch, Rob Krier, and others. Urban studies involved the historical forms of cities, so it had to face the problem that it was difficult to know its accurate urban morphology at that time. Fortunately, many historical changes in urban morphology could be traced through historical maps. The Conzenian School built a theoretical framework for the study of urban morphology [3] by using large-scale maps as an important supplement to field surveys and documentary materials, with a focus on "town plan patterns" [3]. The role of feature elements expressed in maps is decisive in the process of defining urban morphology. (It contains a complex of three well-defined plan elements: (i) streets and their clustering in the street system; (ii) plots and their clustering in the street system; (iii) houses or, more precisely, the block plan.) Spiro Kostof's understanding of urban morphology was similar to that of Kevin Andrew

Lynch, which contained the three models: the "cosmic" model, the "practical" model, and the "organic" model. "The difference was that Spiro Kostof used historical maps, through urban planning or aerial perspective, to study urban morphology in a holistic urban context [4]. He interpreted the characteristics of urban form changes in the process of urban evolution from several important elements, such as urban boundaries, urban divisions, public places, and streets. [5].

Since the 1980s, with the development and increasing sophistication of geographic information systems (GIS), the grasp of historical maps began to establish accuracy in a truly modern geographical sense, and quantitative description and analysis became a significant research trend that emerged in the field of urban spatial morphology [6], and researchers began to evaluate the impact of different georeferencing strategies on maps and to assess the accuracy of models and the accuracy obtained from the maps, respectively [7]. At the same time, digital tools and digitally processed historical materials gradually started to be introduced in large quantities into the study of urban historical morphology with the help of GIS. The change of the spatial extent of cities [8] and the migration of urban centers [9] could be more easily traced through GIS. GIS was used to examine the spatial extent of cities by tracking the migration of urban centers through a series of historical maps. The China historical geographic information system (CHGIS) of research institutions such as Harvard University, Academia Sinica of Taiwan, Zhejiang University, and Fudan University (China's historical geographic data platform) provided corresponding research spatial geographic data resources. In this kind of research, a large number of studies on the spatial distribution of historical towns were promoted in the process of map information digitization, but due to the differences in map accuracy and drawing methods, the analysis of spatial elements inside cities was still quite rare.

The above discussion naturally leaded to the question: Was it possible to digitally translate historical maps based on modern GIS to achieve quantitative descriptions and spatiotemporal mathematical analysis of historical urban spaces with sufficient accuracy? This study tried to take the measured latitude and longitude map of the city as the data source and concretized the abstract "urban form" —represented by the three elements of "road network, water area, bridges and gardens," which were the most decisive to show the characteristics of urban form, to solve the aforementioned problems.

To further refine and validate method of extracting urban morphological elements based on a series of historical maps, the historical morphological changes of the former British Concession in Tianjin, China, were incorporated into the research process. The historical importance of the British Concession was the reason why we study it: Tianjin was once an important hub for the transport of goods in northern China and was forced to open a port from 1860, where nine countries established their concessions in succession, and the total area of these concessions was about eight times that of the urban area of Tianjin at that time (Figure 1).

The development of the concessions by the colonial powers constituted a unique "collage" type of urban texture. The former British Concession, located in the south of Tianjin Old Town, was the earliest and most influential concession, whose scope expanded three times. Before being reclaimed by the National Government in 1947, the British ruled over this land for 87 years, making it the longest existing foreign concession [10]. There were numerous and variety of these historical maps, which recorded this unique urban form. According to incomplete statistics, there were as many as a thousand maps of the former British Concession area of Tianjin from the Qing Dynasty to the establishment of People's Republic of China.

Therefore, by combining fieldwork and literature review, we attempted to organize and extract historical maps and at the same time draw on the research results of previous scholars on the structure and constituent elements of urban forms; we were able to conduct a quantitative study of the research object, retrace the process of changes in the elements of the urban environment over time, explore the rules by which urban form continues to evolve, and verify the feasibility and effectiveness of the method of digitally organizing and extracting historical maps.

From the series of historical maps, it could be seen that, in nearly 100 years, 8 bridges were built over the section of the Haihe River, flowing through the British Concession from scratch, and the territorial extent of the British Concession increased from about 31 hm^2 at the beginning to about 410 hm^2. We used historical maps of Tianjin from different periods to locate and overlay on the Earth and geocorrected the historical maps with an average accuracy of 1.8 m (range 1 m~2.4 m) per map identifying 12~128 typical points, which were sufficient to present the changes of spatial environment within the British Concession over time.

By extracting the elements of the urban environment of the former British Concession in Tianjin from a series of historical maps to explore urban morphological changes, we addressed two main questions:

(1) Could historical maps extract sufficient and consistent information to track the development of urban environmental elements and explain the patterns of their development?

(2) Were the drivers of the incremental development, in the number of urban roads, waters, and other environmental elements, rigorous urban planning activities or merely from random decisions?

First of all, modern historical maps with geographical registration could provide enough spatial information, and on this basis, it was possible to scientifically interpret the progressive development of urban environmental elements. Combined with historical records, we gradually realized that although some urban environmental elements develop from random decisions, rigorous urban planning activities constitute the main reason for such development.

2. Materials and Methods

2.1. Study Site and Map Data Sources. After Tianjin's Former British Concession was demarcated in 1860, it expanded in 1895, 1902, and 1903, respectively. The expanded scope was

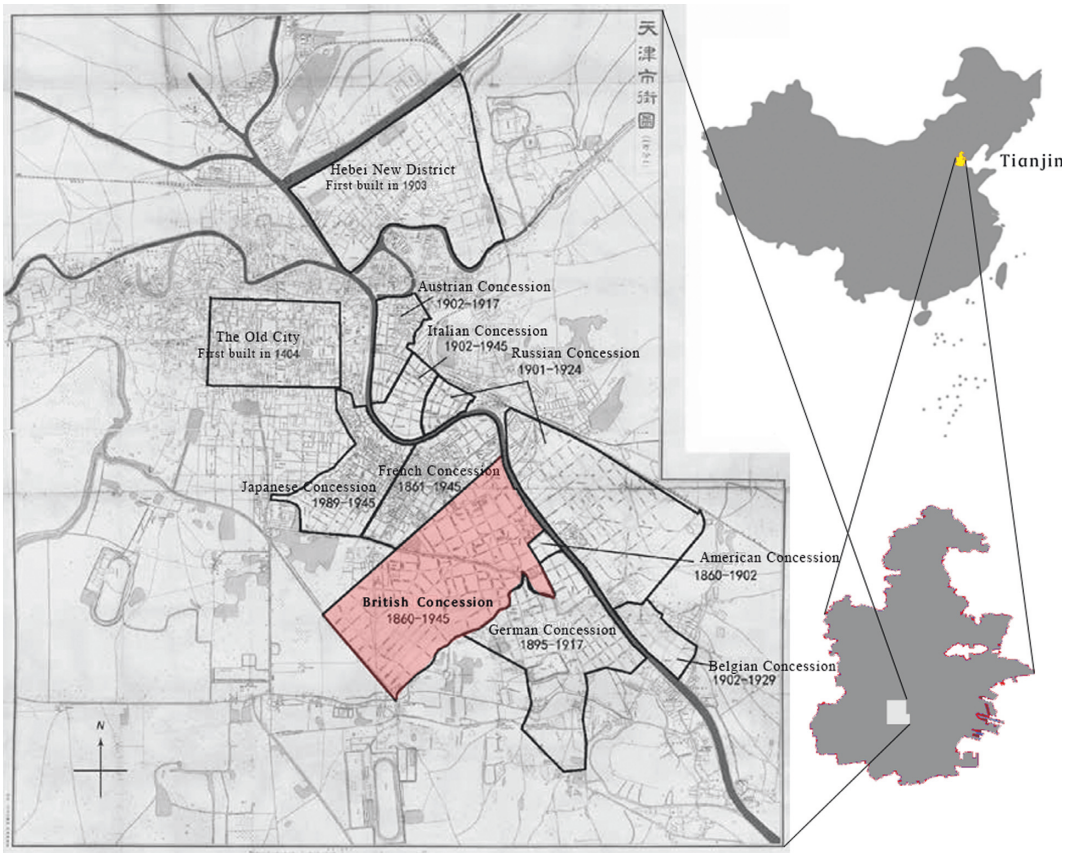


Figure 1: Location of the former British Concession in Tianjin (map of China (right) was provided by ministry of natural resources of China (approval number: GS (2016)1553)).

equivalent to today's: Haihe River in the north, Xikang Road in the south, Yingkou Road in the west, and Machang road in the east. Taking the historical map of the British Concession in Tianjin as the research object and the spatial elements such as roads, buildings, water areas, bridges, and green space within this scope as the research content, this paper analyzed the morphological evolution of the British Concession from the two aspects of the overall scope and single elements and then cited the effectiveness of urban spatial element extraction and digital translation based on a series of historical maps.

According to incomplete statistics, from the Qing Dynasty to the founding of People's Republic of China, there were more than 1000 maps of the former British Concession area of Tianjin. At present, our team obtained 29 map photocopies, 87 file illustrations, 105 online maps, 33 purchased maps, and a total of 254 maps. Considering the factors such as mapping accuracy, emphasis of information expression, and statistical significance of time gradient, 141 pieces were finally selected, including 75 maps and 66 illustrations from the archives. The distribution was shown in Figure 2.

When selecting the map, we focused on the following four aspects (a) Selecting the measured longitude and latitude map [11]. As the translation object, according to the drawing means and accuracy of the map, the map could be roughly divided into the top view vertical projection diagram and measured longitude and latitude map, as shown in Figure 3. The measured longitude and latitude map was drawn based on Modern Surveying and mapping technology. (b) Comparing and selecting maps with relatively high resolution (the position was accurate and the content was rich). (c) Comprehensively considering the time gradient of the map (it was convenient to track the continuous process of change with time and summarize the trend of morphological change). (d) Considering the expressed focus of the content.

1900 was the dividing node between the top view projection diagram and the measured map in the map of Tianjin. Before that, except for the map of Tianjin (PLAN OF TIEN-TSIN) in 1860, the map of Tianjin city to Zizhulin in 1888, the full map of the British, French, and German concession in 1895, the map of Shangbei River, and the figure below Beihe River in 1899 was the measured drawing, and the rest was the schematic diagram of top projection. The existing maps after 1900 were all measured maps.

By comparing the map information, the British Concession developed rapidly from 1900 to 1950, and the content of the maps changed with each passing day, while the information contained in the maps did not vary much from 1950 to 2010. Therefore, the maps selected in this study were divided by the time gradient, mainly from 1880 to 1950 and from 1980 to 2016.

In addition, due to the different identities of map makers, the emphasis on the information conveyed through the map

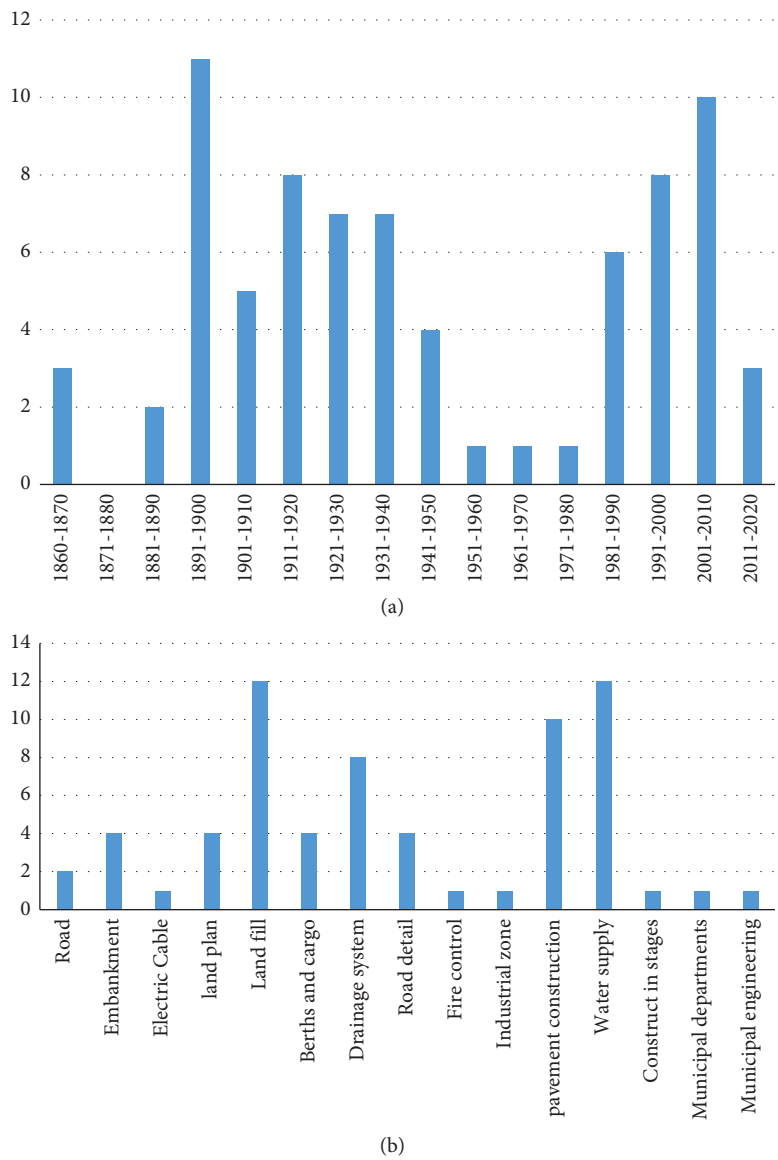


Figure 2: (a) Number of maps (distributed by time). (b) Illustrations in the archives (by topical content).

Figure 3: (a) Perspective map source: full view of Tianjin Old Town (1899). (b) Measured latitude and longitude map source: map of Beijing and Tianjin (1917).

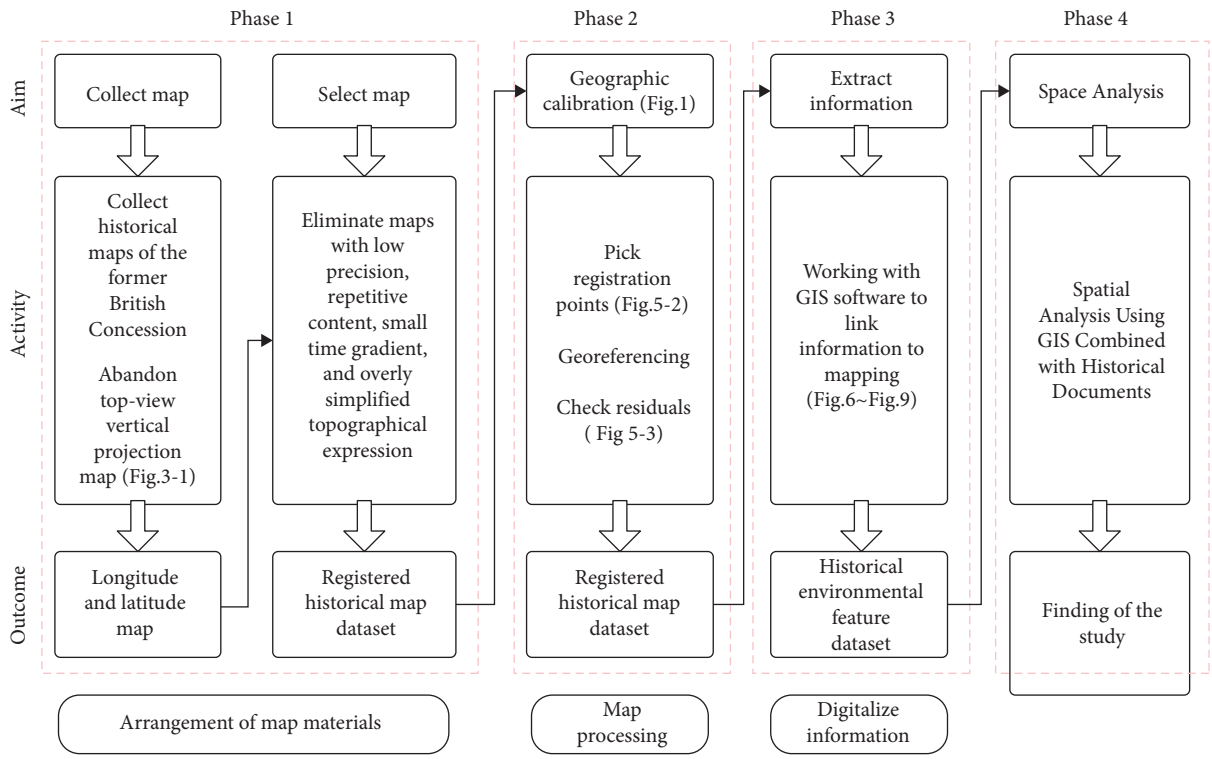


Figure 4: Design of research for extraction and digital translation of urban spatial elements.

was also different. Therefore, this paper would also select different versions of maps in the same year as the research object.

After the above statistics and screening, the maps became the basic data for database construction. The research process design based on these maps was shown in Figure 4.

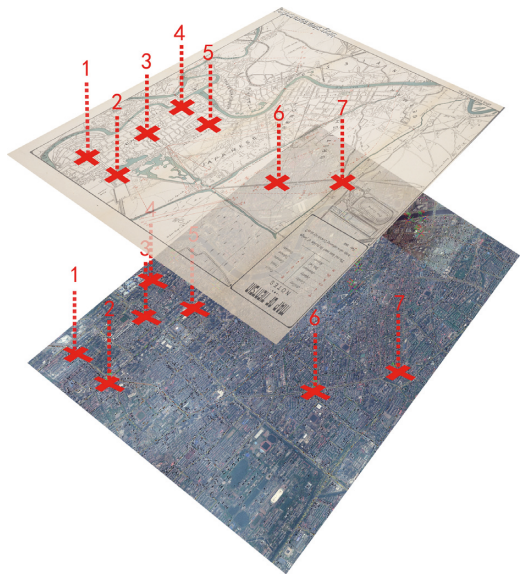
2.2. Map Processing. Based on the satellite remote sensing map, the important buildings or landmarks contained in all maps without any change of position were selected as reference points; we applied the geographic registration function of GIS to carry out geometric correction and coordinate registration of local maps [11] in four steps: Step 1: Load the required calibration map into the geographic information system; Step 2: Select the corresponding points by geographic registration function based on remote sensing map as the benchmark (the more calibration points are selected, the more accurate the calibration results are); Step 3: Check and correct the residuals and total residuals. The first-order polynomial (affine) is used to correct the points with large residuals; finally, save the correction path (Figure 4).

The calibration points of geographical areas (such as the border zone of the Tianjin Old Town district, the trend of Haihe River, etc.), the important buildings whose location is known to have not changed (such as racecourse, Haiguang temple, Drum Tower, etc.), and the boundary of the British Concession (after the original boundary of the British Concession was delimited for the first time in 1860, it can be corrected according to the boundary of the British Concession) were selected as reference points. See Figures 5(a)–5(c) for the principle of correction.

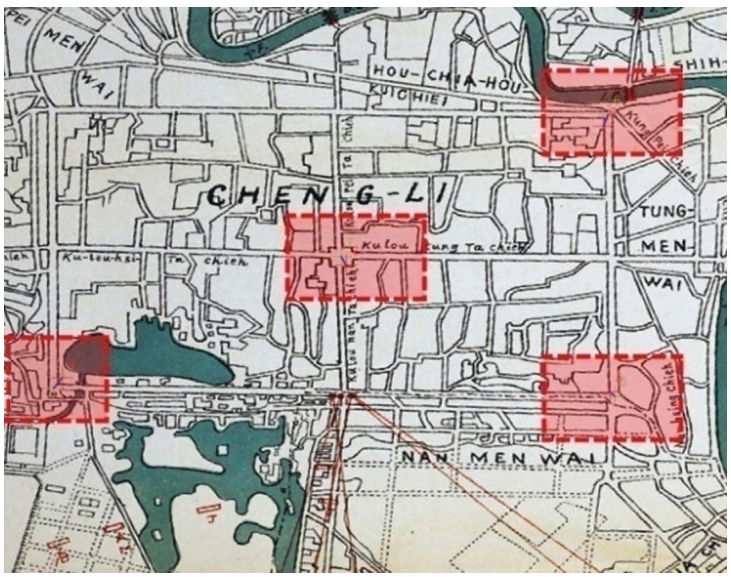
After the first-order affine correction, the calibrated map could be superimposed and compared with the base map to observe whether the results were accurate. For example, as shown in Figure 5(d), the trend of Haihe River was the same, indicating that the correction was more accurate.

By assigning the two-dimensional coordinated projected by a given map to different archive source materials (called geographic references), GIS enabled "messy" historical data to be accurately located on maps and urban spatial plans. Mapped data could help identify the relationship between phenomena that was not clearly linked by revealing their shared location [12]. Although GIS provided a platform for the mapping, analysis, and visualization of historical spatial data sets, the relationship between these geospatial data and urban spatial structures, especially urban street network, was rarely processed systematically. One reason for this was that large amounts of historical data (and general data) were suitable for aggregation within the administrative boundaries where they were originally collected; another simple explanation was that, in the absence of specific spatial form propositions, it was not clear how an understanding about the structure of the road network would facilitate historians' interpretation of urban life itself.

2.3. Extraction of Spatial Environment Elements. Cities and landscape were the results of a historical-geographical process. The changes of plane pattern were usually constrained by the planar characteristics of the present situation. The theoretical framework of Conzen's urban morphology research [13] was instructive for us to understand the environmental elements of the British Concession, in particular, his



(a)



(b)

链接

RMS(E): Forward:0.000407774

Link	X Source	Y Source	X Map	Y Map	Residuals_x	Residuals_y	Residuals
1	507.496961	-1423.225398	117.180569	39.110410	-0.0004494...	8.22165e-0...	0.00045694
2	696.988482	-1694.134320	117.189962	39.101176	0.000156647	-0.00049086	0.00051525
3	1119.964487	-949.301576	117.206277	39.127584	-0.0001765...	-1.8783e-005	0.000177529
4	184.843918	-638.054950	117.165645	39.136298	0.000298642	0.000359282	0.000467194
5	621.201601	-674.638539	117.184155	39.135815	-0.0001349...	0.000121266	0.000181415
6	630.777774	-391.715558	117.183924	39.144795	-0.0001588...	-0.0004104...	0.000440091
7	415.550966	-520.663361	117.175241	39.140100	0.000178716	-0.00029595	0.000345725
8	1267.843238	-1247.862560	117.213012	39.118246	-0.0004906...	0.000325617	0.000588849
9	1298.678798	-1299.619966	117.215490	39.116000	0.000540703	-0.0002538...	0.000597318
10	1228.667777	-1338.757829	117.212258	39.114517	0.00024997	-0.0002660...	0.000365082
11	881.890655	-1246.222863	117.196801	39.117384	-1.39966e-...	0.000276931	0.000277285
12	963.572531	-1199.137480	117.200328	39.119166	8.57461e-0...	0.000295482	0.000307672
13	1004.471382	-1150.540275	117.201817	39.120868	-8.59764e-...	0.000275124	0.000288245

(c)

(d)

Figure 5: (a) The principle of calibration. (b) Pick calibration point. (c) Residuals of calibration points (the first-order polynomial (affine)). (d) Map distortion after calibration.

cognition of the different features of the urban scene or the town landscape that constituted the urban form and his emphasis on the evolution process of urban form. The translation of the historical maps was divided into two steps: Firstly, the spatial elements were classified, reorganized, and correlated. Grouping the same elements together helps to compare the evolution of the same elements in different historical periods. Secondly is vectorization of spatial elements based on GIS creation elements function.

2.3.1. Classification. By combining and classifying the spatial collection information loaded by the maps in each historical period, seven spatial elements of the historical boundary of the British Concession, built-up area, roads, buildings, greening, water area, and bridges were obtained. Among them: the scope of built-up area reflected the scale and perceived field of "space collection," which was the initial level that determines the feeling; road network and its accessibility reflected the structure, connection and perception of space, and the cornerstone of overall feeling [14]. In addition, the evolution of rivers and green spaces directly reflected the interaction between urban development and natural space. Buildings and bridges were the basic elements of space and the direct medium for people to use space. The following would analyze the overall spatial form of the British Concession through the road network, rivers, and greening and analyze the spatial form of each single element, respectively.

2.3.2. Translation. It was necessary to vectorize the classified elements into point elements, line elements, and area elements according to their characteristics, for GIS could not identify the spatial elements in the historical map directly. Historical data quality was not always good enough to apply uniformly to the historical and contemporary maps of all cities; therefore the method of translating urban environmental elements must be simple.

(1) Translation of Built-Up Areas. The main work of translation of built-up areas is to fill the internal void and expand the scope of the external boundary. The built-up area in the British Concession space was represented by the filling of roads in the new extension.

(2) Translation of Road Network. In this paper, roads of different ages were superimposed and compared. The superposition of line elements could only obtain the intersection point. It was uncertain whether the two roads with slight deviations in the map in different ages were the same. Therefore, choose the surface elements to translate the roads in the map.

(3) Translation of Architecture. Among the maps we collected, only a few maps (like the building drawn on 1913 map) judged and selected the shape of the building plane and depicted it as surface elements. In addition, the architectural functions marked in 1912, 1917, 1930, 1934, 1940, 1946, and 1951 were used to analyze the evolution of architectural functions each year.

3. Results and Discussion

3.1. Accuracy of the Geo-Referencing Process. The number of control points required for maps between 1860 and 2020 varied between 12 and 128, depending on the richness of detail, clarity of the image, spatial extent, and age of each map. Since the recent maps had more details and provided more geo-referencing capabilities (36 to 128 control points after 1949 compared to 12 to 43 before), each map was corrected using a first-order (affine) transformation. The comparison of the root means square error with and without cross-validation indicated that the root mean square error was between 1 and 2.4 m for all the years, which indicated that the data were well calibrated. All RMS errors and maximum residuals were relatively small compared to the change in city size over time, so the geo-referencing process was successful overall.

3.2. Roads That Change over Time. How the road network was progressively improved over time is shown in Figure 6.

The development of the road network could be divided into three stages: the construction of British Municipal (the original boundary), the construction of the British Municipal Extension (and the Southern Extension), and the construction of the British Extra Rural Extension.

According to Figure 6 and the literature analysis, we could see the following: (a) the road network of British Municipal consisted of a grid of three (east-west) roads parallel to the Haihe River and six (north-south) roads perpendicular to the Haihe River; (b) the new roads of the expanded boundary in 1895 intersected with the roads of the British Municipal in a dingbat shape and were not connected to the roads of the original boundary. Such a form may originate from the path between the puddle and the cemetery in 1888, not as a result of planning. The road in the South Extension (American Concession) also developed from the original path, and the most recently developed part of the road in the northwest corner of the British Municipal Extension was planned, and the overall shape of the road was grid-shaped, and the irregularities were corrected to the maximum extent possible with a grid; (c) the roads in the Extra Rural Extension originated in 1918. According to Anderson's overall planning, the road could be divided into three major parts of the road in form, concentric circle part, square grid-shaped part, and free form part as shown in Figure 7.

3.3. Rivers and Bridges Built over Time. The main river in the British Concession, the "Wall River," was an artificial river dug by the Qing government on the outside of the trench wall (the bottom of the wall is 12–15 meters wide, the top is 4 meters wide, and the height is 3.67 meters.) to strengthen its defense. Until 1970, when the Wall River was filled in, there were eight bridges over the Wall River in the former British Concession area, from the west to the east, namely, Yingkou Road Bridge, Yaohua Bridge, Shanxi Road Bridge, Hebei Road Bridge, Chengdu Road Bridge, Xinhua Road Bridge, Hubei Road Bridge, and Ping'an Bridge. Through the digital

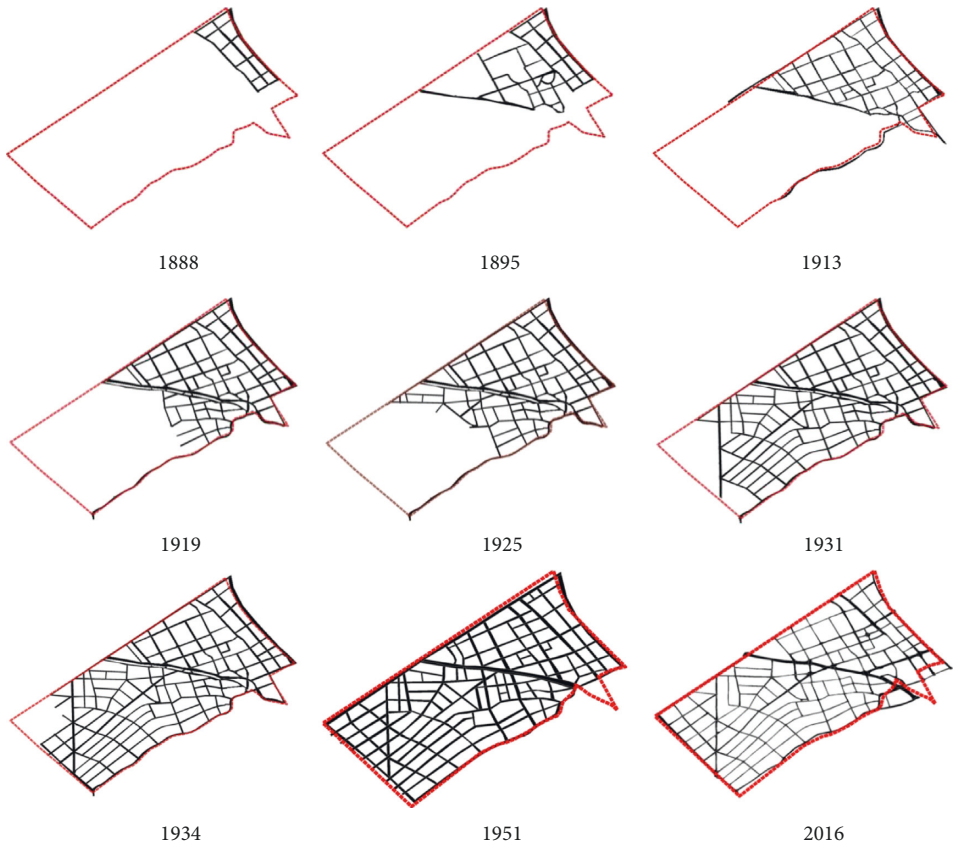


Figure 6: Historical road map obtained by GIS. (a) 1888. (b) 1895. (c) 1913. (d) 1919. (e) 1925. (f) 1931. (g) 1934. (h) 1951. (i) 2016.

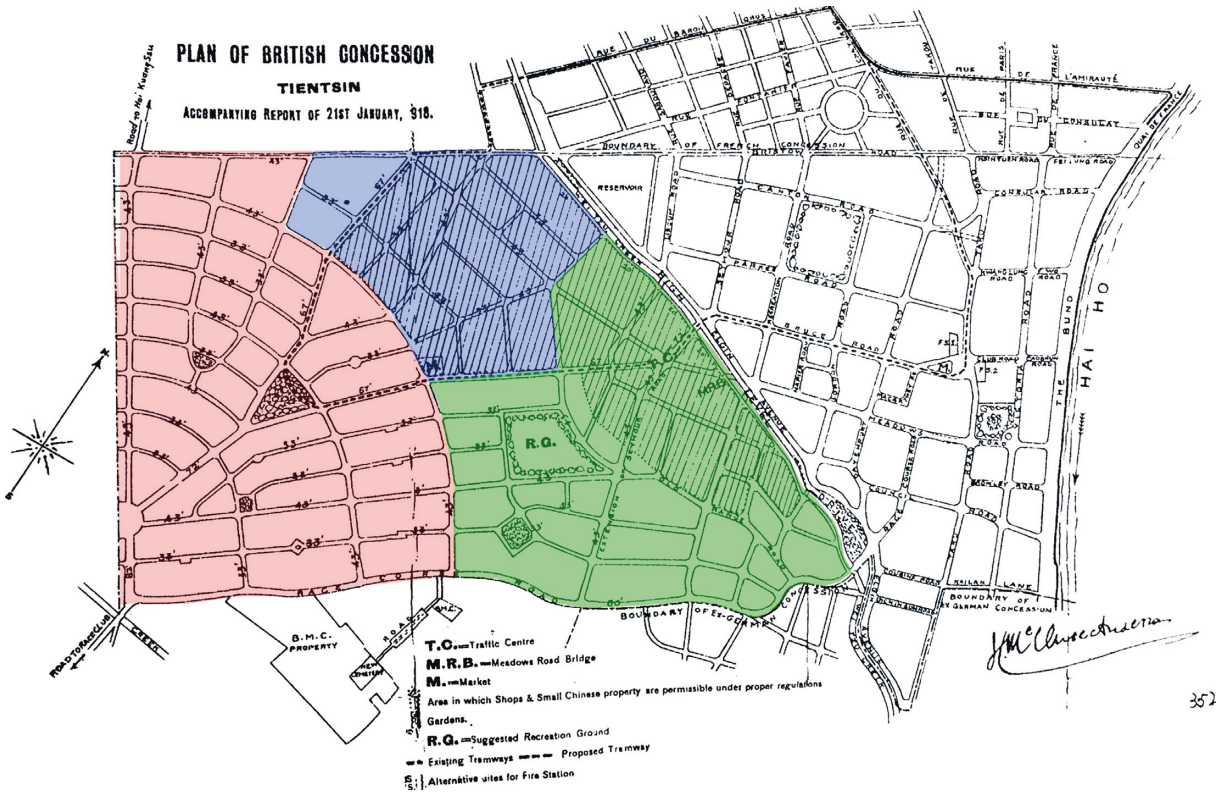
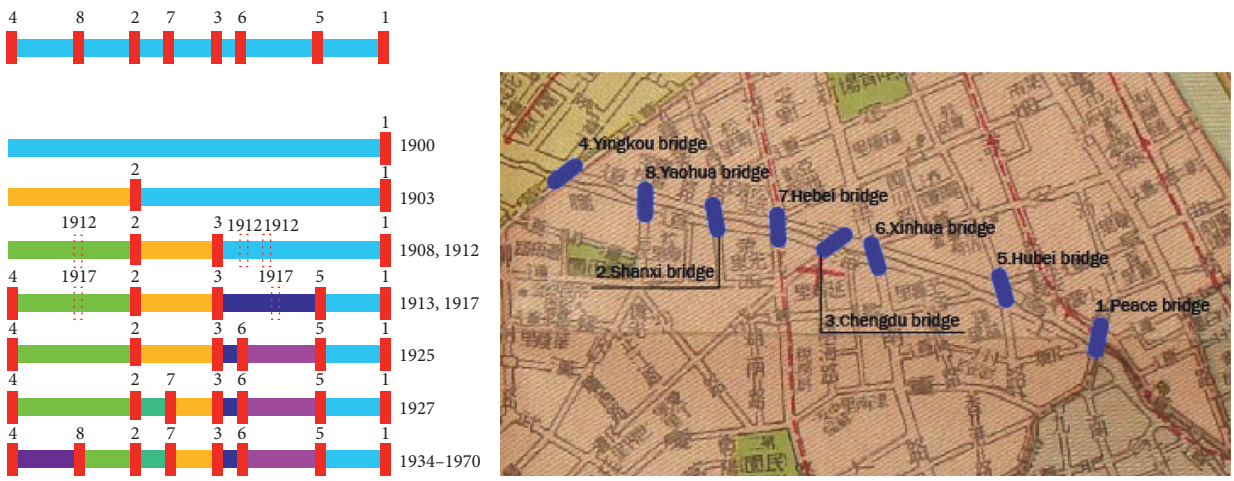


Figure 7: Road pattern division of the extrarural extension (red-concentrically/blue-grid/yellow-free form).



the number and location of bridges in maps over the years

The locations of bridges on the historical map (use the 1951 map as the basemap)

Figure 8: Bridges on the Wall River ((1) Peace bridge; (2) Shanxi bridge; (3) Chengdu bridge; (4) Yingkou Road; (5) Hubei bridge; (6) Xinhua bridge; (7) Hebei Bridge; (8) Yaohua bridge). (a) The number and location of bridges in maps over the years. (b) The locations of bridges on the historical map (use the 1951 map as the basemap).

translation and extraction of a series of historical maps, the location and construction sequence of the bridges built on the Wall River could be more clearly presented (Figure 8).

1917 and 1934 could be used as the cut-off points for bridge construction, before 1917 and after 1934 bridge construction to equalize evacuation traffic flow. The construction between these two years was to communicate different parts of the same road on both sides. The location of the bridge was usually considered in relation to the road network while allowing itself to be approximately located at the golden section of a river segment or the existing bridge to be located at the golden section of the whole river segment.

3.4. Gardens That Change over Time. The greening of the British Concession mainly included the construction of gardens and the planting of street trees. The map did not show the location and number of street trees but accurately recorded the information of the gardens. From the laws and regulations promulgated during the construction of the Concession, it could be seen that the British intended to make the concession a high-end and civilized community when building it. Therefore, not only take into account people's material needs in the construction, but also pay attention to meeting people's spiritual needs for leisure and entertainment. During the development and construction of the concession, many gardens were built before and after.

The gardens were marked in green on historical maps; few maps before 1949 showed gardens, except the 1888 map of Tianjin city with Zizhu forest in 1888, the recent detailed map of Tianjin in 1913, the map of Tianjin city streets in 1930, the latest Tianjin city street map in 1939, the latest map of Tianjin downtown in 1946; after 1949, the location and number of green areas had not changed, so we picked the new dual-use map of Tianjin in 1951, Tianjin downtown traffic map in 1984, and remote sensing map in 2016 for analysis.

According to the extraction of the map on the green space, the British Concession had sporadic distribution of many pieces of green space, as shown in Figure 9.

Through the digital translation of maps from 1888 to 2016, combined with documentary materials, it could be seen that the green space of the original British Concession mainly contains three categories: road greenery, park greenery, and sports field greenery, among which road greenery was carried out along with road construction and was less reflected on historical maps; park greenery was generally carried out gradually along with the urban development of the concession area, and a few of them were intentionally carried out for expanding the territory of the British Concession. Sports fields were another type of green space; sports fields were gradually transformed into recreational grounds for citizens in later years. Sport fields construction in the late period is generally the derivative of school construction. The purpose of building green space was to improve the living environment of residents, but the specific construction activities did not always come out of a preplanned overall plan but were often the result of a conscious effort to utilize unused space in the process of urban development. Although green space was not difficult to transform, it usually retained its recreational function and did not disappear completely in the process of construction and development.

3.5. Discussion. It was found that the use of a series of historical maps as a data source to extract statistical information on roads, water bodies, and greenery in the former British Concession of Tianjin did allow for the continuous capture and measurement of the dynamics of the entire area and was able to ensure accuracy in a geographical sense:

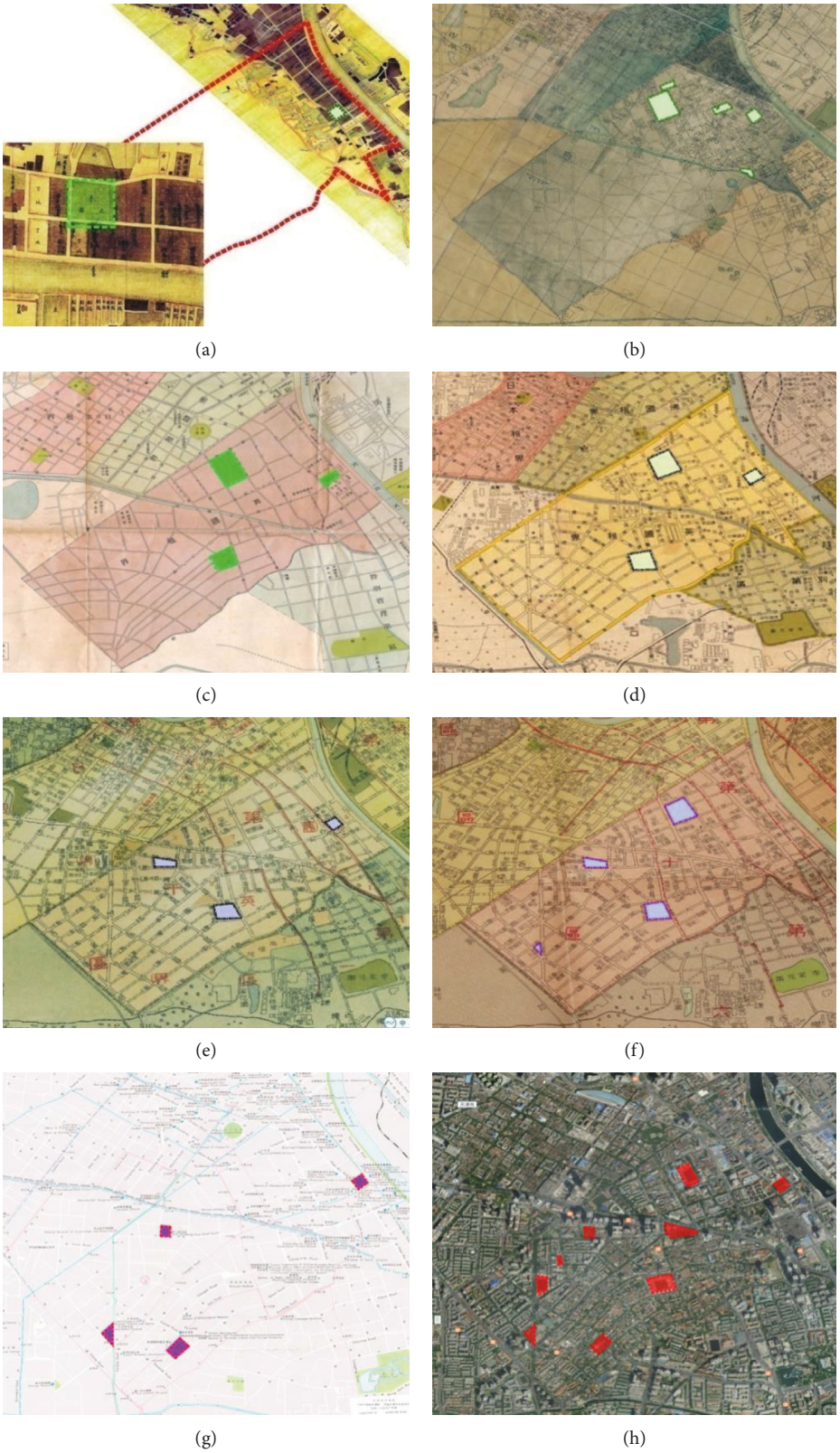


Figure 9: (a) Distribution of green space in 1888 (source: the map of Tianjin city with Zizhu forest in 1888). (b) Distribution of green space in 1913 (source: the recent detailed map of Tianjin in 1913). (c) Distribution of green space in 1930 (source: the map of Tianjin city streets in 1930). (d) Distribution of green space in 1939 (source: the latest Tianjin street map in 1939). (e) Distribution of green space in 1946 (source: the latest map of Tianjin downtown in 1946). (f) Distribution of green space in 1951 (source: the new dual-use map of Tianjin in 1951). (g) Distribution of green space in 1984 (source: traffic map of downtown Tianjin in 1984). (h) Distribution of green space in 2016 (source: remote sensing map in 2016).

(a) The road morphology could be summarized by dividing the road network into five parts according to the muscle characteristics: British Municipal, British Municipal Extension (and South Extension), Extra Rural Extension (Wall subriver part), Extra Rural Extension (Race Course Road part), and Extra Rural Extension (Concentric circles part). Considering the historical background, it could be found that the road morphology was not only related to the planning but also related to the identity of the inhabitants. The road in the Machang road section was inhabited by foreigners, and the road in this area had an European liberal flavor, while the road in the Wall River section was inhabited by Chinese, and the road in this section was oriented north-south.

(b) Architectural part: from the two editions of the map in 1913, it could be seen that the distribution pattern of public buildings in the British Concession was mostly distributed near the original boundaries and the Victoria Gardens, which was not only related to the planning at that time, but also had the characteristics of spontaneous convergence to the political and civic center (Victoria Gardens). In the section of waters and bridges, the spontaneous construction pattern of bridges and the construction characteristics after planning were summarized by sorting out the construction time and location of the walls and upper bridges over the years. In addition, the analysis of the evolution of the waters of the British Concession verified the process of land filling in the British Concession.

(c) The analysis of the bridge installation process on the river revealed that each activity of building additional bridges was built at the location where the two bridges were farthest apart within each section of the watershed in a relatively low traffic area at that time. And the changes in watersheds such as ponds and marshes were based on the need for the land filling.

(d) Based on the changes in the number and location of green spaces in the historical map, this paper summarized the construction history of gardens in the British Concession and introduced the planting scheme of street trees in the British Concession.

4. Conclusions

The purpose of this paper was to assess whether historical maps could provide consistent information about changes in elements of the urban environment location and whether elements of the urban environment exhibit inertia of change and to consider the implications of this inertia for changes in urban form today. Our analysis reemphasized the value of historical maps using geographic markers as a way to understand how cities developed and evolved over time.

The process of geo-locating historical maps in use always leaves some residual errors due to the measurement techniques used in their preparation, the deformation of the paper over time, and the lack of precision in their preparation [15]. Therefore, assessing the accuracy of the geo-location process by analyzing the root mean square error (RMSE) obtained was essential to explain the uncertainty in the results of the assessment prior to the change [16–18]. The RMSE obtained here for the 75 historical maps ranged between 0.2 m and 2.3 m, which was within a reasonable range. Overall, the RMSEs obtained here were small enough to make the results of the analysis credible, especially when the positioning errors in cartography are likely to be much larger than the errors that may remain after the geo-referencing process. With confidence in the historical maps, it was possible to digitize and map each map and to determine the variability of elements of the urban environment in relation to time and to further analyze the patterns and mechanisms of their evolution.

The exploration of urban spatial morphology in this study focused on the environmental elements of the historical urban areas and paid attention to the interaction between urban environmental elements and the dynamic development of the city. The main significance of extracting urban spatial elements based on a series of historical maps and digitally translating them with the help of GIS tools was as follows:

(a) The overlay analysis of maps from different periods was used to outline a spatial and temporary framework for the creation and development of environmental elements in the British Concession and contradictions in the temporal and spatial presentations in past literature were found along with trying to reasonably identify them.

(b) The former British Concession was repositioned at the level of roads, river, and greenery, and the complexity, adaptability, and trend of the urban pattern shaped by various factors were deeply understood through the pattern comparison.

The focus of attention on the historical evolution of urban form was not on individual buildings, but it extended to historical urban landscapes at the scale of building clusters and even city blocks [19]. At the same time, the method of using a series of maps as data sources to obtain more reliable distributions of spatiotemporal elements through geographic calibration and digital transcription was maturing. On the introduction of big data and machine learning [20], the application of multisource large geospatial data for urban spatial morphology extraction became possible [21], but for historical maps, the alignment process and information translation was not yet completely free from human intervention, and the auxiliary correction of documents is a necessary step to ensure the accuracy of information translation.

This study provided a reasonable paradigm for extracting information from historical maps for urban morphology research and further broadened the scope of material sources for urban spatial morphology research. But the historical map approach still had some limitations nowadays. The

registration process and the information process might be further intelligent by machine learning, but so far, on the one hand, it was difficult to extract more high-quality historical information from the top view vertical projection diagram and other earlier maps; on the other hand, the process of information translation could not be completely free from human intervention; the auxiliary correction of documents was a necessary step to ensure the accuracy of information translation.

Data Availability

The team obtained 29 photocopies of the maps, 87 archive illustrations, 105 online maps, and 33 purchased maps, for a total of 254 maps. The data of this study mainly come from three sources: (a) edited by Tianjin Municipal Bureau of Planning and Land and Resources, Tianjin Urban History Atlas, and Tianjin Ancient Books Press; (b) Tianjin Map obtained through the Internet; (c) edited by Tianjin Archives, Tianjin English Selected historical materials of the Ministry of Industry and Bureau of the Concession (top, middle, and bottom), and the city map of Tianjin over the years purchased by Tianjin Ancient Books Publishing Press.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] K. Shen, J. N. Crossley, A. L. Wah-cheung, and H. Liu, *The Nine Chapters on the Mathematical Art: Companion and Commentary*, Oxford University Press, Oxford, UK, 1999.

[2] C. Sitte, *The Art of Building Cities*, Martino Fine Books, Eastford, CT, USA, 2013.

[3] M. R. G. Conzen, *Alwick,Northumberland:A Study in Town Plan Analysis*, Insstitue of British Greographers, London, UK, 2nd edition, 1969.

[4] S. Kostof, *The City Shaped:Urban Pattens and Meanings Though History*, Thames&Hudson Ltd, London, 1991.

[5] G. Castillo and S. Kostof, *The City Assembled: The Elements of Urban Form through History*, Thames and Hudson, London, UK, 2005.

[6] M. Bhatt and J. Wallgrün, "Geospatial narratives and their spatio-temporal dynamics: commonsense reasoning for high-level analyses in geographic information systems," *ISPRS International Journal of Geo-Information*, vol. 3, no. 1, pp. 166–205, 2014.

[7] V. Baiocchi, K. Lelo, M. Milone, and M. Mormile, "Accuracy of Different Georeferencing Strategies on Historical Maps of Rome," *Geographia Technica*, 2013.

[8] A. Berila and F. Isufi, "Two decades (2000-2020) measuring urban sprawl using GIS, RS and landscape metrics: a case study of municipality of prishtina (kosovo)," *Journal of Ecological Engineering*, vol. 22, no. 6, pp. 114–125, 2021.

[9] T. Alvares-Sanches, P. E. Osborne, P. A. B. James, and A. S. Bahaj, "Tracking a city's center of gravity over 500 years of growth from a time series of georectified historical maps," *Cartography and Geographic Information Science*, vol. 47, no. 6, pp. 524–536, 2020.

[10] Y. Liu and M. Fujikawa, "The development process OF the original BRITISH concession IN tianjin, China," *Journal of Architecture and Planning (Transactions of AIJ)*, vol. 80, no. 712, pp. 1285–1294, 2015.

[11] X. A. Yao, "Georeferencing and geocoding," *International Encyclopedia of Human Geography*, vol. 111–17, 2020.

[12] S. Griffiths and L. Vaughan, "Mapping spatial cultures: contributions of space syntax to research in the urban history of the nineteenth-century city," *Urban History*, vol. 47, no. 3, pp. 488–511, 2020.

[13] J. W. R. Whitehand, "The Urban Landscape: Historical Development and Management. Papers," Edited by M. R. G. Conzen, Ed., Academic Press, London, UK, 1981.

[14] He Zhang, C. H. E. N. Tian, C. H. E. N. Tian, \Z. H. E. N. G. Jiaxuan, and L. I. Wei, "Study on urban spacial characteristic based on historic map digital analysis," *Urban Studies*, no. 7, pp. 143–148, 2013.

[15] M. Tucci and A. Giordano, "Positional accuracy, positional uncertainty, and feature change detection in historical maps: results of an experiment," *Computers, Environment and Urban Systems*, vol. 35, no. 6, pp. 452–463, 2011.

[16] M. Brovelli and M. Minghini, "Georeferencing old maps: a polynomial-based approach for Como historical cadastres," *e-Perimetron*, vol. 7, no. 3, pp. 97–110, 2012, http://www.e-perimetron.org/Vol_7_3/Brovelli_Minghini.pdf.

[17] D. Liu, E. Toman, Z. Fuller et al., "Integration of historical map and aerial imagery to characterize long-term land-use change and landscape dynamics: an object-based analysis via Random Forests," *Ecological Indicators*, vol. 95, pp. 595–605, 2018.

[18] F. Manzano-Agugliaro, C. San-Antonio-Gómez, S. López, F. G. Montoya, and C. Gil, "Pareto-based evolutionary algorithms for the calculation of transformation parameters and accuracy assessment of historical maps," *Computers & Geosciences*, vol. 57, pp. 124–132, 2013.

[19] B. Ringbeck, "The world heritage convention and its management concept," in *Aspects of Management Planning for Cultural World Heritage Sites: Principles, Approaches and Practices*, S. Makuvaza, Ed., Springer International Publishing, Manhattan, NY, USA, 2018.

[20] R. J. van Lanen, R. van Beek, and M. C. Kosian, "A different view on (world) heritage. The need for multi-perspective data analyses in historical landscape studies: the example of schokland (NL)," *Journal of Cultural Heritage*, vol. 53, pp. 190–205, 2022.

[21] J. A. García-Esparza, P. Altaba Tena, and P. Altaba Tena, "A GIS-based methodology for the appraisal of historical, architectural, and social values in historic urban cores," *Frontiers of Architectural Research*, vol. 9, no. 4, pp. 900–913, 2020.