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Understanding Urban Growth in Beijing-Tianjin-Hebei Region over the Past 100 Years Using Old Maps and Landsat Data

Shuang Li [1], Zhongqiu Sun [2], Yafei Wang [3,*] and Yuxia Wang [4]

[1] Center for Historical Geography Studies, Fudan University, Shanghai 200433, China; li_shuang@fudan.edu.cn
[2] Academy of Forest Inventory and Planning, State Forestry Administration, Beijing 100714, China; sunzhongqiu@afip.com.cn
[3] Key Laboratory of Regional Sustainable Development Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[4] School of Geographic Sciences, Key Lab of Geographic Information Science (Ministry of Education), East China Normal University, Shanghai 200241, China; yxwang@geo.ecnu.edu.cn
* Correspondence: wangyafei@igsnrr.ac.cn; Tel.: +86-021-5566-5097

Abstract: Studying urban expansion from a longer-term perspective is of great significance to obtain an in-depth understanding of the process of urbanization. Remote sensing data are mostly selected to investigate the long-term expansion of cities. In this study, we selected the world-class urban agglomeration of Beijing-Tianjin-Hebei (BTH) as the study area, and then discussed how to make full use of multi-source, multi-category, and multi-temporal spatial data (old maps and remote sensing images) to study long-term urbanization. Through this study, we addressed three questions: (1) How much has the urban area in BTH expanded in the past 100 years? (2) How did the urban area expand in the past century? (3) What factors or important historical events have changed the development of cities with different functions? By comprehensively using urban spatial data, such as old maps and remote sensing images, geo-referencing them, and extracting built-up area information, a long-term series of urban built-up areas in the BTH region can be obtained. Results show the following: (1) There was clear evidence of dramatic urban expansion in this area, and the total built-up area had increased by 55.585 times, from 126.181 km^2 to 7013.832 km^2. (2) Continuous outward expansion has always been the main trend, while the compactness of the built-up land within the city is constantly decreasing and the complexity of the city boundary is increasing. (3) Cities in BTH were mostly formed through the construction of city walls during the Ming and Qing dynasties, and the expansion process was mostly highly related to important political events, traffic development, and other factors. In summary, the BTH area, similarly to China and most regions of the world, has experienced rapid urbanization and the history of such ancient cities should be further preserved with the combined use of old maps.

Keywords: land use changes; long-term urbanization; urban expansion; historical geography; spatial pattern; Beijing-Tianjin-Hebei urban agglomeration; capital–port–hinterland

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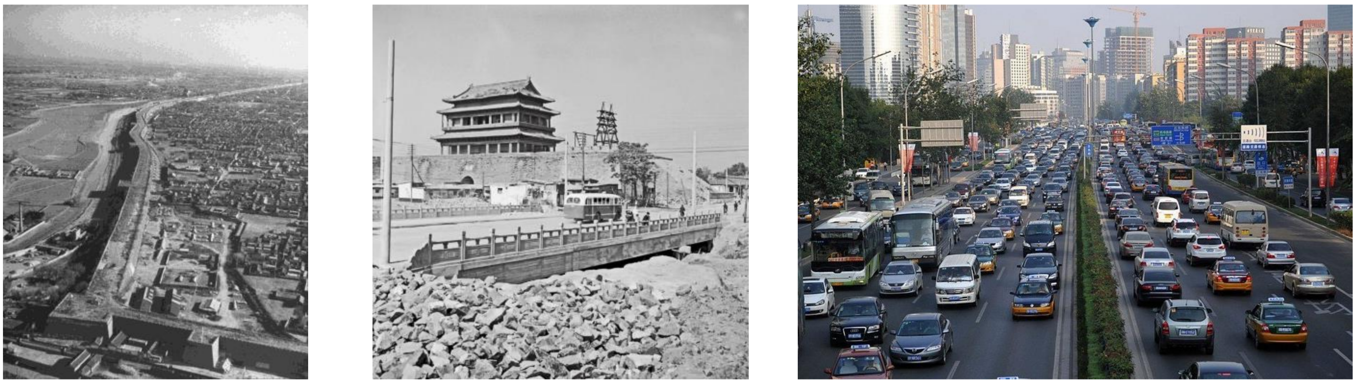
1. Introduction

Together with the increasing importance of cities to national economies, urbanization has been unfolding rapidly worldwide. Here, China is no exception, having gone through a stage of rapid urbanization and now constructing several urban agglomerations [1,2]. Land use or cover change includes multiple towns and stakeholders, and inter-urban and urban–rural differences are significant, so urban agglomerations are also "rich mines" for the research on spatial and temporal land use changes [3–5]. However, when the time span is hundreds of years or longer, the process and mechanism of the spatial and temporal land use change are significantly complex, reflecting the natural changes at different stages, as well as the era and social background [6,7]. Take Beijing as an example. Beijing once had a complete wall around the city, which was later continuously demolished, and the current

Second Ring Road was built on the original site (Figure 1). Therefore, studying the spatial evolution of urban land use over a long time span is of substantial research significance, and is practically beneficial in elucidating the urbanization process, thus optimizing the urban spatial structure and enhancing the cognition of the historical characteristics of China's urbanization.



(**a**) (**b**) (**c**)

Figure 1. City walls of Beijing in different periods: (**a**) the complete city wall in the past; (**b**) the city wall being demolished; (**c**) the Second Ring Road built on the original site.

Urban expansion is a dynamic process of urban development, which is spatially manifested by the continuous expansion of urban built-up areas, which in turn triggers changes in urban morphology. In the specific study of a long time-series, it is first necessary to collect urban spatial information from different periods to describe the urban space and expansion process in a long time span, such as old maps, aerial images, remote sensing images, etc. [8]. Then, we will discuss the related work on old maps, aerial/remote sensing images, and longer time series, respectively. (1) Old maps: Studies that employ old maps and historical documents are mostly concentrated in history and historical geography fields, whereas studies that adopt remote sensing are concentrated in GIS and remote sensing fields [9]. For example, historical researchers have proposed historical city restoration methods based on the characteristics of historical documents and old maps, and they believe the restoration methods primarily include the retrograde and flashback methods [10,11]. Accordingly, they have performed restoration works around metropolises with history, including the "Analysis of Historical Changes in Paris City" (ALPAGE), "Locating London's past 1660–1800", etc. In China, examples of such studies include the work of He et al., who considered the area of urban land use in the Qing Dynasty in China and its comparison [12]. In addition, Cheng determined the scale of Qing Dynasty cities based on the perimeter of ancient city walls and established a database of cities in the Qing Dynasty [13]. Ioannides and Zhang reported an empirical analysis using hand collected and previously unutilized data on city walls in the Ming (1368–1644) and Qing (1644–1911) Dynasties [14]. Finally, Wan used the historical topographic maps and studied the pattern analysis in Zhejiang Province, China in the 1910s [15]. By analyzing the historical information provided in ancient city maps, they identified and reconstructed the structural characteristics and evolutionary process of the historical urban space via systematic analysis methods. In addition, they formed an historical urban spatial database [16]. These studies preliminarily explored the basic ideas and steps of the digital transformation of historical maps, but they did not connect the relevant results to the natural evolutionary process of urban space. (2) Remote sensing data: Currently, remote sensing technology has become an important method for monitoring the evolution of urban spatial and temporal patterns, owing to its ability to periodically obtain surface information on a large scale [17]. Landsat satellite images have become the most important visible remote sensing data for city expansion studies, owing to their long time series, global coverage, and open data; using maximum likelihood, support vector machine, decision trees, neural networks, and other methods to extract the urban impervious surface of visible remote sensing images and construct time series from the 1970s to the present [18]. Liu et al. produced a 30 m annual urban area data set (GAUD) from 1985 to 2015 [19]. Gong et al. produced a global artificial impervious area (GAIA) to quantify the annual dynamics of urban ISA from 1985 to 2018 [20]. Recently, JRC released a new version of Global Human Settlement Layer (GHSL), including the 2018 global ISA probability grid [21]. In addition, remote sensing satellites with nighttime lights have emerged as the primary monitoring objects, such as DMSP/OLS, NPP/VIIRS, etc. [22]. Owing to the high correlation between nighttime lights and human activities, they have become more important for urban expansion and monitoring the population, GDP, and other socio-economic indices [23]. (3) Integration of multi-source data for longer time series: Regarding long time series, Long et al. reconstructed the historical arable land use patterns using constrained cellular automata in Jiangsu China [24]. Chen employed year-specific maps and remote sensing to study the land use or cover changes in Taiwan from 1904 to 2015 [25]. Szombara et al. analyzed the shape of the Prądnik riverbed based on archives and modern data sets (old maps, LiDAR, DTM, orthophotos and cross-sectional profile measurements) [9]. Zohar integrated multi-source data to evaluate the development of routes in the Negev region during the twentieth century [26]. Jin and his team combined historical documents, old maps, and remote sensing, especially using the large-scale topographic maps of the Republic of China, to carry out urban recovery in the Jiangsu or Yangtze River Delta for 200 and 600 years [27–29]. Yu et al. reconstructed a continuously covered cropland distribution dataset in China spanning from 1900 to 2016 by assimilating multiple data sources [30].

In this study, the Beijing-Tianjin-Hebei region is selected as the study area because, on the one hand, it is the political and cultural center of China, as well as a national or world-class city agglomeration, which has important research significance. On the other hand, the BTH integration has a long history, with a large number of historical documents and old maps, providing substantial materials for the study [31]. The BTH urban agglomeration includes the two municipalities of Beijing and Tianjin, as well as 11 prefecture-level cities and two provincial municipalities in Hebei Province, which fulfill "capital–port–hinterland" functions [32]. Beijing, the capital of China, has been the political center of the country since the Yuan Dynasty, Tianjin, a typical port city, plays an important role in China's modern urbanization process, while Hebei is an important hinterland of urban agglomeration. Therefore, an overview of the process and mechanism of urban expansion in the BTH region in the past century will provide important historical experience for contemporary times, a reference path for the development of other urban agglomerations, and a basis for exploring the historical background, including the historical and cultural protection of this region [33,34].

Section 2 outlines the study area, data, and methods. Section 3 presents and analyzes the results of reconstructing the urban built-up areas using old maps and remote sensing images. Finally, Section 4 concludes the study.

2. Materials and Methods

2.1. Study Area

The Beijing-Tianjin-Hebei region is a political and cultural center of China, an important economic region of northern China, and a national urban agglomeration [2], as shown in Figure 2. The region accounts for 2.3% of the country's area and 7.81% of its population [18]. Its overall positioning is as "a world-class urban agglomeration with the capital at its core, a leading area for reforming the overall coordinated development of the region, a new engine for innovation-driven economic growth in the country, and a demonstration area for ecological restoration and environmental improvement."

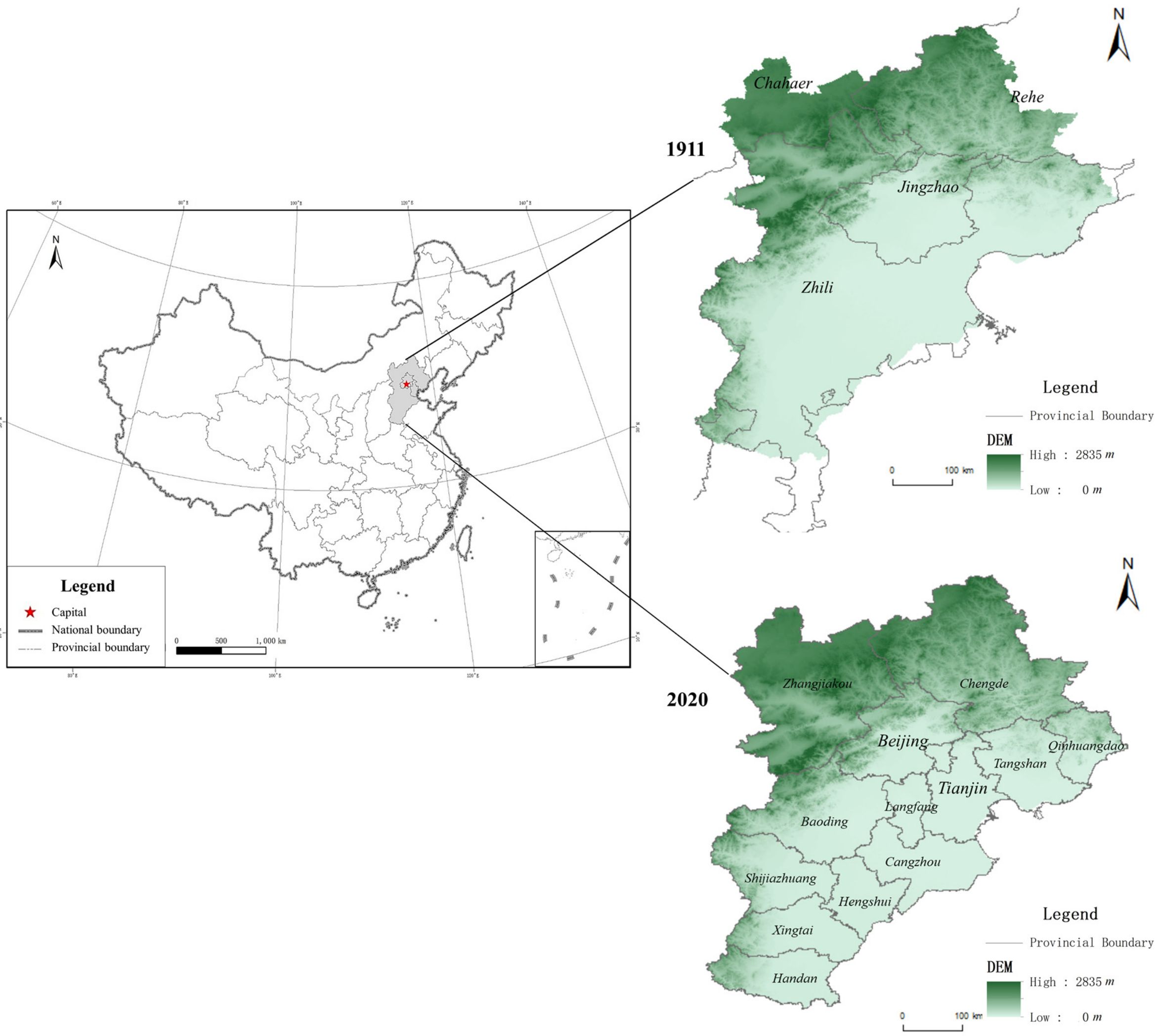


Figure 2. The spatial location of the Beijing-Tianjin-Hebei (BTH) region (1911 in late Qing Dynasty and 2020 for today).

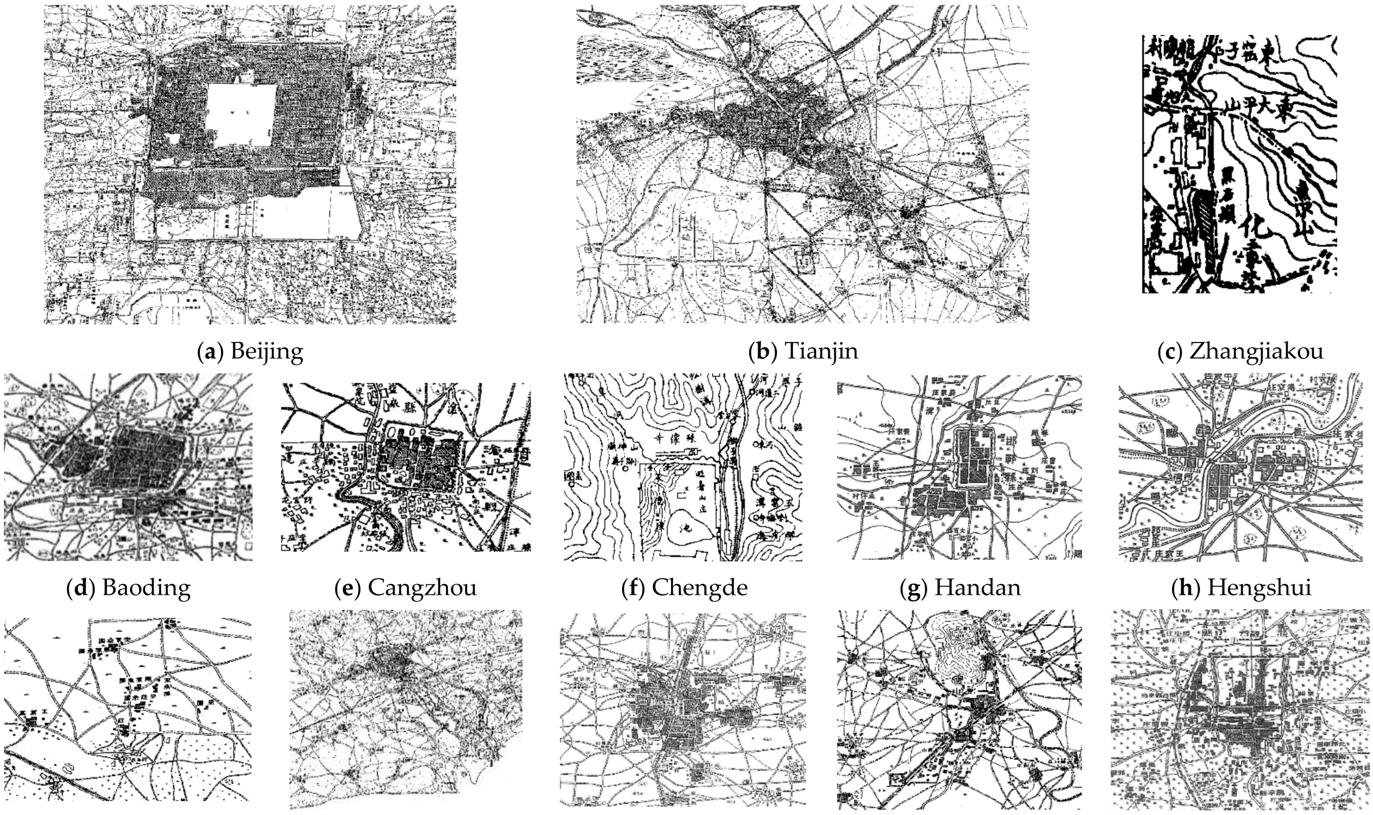
The BTH region has a long history and unique natural conditions. From a historical perspective, as early as the Western Han Dynasty, the BTH region around the Bohai Sea belonged to the Youzhou Cishi Department. The Hebei counties established during the Sui Dynasty also provided an outline for the resulting BTH region [31]. During the Yuan, Ming, and Qing Dynasties, Beijing became the political center of the country, Hebei was directly subordinated by the central government as a hinterland, and Tianjin developed into an important port that was used to open up modern China to the outside world, after the opening of the port in 1860 (Qing Dynasty). Hence, it preliminarily formed the "capital –port–hinterland" functional zoning and spatial pattern [32]. Regarding the overall natural pattern, the BTH region is surrounded by mountains on two sides, and the sea on the other side: the Taihang Mountains to the west, Yanshan Mountains to the north, and Bohai Sea to the east. From the perspective of spatial location, the area is complete and independent. From the natural geomorphic evolution perspective, the plain area of BTH is formed by the combined alluvial force of the ancient Yellow and Hai Rivers. Based on the analysis of the river system, the geographical scope of the BTH region and Haihe River system are basically the same, with the same independence and integrity.

2.2. Urban Land Use Data

This study primarily adopts objective spatial data to describe the distribution of urban space and built-up areas in different periods, such as old maps and remote sensing data (Table 1). Old maps are mainly obtained from the large-scale surveying maps of the Republic of China in Zhili, Chahar, and Jehol provinces (including the 1:50,000 scale map, which covers the Zhili province, and the other two provinces complemented by the 1:100,000 map), as well as the actual measured city maps in the late Qing Dynasty and Republic of China. The remote sensing data, which cover the entire Hebei area, were downloaded from the USGS center, of which Landsat was adopted for the remote sensing data, with a spatial resolution of 30 m. The topographic maps of 13 cities are shown as Figure 3.

Table 1. Data source overview.

Data	Data Type	Source	Original Resolution or Scale
Military topographic maps surveyed in the Republic of China	Old maps	Surveying and mapping agency of local government	1:50,000, 1:100,000
Landsat	Remote sensing images	USGS (United States Geological Survey)	30 m
Administrative border	Vector data (.shp)		1:250,000



(**a**) Beijing (**b**) Tianjin (**c**) Zhangjiakou
(**d**) Baoding (**e**) Cangzhou (**f**) Chengde (**g**) Handan (**h**) Hengshui
(**i**) Langfang (**j**) Shanhaiguan (Qinhuangdao) (**k**) Shijiazhuang (**l**) Tangshan (**m**) Xingtai

Figure 3. Systematic illustration of the BTH military topographic maps (1: 50,000 or 1: 100,000) in the Republic of China. (**a**) Beijing; (**b**) Tianjin; (**c**) Zhangjiakou; (**d**) Baoding; (**e**) Cangzhou; (**f**) Chengde; (**g**) Handan; (**h**) Hengshui; (**i**) Langfang; (**j**) Qinhuangdao; (**k**) Shijiazhuang; (**l**) Tangshan; (**m**) Xingtai.

2.3. *Extract and Analyze Built-Up Areas from Multi-Source Data*

Studies on the boundaries of urban built-up areas usually require a uniform data source and the same boundary extraction method. In addition, the definition of urban boundaries must be consistent to ensure extraction accuracy. When the study period spans decades or even centuries, the extraction methods of built-up boundaries need to be differentiated according to data sources. Considering the fact our data sources include old maps and RS images, we will then discuss how to extract urban built-up areas from the spatial information of different periods and categories from both sources, separately. The flowchart of our study is shown in Figure 4.

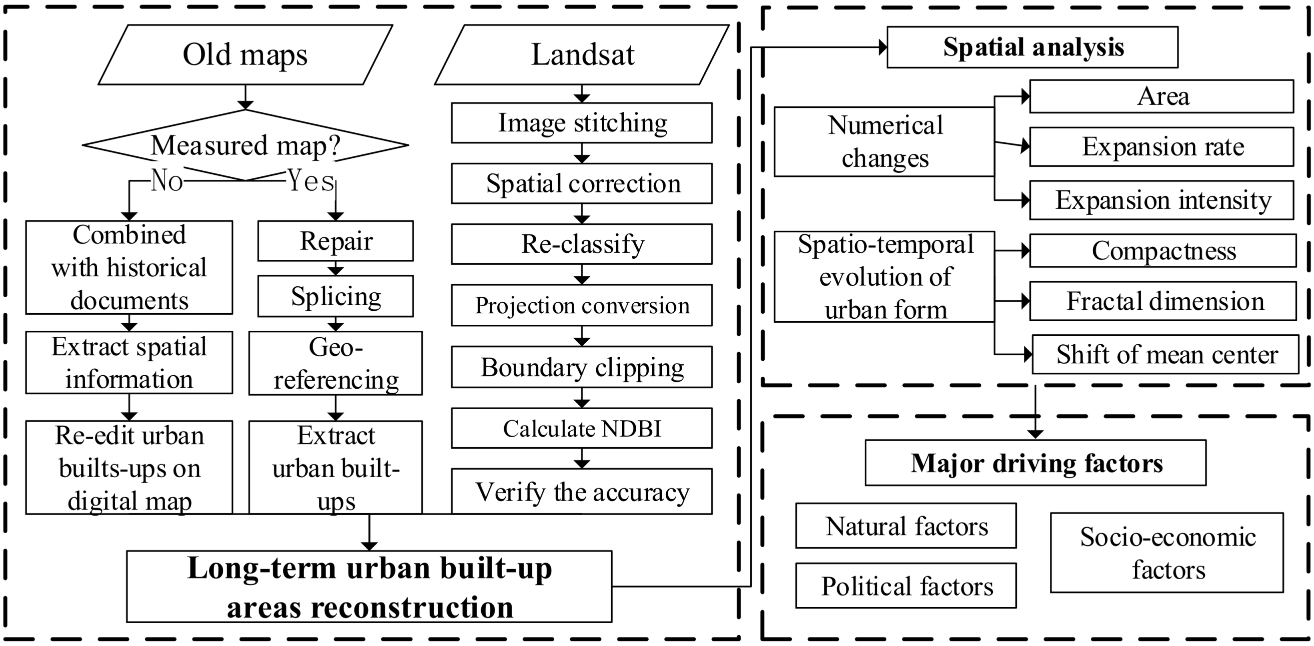


Figure 4. The flowchart of this research.

2.3.1. Extract Built-Up Area Information from Old Maps

The government of the Republic of China has organized several provinces to survey and map large-scale maps, as well as formulated unified cartographic specifications, which have provided basic data conditions for regional or larger scale studies [15]. In the BTH region, the former Zhili Province area was mapped with a 1:50,000 topographic map, with a $15' \times 10'$ map area and latitude and longitude corner points, which can be directly aligned. For the Chahar and Jehol regions, the topographic map was set at a scale of 1:100,000, with a map area of $30' \times 20'$ and latitude and longitude corner points, which can be directly aligned. After the maps were aligned, according to the national unified cartographic norms, urban areas were drawn with city walls or color blocks, which can be easily identified and used for urban land reconstruction. Considering the technical limitations of surveying and mapping in historical periods, as well as the errors in mapping processes and map information, the current location of city walls, city gates, and typical buildings (bell and drum towers, temples) can be analyzed and determined according to the records obtained from historical documents (e.g., local chronicles, Unification Chronicles of the Qing Dynasty, etc.), including references to today's digital maps and remote sensing images. In Google Earth, based on the determined locations of the city gates, the city boundaries are mapped and imported into ArcGIS to calculate the perimeter and area, which are verified against the city perimeter data recorded in historical documents.

Notably, during the feudal dynasty, Chinese cities were mostly identified by city walls, and the mapping of city walls was relatively clear and precise [13]. However, there are also built-up areas outside the city walls ("outer cities"). Therefore, to identify the built-up areas more objectively and comprehensively, this study does not simply adopt city walls as city boundaries but considers the definition of built-up areas (boundaries of built-up areas contiguous with the central city), combined with the actual drawings in the map (Table 2).

Table 2. Map recognition of urban built-up areas.

Urban Built-Up Areas	City Inside the Walls		Outer City
Spatial distribution characteristics	Located at the center of the city, surrounded by city walls		Mainly located on the outer edge of the city, or along the traffic line
	In this example, Area *A* is the city inside the wall, while areas *B*, *C*, and *D* are the outer cities.		
Interpretation examples of old maps		⇨	

2.3.2. Extract Built-Up Area Information Remote Sensing Images

In this study, Landsat optical images from 1990, 2000, 2010, and 2020 were downloaded. Firstly, we combined the bands of Landsat data into a multi-band image to facilitate the extraction of the *NDBI* of the study area. Then, the data were geometrically corrected, so that the position of the feature on the image corresponded to its actual position, which provided a position reference for the analysis of the data. In the process of correction, the neighboring element method was used to perform geometric precision correction on the image. Finally, the corrected data were clipped with the boundary of BTH region.

After data preprocessing, we started the extraction of land use, and impervious surfaces were extracted to obtain information on urban built-up areas. Here, the impervious surface was adopted to prevent the infiltration of water down the soil. Natural impervious and artificial impervious surfaces were adopted. The spatial and temporal distribution of impervious surfaces directly reflects the trend of urban expansion. This study primarily calculates *NDBI* (normalized difference built-up index) to obtain impervious surface data [35].

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR} \quad (1)$$

In Equation (1), *SWIR*, and *NIR* represent the infrared band reflectance and near-infrared band reflectance, respectively, and *NDBI* is calculated in the range of -1~1. Regarding the accurate extraction of impervious surface, the boundaries of the built-up area are extracted according to the principles of "continuous built-up area, non-agricultural landscape, and closed contour," based on the characteristics of the built-up area on the remote sensing map. Because the research and technology for urban built-up area extraction and analysis, based on remote sensing, are relatively mature, we will not elaborate them here.

Then, we selected the high-resolution built-up area product set as an independent verification sample to evaluate the accuracy of the built-up area extraction [36]. Specifically, we require the selected verification sample points to have a built-up area ratio of more than 85% within the range of 30×30 m, and the distance between the verification sample points should be kept to at least 100 m to ensure their spatial independence. In each city in the BTH agglomeration, the number of samples collected is proportional to the product area of the built-up area, and the correctness is judged by visual judgment. The final extraction accuracy is 87.39%, which meets the accuracy requirements of our study.

2.3.3. Analysis of Built-Up Areas in Different Periods

After extracting the built-up area, the analysis of the built-up area started with a suitable segmentation of the study time frame, owing to the long time span involved in this study and the complexity of the urban land change processes and mechanisms. After segmentation, further analysis of urban built-up area expansion was carried out. Specifically, this analysis includes the quantitative urban expansion rate, expansion intensity, compactness of urban form, fractal dimension, and mean center shift distance.

Rate of urban expansion: The rate of urban expansion is the change in urban land area per unit time [27], which is expressed as:

$$C_{UE} = \frac{\triangle s}{\triangle t} \times 100\% \tag{2}$$

where C_{UE}, ΔS, and Δt represent the change in the urban built-up area of the study area, area of the built-up area's expansion during the given time period, and study time interval, respectively.

Urban expansion intensity: The urban expansion intensity is the growth magnitude of the urban land area per unit time, which can reflect the rapidity of a city's development and level of urbanization [28], specifically calculated by:

$$V_{UE} = \frac{\triangle s}{S_a \times \triangle t} \times 100\% \tag{3}$$

where V_{UE}, S_a, ΔS, and Δt represent the intensity of urban expansion in the study area, built-up area at the beginning of the urban study, area of built-up area expansion during the given time period, and study time interval, respectively.

Compactness of urban form: Compactness is used to reflect the relationship between urban spatial form and functional layout, as well as the density and fullness of the built-up area of the city [29]. Generally, the larger the compactness value, the denser the urban form. The specific calculation formula is expressed as:

$$c = \frac{2\sqrt{\pi S}}{L} \tag{4}$$

where c, S, and L represent the compactness of the urban built-up area, area of the urban built-up area, and perimeter of the urban built-up area, respectively.

Fractal dimension: The fractal dimension is a measure of the irregularity of complex shapes and can reflect the complexity of the shape of urban boundaries. The fractal dimension is 1 for straight lines and 2 for rectangles, and the calculated value should be in the theoretical range between 1 and 2. Accordingly, the larger the value, the more complex the shape of the city [27].

The specific calculation formula is given by:

$$FD = 2\frac{\ln(L/4)}{\ln(S)} \tag{5}$$

where FD, S, and L represent the fractal dimension, area, and perimeter of the built-up area of the city, respectively.

City mean center shift: By comparing and analyzing the distribution of the location of the city's mean center, we obtain the direction of the mean center shift and the distance of this shift in different periods. It is important to elucidate the process of urban spatial dynamic change and the pattern of urban expansion. The formula for calculating the mean center is:

$$\begin{aligned} X_t &= \sum_{i=1}^{n} (C_{ti} \times X_i) / \sum_{i=1}^{n} C_{ti} \\ Y_t &= \sum_{i=1}^{n} (C_{ti} \times Y_i) / \sum_{i=1}^{n} C_{ti} \end{aligned} \tag{6}$$

where X_t and Y_t are the coordinates of the mean center of the city at time t, X_i, and Y_i are the coordinates of the mean center of the i_{th} spot, and C_{ti} is the area of the i_{th} spot at time t. Next, the actual distance between the two points was calculated from their coordinates.

After that, the mechanisms behind the urban built-up area expansion process are analyzed based on the evolution of the urban built-up area expansion process, considering the influencing factors in different periods. The driving factors, which include natural, political, economic, population, and transportation factors, are particularly complicated when the study period is long. Political factors, for example, have long been a dominant factor in urban expansion. During the feudal dynasty, urban functions such as capital, accompanying capital, and border defense functions, directly influenced regional urban populations and city sizes. However, the opening of Tianjin as a port city to the outside world from 1860 onwards significantly facilitated the modern urbanization of Tianjin and influenced its urban agglomeration patterns. Afterwards, the location of the provincial capital was changed several times since the establishment of Hebei Province was approved by government of the Republic of China in 1928. Later, the founding of the People's Republic of China, reform, opening up, implementation of BTH integration, and the establishment of the Xiong'an New Area, were all important driving political factors that directly influenced the city scale and urban hierarchy. In general, the main driving factors vary from period to period. This study will conduct an in-depth analysis insofar as possible to reconstruct the expansion process of the BTH urban agglomeration and its mechanism.

3. Results

Without understanding the history of cities, it is impossible to understand their present realities, and it is significantly less possible to predict their future. Via the comprehensive integration of long time series and multi-source spatial data over a century in the BTH region, and the extraction of information on urban built-up areas, we obtained reconstruction results of urban built-up areas in the BTH region from the 1920s to 2020 (Figure 5). The results will help us to elucidate how urban built-up areas expand from a century scale, and thus to understand the urbanization process comprehensively. In general, the expansion of cities was mostly based on the continuous outward development of the original walled city area, after which there were trends of faster or slower expansion along with the introduction of Western forces, such as the opening up of Tianjin, upgrading or downgrading of the cities' own administrative levels, development of transportation routes, etc. However, on a century scale, the proportion of urban built-up area land still increased significantly, and the functional land use of the urban agglomeration evolved rapidly. The following discussion considers the numerical changes in urban built-up area, its expansion rate, and intensity, as well as the spatial and temporal evolution of urban form in terms of compactness, fractal dimension, and mean center shift.

3.1. Numerical Changes in Built-Up Area

3.1.1. Area of Urban Built-Ups Areas

Each city was experiencing outward expansion during the study period, and the sizes of these cities have been increasing (Figure 6). The total size increased from 126.181 km^2 to 7013.832 km^2 from 1920s to 2020, which is an expansion of 55.585 times. Because the original city wall area of Beijing experienced the largest expansion, relatively, its expansion intensity is the smallest, with its built-up area increasing from 61.721 km^2 to 3895.114 km^2, a 63.108-fold expansion. The city with the largest expansion intensity is Langfang, with its built-up area increasing from 1.86 km^2 to 1420.027 km^2, a 763.455-fold expansion. Although the expansion intensity of each city at different stages differs, a general trend of continuous acceleration exists between them. This basically indicates a strong correlation between expansion area and urban hierarchy. We further compared the obtained results with those of Jiang et al., who conducted a centennial-scale analysis of the urban built-up area expansion in the Jiangsu and Shanghai regions of China (typical urban agglomeration in China as well) and concluded that the built-up area size increased from 127.1 km^2 to 7736.4 km^2, a 59.9-fold expansion. Considering the possible data and cartographic errors in the century-scale study, the results of this study can be considered close to our obtained urbanization results.

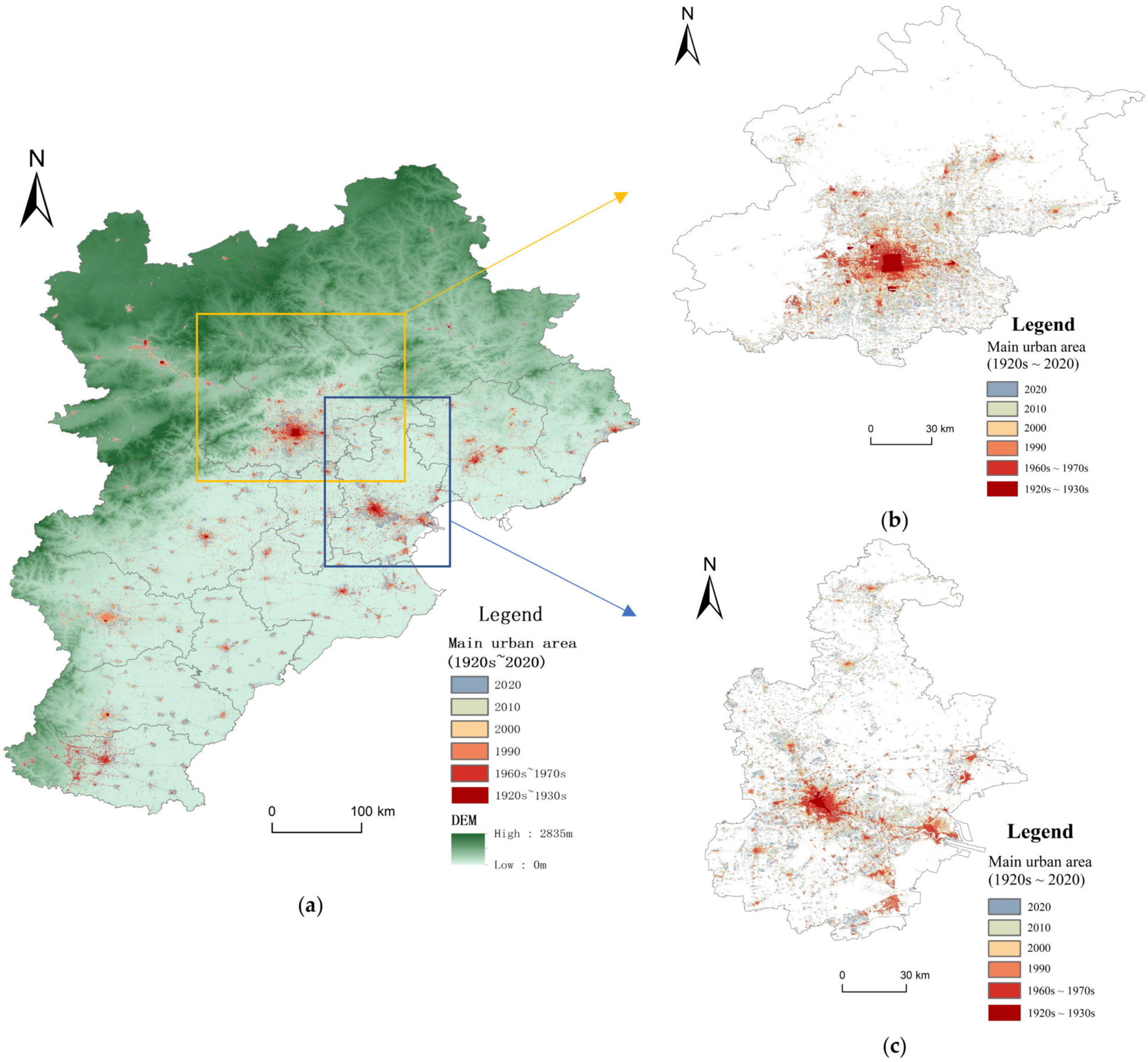


Figure 5. The reconstruction result of urban built-up area: (**a**) BTH region (yellow for Beijing and blue for Tianjin); (**b**) Beijing; (**c**) Tianjin.

3.1.2. Expansion Rate

The average annual expansion area in a certain period is used to characterize the expansion rate of urban built-up areas (Figure 7a). According to the calculation results, the average expansion rate of cities during the study period is approximately 16.247 km^2 /year. Further analysis of the difference in the expansion rate of built-up areas among different cities indicates that Beijing tops the list with a rate of 38.334 km^2/year, whereas Tianjin is in second place with a rate of 30.061 km^2 /year, which is also consistent with the status of the two mega municipalities in the BTH region. After them, the cities with the largest expansion rates in Hebei are, respectively, Tangshan, Baoding, and Shijiazhuang, among others. These cities have played important roles in the industry and politics of the region in the past and continue to do so. For example, Tangshan was once the "Beijing-Tianjin-Tang" industrial base (one of the four major industrial bases in China), together with Beijing and Tianjin, whereas Baoding and Shijiazhuang have been successively adopted as the capital of the Hebei Province (including its predecessor, Zhili Province), which are also relatively well developed in terms of their transportation and economic sectors. Chengde, which is at the end of the list, is located at a higher altitude, with a cooler climate, and has been the second political center since the Qing Dynasty, owing to its summer resort. However, it is now a national model tourism area. Owing to topography, functional positioning, and other factors, the expansion of its urban built-up area is relatively slow.

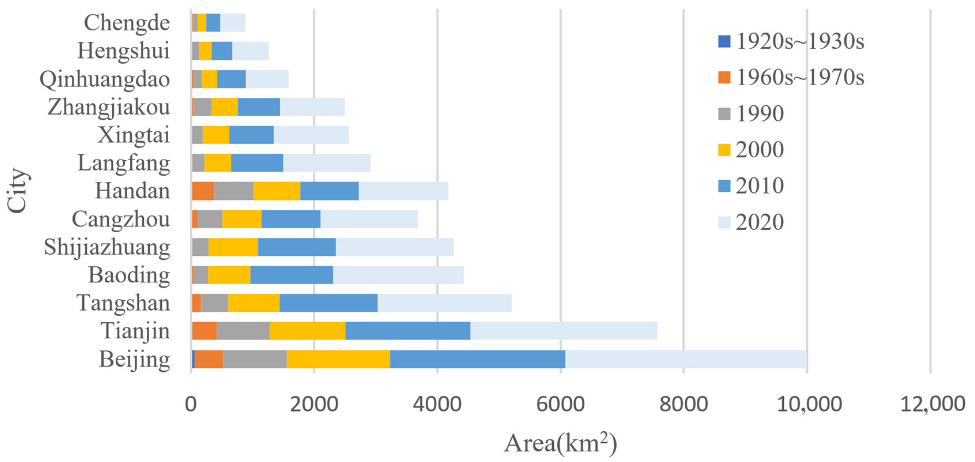


Figure 6. Change in the area of urban built-up areas of major cities in the BTH region.

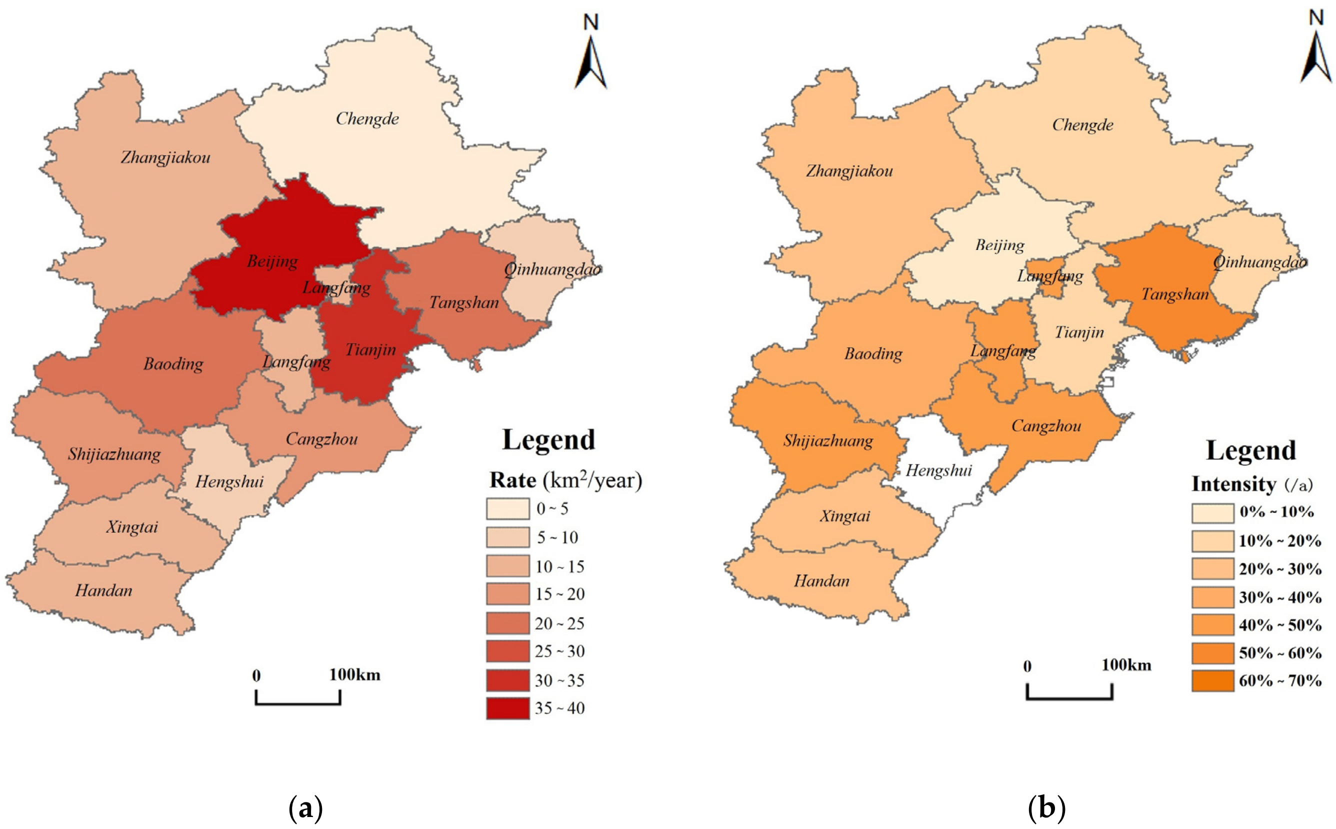


Figure 7. Expansion rate and intensity of different cities: (**a**) expansion rate; (**b**) expansion intensity.

3.1.3. Expansion Intensity

The average annual expansion ratio over a certain period of time is used to characterize the expansion intensity of urban built-up areas (Figure 7b). According to the calculation results, in general, the expansion intensity is not strongly correlated with the city hierarchy and scale, unlike the expansion rate. In the BTH region, Tangshan is the city with the largest expansion intensity, with 58.728%/a, and Shijiazhuang is the second largest with 45.335%/a. Beijing is surprisingly the lowest, with an expansion intensity of only 6.211%/a. Taking

Beijing as an example, although Beijing has the largest expansion area and expansion rate, it has been the largest city in China, since the early Ming and Qing dynasties, and it has a significantly larger city area than the other cities. Hence, its expansion intensity is relatively lower than that of the other cities.

3.2. Spatio-Temporal Evolution of Urban Form

Urban expansion is not only expressed as the expansion of built-up areas, but also as the change in urban spatial form. Compactness can effectively demonstrate the relationship between the urban spatial form and functional layout, as well as the compactness and fullness state of the land in the built-up area of the city. Fractal dimension is a measure of the irregularity of complex forms, which can reflect the effectiveness of the space occupation of complex forms. However, mean center shift can identify the direction of urban expansion to a certain extent.

3.2.1. Compactness of Urban Form

First, compactness was analyzed, and the values of compactness were varied considerably in the last hundred years as outward expansion was the dominant form of urban development (Figure 8a). From the 1920s to 1930s, the cities with higher compactness were Cangzhou, Baoding, and Beijing, whereas in 2020, the cities with higher compactness were Qinhuangdao, Baoding, and Xingtai. During this century of compactness changes, the city with the most significant change is Beijing, followed by Tianjin, and then Shijiazhuang. The mean compactness decreases from 0.916 in the 1920s to 0.492 in 2020, thus indicating a decreasing trend, as the compactness of the construction land within the city keeps decreasing. The more significant the expansion and irregular expansion pattern in the same time period, such as the continuous expansion of the transportation network and establishment of satellite cities, the lower the compactness of the city. Therefore, urban planners should focus on the internal space of the city in the future and increase its compactness appropriately.

3.2.2. Fractal Dimension of Urban Form

Regarding the specific measurement of the fractal dimension, the fractal dimension of every city in the historical period was lower than those in the modern period, because the cities in the historical period were more regular and mostly enclosed by walls. The fractal dimension of every city has increased in the last hundred years, and although it has decreased in some cities in individual periods, it has generally exhibited an increasing trend (from 1.225 in the 1930s to 1.466 in 2020, shown in (Figure 8b). City boundaries have developed in the direction of complexity. Regarding specific cities, in the 1920s–1930s, the cities with higher fractal dimensions were Handan, Xingtai, and Tianjin. In 2020, the cities with higher fractal dimensions were Beijing, Tianjin, and Shijiazhuang. Accordingly, the city with the most significant change was Beijing, followed by Tianjin, Shijiazhuang, and Baoding. These measurements also indicate the increasing complexity of urban morphology and agree well with the administrative hierarchy of cities. Hence, cities with high fractal dimensions generally have high administrative rank.

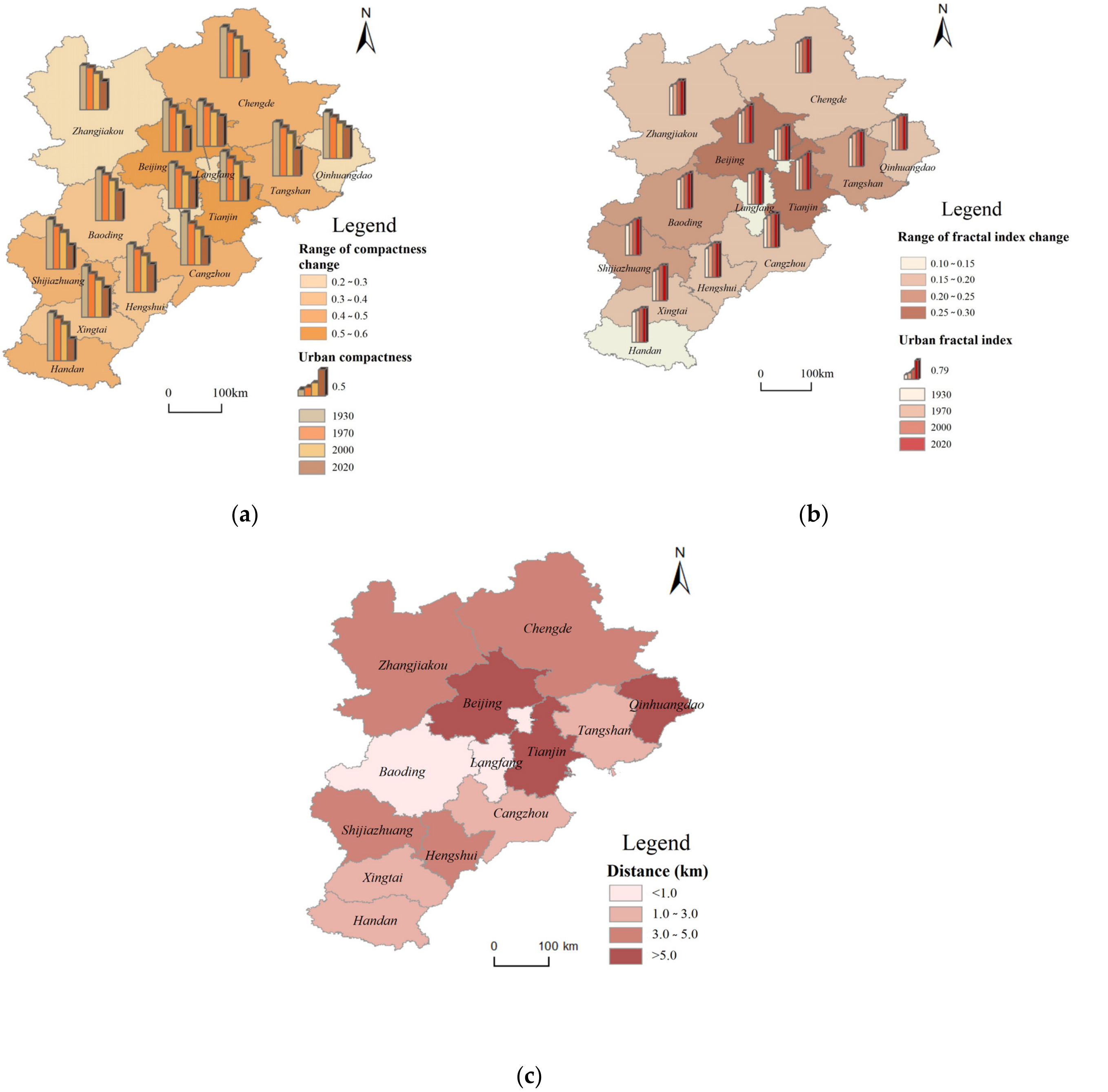


Figure 8. Changes in urban form: (**a**) urban compactness; (**b**) fractal dimension; (**c**) distance of the city mean center.

3.2.3. Shift of the Mean Center

The direction of urban expansion is significantly influenced by the geographical location and transportation conditions of the city. In areas with flat topography, cities mostly expand outward more evenly along the ancient cities. Regarding the change in the mean center of cities, in the past hundred years, there are three cities whose mean center shifted by more than 5 km. These cities include Beijing, Tianjin, and Qinhuangdao. In addition, there are four cities whose mean center shifted between 3 and 5 km, which include Zhangjiakou, Chengde, Hengshui, and Shijiazhuang. Furthermore, there are two cities whose mean center shifted by less than 1 km, which include Baoding and Langfang. Table 3 and Figure 8c presents the migration distance and direction of the mean center of each city.

Table 3. Shift of the mean center of the built-up area.

City	Mean Center (1920s)		Mean Center (2020)		Offset Distance	Offset Direction
Beijing	116.390° E	39.907° N	116.413° E	39.969° N	7.175 km	Northeast
Tianjin	117.185° E	39.138° N	117.301° E	39.088° N	11.461 km	Southeast
Baoding	115.491° E	38.858° N	115.484° E	38.853° N	0.823 km	Southwest
Cangzhou	116.856° E	38.308° N	116.868° E	38.312° N	1.139 km	Northeast
Chengde	117.932° E	40.975° N	117.891° E	40.971° N	3.475 km	Southwest
Handan	114.481° E	36.606° N	114.483° E	36.589° N	1.901 km	Southeast
Hengshui	115.704° E	37.727° N	115.722° E	37.752° N	3.202 km	Northeast
Langfang	116.693° E	39.515° N	116.718° E	39.530° N	0.738 km	Northeast
Qinhuangdao	119.598° E	39.924° N	119.539° E	39.928° N	5.056 km	Northwest
Shijiazhuang	114.478° E	38.009° N	114.515° E	38.038° N	4.577 km	Northeast
Tangshan	118.199° E	39.621° N	118.175° E	39.629° N	2.242 km	Northwest
Xingtai	117.501° E	37.065° N	117.497° E	37.052° N	1.490 km	Southwest
Zhangjiakou	114.878° E	40.819° N	114.896° E	40.789° N	3.668 km	Southeast

3.3. Major Driving Factors and Urbanization

The Beijing-Tianjin-Hebei region contains distinct political centers, port cities, and regional hinterlands, constituting a "capital–port–hinterland" urban system with different sizes, functions, labor divisions, and interdependencies. In general, most modern cities and towns are formed due to a continued and gradual development of historical cities and towns. The results of our study on the expansion of cities and towns also demonstrate that cities have mostly grown outward from their original city walls, with expansions varying from period to period according to their corresponding driving forces. The analysis of the various drivers behind their expansion includes natural, political, and socio-economic factors. In the span of a century or more, natural factors may determine the initial location, expansion direction, and general size of the city. At the same time, important national and local historical events, population build-up, and economic development may influence the long-term expansion of cities.

3.3.1. Natural Factors

Natural factors largely determine the location and scale of cities, providing an objective basis for the evolution of urban spaces, which affects the density and spatial distribution of the population and economy. The BTH region is located in China's North China Plain, surrounded by mountains on two sides and a sea. It is bordered by the Taihang Mountains to the west, the Yan Mountains to the north, and the Bohai Sea to the east, and is strategically defensible due to its relative isolation. It also largely overlaps with the Haihe River basin and Bohai Sea Gulf and is far from the Yellow River floodplain. The region features prerequisite natural conditions for developing historical settlements and urban systems and rich mineral resources such as coal, iron, and oil. Specifically, Zhangjiakou and Chengde, located in the northern part of the BTH region, are a part of the Yan Mountains, featuring terrain dominated by mountains, limited available land for construction, poor urban development conditions, smaller cities, and relatively homogeneous urban functions. For example, in historical periods, Zhangjiakou and Chengde were mainly used for government functions, accommodating military fortresses and imperial palaces. In contrast, the terrain of the southeastern area of the BTH region falls under the North China Plain, where there is more land available for construction and low construction costs, making it possible to form integrated regional cities. This, in turn, leads to relatively large cities compared to other cities on the same political level. For example, the population of the historical city of Daming Prefecture (which is now part of Handan city) used to be more than a million. Tianjin, Qinhuangdao, and Tangshan are important port cities with well-developed shipping and prominent transportation functions. Tianjin has now become the largest port in North China since its opening. Due to rapid economic development and population growth, its urban built-up area is second only to Beijing in terms of size. The Beijing-Tianjin-

Tangshan area is one of China's four major industrial bases, and Tangshan contains iron and steel, petrochemical, and other industries. Tangshan has iron and steel, petrochemical, and other industries. Its urban built-up area is smaller than Beijing and Tianjin, ranking the third in BTH. Qinhuangdao, originating from Shanhaiguan, is located at the intersection of Northeast China with North China. It later became a tourist destination as it is a scenic seaside city.

3.3.2. Political Factors

From a political perspective, the urban development from as early as the Ming and Qing dynasties, particularly the nationwide culmination of fortifications built during the Ming dynasty, established the basic structure of present-day Chinese cities. Historically, cities were essentially political centers at different levels, gaining the ability to gather resources due to their political status and thus exhibiting prosperous consumption characteristics, as is most evident in the development of the capital as the country's political center. As can be seen from built-up areas, the size of the country's capital was much larger than other cities in the Beijing-Tianjin-Hebei region, fully reflecting its political rank as a regional political center or even a national political center. By the late Qing dynasty and early Republican Era, many cities along China's coasts and rivers were forced to open their ports under the influence of modern Western civilization, with Tianjin as the first city to become a large port city in North China and the country. The nation's industry and commerce rose with the influx of outside forces, which likewise increased the inflow of population. The preexisting law of preferential growth in political centers was gradually phased out, and the urban structural system evolved rapidly. By the late Republican Era, China's economy was in trouble and many cities were severely damaged due to the Second Sino-Japanese War and the Chinese Communist Revolution. After establishing the People's Republic of China in 1949, a hundred cities were waiting to be rebuilt. The economy began to take off on all fronts especially after the reform and opening up of China in 1978. The regional economy continued to achieve breakthroughs and constantly drove the expansion of urban built-up areas. With new policies driven by the integration of Beijing, Tianjin, and Hebei, the construction of the Beijing-Tianjin-Hebei world-class city cluster, and the establishment of the Xiong'an New Area, the region was more able to develop synergistically. It also helped the region to optimize the urban layout and labor division structure and promoted inter-city labor division and collaboration, thereby enhancing the integration of the city cluster. One of the more interesting and complicated changes at the political level is the administrative divisions of the BTH region, which has undergone many adjustments. The provincial capital of Hebei province has been constantly moved back and forth between several cities, such as Tianjin, Baoding, Beijing, and Shijiazhuang, which is rare in China (Table 4). The location of the provincial capital also directly impacts the political hierarchy and size of the cities.

Table 4. Migration of the capital of Hebei Province since late Qing Dynasty.

Year	Provincial Capital	Year	Provincial Capital
1860	Baoding	1945	Beiping (Beijing)
1870	Baoding & Tianjin	1946	Baoding
1902	Tianjin	1947	Beiping (Beijing)
1928	Beiping (Beijing)	1949	Baoding
1930	Tianjin	1958	Tianjin
1935	Baoding	1966	Baoding
1937	Tianjin	1968 to present	Shijiazhuang
1939	Baoding		

3.3.3. Socio-Economic Factors

The continuous accumulation of urban population is one of the important signs of urbanization and a very crucial figure in measuring urbanization level. According to the statistics on the urban population (populations over 50,000) by Ruisheng Shen, a geographer and research member of the Sun Yat-sen Industrial Planning Research Association during the Republican Era, in the 1930s, Beijing had a population of approximately 1,564,877,000 people, Tianjin 1,067,900, Baoding 312,000, Tangshan 85,000, Shanhaiguan (now Qinhuangdao) 70,000, and Shijiazhuang 60,000. There were six cities with a population of more than 50,000. On a national level, the only cities with more than one million people were Shanghai, Beiping, Guangzhou, Tianjin, and Nanjing, which showcases the large population size of the Beijing-Tianjin-Hebei region. Afterward, following a series of urbanization processes, such as reforms and opening up, and the integration of Beijing, Tianjin, and Hebei, the proportion of the national urban population increased from less than 20% to 63.89% (according to the latest Seventh Census results) and the population of the Beijing-Tianjin-Hebei region accounted for 7.81% of the country's total population. Beijing had a population of 21,893,100 people. The problem of urban diseases had become increasingly prominent, so the government carried out corresponding industrial adjustments and household population control. Hebei took over some of the population and urban functions.

In terms of transportation and economy, railway construction, economic development, and regional urbanization have brought about changes in the functions of cities. As a result of railway construction, some industrial and mining cities along the railway lines began to grow, and with transportation network improvements, transportation hub cities also began to rise (Figure 9). Shijiazhuang was originally a sparsely populated village, but in modern times, with the construction and opening of the Beijing-Hankou and Zhengtai railways, it took advantage of the railways and rapidly developed into a transportation hub. Similarly, Zhangjiakou became a transit and trade hub due to the construction of the Beijing-Zhangjiakou Railway, which facilitated transportation from Zhangjiakou to Tianjin. Langfang, on the other hand, gradually developed itself and its surrounding areas from a railway station into the built-up area it is today as a direct result of the Beijing-Shanhaiguan railway, which has a station in Langfang. After several years of basic transportation construction, the Beijing-Tianjin-Hebei region achieved interoperability between regular and high-speed railway, making inter-regional exchanges more convenient. Transportation development directly promoted the development of the economy and trade. Later on, with the influx of population and foreign capital and the development of the transportation network, the economic functions of the city were continuously strengthened. The monolithic structure of traditional cities dominated by political functions changed into a diversified structure with equal emphasis on political, economic, and educational functions of modern cities. The urban system also changed gradually from the traditional monocentric structure to a multi-functional multi-core urban system with Beijing and Tianjin as the center, forming the functional structure of the BTH region. In consideration of the high population and industrial density of the Beijing-Tianjin region and given the integration of Beijing, Tianjin, and Hebei lies in the carrying capacity of Hebei, relevant mature industry chains should be further diffused and sub-transferred to the surrounding cities in the future to better utilize the city outskirt capacity of Beijing and Tianjin. The redundant labor force of the two cities should also be absorbed to achieve a balanced regional industrialization and urbanization development.

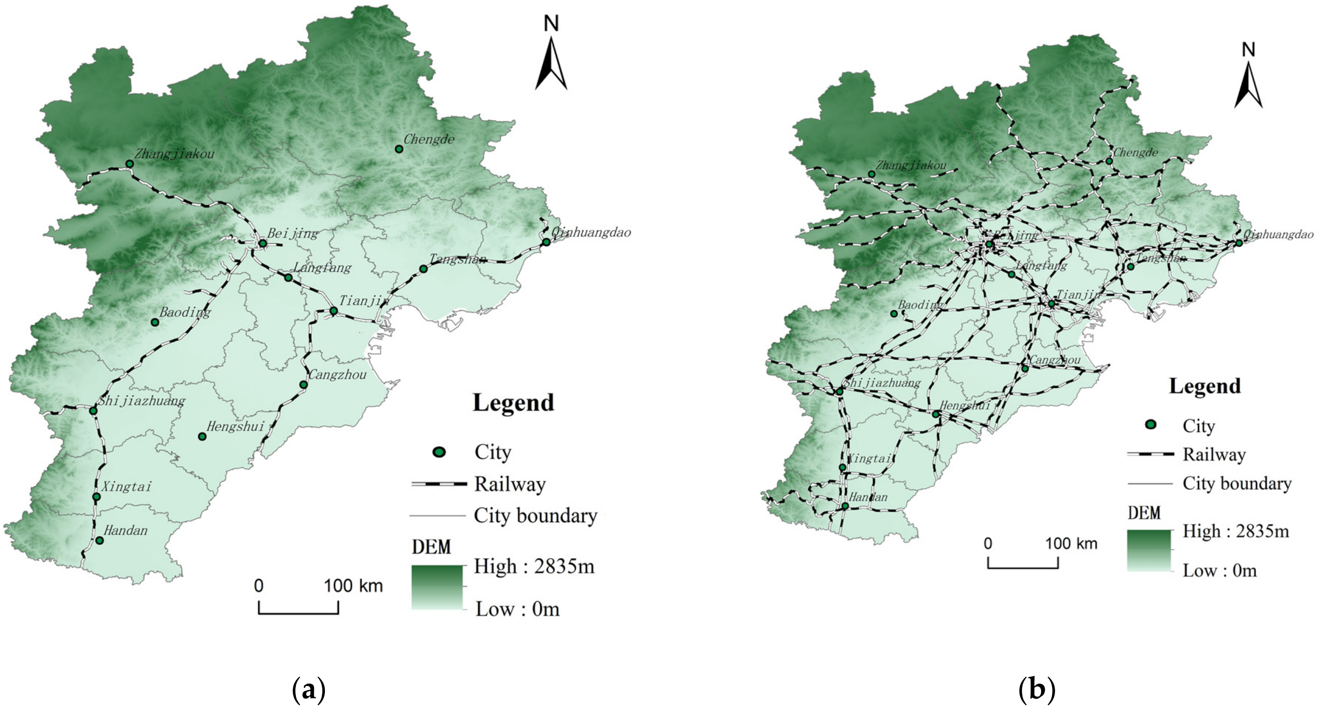
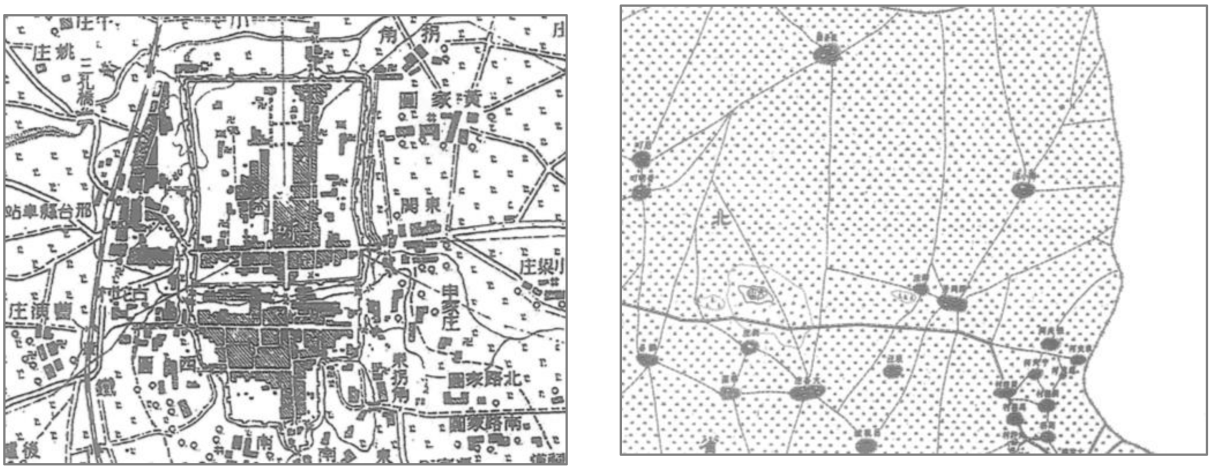


Figure 9. Railways in BTH: (**a**) 1934; (**b**) 2018.

4. Discussions

4.1. Data Availability of Historical Data

The availability of historical data and data quality represent an important and difficult challenge in the analysis of land use, land cover change, and urban built-up area, especially when using historical information dating back to the period before remote sensing data became available. Historical data, especially old maps, often introduce higher levels of positional error and uncertainty owing to the use of different sources and lack of georeferenced coordinates. These "inaccuracies" and "uncertainties" can affect the results of land use change, including landscape indicator calculations. It is challenging to adopt a standardized approach to process all the old maps, owing to the unique styles and cartographic habits of different institutions and different time periods. The drawing style and precision are also different in cities and rural areas (Figure 10). Because the focus of this study is on urban built-up area change at the scale of urban agglomerations, maps from historical periods should be selected to ensure that the mapping time and mapping specifications are consistent or as close as possible. The large-scale topographic maps surveyed and mapped by the Republic of China, which were based on swift survey plans and outlines, are more significantly comparable horizontally than the urban maps produced by different agencies in different cities. First, the remote sensing and historical data were also geo-corrected using remote sensing data based on unaltered important landmarks such as the Forbidden City, buildings in concessions, and ancient city ruins. Despite the errors in the historical data, they are in most cases meaningful in terms of the urbanization process and the historical trajectory of the city.



(**a**) (**b**)

Figure 10. Cities and rural areas on the map: (**a**) City; (**b**) Rural area.

Owing to data limitations, it is more difficult for us to study internal changes in urban development. For example, significant internal changes have also occurred within urban agglomerations via urban renewal and housing demolition. Internal changes and increases in building heights are important parts of urbanization research and will be further emphasized in our future studies via data collection and examination. Notably, the uncertainties in the processing of multi-source data when extracting urban boundary information may trigger errors in the area and perimeter of the urban boundaries. For example, early surveys and maps are mostly hand-drawn. The boundaries are not strictly natural boundaries, and there may be cases where non-urban land is included in urban areas, thus shortening the boundary perimeter. However, although remote sensing images in recent years present the extent of urban built-up areas with natural boundaries, and extraction results are practical, the perimeter may be increased, owing to more curvatures in the boundaries. In addition, different data sources may influence the data calculation results to a certain extent, owing to coordinate alignment and mapping errors. However, because this research is a regional study, the same batch of surveys and maps are comparable, and these effects have been controlled within acceptable limits for macro trend analysis.

4.2. Why Do We Need Longer Time Series Studies?

The comprehensive integration of multi-source, multi-category, and multi-temporal spatial data, and longer-term research, will help to understand the relationship between man and land, better understand the history of the city, and use historical experience to better help future decision making.

Firstly, long-term research on land use and cover change (LUCC) changes helps to understand the relationship between human and land. In the past 100 years, humans have carried out high-intensity and large-scale urban construction, which has greatly changed the natural landscape of the land. It has become a consensus that human activities on land and the resulting changes have increased the vulnerability of the Earth's surface ecosystems. Comprehensive use of multi-source, multi-category, and multi-temporal spatial data to restore the detailed process of land use and land cover changes in historical periods can provide an in-depth understanding of the impact of human activities on landmark landscape changes in the past hundreds of years. It also provides historical knowledge and basic data for research on simulating past climate change processes, diagnosing climate formation mechanisms, and carbon emissions due to LUCC. It meets the requirements for the construction of earth observation spatio-temporal data sets in the 2030 Sustainable Development Goals (SDGs) proposed by the United Nations Development Summit.

Then, focusing on urban areas, only by understanding the history of the city can the history itself be better protected. In the process of rapid urbanization, urban historical landscapes have suffered the most serious threats in history, and many historical landscapes have been destroyed. The UNESCO and the international cultural heritage protection community therefore pay particular attention to the protection of urban historical landscapes and have promoted the implementation of new methods of urban protection (Recommendation on the Historic Urban Landscape). The integration of multi-source, multi-category, and multi-temporal spatial data in the past hundred years can be directly used for the census of historical and cultural resources to help delineate the red line of historical and cultural protection, and even establish a historical and cultural heritage information platform. At the same time, in addition to the ancient buildings, there are a large number of old place names in the old maps, which can further reveal the memory of the city and contribute towards a collective sense of belonging.

Finally, combining effective historical experience in historical trends can inform better decisions about the future. Understanding the historical trend and the influencing factors of urban growth can support predictions pertaining to the future growth of the city. These studies can provide historical reference for the government to formulate land policies and adjust land use methods and summarize experience and lessons. For example, historical and cultural protection decisions can be added to the geographical process decision-making, and the resource carrying capacity that considers historical topography and landforms can also be increased. We believe that, comprehensively considering historical trends and historical references, the policies formulated must be more scientific and effective.

5. Conclusions

Nowadays, China is actively promoting the integration of Beijing-Tianjin-Hebei, an important national development strategy. It is of practical significance to understand the urban development process and characteristic influencing factors of the region since modern times, to formulate a more scientific and effective spatial optimization adjustment plan. By comprehensively using urban spatial data, such as old maps and remote sensing images, geo-referencing them, and extracting built-up area information, a long-term sequence of urban built-up areas in the BTH region can be obtained. We analyzed the changes in the area value and spatial pattern at different stages, and then combined historical and statistical data to discuss the natural, political, and socio-economic factors of urban agglomeration expansion. After years of development, there was clear evidence of dramatic urban expansion in this area, and the total built-up area increased 55.585 times. Cities in BTH were mostly formed through the construction of city walls during the Ming and Qing dynasties. Looking at the urban expansion process that has affected the BTH region in the past hundred years, the level of urban development and the size of the regional population are the most important and fundamental factors that have always affected the urban built-up area. Transportation construction is an important factor in attracting economy and population. The cities of the Ming and Qing dynasties and the transportation modes developed by the Republic of China laid the foundation for the initial urban system. Later, the opening of Tianjin, the reform and opening up of China, and the creation of new urban areas continued to promote the development of cities. Through scientific and effective urban planning, actively guiding the rational layout of industries and the population and guiding the population flow economy to optimize the concept of urban development, it has exemplary significance for solving the urbanization problems caused by advanced and disorderly urbanization.

Our study has proven that the historical topographic map of the Republic of China can help expand the research period and promote longer-term research. We use remote sensing and GIS methods to integrate multi-source, multi-category, and multi-temporal spatial data to carry out long-term urbanization research, which is a very good attempt. Up till now, we have geo-referenced all old topographic maps in two sets of publicly published atlases. This series of maps has a scale of 1:50,000 and a total of 6033 maps, covering 21 provinces in China, and can be directly used for land use research in China before the advent of remote sensing. In terms of the extraction of built-up areas, we have extracted historical towns in the Beijing-Tianjin-Hebei region. We will further extract the Yangtze River Delta region and the Pearl River Delta region, and systematically study the centennial-scale urban spatial expansion of China's three largest urban agglomerations. We hope that, in the future, there will be more research on the spatial expansion of multi-source integration. However, there are some limitations to this study. First, currently, other accurate old map data cannot be used to confirm the veracity of the research. Further, the selected historical event cross-sections are inconsistent, resulting in a rough division of the urban expansion stage. Second, old maps may have map and boundary errors, while remote sensing images are more detailed, providing a longer perimeter of the built-up area. However, because this was a regional study, the same batch of mapping was still comparable, and these effects were controlled within an acceptable range for macro-trend analysis. In follow-up studies, mining historical data should further broaden the research horizon and strengthen the analysis method to obtain a new understanding.

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