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Assessing Polycentric Urban Development in Mountainous Cities: The Case of Chongqing Metropolitan Area, China

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Abstract: Mountainous settlements accommodate nearly one tenth of the world’s population. Most mountainous cities have adopted the strategy of polycentric urban development due to an asymmetric geography, which has received little attention from mainstream research. To fill the research gap, we proposed an analytical framework and conducted a multi-dimensional measurement of polycentricity. Taking Chongqing for the case study, this work confirmed that polycentricity is morphological and functional in mountainous cities. Polycentricity is believed to be particularly applicable to mountainous and water-rich landscapes, leading to an appropriate, balanced distribution and the strong multi-directional connectivity of urban nodes. This characteristic may partly result from natural determinism and long-term planning adaptation, complementary to market forces. Policy implications for planning such as avoiding excessive encroachment on natural barriers and increasing functional linkage in newly established subcenters were also proposed.

Keywords: mountainous city; polycentricity; urban form; morphological; functional

1. Introduction

Mountainous settlements accommodate nearly one-tenth of the world’s population [1]. Mountainous cities refer to cities with a large proportion of hilly area or cities situated in isolated and narrow inner basins and plateaus surrounded or backed by mountains [2] (in China’s context, Huang (2006) [2] defined the criterion of mountainous cities as a large proportion of area of at least 300 m altitude and above a 25% slope. However, there are different criteria. For example, Dorward (1990) argued that mountainous cities are characterized by a rugged terrain, high elevation, relatively remote location, and sparse population). Pressure from urbanization in mountainous cities in the developing world is more intensive than that according to their US–European counterparts, which are smaller in scale and are oriented for leisure [3]. For example, mountainous cities, which account for nearly one-third of Chinese cities, are growing rapidly at an immense scale. Such growth exerts huge pressure on the protection of the fragile and sensitive mountainous environment [4].

To shift the burden of concentric and concentrated development, many mountainous cities has selected polycentricity as their traditional urban form [5]. To some extent, polycentricity is naturally born and particularly applicable to mountainous cities arising from the concerns of natural constraints, traffic congestion, and ecological disturbance [6]. Huang (2006) claimed that if an urban population
exceeds 100,000, polycentricity might be an appropriate choice for a mountainous city. In contrast, McMillen and Smith [7] implied that US cities on the flatlands with a low congestion develop their first subcenter when their population reaches 2.68 million and their second subcenter at a population of 6.74 million.

However, mainstream studies have paid little attention to the natural determinism of polycentricity in a high spatial heterogeneity in mountainous and water-rich settings. For example, Alonso [8] proposed a monocentric urban model in flat homogeneous land and assumed that all cities were circular and homogeneous in all directions from the CBD. Muth [9] and Mills [10] made some revisions to allow for natural geographies and infrastructure to affect the available land by taking out certain “radians” of the circle. Universal urban theories of polycentricity were usually replicated to mountainous cities without adjusting and adapting them to local conditions [2]. As Barca, et al. [11] suggested, we need to explore place-based approaches that stress the individual characteristics and specificity of mountainous cities, rather than a “one-size-fits-all” approach.

Thus, exploring whether mountainous cities can achieve the ideal polycentric urban form and avoid the problems found in cities based on flatlands is interesting. In the current research, we attempt to propose a coherent measurement of polycentricity based on multi-dimensional geospatial data, and to disclose the unique characteristics of polycentricity in mountainous cities.

2. Literature Review and Analytical Framework

2.1. Literature Review

Polycentricity generally refers to an inter-connected urban network structure consisting of multiple urban centers, which is characterized by an outward diffusion from the central business district (CBD) to smaller nearby centers within the spheres of influence and the rising importance of centers relative to the contiguous urban core [12,13]. Polycentricity combines the advantages of compact and dispersed models and is thus widely regarded as a desirable urban form [14].

Empirical studies, such as the surveys of Garreau [15] and Anas, Arnott and Small [13]’s survey in the US cities, and Hall and Pain [16]’s POLYNET research on European cities, confirmed that many US–European cities have evolved from monocentric forms to polycentric urban forms. Currently, polycentricity has also been widely adopted in developing countries. For example, China has deliberately pursued polycentricity as a spatial planning strategy [5]. Sun and Wei [17] reported that 133 out of the 144 surveyed prefectural-level cities in China are planning to develop new subcenters.

Existing research focuses on the hypothesis of spatial homogeneity for cities on flatlands and emphasizes the importance of economic determinism in polycentricity [15]. In the “classic” urban economic theory from western literature [8], the idea of a ‘center’ is developed solely as a place of employment. Polycentric cities were assumed to evolve by market forces, particularly looking at employment and firm location [18,19]. Many researches view polycentricity as a result of multiple equilibria caused by centripetal and centrifugal forces [20,21]. For example, Hall and Pain [16] argued that the centripetal aggregation of advanced productive services and the centrifugal diffusion of social and personal services largely explain the formation of polycentricity.

Recent studies focus on the relations between morphological and functional polycentricity [22]. The morphological dimension relates to the geographic distribution of multiple urban centers of different sizes, whereas the functional dimension refers to the mutual or crossing functional linkages between centers [16]. A balance in the size distribution of centers would not necessarily mean a strong functional linkage between them. Burger and Meijers [23] showed that many cities tend to be more morphologically polycentric than functionally polycentric, whereas other places display the contrary. In China, many coastal cities on the flatlands are proactively evolving toward morphological polycentricity, but the newly established subcenters have relatively weak functional linkages and are highly dependent on the CBDs [24,25].
A commonly acknowledged measurement of polycentricity is lacking because of its complexity and inherent interdisciplinary characteristics. Many studies measure morphological polycentricity by considering different perspectives (e.g., population, employment, business, and land use) and employing various methods (e.g., density slicing analysis, clustering analysis, and size–rank analysis) and data (e.g., census, sampling, and remote sensing) [26,27]. Several studies also investigate the issue on the basis of newly available “big” data (e.g., points of interest (POI), social media data, and location-based services) [28].

Recently, the literature on functional polycentricity has rapidly expanded. Existing studies often use network analysis based on flow data (e.g., trade and commuting) to measure the degree of functional linkages [16,23,29,30]. Recent research also attempts to link the measurement of morphological and functional aspects. Typical examples include the knowledge-based flows of people and information (e.g., face-to-face communication and advanced producer services) by Hall and Pain [16], network density analysis by Green [29], and network commuting flow analysis by Burger and Meijers [23].

Despite the proliferation of the literature on urban form, related studies on the polycentricity of mountainous cities remain limited. This paper investigates two research questions that need to be resolved: What is the degree of morphological and functional polycentricity in mountainous cities? What are the unique characteristics of polycentric mountainous cities distinct from the well-studied cities on the flatlands?

2.2. Analytical Framework

We proposed an analytical framework of polycentricity at the intra-urban scales of mountainous cities by drawing insights from the existing literature (e.g., [5,23,30]).

First, we emphasized that polycentricity would be a suitable choice for conserving nature and addressing the environmental concern, considering the specific characteristics of the natural mountainous landscape. Natural barriers separate mountainous settlements from contiguous development into scattered clusters, leading to a natural polycentricity. In the ecological view, water buffer areas and green belts/wedges should be planned as ecological protection zones to preserve the unique mountainous landscape and reduce ecological disturbance [31]. The polycentric model is critical for a livable mountainous city in a fragile environment [6], because it indicates minimal occupation, the intrusion of sensitive areas and few human disturbances to the natural ecosystem. Thus, the natural choice for mountainous cities is not simply to encourage the growth of the biggest urban core, but to raise the growth potential of outlying areas in a synchronized manner.

Second, we assumed that the polycentric urban form is particularly applicable to mountainous cities, because “decentralized concentration” is crucial in mountain regions considering the tradeoff between the dispersion and scale effects [6]. At the large scale, the urban form exhibits in a decentralized and polycentric structure. Urban settlements are dispersed and foot-loose, in order to reduce costs in undulating terrains and to seek favorable areas. This leads to a massive growth of subcenters/clusters in order to expand coincidental with the centers. Some specialized small to medium-sized clusters can achieve high productivity in which they are best suited, compared with one city core at the top of the urban hierarchy [11]. At the small scale, the urban form displays a compact and concentrated pattern. Urban developments are better concentrated at specific sites rather than overly dispersed to make full use of limited facilities. The provision of municipal facilities and services is often difficult and costly in a mountainous setting. Therefore, the (sub)centers should address their basic municipal needs and simultaneously link each other by a convenient network [32], possibly leading to high degrees of connectivity.

Thirdly, we linked a morphological approach focusing on nodal features and a functional approach concentrating on the relations between nodes (Figure 1). Morphological polycentricity highlights a balanced distribution in the sizes of multiple centers, and a functional polycentricity emphasizes the balance in the strength and structure of flows [33,34].
we preferred to measure the actual flow among centers using statistical analysis of commuting data. Considering the availability of data, we proposed the measurement of dimensions of buildings, facilities, and population representing different facets of urban elements (e.g., physical/human and static/dynamic). Different methods can be used to identify (sub)centers, including the absolute or relative criteria of the cut-off approach [35]. Among the various methods, we preferred a working approach based on spatial clustering analysis, which can identify highly clustered areas [30,36]. Based on the clustered result, we need to assess the balance in the size distribution of the subcenters within urban fields. Although rank–size distribution is a widely applied technique [33], we prefer a more straightforward method, that is, the visual interpretation of clustering maps. This method can be used to inspect the balanced distribution of subcenters with relative importance within a given city by combining local knowledge and urban planning. The urban form consisting of multiple subcenters with a significantly higher density than the surrounding areas is viewed as morphologically polycentric. By contrast, the urban form with a strong center and weak satellite towns is regarded as morphologically concentric [22] (Figure 1).

Morphological polycentricity is measured by identifying subcenters of different sizes, ranks, and distributions at a specific analytical unit (e.g., grids) according to the density of interest urban actors (e.g., inhabitants and workforces). Functional polycentricity is measured according to the crisscross connectivity of functional linkages. The functional approach examines urban network density and structure based on people flow (commuting), information flow (communication), or goods flow (trade) among individual centers [29,37]. In intra-urban research settings, large sample flow data are difficult to obtain. Nowadays, urban “big” data (such as automatic smart card records, taxi trips, shared bicycle routes, and mobile phone calls) provide high-quality interaction data [28]. By using a “big” data set, daily interactions can be efficiently monitored [38]. However, commuting flow remains one of the most important measures, since the collection of information/goods flow data is costly and time consuming. As such, we preferred to measure the actual flow among centers using statistical analysis of commuting data. Network density and visual interpretation are employed to analyze the functional organization of urban elements (e.g., physical/human and static/dynamic). Different methods can be used to identify (sub)centers, including the absolute or relative criteria of the cut-off approach [35]. Among the various methods, we preferred a working approach based on spatial clustering analysis, which can identify highly clustered areas [30,36]. Based on the clustered result, we need to assess the balance in the size distribution of the subcenters within urban fields. Although rank–size distribution is a widely applied technique [33], we prefer a more straightforward method, that is, the visual interpretation of clustering maps. This method can be used to inspect the balanced distribution of subcenters with relative importance within a given city by combining local knowledge and urban planning. The urban form consisting of multiple subcenters with a significantly higher density than the surrounding areas is viewed as morphologically polycentric. By contrast, the urban form with a strong center and weak satellite towns is regarded as morphologically concentric [22] (Figure 1).
an urban system [29]. A multi-directional set of exchange flows among centers is considered as functionally polycentric. By contrast, unidirectional flows toward the CBD are identified as functionally polycentric [23] (Figure 1).

According to Figure 1, we will assess the morphological and functional polycentricity in mountainous settings and then assess the impacts of natural elements (e.g., rivers, streams, hill ridgetops, and mountain ranges) and adaptive planning measures (e.g., planning subcenters/clusters and green belts/wedges) on polycentricity.

3. Study Area, Data, and Methods

3.1. Study Area

We selected the Chongqing metropolitan area (metropolitan area is defined by district or county boundaries, similar to the “Metropolitan Statistical Area” used by the US and the EU) (hereafter referred to as Chongqing), with an area of 3175 km\(^2\) that covers the major urban area of nine core urban districts, as the study area, instead of the entire Chongqing Municipality (the term of “municipality” refers the legal boundaries of a city as administrative entity in China; however, four directly-controlled municipalities by the central government (i.e., Beijing, Tianjin, Shanghai, and Chongqing) rank higher than other ordinary municipalities in China’s administrative system) with an area of 82,403 km\(^2\). The Chongqing municipality is one of China’s four municipalities under the direct administration of the central government of China. The Chongqing Municipality is often wrongly referred to as the biggest city in the world, since much of its administrative area is rural. The Chongqing metropolitan area occupies less than 7% of the Chongqing Municipality, which is comparable in size to Shanghai (6340 km\(^2\)). Located on the upper reaches of the Yangtze River, Chongqing covers a large area, crisscrossed by mountains and rivers. Chongqing is thus regarded as the most famous “mountainous city” in China. Four parallel north–south mountains (Jinyun, Zhongliang, Tongluo, and Mingyue Mountains) and two west–east rivers (Jialing and Yangtze Rivers) cross Chongqing. The city is built into steeply folding mountains that shield a vast basin of land carved by a confluence of rivers (Figure 2). Mountains and rivers serve as a natural base for polycentricity. Urban development was previously confined to the narrow Yuzhong Peninsula. As a trade port in the late Qing Dynasty (1890), Chongqing developed northern and southern subcenters along its river banks. As the wartime capital (1938–1946), Chongqing planned one subcenter near the verges of the mountains to shelter residents from air bombings. During the third-line construction period (1960–1978), as the largest inland industrial city, Chongqing planned many suburban working units (Danwei) to host massive inward-moving industries and institutions for national defense. Nowadays, Chongqing has evolved into a polycentric city composed of one CBD, six subcenters, and many urban clusters. The urban built-up area (urban built-up area is determined by developed land use with buildings, compared with the “urbanized area” that is determined by population density cutoffs in the US or EU) expanded from 158 km\(^2\) to 595 km\(^2\) and the urban population rose from 2.89 million to 7.58 million between 1994–2016 (CMBS, [39]). Chongqing thus offers an excellent case for studying polycentricity. We defined the area within the inner ring road as the central city and the surrounding territory as the suburbs according to the local knowledge. In line with the master plans, we differentiated large subcenters from lower-ranked small clusters according to their relative importance in the hierarchical urban structure.
3.2. Methods

We adopted interdisciplinary methods that are based on multi-source geospatial data to increase the robustness of our analysis. Four specific indexes were used to measure morphological polycentricity: floor–area ratio, POI mix, check-in frequency of social media, and the point density of bus stations. These indices reflect the density of urban elements from the aforementioned dimensions of buildings, facilities, and population.

The floor–area ratio was selected as an effective measure for subcenter identification as it can indicate the number of dwelling units and built-up volumes [40]. It denotes the accumulated built-up volume (m$^3$) per reference unit of land (m$^2$). Areas with agglomerations of high-rise buildings can be classified as subcenters.

The POI mix can provide an efficient measurement because it can be used as a proxy of the functional diversity of urban facilities [41]. POI data are gathered and geo-coded in maps, which contains functional categories such as financing, shopping, living, residential, recreation, and public services. The POI mix reflects the even distribution of different categories, which is calculated using the entropy method:

$$E = -\sum_{i=1}^{n} p_i \times \ln(p_i),$$

where $j$ represents the POI category, $p_i$ denotes the proportion of $i$ category within a 500 m radius, and $n$ is the number of total categories. Entropy ranges between 0 (mono-functional) and 1 (multi-functional).

The Easygo heat map was used to reflect the population distribution with respect to polycentricity because it represents spatially concentrated information with internet users. The heat map, a type of

Figure 2. Location of the study area.
A location-based service, records the location of check-in events from social media platforms in China. The large user base of this platform could provide a real-time and high-resolution picture of population dynamics. Heat maps can indicate the updated crowd density of population in a timely and accurate manner relative to the population census data collected every decade and at census blocks [28].

The presence of public transit stations was used to evaluate the polycentric level of subcenters, since it can reflect the supply of public facilities and the mobility for human beings. It is measured by the total amount of bus stations that fall within the circle at a search radius of 1000 m. The areas in which there is a lack of public facilities belong to the latter clusters.

Subcenters were detected through the kernel density analysis and spatial cluster analysis of multiple indices while considering that a single index cannot represent the location of a subcenter because of distribution inequality or information collection bias [28]. All indices were uniformed into grids of 100 × 100 m using the kernel density approach. The value of each index was linearly rescaled to fit the 0–100 range using the original value divided by the maximum score. K-means clustering was used to spatially distinguish the location of subcenters, combining all the indices. The (sub)centers were detected according to our local knowledge and the interpretability of the results. The final solution was found as a five-cluster outcome based on the similarities and dissimilarities of urban element distribution.

Functional polycentricity was examined by conducting a statistical analysis of actual commuter flows [29,42]. Taxi trajectories with the origins and destinations as well as the passenger flow using the metro system (two subway lines and two light-rail lines) were used here. However, high-quality data on flows remain difficult to obtain. Unlike in Beijing, passenger flow data from bus swiping cards in Chongqing do not record both origins and destinations. Hence, we alternatively utilized time schedule data that record the daily number of buses for each route connecting major urban nodes.

The statistical unit for traffic flows was determined by the scope of previously identified (sub)centers and the planning boundaries delineated in their master plans. Internal flows, which have origins and destinations in the same (sub)center, were used to reflect the local balance of job–housing within respective regions. Exchange flows, which connect individual (sub)center with the others, were used to analyze the network density and functional organization [37].

We focused on how intensely a particular (sub)center is functionally connected to the rest of the polycentric system by measuring the directional flows between them. The stronger the flows and the higher the average connectivity of the (sub)centers, the higher functional linkages exist within the urban system [23].

3.3. Data Sources

Data on floor–area ratio were sourced from large-area 3D building models, which was collected in February, 2018 from the online maps of Baidu, one of the largest search engines companies in China (https://map.baidu.com/). The building models gave the footprints and heights of individual buildings, and indicated a high spatial resolution. Data on POI and bus stations were collected recently from an online map of a navigation company (https://www.amap.com/). The Easygo heat map datasets for a whole workday (9:00 am to 11:00 pm on 23 January 2018) with a spatial resolution of 25 m were released through a map service (https://heat.qq.com/) by the Tencent company, a popular social media platform in China. The map locates active users who are using Tencent products, such as QQ (an instant messenger), WeChat (a mobile chatting application), online maps (a web mapping service), and other location-based services [28]. The number of active users in each point of Easygo (25 m × 25 m) was resampled into the heat map by kernel density in ArcGIS. The daily operation frequency of each bus route was collected from the local public traffic group. Payment data from bus/subway swiping cards (between August 2016 and July 2017) were collected from the Bus Card Payment Group. The taxi ridership data (March 2017) came from the Road Transportation Bureau. A digital elevation model was employed to derive natural slopes and mountain ridges. A wide variety of secondary data were collected, such as the population census (2000, 2010) and statistical yearbooks (2001–2016) from the

4. Results

4.1. Morphological Polycentricity

Figure 3 and Table 1 show the results of measuring morphological polycentricity based on four indices. The peak values of the four indices mainly concentrated on the inner ring road. First, high-density and high-rise buildings occurred in the small basins and valleys in Chongqing (Figure 3a). The Jiefangbei Center in the narrow peninsula had an extremely high floor–area ratio, as indicated by the dozens of skyscraper hotels and offices, as well as hundreds of tower apartments. The subcenters inside the inner ring road, particularly Guanyinqiao and Nanping, also had high built-up volumes, as implied by the dense and tall buildings. The area between the inner and outer ring roads had relatively low built-up volumes. Second, the POI mix exhibited significant spatial differences (Figure 3b). The (sub)centers within the inner ring road had compound and mixed functions of POI. The newly established subcenters, including Xiyong and Chayuan, lagged behind existing subcenters in terms of the POI mix. Some peripheral urban clusters, such as Beibei and Konggang, had a relatively high mix of POI. Third, the population heat map revealed a similar pattern (Figure 3c). Jiefangbei was the most densely populated center, followed by the Guanyinqiao, Dayangshi, Nanping, and Shapingba subcenters. This result indicates that most inhabitants and workplaces were located in the subcenters within the inner ring road, leaving small fractions in the peripheral clusters. Fourth, the density of bus stations within the inner ring road was relatively high, particularly along the major transport corridors. The density of public facilities was still low in the rapidly urbanized peripheral areas (Figure 3d).
Table 1. Statistics of the urban built-up area and clustering types among urban centers/clusters (unit: square kilometers).

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Land Area</th>
<th>Urban Built-Up Area</th>
<th>Very High Clusters</th>
<th>High Clusters</th>
<th>Moderate Clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBD</td>
<td>a. Jiefangbei</td>
<td>9.51</td>
<td>9.43</td>
<td>3.92</td>
<td>2.58</td>
<td>0.23</td>
</tr>
<tr>
<td>Subcenters</td>
<td>b. Guanyinqiao</td>
<td>95.55</td>
<td>86.56</td>
<td>6.26</td>
<td>24.42</td>
<td>11.22</td>
</tr>
<tr>
<td></td>
<td>c. Shapingba</td>
<td>44.52</td>
<td>35.73</td>
<td>1.69</td>
<td>7.65</td>
<td>3.79</td>
</tr>
<tr>
<td></td>
<td>d. Dayangshi</td>
<td>43.27</td>
<td>42.34</td>
<td>4.65</td>
<td>15.38</td>
<td>5.43</td>
</tr>
<tr>
<td></td>
<td>e. Nanping</td>
<td>39.91</td>
<td>34.44</td>
<td>3.33</td>
<td>8.89</td>
<td>4.64</td>
</tr>
<tr>
<td></td>
<td>f. Xiyong</td>
<td>142.68</td>
<td>68.05</td>
<td>0</td>
<td>1.66</td>
<td>5.74</td>
</tr>
<tr>
<td></td>
<td>g. Chayuan</td>
<td>100.84</td>
<td>36.43</td>
<td>0.47</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>Urban Clusters</td>
<td>h. Beibei</td>
<td>38.04</td>
<td>24.04</td>
<td>1.03</td>
<td>4.37</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>i. Caijia</td>
<td>50.77</td>
<td>16.84</td>
<td>0</td>
<td>0</td>
<td>1.03</td>
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<tr>
<td></td>
<td>j. Lija</td>
<td>61.94</td>
<td>28.62</td>
<td>0</td>
<td>0.46</td>
<td>3.05</td>
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<tr>
<td></td>
<td>k. Lianglu</td>
<td>136.85</td>
<td>68.88</td>
<td>1.68</td>
<td>8.5</td>
<td>9.11</td>
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<tr>
<td></td>
<td>l. Tangjiahu</td>
<td>31.28</td>
<td>11.99</td>
<td>0</td>
<td>0</td>
<td>0.37</td>
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<tr>
<td></td>
<td>m. Yuzi</td>
<td>46.95</td>
<td>16.08</td>
<td>0</td>
<td>0</td>
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<tr>
<td></td>
<td>n. Dadukou</td>
<td>98.09</td>
<td>62.77</td>
<td>0.86</td>
<td>5.71</td>
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<td></td>
<td>o. Xipeng</td>
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<td>22.2</td>
<td>0.02</td>
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<tr>
<td></td>
<td>p. Lijiatuo</td>
<td>61.25</td>
<td>41.65</td>
<td>1.63</td>
<td>4.61</td>
<td>6.62</td>
</tr>
</tbody>
</table>

The k-means clustering method that combines all indices was used to generate five clusters ranging from low to high scores (Figure 4). The balanced rank–size distribution of high-density areas reflected a clear polycentric development. A considerably high density of urban elements was primarily found in the CBD and in several subcenters. The CBD of Jiefangbei and the subcenters of Guanyinqiao, Nanping, Shapingba, and Dayangshi (which consist of three subordinate centers, namely, Yangjiaping, Daping, and Shiqiaopu) were easily identified (Figure 4). The sub-peak values of urban elements were distributed in the subcenters of Xiyong and Chuyuan, as well as in the urban clusters of Beibei, Konggang, and Longzhouwan. Compared with the main subcenters, the Xiyong and Chayuan subcenters had a relatively low building volume density and population density (Table 1). Moderate and low densities of urban elements were identified in the newly developed clusters. These clusters were far from the existing urban built-up area and functioned like satellite towns.

Figure 4. Clustered results combining all the indexes.
4.2. Functional Polycentricity

Chongqing’s subcenters formed self-sufficient nodes, thus offering a full range of functions. Such features decreased the necessity of trips to the principal center and encouraged internal trips within the subcenters. Internal flows in the same (sub)center/cluster accounted for 70% of the total flows. The value of internal flows was higher than that of the exchange flows. This finding indicated that comprehensive functions in subcenters can substitute for traditional functions in the CBD. Multi-functional urban complexes, such as the North Paradise Walk in Guanyinqiao, West Paradise Walk and Times Paradise Walk in Dayangshi, Three Gorges Square in Shapingba, and the Wanda Plaza in Nanping, were found in the subcenters. These complexes consist of hotels, offices, parking lots, shopping malls, convention centers, and apartments that can provide basic goods, services, and jobs to surrounding areas. As a result, most commuters living in the subcenters reduce their need to travel to the city center. By comparison, some specialized functional clusters in the periphery, such as Lijia and Renhe, were highly dependent on the other centers, resulting in high exchange flows.

The pattern of exchange flows in main (sub)centers indicates a functionally polycentric development of the central city because of good accessibility and high-order functions. By contrast, a low degree of exchange flows in peripheral clusters means that the relationship is not strong. First, bus flows accounting for half of the motorized flows confirmed strong functional linkages between the main (sub)centers. The (sub)centers in the central city had a relatively high network density and high degree of reciprocal commuting, signifying the existence of multi-directional flow patterns (Figure 5a). The commuting rate between the suburban clusters was relatively low, suggesting unequal connectivity with their neighbors. Second, the flows by taxis, which make up 9% of the motorized flows, were mainly distributed along the north–south direction, similar to the bus flows. The central city was characterized by a high degree of crisscross commuting by taxis (Figure 5b). Surrounding territories, such as the Xiyong and Chayuan subcenters, attracted few taxi commuters. Third, the flows of the metro system, which accounted for 10% of the motorized flows, revealed a balanced distribution of metro ridership in the central city and a low degree of flows in the suburban areas (Figure 5c). The metro lines from Guanyinqiao to Nanping and from Jiefangbei to Shapingba drew the majority of commuter flows, whereas the other sections extending to the urban fringes attracted few commuters.

Figure 5. Connectivity of the (sub)centers/clusters by commuting flows.
5. Discussion

We confirmed that mountainous cities achieved a morphological and functional polycentricity. In this section, we will explain the reason considering the determinants of natural factors and planning practices. Then, we highlight some reflections on the analytical framework and discuss planning implications of the study.

5.1. Natural Determinism and Planning Adaptation

The case of Chongqing confirms that polycentricity in a mountainous city tends to be a passive choice concerning natural determinism and landscape amenity, which is aligned with the finding of McHarg [31]. The (sub)centers in Chongqing were scattered in low-lying valley floors and upper natural slopes. They were separated from contiguous development by wooded mountain ridges (e.g., Zhongliang and Tongluo Mountains) and river buffer areas (e.g., Yangtze and Jialing Rivers). This choice is primarily ascribed to Chongqing’s distinctive physiographic characteristics. The unique feature involves a series of parallel ridges and valleys that rise from elevations of 100–1000 m. The long and narrow parallel mountain ridges alternate with broad valleys oriented in the north–south. The physiographic variety is manifested in mountains, hills, cliffs, valleys, terraces, rivers, streams, and marshes. Chongqing has adopted the strategy of polycentricity to maintain its dramatic and rich landscapes, which echo the ecological wisdom of “overall dispersion and specific-site concentration” in hilly and water-rich areas [4]. Appropriate diffusion can reduce development costs in undulating terrains and seek out favorable areas, such as flat terraces, valley floors, and riversides [4]. The dispersion can help to alleviate the overcrowding problem in densely populated city centers and accommodate the ever-increasing migrant population in (sub)centers.

Polycentricity also serves as a long-term planning strategy adapted to mountainous settings. Polycentricity may be an intended effort in Chongqing’s master plans in a planning history spanning more than 50 years. Historically, Chongqing’s development was constrained to the narrow peninsula, taking a monocentric form. The first step of planning toward polycentricity was initiated in the early master plan (1960–1980), which planned four subcenters in the central city and nine industrial clusters and four satellite towns in the periphery. The second master plan (1981–2000) delineated 14 regions as separate planning units to provide more space for development. The third master plan (1996–2020) sought seven urban clusters in the central city and eleven ones in the periphery. The recent master plan (2007–2020) involves the newly added Xiyong and Chayuan subcenters that first leapfrogged outside the Zhongliang and Tongluo Mountains. The master plan revised in 2014 further incorporated the newly established Liangjiang New Area in the north, a giant national-level economic area, to ensure the availability of developable land. In the master plans, greenbelts and green wedges were planned as the boundaries of the (sub)centers to prohibit contiguous development.

5.2. Morphological and Functional Polycentricity

The case of Chongqing indicates a close correlation between the degrees of morphological and functional polycentricity. This outcome differs from the findings of Yue, Liu and Fan [25] which demonstrate that functional polycentricity lags behind the morphological one.

Chongqing was morphologically polycentric because the high index scores were relatively concentrated in the (sub)centers. Biophysical constraints forced the individual centers to build vertically instead of merely expanding outward. Most centers contained dense populations, high-rise buildings, and mixed land use, resulting in a high density of human activities. Several densely populated subcenters and their effective spatial organization appear to be inherent to mountainous cities. This picture differs from the “many stars encircling the moon” approach found in many cities on flatlands (one dominant center with many surrounding subordinate towns).

Chongqing was functionally polycentric as inferred from the strong functional linkages between the major centers. Chongqing encouraged the formation of self-sufficient centers to increase the
internal flows within the same center. Since providing municipal facilities and delivering services are difficult in a mountain setting [32], the centers need to balance jobs and housing locally to reduce journey-to-work commuting. Simultaneously, Chongqing made a considerable public investment on bridges over rivers, tunnels across mountains, and subways through rocks to connect the urban nodes conveniently. The exchange commuting flows by public transit showed a high degree and a relative balance of multi-directional commuting flows in the central city. Such a polycentric system is unlike the star-shaped pattern of interactions in which the flows of commuters are centralized between nodes of cities on flatlands [23].

5.3. Reflections on Analytical Framework

This work offers two main contributions. First, we developed a uniformed measurement framework to integrate morphological and functional polycentricity from the perspective of the distribution and connectivity of urban centers. Second, we also highlighted how the integration of natural determinism and planning adaptation results in polycentricity in mountainous cities.

The current framework for measuring polycentricity at an intra-urban scale can be expanded from single-city to cross-city studies. The multi-dimensional framework based on multi-source data and interdisciplinary methods has overcome the bias sourced from single-source data or single method. “Big” data, such as mass builds, POI, social media check-in data, provide high-quality and dynamic spatial data at intra-urban scales [28]. The method used in this case study offers general criteria to identify areas with an inadequate density of agglomeration and low degrees of connectivity, which calls for subsequent policies to facilitate the catch-up of lagging areas [43].

The current framework highlights that mountainous cities can achieve functional polycentricity compared with their counterpart cities on flatlands. Mountainous cities are generally composed of multiple subcenters, each of which functions independently but is linked in various ways to its neighbors, as indicated from our findings. By contrast, many subcenters on flatlands have a relatively low concentration of human activities and weak mutual functional linkages, resulting in their high dependence on CBDs [25,44]. This finding indicates that polycentricity in many cities on flatlands might be a deliberate result of the spatial planning strategies of municipal governments, whereas polycentricity is a natural choice in mountainous cities [4]. The mountainous environment lays a natural foundation for polycentricity in mountainous cities, whereas the transition toward polycentricity in many cities on flatlands is largely driven by the blueprint laid out by proactive master plans [25]. Understandably, natural constraints, such as mountains and river separations, as well as undulating terrains, are more effective than delineated planning restrictions.

Despite such findings, we acknowledge certain limitations of this research. For instance, we did not analyze the patterns of residence/employment and distinguish between different journey-to-work patterns because of data limitations. We mainly used a visual inspection method to assess the spatial results instead of applying quantitative methods because of the complexity and multi-dimensional characteristic of polycentricity. We failed to consider the different impacts of different mountains patterns on urban spatial structure since we chose only Chongqing as the represented mountainous city. We hope to explore these issues in the future.

5.4. Policy Implications

We would like to highlight the policy implications for planning of our findings. First, the policy decision makers can be more sensitive to mountainous environments. Chongqing faces a continual challenge due to rapid urban expansion, especially when its urban population is growing to 12 million. Recent experience indicates that there are no permanent barriers to urban development, since infrastructure construction has created great development potential. Urban encroachment on sensitive areas, such as felling forests, sterilizing farmland, bulldozing hills, filling marshes, and culverting streams, has occurred frequently in the past two decades [6]. For example, nearly half of the urban area is located on slopes over 25%, because such development is often allowed in
Chongqing considering the scarcity of flatland. Some vegetated hills and streams have been partially flattened or fragmented by urban encroachment, because hilly and water-rich areas are ideal locations for high-profile real estate projects. If uncontrolled, this growth would obliterate the distinctive characteristics and amenities of the mountainous city. Thus, excessive development that disrupts natural processes need to be restricted rigorously. In this respect, we agree with the argument by McHarg [31] that the form of urban growth and open space was determined by fundamental natural processes.

Second, the aggregation of urban functions in newly emerging subcenters and their functional linkages need to be strengthened. Our results show that the lower-ranked peripheral clusters attract a low proportion of activities and commuters. There clusters were placed in areas relatively far from major infrastructures and services as well as the main economic flows. Of particular focus are the Xiyong and Chuayuan subcenters, which had relatively low concentrations of urban elements and weak functional linkages. In the future, local government officials can enhance the potential for growth in the periphery and increase the subcenters’ share of higher-order functions and improve their functional connectivity [11]. This suggestion is also applicable in other cities that are predominantly morphologically polycentric [25]. As claimed by Hall and Pain [16], the change from a mere morphological object to an increasingly functional entity is determined by flows rather than by the physical structure of a city.

6. Conclusions

With a focus on a mountainous environment, we proposed an analytical framework that is based on the multi-dimensional measurement of morphological and functional polycentricity. The polycentric structure was identified using newly available high-quality data, including building volumes, POI mix, social media heat maps, and commuting flow data. A series of quantification methods were employed, including spatial analysis, cluster analysis, and statistical analysis. In the case of Chongqing, we revealed that polycentricity in the mountainous city was morphological and functional. The CBD and the six subcenters with the majority of urban activities were identified. A few peripheral urban clusters were also detected as high-density areas of elements. The main centers formed a balanced pattern of multi-directional traffic flows, but the peripheral clusters had relatively weak functional linkages. We confirmed that polycentricity is applicable to mountainous cities, for which polycentricity is used as a normal planning strategy. Polycentricity in mountainous cities is a natural choice arising from the ecological view of “natural determinism” and a long-term planning asset stemming from the strategy of “decentralized concentration”.

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References


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