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## Evolving walkability of major cities in the People's Republic of China

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**ADB Working Paper Series**

**EVOLVING WALKABILITY  
OF MAJOR CITIES IN  
THE PEOPLE'S REPUBLIC OF CHINA**

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## **Evolving walkability of major cities in the People's Republic of China**

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## **Abstract**

**Context:** Walkability is an important element for assessing urban sustainability. There are increased concerns that more cities in the People's Republic of China (PRC) have become less walkable.

**Objectives:** We aim to develop a composite walkability index. We intend to use it to evaluate the spatio-temporal evolution of the walkability of PRC cities in the context of the rapid urbanization.

**Methods:** We developed a comprehensive walkability index that integrates five aspects of the urban built environment: dwelling density, street connectivity, land-use mix, access to public transit, and elevation variation. Using Shanghai, Hangzhou, Chongqing, and Lanzhou as cases, we evaluated the spatio-temporal patterns and changes of walkability in the context of rapid urban expansion.

**Results:** All four cities expanded their urban land from 1990 to 2010, but that there was a higher expansion rate in 2000–2010 than in 1990–2000. For inner cities, Shanghai had the highest average walkability index, whereas Lanzhou held the lowest. In 2000–2010, however, the inner cities of Hangzhou, Chongqing, and Lanzhou and the entire cities of Shanghai and Chongqing increased their walkability index, whereas the inner city of Shanghai had decreased walkability. Furthermore, while inner cities of Shanghai and Hangzhou experienced decreased or stable walkability, inner cities of Lanzhou and Chongqing enjoyed moderate to high increases in walkability.

**Conclusions:** The spatiotemporal changes in walkability seem to be directly associated with governmental policies at both central and local levels. The walkability index method can be

widely implemented for any urban landscape because of its comprehensiveness, simplicity, and flexibility.

**Key words:** walkability index; urban landscape; dwelling density; street connectivity; land-use mix; public transit; elevation

## **1. Introduction**

Walkability, defined as “the extent to which walking is readily available as a safe, connected, accessible and pleasant mode of transport” (TfL 2004), is an important element in assessing urban sustainability. It not only benefits the economy, such as consumer savings through reduced vehicle use, public cost savings for transportation infrastructure, and cost saving from the improved land use efficiency, but also benefits sustainability in environment and equity, such as less environmental damage from vehicle emissions and waste of resources, increased safety, community livability and cohesion, and personal health benefits (Littman 1994 & 2003; Cortright 2009; Frank et al. 2006; Sturm and Cohen 2004). For example, studies have found strong relationships between a neighborhood’s walkability and level of physical activity, body mass index (BMI), and the prevalence of chronic diseases (Sturm & Cohen 2004; Doyle et al. 2006; Frank et al. 2006; Smith et al. 2011).

Since 2011, the world is entering into an urban era, having more people than ever dwell in cities. Urban sprawl has been ubiquitous and has prevailed at a much faster pace than its urban population growth, often with poor walkability for newly built urban communities. While most PRC cities were walkable at the beginning of the economic reform in the late 1970s and the 1980s, there were increased concerns that more and more parts of PRC cities, especially newly expanded areas at urban fringes, had become less walkable. Meanwhile, even though a plethora of literature on the People’s Republic of China (PRC)’s urbanization and urban expansion has been written, little research has been conducted on walkability in PRC cities.

We developed a comprehensive walkability index to evaluate the spatial patterns and the evolution paths of walkability of four cities in the PRC that had experienced rapid urban expansion. The walkability index is the integrated index of the five aspects of the built

environment: dwelling density, street connectivity, land-use mix, access to public transit, and elevation variation. We aim to achieve the following objectives: (1) evaluate the expansion of urban built-up area of selected cities, using data processed from satellite images and aerial photos, in combination with existing land use maps of different periods; and (2) evaluate walkability through constructing walkability index maps for each city based on the urban land use data, population distribution, and other spatial data, such as road networks, access to public transportation, and elevation. We selected four cities—Shanghai, Hangzhou, Chongqing, and Lanzhou—as our case studies to evaluate urban land expansion from 1990 to 2010 and walkability of urban built-up area in 2000 and 2010.

## **2. Methods**

### **2.1 Materials and data**

#### ***Land use data***

We derived the urban built-up land and major land use classification from multiple satellite imagery, including Landsat 7, Enhanced Thematic Mapper plus (ETM+), Landsat 5 Thematic Mapper (TM), and SPOT5. All level 1G Landsat images, downloaded from the United States Geological Survey (USGS) website, were geometrically corrected to the UTM coordinate system. After radiometric enhancement, one-year SPOT 5 images of Shanghai were registered to the Shanghai ETM+ images, and resampled (RMSE <0.5 pixels) to a nominal pixel size of 5m×5m using the nearest neighbor algorithm.

To extract urban built-up land and major land use classification of our selected cities, we combined supervised classification, unsupervised classification, and visual interpretation. The classification and post-classification enhancements were completed using Erdas Imagine 9.3.



Except for the urban built-up land data of Shanghai in 2010 that was from SPOT5, all other data were extracted from Landsat.

For coastal cities with low elevation and less terrain complexity (e.g., Shanghai and Hangzhou), we had first performed a supervised classification with a maximum likelihood algorithm to derive the primary urban built-up land data. By comparing this with Google Earth and other high-resolution images, we conducted a visual interpretation classification to enhance the above classification result. Then, a serial of post-classification processes were employed to refine the classification. For Chongqing and Lanzhou, the terrain's complexity had made automatic extraction of urban information difficult, with lower accuracies using the machine-classified procedures. We therefore used visual interpretation in addition to supervised and unsupervised classification to identify urbanized areas, including large townships or villages in suburban areas and the concrete surfaces in the cities. We conducted an accuracy assessment for the 2010 urban land maps, based on independent literature and Google Earth high-resolution images. We used the land use maps of local agencies to further verify the classifications of our land use maps. We considered our classification sufficiently accurate with kappa coefficients ranging from 0.80 to 0.93 and producer and user accuracies of all cities over 0.9 except for Hangzhou's producer accuracy (0.83) and Chongqing's user accuracy (0.87).

### ***Other data***

We had obtained most of the raw data from local government agencies and converted and processed them into the same spatial scale of 100 m. Population data of each city are from the Chinese National Census 5 and 6 (2000 and 2010) for Chongqing and Hangzhou and Landsat Global population data for Shanghai and Lanzhou (<http://web.ornl.gov/sci/landscan/index.shtml>). Road data for Shanghai, Hangzhou, and Chongqing are from the Land and Resources

Administration of Shanghai Municipal Planning Bureau, Hangzhou Urban Planning Bureau, and Geographic Information Center of Chongqing, respectively. We obtained and processed data regarding bus stops and subways/light rails for Shanghai, Hangzhou, and Chongqing through Google Maps. We derived the road data and bus stop data of Lanzhou by digitizing the information from the Lanzhou City Map of Transportation and Tourism. We acquired the elevation data from the surveying and mapping agencies of Chongqing and Lanzhou and derived SRTM 30M DEM dataset for Shanghai and Hangzhou (<http://earthexplorer.usgs.gov/>).

## **2.2 The walkability index (WI)**

Although researches developed a walkability index range from using only a single factor to employing over a dozen factors, most studies intend to adopt just several major components. For example, Smith et al (2008) used only street connectivity to assess the pedestrian environment of the neighborhood. However, Walk Score used 13 categories to evaluate walkability for anywhere in Australia, Canada, New Zealand, and the United States (<http://www.walkonomics.com>). Nevertheless, it is generally considered that a walkable neighborhood has well mixed land use, well-connected streets, and high residential density (Saelens et al. 2003; Lake et al. 2010). Most researchers have adopted the integrated walkability index including just these three elements (e.g., De Meester et al. 2012; Marshall et al. 2009; Owen et al. 2007; Leslie et al. 2005; Brown et al. 2009). For example, Frank and colleagues (Frank et al. 2005, 2006, & 2010) had constructed one of the most popular indexes including these elements.

Frank et al (2005) proposed three components to construct a WI: net residential density, street connectivity, and land-use mix. Later, his team refined their walkability index by adding

the fourth component: the retail floor area ratio (Frank et al. 2006 and 2010). He defined net residential density as the ratio of residential units to the land area devoted to residential use per block group and the retail floor area ratio as the retail building floor area footprint divided by retail land floor area footprint. Street connectivity, which reflects the connectivity of the street network, was the ratio of the number of true intersections (three or more legs) to the land area of the block group in acres. He defined land-use mix as the diversity of five land use types, with 0 being single use and 1 indicating a completely even distribution of floor area across the five uses. Other researchers proposed to add transit access (Lovarsi et al, 2009; Brown et al, 2009) as an important aspect for walkability. In our study, steep slopes that discourage walking and make it very difficult in mountain cities like Chongqing and some areas of Lanzhou had been considered and, consequently, included as the fifth factor, elevation, for calculating walkability.

In this study, we dropped the retail floor area ratio component from Frank's index because of the unavailable data for our case cities and included the other three commonly accepted components, adding the components to reflect the access to public transit and the flatness of the land, i.e., our walkability index for PRC cities includes five components: net residential density, street connectivity, land use mix, transit stops, and flatness. Furthermore, most research on walkability's spatial pattern has focused either on 1 km x 1 km or neighborhood/district blocks, mostly due to limitation of data. However, in this study, we had chosen to use a resolution scale of 100 m x 100 m, because 1 km seemed too coarse to reflect the spatial differences in PRC cities, which tend to be more compact than Western cities.

### ***Detailed calculation of each sub-index***

Each component was modified or redefined from Frank et al (2005) and Lovarsi et al (2009) to fit the data reality in PRC cities:

- Net residential density (NRD): measured by the number of household (population) per 0.01 km<sup>2</sup> of residential use, as an indicator of residential density;
- Street connectivity (SC): measured by the number of true intersections (i.e., intersections with three or more legs) per 0.01 km<sup>2</sup> as an indicator of street connectivity; to calculate the street connectivity of a grid cell, a 500 m radius around its center was drawn to tally the number of intersections within it;
- Land-use mix (LUM): an indicator of the mixed level of six land use types of (1) residential, (2) commercial and office, (3) industrial, (4) institutional (e.g., schools, libraries, kindergartens), (5) green/park area, and (6) water and wetland; LUM of a grid cell is calculated with a 500 m radius around its center;
- Transit Stops (TS): measured by number of bus (BS) and subway/light rail stops (SLS) per 0.01 km<sup>2</sup>; the BS or SLS of a grid cell is calculated with a 500 m radius around its center;
- Flatness of Land (FL)/Elevation Difference (ED): measured by the difference between maximum elevation and minimum elevation of the 100m x 100m land area.

These variables are normalized into sub indexes (valuing between 0–1), as following:

$$NRD\ Index\ (NRDI) = NRD / \max(NRD) \quad (1)$$

$$SC\ Index\ (SCI) = SC / \max(SC) \quad (2)$$

$$LUM\ Index\ (LUMI) = LUM / \max(LUM) \quad (3)$$

where

$$Land\ use\ mix\ (LUM) = (-1) \times [ (b1/A)\ln(b1/A) + (b2/A)\ln(b2/A) + (b3/A)\ln(b3/A) + (b4/A)\ln(b4/A) + (b5/A)\ln(b5/A) + (b6/A)\ln(b6/A) ] / \ln(N); \quad (4)$$

where A is the total area of land for all six land uses present in the 500m radius buffer zone. The b1-b6 measure areas of land use for: residential (b1); commercial and office (b2); industrial (b3); institutional (b4); green space (b5); and water and wetland (b6). Here, N = 0 through 6, summing the number of different land uses present.

$$\text{Transit Stop Index (TSI)} = 2/3 \text{ SLSI} + 1/3 \text{ BSI} \quad (5)$$

Here we put more weight on subway/light rail stops due to its relative importance to bus stops in the PRC; or

$$\text{Transit Stop Index (TSI)} = \text{BSI} \quad (6)$$

when subways are absent; here

$$\text{Subway/Light Rail Stop Index (SLSI)} = \text{SLS} / \max(\text{SLS}) \quad (7)$$

$$\text{Bus Stop Index (BSI)} = \text{BS} / \max(\text{BS}) \quad (8)$$

$$\text{Flatness of Land Index (FLI)} = 1 - [\text{ED} / \max(\text{ED})] \quad (9)$$

$$\text{Walkability Index (WI)} = 1/7 \text{ NRDI} + 1/7 \text{ SCI} + 2/7 \text{ LUMI} + 2/7 \text{ TSI} + 1/7 \text{ FLI} \quad (10)$$

In principal we followed previous research and put equal weight on most sub indexes. However, we doubled the weight on LUMI and TSI due to the following reasons. First, land use mix has been found to have the greatest explanatory power of variation in the valid number of minutes of moderate activity per day (Frank et al, 2005). Second, transit stops have been an influential factor as they encourage walking to and from stops (Brown et al, 2009). In PRC cities, most residents heavily rely on public transportation.

As indicated above, raw variables (x) were normalized into unit-free variables (x'), so that their respected values would be between 0 and 1:

$$x' = x / \max(x) \quad (11)$$

where max(x) are the minimum and maximum values of the variable x, respectively (Table 1).

After we developed walkability maps from 2000 and 2010, we passed the results (including the sub-components) to our collaborators in these four cities and sought their feedback on the findings to validate our quantitative analysis of the walkability index. In addition to mapping out the spatial distribution of the walkability index in the four cities, we also conducted an analysis to see how walkability index changes over a distance from the city center. Due to the varying physical conditions and scales of the four cities selected, it is an effective way to understand the spatial variations of walkability.

# Table 1 approximately here #

### **2.3 Study area**

We selected Shanghai, Hangzhou, Chongqing, and Lanzhou as our study cases to evaluate walkability of urban built-up area in 2000 and 2010 (Fig 1; Table 2). These four cities represent two types of cities in the eastern and western regions of the PRC. With large populations, Shanghai and Chongqing are two of the PRC's four direct-controlled municipalities in the eastern and western regions. Hangzhou and Lanzhou represent typical major cities of the eastern and western regions. As the provincial capitals in their respective provinces, they have faced fierce competition from other cities in their respective region. Studies on these four cities provide comparisons not only between different tiers of major cities in the PRC's, but also between different regions. Furthermore, we also focused on inner cities, areas defined by the four respective four municipal governments, and particularly studied walkability of inner city vs. the entire city of Shanghai and Chongqing.

# Figure 1 approximately here #

# Table 2 approximately here #

Shanghai is located at the eastern end of the Yangtze River and halfway along the PRC's eastern coastline. Situated on an alluvial plain with an average elevation of 4 m above sea level, the city proper has a total area of 6340.5 km<sup>2</sup>. Located in the subtropical monsoon climate zone, Shanghai has four distinct seasons with hot, humid summers and cool, wet winters. Shanghai has been the PRC's largest economic center since the early 20<sup>th</sup> century. Despite falling behind other coastal cities' rate of economic development at the beginning of the 1978 economic reform, Shanghai eventually caught up with other coastal cities and resumed its leading economic position in the PRC after the central government established the Pudong New Area in the 1990s. It has the largest population and the highest GDP per capita of all four cities in 2014 (Table 2). The inner city of Shanghai, named as "central Shanghai", is defined as the area inside the Outer Ring Road, which has been used widely in different government documents and studies. With an area of 666.2 km<sup>2</sup>, central Shanghai covers 10.51% of the whole city. The Huangpu River, the tributary of the Yangtze River, has traditionally divided central Shanghai into two parts: (1) Puxi area, west of the Huangpu river; and (2) Pudong area, east of Huangpu river.

Hangzhou is located 180 km southwest of Shanghai. Similar to Shanghai, Hangzhou has a humid subtropical climate with four distinctive seasons. It has a total administrative area of 16596 km<sup>2</sup>, with 3068 km<sup>2</sup> in the city proper. Although its 7.16 million population was much lower than that of Shanghai, its GDP per capita closely followed Shanghai by \$20,941 in 2014. Similar to other large coastal cities in Asia, Hangzhou experienced rapid urban expansion and transformed itself from a medium city to a mega-city. Until the 2000s, the inner city of Hangzhou, called "central Hanzhou", only included the main city area north of the Qiantang River and the land around West Lake, with districts such as Shangcheng District, Xiacheng District, Gongshu District, Xihu District, and Jianggan District. As the city expanded eastward,

the inner city definition also changed; it expanded to include the area south of the Qiantang River. Now, central Hangzhou currently refers to the area located in the Loop Expressway of the city, as defined by the "Hangzhou Urban Development Concept Plan" (2009). It covers about 23.7% of the whole city.

Chongqing is located at the southeast corner of Sichuan Basin and the upper reach of Yangtze River. With a total area of 82,401 km<sup>2</sup>, including the city proper and the counties under its administration, Chongqing is the largest direct-controlled municipality— at 2.39 times the total area of Beijing, Tianjin, and Shanghai. Chongqing has a monsoon-influenced humid subtropical climate and is very humid most of the year. Chongqing's GDP per capita for the municipality was only \$6,883 in 2014 (Table 2). Chongqing is often erroneously described as the largest city in the world because Chongqing is administratively considered a municipality. For instance, the population of the municipality is 33.75 million, which is much higher than any other municipality in the PRC. In this paper, our study area for Chongqing is defined as Chongqing's city proper consists of nine core districts, covering 5472 km<sup>2</sup>, i.e., 6.6% of the area of Chongqing Municipality. In 2014, it had population of 6.43 million. With the surrounding mountains to its north, east, and south, Chongqing is known as the "Mountain City." We also define the inner city of Chongqing, called "central Chongqing", as the area located in the Inner Ring Road of the city proper. Central Chongqing, covering 9.2% of the city proper, is regarded as the old urban core on the Yuzhong Peninsula and the confluence of two rivers.

Lanzhou is located in the upper course of the Yellow River and is bounded by mountains to the south and north. Due to its unique geography, Lanzhou has developed into a "dumb-bell" shape. The distance between the west and the east of the city is about 35 km whereas the distances from the north to the south vary dramatically from 2 km to 8 km, respectively.



Belonging to the middle temperate zone and with the average altitude 1520 m, Lanzhou has a moderate climate with an annual average temperature of 11.2°C without freezing winters or hot summers. Like other cities in northwestern the PRC, Lanzhou is dry with an annual precipitation of 327 mm, which primarily occur June through September. As one of the oldest industrial bases of the PRC, Lanzhou is the largest industrial city in the upper stream of the Yellow River and is an important base of the raw material industry in the PRC's west. It had the smallest population (3.75 million) of the four cities (Table 2) and had a GDP per capita of \$8,690 USD in 2014, which was slightly higher than Chongqing yet significantly lower than Shanghai and Hangzhou. Following the Lanzhou Master Plan, we adopted the definition of the inner city of Lanzhou, i.e., “central Lanzhou”, as the area that is confined by the two basins constrained by the surrounding mountain. Central Lanzhou is widely acknowledged by residents of Lanzhou as well. The area is about 11.5% of the Lanzhou's city proper.

### **3. Results**

#### **3.1 Urban expansion**

All four cities had experienced rapid urban land expansion from 1990 to 2010 (Fig 2). Shanghai had the largest urban built-up area and its urban built-up area in 2010, 2,815 km<sup>2</sup>—far above the other three cities, was more than five times of that of 1990. For both 1990–2000 and 2000–2010, Shanghai added over 1000 km<sup>2</sup> to its urban built-up land. Before 1990, the city had mainly expanded along the axis of northeast-southwest; however since 1990, Shanghai has expanded east and west. From 2000 to 2010, most of the urbanization took place around the existing urban areas, such as the city center and the district centers, and along the northwest–southeast axis, changing the original city's development pattern along the northeast-southwest axis.

# Figure 2 approximately here #

Hangzhou expanded its urban built-up area in its city proper over seven times in 20 years, from 118 km<sup>2</sup> in 1991 to 841 km<sup>2</sup> in 2010, with a much faster rate in the second decade.

Although the newly added urban built-up area is mainly located north of the Qiantang River around the main city area, the area of south of the Qiantang River also experienced fast growth. Hangzhou's urban expansion reveals a close relationship between newly developed lands with the locations of original towns, such as Xiaoshan, south of the Qiantang River, and Linping, northeast of the main city.

The built-up area in Chongqing has experienced rapid growth since 1988, expanding its urban built-up area 4.3 times, from 67 km<sup>2</sup> in 1988 to 296 km<sup>2</sup> in 2010, mainly towards the north and south. In earlier periods, the core urban area was built at the intersection of the internal valleys of the Yangtze and Jialing Rivers and inside the valley floor between Zhongliang Mountain and Tongluo Mountain. However, Chongqing's urban spatial pattern has undergone rapid transformation from concentration to diffusion since 1997, including our study period from 2001 to 2010, and has been dominated by polycentric development and outer area urban growth.

The urbanized area of Lanzhou grew over two times from 1990 to 2010, mostly occurring between the existing urban built-up areas and at the northern bank of the Yellow River. The city experienced fast expansion, particularly in the last decade. Although Lanzhou's expansion has been constrained by its geography, it is worth mentioning that in the recent decade, the city has leapfrogged its surrounding mountains and established new industrial zones as well as residential communities outside the original core.

## **3.2 Walkability**

All cities have increased their walkability index from 2000 to 2010, except Central Shanghai. However, great variations exist among the four cities in terms speed, scale, and locations of changes in walkability (Figs. 3–7). When we only compare the inner cities, Shanghai led in average walkability index whereas Lanzhou held the lowest (Fig. 3a). Not surprisingly, central Shanghai and central Chongqing were much more walkable than the metropolitan areas of Shanghai and Chongqing, respectively. When the whole cities of Shanghai and Chongqing are compared, Shanghai retained a high walkability, whereas Chongqing dropped its walkability value significantly. While central Shanghai and central Hangzhou had decreased or discontinued increases, central Lanzhou and central Chongqing had moderate to large increases in walkability. When distributions of walkability index are compared (Fig. 3b), all central cities and except of Shanghai had increased their portions of areas in ranges of higher walkability values. At the metropolitan level, both Shanghai and Chongqing increased their proportions of areas in the range of higher walkability values (Fig. 3c). Each city demonstrated its own spatial pattern and dynamics of walkability, as entailed below.

# Figures 3-7 approximately here #

### **3.2.1 Shanghai**

Overall, walkability in Shanghai remained high in both 2000 and 2010. In addition to high walkability index in the central Shanghai, the rest of Shanghai also demonstrated high walkability scores in both 2000 and 2010. Shanghai also experienced an increasing trend of walkability index from 2000 to 2010 for most areas (Figures 6 & 7). However, spatial variations

do exist in terms of degrees of change. Here we highlight several issues. First, it is interesting to note that most of central Shanghai had experienced declined walkability. Further examination on subcomponents indicated that decreased population density in central Shanghai contributed significantly to this decrease and street connectivity and land use mix had not changed much.

Second, areas that had very little to small increases in walkability (0–0.15) were mostly the outer suburbs of Shanghai, such as Minghang, Fengxian, Songjiang, Jinshan, Qingpu, Baoshan, Jiading, Changxing Island, Chongming Island, and the old inner-city district Yangpu District. For these areas, there was little change of land use or population density.

Third, the areas that had large increases in walkability index include Pudong New Area, the former Zhabei District of the central city, some areas in Jiading District, located in the northwest corner of Shanghai, and some suburban new growth poles, such as Yangshan Port at the southeast corner of Shanghai.

### ***3.2.2 Hangzhou***

Hangzhou's central city overall was quite walkable in both 2000 and 2010. The old city core had a very high walkability index score but a small increase from 2000 to 2010 in its value because well-developed street networks, public transport, and high-level of mixed land use had not changed much during the study period. Other areas that had low walkability index scores and little increases included two types of areas: first, the scenic areas such as the West Lake, the Xixi Wetland and the Xianghu Wetland; second, the rural area of the West Lake District and the Bingjiang District. Some areas of Hangzhou actually experienced low and decreased walkability, mostly in the urban fringe.

The walkability map of 2010 illustrates that areas around the two sub centers (Binjiang and Xiaoshan) started to distinct themselves with their high WI. From 2000 to 2010, the areas that had the largest increases of walkability included the planned university towns (Zhejiang University Zijingang Campus, Xiasha High Education Zone), the transportation hub (Jiubao), and the new development area (Xiaoshan). With dramatically improved public transportation, these areas had the most land use transformation and had attracted large populations. The trickle-down effect provided the surrounding areas with substantial increases in walkability, including the China Academy of Art Xiangshan campus in Zhuantang, the development of Huajiachi Campus of Zhejiang University and Four Season Green Clothes Whole Sale Market in Jianggan, and the Qiantang New Town in Bingjiang, the new sub center of Hangzhou. Furthermore, the north and eastern parts of the city directly adjacent to the old city core experienced moderate increases in walkability due to substantial urban redevelopment, leading to the improvement of road networks and land use changes.

### ***3.2.3 Chongqing***

The central business district area (Jiefangbei) of Chongqing enjoyed very high walkability despite the undulating terrain issue (Figs. 4–5). Several high walkability spots appeared at the sub centers (Guanyinqiao and Shapingba) inside the inner ring road as a result of polycentric urban form because of the natural limits from the mountains and rivers. In 2010, more areas with high walkability index occurred in the northern and western parts of the city proper (Liangjiang Area, Chongqing University Town and Xiyong MIP).

The increase in walkability index was detected for many areas from 2000 to 2010, with several hot spots appearing (Figs. 6–7). The walkability index increased substantially in

Guanyingqiao and Shapingba. Street connectivity increased the walkability index for the above areas and was a major driver. Another area with significant increases in walkability was located in Banan, south of the Yangtze River (Fig. 6), due to contribution from land use mix and net residential density.

Two areas outside the Inner Ring Road (Fig. 7) had notable increases in walkability. The first area was the newly developed core of Liangjiang New Area, which runs north of the Jialing River, along the highway from Guanyingqiao to the airport and the corridor area; this area increased its walkability due to the increase of land use mix, net residential density, street connectivity, and transit stops. The second area, Chongqing University Town and Xiyong MIP, located in the western of the Inner Ring Road, increased walkability index significantly. In this area, land use mix and net residential density were major drivers to increase walkability.

### ***3.2.4 Lanzhou***

Lanzhou is a rather compact city with high urban population density. Increased land use mix and net residential density appeared to be the major drivers of increasing walkability during the 2000–2010 period. The areas enjoyed high scores of walkability in 2000 and experienced an increase of walkability in 2010 include Chengguan, Qilihe, and Xigu, all along the Yellow River from east to west (Figs. 4 & 6). Street connectivity, i.e., improved road networks for pedestrians boosted walkability of Chengguan. As the second most important area next to Chengguan, Qilihe links major districts of Lanzhou (Chengguan, Anning, and Xigu) and is also the major passenger and freight transportation hub. The increases in land use mix, street connectivity, and net residential density had contributed to its fast increase in walkability. The Xigu area featured a

high increase of walkability in its newly developed public transport hub and in the industrial/residential area.

Other areas that experienced large increases in walkability index scores include Santan, Jiuzhou, and Yantan. Santan had the largest increase in walkability index due to the increases in land use mix, street connectivity, and transit stops, whereas Jiuzhou had experienced a significant rise in walkability index due to the high increases in land use mix, net residential density, and transit stops. Yantan had increased walkability due to effects of public transportation access caused by the dramatic increases of bus stops.

## **4. Discussion**

### **4.1 Variations in urban expansion**

Although all four cities had experienced rapid urban expansion, there existed great variations in terms of spatial and temporal scales. We plotted the four cities' urban built-up land vs. population (Fig. 8a) to quantify the speed of urban land expansion vs. total population growth. Four major issues were discovered and are highlighted here.

# Figure 8 approximately here#

First, it is clear that urbanization has become more intensive in the last decade, as both urban land expansion and population increased more in 2000–2010 than in 1990–2000, except for Chongqing's population growth. In this case, Chongqing's city proper dramatically increased in total population in 1990–2000 probably due to the increased immigration triggered by its change of administrative status in 1997, changing it from a sub-provincial city in the Sichuan Province to one of the four direct-controlled municipalities in the PRC. Nevertheless, Chongqing

followed others and expanded its urban built-up area at a much faster speed in the 2000s than in the 1990s.

Second, coastal cities of Shanghai and Hangzhou had experienced larger scales of urban land expansion than the inland cities of Chongqing and Lanzhou. For instance, the urban built-up land for Chongqing was only 60% of that of Hangzhou, even though Chongqing's population (6.12 million) was slightly smaller than that of Hangzhou (6.8 million) in 2010. Third, while the total population density increased from 2000 to 2010 for all cities, the urban population density actually decreased for all cities except Hangzhou (Figure 8b).

Fourth, although Shanghai and Hangzhou had been considered highly dense urban areas, Chongqing and Lanzhou were actually ahead of Hangzhou in terms of urban population density for both 2000 and 2010. Lanzhou particularly possessed a higher urban population density than Shanghai for both 2000 and 2010. This indicated that the typographic and geographic constraints for urban land expansion remain extremely important for mountainous cities, such as Chongqing and Lanzhou.

#### **4.2 Walkability and distance to the center**

How has the distance to city center played a role in affecting the walkability index of a place in PRC cities? Our analysis on walkability vs. distance from the city center offered interesting insights (Fig. 9). First, these four cities generally followed the trend of decline in walkability as distance to the center increased but exhibited different patterns. For instance, while Hangzhou declined its walkability sharply as the distance increased, especially when distance to the city center increased from 5 km to 10 km, Lanzhou declined very little.



When comparing the four cities, except their very central parts, Shanghai lead in walkability in almost all areas regardless their distances to city centers; next were Hangzhou, Chongqing, and Lanzhou, in that order. It is also interesting to note that even the outer suburb area of Shanghai (up to 65 km distance from the center) exhibited a higher walkability than anywhere in Lanzhou and in most areas of Chongqing, where areas are more than 20 km away from the center.

Further, all cities had generally improved their walkability from 2000 to 2010, except within the areas that are 5–15 km distance to the city center in Shanghai, which declined in walkability, and the areas that are 5–10 km distance to the city center of Hangzhou, which had no change in walkability. These interesting differences can be attributed to the decreasing population density of the very central part of Shanghai.

Our analysis indicates that although a polycentric pattern has been in progress for all cities—as described in our last section and other literature (e.g., Yue et al, 2010)—city centers remain the most walkable places, as they are the civic, economic, cultural, and entertainment centers of their respective cities. For policy makers, improving walkability in sub centers shall be put in priority as walkability is to attract both residents and visitors, thus growing the sub center.

#Figure 9 approximately here#

### **4.3 Impacts of planning and policy**

Although the PRC had gradually embraced the market-based economy, our study indicates that planning and governmental policies still had significant impacts on both urban expansion and walkability. The fast rate of urban expansion and the changing walkability of all four cities in

2000–2010 appeared directly related to the governmental policies at both central and local levels. For Shanghai, the most distinguished urban development appeared in the Pudong New Area—a central government initiative facilitate Shanghai’s economic development. For Hangzhou, the central government induced large-scale urban development by the land market reform (Liu et al, 2015). Furthermore, the West Development Program for the PRC’s western region, where Chongqing and Lanzhou are located, has been instrumental in Chongqing and Lanzhou’s rapid development since 2000. In particular, the promotion of Chongqing from a provincial level city to a direct-controlled municipality in 1997 further accelerated both its population and urban expansion since 1997. The overall increase in walkability of the cities, particularly in sub centers and suburb areas, can be closely associated with the establishment of sub centers, economic/industrial development zones, and university campus towns by local governments, which have stimulated urban expansion and infrastructure development in the four cities’ suburb areas (Fan et al, 2014; Yue et al, 2014; Liu et al, 2015). For instance, in Chongqing, several sub centers achieved great strikes for walkability during 2000–2010 when they developed their corresponding sub center functions. While Guanyingqiao became a high-end commercial core and residential neighborhood, Shapingba concentrated their first-class high schools and universities and top-rank hospitals. Banan, once a remote area, now enjoys the benefits of a new metro line and a new commercial center Wanda Plaza. Central Shanghai, the only city that experienced a decrease in WI, can attribute its decline to its local government’s policy, which controlled the central city’s high population density by converting several inner city neighborhoods into urban parks. In the following paragraphs, we will illustrate how planning and policies or the lack of affects walkability in different areas of each city.

For the areas of Shanghai that had large increases of walkability, the impact of policy and planning were obvious. The Pudong New Area had experienced large increases in walkability, especially within the Outer Ring Road. The former Zhabei District increased its walkability significantly due to the redevelopment of the Shanghai Railway Station and the improvement of public transportation, such as subways and buses. The Jiading District had rapid industrial development that led to the rapid increase of population, thus leading to a large increase of walkability. New suburban growth, such as Yangshan Port, had been developed quickly due to the port facilities as well as improved public transportation facilities.

In contrast, the experience of Hangzhou indicated that policies or the lack of planning/policy could have adverse impact on walkability. For instance, some of Hangzhou's urban fringe had low and decreased walkability. It contained all types of functions such as wholesale markets, industrial districts, old residential buildings, economic housing, new types of housing, village settlement, and agricultural fields intermingled together. These areas grew without strong policy guidance and they lacked good infrastructure and amenities such as urban green spaces— thus unattractive to residents. Likewise, rural areas of the West Lake District and the Bingjiang district kept their low values in walkability due to the lack of government's planning, resulting in unchanged low street connectivity (e.g., less dense road network) and low access to the public transport. In contrast, scenic areas of West Lake, Xixi Wetland, and Xianghu Wetland also had low and unchanged walkability scores, due to the persistent preservation policy of scenic areas and elevation differences.

For Chongqing, the appearance of high walkability index in the northern and western parts of the city proper in 2010 were primarily due to the fact that the urbanized area expanded rapidly and leapfrogged outside the Inner Ring Road in the last decade, simulated by government

strategies to develop the Liangjiang New Area (similar to Shanghai's Pudong New Area) in the north and to develop the University Town and Micro-electronics Industry Park (MIP) in the west. First, the corridor area in Liangjiang New Area had been provided by high-profile urban facilities, such as Expo Center, Outlet Mall and Central Park. This area concentrated a large amount of well-organized neighborhoods, including golf courses, villas and townhouses. Second, Chongqing University Town and Xiyong MIP had been developed since the mid-2000s as a newly planned sub-center in Chongqing. It accommodates about 160 enterprises and 14 universities and colleges, such as HP, Foxconn, IBM and Chongqing University. The close proximity to University Town enabled Xiyong MIP to hire plenty of highly skilled employees. However, this sub-center featured wide roads, low-density buildings and monotype uses of land, a sharp contrast to that of the congested urban core.

In Lanzhou, the impact of planning and government policies can be observed in all of its core areas and newly arising areas. Unlike Shanghai or Hangzhou, the city core area (Chenguan) experienced an increase of walkability because the city further improved its infrastructure within the old city core. This area had witnessed high-end residential condominium neighborhoods and financial and commercial clusters, which lead to the continuous expansion of the city core and diverse land use. For another core area, Qilihe, enhanced public transportation contributed to the increase of the core area's walkability. Lanzhou West Rail Station finished its construction in 2014 and the Subway No. 1 will be completed in 2016. This area will continue to improve its road network and dramatic transformation of land use. For Xigu Area, Xigu New Town, another major government development initiative, is where the main population of the district congregates with government buildings and educational, health, and commercial facilities clustering together. The area witnessed a new, large-scale residential development area with the

most mixed land use and the best street network in Lanzhou. In addition to these core areas, rising areas such as Santan, Jiuzhou, and Yantan, benefited from the improved public transportation access. Santan is what the government planned for future central business district. Under the planning and development incentives provided by the government, large shopping malls, high priced condominiums, the major road of Rt. 188, and integrated management of Datan South River all contributed to land transformation and the improvement of street networks. Jiuzhou, the earliest new development zone started by the Lanzhou government in 1988, became the ideal location for high-tech industries, as it was complemented with residential, recreational, and other facilities. In recent years, the area attracted a high population and had experienced significant land transformation; now it continues to improve transportation infrastructure. Finally, Yantan is a typical urban fringe area that reflected the urbanizing process of PRC cities (i.e., large amount of agricultural land converted to urban built-up areas) under governmental planning.

#### **4.4 Policy implications & limitations**

The major contribution of this paper lies in its methodology and its finding's policy implications. First, the walkability index method can have wide applications due to its comprehensiveness, simplicity, and flexibility. It is comprehensive as it includes not only the traditional elements of net residential density, street connectivity, and land-use mix, but also the necessary elements "access to public transportation" and "elevation differences", which have been marginally mentioned or totally ignored in previous literature. The index is also simple and flexible, as it drops the retail floor area ratio, which is usually very difficult data to obtain. Our scale is also larger than other studies and uses a 100 m grid cell rather than 1 km grid cell, which provides more detailed information and a greater insight for policy makers and planners.

Second, the case studies of these four cities directly map out walkability both spatially and in different time periods. Areas that need further improvement can be identified easily and provided reasons for what is decreasing or limiting walkability. The walkability index developed in this study can significantly improve our understanding of urbanization and how the effectiveness of planning guides future urban policies in the PRC. In particular, it helps the policy makers identify the areas with low walkability and make corresponding land management planning decisions to achieve urban sustainability.

Needless to say, the study has its own limitations. For instance, the composite index incorporated only five dimensions and did not other important aspects of walkability, such as pedestrian infrastructure, safety, and amenity (Southworth, 2005), due to lack of appropriate data and difficulty in quantifying the measurements. However, we consider it necessary for a neighborhood-scale study to incorporate more indicators when resources and data are available to reveal how pedestrian's behavior can be affected by these variables.

## **5. Conclusions**

Walkability has been increasingly emphasized as an important element of urban sustainability. We constructed a comprehensive walkability index that incorporates five components: net residential density, street connectivity, land-use mix, transit stops, and flatness. Relying on satellite imagery, we first evaluated urban land expansion to provide a background for our walkability study. We then conducted our walkability analysis on four rapidly urbanizing cities in the PRC: Shanghai, Hangzhou, Chongqing, and Lanzhou.

We found that all cities had experienced rapid urban land expansion from 1990 to 2010. Moreover, urbanization had become more intensive in the last decade, as both urban land

expansion and population increased more in 2000–2010 than in 1990–2000, except for Chongqing's population growth. All cities had increased their walkability index from 2000 to 2010, except for central Shanghai. However, great variations existed between the four cities, as the inner cities of Shanghai and Hangzhou experienced decreases or little increase in walkability while the inner cities of Lanzhou and Chongqing enjoyed moderate to large increases of walkability. For inner cities, Shanghai held the highest average WI, whereas Lanzhou held the lowest. Finally, the walkability index method developed in this paper can be widely adopted due to its comprehensiveness, simplicity, and flexibility. Our results on walkability can also improve the effectiveness of planning, as policy makers can strategically target the areas low in walkability index with a better understanding of what causes to consider.

## **Acknowledgements**

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## Tables

Table 1. Walkability index component

<i>Sub Index</i>	<i>Measurement</i>	<i>Minimum Value</i>	<i>Maximum Value</i>	<i>Formula</i>
<b>NRDI</b>	Based on value of net residential density (NRD)	0	the maximum value of NRD of all grid cells of all cities of all periods	NRD/max (NRD)
<b>SCI</b>	Based on value of street connectivity (SC)	0	the maximum value of SC of all grid cells of all cities of all periods	SC/max (SC)
<b>LUMI</b>	Based on the value of LUM	0	the maximum value of LUM of all grid cells of all cities of all periods	LUM/max (LUM)
<b>BSI</b>	Based on the value of bus stop	0	the maximum value of BS of all grid cells of all cities of all periods	BS/max (BS)
<b>SLSI</b>	Based on the value of subway/light rail stop	0	the maximum value of SLS of all grid cells of all cities of all periods	SLS/max (SLS)
<b>FAI</b>	Based on the value of elevation difference (ED)	0	the maximum value of ED of all grid cells of all cities of all periods	1-ED/max(ED)

Table 2. Profile of Shanghai, Hangzhou, Chongqing, and Lanzhou, 2014.

	<b>Location</b>	<b>GDP per Capita (USD)</b>	<b>Population (in million)</b>
<b>Shanghai</b>	31°12'N 121°30'E	26674	14.39
<b>Hangzhou</b>	30°15'N 120°10'E	20941	7.16
<b>Chongqing</b>	29°33'N 106°34'E	6883	6.43
<b>Lanzhou</b>	36°02'N 103°48'E	8690	3.75

## Figure Captions

Figure 1. Study area: Shanghai, Hangzhou, Chongqing, and Lanzhou

Figure 2. Urban expansion in Shanghai, Hangzhou, Chongqing, and Lanzhou

Figure 3a. Walkability index of Shanghai (SH), Central Shanghai (CSH), Central Hangzhou (CHZ), Chongqing (CQ), Central Chongqing (CCQ), and Lanzhou (LZ) for years 2000 and 2010.

Figure 3b. Walkability index distribution of central cities of Shanghai (SH), Hangzhou (HZ), Chongqing (CQ), and Lanzhou (LZ) (%), where 2000 is indicated by “00” and 2010 is indicated by “10” after the city’s name.

Figure 3c. Walkability index distribution of Shanghai’s (SH) city proper and Chongqing (CQ)’s city proper (%) in 2000 and 2010.

Figure 4. Spatial distribution of walkability in the central cities of Shanghai, Hangzhou, Chongqing, and Lanzhou, in 2000 and 2010.

Figure 5. Spatial distribution of walkability in Shanghai and Chongqing, 2000 and 2010.

Figure 6. Difference of walkability in the central cities of Shanghai, Hangzhou, Chongqing, and Lanzhou, in both 2000 to 2010.

Figure 7. Difference of walkability in Shanghai and Chongqing, 2000 to 2010.

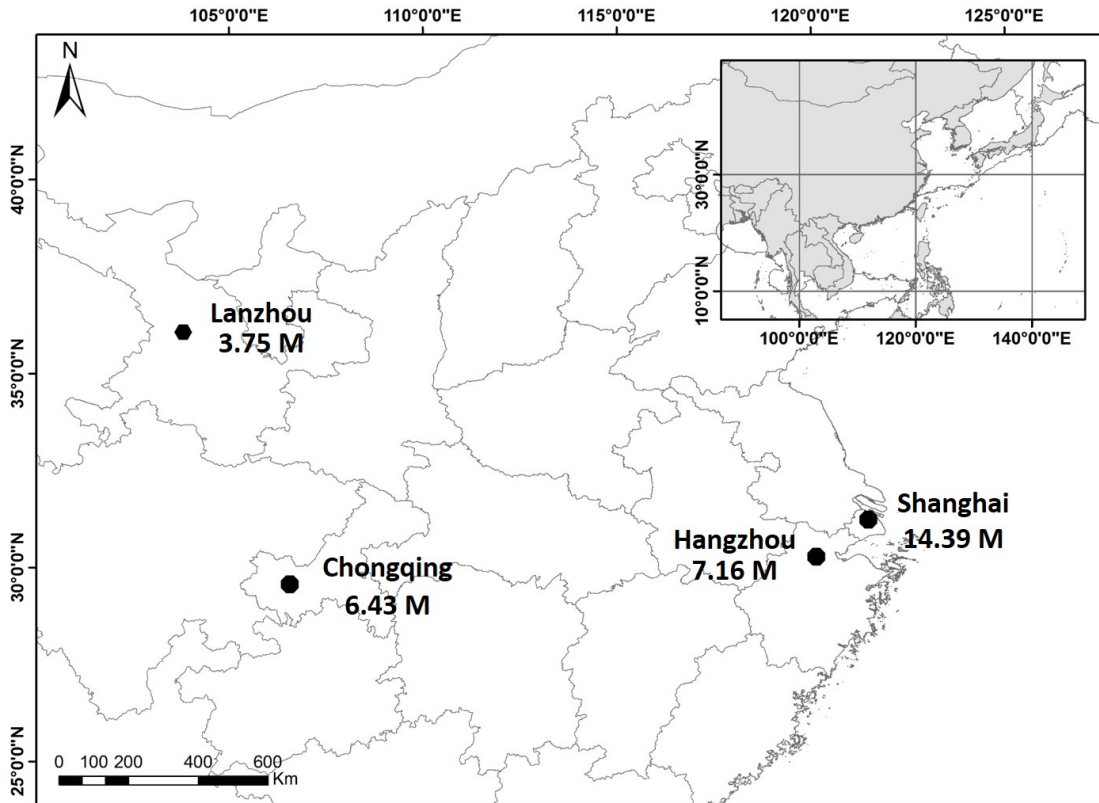
Figure 8a. Urban built up land (X axis, in km<sup>2</sup>) vs. total population (Y axis, in 10,000 people) in 1990, 2000, and 2010.

Figure 8b. Urban population density in 2000 and 2010 (people/ km<sup>2</sup>)

Figure 9. Change of walkability regarding buffer distance (radius) from the city center.

## Figures

Figure 1. Study area: Shanghai, Hangzhou, Chongqing, and Lanzhou



Note: The year 2014's population data from *China Statistical Yearbook* (NBS, 2015).

Figure 2. Urban expansion in Shanghai, Hangzhou, Chongqing, and Lanzhou

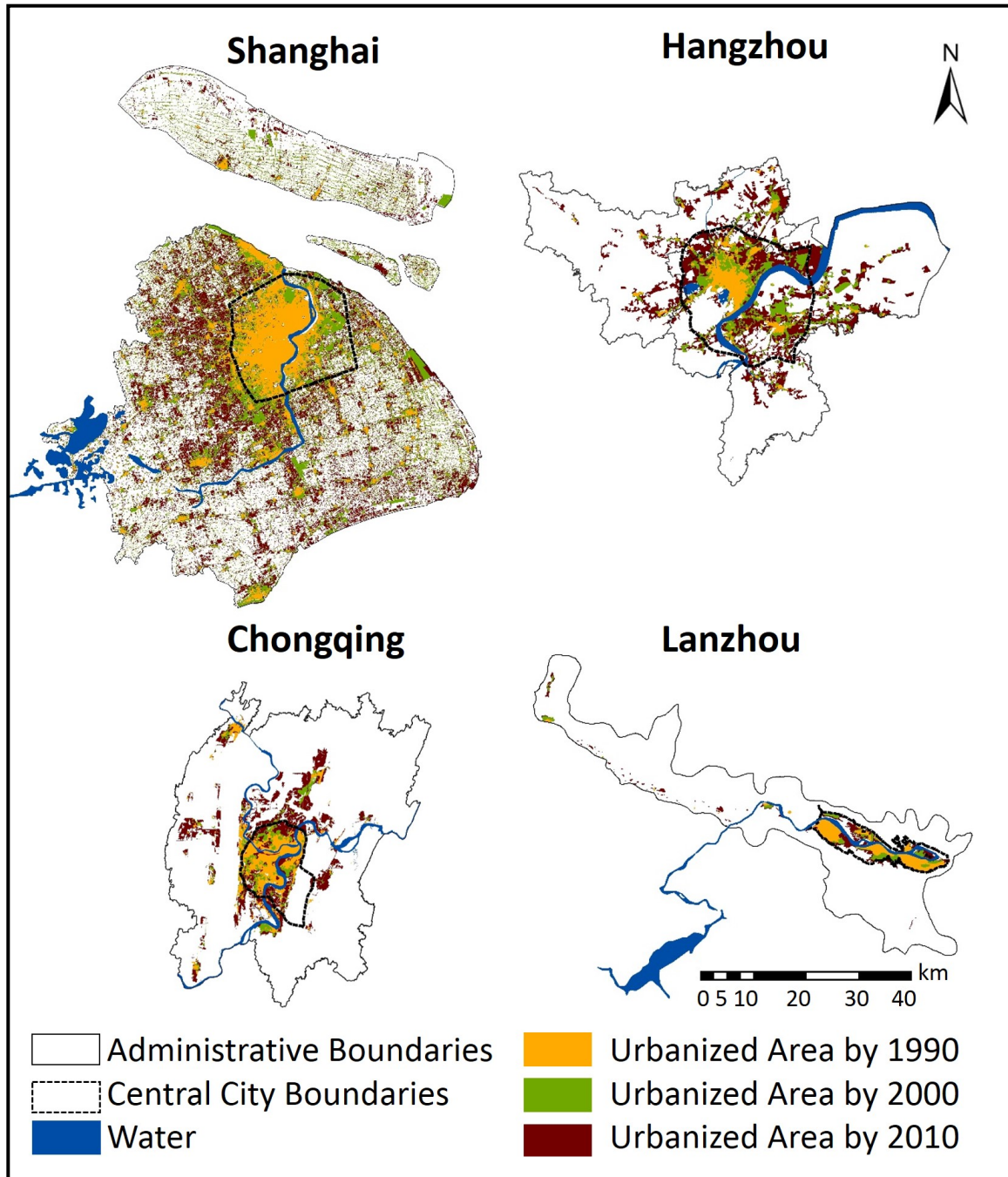


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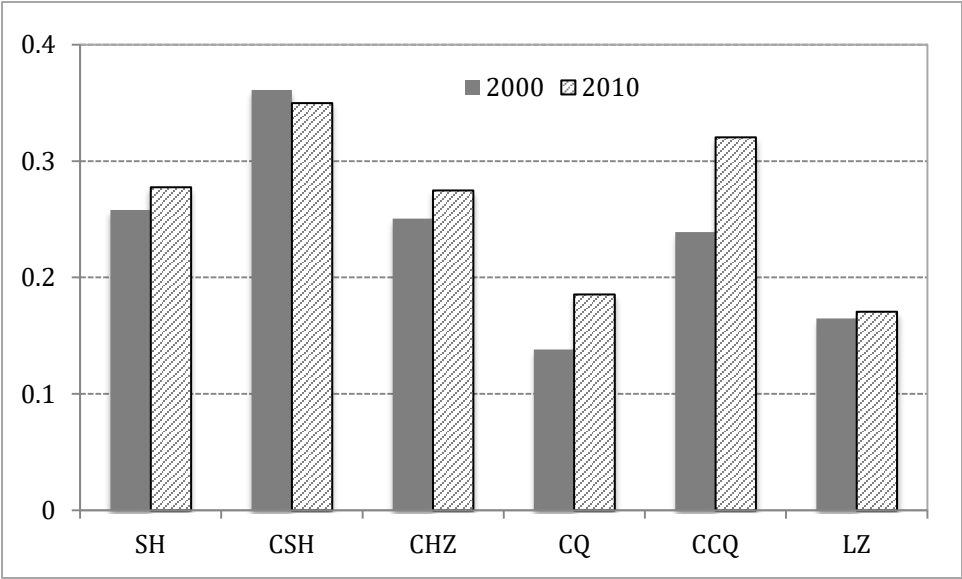


Figure 3b. Walkability index distribution of central cities of Shanghai (SH), Hangzhou (HZ), Chongqing (CQ), and Lanzhou (LZ) (%), where 2000 is indicated by “00” and 2010 is indicated by “10” after the city’s name.

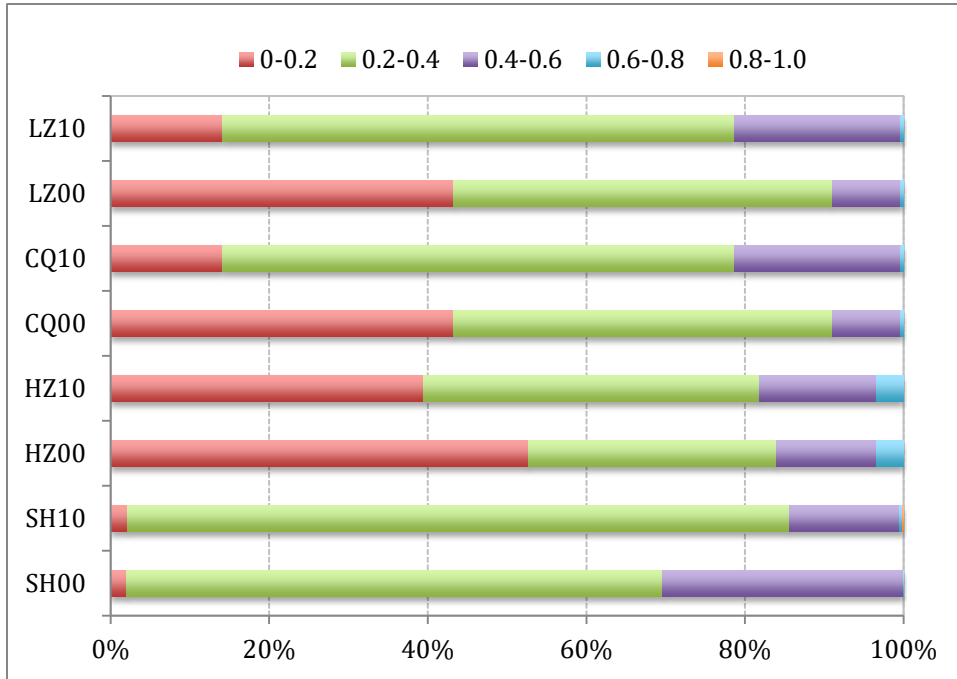


Figure 3c. Walkability index distribution of Shanghai’s (SH) city proper and Chongqing (CQ)’s city proper (%) in 2000 and 2010.

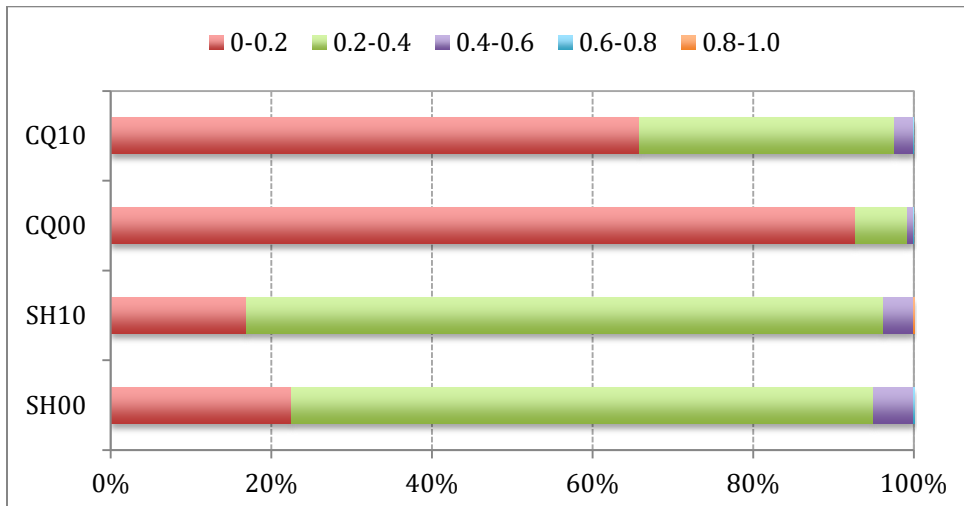


Figure 4. Spatial distribution of walkability in the central cities of Shanghai, Hangzhou, Chongqing, and Lanzhou, in 2000 and 2010.

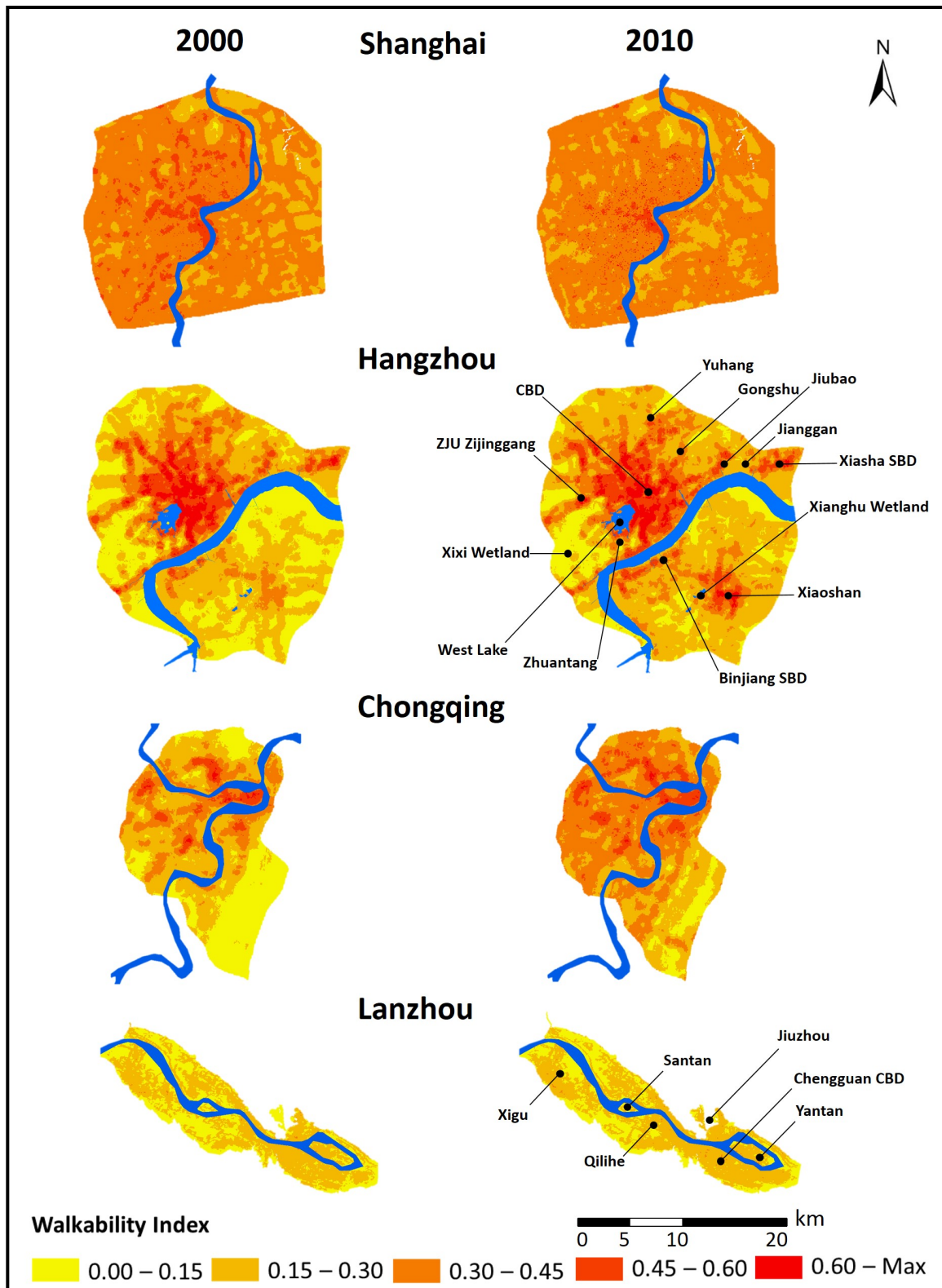




Figure 5. Spatial distribution of walkability in Shanghai and Chongqing, 2000 and 2010.

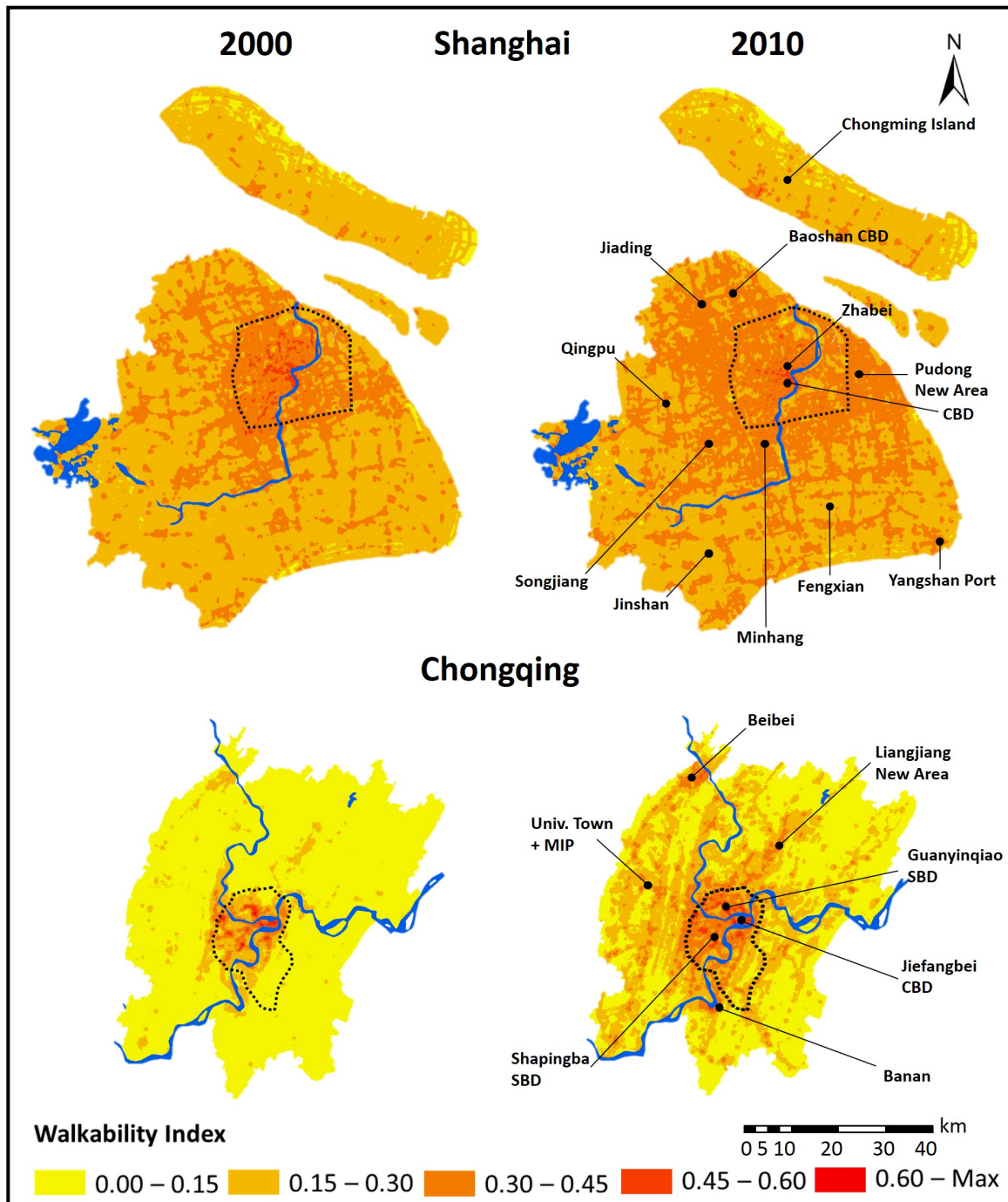


Figure 6. Difference of walkability in the central cities of Shanghai, Hangzhou, Chongqing, and Lanzhou, in both 2000 to 2010.

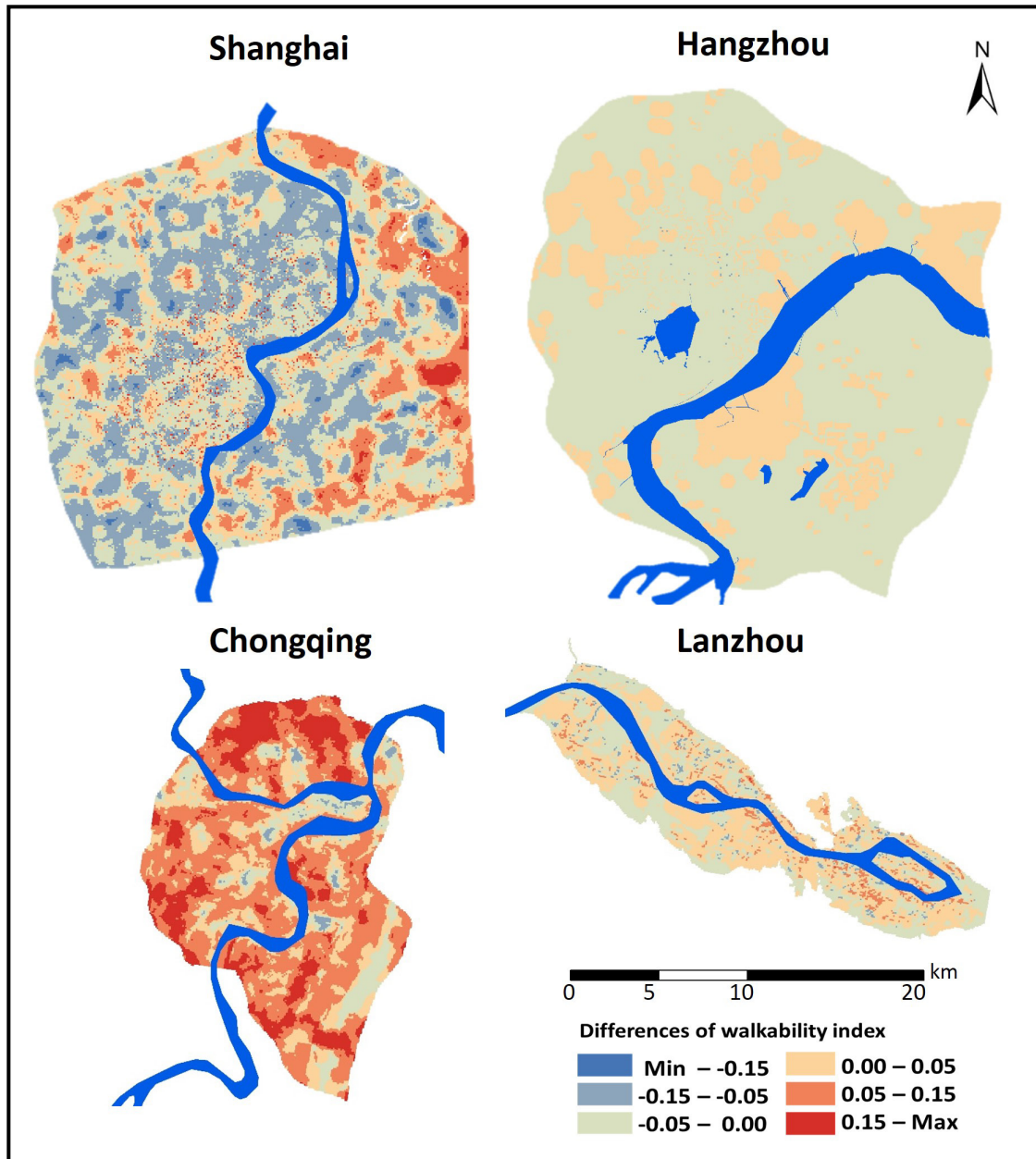


Figure 7. Difference of walkability in Shanghai and Chongqing, 2000 to 2010.

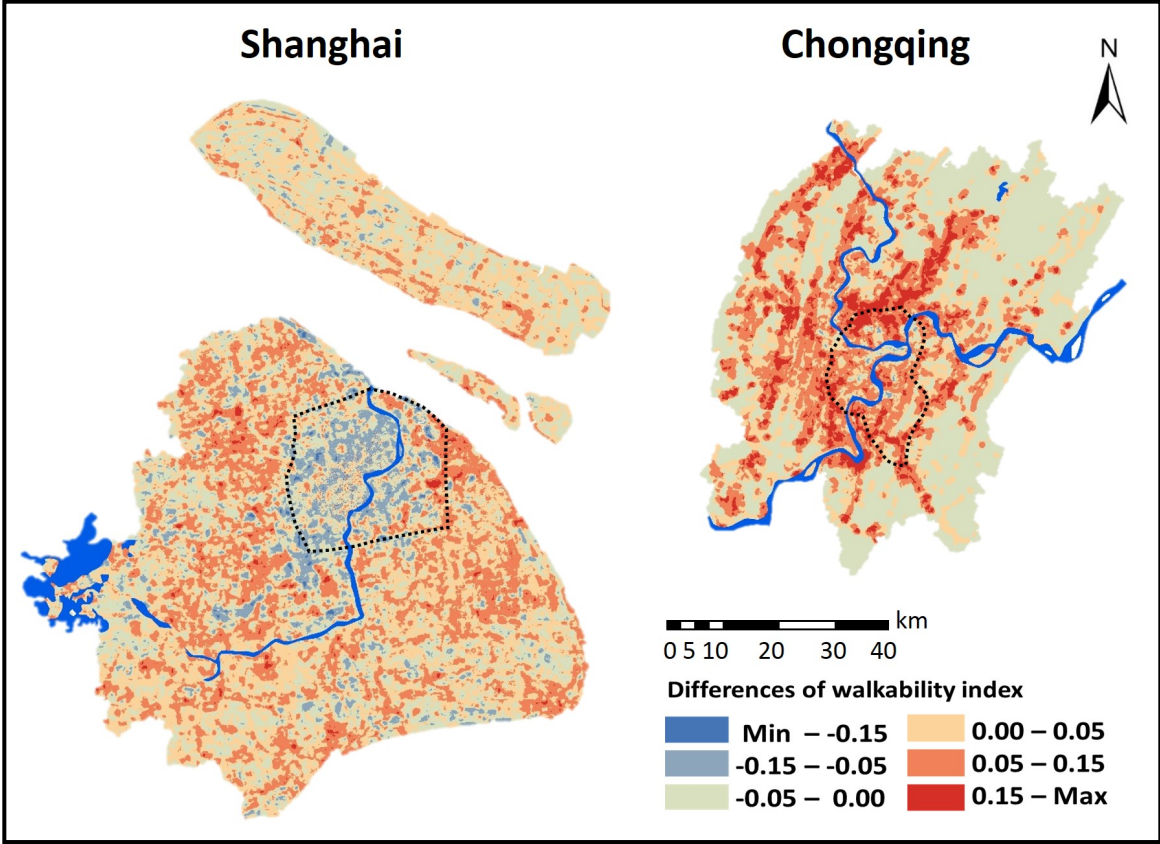


Figure 8a. Urban built up land (X axis, in km<sup>2</sup>) vs. total population (Y axis, in 10,000 people) in 1990, 2000, and 2010.

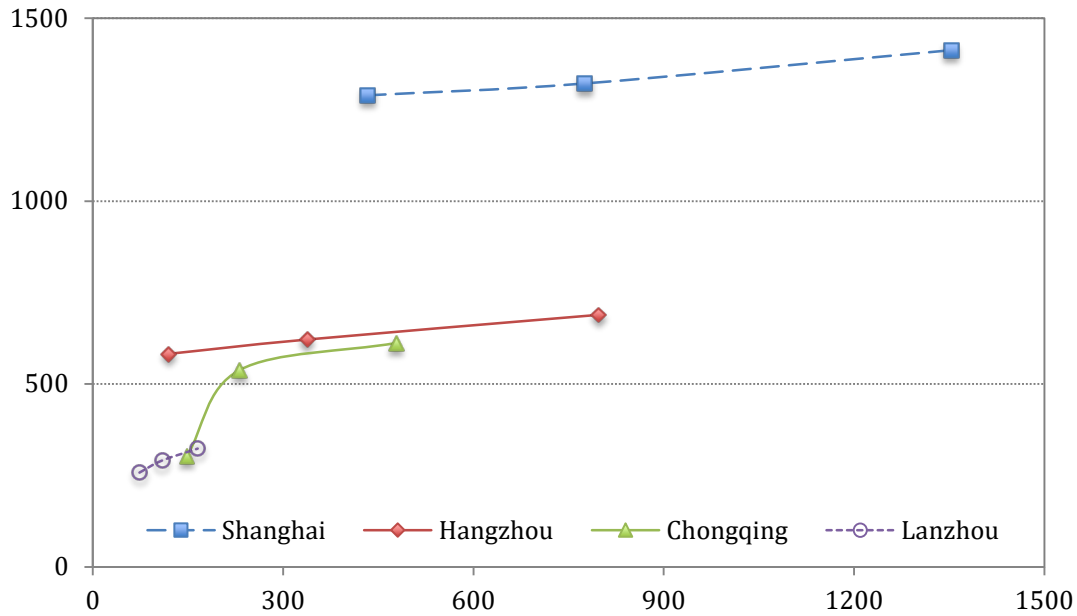
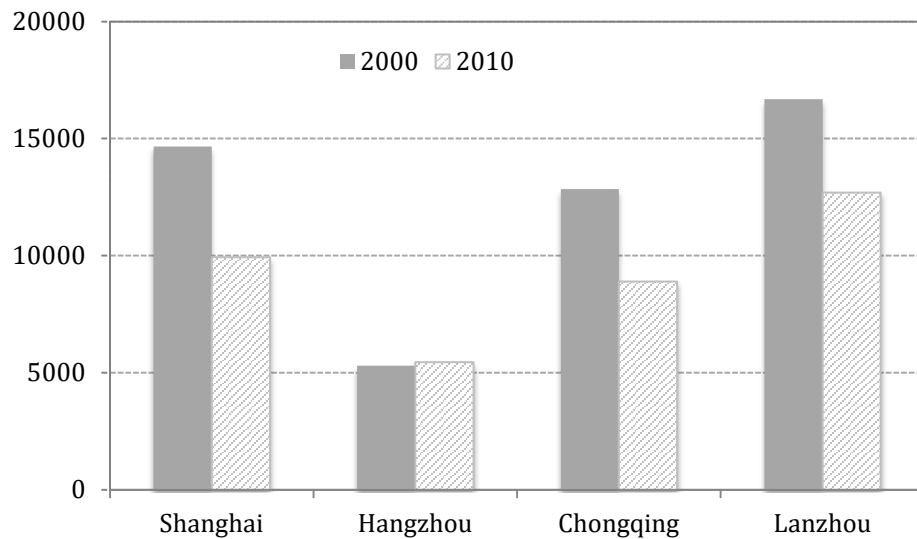
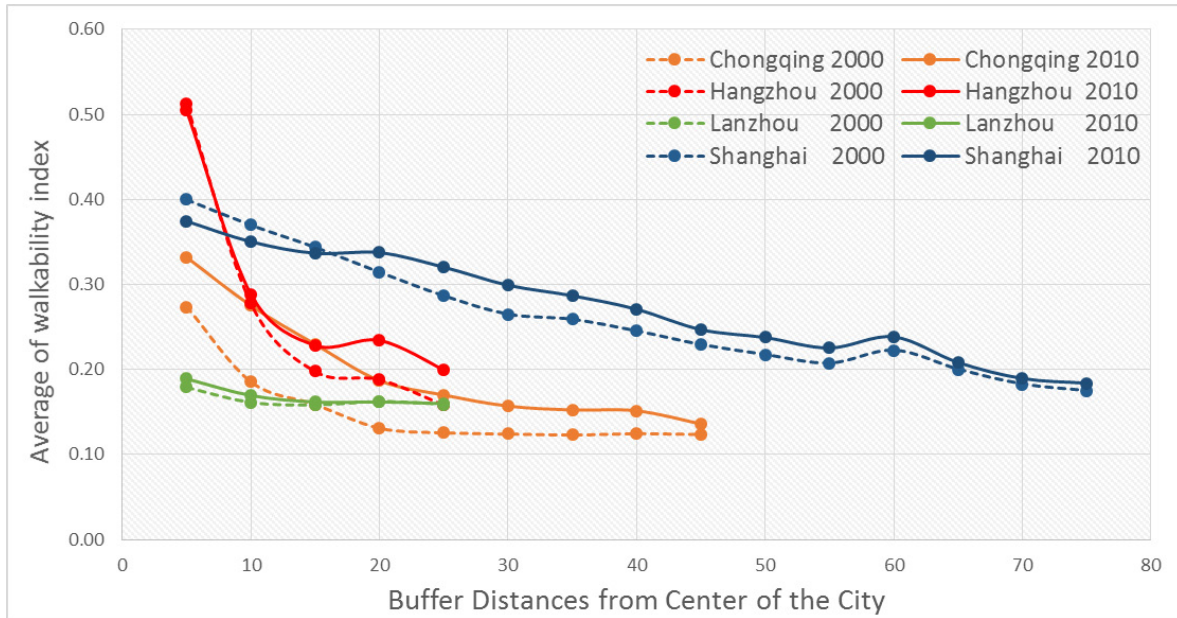


Figure 8b. Urban population density in 2000 and 2010 (people/ km<sup>2</sup>)



Sourced data: Urban built-up land was processed by the authors; total population and urban population of each city are from China's City Statistical Yearbook for various years (1993–1994, 2001, 2011). We used 1992's data for 1990's population, as 1990's data was unavailable. Urban population density was defined as urban population divided by urban built-up land.

Figure 9. Change of walkability regarding buffer distance (radius) from the city center.



Note: We measured the average value of walkability in each of the 5 km buffer zones from the center of the four cities, respectively, in 2000 and 2010.

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