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Cities and epidemics: Reflection based on spatio-temporal spread and medical carrying capacity of early COVID-19 outbreak in China

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Abstract

New and more dreadful viruses may emerge again in the future and cause a large demand for medical care. It is essential to explore different cities' early spatio-temporal spread characteristics of the COVID-19 epidemic and the medical carrying capacity. This study examined the situation of six high-incidence Chinese cities using an integrated manual text and spatial analysis approach. Results show that the initial COVID-19 outbreak went through three phases: unknown-origin incubation, Wuhan-related outbreak, and local exposure outbreak. Cities with massive confirmed cases exhibited the multicore pattern, while those with fewer cases exhibited the single-core pattern. The cores were hierarchically located in the central built-up areas of cities' economic, political, or transportation centers, and the radii of the cores shrank as the central built-up area's level decreased, showing the hierarchical decay and the core-edge structure. That is, a decentralized built environment (non-clustered economies and populations) is less likely to create a large-scale epidemic cluster. Besides, the clusters of excellent hospital resources were consistent with those of COVID-19 outbreaks, but their carrying capacity still needs urgent improvement. And the essence of prevention and control is the governance of human activities and the management, allocation, and efficient use of limited resources about people, places, and materials leveraging IT and GIS, to confront the contradiction between supply and demand.

Highlights

- The epidemic cores were hierarchically located in the central built-up areas of cities' economic, political, or transportation centers.
- The radii of the epidemic cores shrank as the central built-up area's level decreased, and showed the hierarchical decay and the core-edge structure.
- A decentralized built environment (non-clustered economies and populations) is less likely to create a large-scale epidemic cluster.
- The essence of prevention and control is the governance of human activities and the management, allocation, and efficient use of limited resources about people, places, and materials leveraging IT and GIS.

1 Introduction

The coronavirus disease 2019 (COVID-19) is an infectious disease caused by a new strain of the coronavirus family, the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [1] which is in the same family as SARS-CoV-1 that caused the severe acute respiratory syndrome (SARS) pandemic in 2003 [2]. Up to August 26, 2022, more than 596 million confirmed cases of COVID-19 were reported to the World Health Organization (WHO) globally. As of October 2022, the COVID-19 pandemic is still raging in many countries due to the highly contagious variants Delta and Omicron [3–4]. This pandemic has severely disrupted people's normal lives and wreaked havoc on the global economy, rendering

suppression and reduction have become the dominant theme in fields like medicine, health, public administration, and city planning.

In retrospect, there have emerged lethal viruses (like cholera, typhus, smallpox, measles, tuberculosis, leprosy, and malaria) and grave epidemics such as the Black Death (1331–1353), the Great Plague of London (1665–1666), the San Francisco plague (1900–1904), and the Spanish flu (1918–1920). In the last 20 years, the SARS (2002), Middle East respiratory syndrome (MERS) 2014, influenza A (H1N1) (2009), Ebola (2014), and Zika (2016) have mainly attacked Africa, Asia, Europe, and Arabia [5]. All viruses and plagues above first appeared and gathered in cities, and 95% of the COVID-19 pandemic cases are in cities [6], as Alirol et al.[7] said that large cities have become infectious disease centers. Yet, today 55% of the world's population lives in urban areas, and this proportion is expected to increase to 68% by 2050 [8], and in the future, novel dreadful viruses and infectious diseases may re-emerge. Hence, cities may face public health crises, economic downturns, political tensions, and multiple social problems because of inadequate pandemic control.

Analyzing spatiotemporal patterns of diseases has become an increasingly common task in epidemiology, public health, and geography in recent decades [9]. The main goal of analyzing the spatiotemporal patterns of a disease is to identify disease clusters, interpret the spatial patterns of the clusters, and predict the risk of disease transmission [10]. Besides, timely and accurate spatial and temporal disease surveillance is essential to detect outbreaks and identify areas at high risk of transmission [11]. Because the risk of transmission of infectious diseases varies over time and space, monitoring the spatial and temporal trends in disease occurrence can highlight dynamic patterns of risk and help slow the spread of disease.

Hence, understanding the spatial and temporal spread characteristics of COVID-19 in the early stage and the medical carrying capacity at the time is of great significance for the prevention and control of future novel pandemics and the construction of resilient cities. Since China was the first country to report and respond to the COVID-19 outbreak, this paper selected six high-pandemic prevalence Chinese cities to compare the spread of the outbreak to find commonalities. And, given the enormous pressure on public health systems at the peak of the epidemic and the general disparity in their ability to respond to surges in demand [12], this paper also explores the cities medical carrying capacity, as it is an important aspect of a city's ability to fight the epidemic. And finally, the article makes short discussions about city planning, building design, medical service, and epidemic control.

2 Data And Methods

2.1 Study areas

Yueyang, Xinyang, Hefei, Wenzhou, Shenzhen, and Chongqing were selected as the study areas. Each of them has a different location, economic, and cultural characteristics. The first three are located in the south, north, and northeast of Wuhan (Fig. 1), respectively, within the two-hour high-speed rail range.

While the latter three are more than four hours and are located in the Yangtze River Delta city cluster, the Pearl River Delta city cluster, and the upper middle Yangtze River, respectively. There are both coastal and inland cities, and the city levels cover prefecture-level cities, municipalities directly under the central government, provincial capitals, and special economic zones, with wide differences in city area and economic levels. Besides, these cities all had relatively severe outbreaks and thus were suitable for this research.

2.2 Data collection

This study obtained pandemic data from six cities' Health and Wellness Committee websites, the WeChat public accounts, and other official media through Python. As of 0:00 on February 15, 2020, Beijing time – the outbreak had been controlled and was in the lasting period [13], total of 2029 confirmed cases were extracted, including information such as sex, age, address, date of earliest clinical symptoms, date of the first visit, date of diagnosis, designated treatment hospital, activity pathway, and relationship with other confirmed patients. Shenzhen's demographic travel characteristics were collected manually from the "Baidu Migration" big data visualization platform. Vector administrative boundaries data were obtained from the National Geomatics Center of China.

2.3 Methods

Based on the human, event, and spatial-temporal dimensions, this study employed a combination of manual textual analysis, spatial-temporal analysis, and mathematical and statistical methods, using Excel 2019, and ArcGIS 10.6.

2.3.1 Manual text analysis

Text analysis is to select feature items of text and quantify them to represent text information. Age, sex, activity trajectory, and other information were manually extracted from case texts to create a data basis for further analysis.

2.3.2 Spatial overlay analysis

Spatial overlay analysis overlays layers of two or more geographical objects in the same area to produce multiple attribute features of the spatial region. In this study, the spatial distribution of the pandemic and the spatial distribution of sentinel hospitals were overlaid to explore the characteristics of their spatial pattern.

2.3.3 Kernel density estimation (KDE)

Kernel density estimation (KDE) is a measurable event density at any location in a certain area estimated by the number of event points within the unit area surrounding the location. The study used the KDE method to estimate the agglomeration degree of the confirmed cases at a certain location to reveal the pandemic's concentration. The KDE calculation formula is:

$$f\ x\ = \frac{1}{nh_n}\sum_{i=1}^{n} k\left(\frac{x-x_i}{h_n}\right)$$

1

where n is the total number of confirmed cases, h_n is the bandwidth, namely the search radius, and $k\left(\frac{x-x_i}{h_n}\right)$ is the kernel function.

2.3.4 Medical carrying capacity

According to the infrastructure capacity index formula [14] and the standard of “Guideline for Setting Up Medical Institutions (2016–2020)” (Chinese National Health and Family Planning Commission 2016), this study constructed the medical carrying capacity index (MCCI), with the number of permanent residents as the object of carrying and the total number of beds in medical and health institutions as the medium of carrying. By replacing the number of permanent residents with the cumulative total number of confirmed patients in MCCI, and exchanging the numerator and denominator – considering the realistic meaning and comprehensibility, the formula of COVID-19 MCCI is constructed. The calculation formulas are as follows:

$$MCCI = \sum_{i=1}^{n} CCM_i/CCO_i \times 1000$$

5

$$\text{COVID19 } MCCI = \sum_{i=1}^{n} CCA_i/CCM_i$$

6

Where n is the total number of districts or counties under the jurisdiction of case cities; CCM_i are the i th district or county medical institution’s total beds; CCO_i is the resident population of the ith district or county; CCA_i is the total cumulative diagnoses in the ith district and county.

3 Results

3.1 Demographic characteristics

3.1.1. Age and sex structure

The diagnosed patients were divided into nine age groups at ten-year intervals. Figure 2 shows that excluding Shenzhen, diagnosed patients in case cities were predominantly male, with sex ratios above 100 and age concentration between 30 to 59 years. Among them, the highest sex ratio (139.22) was

found in Xinyang city, with male confirmed cases concentrated between 20 and 49 years old. The manual text analysis showed that these young and middle-aged diagnosed men are mostly migrant workers in Wuhan, indicating that Xinyang had closer social ties with Wuhan. While Shenzhen (its population sex ratio in 2019 was 101.1) had the lowest sex ratio of confirmed cases (89.04), with a concentration of confirmed females between 30 and 39 and 60 and 69 years.

3.1.2. *Infection groups clustering*

Patients infected with COVID-19 were classified into four categories according to their activity range: “Local exposure,” “Wuhan-related” (had been to or through Wuhan), “Out-of-town experiences” (had been out of the city but had no link with Wuhan), and “Not available” (no activity information). Excluding Shenzhen, selected cities all showed a similar infection structure – predominantly the “Local exposure” (Fig. 3a).

Shenzhen was dominated by “Wuhan-related” and “Out-of-town experiences” (mostly to Hubei). The majority of its confirmed cases were middle-aged and elderly residents of Wuhan who travel to Shenzhen to visit their relatives. This different structure was caused by Shenzhen’s characteristics of demography (dominated by outsiders) and China’s social culture (going home for New Year’s Eve dinner or reuniting with family during the Spring Festival).

However, many “Wuhan-related” and “Out-of-town experiences” confirmed patients did not result in large-scale local transmission. This is related to Shenzhen’s rich experience in prevention and control accumulated since SARS and its special demographic characteristics (Fig. 3b). In 2020, Shenzhen’s out-migration population size index rose sharply from January 16 while its intra-city travel intensity began to decline. Both them dropped to the lowest at the beginning of the Lunar New Year. The impact of the pandemic prevention policy caused its in-migration population size index and intra-city travel intensity index to not increase significantly after the Chinese New Year holiday. These factors blocked the large-scale local spread of the outbreak [13].

Hence, the fact that COVID-19 caused large-scale local transmission in other selected cities but not in Shenzhen suggests that the spread of the pandemic is related to population mobility [15–17] and cities’ social, economic, and cultural contexts [18].

3.2 Spatio-temporal characteristics of the COVID-19 pandemic

3.2.1 Temporal evolution process

For the districts and counties of selected cities, the earlier the date of clinical symptoms, the more severe the outbreak (the deeper the color of the districts or counties in Fig. 4), accompanied by more cases of

“Local exposure.” This implies that early detection of asymptomatic infected patients and contact tracing can play a key role in outbreak prevention and control [19].

In terms of the daily series of confirmed COVID-19 cases in selected cities (Fig. 5), the number of “Wuhan-related” confirmed cases (blue columns) peaked at the end of January, followed by the number of “Local exposure” cases (orange columns) at the beginning of February. Although lockdown measures started in Wuhan on January 23, 2020, the incubation period of SARS-CoV-2 and the outflow of Wuhan’s population prior to the travel restrictions led the selected cities to continue to experience the Wuhan-related outbreak and triggered the local exposure outbreak. Thus, the initial spread of COVID-19 in these cities underwent three stages of evolution from an unknown-origin incubation period to a Wuhan-related outbreak, and then to a local exposure outbreak. Besides, the fact that the confirmed dates of “Local exposure” were generally later than that of “Wuhan-related” support the ideas that SARS-CoV-2 has an incubation period and requires attention to identify asymptomatic infected patients [20].

The cumulative number of confirmed patients (blue lines) started to rise in late January 2020, but stopped increasing and maintained a stable trend in mid-February due to case cities’ implementation of intra-city travel restrictions. This corroborates that travel restrictions can mitigate the spread of the outbreak [21–22]. Yet, human beings have a natural tendency to move freely and cannot tolerate "home confinement." Therefore, the key to pandemic control lies in the rational planning and management of human behavior while striving to meet the basic needs of human beings.

3.2.2 Spatial distribution patterns

According to Figs. 5, 6, & 7, cities with massive confirmed cases usually showed the multicore pattern, while those with fewer cases exhibited the single-core pattern. Specifically, Yueyang and Hefei had relatively low confirmed cases and both showed the single-core pattern. In contrast, the other cities had a high number of confirmed cases showing the multicore pattern. Among them, Xinyang is under the jurisdiction of Henan Province, but has a stronger social connection with Wuhan (the capital city of Hubei Province) due to its geographical proximity, resulting in numerous confirmed cases and a multicore pattern. Wenzhou (Wuhan is known as the “second hometown” of Wenzhou businessmen) and Shenzhen (China's first special economic zone with a leading economy and unique urban charm) are distant from Wuhan but have close socio or economic ties with the city, resulting in a higher number of confirmed cases and multicore structural features.

In addition, we find that the pandemic’s clusters are not located in any parks, which is consistent with [23], but are typically located in the central built-up areas of a region where economic, political, or transportation centers are located, such as Yueyanglou District of Yueyang (Fig. 6a), the Luoshan county (a crucial transportation hub in Xinyang) (Fig. 6b), Shenzhen Nanshan and Futian Districts (Fig. 7b), and the main urban area of Wanzhou District of Chongqing (Fig. 7c). Particularly, the junction of two or more administrative areas with a superior natural and social location usually attracts all sorts of things and people together thus forming one serious pandemic core, such as the junction of Shihe and Pingqiao Districts (Fig. 6b), the main urban areas in both Hefei (Fig. 6c) and Wenzhou (Fig. 7a).

Furthermore, we observe that within each selected city, the pandemic diminished as the central built-up area's level decreased, which can be illustrated by the different sizes and color shades of the KDE kernels (Figs. 6b & 7). For example, in Xinyang, the most severe outbreak area was at the junction of Pingqiao District (the station of municipal government) and Shihe District (the commercial and financial center), which had the largest and darkest KDE core. The sub-serious pandemic area was the built-up area of Luoshan County (the county is an important transit hub for Xinyang's external links). The less severe pandemic areas were the built-up areas of other counties, such as Huangchuan County and Guangshan County, which have lower political or economic levels with smaller radii and lighter colors of KDE cores.

Besides, the highest KDE values were usually located in the areas with the highest number of confirmed cases in the urban administrative units. While Wenzhou is an exception: its highest KDE was found in the main urban area, but its highest number of confirmed cases was in its county-level city – Yueqing, with three smaller, dispersed outbreak cores (Fig. 4d & Fig. 7a). This is because Yueqing has a wider jurisdictional area and a more dispersed built-up area than the main urban area, which made its pandemic distribution less concentrated than that of the main urban area. This suggests that decentralized built environments have a lower risk of large outbreaks compared to concentrated built environments of political and economic centers.

3.3 Deployment and carrying capacity of designated medical institutions

3.3.1 Spatial deployment

The spatial distribution of the outbreaks and designated hospitals' overlay analysis (Figs. 6 & 7) indicates that areas with the highest KDE values had a correspondingly high number of designated hospitals, while, the areas with low values had only one.

Except in Shenzhen, the spatial arrangements of designated hospitals in selected cities showed a pattern of "local concentration, overall balance" – more designated hospitals in the main city while fewer in the county (most were only the "County People's Hospital" – usually the best). Apart from a few cases transferred to higher-level hospitals, all the confirmed patients were sent to local designated hospitals.

Shenzhen was a little special. It had 49 designated medical institutions [24], but its confirmed cases were all admitted to the No. 3 People's Hospital (Fig. 7b). This is due to the hospital's more advanced equipment and specialized knowledge in the treatment and management of infectious diseases, as well as the city's extensive experience in controlling infectious diseases accumulated after SARS and the relatively small administrative area (Table 1).

3.3.2 Medical carrying capacity

According to the Guiding Principles for Medical Institution Setting Planning (2016–2020) (Chinese National Health and Family Planning Commission 2016), the number of beds in medical and health institutions must reach the standard of six per 1,000 permanent residents in 2020. However, less than

half of the six cities meet this standard (Table 1), indicating that the carrying capacity of their medical institutions is insufficient. Although they were not overloaded during the outbreak (COVID-19 MCCIs are low), this does not mean that they could withstand a more severe epidemic. China's population will continue to be concentrated in urban areas with urbanization, especially in three major urban agglomerations southeast of the Hu Line [25]. How to flexibly match the concentrated urban population with the shortage of medical and health resources to have cities with the resilience to deal with public health emergencies was discussed in the following section.

Table 1
Medical carrying capacity in study areas

City name	City size (km^2)	Number of medical and sanitary beds in 2018 (10,000 beds)	MCCI (a bed per 1,000 people)	COVID-19 MCCI (a patient per bed)
Yueyang	15019.2	3.366	5.831	0.005
Xinyang	18925.0	3.636	5.625	0.007
Hefei	11445.1	5.220	6.374	0.003
Wenzhou	12110.0	4.236	4.556	0.012
Shenzhen	1997.5	5.132	3.819	0.008
Chongqing	82402.0	23.190	7.422	0.002

4 Discussion

4.1 Spatial distribution characteristics of the epidemic

First, our findings show that in the initial stage the outbreak concentrations were typically located in the centrally built-up areas in a region's economic, political, or transportation centers. These central built-up areas usually gather more city functions with well-developed built environments and excellent service, and thus cause a great population congregation, a high population density, and a high degree of human mobility, eventually becoming the harder-hit areas of the COVID-19 epidemic [26–28]. In other words, early in the outbreak, COVID-19 outcomes were typically highest in areas with high population densities, and this pattern was evident [29].

Second, the results indicated that within a city (macroscopically), as the level of the central built-up area of a region declines, the severity of the regional epidemic had been reduced. Besides, microscopically the farther a neighborhood is from the central built-up areas, the fewer cases it recorded [30]. These findings show that the spread of the pandemic in the early stages without intervention was not limited by

administrative boundaries and distances, but by the structure and the social, economic, and cultural context of a city [18], which was reflected in the activities of the people involved.

To be more specific, structurally, towns in a city always tend to exhibit core-periphery characteristics [31–32], and the cores are often a city's economic, political, or transportation centers macroscopically or the central built-up areas microscopically. The higher the level of administrative functions and the more prosperous the economy of a region, the stronger the attraction of the core, the closer the social and economic ties with other regions, the more active and concentrated the population, the more serious the epidemics were [28]. On the contrary, the epidemics were generally lower in periphery or suburban areas [33] because the density of the built environment is poor and the economy is not prosperous resulting in lower density, clustering, and mobility of people. The above analysis of the Wenzhou epidemic (3.2.2) also confirmed this point.

In terms of the social, economic, and cultural context, the mobility and connectivity also affect the spread of outbreaks, and their impacts may be greater than population density [34], which could be confirmed from the previous analysis (3.1.2) that Shenzhen's unique foreign population structure and Spring Festival population outflow hinder the local spread of the epidemic. Hence, epidemics can be controlled by regulating social and economic elements [35].

In summary, the spread of the epidemic presents a hierarchical decay and a core-periphery structure, and a decentralized built environment is less likely to create a large-scale epidemic cluster. The COVID-19 pandemic, which has dealt a heavy blow to the world's society and economy and has yet to subside, has led urbanists to rethink urban and architectural design [5, 36]. Is the current agglomerated urban form with high-rise buildings livable? How can cities coordinate the contradiction among the combined effect of economic development, epidemic prevention and control, and human well-being during the epidemic?

4.2 Future city planning and building design

During the lockdown period, the implementation of various social distancing measures by governments like closure of business service facilities and sports and recreational facilities, stay-at-home orders, and travel restrictions, caused the decrease of outdoor physical activity of urban residents [37], the shrinkage of social life in public places, and the decline of physical and mental health level in many populations and countries [38–39], and the increase of the frequency of tele-activities like teleconferencing, telework, telehealth, online learning, virtual meetings with friends and family, online live concerts, virtual weddings [40]. After the lockdown ends, people expressed an urgent need for social interaction in social spaces [41] and a strong desire to be close to nature in green spaces [42].

These phenomena caused by the COVID-19 epidemic indicate the necessity of transforming urban development patterns in the post-pandemic era. There might be some changes in the future urban social and living space. As the demand for green and outdoor activities surged during the pandemic period, small pocket parks and gardens had been created and parking lots been turned into parklets in cities like

San Francisco, Birmingham [43]. And walking path and safe cycling along London's arteries and streets were created, and, more than 150 km of streets were announced to open for creating safe social recreation spaces in New York. Similar examples could be multiplied in Rome, Mexico, and other cities [44]. These temporary coping strategies revealed the disadvantages of current prevailing agglomerated urban form with high-rise buildings which is companied with high-density populations, high outbreak risk, limited green outdoor activity spaces and small indoor living space causing high pressure of epidemic control.

The city planning and building design should try to match the Sustainable Development Goals like sustainable cities and communities and good health and well-being and consider more about people's welfare like reducing the density of high-rise buildings, expanding outdoor activity spaces, and increasing green spaces than agglomeration economic effects. And many studies have already recommended that urban land use should be more evenly distributed and not concentrated in specific areas [45].

Both cities and villages have their own magnets, but obviously the superior social living conditions in cities have a stronger magnetic force, thus attracting 55% of the global population to live [8]. People want a better life, and they flock to cities because they think cities have better employment opportunities, higher wages, more social opportunities, and places of entertainment, etc.; city dwellers, however, yearn for the natural beauty, fresh air of the countryside [46]. Therefore, breaking the urban-rural dual structure, that is following the concept of Howard’s Garden City that combining the advantages of urban and rural areas to create a new settlement form [47], is the best solution to increase the resilience of communities, response to epidemics, and realize the good health and human well-being.

Besides, in the post-epidemic era, with the persistence of tele-activities, commuting may be no longer the main theme of urban residents, while spacious living space and green space may become the main needs of urban residents. And the offline physical spaces such as enterprise office space, sales space and traffic space might be reduced to some extent, while the minimum family living space would be increased to adapt to the production of home office, home garden [48], personal balcony and other living space. Such changes can save time spent commuting to work, reduce energy consumption, increase daily leisure time, and provide nature contact just in home, thus being functional and appealing even when there is no epidemic [49].

4.3 Urban medical carrying capacity

The carrying capacity of the six selected cities’ medical institutions was not overloaded during the epidemic, but that does not mean they could withstand a more severe outbreak. In fact, the COVID-19 pandemic posed great challenges to healthcare systems in many cities worldwide. During the severe outbreak in Wuhan, China, there were more than ten Fangcang shelter hospitals opened by converting exhibition centers and stadiums to address and cater for confirmed patients [50], and similar large ‘tent’ venues also had been erected in other countries. In Melbourne, Australia, a pre-fabricated semi-containerized two-story COVID-19 hospital in a car park was erected [51]. In London, United Kingdom, a

500 bed Nightingale Hospital with the capacity increased to treat approximately 4000 patients was created within the Excel Exhibition Center in the Docklands [52]. And India transformed spaces like train carriages to serve COVID-19 patients [53]. These instances all illustrate that medical facilities and their human resources are overwhelmed during the outbreaks [54]. Resources are limited, and the key is to think of ways to make full use of them.

Urban medical services during an epidemic are essentially the management, allocation, and efficient use of resources about people, places, and materials to confront the contradiction between supply and demand [55–56]. Above built fabric restructuring is an excellent example about the use of the static 'place' resource. As people and materials are movable, their management and distribution will be better with the support of big data, cloud computing, geographic information system (GIS), artificial intelligence (AI), and other technologies. Hence, there is need to construct a medical resource platform based on the dynamic database of medical personnel and supplies containing the professional background, skill level, career stage (in-service, internship, or school student), workplace, and home address of all (potential) doctors and nurses, as well as information on the name, production date, shelf life, storage location and quantity of medical products in storage and on the resource utilization and consumption in a region. Then, based on hospitals' real-time carrying capacity and resource consumption, the medical staff scheduling contingency plan and the backup medical supplies circulation replenishment plan can be automatically calculated and developed. Besides, maximizing the service life of medical equipment and the shelf life of medical products and developing a reusable, ultra-light, and intelligent mask is important for achieving materials' large-scale long-term storage and avoiding waste of resources and environmental pollution [57].

Furthermore, with the development of the technologies above and the establishment of digital health systems [58], medical and therapeutic activities have become more flexible and location-independent. The telehealth service is a prime example that is expected to increase strongly and permanently [59–62]. Given this, it is essential to disseminate basic medical knowledge and develop nursing skills (which better be included in compulsory public courses in universities) to better accommodate the remote diagnosis and treatment and home care wards [63] to address the shortage of medical staff and hospitals during a pandemic [64].

4.4 Implications for prevention and control

An overview of the above, the spread of the COVID-19 epidemic at the early stage showed hierarchical and core-edge structural characteristics within cities, which is closely related to human activities. And the urban medical services during epidemics are essentially the contradiction between supply and demand among people, places, and materials. Therefore, the prevention and control of epidemics are ultimately the planning and management of human activities and limited resources, which must focus on human nature, respect for humanitarian principles, and be people-centered and inclusivity [65] and must be aided by information technologies (IT) like big data, the internet of things, and intelligent monitoring and control. "People" with different social, economic and cultural backgrounds and autonomous initiative are the most difficult to manage, and all activities are related to people, including the management and

allocation of various limited resources. Thus, the construction of a regional integrated emergency management GIS [66] are crucial for the precise prevention and decision support [67], which forms a part of the smart city construction that has been confirmed to be conducive to pandemic control [13].

The regional integrated emergency management GIS should at least include a dynamic medical case geo-information database, a wisdom trip platform, and a medical resource platform (4.3).

Medical cases with spatial attributes especially the earliest confirmed cases could offer valuable information on high potential risk areas, hence they are extremely important for timely controlling the source of infection, interrupting transmission routes, and warning of new pandemics. So, it is necessary to construct a dynamic geo-information database of medical cases. And the database should be based not only on diagnosis and treatment data, but also on crowdsourced data. Because the crowdsourcing data, such as Chinese Ding Xiang Yuan, can provide geotagged high-frequency data and alternative information, improve the resolution of disease spatial-temporal analysis, and increase public health awareness through public engagement process [68–69].

And the wisdom trip platform should be constructed based on the dynamic geo-information database of medical cases above to ensure normal outdoor activities while reducing direct contact between people, as person-to-person contact are the major mode of SARS-CoV-2 transmission [70]. Before the nationwide lockdown in mid-March in Italy, spending time outdoors was allowed. Because of no deployment and no intervention, gardens and parks then became public gathering places, increasing the potential contagion risk and resulting in the close of gardens and parks and more strict outing restrictions [71]. Hence, the wisdom trip platform is indispensable. On the platform, all outdoor places available for people's activities in the high-risk areas should be mapped first (including unused driveways and parking lots in the control areas). Then, combined with the temporal geography method, the maximum number of safe trips in each region should be designed, and the number of trips be categorized and dynamically counted by each household, daily and hourly, to reasonably plan, arrange, and adjust the activity places and ranges, activity periods and frequencies of all people with outdoor activity needs. By this way, maximum efforts are made to meet the basic demands of people's outdoor activities in high-risk areas during the epidemic, and to regulate and promote their physical and mental health levels, to achieve efficient control of people's activities ultimately.

In addition, the epidemic spreads hierarchically and exhibits a core-fringe structure, and the built environment varies greatly among different social, economic, and cultural backgrounds. And different groups have different activity characteristics. Therefore, different detailed policies should be developed according to the specific conditions of the time and place. The concept like science first, hierarchical planning, situational awareness, people-oriented, individualized treatment, and eco-friendly should be used throughout the prevention and control process to maximumly meet people's needs, win their trust, and ultimately gain their support to fight the epidemic together.

5 Conclusion

The objective of this study is to explore the temporal spatial spread and medical carrying capacity in the early stage of the COVID-19 pandemic to make some reflection, to better respond to possible novel outbreaks in the future. Results show that in six selected cities the initial COVID-19 outbreak went through three phases: unknown-origin incubation, Wuhan-related outbreak, and local exposure outbreak. Cities with massive confirmed cases exhibited the multicore pattern, while those with fewer cases exhibited the single-core pattern. These cores were hierarchically located in the central built-up areas of cities' economic, political, or transportation centers, and the radii of the cores shrank as the central built-up area's level decreased, showing the hierarchical decay and the core-edge structure. That is, a decentralized built environment (non-clustered economies and populations) is less likely to create a large-scale epidemic cluster. Besides, the clusters of excellent hospital resources were consistent with those of COVID-19 outbreaks, but their carrying capacity still needs urgent improvement. And the essence of prevention and control is the governance of human activities and the management, allocation, and efficient use of limited resources about people, places, and materials leveraging IT and GIS, to confront the contradiction between supply and demand.

Our work has some shortcomings. For example, the number of selected cities is small, which may have an unconvincing influence though the results of the analysis is consistent with that of other scholars. Anyhow, it has revealed some commonalities among cities at the beginning of the pandemic, which could extend to other cities and the future novel pandemic prevention. Besides, the calculation of MCCIs is imprecise. And the formula of COVID-19 MCCI does not take into account the number of patients other than COVID-19 and thus cut down the COVID-19 MCCI value, forming a relatively optimistic impression of the situation.

Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Data availability

The data used in this study are from the network, like six cities' Health and Wellness Committee websites, the official WeChat public accounts, and other official media (some example links to these web pages are provided below). The datasets used during the current study are available from the corresponding author on reasonable request.

http://wsjkw.xinyang.gov.cn/a/news/tongzhi/2020/0215/4831.html

http://wjw.wenzhou.gov.cn/art/2020/2/15/art_1209919_41919646.html

http://wjw.sz.gov.cn/yqxx/content/post_8410036.html

http://wsjkw.cq.gov.cn/ztzl_242/qlzhxxgzbdfyyqfkgz/yqtb/202002/t20200215_6478480.html

http://www.rongchang.gov.cn/zwxx/rcdt/202003/t20200327_6286762.html

https://opendata.sz.gov.cn/data/dataSet/toDataDetails/29200_01503676

https://mp.weixin.qq.com/s/mzlioQyWlUN9-kB46MO2sA

https://mp.weixin.qq.com/s/6yRXdeZFXzwdq2mjqsDuwQ

Ethics declarations

No human or animal experiments were involved in this study.

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Figures

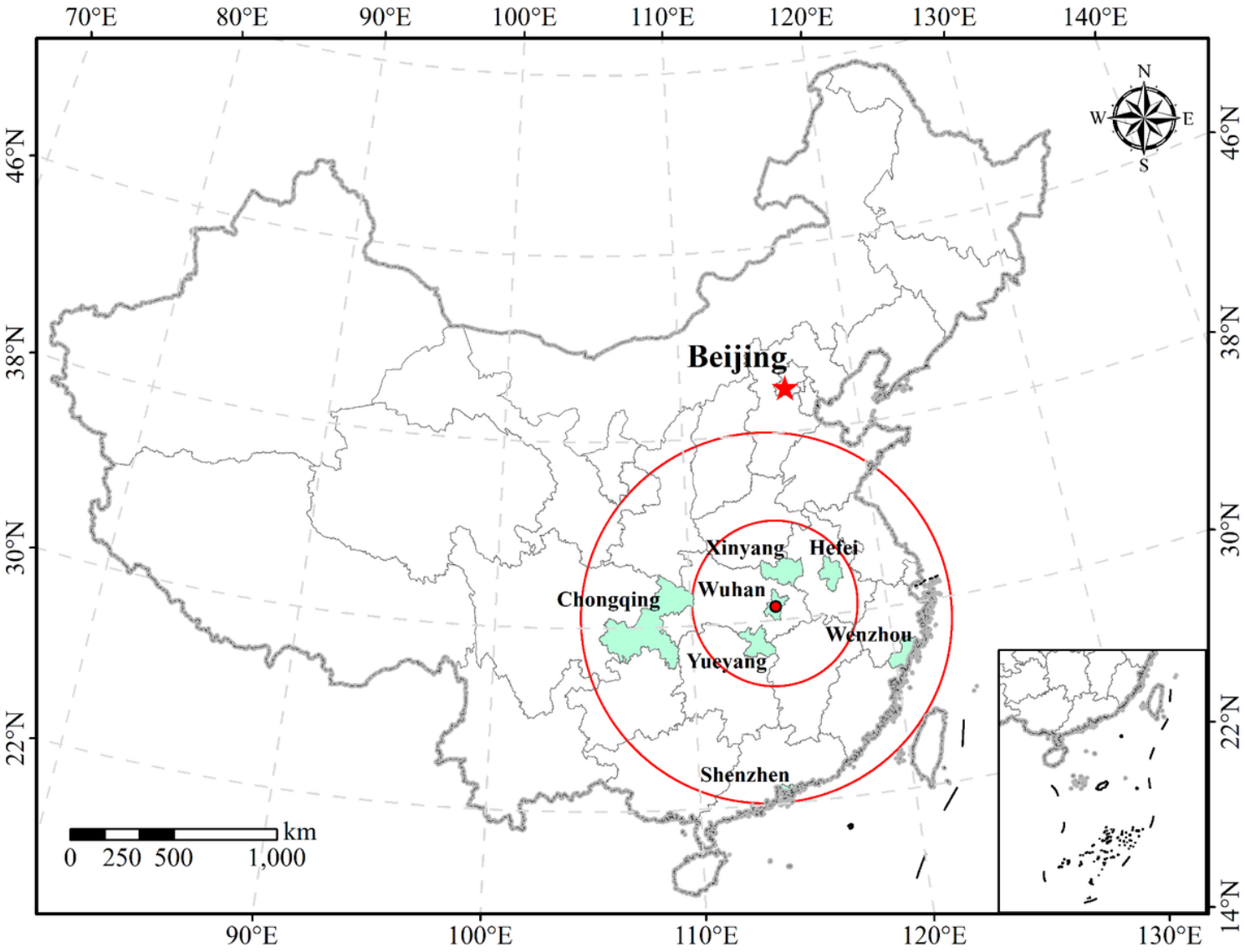


Figure 1

Location map of study areas

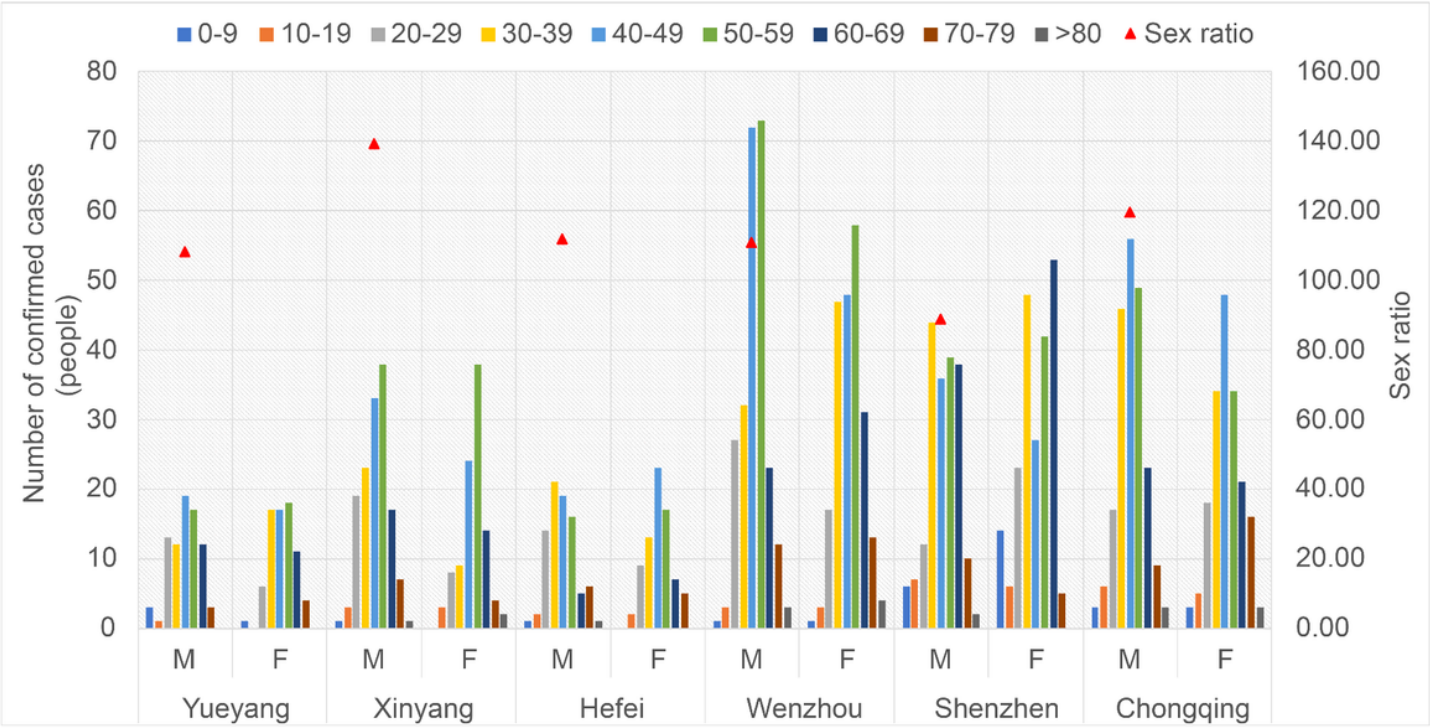


Figure 2

Age and sex structure of the confirmed group

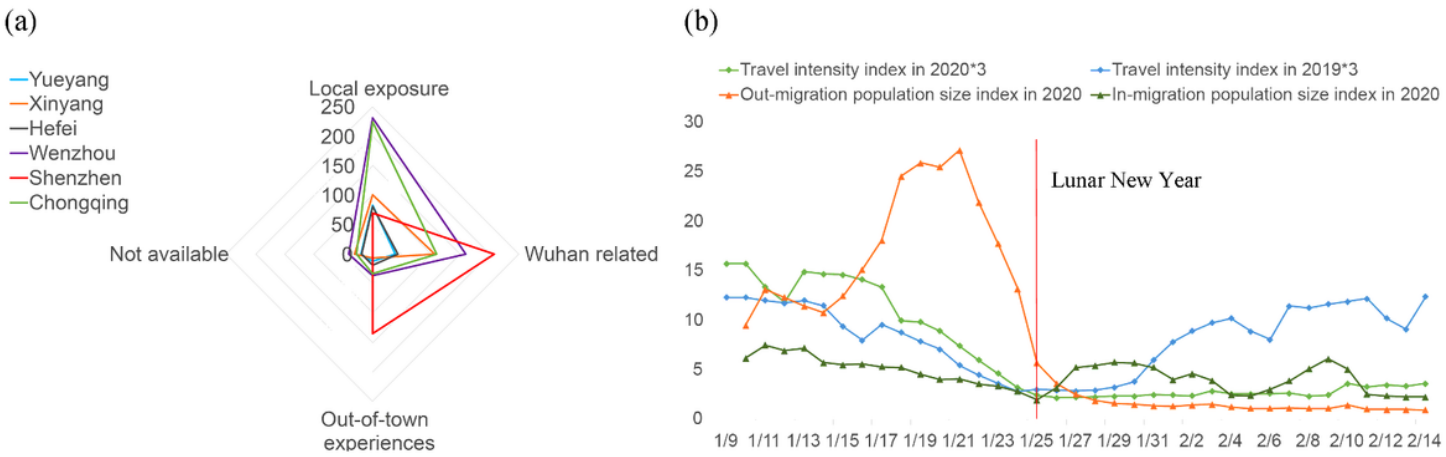


Figure 3

a, infection groups of the confirmed in case cities; b, Shenzhen's demographic travel characteristics

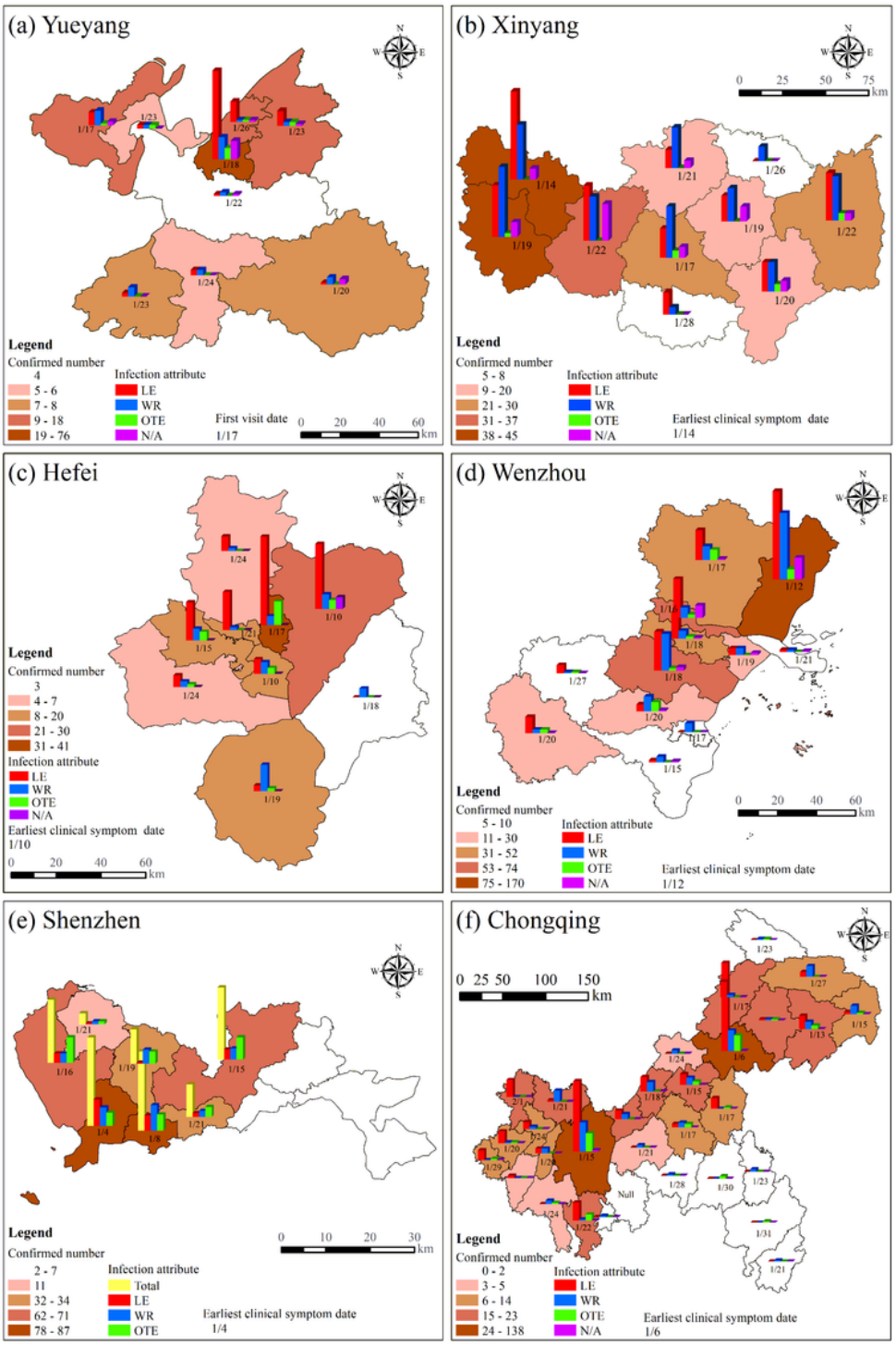


Figure 4

The spatial and temporal distributions and infection groups of COVID-19 (LE = Local exposure; WR = Wuhan related; OTE = Out-of-town experiences; NA = Not available)

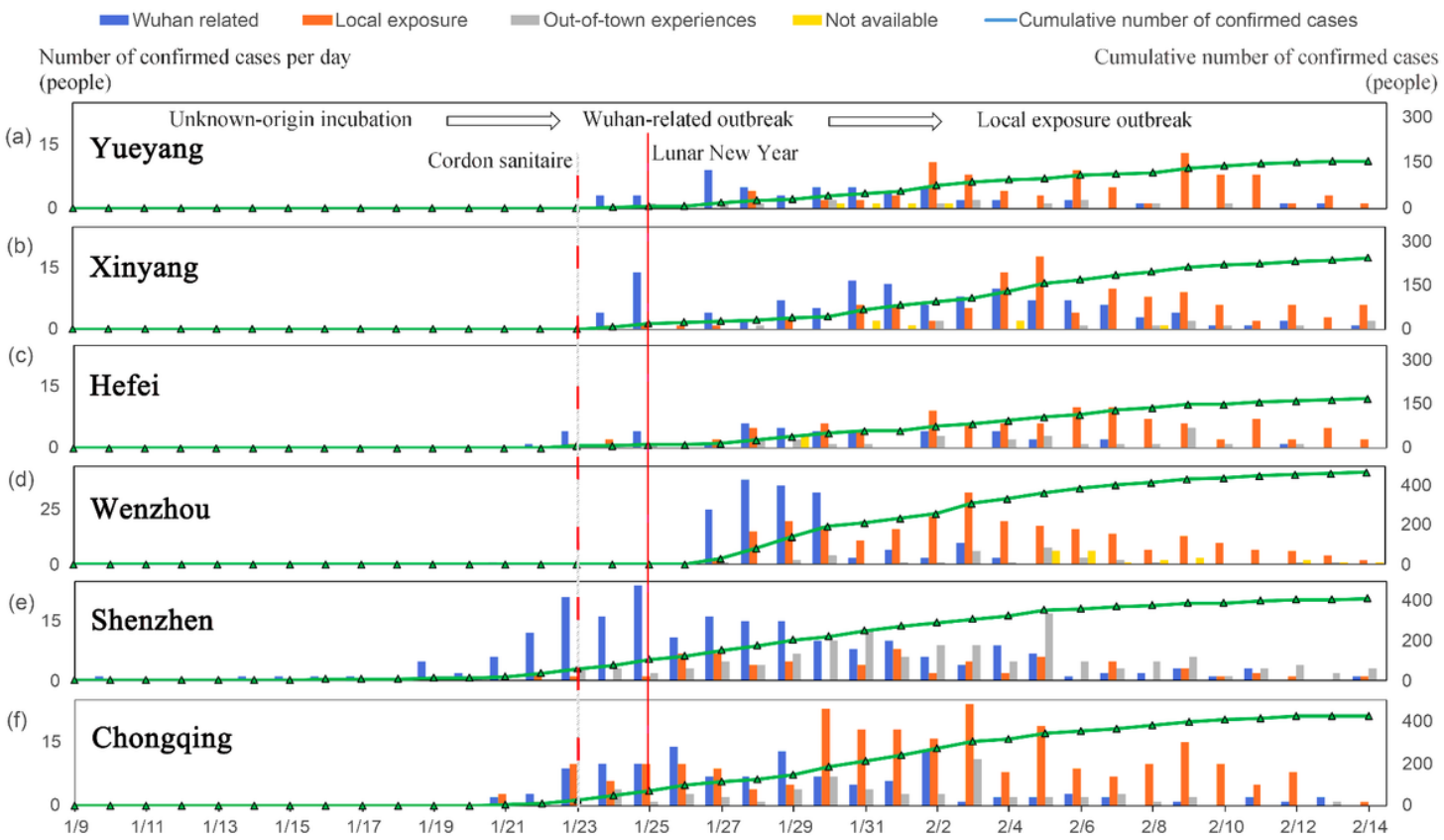


Figure 5

Time evolution of confirmed patients in 2020 in selected cities (the dates of confirmation in Shenzhenwere replaced by the first visit dates)

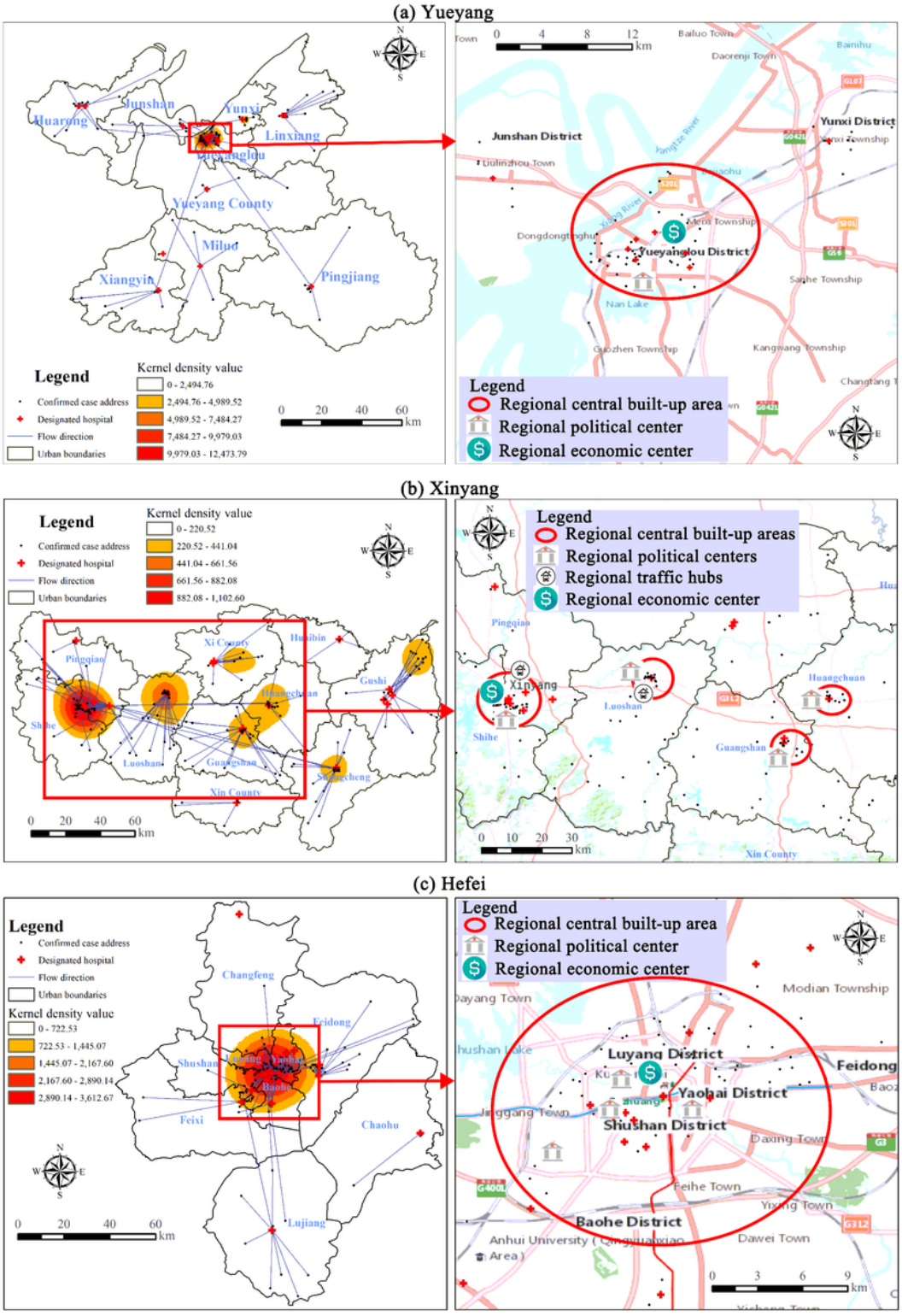


Figure 6

The pandemic and designated hospitals' spatial distributions of cities near Wuhan

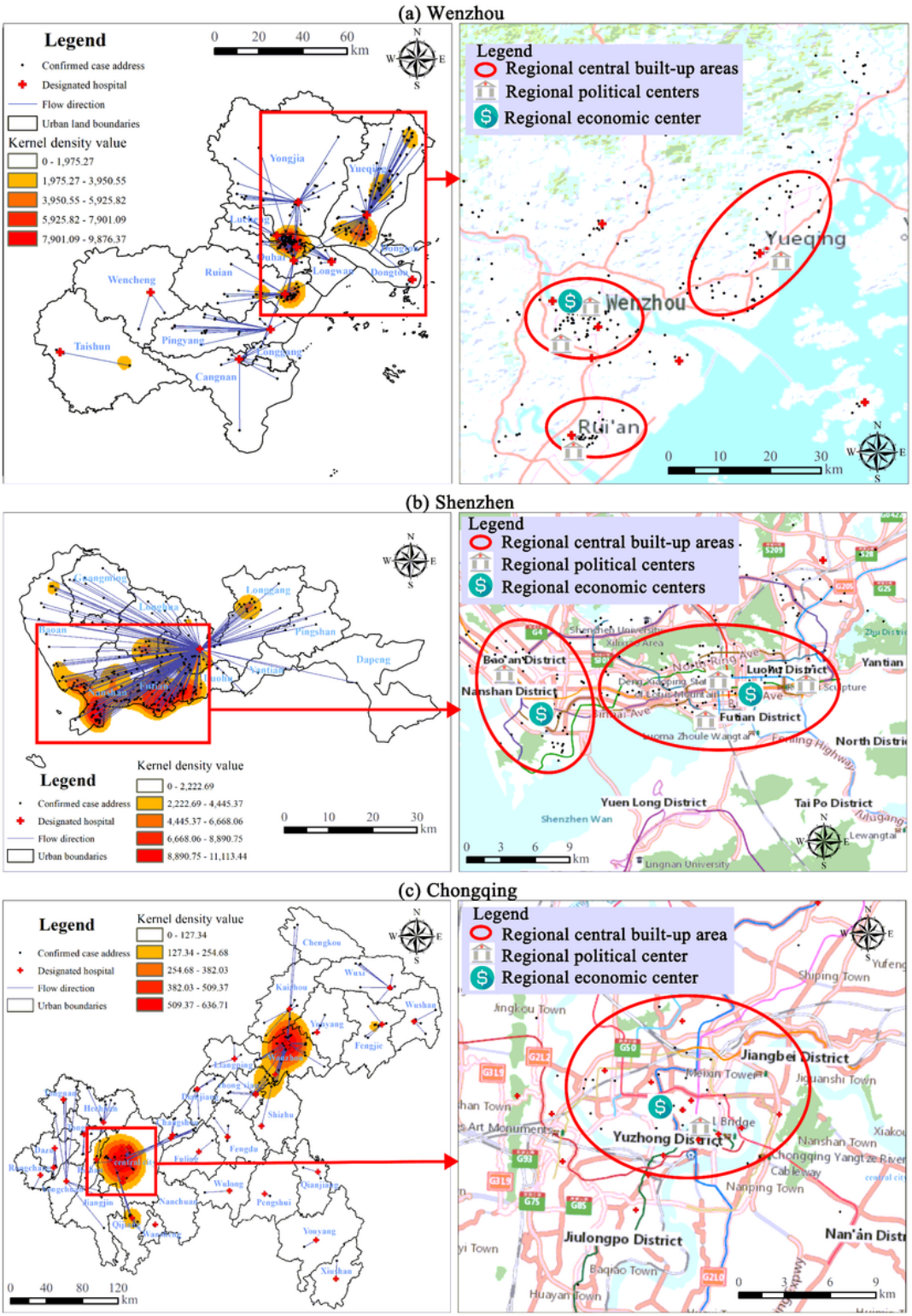


Figure 7

The pandemic and designated hospitals' spatial distributions of cities remote from Wuhan