Associating the COVID-19 Severity with Urban Factors: A Case Study of Wuhan

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Research

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Abstract

Wuhan encountered a serious attack in the first round of the COVID-19 pandemic which has resulted in serious worldwide consequences politically and economically. Based on the Weibo help data, we inferred the spatial distribution pattern of the epidemic situation and its impacts. Seven urban factors, i.e. urban growth, general hospital, commercial facilities, subway station, landuse mixture, aging ratio, and road density, were selected for validation with the ordinary linear model, and the former six presented globally significant association with the epidemic severity; thereafter, the geographically weighted regression model was further adopted for local test to identify their unevenly distributed effects in urban space. Among the six, the place where general hospitals exert effects on epidemic situation highly is associated with their distribution and density; commercial facilities appear the most prevalently distributed factor over the city; newly developed residential quarters with high-rise buildings face greater risks, mainly distributed around the waterfront area of Hanyang and Wuchang; the influence of subway stations concentrates at the adjacency place where the three towns meet and near-terminal locations; aging ratio dominantly affects the hinterland of Hankou in a broader extent than other areas in the city. Upon the result, a series of managerial implications that coordinate various urban factors have been proposed. This research is conductive to developing specific planning and design responses for different areas in the city based on a better understanding of the occurrence, transmission, and diffusion of the COVID-19 epidemic in the metropolitan area.

1. Introduction

Since the new era of 21st century, despite great progress of medical technology, vaccination programs, and public health systems (Matthew & Mcdonald, 2006), severely infectious diseases, such as the 2003 SARS and the 2009 H1N1, never disappear but evolve into novel ones to cause a series of pandemics, which have demonstrated that infectious events could develop rapidly to interfere with social order and even threaten global stability (Morens, Taubenberger, & Fauci, 2009; Thompson et al., 2003)(Garten, Davis, & Russell, 2009).

At the end of 2019, a novel severe acute respiratory syndrome coronavirus, i.e. COVID-19, rapidly developed and eventually became a global pandemic, causing over 1.6 million cases and 95000 deaths worldwide by April 10, 2020. Wuhan, the capital city of Hubei province in China, was under an early siege to encounter the sudden attack from COVID-19, which almost pushed the medical system to the brink of collapse (Feng, Tang, & Chuai, 2018). The number of cases confirmed in Wuhan has accounted for over 60% of all cases in China by the end of March, 2020. The impact of COVID-19 pandemic is significant and thorough since 1918, resulted in wide-ranging consequences politically and economically.

Compared to the past century, although our modern society has become more robust and resilient to deal with unexpected attacks from hazards, some disruptive factors within urban environments still need to be addressed for the purpose of global health and security. Meanwhile, urban expansion and population agglomeration have increased the risk of encountering epidemic diseases in urban settings, as more than half of the world’s population (55%) have moved to cities by 2018 and this proportion will reach to 68% by 2050 (Lee, Aguilera, & Heymann, 2020). The ongoing pandemic of COVID-19 reminds us of the strong impact of massive urbanization, which has changed the traditional society and needs imperative updates of urban systems to prevent the damage from severe infectious diseases. In order to reduce the threatening of infectious diseases that pose to the metropolitan area with a large population, specific planning strategies adapted to urbanized settings are required based on a better understanding about how infectious diseases transmit in urban environments (Matthew & Mcdonald, 2006).

In the past two months, a plethora of epidemiological investigations on COVID-19 have been made, mainly focusing on the disease characteristics, pathogenic mechanism, and population distribution (Chan, Yuan, & Kok, 2020; Chen, Zhang, & Yang, 2020; Guan, Ni, & Hu, 2020; Lee et al., 2020). However, previous experience with controlling similar diseases, such as SARS, H1N1, and MERS, has proved that effective prevention in advance is more constructive before too many people have been affected by these diseases. Therefore, we face an urgent demand for investigating the spatial pattern of epidemiology and its potential impact on urban lives. Characterizing human-space interactions within urban settings contributes to the prevention of disease transmission (not only COVID-29 but also other infectious diseases), by actively navigating human-mediated process (Stoddard et al., 2013) (Eubank et al., 2004). Analyzing environmental factors of the infectious disease is an indispensable component of understanding the mechanism of transmission (Carlson, Eberle, Kruglyak, & Nickerson, 2004).

As researchers found out, COVID-19 spreads easier and faster than its ancestry SARS, mainly through respiratory droplets of pathogen carriers (Chan et al., 2020). In confined indoor spaces or shared environments with crowded people, the potential aerosol transmission of COVID-19 could be possible, almost catching up to the spread rate of the common influenza. The idea of spatial diffusion, i.e. an outward movement from a single spot to a broader coverage, is conducive to elucidate how this disease spreads in the city through urban flows. Different from the ideal model of even exposure to infectious agents within a homogenous environment, variations in potential disease transmission always happen due to various urban factors (Anderson & May, 1991; Gonzalez, Hidalgo, & Barabasi, 2008), resulting in highly heterogeneous infection patterns within the city (Danon, House, & Keeling, 2009; Lloyd-Smith, Schreiber, Kopp, & Getz, 2005).

Previous studies on SARS have provided evidences to establish associations between the epidemic incidence and urban factors, inferring that the spread of COVID-19 may also follow the similar multidimensional characteristics, which could be reflected in the variation of epidemic situations with demographic conditions, proximity, transportation, and socioeconomic activities (Wang, Meng, Zheng, Liu, & Song, 2005). For instance, the experience of fighting against SARS at Toronto medical systems indicated that the hospital was a major source that introduced higher risks to its surroundings, as the virus could easily transmit not only among health care workers, patients, and hospital visitors, but also make more people and families exposed to infectious environments when pathogen carriers move around the hospital (Affonso, Andrews, & Jeffs, 2004). The clinical uncertainty for such a novel virus makes it more difficult to seize the window period of early control at the beginning of outbreak. Some other spatial-related dimensions in metropolitan areas could also be recognized as essential factors to evaluate the transmission mechanism of COVID-19 in the urban context, as the density of residential blocks, shopping amenities, and the ration relying on mass transportations is extremely high, creating suitable urban environment for the disease transmission (Wang et al., 2005). Moreover, along with the influx of migrants, the squatter settlements with limited housing conditions, sanitation facilities, and access to urban infrastructures, may change the pattern of risks (Lee et al., 2020).

In previous studies, investigations on the epidemiological characteristics and spatiotemporal nature of infectious pandemics on the provincial or national scale seemed prevailing (Mo et al., 2020; Shi, Xiang, Zhang, Chen, & Feng, 2012), whereas few case studies have been carried out to address the impact of urban environment on disease spread specifically based on patients' living locations. Identifying urban environments that may help controlling potential risks becomes increasingly important in the current circumstance. However, it is still difficult to evaluate how the impact varies on the city level as previous epidemiology investigation used to focus on a coarse resolution across provincial or regional boundaries. Therefore, a more incisive investigation with credible location-based details is imperative to further explore the distribution pattern of COVID-19 and influencing urban factors on the city level. We aim to extend the understanding of COVID-19 and its spatial impact not only by validating important urban factors, but also by providing convincing evidence to identify corresponding locations where these factors shed significant influences. Instead of providing a universal antidote, a more precise strategy could be proposed for different areas to better deal with similar public health emergencies in the future, if the spatial variation is taken into consideration.

2. Research Design

2.1 Study area

Wuhan is the centre of the economic geography of China, with a permanent population of over 10 million by 2019. As the hub city of the Yangtze River economic belt and the railway artery of China, Wuhan has been well-known as the "thoroughfare of nine provinces". The largest tributary of Yangtze River (the Han River) converges here and splits Wuhan into three towns that stand close to each other, i.e. Wuchang, Hankou, and Hanyang (Fig. 1). The coverage of water accounts for more than a quarter of the city, with rivers, lakes, and port crisscrossing each other. We select the third-ring core area within Wuhan as the study area, covering seven administrative districts with an area of about 860 square kilometres.

The north and south regions of Wuhan are different in terms of the urban pattern, spatial form, socio-economical situation, and etc. The north bank stands Hanyang and Hankou, which is further divided into three administrative Districts, i.e. Jiang'an, Jianghan, and Qiaokou. As a well developed commercial centre, Hankou occupies a flat terrain with few natural obstacles but convenient transportation infrastructures. In particular, highly concentrated populations and development intensity could be found at the old downtown area of Hankou with agglomeration of urban facilities, such as shopping malls, general hospitals, and subway stations. The influence of aging ratio also highly concentrates within this area.

Situated to the west part of the city, Hanyang was initially operated as an industrial zone in the early 19th century. After the completion of the first bridge on the Yangtze River in 1950s, Hanyang began to occupy the hinge place to connect the other two towns. In particular, due to the adequate stock of reserved land and preferential policy support, the riverside area of Hanyang keeps upgrading along with the prosperous real estate market, and has become a hot place for newly developed residential projects of high-rise buildings.

On the south bank locates three Districts, among which Wuchang is part of the original birthplace of Wuhan city. Between the Sha Lake and the Ziyang Lake locates another old downtown area, which also possesses highly concentrated urban facilities and aging ratio, whereas the intensity is slightly lower than that of Hankou downtown area. The strip zone between the riverside area and the East Lake is another important place for newly developed real estate projects. For the other two Districts, Hongshan was the outer city of Wuchang but these years it gradually evolves into a sub-centre when the city extends to the east, and Qingshan is based on the compound of the large state-owned enterprise, Wuhan Steel Co. and its affiliated residential area.

2.2 Data source

In the early stage of the outbreak at the beginning of February, 2020, medical recourses were seriously squeezed in a short period of time and few beds in hospitals were available for treating patients. Many suspected or confirmed patients with mild to moderate syndrome had to stay at home, waiting for admission to hospital. However, some patients with mild syndrome might break the rules of staying at home and go outside for some reasons, making a broader spread of the disease. More seriously, quite some patients' situation exacerbated because staying at home cannot be rigorously enforced with effective health care and treatment. Therefore, Tencent Weibo opened an online help channel for the infected ones. To ensure the authenticity of help-seeking information, it was required to provide help-seeker's personal information, including name, age, gender, dwelling address, contact information, illness description, etc. Some designated departments were involved to check the authenticity of the information before it was posted online. Therefore, the Weibo help data can be used to infer the severity of the epidemic in Wuhan with precise positions. Until the middle of February 2020 when many shelter hospitals were built to admit these patients, Weibo has been one of the most important channels for seeking help.

We obtained the open data from Weibo help channel from January 23 to February 13, 2020, as it was the most severe period of the epidemic in Wuhan. The patient's address was converted to geographic coordinates of WGS84. Eventually, a total number of 327 locations (families) within Wuhan third ring area were collected. A total of 415 infected persons were identified with an average age of 59.9 years old. In order to ensure the representativeness of the Weibo data, we compared the distribution of help-seeking data with the actual number of confirmed cases in each jurisdiction. The result shows strong consistency between the two (Table 1, Fig. 2), as the chi-square test further confirmed that there was a non-significant difference for the data distribution (Chi = 9.977,p = 0.126). In addition, other basic spatial data were included, such as digital maps, the shapefile of the features within the study area, POI, and population data on the community level.

Table 1
Staristics of the Weibo data and the confirmed cases

Data	Jiang'an	Jianghan	Qiaokou	Hanyang	Wuchang	Qingshan	Hongshan	Total
Cumulative confirmed (March 5)	6521	5137	6789	4661	7431	2773	4652	37964
Weibo help	72	35	50	37	62	22	49	327
Chi	9.977							
Sig.	0.126							

2.3 Measures

2.3.1 Outcome variable

As the study area covers 1025 urban communities, the Weibo help data seem relatively sparse. Unexpected bias might exist if the community is expected to be adopted as the statistical unit. In addition, these communities are subject to significant variation on the size and shape, and this situation is difficult to conform with the analysis requirements. Therefore, the study area was divided into uniform grids according to Griffith's method (Griffith D A, 1994). After removing substantial vacant land and water, such as the Yangtze River and East Lake, 502 urban grids of 1 km^2 coverage were obtained for analysis. The kernel density of Weibo help data was calculated to denote the epidemic severity as the outcome variable. This method is beneficial not only for eliminating a large number of invalid statistical units, but also for presenting the pattern of epidemic spread in the city with good spatial continuity.

Further, we adopted the concept of kernel density to associate epidemic severity with urban factors. According to the Tobler's First Law of Geography (Tobler, 1970), for any given incidence, there exists a spatial probability around its location. Conceptually, we can fit a smoothly curved surface over this given point to represent the probability of occurrence, which is highest at the location of the given point and diminishes with increasing distance away from it. As the epidemic is associated with all kinds of social activities which rely urban facilities to take place, in this sense, although the location of Weibo data is based on the home address of confirmed or suspected cases, the potential association between the Weibo data and hospitals could be reasonable, because our method is also based on the probability rather than the incidence itself (Xu, Liu, Zhou, & Jiang, 2017).

2.3.2 Urban factors

Since COVID-19 is a novel coronavirus which is homologous to 2003 SARS, the rationale of adapting the transmission mechanism of SARS as highly related influencing factors, i.e. hospitals, vehicles, public places, households, should be reasonable for explorative investigation (Wang et al., 2005).

Eventually, seven urban factors among four categories of indicators from socio-demographic, urban growth, urban facilities, and land-use, were selected for testing (Lee et al., 2020). For instance, infectious diseases are usually associated with the distribution of population density in the urban context. In particular, elderly groups have been subjected to the highest level of risk among the cases in Wuhan (Fig. 3) (Verity, Okell, & Dorigatti, 2020). According to a recent study of a large sample size with 1099 COVID-19 patients, people over 60 years old suffered from the highest risk of severe symptoms and mortality due to COVID-19 infection (Guan et al., 2020), especially those with underlying conditions, such as hypertension, diabetes, cardiovascular disease, and chronic respiratory disease, inevitably faced more exposure because of frequent visiting to the hospital. Therefore we took the aging ratio (the proportion of elderly people over 65 years old within the community) as the socio-demographic indicator in this study. In this study, the population density was excluded to reduce the multicollinearity as a high correlation with the aging ratio.

With regard to indicators of urban growth, building floor area ratio (FAR) and road density were adopted. These two factors are suitable proxy variables of population density without introducing multicollinearity. Indicators of urban facilities included the density of general hospitals, commercial facilities, and subway stations. Among them, hospital density denotes the risk of infection during medical services or due to adjacencies, and the rest two factors denote the major public contact with people in urban environments. Besides, the degree of land-use mixture was calculated based on the Shannon Entropy to denote the diversity of urban functions. All these urban factors are listed in Table 2.

As no serious multicollinearity was found among the seven urban factors, they were all included in the model for testing at the beginning. The significance of variables and VIF values were analyzed to screen out invalid factors.

Table 2
Summary of urban factors

Categories	Factors	Description
Socio-demographic	Aging	The proportion of elderly people over 65 years old within the community.
Urban growth	FAR	The ratio is determined by dividing the gross floor area of buildings by the gross area of the lot on which buildings stand.
Urban facilities	Hospital density	The kernel density of measuring the probability of existence of the general hospital within a given area.
	Subway density	The kernel density of measuring the probability of existence of the subway station within a given area. The value is highest at the location of the given point and diminishes with increasing distance away from it.
	Commercial density	The kernel density of measuring the probability of existence of commercial facilities within a given area. The value is highest at the location of the given point and diminishes with increasing distance away from it.
	Road density	The ratio is determined by dividing the gross length of roads within a given grid by the gross area of the grid.
Land use	Land-use mixture	Calculating the information entropy based on the proportion of land use types within the selected study area.

2.4 Method

In the analysis process, the dwelling locations of all the help-seekers were geo-coded to latitude and longitude coordinates with the World Geodetic System 1984 (WGS-84) and visualized on the map in the ArcGIS Desktop software (version 10.3, Environmental Systems Research Institute, Inc). The kernel density analysis was conducted with the geo-coded data before statistical models were established.

The spread of infectious epidemic is affected not only by the human interaction, but also related to urban environments in which all kinds of social activities took place. Through establishing models, we can verify the impacts of various urban factors on the distribution of disease. Therefore, the overall effects of urban factors could be tested with the OLS model, assuming that the effects are evenly distributed in urban space. However, the area with high population density may not necessarily result in a serious outbreak when the disease spreads with population movement. On this basis, by calculating Moran's I, we can determine whether the data are subject to spatial autocorrelation.

If Moran's I is significant, it means that the OLS model with global estimation cannot fully explain the spatial heterogeneity of influencing factors, then we will adopt the geographically weighted regression (GWR) for local estimation. In the GWR model, we assume that the regression coefficient is a spatial function of the observation point (focal point). In other words, the regression coefficients no longer fix as constants from global estimation, but changes by adopting adjacent neighbors of the designated focal point as sub-samples in the local regression. As GWR incorporates the spatial characteristics of independent variables for local estimation, it could be used to detect the heterogeneity of disease severity along with the environment variation in different regions. The function of GWR is as follows:

$$Y_i = \beta_0(\mu_i, v_i) + \Sigma \beta_j(\mu_i, v_i) X_{ij} + \varepsilon_i \quad (1)$$

Where Y_i denotes the outcome variable of the spatial unit i; X_{ij} denotes the urban factor in this study; $\beta_j(\mu_i, v_i)$ is the variable estimate, and ε_i is the random error term. The estimated value of β_j changes with the spatial weight matrix $W(\mu_i, v_i)$, in which the attenuation function $f(d)$ could be defined as:

$$f(d) = (1- d^2/h^2)^2,\ d < h \text{ or } f(d) = 0,\ d \geqq h \quad (2)$$

Where d is the distance between unit i and j; and h is the bandwidth which could be determined by using the Akaike Information Criterion (AIC). When the $W(\mu_i, v_i)$ is obtained, $\beta_j(\mu_i, v_i)$ could be estimated by using the standard weighted least square regression with the following function:

$$\beta_j(\mu_i, v_i) = [X^T W(\mu_i, v_i) X]^{-1} X^T W(\mu_i, v_i) Y \quad (3)$$

3. Result

3.1 Distribution of cases

According to the distribution of Weibo help data, we can estimate the severity of COVID-19 in the core area of Wuhan city (Fig. 4). The help-seeking signals mostly concentrated at Hankou town on the north bank of the Yangtze River, especially at the adjacencies of Jiang'an, Jianghan, and Qiaokou jurisdiction. The situation developed from Hua'nan Seafood Market, in which the outbreak was detected, all the way to the south, spreading along the highly concentrated commercial areas such as Jianghan business loop, Jiefang Avenue, and the large surrounding areas of Hanzheng wholesale market. The infectious situation was also widespread in the vast area along the Yangtze River and the Han River. Another spreading trajectory went upstream along the north bank of the Yangtze River (the No. 1 subway line), ending with a hotspot with high incidence around the Baibuting community. A sporadic situation was found at the Gutian community on the upper stream of the Han River. In Hanyang District, the epidemic mainly concentrated around two business centers, i.e. Zhongjiacun and Wangjiawan.

The overall severity of the epidemic on the south bank was relatively lower than that on the north bank. One of the strip areas with concentrated incidence went along the Yangtze River waterfront, extending from the Baisha community at the south to the northern area of Qingshan District, where the Wuhan Steel compound and affiliated residential areas are located. Several hotspots with high incidence were mainly detected around the important nodes that closely connected to Hankou or Hanyang, such as the Renmin Hospital of Wuhan University near the Yangtze Bridge, and the Xudong commercial loop near the Second Yangtze Bridge. And the epidemic continued to develop until reaching a sub-climax in the surroundings with high density between the Sha Lake and the East Lake. Although the epidemic severity attenuated during its spread from Wuchang to the hinterland of Hongshan because of the block with natural environments, concentration points fluctuated around the commercial nodes or densely populated places, such as Hongshan Square, Bairuijing Central Community, Optics Valley Plaza.

3.2 OLS model

For the OLS model, the F value is significant at a 99% confidence level (Table 3), indicating that at least one factor has significant influence on the epidemic. The model presents a moderately high explanatory power with 64% of the variation explained by selected factors, among which aging, FAR, and commercial density are highly significant at the 99.9% confidence level ($p < 0.001$). The coefficients of hospitals, subway stations, and land-use mixture are significant at the 99% confidence level. Among them, the coefficients of aging, FAR, commercial density, hospital density, and subway station density, are positive, indicating that these factors exacerbated the epidemic severity and incurred more help-seeking. Conversely, the coefficient of the land-use mixture is negative, as it means that the diversity of urban functions has the inhibitory impact on the epidemic. Compared with the previous factors, the road density presents the non-significant influence on the epidemic severity.

In the Null model in which only the outcome variable was adopted, the Moran's I index was 0.796 ($P < 0.001$), indicating a significant spatial autocorrelation. After we finished the OLS regression, the Moran's I index was reduced to 0.611 ($P < 0.001$). Therefore, it is still necessary to consider other effectively alternative means to eliminate the estimation error caused by spatial heterogeneity, so as to optimize the model fit.

Table 3
OLS model results

Variable	Estimates	Robust-S.E.	Robust-t	Robust-p	VIF	Model-fit	
intercept	-0.002	0.034	-0.054	0.957		F	128.498
Aging (hundred / km^2)	0.279	0.534	5.215	< 0.001***	2.492	Wald	717.899
FAR	0.145	0.053	2.729	0.007***	2.266	R^2	0.646
Hospital density	0.333	0.121	2.754	0.006***	2.530	Adjusted R^2	0.641
Subway density	0.086	0.030	2.886	0.004***	2.534	AICc	320.042
Commercial density	0.016	0.003	6.325	< 0.001***	3.603		
Road density	0.002	0.004	0.528	0.598	1.515		
Land-use mixture	-0.075	0.038	-1.978	0.048*	1.134		

3.3 GWR model

As road density presented non-significant impact on the epidemic in the OLS model, it was removed from the GWR model to simplify the model complexity. The results show that the GWR model has an average adjusted R^2 of 0.822, indicating a very high explanatory power (Table 4). Through analyzing the significance graph of local R^2 (Fig. 5), the data in most grids can be well fitted using the GWR model. The model fits were over 0.65 for most of the grids at Hankou, where the epidemic situation was the worst and most concentrated, and the distribution of areas with high local R^2 value is highly consistency with the places of high incidence, indicating that the selected urban factors could well explain the epidemic situation in this region. Even for those grids in which the model-fit is very low, the local R^2 value is mostly close to 30%, which still means an acceptable level. Compared to the OLS model, the adjusted R^2 of the GWR model is significantly improved and the residual is effectively reduced.

We can also compare the model-fit by using the Akaike Information Criterion (AIC), which can be applicable to any sample size by using AICc (Burnham & Anderson, 2002). A decrease of AICc by more than 3 points could be regarded as a significant improvement for the model performance (Mcmillen, 2004). In this study, the AICc of the

GWR model is decreased by nearly 257 compared with that of the OLS model, as means the model-fit is improved by 80%. In addition, the Moran's I of the GWR model is reduced to 0.314 ($P < 0.001$), as means the spatial autocorrelation is reduced by 48.6% compared with the OLS model. Therefore, These results reveal that the GWR model is a better choice.

The regression coefficients of the six factors are subject to some degrees of variation for different grids, and even present opposite effects (Table 6). The distribution of variable significance also presents noticeable spatial heterogeneity (Fig. 4), indicating that these factors shed non-stationary influences on the epidemic in different areas.

Table 5
GWR model results

Variable	Est. (lower)	Est. (upper)	S.E. (lower)	S.E. (upper)	Model-fit	
intercept	-0.993	0.460	0.071	0.335	R^2	0.871
Aging (hundred / km^2)	-1.268	1.176	0.087	3.7146	Adjusted R^2	0.822
FAR	-0.672	1.110	0.096	0.738	Local R^2	0.263–0.855
Hospital density	-2.905	2.135	0.157	4.533	AICc	63.111
Subway density	-0.790	0.414	0.042	0.927		
Commercial density	-0.012	0.082	0.003	0.038		
Land-use mixture	-0.303	0.474	0.078	0.285		

Table 6
Spatial autocorrelation test

Model	Moran' I	z	p
Nulll	0.796	32.886	< 0.01
OLS	0.611	25.252	< 0.01
GWR	0.314	13.036	< 0.01

4. Patterns Of The Influence Of Urban Factors

4.1 Hospital

By comparing the locations of major hospitals and the first group of designated fever hospitals with the epidemic distribution, we found that these hospitals appeared within or close to almost every hotspot where the epidemic is highly concentrated (Fig. 4), formulating the hypothesis that major hospitals probably intensified the epidemic spread to the surrounding areas in the early stage. As people in China normally prefer general hospitals to have medical services, during the outbreak of COVID-19 which coincided with the flu season, the increasing number of people with high frequency of hospital visiting may cause the extra risk of cross-infection around these places.

Such hypothesis is supported as the result of the GWR model shows that the influence of hospitals on epidemic severity is indeed unevenly distributed in the city, resulting in three agglomeration blocks with statistical significance. Statistical evidance reveals that COVID-19 severity is highly associated with the distribution of general hospitals, particularly in Hankou (Fig. 6). The spatial pattern is in agreement with the hypothesis that the epidemic risk diffused from the place where the first several confirmed cases were found, i.e. Hua'nan Seafood Market (Fig. 4), perpendicularly to the waterfront area of the Yangtze River. The risk of infection is concentrated along with the increase of hospital density.

A possible explanation could be made for the grids with significantly negative effects from hospitals. The infection was still considerably intensified near a few major hospitals with low density. For instance, there are only two major hospitals situating at the north and south ends of the residential area between the Sha Lake and East Lake. Because of the geographical restriction of these natural element, nearby residents have to rely on the only two existing hospitals, intensifying the risk of cross-infection during the COVID-19 epidemic. In addition, fallacy correlation between hospital and epidemic severity may exist for specific locations, implying the existence of other interfering factors. For instance, although there is not any major hospital near the Baibuting community which situates at the northern end of Hankou, there was still a hotspot of confirmed cases. After investigation, we found it was the large scale public banquet that aimed to celebrate the Spring Festival eventually incurred the spreading because of the participation of some latent pathogen carriers.

4.2 Commercial

The result reveals that the epidemic situation is significantly affected by the commercial density and such influence is prevalent in the study area (Fig. 7), particularly in most areas of Hankou and Hanyang, and the east-west commercial corridor from Wuchang District to Hongshan District, where large scale commercial plazas and supermarkets are located. As the outbreak happened to occur just before the Spring Festival, the number of people who visited commercial places busily preparing for festival purchases soared up tremendously. Most of these commercial places are indoor spaces with relatively weak natural ventilation. In the winter, doors and windows were mostly closed in order to keep warm, further reducing the efficiency of air exchange from outside. Once the central air conditioner is activated, the circulating air accelerates the spread of the pathogen in the crowd, as aggravated the epidemic situation in neighboring areas.

For the urban fringe areas that are distant to the city centre, the situations are more complex. For instance, the impact of commercial factors seems heavier for some fringe communities, such as Wangjiawan and Baibuting, where commercial supplies concentrated on some major supermarkets or malls, whereas the other fringe areas, such as Qingshan District and Gutian community, are subject to non-significant impact with commercial density.

In contrast, the commercial factor around Ziyang Lake in the old city centre of Wuchang presents a non-significant effect on the epidemic situation. On the one hand, due to the large water coverage, the probability of virus spreading in the open air is much smaller than that of closed indoor spaces. On the other hand, its surroundings are covered with quite some military and institutional units, and the strict control of the surrounding area inhabits not only commercial activities but also personnel movements. Therefore the impact of commercial facilities on the disease was confined.

4.3 Urban growth

As a result, a continuous strip zone in which the epidemic situation is significantly affected by urban growth could be identified, from the riverside area at Hanyang District to the broad area on the north-west bank of East Lake, covering the old downtown of Wuchang (Fig. 8). Due to the existence of a large number of natural elements, many new real estate developments in the central area of Wuhan city concentrated along this direction as the reserved land for residential construction is scarce and restricted. Many people prefer to living within such a decent living environment surrounded by waterfront landscapes, resulting in higher residential occupancy than that of the urban fringe area. In this circumstance, high-rise buildings were considered an economical choice to meet the increasing accommodation needs, so as to save more in-between spaces for landscape which is supposed to increase the value of the real estate. However, such a prototype enforces residents relying heavily on the elevator, which easily becomes a high-risk place through human contact in such a narrow confined space. Therefore for these newly developed high-rise communities, the epidemic severity was intensified along with the increase of FAR.

In contrast, the FAR exerts a significant negative effect on the epidemic situation for some communities on the upper stream of the Han River. Although quite some real estate developments have been finished in these urban fringe areas, the residential occupancy is still low, resulting in a fallacy that the epidemic seems suppressed when the FAR increases.

4.4 Aging

The result shows that aging problem dominates most communities in Hankou and such factor exacerbates the epidemic severity significantly. The impacted area overlaps with the epidemic distribution. The elderly are reported as the most vulnerable group in this epidemic (Verity et al., 2020), while Hankou is where aging communities mostly concentrated in Wuhan city. Therefore, this area naturally became the epicentre that suffered the worst in this event. The impact of aging on the epidemic severity is relatively low on the other side of the Yangtze River, and the impacted area with significance is much smaller and dispersed (Fig. 9), mainly concentrating in Qingshan District to the north and the Baisha community to the south. For the broad area between the East Lake and the South Lake where dozens of universities are located, the aging factor presents a non-significant effect on the epidemic severity. As university students account for the majority in these communities, the epidemic situation was not seriously influenced by the aging factor.

Although the impact of aging on the epidemic situation is somewhat different for communities on both sides of the Yangtze River, its influence seems greater for communities of the urban fringe. The supply of urban support system is relatively scarce, particularly the medical resources around these communities. Therefore, residents who live away from the urban centres are easily prone to panic when facing such a serious emergency, resulting in more help-seeking data in these areas.

On the contrary, the epidemic severity turned out to be serious around the Zhongjiacun commercial loop in Hanyang District, although the aging ratio of this area is low. As found, this place is very close to the high-risk area, with two bridges directly connecting to the epidemic hotspot in Hankou. The frequent communication between the working class with better mobility might contribute to the epidemic diffusion.

4.5 Subway

At the adjacency place where two major rivers meet, the epidemic situation was intensified with increasing subway stations (Fig. 10). This result further reinforces the hypothesis that the severity of epidemic intensified although the aging ratio decreased around the Zhongjiacun commercial loop in Hanyang District. As the connection hub between Hankou and Wuchang, this place was under the influence on both sides. The younger population is subject to better mobility than seniors. In particular for the working class who relies on the subway for commuting, the frequent contact via mass transportation (e.g. subway), exacerbated the epidemic severity in the area. Similar situation also took place near Jiyuqiao and Pangxiejia at Wuchang District, possibly because the Line-2, which is the major artery line that connects both sides of the Yangtze River, sets up an important front station in this area before heading to the epidemic hotspot in Hankou. Another significantly impacted area because of the dense subway stations appears in the residential area of the steel enterprise in Qingshan District, which is located near the terminal of Line-4 with a large number of residents, therefore the cumulative effect is possible to intensify the epidemic severity.

The distribution of newly built subway stations or those under construction is mainly distributed within the areas with cold colours on the right of Fig. 10, and the frequency of usage is quite low. Therefore, these areas present a significant inhibitory effect on the epidemic. The Only exception is the Optics Valley Plaza, where a concentration of the epidemic emerged although the density of subway stations is very low. The situation is probably due to commercial factors as discussed before, because it is adjacent to a very popular commercial district which is composed of several commercial streets across multiple blocks with the total length of 1.5 kilometres. Featured with stylish architectural characteristics of European countries, this district becomes one of the most favourite places for shopping and leisure, playing a major role in the epidemic diffusion around this area.

4.6 Land-use mixture

The result indicates that the impact of land-use mixture on the epidemic situation is relatively limited. Different effects appeared in Hankou and Wuchang (Fig. 11). According to Cervero (1995), urban communities can be roughly categorized as three groups: the balanced community of residence and employment, the residence-based community, and the employment-based community. It was argued that commuting patterns are different among these types of communities (Cervero, 1995).

In Hankou, the significantly impacted area with negative effect exists among the in-between space of Northwest Lake, Zhongshan Park, and Fountain Park. This area generally belongs to the type of balanced community, in which people can enjoy the spatial proximity to community services and the diversity of urban functions. People can easily obtain basic needs within the walking distance, as it reduces the frequency of long-distance commuting across different regions (Cervero, 1996). The frequency of traversing across surrounding high-risk areas could be avoided, particularly for the office staffs who basically work within a designated area. In addition, some large scale water pools that are dispersed in this area also play the role of barriers to reduce people's mobility.

In contrast, the area between the Sha Lake and East Lake is dominated by the residence-based communities, for which residents' commuting distance and their dependence on public transportations increase with a higher degree of land-use mixture (Zhao, 2018), elucidating why mixed land-use intensified the epidemic severity at this place.

5. Implications

In the early stage of the outbreak, unexpected exposure to the infectious environment in the hospital during medical treatment was prone to happen as the public had not formed a clear awareness of the characteristics of such novel virus. After then, those suspected fluxed into general hospitals, not only leading to more serious cross-infection, but also accelerating the collapse of the medical system. The well-developed commercial network and subway system facilitated the spread of this disease to a wider area within the city.

Verification of these urban factors and their unevenly distributed effects that were identified in the city will be conductive to developing specific planning and design responses for different areas in the city, making communities less susceptible in dealing with similar diseases in the future. According to the lessons and experience in this case, the construction of a multi-level emergency medical system should be fully considered and rationally configured in future urban planning to relieve the pressure of treatment in large general hospitals and to prevent precautions. For instance, the first level of local hospitals could serve for the diagnosis of suspected patients; the second level is the general hospital, which is responsible for treating severe cases; the third level is the shelter hospital, which serves to isolate patients with mild to moderate symptoms; while the fourth level consists of a large number of centralized quarantine facilities for receiving discharged patients. In addition, distribution of emergency medical units, especially general hospitals, should be also considered with lower density and even distribution within a certain distance. A high concentration of general hospitals as the single-level emergency medical system turns out to be less effective and even dangerous in dealing with epidemics. Besides, plans of allocating large scale indoor commercial facilities should be more cautious to avoid the potential relay spread from the hospital to commercial facilities. Positive prevention with detecting and sterilizing devices could be considered before customers enter these places.

In addition, high-density communities of high-rise buildings face higher risks toward the severe impact of COVID-19. For some communities located on the urban fringe, the aging problem exacerbated the situation and made them more vulnerable when encountering emergencies. More attention should be paid to establish and improve the emergency medical system around these places. At present, the FAR of many residential quarters in Wuhan core area exceeds 2.0 or even reaches to 3.0. Therefore, reasonable control of FAR for residential quarters, in particular around general hospitals, is necessary so as not only to create a more liveable environment, but also for the purpose of ensuring public health. In particular for those places located around general hospitals as discussed before, a stricter control should be made for the implementation. For those communities with high-rise residential buildings, each unit connects hundreds of residents who have to rely on elevators to circulate. Exploring preventive methods to improve the sanitary conditions of frequently used public spaces of residential buildings, such as hallways, elevators, stairs, handles, is also encouraged.

Along with the rapid urbanization process, large cities heavily depend on the rail transit, which may also serve as the fast passage of epidemic transmission. In particular for the "near subway housing" within one kilometre on both sides of the rail transit, it has to face greater exposure risks. Therefore, appropriate "buffering space", such as street parks, open spaces, and green belts along the rail transit, should be considered and integrated into existing natural systems. It's also helpful to encourage slow traffic modes within the 15-minute life circle by improving the pedestrian system and greenways around these nodes to create a humanized urban environment. In this way, the crowd of passengers who rely on the subway could be automatically reduced or dispersed via staggering peak travels, contributing to the ease of disease prevention. Not only can these strategies relieve the pressure of public transportation, but also play an important role in trading space for time during the emergent public health event.

6. Conclusion And Limitations

Wuhan encountered a serious attack in the first round of the COVID-19 pandemic which has resulted in serious worldwide consequences politically and economically. In this study, we adopted the Weibo data to infer the spatial pattern of the COVID-19 distribution of early stage in Wuhan city. The theoretical assumption that adopts some important urban factors that may shed influence on the epidemic severity was validated, such as urban growth, location of general hospital, commercial facilities, subway station, and aging ratio. The result further identified the unevenly distributed effects and spatial heterogeneity of these influencing factors in the city.

Among them, the place where general hospitals exert effects on epidemic situation is associated with their distribution and density; commercial density is the most prevalently distributed factor over the city; newly developed residential quarters with high-rise buildings face greater risks, mainly distributed around the waterfront area of Hanyang and Wuchang; the influence of subway stations concentrates at the adjacency place where the three towns meet the influence of subway stations concentrates at the adjacency place where the three towns meet and near-terminal locations; and last but not ther least, aging ratio dominantly affects Hankou in a broader extent than other areas in the city.

Although isolation has caused unexpected stagnation or even suspension of daily life in the short term, development and prosperity are the normal status of urban life because people's pursuit for a better life will never change. We should regard this low-probability event as an opportunity to improve the planning system and make it more resilient based on the concept of "peace-war" combined operation. So as to develop effective planning strategies in the future, a series of managerial implications that coordinate these urban factors have been proposed. For instance, the multi-level emergency medical system should be considered to replace the current single-level medical system which heavily relies on general hospitals, the distribution of which should be also reconsidered with lower density within a certain distance. Plans for allocating large scale indoor commercial facilities should be more cautious to avoid the potential relay spread. Stricter control of FAR for residential quarters, in particular around general hospitals, is necessary. Besides, slow traffic modes within the 15-minute life circle should be encouraged by adding or improving green belt, pedestrian system, and greenway around transit nodes. These spaces could be integrated into existing natural systems as an effective buffer-zone to play an important role in trading space for time during the emergent public health event.

We end this study by acknowledging some limitations. First, as Weibo help data is sparse compared with the confirmed cases, we adopted the kernel density to simulate the epidemic situation. In the future study, we will collect more data of the confirmed cases with location information to ensure a more reliable result. Second, other urban factors that might have been neglected should be investigated to increase the model prediction. In addition, we should try to compare other models, e.g. spatial error and spatial lag, to optimize the model-fit. Once more data is expected to be available, the Bayesian conditional autoregressive model could be implemented to dive into this study with more advanced methods.

Declarations

Ethics approval and consent to participate

There is no potential harmful indication to subject's biological identification and one's interests in our study. All subjects have been properly instructed and indicated of the guarantee to the privacy and anonymity of the collected data. The written consents have been obtained from all the participants according to the principles of Declaration of Helsinki. The process has been reported to the IRB of school of architecture and civil engineering at Xiamen University, and an approval has been issued. The required statement has been included in the described method. All relevant data are in the paper and its supporting information files.

Availability of data and material

The datasets during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests" in this section.

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Authors' contributions

Xin LI conceptualized and wrote the paper; Lin ZHOU collected data and processed analysis; Tao JIA conceptualized this work; Ran PENG and Xiongwu FU collected data; Yuliang ZOU did literature review.

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Figures

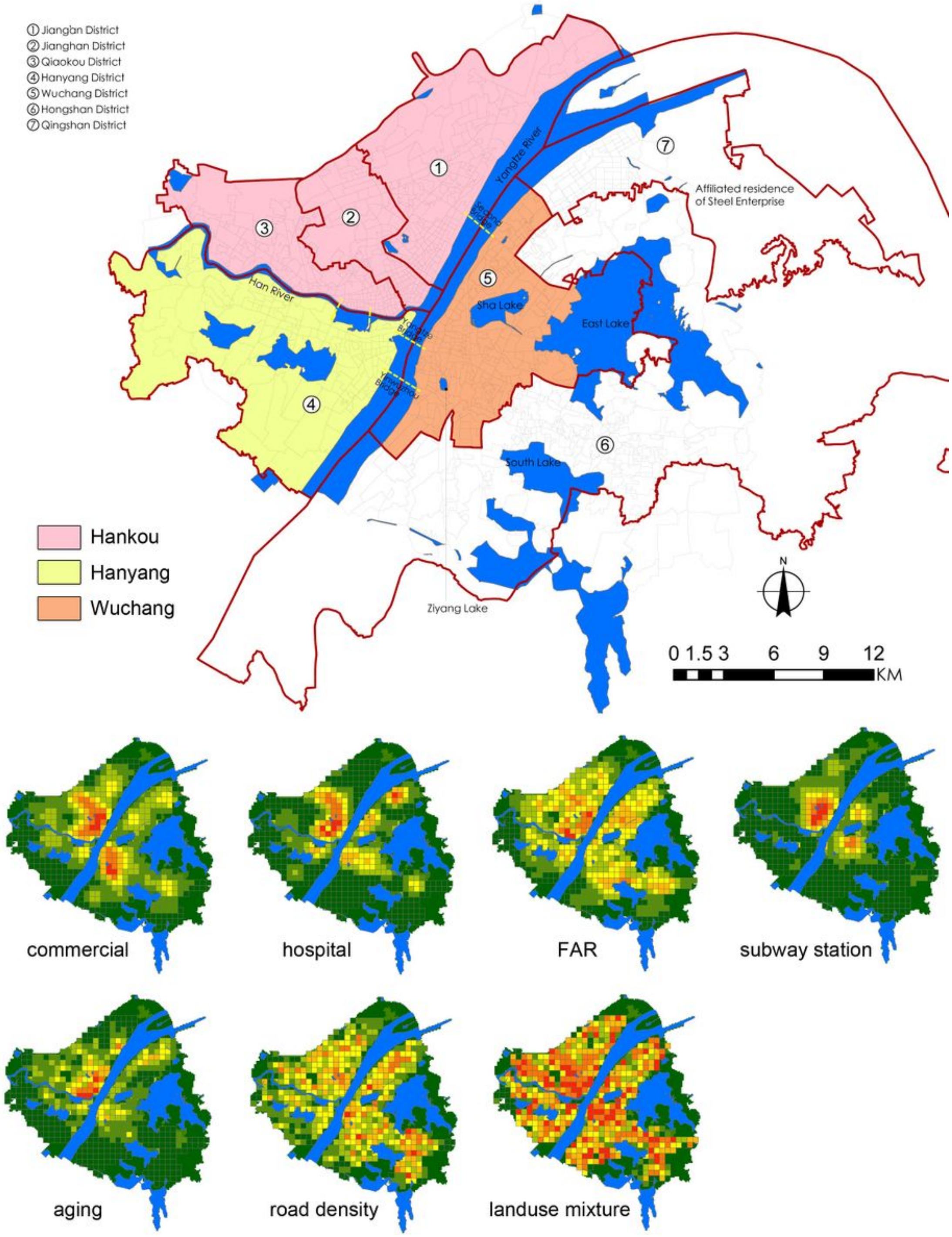

Figure 1

The basic geographic information of the study area and characteristics of urban factors. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

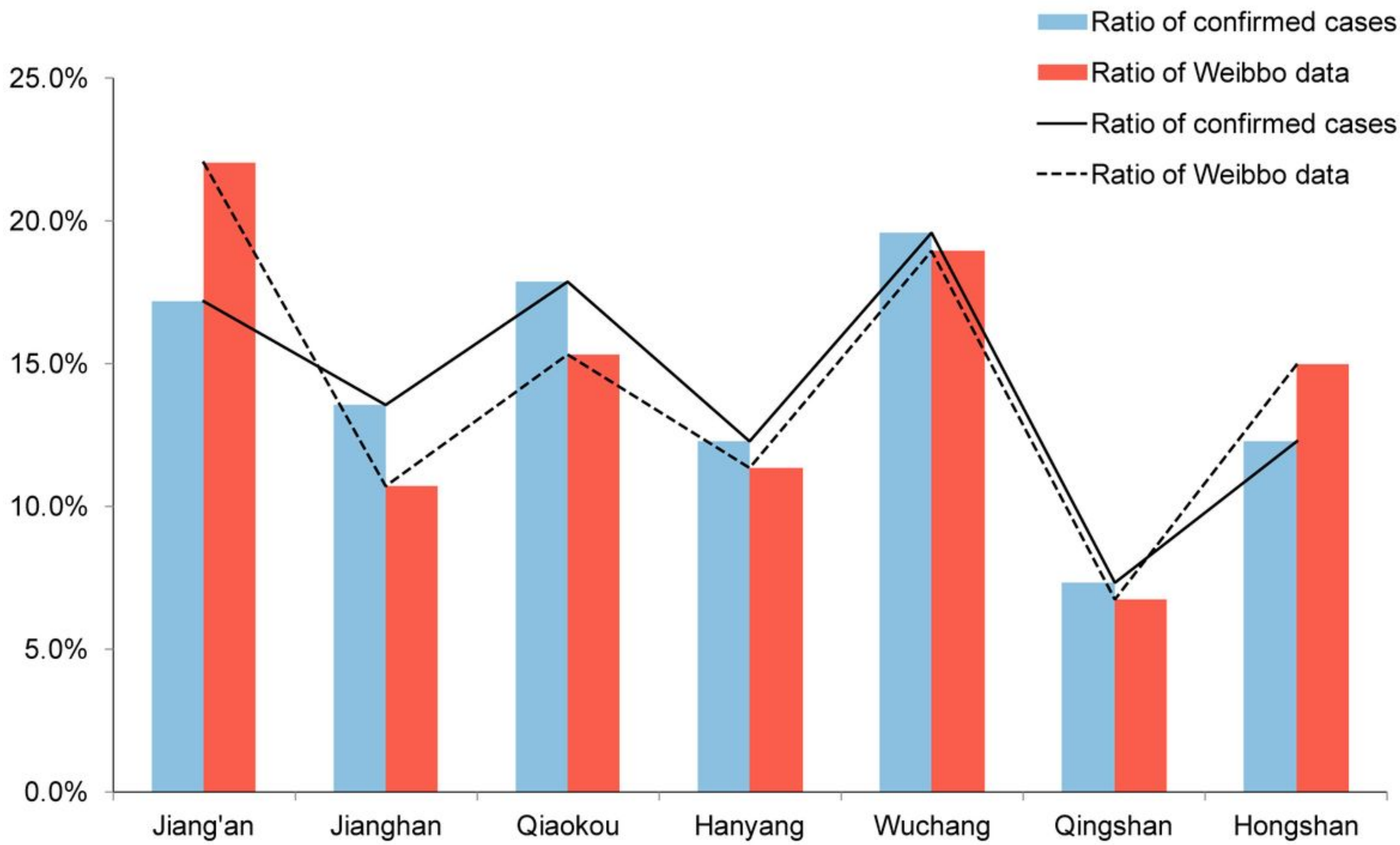

Figure 2

Comparison between the Weibo data and the confirmed cases

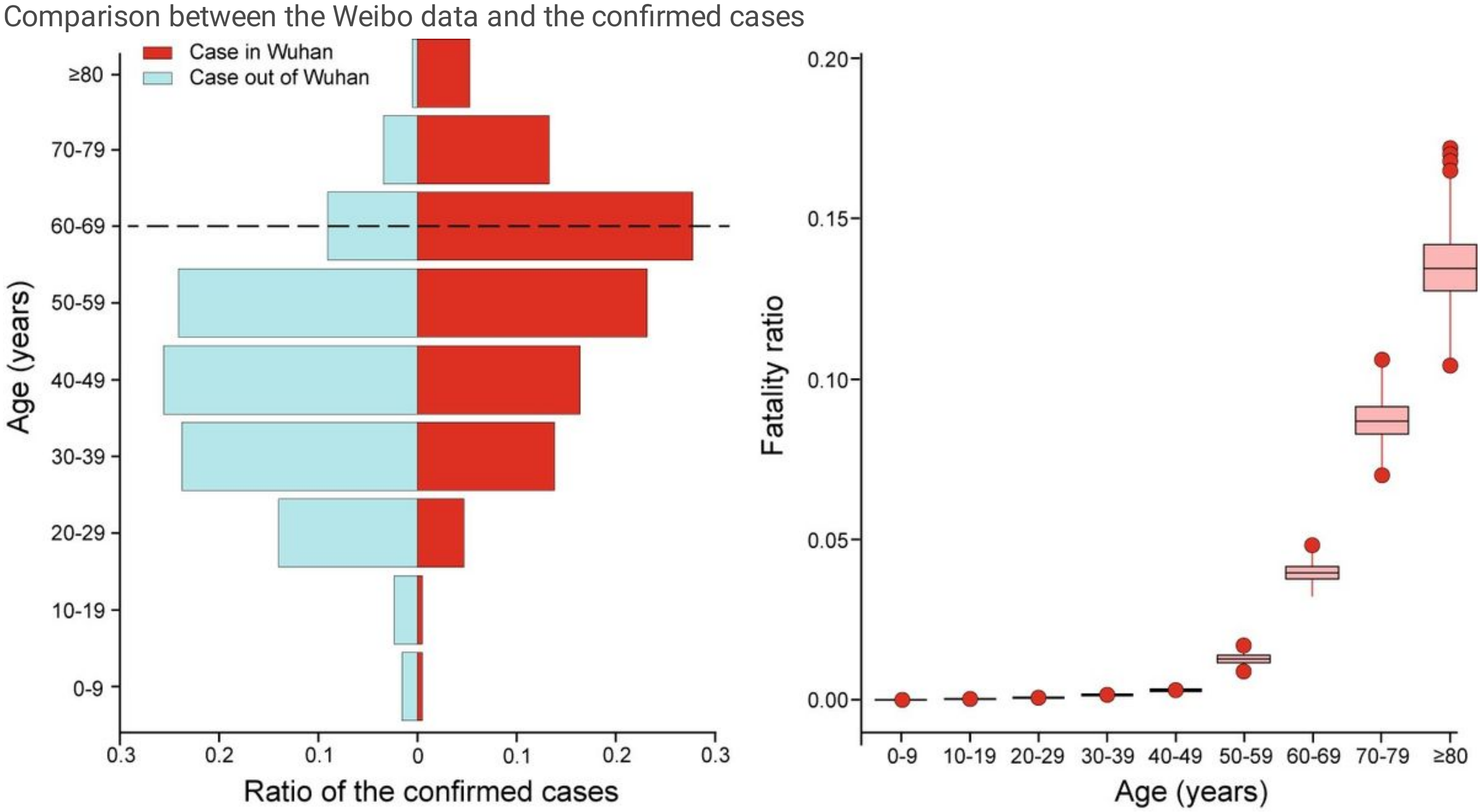

Figure 3

Thconfirmed cases by age and fatality ratio (adaptet from Verity, et al., 2020). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

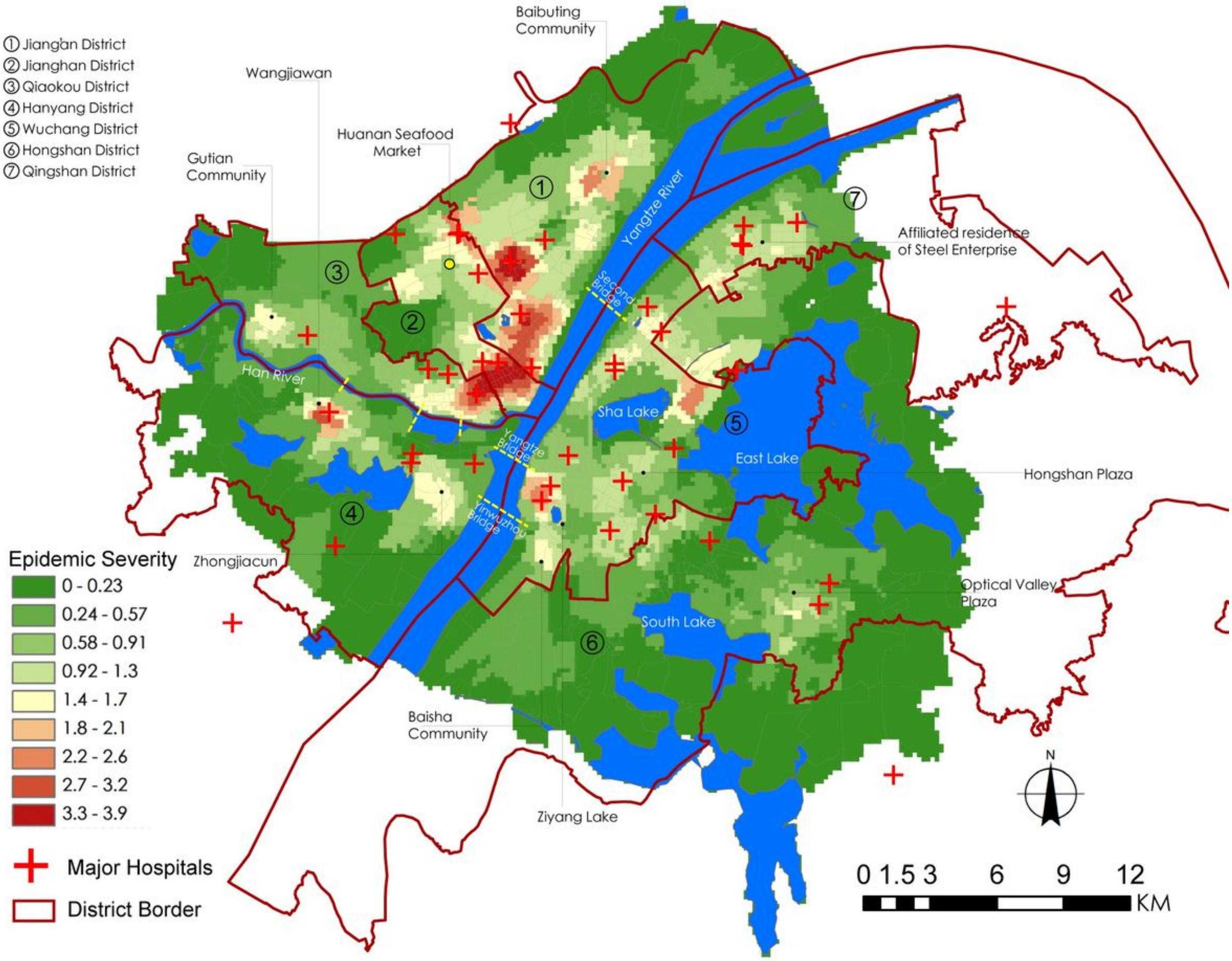

Figure 4

Kernel density of the epidemic severity based on Weibo help data. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

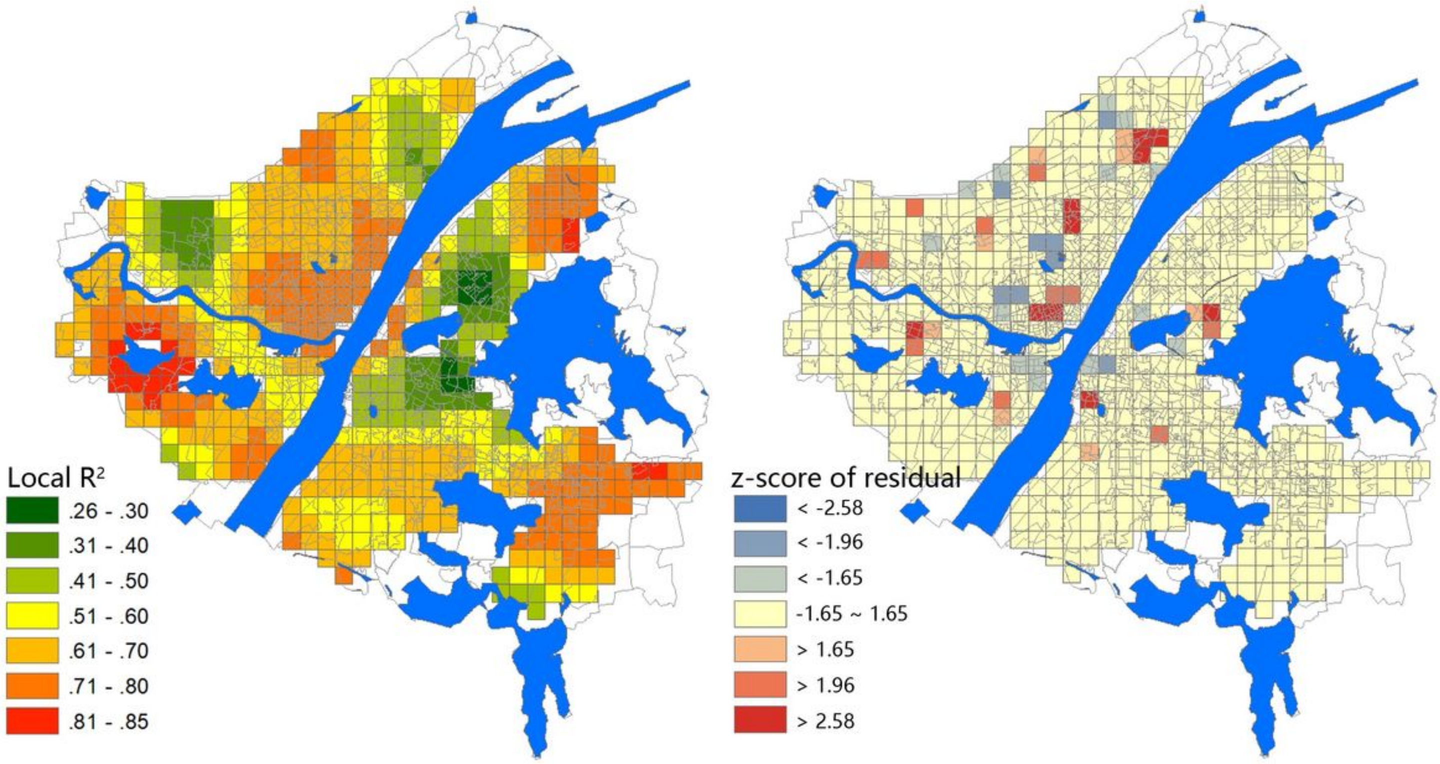

Figure 5

The local R2 value of GWR model and the residual standard deviation with z-score. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

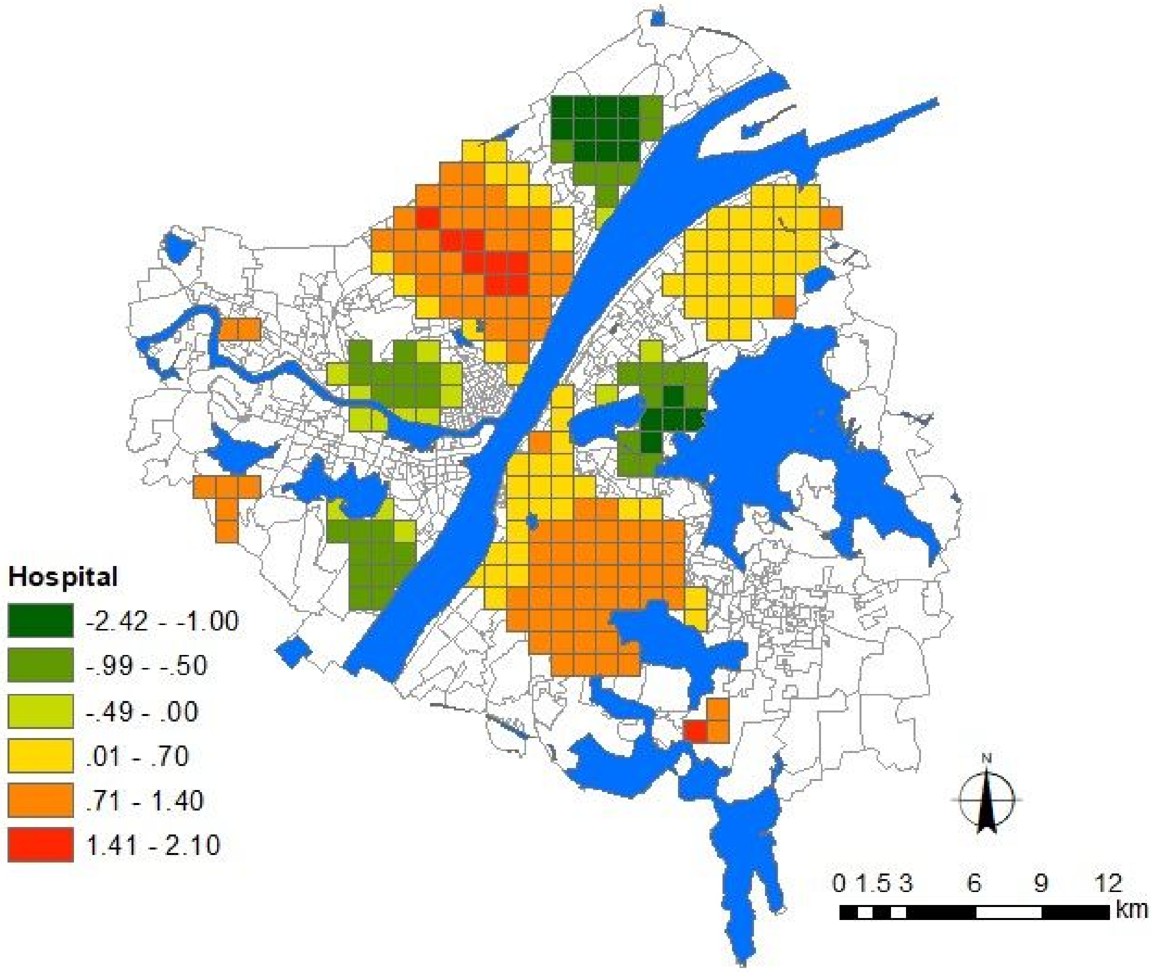

Figure 6

Areas significantly affected by the hospital factor. The legend denotes the corresponding intensity of influence. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

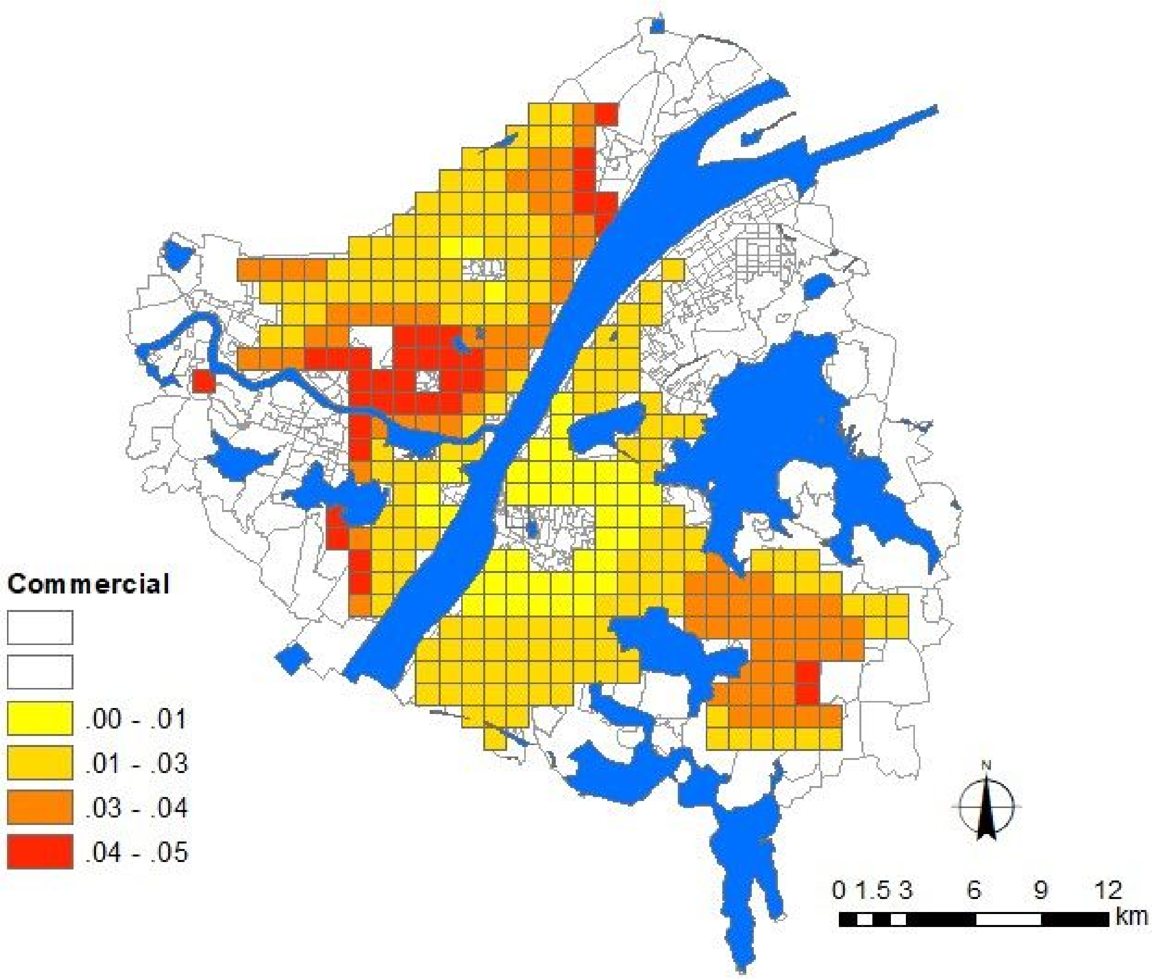

Figure 7

Areas significantly affected by the commercial facilities. The legend denotes the corresponding intensity of influence. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

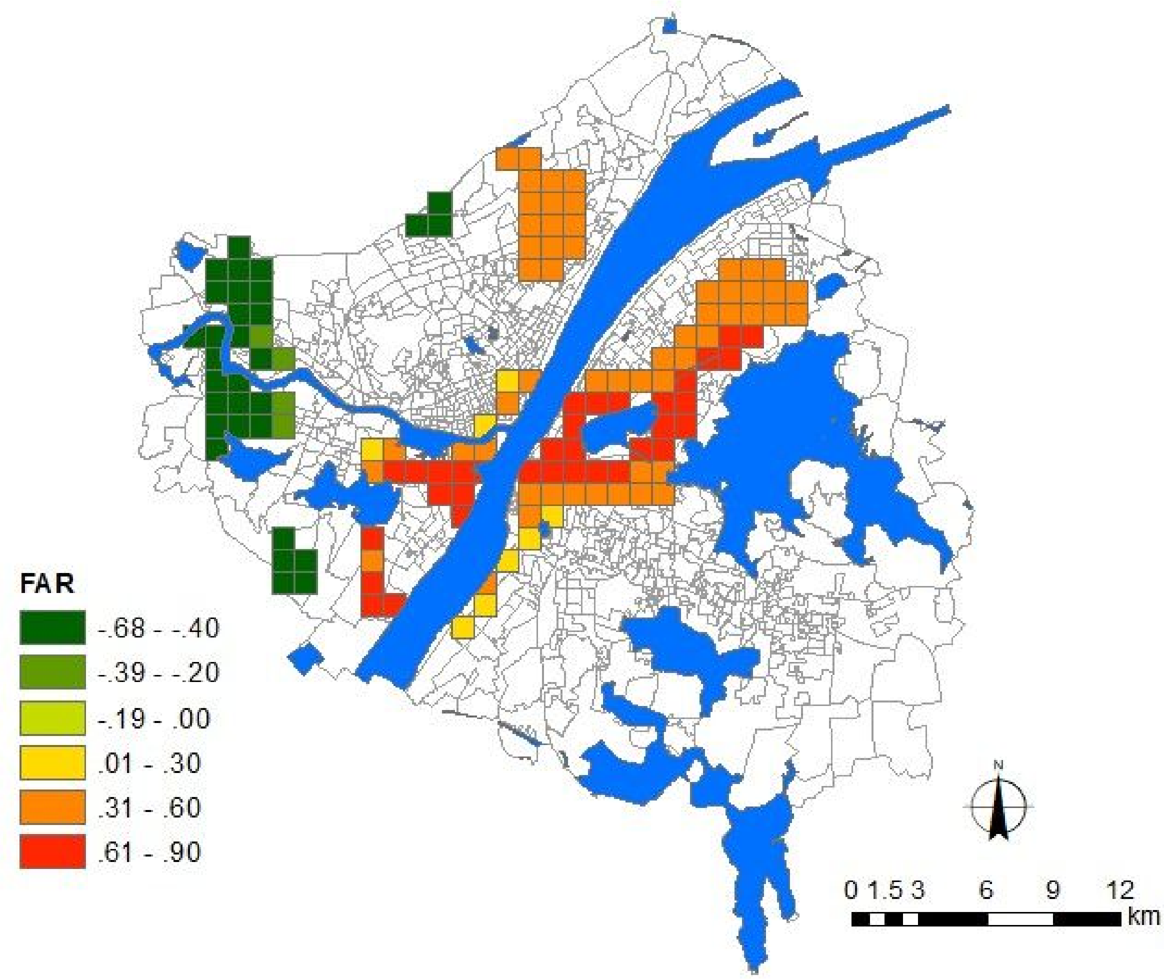

Figure 8

Areas significantly affected by the floor area ratio. The legend denotes the corresponding intensity of influence. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

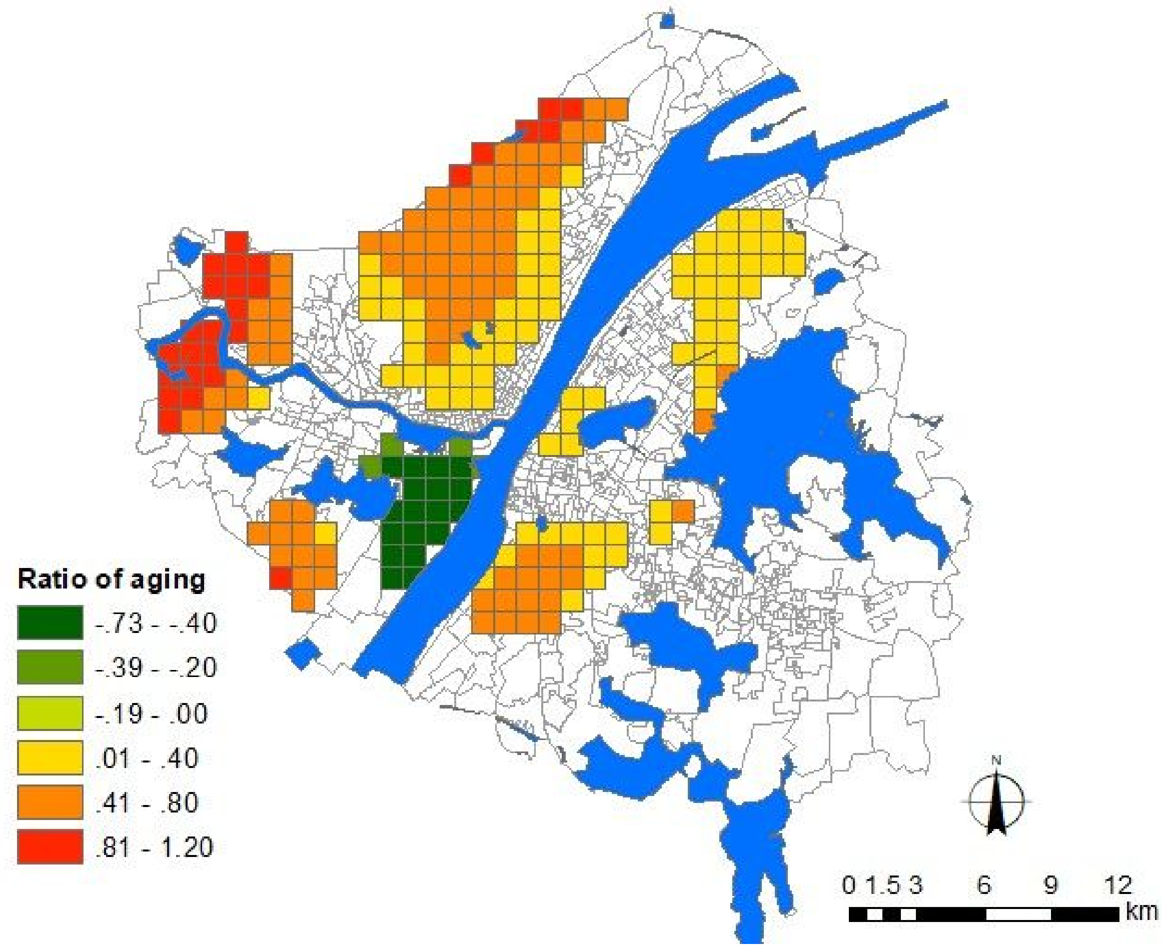

Figure 9

Areas significantly affected by the ration of aging population. The legend denotes the corresponding intensity of influence. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

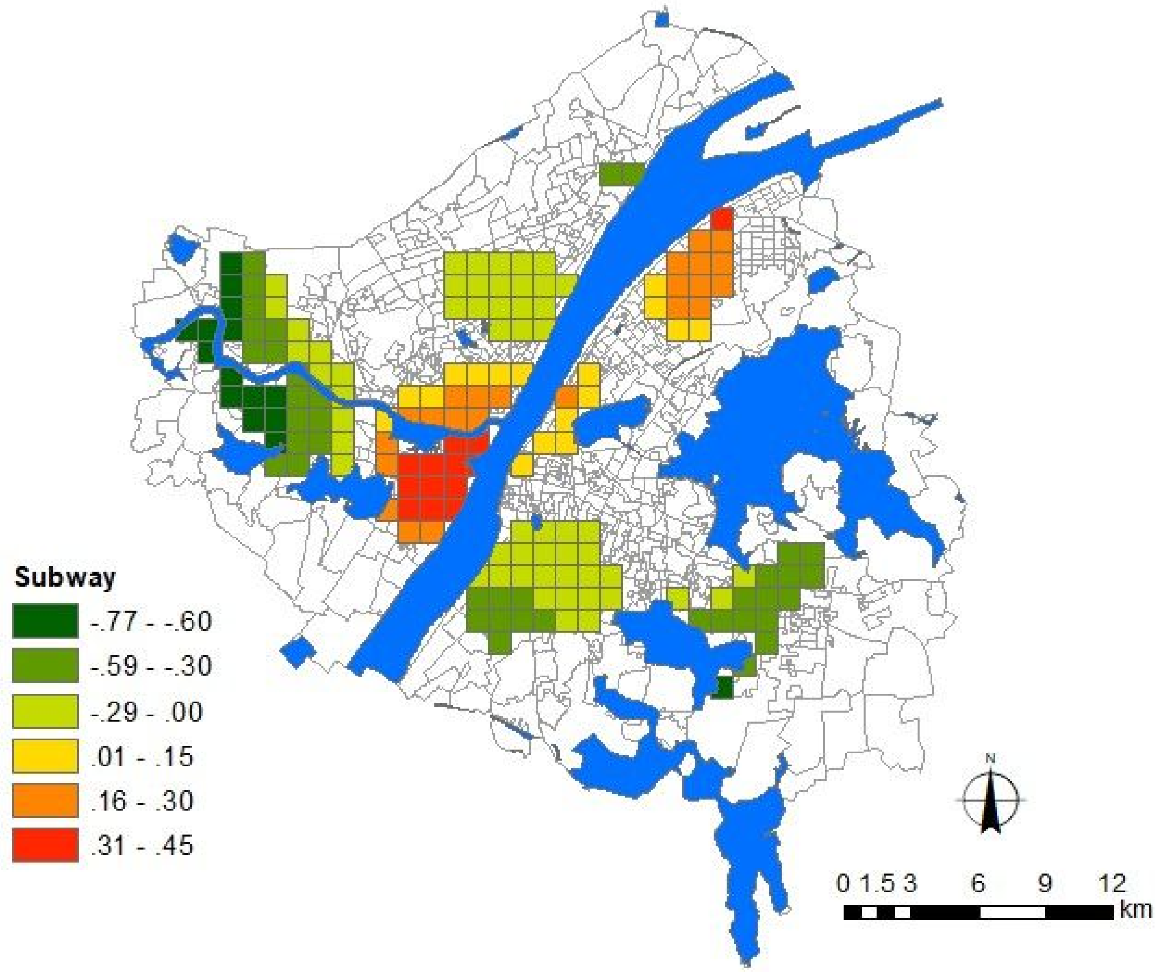

Figure 10

Areas significantly affected by the subway station. The legend denotes the corresponding intensity of influence. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

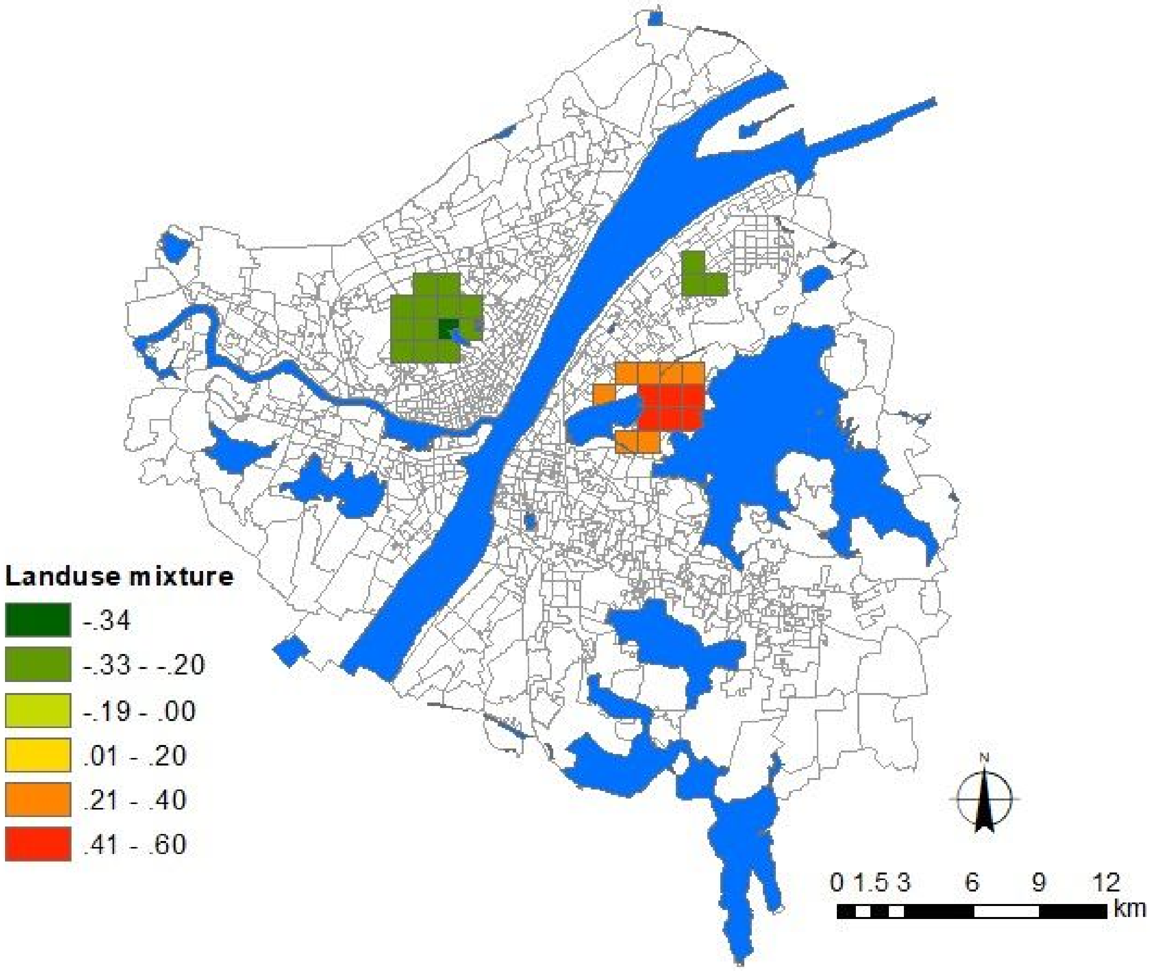

Figure 11

Areas significantly affected by the landuse mixture. The legend denotes the corresponding intensity of influence. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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