1 **Spatial accessibility of emergency medical services under inclement**

2 **weather: A case study in Beijing, China**

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Abstract

18   The accessibility of emergency medical services (EMSs) is not only determined by

19 the distribution of emergency medical facilities but is also very vulnerable to weather

20 conditions. Inclement weather could affect the efficiency of the city's traffic network

21 and further affect the response time of EMSs, which could therefore be an essential

22 impact factor on the safety of human lives. This study proposes an EMS-accessibility

23 quantification method based on selected indicators, explores the influence of inclement

24 weather on EMSs accessibility, and identifies the hotspots that have difficulty accessing

25 timely EMSs. A case study was implemented in Beijing, which is a typical megacity in

26 China, based on the ground-truth traffic data of the whole city in 2019. The results show

27 that inclement weather has a general negative impact on EMSs accessibility. Under

28 inclement weather scenario, the area in the citywide that could get EMSs within 15

29 minutes would decrease by 13% compared to normal scenario, while in some suburban

30 townships, the population that could get 15-min EMSs would decrease by 40%. And

31 we found that snowfall has a greater impact on the accessibility of EMSs than rainfall.

32 Although on the whole, the urban area would have more traffic speed reduction.

33 Furthermore, towns with lower baseline EMSs accessibility is more vulnerable to

34 inclement weather. Under the worst scenario in 2019, 12.6% of population (about 3.5

35 million) could not get EMSs within 15 minutes, compared to 7.5% with the normal

36 condition. This study could provide a scientific reference for city planning departments

37 to optimize traffic under inclement weather and the site selection of emergency medical

38 facilities.

39

40 **Keywords**

41 Emergency medical services (EMSs), spatial accessibility, inclement weather, service

42 area coverage

1 Introduction

Emergency medical services (EMSs) are a pivotal part of the public health system, and the response time of EMSs is a vital factor in decreasing morbidity and improving survival(Blackwell and Kaufman, 2002). In China, the EMS system is mainly composed of prehospital emergency services and in-hospital emergency services. Prehospital emergency service refers to on-site emergency treatment, guardianship in transit, and handover with in-hospital emergency institutions. The efficiency of emergency services is highly vulnerable to inclement weather conditions such as rain, snow, frog, etc. Because inclement weather conditions would reduce road capacity, increase transfer time, and sometimes block roads completely(Agarwal et al., 2006; Chang et al., 2013; Cools et al., 2010; Suarez et al., 2005; Zhang and Chen, 2019), resulting in reduced spatial accessibility and delayed the response time of EMSs. In addition, accidents such as traffic accidents and lightning accidents are more prone to occur in inclement weather, which increases the demand for EMSs (Edwards, 1996; Ramgopal et al., 2021). For example, on July 21, 2012, Beijing was hit by a rainstorm, with the average cumulative rainfall reaching 170 mm, caused 63 roads to be seriously flooded, and led to a one-third increase in the number of calls to the emergency center, and the transfer time of ambulances was significantly prolonged, taking approximately 1.5~2 hours for each evacuation during the rainstorm, while the transfer time wouldn't be more than 1 hour on usual (Wang et al., 2013; Beijing Evening,2012). On February 6, 2022, in Cleveland, US, an ambulance got stuck in the snow causing a long delay getting the patient to the hospital (Fox 8 News, 2022). On August 3, 2021, in Chattogram, Bangladesh, a daily rainfall of 190.6mm caused many ambulances with patients stuck in different areas of the city (Business Standard, 2021). In the context of

global climate change and rapid urbanization, extreme inclement weather events strike cities more frequently(Huber and Gulledge, 2011; Stott, 2016; Stott et al., 2016), the problem of urban rainstorms and waterlogging(the phenomenon of a stagnant water disaster in an urban area due to heavy rainfall or continuous precipitation) has become increasingly prominent. It is therefore of great importance to investigate the influence of inclement weather on the spatial accessibility of EMSs.

The spatial accessibility of EMSs is defined by the travel impedance (distance or time) between service locations and the scene (Guagliardo, 2004). A large body of research on spatial accessibility is concerned with access to hospitals (Luo and Wang, 2003; Mao and Nekorchuk, 2013; Pan et al., 2018; Yang et al., 2020; Yin et al., 2021) and first-aid stations (Hashtarkhani et al., 2020; Jones and Bentham, 1995; Shin and Lee, 2018). To measure the EMSs accessibility, the two-step floating catchment area (2SFCA) method is one of the common methods (Chen and Jia, 2019; Kanuganti et al., 2016; Li et al., 2021; Luo and Qi, 2009). The 2SFCA method considers accessibility to be mediated by not only the distance decay but also the interactions between supply and demand (Chen and Jia, 2019), which is more suitable for normal scenarios. While for studies focusing on the influence of inclement weather on EMSs, people concern more about the transportation situation, instead of the interaction between supply and demand. The coverage analysis method (Coles et al., 2017; Green et al., 2017; Yu et al., 2020) or shortest path analysis method(Albano et al., 2014; Andersson and Stålhult, 2014) are more widely used. These methods could better characterize the reduction of accessibility caused by the road service degradation. For example, Yu et al. (2020) analyzed the accessibility of emergency service in England and identified vulnerability hotspots by quantifying the EMSs coverage of area and population within different time radii under different flood scenarios; Coles et al. (2017) measured the travel time and

92 service area coverage of EMSs in York, UK under flood scenarios by using FloodMap-

93 HydroInundation2D to model flood inundation; Yin et al. (2021) assessed the

94 vulnerability of EMSs to surface water flooding in Shanghai, China by quantifying

95 accessibility in terms of service area, response time, and population coverage,

96 considering four temporal scenarios (nighttime, evening, daytime, and morning–

97 evening peak) of average drive speeds based on a real-time traffic analysis from GPS

98 big data; Andersson and Stålhult (2014) used network analysis methods to generate the

99 shortest paths from hospitals to various administrative areas in Manila, Philippines, and

100 evaluated the impact of different flood events on these paths. Most of these studies

101 assumed that roads are impassable or traffic speed has a certain degree of reduction

102 when the flooded water depth reaches a specific depth, and further evaluated the impact

103 of rainstorm on EMSs accessibility. Due to insufficient recorded traffic data, relatively

104 few studies have been performed to analyze the impact of road access capacity on EMSs

105 accessibility according to actual traffic speed variation.

106   In this study, we explore the impact of inclement weather on traffic and EMS

107 accessibility based on ground-truth traffic data. Beijing which is the capital of China is

108 used as a case study. The reductions in EMSs accessibility of Beijing under inclement

109 weathers in 2019 are quantified, and the urban-rural disparities in the distribution of

110 emergency medical facilities are further analyzed. Our study provides an approach for

111 evaluating the effectiveness and fairness of EMSs based on ground-truth traffic data,

112 and the results can not only provide reference for the optimization of EMSs in Beijing,

113 but also provide reference cases for other cities, which has a great practical significance.

114

2 Study area and dataset

2.1 Study area

Beijing, the capital of China, is located in the northern part of the North China Plain, with a total area of 16,410.54 square kilometers (Figure 1a). According to the seventh national census (http://www.stats.gov.cn/tjsj/tjgb/rkpcgb/), Beijing has a population of 21.89 million. As one of the largest metropolises in the world, Beijing has a monsoon-driven humid continental climate, with an average annual precipitation of approximately 600 mm, 80% of which is concentrated from June to September (Song et al., 2014). The terrain of Beijing is high in the northwest and low in the southeast, which is conducive to the formation of heavy rain and triggers strong convective weather. Beijing has a typical monocentric urban structure, and the area within the Six Ring Road is generally recognized as the urban core area. It is obvious that the density of transportation network and medical facilities in the urban area of Beijing are much higher than those in the suburbs (Figure 1b).

(a)   (b)

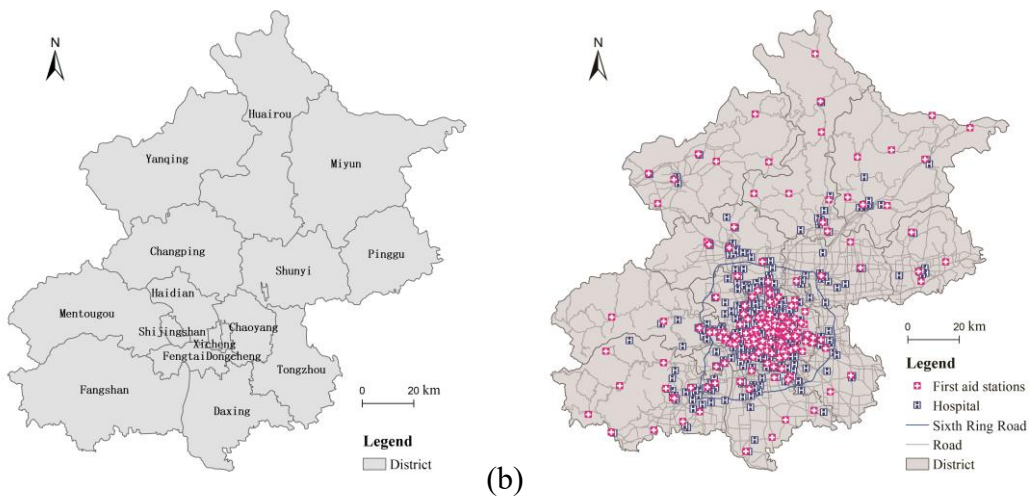



Figure 1. (a) Administrative division of Beijing and (b) EMS facility locations in Beijing

2.2 Dataset

The data involved in this paper mainly include traffic data, meteorological data, EMSs data, and demographic data. Based on traffic data and meteorological data, we could build a topology road network (using node and edge primitives to describe interconnected linear features (roads) and points (roads junctions) on a map) with transfer time as impendence under inclement weather conditions and corresponding normal weather conditions. Combining the topology road network with medical facility locations and the distribution of the population by ArcGIS 10.8, we could further analyze the spatial accessibility of EMSs.

2.2.1 Traffic and road network data

The traffic data of Beijing are obtained from the Beijing Municipal Commission of Transport. The data span is from January 1, 2019, to December 31, 2019, including the average traffic speed (m/s) of each road section, updated every 2 min. The road network data contain 71,188 nodes and 81,523 edges, which can basically cover all the main roads in the whole Beijing area.

2.2.2 Meteorological data

The meteorological data utilized in this paper are TRMM precipitation data obtained from NASA, with a spatial resolution of 0.1°×0.1° (approximately 10 km×10 km) and a temporal resolution of 30 minutes. The whole city of Beijing is covered by 175 grids.

According to the China Meteorological Administration, the moderate rain is defined as the rainfall is 5.0~14.9 mm within 12 hours. We chose intermediate value of the interval and average it to each hour. In this study, we set a rule that if the precipitation

of more than 10 grids (over 5% area of the city) in Beijing is greater than 1.5 mm in 2 hours, it is considered a precipitation event. The average precipitation of the whole city on each date is averaged by the precipitation of all grids. In 2019, 19 working days of rainfall and 3 working days of snowfall were selected.

2.2.3 Medical facilities data

The medical facilities mentioned in this paper mainly refer to two categories. One is the first-aid stations, and the other is hospitals, as shown in Figure 1b. The locations of these first-aid stations were obtained from the distribution map of first-aid stations published on the official website of the Beijing Emergency Center, including 72 stations in the downtown area and 98 stations in the suburbs. The hospital point data were extracted from the online map point of interest (POI) data of Beijing in 2019. After coordinate correction and deduplication, it contains a total of 630 general hospitals, 76 of which are third-level grade-A hospitals (the highest level in the evaluation system of hospitals in mainland China).

2.2.4 Demographic data

The demographic data of 2019 were obtained from WorldPop with a spatial resolution of 100 m×100 m. The data records present the population size.

3 Methodology

Figure 2 illustrates the methodology of this study. We first divide the weather conditions into two categories, inclement weather conditions and normal weather conditions, according to precipitation data. Second, the time impedance of each road

182   section is analyzed based on the road network and traffic speed for both inclement and

183   normal weather conditions, and the respective coverage rate of first-aid stations and the

184   shortest transfer time to hospitals are calculated. Finally, the spatial accessibility to the

185   population is calculated, and hotspots are identified. Both service area analysis and OD

186   Cost Matrix analysis are GIS-based, and was done in ArcGIS 10.8. In this study, we

187   assume that (1) The ambulances move at the average speed all the time and would

188   always take the shortest path in space; (2) In network analysis, the location of facilities

189   is approximately considered to be on the nearest road point vertically; (3) In OD

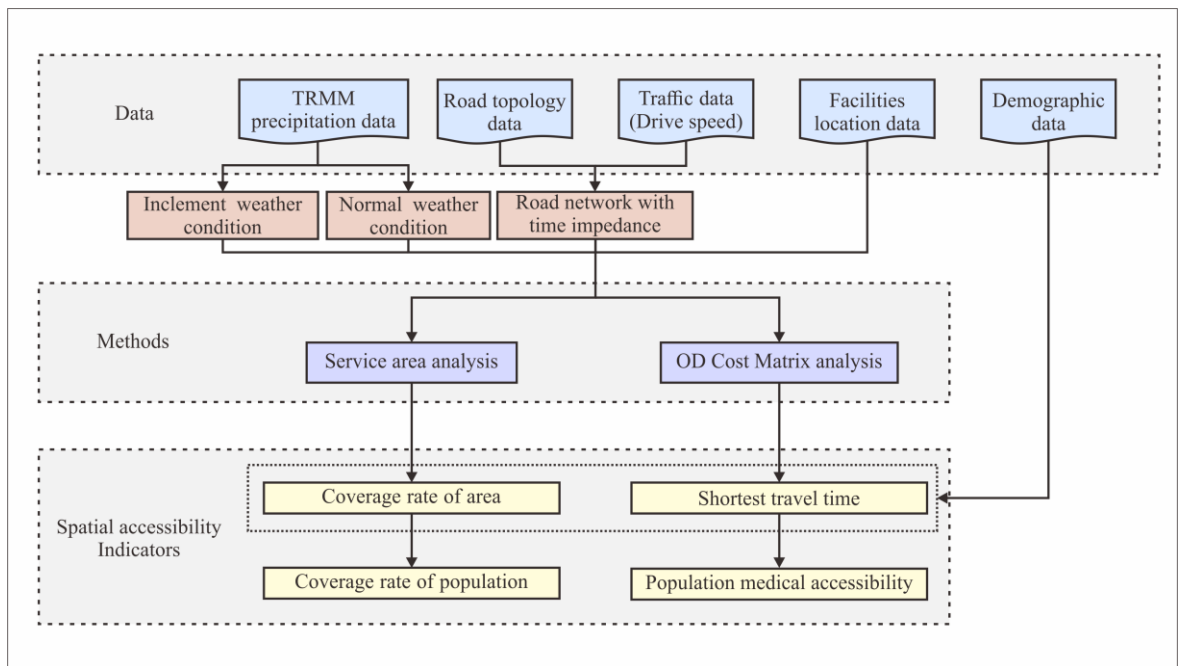
190   analysis, we use the centroid as the origin point to represent the whole grid, and the

191   shortest path to hospital of all points within the grid is the same; (4) The prehospital

192   EMSs is divided into two parts: the ambulances depart from the first-aid station to the

193   scene and from the scene to the nearest hospital. The case where patients transfer

194   directly from the scene to an EMS facility via private transportation will not be

195   considered in this study.

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197   **Figure 2**. Methodology of this study

3.1 Fluctuation of traffic speed under inclement weather

For each weekday with precipitation, the traffic speed data of the selected period are extracted and averaged. To avoid the inherent temporal variations of traffic speed resulting from the day-of-week effects, holiday effects(Cools et al., 2007), season, and other non-meteorological related factors, we introduce baseline days for inclement weather days in this study to calculate the traffic speed fluctuation. For a given precipitation day, we search for the same day of week in the 2 weeks forward and backward to obtain the corresponding baseline days without precipitation. Only nonholidays without precipitation events are selected as baseline days; otherwise, we would continue to look forward or backward until 4 baseline days are found. The average speed data of the four baseline days in the selected period were then averaged as the baseline speed for the given precipitation day, and the traffic speed reduction rate was calculated by eq. (1):

$$r_c = \frac{v_p - \frac{\Sigma_{j=0}^m v_{d_j}}{m}}{\frac{\Sigma_{j=0}^m v_{d_j}}{m}} \quad (1)$$

where r_c is the traffic speed reduction rate in the selected period of the precipitation day to its corresponding baseline days; v_p is the traffic speed in the selected period of the given precipitation day; v_{d_j} is the traffic speed in the selected period of a baseline day, and m is the number of baseline days. In this case, m equals 4. The average traffic speed reduction rate is obtained by averaging the reduction rates of all roads with reduced speed in the city.

3.2 Analysis of coverage rate

3.2.1 The coverage rate of area

A service area is a region that encompasses all roads that are accessible within a

221   specified impedance. Either distance or time can be used as impedance. In this study,

222   the time needed to pass through the road is calculated by the length of each road divided

223   by its corresponding traffic speed, and the service area analysis is carried out with time

224   as the impedance. The core idea of the service area analysis function is to generate

225   service area polygons by setting each first-aid station as the starting point and the

226   traveling time as the driving radius. Under the inclement weather conditions and their

227   corresponding baseline conditions, the service area analysis of the 15-minute(Yin et al.,

228   2021) arrival time was carried out. The total area of the obtained service area polygon

229   is calculated to obtain the EMS coverage. The coverage rate of area is calculated by eq.

230   (2):

231 $$r_a = \frac{\sum A_s}{A} \times 100\% \qquad (2)$$

232   In eq. (2), r_a is the coverage rate of the area; A is the total area of the city, and A_s is

233   the area of the service area.

234   **3.2.2 The coverage rate of population**

235   To analyze the matching degree between the EMS coverage and the population

236   distribution and identify the hot spots whose EMS coverage of the population is most

237   affected in inclement weather, we downscaled the calculation to the township scale.

238   Based on the grid population data of WorldPop and the coverage areas of EMSs under

239   different scenarios analyzed by service areas, we calculated the coverage rates of EMSs

240   of the population for each township. In each scenario, the polygon of service area

241   obtained from the result of service area analysis is used to mask the population grid,

242   and the covered population divided by the total population is the population coverage

243   of the township (eq. (3)).

244 $$r_p = \frac{\sum P_s}{P} \times 100\% \qquad (3)$$

245   In eq. (3), r_p is the coverage rate of the population; P is the total population of the

246   township, and P_s is the population that is covered by the service area.

247

248   **3.3 The spatial accessibility to hospitals**

249   The spatial accessibility to hospitals is quantified by two indicators: the shortest

250   transfer time and the total transfer time. The shortest transfer time is calculated by the

251   OD (Origin-destination) cost matrix analysis method, which can find and measure the

252   minimum cost path from multiple starting points to single or multiple destinations in

253   the network. In this study, we calculate the minimum transfer time od_i required for

254   each population grid centroid to reach the nearest hospital. To reduce the calculation

255   cost, the population grid data with 100 m resolution are aggregated and converted into

256   1000 m resolution. This could be interpreted as a sampling method, because we use the

257   centroid point of the grid to represent the other possible starting points in the grid, and

258   we ignored the tolerance caused by the travel time inside the grids.

259   The total transfer time is introduced to quantify the cumulative transfer time for each

260   population grid based on its population size, which is the number of potential users of

261   EMSs. It is defined in this study by the shortest transfer time of each population grid to

262   the nearest hospital multiplied by its population. For each population grid centroid *i*, its

263   population medical accessibility index (*PA*) is calculated by eq.(4):

264
$$PA = od_i \times P_i \qquad (4)$$

265   In eq. (4), od_i is the minimum transfer time, P_i is the population of the grid.

266

267   **4 Results**

268   Based on the characteristics of morning and evening rush traffic flow on weekdays,

the diurnal variation in traffic can be divided into fourperiods: morning rush hours (7:00-9:00), daily regular hours (9:00-17:00), evening rush hours (17:00-19:00), and evening regular hours (19:00-22:00). We compared EMS coverage at different periods of the day, and the results show that the period of morning rush hours has the most significant negative impact on the accessibility of EMSs. We divided the city into the inner city and suburban areas along the Sixth Ring Road. Taking the average 15-minute coverage of the area of all Mondays in November as an example: (1) in the whole city (both inner city and suburban), the coverage rate of EMSs is 38.72% in morning rush hours, compared with 40% (±0.3%) in the remaining periods; (2) in the inner city, the coverage rate is 77.37% in morning rush hours, compared with 83% (±0.6%) in the remaining periods. Therefore, the accessibility of EMSs during the morning rush period deserves more attention. Hence, our subsequent analysis is mainly concentrated on the morning rush period.

4.1 Impact of inclement weather on the traffic and EMSs coverage

4.1.1 The correlation between precipitation and traffic speed

Figure 3 shows the relationship between average precipitation during morning rush hours in the city and the average traffic speed reduction rate of all roads that have speed loss in the city on weekdays. The unit of precipitation data is mm/2h, which indicates the total precipitation in the 2 hours of morning rush hours. The negative values indicate that the traffic speed decreases in inclement weather conditions. We could see that the average traffic speed would decrease 10%~15% on most precipitation days. The average speed decreases most on July 1st, July 9th, September 10th and December 16th, reached 18%~25%. July 1st (Party's Day) and September 10th (Teachers Day) are special days in China and the traffic speed is affected by both the inclement weather and traffic

294   control. December 16th was a snowy day with a precipitation of 0.13 mm/2h, and

295   snowfall has a greater impact on traffic than a rainfall with the same precipitation

296   (Agarwal et al., 2005). ==Figure 4 illustrates the spatial difference of traffic speed==

297   ==reduction and distribution of precipitation on precipitation days. A large number of red==

298   ==roads (with traffic speed reduction over 10 km/h) can be observed in the 4 days==

299   ==mentioned above. By comparing the distribution of precipitation and traffic speed==

300   ==reduction on different dates in Figure 4, it can be found that the precipitation in the four==

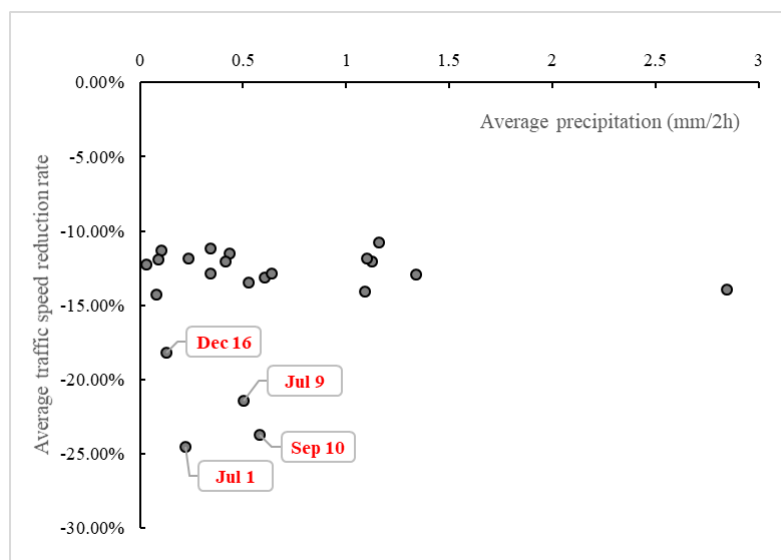
301   ==days with the most severe speed reduction was moderate, and the precipitation==

302   ==distribution of the whole city was relatively uniform. Compared with other rain days,==

303   ==although the precipitation on July 5, August 9 and September 19 was larger and==

304   ==concentrated in the inner city, the traffic speed reduction of the whole city was not as==

305   ==serious as the four days mentioned above, which may be caused by the decrease of==

306   ==people's willingness to travel with the increase of rain.==

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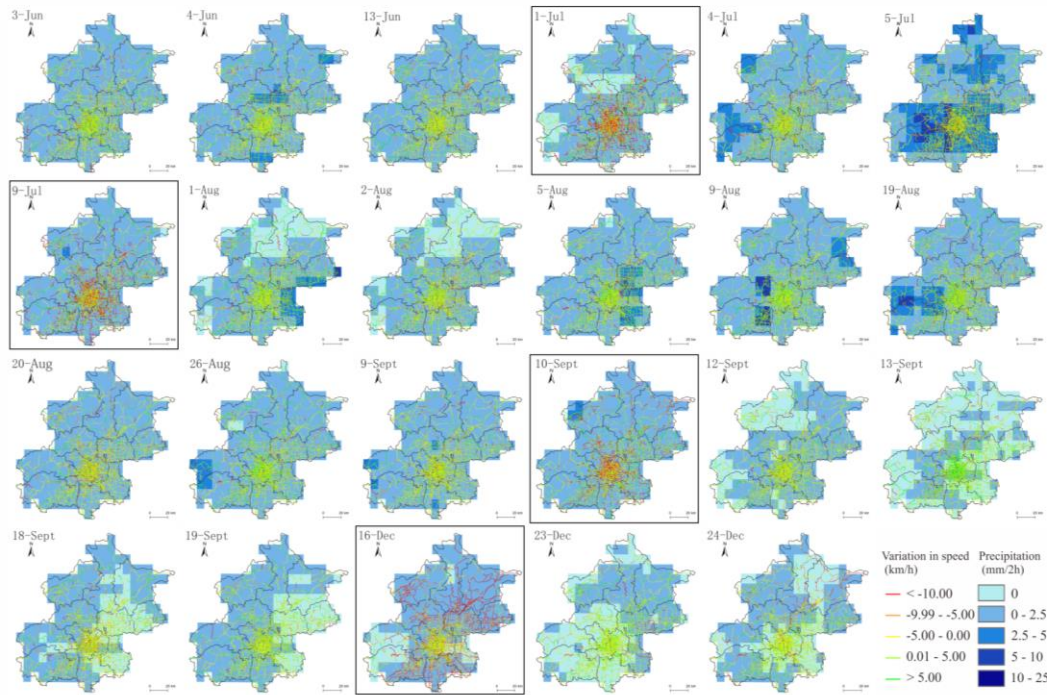
308   **Figure 3.** The correlation between average precipitation and average traffic speed reduction rate

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312 **4.1.2 The correlation between precipitation and EMSs coverage rate**

313   The change in the coverage rate of EMSs was calculated by subtracting the coverage

314 rate under the inclement weather condition from that under the corresponding baseline

315 condition. Figure 5 shows the correlation between the average precipitation during

316 morning rush hours and the relative change values of the EMS coverage rate of the area.

317 The negative values indicate that the coverage of EMSs decreases in inclement weather

318 conditions. Consistent with the pattern of the traffic speed reduction, the worst loss of

319 coverage rate also occurred on three rainy days: 1st July (Mon), 9th July (Tue), and 10th

320 September (Tue), and one snowy day: 16th December (Mon), in which the 15-minute

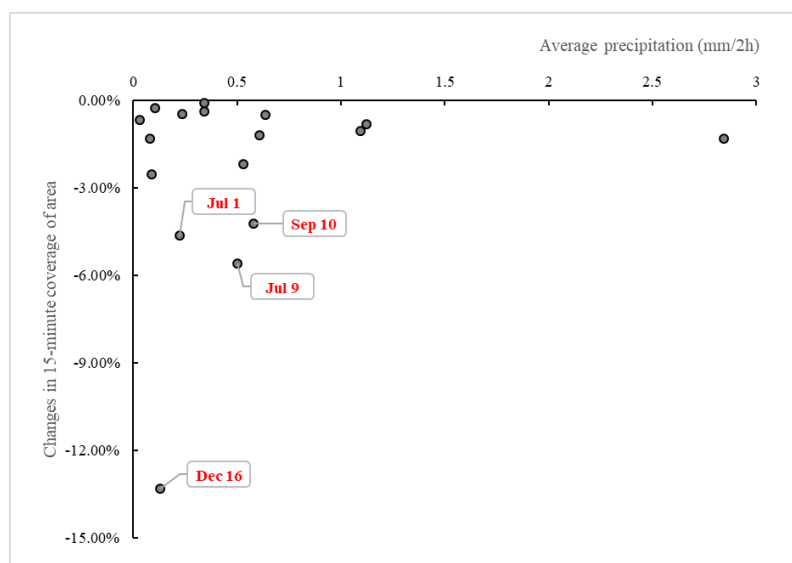
321 EMS coverage rate reduced by 4.6%, 5.6%, 4.2% and 13.3%. Combined with the spatial

322 distribution of precipitation and traffic variation (Figure 4) to analyze, the snowfall on

323 December 16th caused a large traffic speed reduction of the suburban roads, which led

324 to a significant reduction in overall EMS coverage. Therefore, we chose these four days

325   as the worst weather scenario of the year and analysis the spatial differences of medical

326   accessibility in the whole city.

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328   **Figure 5**. The correlation between the average precipitation and the relative change of the EMS

329   coverage rate of the area

330

331   **4.2 The spatial distribution of EMS accessibility under the worst scenario**

332   **4.2.1 EMSs coverage rate of population**

333   We calculated the 15-minute EMS coverage rate of the population under the four

334   most severely affected inclement weather conditions of 1st July, 9th July, 10th September,

335   and 16th December and their corresponding baseline conditions at the township scale in

336   Beijing. Figure 6 shows the 15-minute EMSs coverage rate of population under four

337   most severely affected inclement weather conditions of 1st July, 9th July, 10th

338   September and 16th December and their corresponding baseline conditions at the

339   township scale in Beijing. The results demonstrate that most parts of downtown areas,

340   including Dongcheng District, Xicheng District, Haidian District, and Chaoyang

341   District, could have 90%–100% population coverage of EMSs, regardless of the

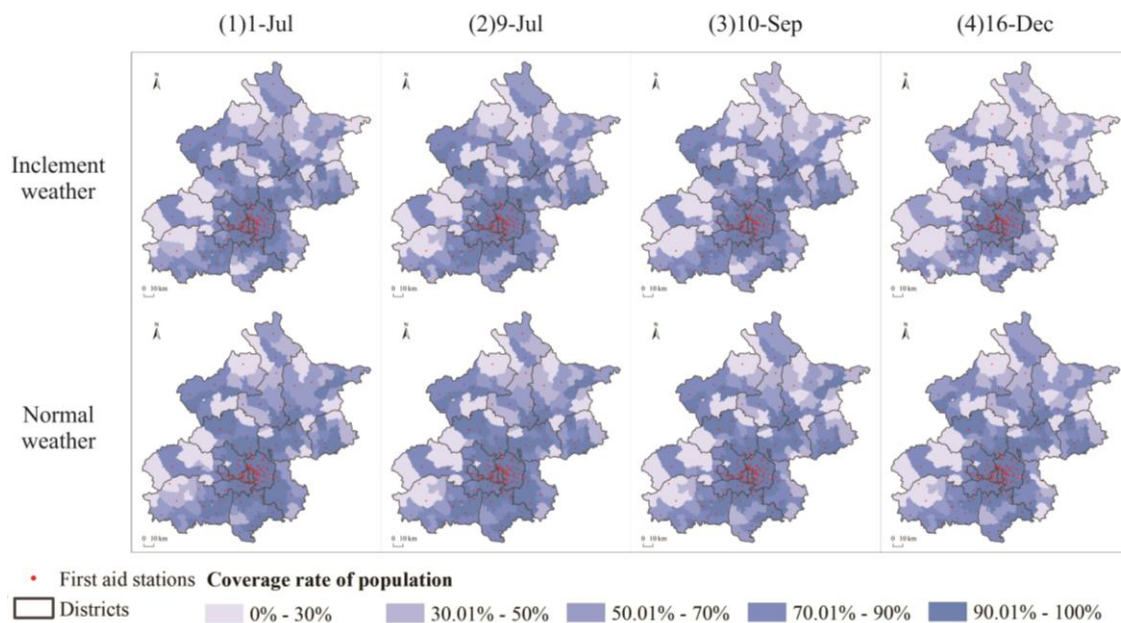
342   weather conditions. In the large area of suburbs, the coverage rate of the population

varied from lower than 30% to 90%. Under inclement weather conditions, the coverage

rate in some towns in the suburbs would drop sharply, with the worst townships having

a 40% reduction. The reason behind this difference is that the distribution of first-aid

stations in Beijing is similar to the distribution of the road network, which is dense in

the central urban area and sparse in the suburbs.

To illustrate the impact of inclement weather on the EMS coverage rate of the

population more clearly, Figure 7 shows the change in the EMS coverage rate of the

population in townships in inclement weather relative to normal weather on the four

days. The results identify several townships in the outer suburbs (Miyun, Huairou,

Pinggu and Yanqing districts) that would experience the most severe decrease in

population coverage under inclement weather conditions, with a maximum reduction

of more than 40%. These areas are hot spots that need to draw attention in EMS

construction planning. Compared with other districts in inner suburbs, such as Shunyi,

Daxing, and Tongzhou, these areas are farther away from the city center and have less distribution of medical facilities and sparser road networks and more vulnerable to inclement weather, and these areas are also regions with a relatively higher proportion of the elderly population over the age of 80 in the total population. The average proportion of the elderly is 1.88% in the whole city, 1.37% in the inner suburbs and 2.04% in the outer suburbs. On December 16th, 12.6% of population (3.5 million) could not get EMS within 15 minutes, compared to 7.5% with the baseline condition.

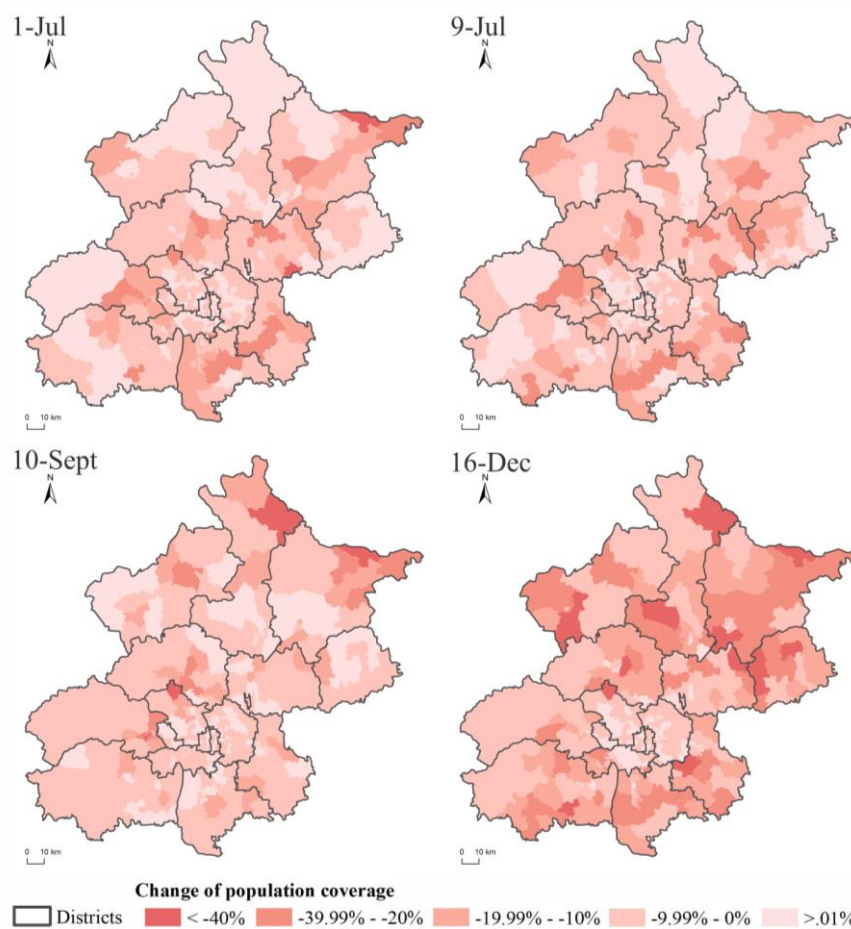



Figure 7. The change in EMS coverage rate of the population in townships in inclement weather relative to normal weather on 1st July, 9th July, 10th September, and 16th December

Figure 8 shows the correlation between the baseline EMS coverage rate of the population of each township and its reduction under inclement weather. The results

373 reveal that the population of the towns with low baseline EMS coverage rate would lose

374 more EMS coverage under inclement weather, especially on snowy day. The average

375 traffic speed reduction in the urban area (within the Sixth Ring road) was -26.64%, -

376 23.27%, -25.20% and -15.77% on 1st July, 9th July, 10th September, and 16th

377 December, while that in the suburban area (outside the Sixth Ring Road) was -19.59%,

378 -19.08%, -17.27% and -23.21%. Based on the results, we analyzed the reasons why that

379 suburban area would become more vulnerable under inclement weather. Combined

380 with the traffic speed reduction and the EMS coverage reduction, on rainy days,

381 although the urban area has more traffic speed loss, the suburban area still experiences

382 more EMS coverage loss. Once the inclement weather affects the traffic on some road,

383 the urban areas still have many other roads than can bypass, but not in suburbs. And on

384 snowy days, the suburban area has more traffic speed reduction, and with the sparser

385 road network, the EMS coverage in the suburban area would shrink much more than

386 rainy days.

387

388

389   (a)   (b)

4.2.2 The accessibility to hospitals

Figure 9 shows the increased transfer time from each population grid to the nearest hospital under the four inclement weather conditions of 1st July, 9th July, 10th September, and 16th December relative to the baseline condition. The value indicates the impact of inclement weather on accessibility to hospitals. The situation is slightly different on rainy days and snowy days. On rainy days, the shortest time to reach the nearest hospital generally could increase by 0–10 minutes in most parts of Beijing due to slower traffic speed on the roads caused by rain. Although in some small parts of suburban areas, the shortest time to the nearest hospital would be slightly shortened on indicating that the traffic will be smoother in some areas when it rains, which may be due to the reduction of traffic demand (Maze et al., 2006). While on 16th December, affected by snow, the whole city's road traffic generally slowed down, and the transfer time to the nearest hospital increased by 10–40 minutes. The western part of Mentougou District and a small part of the northern Yanqing District were the most affected, with the time needed to reach the nearest hospital prolonged by more than 30 minutes, up to 45 minutes. In Huairou district, the eastern part of Yanqing district, and the northern part of Miyun district, the transfer time was also prolonged by 11–30 minutes.

Increased travel time (min): ■ < 0 ■ 0 - 10 ☐ 11 - 20 ■ 21 - 30 ■ > 30

411

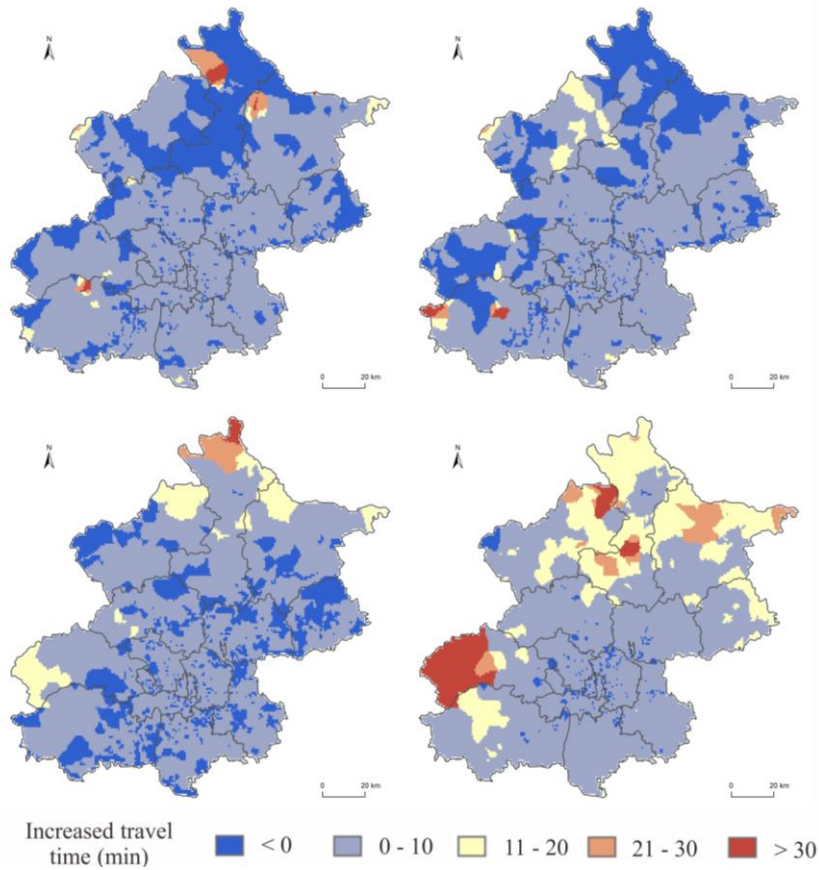
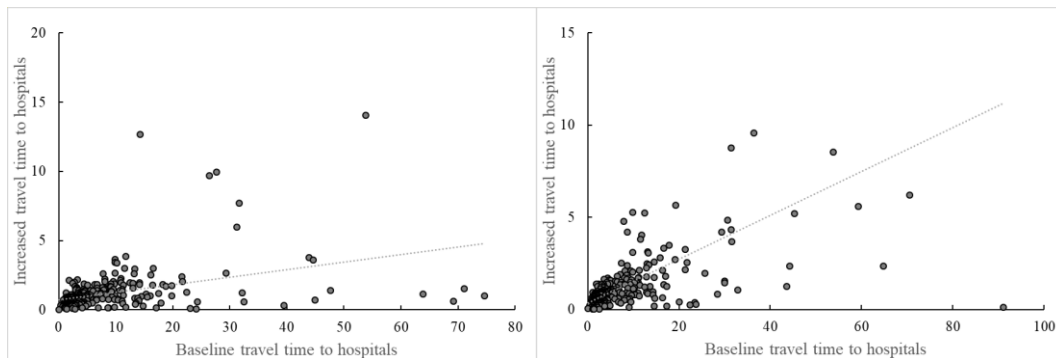
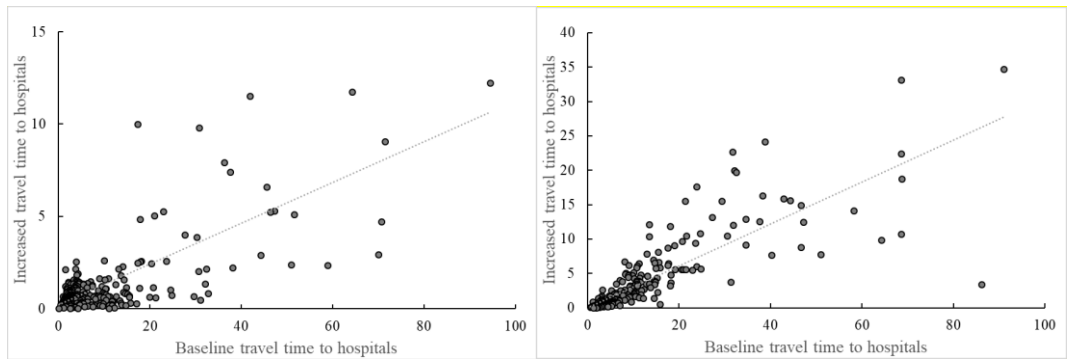



Figure 9. Increased transfer time to hospitals on 1st July, 9th July, 10th September, and 16th

413   December

We did a zonal statistic of the average baseline transfer time to hospital and the average increased transfer time to hospitals to each town, and the correlation between the two indicators shown in Figure 10 indicate the similar pattern with the EMS coverage, which is the towns with low baseline accessibility to hospitals would also more affected by inclement weather.

420   (a)   (b)

421

422   (c)   (d)

423   **Figure 10**. The correlation between the baseline transfer time to hospitals and the increased transfer

424   time in inclement weather. (a) 1st July, (b) 9th July, (c) 10th September, and (d) 16th December

425   Overlaying the demographic grid data, the size of the population affected by a

426 delay of over 10 minutes would be 0.02 million on 1st July, 0.03 million on 9th July,

427 0.05 million on 10th September, and 0.3 million on 16th December.

428   Figure 11 shows the change in the total transfer time under inclement weather

429 conditions on 1st July, 9th July, 10th September, and 16th December, relative to the

430 baseline conditions. The results show that on three rainy days, 1st July, 9th July, and 10th

431 September, within the Sixth Ring Road extent, the total transfer time increased

432 significantly under inclement weather, which means that, although the transfer time

433 would not increase much in urban areas, due to the high population density, the

434 cumulative delay time for total potential demand would be significant. In the suburbs,

435 the total transfer time would increase slightly or even decrease, especially in some areas

436 of Huairou, Yanqing, and Miyun districts, which means that, although the transfer time

437 would increase greatly, due to its low population density, the cumulative delay time for

438 total potential demand would not be serious. However, due to the influence of snowfall

439 on 16th December, the total transfer time in the whole city was slightly or moderately

increased, and there were almost no regions where the total transfer time decreased, which means snowfall would cause an even cumulation of delay time for total potential demand across the whole city, both urban and suburban.

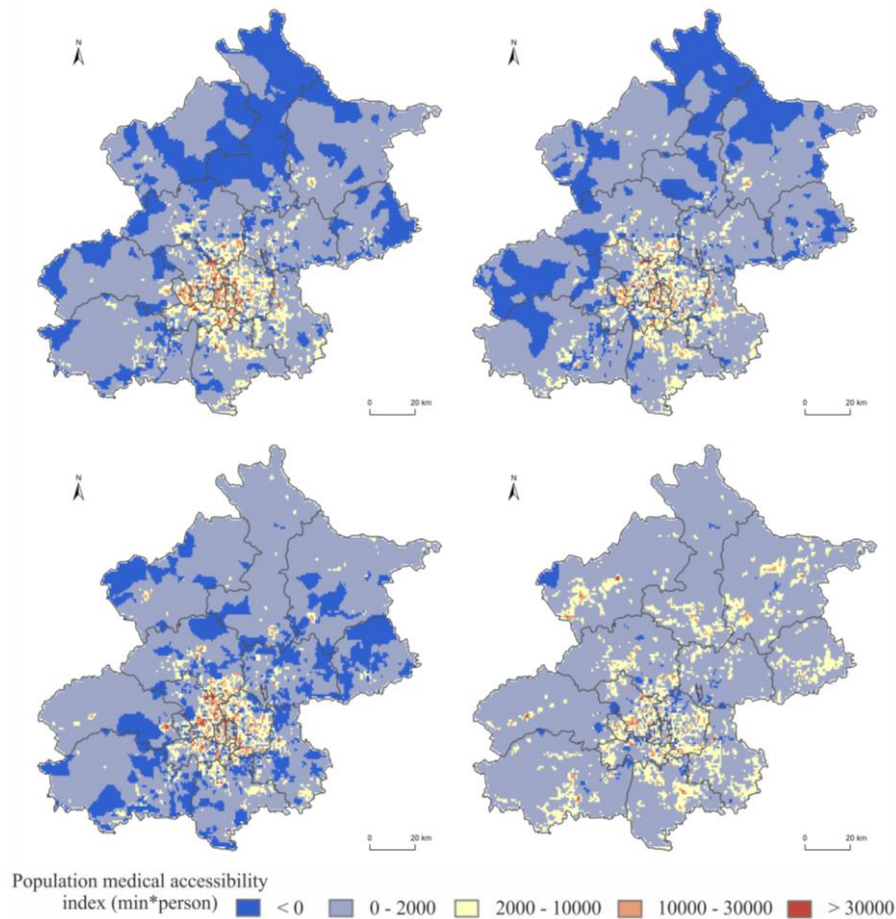



Figure 11. The change in the total transfer time on 1st July, 9th July, 10th September, and 16th December

5 Conclusions and discussion

Our study evaluates the spatial accessibility of EMSs in Beijing under different weather conditions in 2019 based on city-scale ground-truth traffic data updated every 2 minutes. The spatial accessibility of EMSs was quantified by the coverage rate of the first-aid stations' service area, the coverage rate of first-aid stations' service population, and the shortest transfer time to the nearest hospital. Our study reveals the influence of

precipitation on the accessibility and equity of EMSs, which could help guide EMS construction planning in cities, get prepared for extreme weather conditions, and finally assist the decision-making of the corresponding government departments. The main conclusions are as follows:

First, the results show that inclement weather, such as rainfall and snowfall, could have a negative impact on the accessibility of EMSs overall. Precipitation reduces the driving speed of vehicles on the road, thus reducing EMS coverage. In severe cases, the EMS coverage rate of the area can be reduced by more than 10%. Besides, snowfall has a greater impact on EMSs accessibility than rainfall.

Second, the EMSs accessibility is more affected by inclement weather in places with low baseline accessibility to EMSs. And the results reveal a serious rural-urban disparity in emergency medical facilities distribution in Beijing: The EMSs accessibility of population in some townships of the outer suburbs is very low and would also greatly reduce under inclement weather.

Third, some specific days may affect the traffic flow, which has an amplification effect on the traffic congestion caused by inclement weather. When they encounter the inclement weather, there are potential risks of decrease of traffic efficiency and EMSs accessibility, which should be given sufficient attention.

To the best of the authors' knowledge, this study provides a first attempt to analyze the spatial accessibility of EMSs under inclement weather based on city-scale ground-truth traffic data and meteorological data, where the former is usually difficult to obtain. In previous literature, simulation methods were widely used on the research on EMSs accessibility or traffic capacity under inclement weather. The ground-truth traffic data that covers every road in the whole city, was hardly used in the previous studies of the impact of weather on traffic and accessibility. Our study could be a good empirical

verification in this field of study. The reduction extent of EMSs accessibility was close to previous studies. We also found that snowfall may have a greater impact, which is hard to find out using flood simulation methods. The results from this study provide a scientific reference for city planning departments in Beijing to optimize the site selection of emergency service facilities and get prepared for traffic dispersion on inclement weather. The relevant methods mentioned in this paper is also suitable for both holidays and workdays and can be easily applied to other cities once traffic data or empirical formulas regarding the impact of inclement weather on road traffic can be obtained.

However, there are also some limitations in this study. First, we averaged the traffic speed reduction rate of all the roads in the city, as well as the precipitation data, which could conceal congestion hotspots. In further studies, with higher resolution precipitation, along with corresponding traffic data, we could narrow the scale to blocks, pay more attention to local congestions, and analyze the correlation of precipitation and traffic speed on a finer scale. Second, due to the data limitation, we could only analyze the EMSs accessibility in 2019, and the precipitation intensity in this year was not quite high. If with longer time series precipitation and traffic data, we could analyze the impact of precipitation magnitude to the traffic and accessibility, instead of simply dividing the days in a binary manner into inclement and non-inclement weather days. Under such precipitation conditions, the EMSs accessibility has been affected to a certain extent, and it would be much more difficult to get timely EMSs under even more extreme inclement weather condition. So, the future studies should take the risk of extreme precipitation event into account. Third, due to the lack of high-resolution DSM data, we didn't run a hydrological flood simulation in Beijing, which could reveal the relationship of precipitation and the actual amount of water on the streets. And this

503 could be improved in the future studies with more high-resolution topographic data.

504

Data availability

506 All raw data can be provided by the corresponding authors upon request.

Author contributions

508 KL planned the research; JZ, ML provided the traffic data; YZ and KL analyzed the

509 data, YZ wrote the manuscript draft; KL, XN, MW, and DY reviewed and edited the

510 manuscript.

Competing interests

512 The authors declare that they have no conflict of interest.

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