Exposure Assessment of Rainstorm Disaster Based on Land Use and Precipitation Extreme: A Case Study of Beijing, China

Yao Simin
Institute of Public Safety Research, Tsinghua University
ysm5261@sina.com

Zhong Shaobo
Institute of Public Safety Research, Tsinghua University
zhongshaobo@tsinghua.edu.cn

ABSTRACT

The risk of rainstorm disaster is expected to increase with rising disaster losses as a consequence. Besides the uncertainty of frequency and severity of rainfalls, it can also be attributed to the expansion of settlement and industrial areas and the resulting accumulation of population and assets. Therefore, it's important to both analyze historical precipitation and estimate land use condition. In this study, the data of land use status and historical heavy rainfalls of 16 districts in Beijing are collected to obtain the exposure level zoning map and carry out a comprehensive analysis. This is followed by Spearman's rank correlation analysis and the correlations between the exposure and disaster losses have been discussed. This study presents a new perspective of exposure assessment, and some useful ideas about city planning and management are proposed in view of the inevitable trend of rapid urbanization in China.

Keywords

Rainstorm disaster, exposure assessment, land use, precipitation extreme

INTRODUCTION

Every year, catastrophic rainstorms attack many regions in the world including large cities like Beijing, accompanied by some secondary disasters like urban flooding and water-logging, leading to terrible casualty and economic loss. As the frequency and severity of this natural disaster are on the rise, devastating rainstorms will keep posing a great threat on human being's life and property, especially in metropolises where population, buildings and houses, infrastructure and lifelines are in high density. However, the rainstorm, which is commonly referred to as torrential rainfall within a short time, do not necessarily lead to harmful outcome, since the damage results from an interaction of physical and societal process (Cammerer, Thieken and Verburg, 2013). Three aspects comprise the concept of risk in terms of rainstorm disaster, that is, the hazard, characterized by the probability and intensity of heavy rainfall, the extent of which the region is exposed to potential adverse consequences, and the vulnerability of communities (Cavan and Kaźmierczak, 2011). While hazard is the source and vulnerability is the receptor of disaster risk (DEFRA & EA, 2006), exposure plays the role of pathway and can exacerbate or reduce the magnitude of hazard's impact on vulnerable receptors (which can be people, infrastructure, buildings, or other). In the last few decades, many studies have raised awareness of the relationship between land-use and rainstorm disaster, and recognized the land-use condition as a significant or even decisive factor affecting the risk of rainstorm disasters (Liu and Li, 2014). A great many hydrological models have been carried out to evaluate the impact of land use acting on the rainfall-runoff mechanism and disaster magnitude since the end of 1950s (Lin, Verburg, Chang and Chen,2009; Naef, Scherrer and Weiler, 2002; Niehoff, Fritsch and Bronstert., 2002). However, most studies have focused on performing conceptual models to analyze the relationship between land use and disaster risk which is from the view of "pathway-receptor", lacking the analysis of how specific rainfall condition affects the extent of exposure which is from the view of "source-pathway". So this paper is a first attempt to combine both land utilization and precipitation in exposure assessment of rainstorm disaster. We collect land use and historical rainfall data of 16 districts in Beijing, the capital of China. After data processing, the exposure assessment is then conducted using the Exposure Matrix with zoning map displaying the result. With the non-parametric analysis, the correlation between disaster exposure and disaster losses has been found followed by a discussion. Our work is supposed to help mitigate social and economic damages caused by the rainstorm disaster and contribute to a more robust risk assessment.

STUDY AREA

Beijing (115º42'-117º24' East, 39º24'-41º36' North) lies in the north of Huabei plain (Figure 1). The north-western part is located at the intersection of Taihang mountain range and Yanshan mountain range, and south-eastern part is the Beijing Sub-plain. Beijing has a typical temperate and monsoon climate with four clearly distinct seasons. Seasonal distribution of precipitation is uneven, and heavy rainfalls often occur in July and August, leading to catastrophic consequences. In our work, the study area covers 16 districts of Beijing which are frequently affected by rainstorm disasters in summer.

DATA AND METHODS

Data of Land Use

The definition of rainstorm or flood exposure which refers to people and property affected by the disaster indicates that, faced with a similar precipitation level, the areas suffering the greatest loss would be related to high residential use or high value of land (ADCR, 2005). So higher exposure results from more people affected and greater economic loss potentially caused by devastating torrential rain. The extent of exposure is then related to the intensity of people occupation and the economic value of land. In this study, the Landsat TM image of Beijing in 2012 is acquired from "Data Sharing Infrastructure of Earth System Science", offering the recent status of land cover, land vegetation, agriculture activity and surface hydrology. Several other data sources, such as aerial photographs and "2012 Beijing Statistical Yearbook" are combined with the Landsat TM image to form land-use map of Beijing in 2012 (Figure 1). According to the National Land Use Classification Standard, areas in the map are subdivided into the following 7 categories.

1. Agriculture areas: areas for agriculture activities, including paddy field and upland field.
2. Forests: areas for natural reserves, forest parks, wildness areas, etc. , including forest land, shrub land, open wood land and other forests.
3. Grassland: areas for range land and pasture land, including high, medium and low coverage grassland.
4. Water areas: areas including rivers, lakes, reservoirs and wetland.
5. Residential and commercial areas: areas for gated communities, dwellings, family housing, office buildings, schools, supermarkets, etc., including urban areas and rural residential areas.
6. Industrial areas: areas for manufacturing plants, industrial warehouses, mining fields, etc.
7. Unutilized land: areas including marshes and barren land.

In the study, the percentages of built-up areas (residential areas, commercial areas and industrial areas) in the total land areas have been counted for 16 districts of Beijing. And the percentage of built-up areas is assigned into four grades: 0-10% (grade Ⅰ), 10%-25% (grade Ⅱ), 25%-50% (grade Ⅲ), 50%-100% (grade Ⅳ). The grade of land use is then applied as the indicator reflecting the impact of land use condition acting on the exposure to rainstorm disaster.

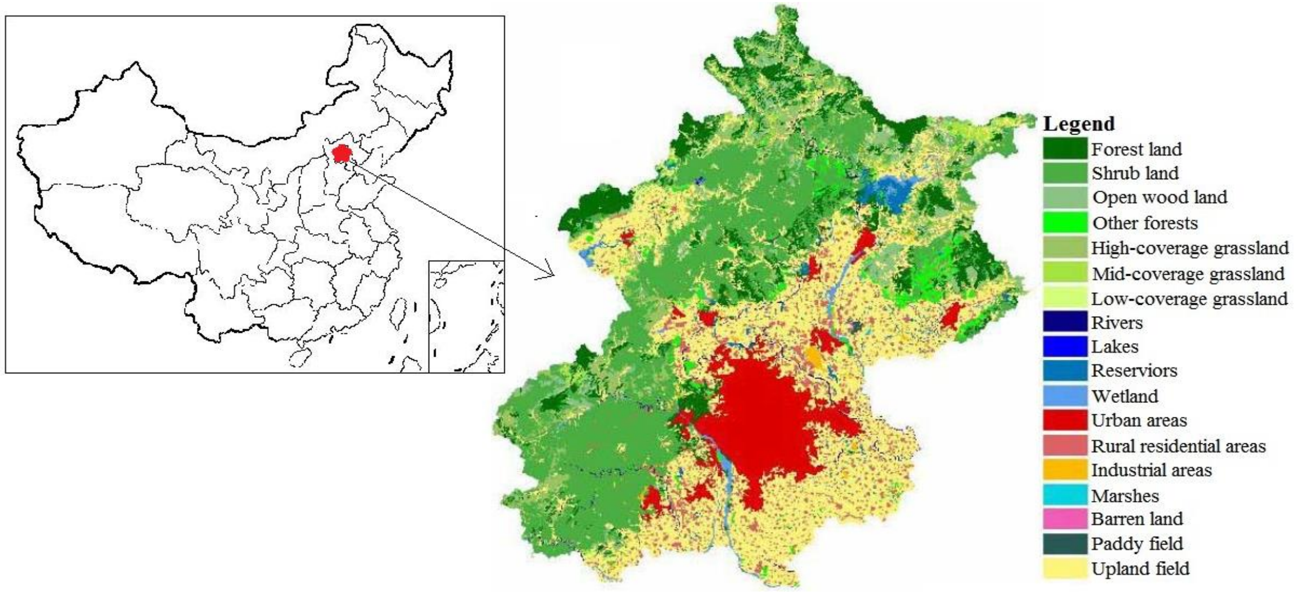

Figure 1. Land use pattern of Beijing in 2012

Data of Historical Precipitation

Extreme precipitation events are closely related to the exposure to rainstorm disasters and in most cases, can be the decisive factor affecting casualty and economic loss. Areas which were frequently attacked by extreme precipitation events in history are more likely to suffer from heavy rainfall in the future, hence a greater extent of exposure to the rainstorm disaster. In the study, daily precipitation data from 1981~2012 of 16 districts in Beijing are collected to analyze historical extreme precipitation events. The topography of Beijing is complex and the climate varies a lot among areas, so defining extreme precipitation events by absolute threshold results in poor comparability among different districts. A commonly used method in extreme climate research is then adopted in our work, in which a certain percentile is taken as the threshold of the extreme climate event. For each district, daily precipitation data from 1981~2012 which are greater than 0.1mm are sorted in ascending sequence, and the 99th percentile is selected as the threshold of extreme precipitation event for this district. According to Bonsal et al.(2001), if *n* values of a certain meteorological element are put into ascending order as $x_1, x_2 \cdots x_m \cdots x_n$, the possibility of which a certain value is less than or equal to x_m is

$$P = (m - 0.31)/(n + 0.38) \quad (1)$$

Where *m* is the sequence number of x_m , and *n* is the total number of all values. For instance, if *n* is 1000, the 99th percentile value is the linear interpolation of x_{990}

(P=98.93%) and x_{991} (P=99.03%) in the ascending order. For every district, data

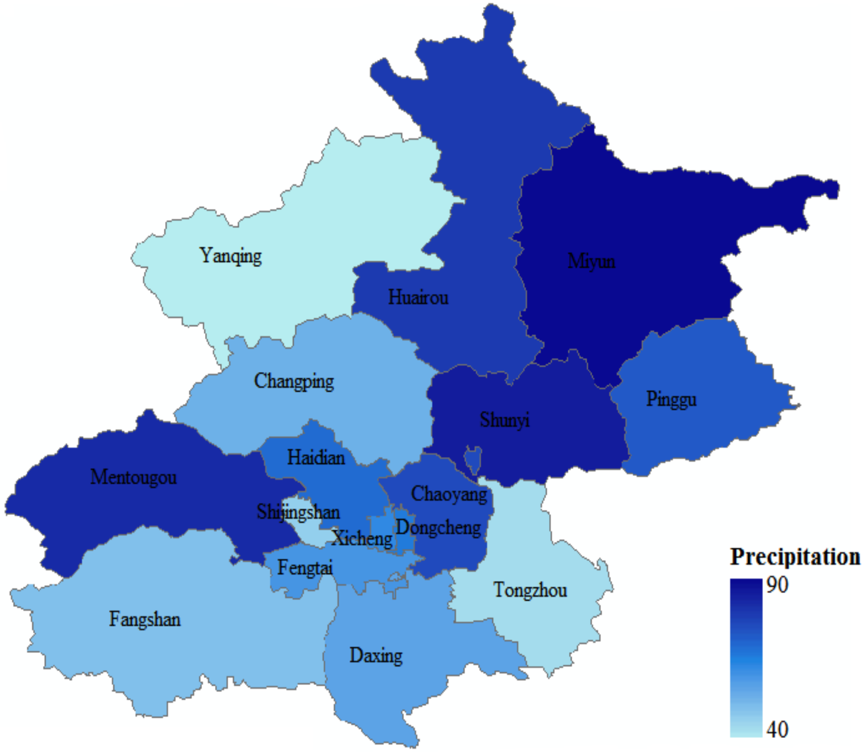

Figure 2. The 99th percentile historical daily precipitation from 1981-2012 of 16 districts in Beijing

processing of historical precipitation has been carried out with the result presented in Figure 2. To quantify the impact of historical precipitation extreme in exposure assessment, the values of the 99th percentile daily precipitation are also assigned into four grades: 40-60mm (grade Ⅰ), 60-70mm (grade Ⅱ), 70-80mm (grade Ⅲ), 80-90mm (grade Ⅳ). Results are shown in Table 1.

District	The 99th percentile (mm)	Precipitation extreme grade
Shunyi	79.70	Ⅲ
Haidian	71.81	Ⅲ
Yanqing	42.72	Ⅰ
Miyun	80.20	Ⅳ
Huairou	74.20	Ⅲ
Pinggu	73.51	Ⅲ
Tongzhou	64.06	Ⅱ
Chaoyang	73.71	Ⅲ
Changping	67.62	Ⅱ
Mentougou	74.44	Ⅲ
Shijingshan	66.32	Ⅱ
Fengtai	68.73	Ⅱ
Daxing	67.93	Ⅱ
Fangshan	66.70	Ⅱ
Dongcheng	71.22	Ⅲ
Xicheng	69.50	Ⅱ

Table 1. Grade of historical precipitation extreme of 16 districts in Beijing

Data of Disaster Losses

The statistics data of rainstorm disasters attacking 16 districts of Beijing in 2012 which led to terrible casualty and great economic loss are collected from different sources including government reports, official statistic yearbook, regional statistical database and so on. To conduct a research about the correlation between disaster exposure and disaster losses, two indicators, which are the affected population and the economic loss of every district, are used to reflect the severity of disaster damage.

Exposure Assessment

In the case of rainstorm disasters, exposure as a significant component of risk refers to the susceptibility of people, assets and social resources to the hazard of extreme precipitation events. Exposure assessment is carried out in order to identify the most exposed areas and the likelihood of casualty, property damage and economic loss in heavy rainfalls (Liu et al., 2011). In this study, the exposure assessment of rainstorm disaster is based on both the probability of being affected by rainstorms

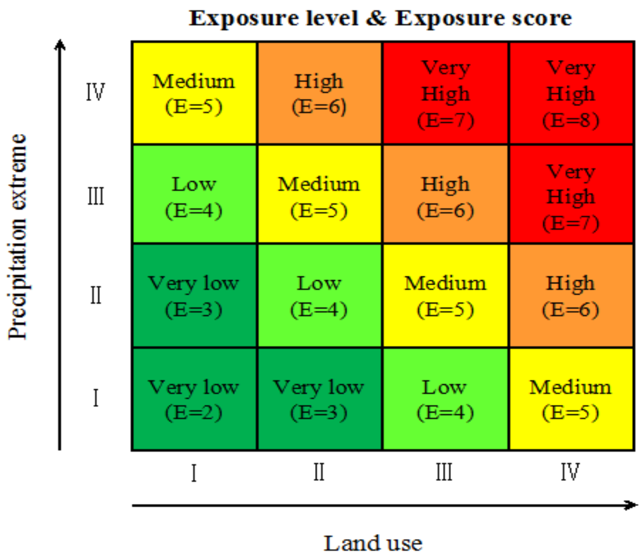

Figure 3. The Exposure Matrix

and the potential damage. The two aspects are evaluated by: (1) the historical extreme precipitation threshold, which represents the chance of areas affected by the disaster. It's determined by the 99th percentile of daily precipitation data from 1981~2012 in every district; (2) the potential consequence caused by the heavy rainfall, which represents the possible damages and casualties. Built-up areas often gather large numbers of people (such as residential areas) and a great many assets or social resources (such as commercial areas and industrial areas). So our study uses the percentage of built-up areas (including residential areas, commercial areas and industrial areas) in total used land areas to represent the potential consequence caused by rainstorm disasters.

According to these two indicators, the exposure of the rainstorm disaster is the sum of precipitation extreme grade and land use grade. That is:

$$E_i = P_i + U_i \qquad (2)$$

Where E_i is the exposure score of the i^{th} region, P_i is the grade of precipitation extreme of the i^{th} region, and U_i is the grade of land use of the i^{th} region.

The exposure scores may vary from 2 to 8. Five levels (very low, low, medium, high and very high) of exposure with the scores of 2-3, 4, 5, 6, 7-8, respectively, are adopted in this study and the Exposure Matrix (Figure 3) is presented to show how to carry out the exposure assessment of the rainstorm disaster based on the two indicators.

Spearman's Rank Correlation Coefficient Analysis

In this study, Spearman's rank correlation coefficient is applied to analyze the relationship between the disaster exposure and two characteristics (the affected population and the economic loss) of rainstorm disasters which attacked Beijing in 2012. As the coefficient varies from -1 to +1, it indicates the degree of the positive or negative correlation between two ranked variables. The equation is

$$\rho = 1 - \frac{6\sum d_i^2}{n^3 - n} \qquad (3)$$

Where ρ denotes the Spearman's rank correlation coefficient, n denotes the number of ranks, d_i is the substraction of the ranks of two variables.

The positive coefficient manifests the positive correlation between two variables, and vice versa. When one of the two variables is a perfect monotone function of the other, the Spearman coefficient is +1 or -1.

RESULTS AND DISCUSSION

Assessing Exposure of Beijing to Rainstorm Disaster

According to the formula for the calculation of exposure scores, namely the equation (2), and the Exposure Matrix which have been presented in the preceding chapter, the exposure scores and exposure levels of 16 districts in Beijing have been evaluated based on historical precipitation extremes and land use conditions. And the exposure level zoning map of Beijing is presented in Figure 4. As shown in Figure 4, while the northwest Beijing is exposed to disasters at relatively lower levels, the southeast is exposed to rainstorm disasters with higher levels. The central part of Beijing including districts like Dongcheng, Xicheng, Haidian etc. where population and economic assets are in high density are exposed with the level of "very high" in terms of rainstorm disasters.

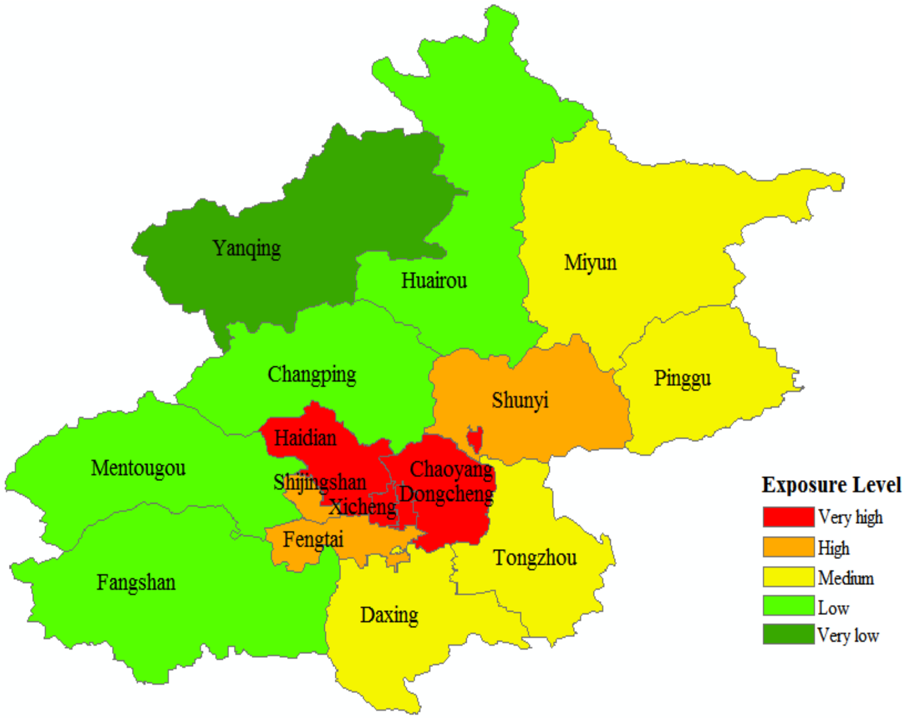

Figure 4. Exposure level zoning map of Beijing

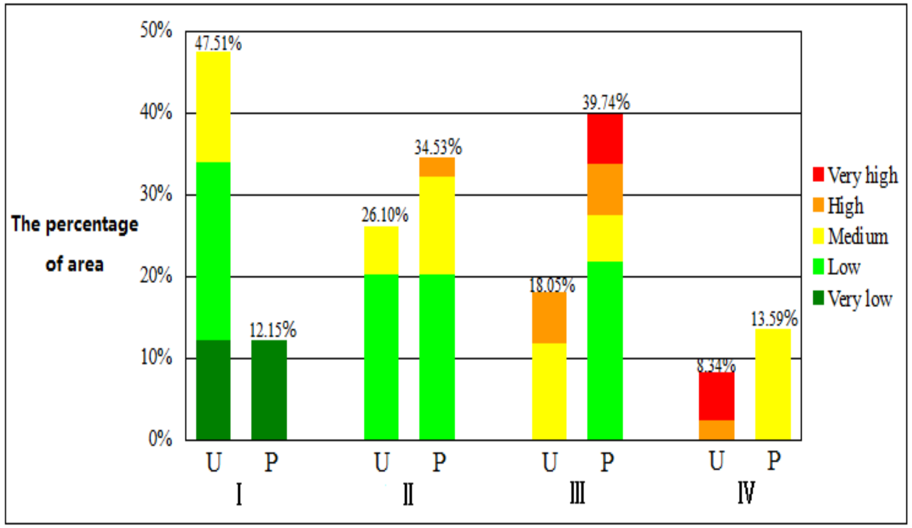

Figure 5. The percentage of area in each grade (*U* stands for land use, *P* stands for precipitation extreme*)*

A comprehensive analysis of land use conditions and historical precipitation extremes of all districts in Beijing has been carried out for a further study. Results are presented in Figure 5 and Table 2. Figure 5 shows the percentage of area in each grade of land use or precipitation extreme, and Table 2 shows the percentage of every exposure level in each grade. As to the land use condition, most part of Beijing is in grade Ⅰ (47.51% area) and grade Ⅱ(26.10% area) , and only 8.34% area is in grade Ⅳ. Of the 8.34% area of grade Ⅳ, 71.47% has "Very high" exposure level and 28.53% has "High" exposure level. As to the precipitation extreme, most part of Beijing is in grade Ⅱ (34.53% area) and level Ⅲ (39.47% area). 13.59% area is in grade Ⅳ, which accounts for more proportion compared with 8.34% in grade Ⅳ of land use. However, areas with "Very high" or "High" exposure level are almost in grade Ⅲ, and areas in grade Ⅳ are exposed with a moderate level of "Medium".

Some preliminary conclusions can be drawn from the results and above analysis. Land use conditions and historical precipitation extremes together determine the exposure level of rainstorm disaster. As the difference of historical rainfall distribution among districts in Beijing is not very significant, the grade of precipitation extreme doesn't play a very important role in our study. Meanwhile, as the topography of Beijing changes significantly from northwest to southeast, the land use conditions vary a lot. Therefore the grade of land use plays the decisive role in determining the exposure level. However, the specific conclusion in our research doesn't necessarily mean one indicator is more important than another in exposure assessment. Actually they are of the same importance and applying the method to other regions or cities may lead to some different conclusions.

Exposure level	Ⅰ		Ⅱ		Ⅲ		Ⅳ	
	U	P	U	P	U	P	U	P
Very high	0	0	0	0	0	15.00%	71.47%	0
High	0	0	0	6.88%	34.41%	15.64%	28.53%	0
Medium	28.59%	0	22.18%	34.28%	65.55%	14.57%	0	100 %
Low	45.83%	0	77.82%	58.82%	0	54.79%	0	0
Very low	25.57%	100%	0	0	0	0	0	0

Table 2. The percentage of every exposure level in each grade (*U* stands for land use, *P* stands for precipitation extreme)

Analysis of the Correlation between Exposure and Disaster Losses

Spearman's rank correlation coefficient is adopted to explore the relationship between the exposure and disaster events. Two indicators (the affected population and the economic loss) are used to represent the severity of damage and casualty caused by rainstorms. Here the exposure of every district is simply the integration of sequences of land use condition and historical precipitation extreme instead of their grades. As table 3 shows, significant positive correlation can be found between the exposure and the economic loss (0.6894), where the more exposure, the greater economic loss. By contrast, no strong correlation has been found between the exposure and the affected population (0.4736).

Spearman rho (ρ)	Characteristics of disaster events	
	The affected population	The economic loss
The exposure	0.4736*	0.6894*

* Significant at 0.01 level

Table 3. Spearman's correlation coefficient between the exposure and disaster events

Analysis of the significant positive correlation between the exposure and the economic loss reveals that economic losses caused by rainstorm disasters will be rising continuously owing to the increasing exposure to extreme precipitation events. As the on-going urbanization process is an inevitable trend, more properties and social resources such as buildings, lifeline constructions, etc. are exposed to disasters. And this gives rise to a larger number of economic assets at risk in the future. In terms of the relatively weak correlation between the exposure and the affected population, the data presented here are limited to fully illustrate the root cause. But according to Camarasa et al. (2011), human exposure is mainly determined by population density. And a remarkable difference between people and assets is that people don't have static locations but rather commute between places of residence, work and leisure. So based on population mobility, the population density is considered to be changed at each time and Spearman's rank correlation coefficient can't accurately reflect the relationship between the exposure and the affected population.

CONCLUSION

This paper presents a method of exposure assessment of rainstorm disaster and its application to Beijing, China. Based on land use conditions and historical precipitation extremes, the exposure level zoning map of Beijing has been obtained and a comprehensive analysis has been carried out. Results show that, the southeastern part of Beijing is exposed to rainstorm disasters at relatively higher levels compared with the northwestern part, and the central part of Beijing has the exposure level of "Very high". As the topography of Beijing changes significantly, the land use condition is considered to be the more crucial indicator in determining the exposure level in our study. Also, Spearman's rank correlation coefficient is applied to explore the relationship between disaster exposure and disaster losses. The study can also inspire useful thinking of city planning and regulation in disaster-prone areas. Due to the current extent and pace of urbanization, more and more population, economic assets and social resources are densely gathered in big cities like Beijing. Short-sighted land-use planning will result in great exposure of population and assets to the rainstorm disaster. And the occurrence of extreme precipitation event may lead to terrible casualty and property damage. To strike a balance between fast-pace urbanization and disaster mitigation, planners and decision makers should focus more on the land-use structure optimization which means consciously directing the development of areas which are exposed or vulnerable to the hazard of rainstorm disasters. Since the uncertainty of frequency and intensity of rainfalls can't be fully overcome, effective land-use planning plays a vital role in implementing mitigation and preparedness strategies to reduce the disaster exposure and minimize the possibility of catastrophic consequences.

In conclusion, our study provides a new perspective of exposure assessment and some useful ideas for stakeholders in developing and managing large cities like Beijing at a time of rapid urbanization.

REFERENCES

1. ADCR (2005) Total Disaster Risk Management Good Practices. Asian Disaster Reduction Centre (ADRC) 89
2. Bonsal B R, Zhang X, Vincent L A, et al. (2001) Characteristics of daily and extreme temperatures over Canada. *Journal of Climate*, 9,14,1959–1976.
3. Camarasa AM, López-García MJ, Soriano-García J (2011) Mapping temporally-variable exposure to flooding in small Mediterranean basins using land-use indicators. *Applied Geography*,31,136 – 145
4. Cammerer, H., A.H. Thieken and P.H. Verburg (2013) Spatio-temporal dynamics in the flood exposure due to land use changes in the Alpine Lech Valley in Tyrol (Austria). *Natural Hazards*, 3,68,1243-1270.
5. DEFRA, & EA. (2006). R&D outputs: Flood risks to people. Phase 2. FD2321/TR1 The flood risks to people methodology. London: Department for Environment Food and Rural Affairs and the Environment Agency.
6. Lin YP, Verburg PH, Chang CR, Chen HY, Chen MH (2009) Developing and comparing optimal and empirical land use models for the development of an urbanized watershed forest in Taiwan. *Landscape and Urban Planning*, 92, 242–254
7. Liu, J., S. Wang and D. Li (2014) The Analysis of the Impact of Land-Use Changes on Flood Exposure of Wuhan in Yangtze River Basin, China. *Water Resources Management*, 9,28,2507-2522.
8. Naef F, Scherrer S, Weiler M (2002) A process based assessment of the potential to reduce flood runoff by land use change. *Journal of Hydrology*, 264,74–79
9. Niehoff D, Fritsch U, Bronstert A (2002) Land-use impacts on storm runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. *Journal of Hydrology*, 267,80–93
10. Kaźmierczak, A. and G. Cavan (2011) Surface water flooding risk to urban communities: Analysis of vulnerability, hazard and exposure. *Landscape and Urban Planning*, 2,103,185-197.