Hotspot Analysis of the Spatial and Temporal Distribution of Fires

Chien-Yuan Chen[1] and Qi-Hua Yang[2]
[1]Dept. of Civil and Water Resources Engineering, National Chiayi University, Syufu Rd., Chiayi City, Tawian, China
[2]Tainan City Government Fire Bureau, Yonghua Rd., Anping Dist., Tainan City, Taiwan, China

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Abstract: Fire can take lives and destroy structures. However, modern technology can assist authorities to make decisions on fire disaster prevention. Geographic information systems can play a vital role in fire prevention and mitigation by predicting potential hotspots for fires. This study collected and analysed data on fires in Tainan City in southern Taiwan. Spatial statistics analysis tools employing average nearest neighbour analysis and global analysis through Moran's I were used to analyse whether the fires had a clustered pattern and to plot a fire hotspot map using Getis-Ord Gi* analysis. The results showed that the highest fire risk index is that for people over 80 years old, followed by those between the ages of 60 and 80. The spatial distributions of fire locations, injuries, deaths, factory fires, house fires, and wild fires have clustered patterns in the city. The fire hotspots surround the downtown districts, which have high population density and highly developed commercial and industry areas. The fire cold spots are located in the lowly developed mountainous and coastal areas, which have lower population density. Residents in hotspots should be able to better understand their fire risk through studying the hotspot map. Moreover, authorities can identify hotspots for decision making on fire prevention and urban development planning.

1 INTRODUCTION

The incidence of fires has been reduced with the progress of fireproof technologies for buildings and products. However, injuries and deaths due to fires still continuously occur, and more attention must be paid to the fire warning signs. Further reduction in the number of fires requires communities to promote disaster prevention cognition and the establishment of public safety warning systems. More than 60% of fires occur in houses, as statistics by the National Fire Agency in Taiwan demonstrate (http://www.nfa.gov.tw/). This indicates that although society is generally concerned with public safety, people often lose sight of safety within their daily environment.

Spatial statistics analysis has been used in various areas for disaster mitigation. Applications that have employed spatial statistics analysis tools include the spatial analysis of crimes committed in the Taichung port area (Lee et al., 2012). The gathering mode used to collect criminal cases was identified using average nearest neighbour analysis, and hotspot analysis was employed to assess cold spot and hotspot positions regarding crime for the reference of coastguards.

In one analysis of spatial clusters of dengue fever in Kaohsiung city (Yan and Hsueh, 2010), research was conducted from the perspective of the geography of the disease, and a geographic information system (GIS) was employed to create a disease map and study the spread of dengue fever. Whether there was a spatial aggregation in the city was determined using the average nearest neighbour method and point density analysis to locate the village with the highest incidence of dengue fever. Hotspot analysis using Getis-Ord Gi* and spatial autocorrelation coefficients Moran’s Index (Moran’s I) was also employed to study the spread of Anopheles gambiae and Anopheles funestus in Kenya (Kelly-Hope et al., 2009).

Spatial analysis was used to examine betel nut plantation hotspots in the upper Shui-Li Creek watershed using the autocorrelation coefficients of Moran’s I and the G-statistic, with the objective of investigating the management strategy of betel nut plantations (Yeh et al., 2013). Liang et al. (2014) used spatial analysis to perform a risk assessment of invasive species and employed hotspot analysis

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Getis-Ord Gi* to identify hotspot areas and plan management strategies. Truong and Somenahalli (2011) used the spatial autocorrelation coefficient Moran's I to identify pedestrian–vehicle crash hotspots and unsafe bus stops using hotspot analysis Getis-Ord Gi*. Pedestrian–vehicle crash hotspots were concluded to correlate strongly with the locations of bus stops.

Hotspot analysis Getis-Ord Gi* and spatial autocorrelation coefficient Moran's I were also used to map forest fire risk zones in the Yeguare Region of Honduras (Cáceres, 2011). Factors such as slope, elevation, and distance to tribute affected the risk of a forest fire. Fires exhibit a spatial aggregation distribution and can be related to population density. The characteristics of fires are well-suited to the use of spatial statistics and an autocorrelation analysis to identify hotspot areas and risk factors for disaster prevention and management.

2 STUDY AREA AND METHODOLOGY

The M_L 6.4 earthquake on 3 March 2010, which had its epicentre in Jianxin village in southern Taiwan, caused a building owned by a spinning and weaving company in Tainan City to catch fire. Furthermore, a technology factory caught fire on 28 July 2011, causing substantial economic losses in the city. The fire on 23 October 2012 at the Beimen branch of Sinying Hospital in the Beimen District of Tainan City resulted in the deaths of 13 elderly people and injured 69 others. These serious fires and various other factors led us to choose Tainan City as a study area because of its variety of lifestyles and areas, including villages, mountainous areas, coastal areas, and industrial areas. The diversity of the city has caused both its population and industrial development to increase rapidly.

This analysis was completed through three steps: a literature review and data collection, statistics analysis, and GIS spatial statistics analysis. The study area was divided into a grid, each square of which was 1000×1000 m^2 in size. Fire-related data were separated by injuries and deaths, age and gender of the injured and deceased individuals, fire location, land use, and population density. The coordinates of the fires were overlaid onto an administrative map to create a fire point density map to represent fire locations.

Tools for average nearest neighbour and global analysis using Moran's I and Getis-Ord Gi* analysis were employed to analyse if the fires displayed a clustered, dispersed, or random pattern on the fire hotspot map. The null hypothesis was the default hypothesis and states that there is no association between fire occurrence and the factors. The null hypothesis was assumed to be true until evidence indicated otherwise. The rejection of the null hypothesis concluded that there were reasons to believe that a relationship between fire and the other factors existed. The tools used for spatial statistics analysis are explained:

(1) Average nearest neighbour analysis

Euclidean distance was used in the nearest neighbour analysis. The average nearest neighbour distance tool measures the distance between each feature centroid and its nearest neighbour's centroid location to predict the nearest neighbour index. Five values obtained by the analysis included observed mean distance, expected mean distance, nearest neighbour ratio, z-score, and p-value. The z-score and p-value were used for judging the possibility to reject the spatial random pattern of the null hypothesis. A z-score less than −2.58 or greater than 2.58 and a p-value lower than 0.01 with a confidence level of over 99% were used to reject the null hypothesis and confirm a clustered pattern.

The average nearest neighbour ratio (NNR) is calculated using the observed average distance divided by the expected average distance, with the expected average distance being based on a hypothetical random distribution with the same number of features covering the same total area. If NNR is less than 1, the study pattern is clustered; if the index is greater than 1, the trend is toward a dispersed pattern.

(2) Global analysis by Moran's I

The spatial autocorrelation tool global Moran's I measures spatial autocorrelation based on both feature locations and feature values simultaneously. The method measures each feature centroid and its nearest neighbour's centroid location to analyse the spatial autocorrelation of each fire. The eigenvalues of this technique included the Moran's I, expected index, variance, z-score, and p-value. The same conditions for z-score, p-value, and confidence level as for average nearest neighbour analysis were used to reject the null hypothesis. The method evaluates the pattern of fires as clustered, dispersed, or random. If Moran's I is greater than 0 (positive value), the fires were clustered; the fires were dispersed if the index is less than 0 (negative value), and the fires were randomly distributed if the index is close to 0.

(3) Hotspot analysis using Getis-Ord Gi*

The point density tool calculates the density of point features around each raster cell; the tool yields a heat map for visualization. However, the hotspot analysis using the Getis-Ord Gi* method yields a true statistical hotspot analysis.

The Getis-Ord Gi* value of the target feature shows where fire hotspots (clusters of high values) and cold spots (clusters of low values) exist in the area accompanied by the z-score and p-value. The z-score and p-value were used to support the rejection of the null hypothesis. The values could help to judge the clustered pattern in high or low values and whether the fires exhibited a random pattern in the analysis. Fires in highly clustered patterns have a higher z-score and lower p-value; fires in a highly dispersed pattern have a lower z-score and a lower p-value. The closer the z-score is to 0, the less visible the clustered pattern. Figure 1 shows the flowchart of the spatial statistics analysis tools used in this study.

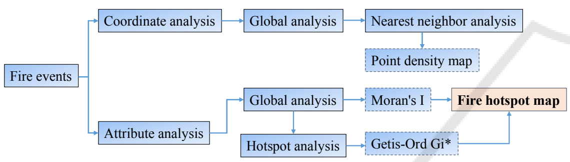

Figure 1: Method and tools used for the fire hotspot analysis using the GIS.

3 RESULTS AND DISCUSSION

3.1 Statistics Analysis of Fires

3.1.1 Number and Types of Fire Events

The number of fires totalled 2179 in 10 years (2004-2013) in the city, which included 1502 building fires (68.94%), 216 traffic-accident fires (9.91%), 176 wild fires (8.07%), 1 boat fire (0.05%), and 284 other type of fires (13.03%) (Figure 2). There were 217.9 fires per year on average, which is equivalent to 0.6 fires per day and three fires every 5 days on average.

Buildings such as houses, factories, shops, and warehouses, are the main buildings used by city residents in daily life. Fire disaster prevention is emphasized in buildings to reduce the threat to human life and economic losses. In relation to fires in buildings, this study demonstrates that there were 0.41 building fires per day, which is equivalent to two building fires every 5 days on average.

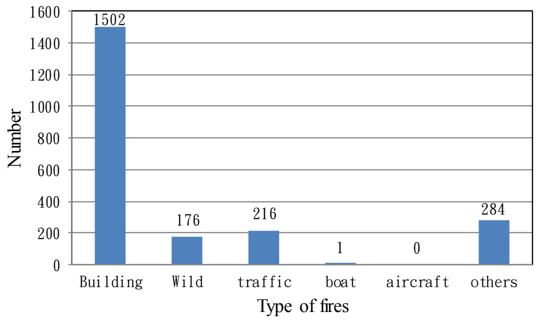

Figure 2: Statistics on the types of fires in the study area.

In general, building fires have decreased in the city in recent years. There were 193.8 building fires per year on average, with a total of 969 building fires in the years 2004–2008. The number of building fires decreased to 106.6 per year in the period 2009–2013, with a total of 533 building fires. The reduction ratio was thus 45% (Figure 3). This finding may be a result of progress in fireproof technologies and the implementation of fire disaster prevention strategies such as those that increased public awareness.

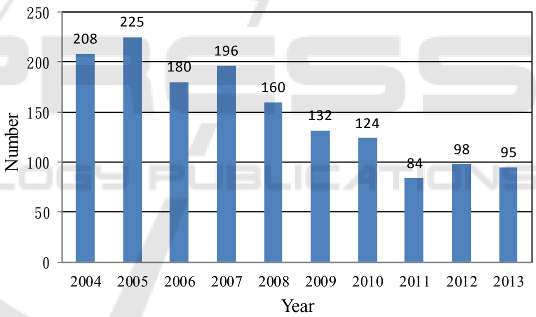

Figure 3: Statistics on building fires in the study area.

3.1.2 Fire Death Rate and Fire Risk Index

The fire death (or injury) rate is the number of fatalities (injuries) per million people in the population. The fire risk index is based on the average death (injury) ratio and calculated as the fire death (injury) ratio in various ages divided by the fire death (injury) ratio in the total population according to the U.S. Fire Administration's report (https://www.usfa.fema.gov/):

Fire death (injured) rate = number of fire deaths (injuries)/ population (in millions) (1)

Fire risk index = fire death (injury) ratio in various ages/fire death (injury) ratio in the total population (2)

The fire death rate was 6.99 in 2004 in the study area, but only 2.13 in 2010. The rate increased abruptly to 12.37 in 2012 because a deadly hospital fire occurred in this year, causing 13 deaths. The average fire death rate was 4.65 over the 10 years this study examined, but would be lower than 6.0 if the year 2012 was excluded, as shown in Figure 4.

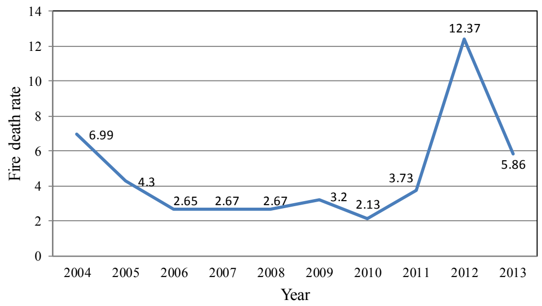

Figure 4: Changes in the fire death rate in the study area.

The statistical analysis discovered that the fire risk index was less than 1.0 on average for those under 60 years old, 1.76 for those aged 60–79, and 4.27 for those aged over 80 years old in the city (Figure 5). This indicates that those aged over 60 are a high-risk group regarding fires. The result coincides with the statistics provided by the Tokyo Fire Department (http://www.tfd.metro.tokyo.jp/), which states that more than 90% of fire deaths are of individuals over the age of 65. The results perhaps reflect the fact that elderly people are less able to escape due to mobility issues and are therefore more exposed to the effects of a fire.

The fire risk index was highest in the Beimen District due to the fire on 23 October 2012 at the Beimen branch of the Sinying Hospital, which caused 59 injuries. These statistics were compared with the spatial statistics analysis for further analysis.

3.1.3 Spatial Statistics Analysis of Fires

This study used the coordinates of fire locations to create a fire point density map and overlaid this with the population density to perform relevance analysis using a GIS. A total of 2179 fires were imported into the spatial analysis for 2004–2013. The fires were concentrated in the southwest area of the city. The highest fire density area was the industrial area of Yongkang District, with 261 fires, including 194 building fires (Figure 6).

There were 163 fire injuries and 69 deaths in 2004–2013 in the city. The fire point density map shows that a high density of fires was concentrated in the high human activity areas surrounding the downtown for industry and commercial purposes (Figures 7 and 8).

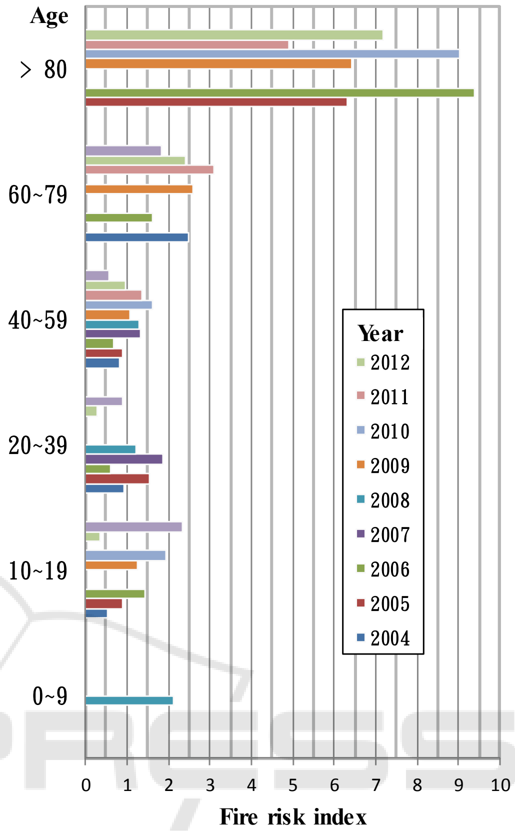

Figure 5: Fire risk index in different ages in the study area.

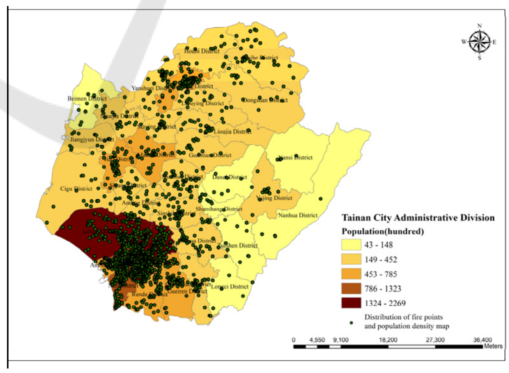

Figure 6: Distribution of fire points and population density map in the study area.

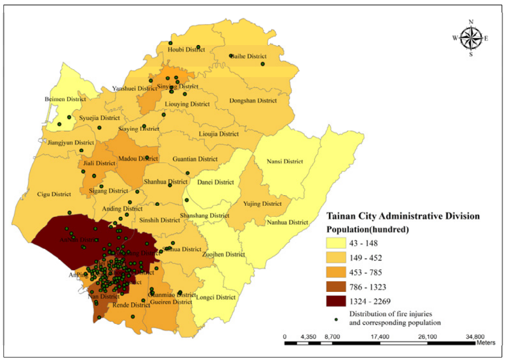

Figure 7: Distribution of fire injuries and corresponding population in the study area.

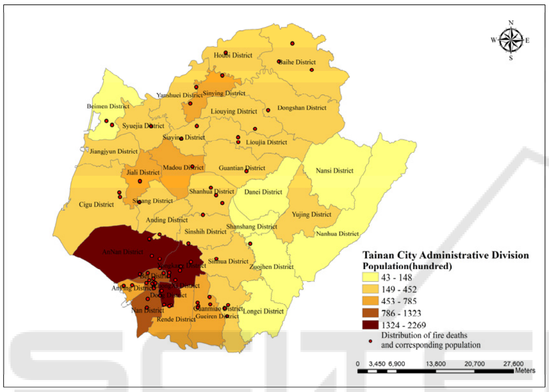

Figure 8: Distribution of fire deaths and corresponding population in the study area.

3.1.4 Spatial Aggregation Pattern of Fires

(1) Average nearest neighbor analysis

In the nearest neighbor analysis, the calculated observed mean distance was 334.6 m and the expected mean distance was 542.2 m. The average NNR was thus 0.62, which is smaller than 1.0 and indicates a clustered pattern of fires. The z-score was −31.62, which is smaller than −2.58, and the p-value was 0.00; thus, the null hypothesis, was rejected. These values demonstrate that the fires were in a clustered pattern in the city, with a less than 1% probability of their being in a random pattern. The results of the average nearest neighbor analysis for fires are shown in Figure 9.

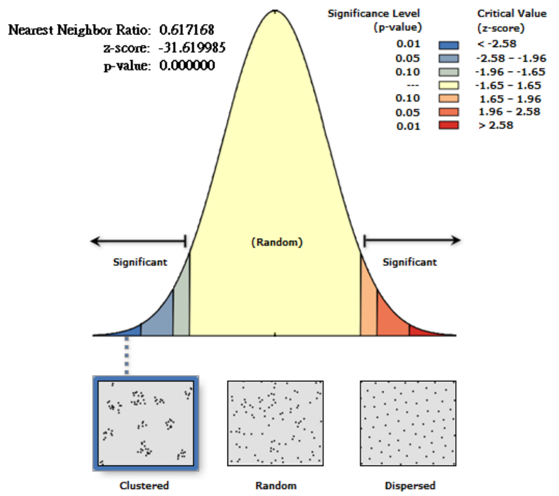

Figure 9: Results of the NNR distribution obtained using average nearest neighbor analysis.

(2) Global Moran's I analysis

Global Moran's I analysis showed that the Moran’s I was 0.48, which is larger than 0.00, and that the fires had a positive clustered pattern. The z-score was 83.96, larger than 2.58, and the p-value was 0.00, which rejects the proposition of complete spatial randomness (null hypothesis). In summary, the fires in the city had a clustered pattern, with a less than 1% probability that they could be in a random pattern (Figure 10).

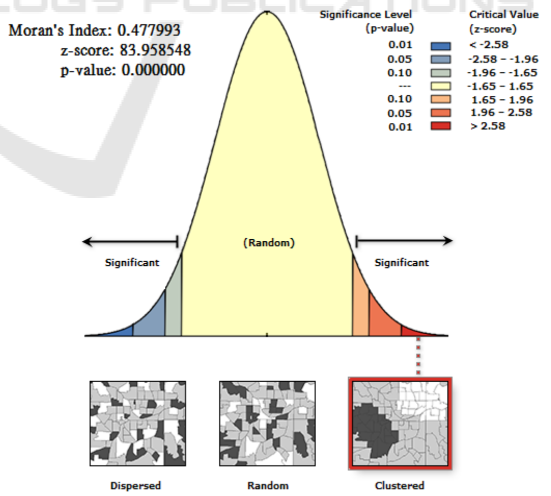

Figure 10: Moran’s I obtained using global Moran's I analysis.

The types of fires including house, industry, and wild fires and those fires that caused injuries and deaths were all found to exhibit a clustered pattern by using the GIS spatial statistics analysis in the study area (Table 1).

Table 1: Summary of the spatial analysis results for fires in 2004–2013 in the study area.

		All types of fire	Industry fire	House fire	Wild fire
Average nearest neighbor	NNR	0.62	0.47	0.58	0.68
	Z-score	-31.62	-16.06	-23.43	-7.78
	p-value	0.00	0.00	0.00	0.00
Global Moran's I	Moran's I	0.48	0.17	0.41	0.04
	Z-score	83.96	29.85	72.02	6.68
	p-value	0.00	0.00	0.00	0.00
Type of distribution		clustered			

(3) Fire hotspot analysis

The outlines of fire concentration areas were analyzed using the tool Getis-Ord Gi* to identify fire hotspots in the city. Figure 11 displays the fire hotspot map of the city. Two major hotspots (standard deviator larger than 2.58) are displayed on the map. The largest fire hotspot surrounds the administrative area of the rapidly developing districts, which is close to the downtown center where more jobs are available, as well as good educational and medical facilities and living conditions. The other hotspot is located at the deputy downtown center, Hsinying District, which has similar conditions to those of the largest hotspot.

A review of the fire spatial distribution on the point density and hotspot maps reveals that all types of fires occurred in the area surrounding the city's administration center, which has a population density of more than a million residents per square kilometer.

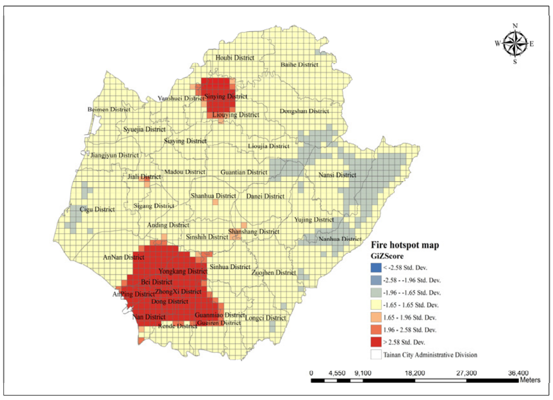

Figure 11: Fire hotspot map in the study area.

(4) Fire cold spot area

Two major fire cold spot areas exist in the map in Figure 11. One is located in the mountainous area, which has a considerably lower population and a low amount of land developed for economic use, as the land is unsuitable for agricultural use. The other is located in the coastal area, which has a similarly small population and low use of land; most of this area is used for fish farms and a limited amount is used for agricultural use.

3.2 Deployment of Firefighters

The ratio of the general population to each firefighter is 1773:1 in Taiwan, and the ratio is 2047:1 in the study area of Tainan City (National Fire Agency in Taiwan http://www.nfa.gov.tw/ on May 2014). The ratio is higher than that in some other developed countries, such as the United States, where the ratio was 1000/1.33 in New York in 2009–2010 (UFOA, 2011). In some districts of Tainan such as Yongkang District, the ratio is as high as 3668:1 in the hotspot area, which is close to the 4000:1 absolute maximum population that can be adequately served by firefighters. The deployment of firefighting teams must be focused on the hotspot areas of the city.

4 CONCLUSIONS

This study used GIS spatial statistics analysis to investigate the fire hotspot area distribution in the study area, Tainan City in southern Taiwan, using fire data from the years 2004-2013. The point density map shows the fire, injury, and death distributions in the city. Spatial statistics analysis tools for the average nearest neighbor and global analysis using Moran's I were employed to analyze whether the fires had a clustered pattern and to plot the fire hotspot map using the Getis-Ord Gi* analysis. The results showed the following:

(1) The highest fire risk index is for people over the age of 80, followed by those aged 60–80.

(2) The spatial distribution of fire locations, injuries, deaths, industrial fires, house fires, and wild fires had clustered patterns.

(3) The fire hotspot is the downtown area, which has high population density, and the cold spot areas are located in underdeveloped mountainous or coastal areas with lower population density.

(4) Fire hotspots are highly correlated with house fires, and fire deaths are concentrated in the downtown area.

Finally, the results can provide valuable insights for governments in relation to land development and urban planning, and could help plan future firefighting resource requirements. This study suggests that other type of disasters can be included in the analysis because non-fire-related disasters also require the assistance of firefighters.

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