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Spatial and statistical analysis of road accidents hot spots using GIS

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Abstract. The prime goal of highway safety engineering is to limit the number as well as severity of traffic accidents by identifying, implementing and evaluating measures to improve highway safety. As the roadway improvements are supposed to be applied to hazardous locations or accident hot spots where they have the most momentous impact, identification of hot spots is a vital step in safety management. There is an ongoing determination by road professional and academicians alike to examine most appropriate methods for identifying road accidents hot spots. There is no universal definition of hot spot and it is open to wide speculation. This research seeks to take advantage of GIS and spatial analysis to identify road accident hot spots both visually and statistically.

Spatial clustering of accidents and spatial densities of hot spots were evaluated using Moran's I method of incremental spatial autocorrelation, Getis-Ord Gi* statistics and Kernel Density Estimation (K). The statistical techniques were compared using five years of accident data (2009-2013) for Varanasi city. Apart from accident counts, severity indices were also employed for analysis and ranking of hot spots using both methods. This approach employed different severity weighing systems to evaluate the effect of Minor and Property Damage Only (PDO) type accidents on overall results. Ranking of hot spots using Gi* was done with the help of Z value associated with statistical significance. Ranking of hot spots using K was done with the help of pixel values of various observed locations.

Results of hot spot analysis delineated various road stretches as well as intersections where hot spots were concentrated. Results indicated that the estimation of hot spots by K and Gi* using three conceptualization of spatial relationships (fixed distance band, inverse distance and inverse square distance) are widely similar. Hot spots evaluated using different severity weighing systems were found to be quite interesting. The results can be effectively utilized by various agencies for adopting better planning and management strategies for accident reduction as well as for improved traffic operating conditions.

Keywords: Accident hot spots, Getis-Ord Gi*, Kernel Density Estimation, spatial autocorrelation, accident severity,

Introduction

Road accidents are considered one of the most negative impacts of developing modern transportation system which result in injuries and loss of lives. Road traffic injury is the eighth leading cause of death at the global level also it is leading cause of death for young people aged 15-29 years [1]. India ranks at number 1 spot in the world in terms of total road accident fatalities [1], which makes traffic safety as one of the most critical matter in planning transportation strategy. Traffic safety engineers around the world face one of the most imperative questions i.e., where to implement safety precautionary measures so that they can have the most momentous impact for traffic safety. "Hot spots", "Black spots" or "High accident locations" are sites on the section of roads and highways with higher accident frequency than expected at some threshold level of significance. The most sensible solution to reduce accident frequency is accurate identification of hot spots. Hot spots can be identified using simple methods such as Accident Frequency (AF) method, Accident Rate (AR) method, Accident Density (AD) method and Accident Severity Index (ASI) method by various agencies around the world. Some other methods for hot spot identification like Empirical Bayes (EB) method [2], Public Participation Approach (PPA) [3], and Sequential pacing data analysis technique [4] are also gaining popularity amongst researchers. EB method is considered best hot spot identification method [5], but it requires special skills and training in statistical analysis. The methods such as AF, AR, AD and ASI are less superior in comparison to EB, but are simple and straightforward to use, that is why many departments of transportation (DOTs) still rely on simple methods [6]. Recently Geographic Information System (GIS) has made a noticeable impact in detecting road accident hot spots. Spatial attribute combine with statistical analysis presents a superior way to understand traffic accidents. GIS based techniques are relatively simple to use and can convert raw statistical and geographical data into meaningful information for spatial analysis, mapping and for identifying any factors contributing to accidents.

The primary objective of this paper is to compare two statistical techniques, Getis-Ord Gi* [7] statistics and Kernel Density Estimation (K) using GIS for hot spot identification. Previous studies done for identification of accident hot spots using aforesaid techniques for Indian demographic and traffic conditions were solely based on analysis using incidental points [8,9]. This work incorporated two different accident severity weighing systems for analysis; this makes this work one of its own kind. Also, three different Conceptualizations of Spatial Relationships (CSR) namely, fixed distance band, inverse distance and inverse distance square were used to determine Gi* and best CSR for hot spot identification. After comparing the results, the best method and specified parameters for identifying hot spots were suggested generating optimum results.It is envisaged that the findings of this study can be used to prioritize hot spots and also help establish a correlation between surrounding environment and safety of accident's victims. This will help for successful traffic management and reduction of traffic accidents.

Literature Review

GIS based accident information system can model relationships between spatial phenomena that are nearly impossible to establish with non spatial database. Since 1900, GIS has been widely used by many researchers to geo-code accident locations, developing pin maps of accidents and to perform database queries [10, 11]. Apart from ranking accident locations as per higher accident rate, they can also be ranked according to severity of accidents. Many researchers had assigned optimum weights to accidents according to their severity, such as, Geurts et al. [12] proposed the weights of 5, 3 and 1 for fatal, grievous and minor accidents respectively. Similarly, RTA [13] assigned weights of 3.0, 1.8, 1.3, and 1.0 for fatal, grievous, minor and property damage only type accidents and Luathep [14] in his study proposed the weights of 125, 9 and 1 for fatal, injury and property damage only type accidents respectively.

Numerous methods have been developed for point pattern analysis and for detecting hot spots. These methods can be classified under two categories [15]: a) methods which analyze first-order effects, which calculate the variation in mean value of process such as Kernel Density Estimation (K), quadrant count analysis etc; and b) methods which examine second-order effects that calculates spatial autocorrelation of points for spatial patterns, like Moran's I Index, Geary C ratio and Getis-Ord Gi* statistics etc. Planer K or simply K was utilized by researchers to identify hot spots for various roads and highways [9, 16]. The major weakness of K is its inability to be tested for statistical significance [17]. Spatial pattern of accident data could be analyzed by spatial autocorrelation statistics which simultaneously combines attribute similarity and location proximity into single index. Unlike K, statistical significance of these methods can be evaluated with the Z scores. Getis-Ord Gi* statistic identifies the hot/cold spots where features with significantly high/low values has to be surrounded by features having simultaneously significant high/low values. Getis-Ord Gi* statistical method was utilized to detect statistically significant traffic accident hot spots on various roads and highways by researchers [8, 9, 18].

Study Area and Data Collection

Varanasi is situated on the banks of the mighty Ganges in the Indian state of Uttar Pradesh, 320 kilometres south east of the state capital Lucknow. It is located at 25°16′55″ North Latitude and 82°57′23″ East Longitude. Mixed traffic composition and narrow carriageways in old city area contribute to slow moving traffic. The main accident prone areas are located on highways constituting fast moving vehicular traffic. The study area selected is area encompassing between NH-2 popularly known as Kolkata-Delhi GT road, Varanasi-Kachhanwa SH-74, Varanasi- Sonauli NH-29 and Varanasi- Kanyakumari NH-7. Roads in these areas are always under extreme pressure of traffic and have greater likelihood of accidents. Apart from these, areas falling under jurisdiction of police stations namely Cantt, Ramnagar and Manduadih were also included in analysis, where large numbers of accident prone or potential hot spot locations were available. These areas contribute to large volume of traffic flow from outer city areas to main city areas since these were located along the periphery of the main city. FIR’s in police records for five years from 2009 to 2013 were surveyed and various police officers were interviewed to create accident database for analysis. Accident locations were plotted with the help of Google street maps and such locations which were not properly specified in police records were cross checked by conducting personal visits and by interviewing the local residents.

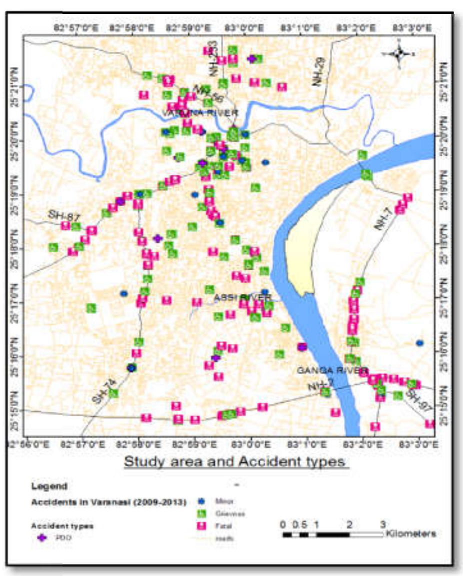


Figure: 1 Study area and types of accident occurred in 2009-2013.

Methodology

Accident Datasets and Map Preparation

This study utilized ESRI's ArcGIS 10.2 for analysis. The digital road map of Varanasi was imported in Arc Map and saved as "roads" layer. Imported digital map and data frame of Arc Map needed to have the same 'projected co-ordinate' system. The co-ordinate system used for the present work is WGS 1980 UCS. The 5 years (2009-2013) accident data of study area were collected from various police stations. Different accident types such as fatal, grievous, minor and property damage only were reported under clauses 304 (A), 338, 337 and 427 of the Indian Penal Code.
The accidents were geocoded by giving X and Y coordinates to each location. For every geocoded point, a Feature Identity (FID) in a form of whole number is automatically created on GIS. Every accident location was attributed with detailed information such as type, landmark, month, date, time, vehicle type etc.

Severity Consideration

Studies were performed using accident incident points in order to determine high and low clustering. But without weighted data, it is very difficult to determine whether the observed clustering is true or not. To identify unsafe locations, crashes should be weighted according to severity. In order to take severity of accident in consideration, this study employs two different severity weighting systems alongside with incidental accident data in analysis of high and low clustering.

Belgium system

This weighing system was adopted by Belgium government as a part of their official methodology for hot spot detection. This system was successfully adopted to identify black spot in three National Highways of Kerala in India [19]. Severity index for each location can be calculated as per Equation 1:

$$SI_1 = 5\times X_1 + 3\times X_2 + X_3 \quad (1)$$

where:
X_1= total number of fatal accidents
X_2= total number of grievous accidents
X_3= total number of minor and property damage only accidents

New South Wales (NSW) system

In contrast of, Belgium system, this system provides discrimination between minor and property damage type crashes [13]. It was successfully employed in identifying pedestrian vehicle crash hot spot in streets of Adelaide in Australia [18]. The severity index is calculated from following equation:

$$SI_2 = 3.0\times P + 1.8\times Q + 1.3\times R + S \quad (2)$$

where:
P= total number of fatal accidents
Q= total number of grievous accidents
R= total number of minor accidents

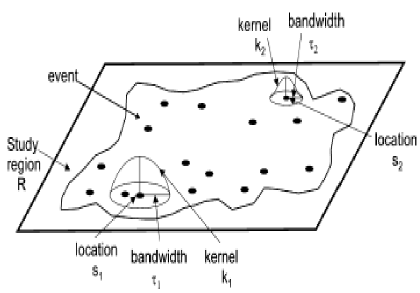
S = total number of property damage only accidents

Kernel Density Estimation (K)

Kernel density is one of the important spatial analysis tools in commercially available GIS software. K was utilized to calculate density of accidents within a search bandwidth of 0.3 km. K divides the entire study area into pre-determined number of cells. It uses a quadratic kernel function to fit a smoothly tapered surface to each accident location as shown in Figure 2 [20]. The surface value reduces from the highest at event location point to zero when it reaches radial distance from event location point. The value of kernel function is assigned to every cell as individual cell values. The resultant density of every cell is computed by adding its individual cell values. To account accident severity, the weight assigned to each accident is represented as its Identification Number (ID). Population field of kernel density function is selected as aforesaid ID. This facilitates counting of each accident according to its weight assigned. In case of no severity, or analysis according to incident points, the population field is selected as "None". Kernel estimator can be defined as in Equation 3.

$$f(\mathrm{x}) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x-x_i}{h}\right) \tag{3}$$

where: h is termed as bandwidth, radius or smoothing factor; K is kernel and f is estimator of probability density function. The kernel estimator depends upon choice of bandwidth (h), hence appropriate bandwidth should be determined according to purpose of study.



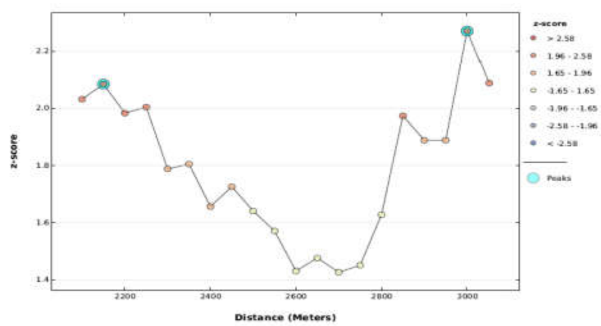


Figure: 2 Principle of kernel density. [16]

Figure: 3 Spatial autocorrelation by function distance.

Spatial Autocorrelation: Moran's I Method

Moran's I is one of the oldest global spatial autocorrelation indicator which evaluates whether the spatial pattern is clustered, random or dispersed. It works on both feature locations and features values simultaneously. It combines the measure of location proximity and attributes similarity into an index. The index can be calculated using the following Equation 4.

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i-\bar{x})(x_j-\bar{x})}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\right)\left(\sum(x_i-\bar{x})^2\right)} \tag{4}$$

where:
w_{ij}= the proximity weight of location i and j with w_{ii} = 0

$\bar{x}$ = the global mean value
x_i= the severity index at location j
n = the total number of accident locations

The Incremental Spatial Autocorrelation (ISA) tool was used to calculate Moran's I index value and associated Z score, which represented statistical significance at different threshold distances. The threshold distance with highest Z score was chosen for mapping cluster using Getis-Ord Gi* function. The distance associated with highest Z score gives the optimum clustering of high and low values. ISA tool gives the result in the form of graphical representation between different distance threshold and their associated Z score. Out of different values, either first peak or highest peak may be chosen for optimum clustering. Figure 3 shows the different distance threshold with their associated Z values. The choice of distances for analysis is solely based on spatial distribution of accident locations. It is the essential condition for analysis that each dataset should have at least one neighbour. The beginning distance for the analysis is chosen as default value which is minimum value for which each accident location has at least one neighbour. This distance was chosen to be 2100m with 50m increment distance for analysis. The first peak was observed at 2150m as it is shown in Figure 3 which was subsequently chosen as distance threshold for optimum clustering in case of fixed distance band CSR.

Getis-Ord Gi* Statistic

The two key processes involved in identification of desired hot spots were, collection of events and mapping of clustering using Getis-Ord Gi* function. It creates a new output feature class for every accident incident with a Z score and P value associated with it. It identifies statistically significant hot spot as a location having high value and surrounded by high valued neighbours as well. The local sum of values of a feature and its neighbours is proportionally compared with sum of all features. When the local sum obtained highly differs from expected local sum, and this difference is so high that it couldn't be a result of random chance, results in highly Z score and low P value. This gives statistically significant high clustering.

In case of incident point data, weighted point feature class with field Icount was created with help of collect event function. This indicated sum of all accidents happened in a unique geographic location. This weighted point feature was used as input for running Gi* function to identify whether features with high or low value tends to cluster in study area. In case of analysis using severity weighing system, the weighted point features also take severity of accidents in account. This was done by adding severities of all accidents at a unique geographic location according to type of severity weighing system. This weighted sum was used as input for running Gi* function. Getis-Ord Gi* statistics and its standardized Z scores based on expected values E (Gi*) and the variances (VAR (Gi*)) are mathematically expressed by equations (5) and (6)

$$G_i^*(d)=\frac{\sum_{j=1}^{n} w_{ij}(d)x_j}{\sum_{j=1}^{n} x_j} \tag{5}$$

$$Z(G_i^*) = \frac{G_i^* - E(G_i^*)}{\sqrt{VAR(G_i^*)}} \tag{6}$$

where:
d = distance threshold
w_{ij}= weight of target neighbour pair

x_j = severity index at location j

In case of fixed distance band CSR, distance threshold was chosen which associated with high Z score. The distance associated with the first peak of graph between distance threshold and Z score was chosen for mapping clusters. This is shown in figure (3). In case of inverse distance and inverse squared distance CSR, the threshold distance was set to “zero”, this indicated that all accident locations were considered neighbours to each other.

Categorization of Hot spots

In case of analysis using Gi* statistics, all accident locations were categorized in four categories based on their Z scores which signifies their statistical significance level. The breaks were provided at Z scores of 1.65, 1.96 and 2.58, which shows statistical significance level of 0.10,0.05 and 0.01 or confidence level of 90%, 95% and 99% respectively. In case of analysis using K since there is no index associated with statistical significance, hot spots were categorized employing Jenks algorithm. As opposed to any arbitrary categorization scheme, this algorithm produces a group of values that best represents the actual breaks observed in data, hence it conserves the true clustering of data values [5]. In this study, the categorization was done in four categories i.e., low, medium, high and very high priorities based on their associated accident densities.

Results and its Discussions

No accidents were found in police records of old city area near Ganga’s ghats, particularly near the old Kashi Vishwanath temple. This was due to absence of high speed vehicles, predominance of pedestrian traffic and presence of police check posts in the area. In other areas, police records revealed that the majority of accident registered were either fatal (45.52 %) or grievous (40.75%). Obviously there was negligence of people towards the filing of complaints for accidents of minor and property damage only type which accounted for 8.15% and 5.56% respectively of total accidents.

The results of hot spot identification done with the help of K and Gi* for different accident severities and CSR’s are shown in Figures 4 to 6. They reveal locations of potential hot spots within the study area of Varanasi city. Analysis was done with and without considering the severity of accidents. Figure 4 shows the analysis without severity consideration. It shows similar hot spots identified using K and Gi*, when inverse distance and inverse distance square CSR was used. Severity was considered in analysis using NSW and Belgium severity systems as shown in Figures 5 and 6. They also show results similar to that without considering severity. This may be due to either one of the reasons: a) due to contributing factors in accident such as speed of vehicle and alignment of road; b) due to existence of any functional relationship between K and Gi*. Since spatial location and severity of accidents were only parameters taken in consideration, the plausible explanation is existence of functional relationship between K and Gi*. Manepalli et al. [5] had earlier verified such functional relationship.

After analysis with and without severities using K and Gi* adopting inverse square and inverse square CSR, 5 locations were identified as potential hot spots. These locations are specified in Table 1 along with their respective ranking according to different severities and CSR's. These rankings were made according to Z score associated with each location. Effect of accident severity over the results can be easily observed after analyzing rankings obtained, with or without severity. Chawka ghat intersection has the highest number of accidents and is the most significant hot spot when analyzed without severity. But after considering severity according to NSW and Belgium systems, Tengra intersection emerges as most significant hot spot. This is due to larger percentage of fatal and grievous accidents.

Both severity weighing systems show identical rankings of hot spots. This is due to lesser percentage of minor and PDO type accidents which do not cast their influence over the final result. It is worthwhile to mention here that above results may have undergone significant variation in case of appreciable percentage of minor and property damage only crashes would have been recorded.

Results obtained from K and Gi* statistic are similar, but the latter produces results associated with statistical significance. This makes Gi* statistic a better method than K when analyzed using specific CSR's. Inverse square and inverse distance square CSR generated identical hot spots as shown in Figure 5 and 6 as well as in Table 1. Hot spots identified from aforesaid CSR's are distinctive as compared to those identified using fixed distance CSR. This reveals that inverse distance and inverse distance square CSR were better alternatives than fixed distance CSR.

Table 1: Rankings of various hot spots as per different severities and CSR.

Severity types & CSR	Rankings of major hot spots based on GiZ score for various severities and CSR											
	Incident Points				Belgium severity				NSW severity			
Hot Spots Identified	K	Gi* (I)	Gi* (I^2)	Gi* (F)	K	Gi* (I)	Gi* (I^2)	Gi* (F)	K	Gi* (I)	Gi* (I^2)	Gi* (F)
Tengra Intersection	4	2	2	X	1	1	1	X	1	1	1	X
Chawkaghat	1	1	1	X	2	2	2	X	2	2	2	X
Harsevanand Intersection	2	3	3	X	3	3	3	X	3	3	3	X
Toll Plaza Dafhi	5	4	4	X	5	4	4	X	5	4	4	X
Varuna bridge	3	5	5	X	4	5	5	X	4	5	5	X

Note: Gi*(I) represents ranking due to Gi* statistic and Inverse distance CSR, Gi*(I^2) represents ranking due to Gi* statistic and Inverse distance square CSR, Gi*(F) represents ranking due to Gi* statistic and Fixed distance CSR and X represents the insignificant ranking (Ranking not in range of 1 to 5).

Conclusions

The present work has exemplified use of GIS for processing of accident data and performing complex spatial and statistical analysis using two different analysis techniques K and Gi* for hot spot identification adopting various CSR's. This study is first of its kind in Indian traffic conditions taking severity of accidents in consideration. Previous studies used aforesaid techniques for Indian traffic conditions, but were limited to using single type of CSR without considering severity of accidents into account. This study has revealed the superiority of Gi* statistic over K when used with inverse distance and inverse distance square CSR's for identification of hot spots. This method produced accurate and distinctive hot spots for given mixed traffic conditions.

Although this study is limited to identification of hot spots but it can also be utilized for identification of cold spots. This analysis would have much easier, accurate, descriptive and reliable if accident records were more detailed and properly formatted. GPS should be provided in every police station which facilitates recording of X and Y coordinates of each accident location rather than name of nearest landmark. The accident severity weighing systems used were adopted from countries having different traffic and demographic conditions than India. Future research aims at development and utilization of optimum severity weighing for hot spot identification.

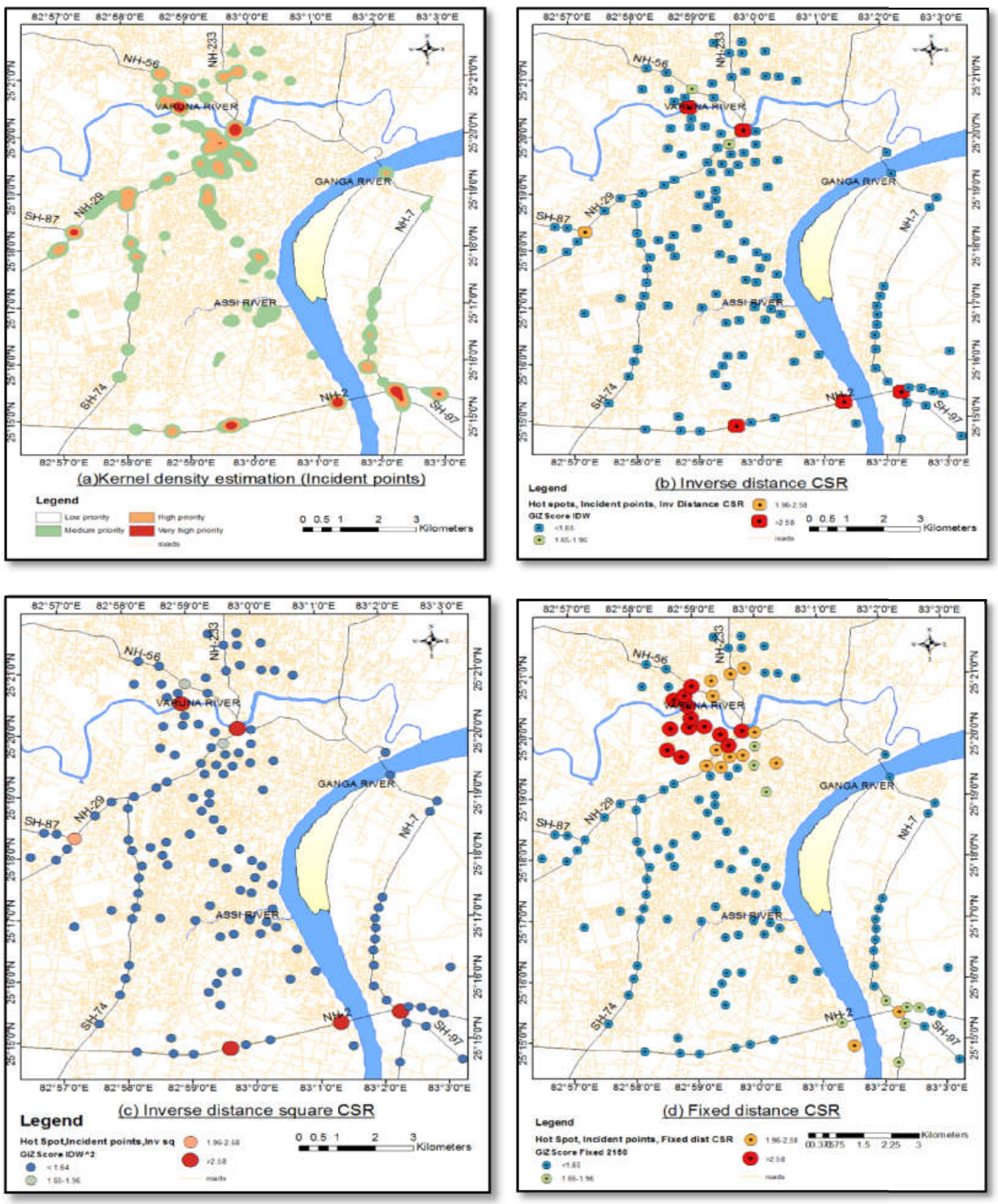


Figure 4: Hot spot identification using K and Gi* statistic for three CSR and employing Incident points.

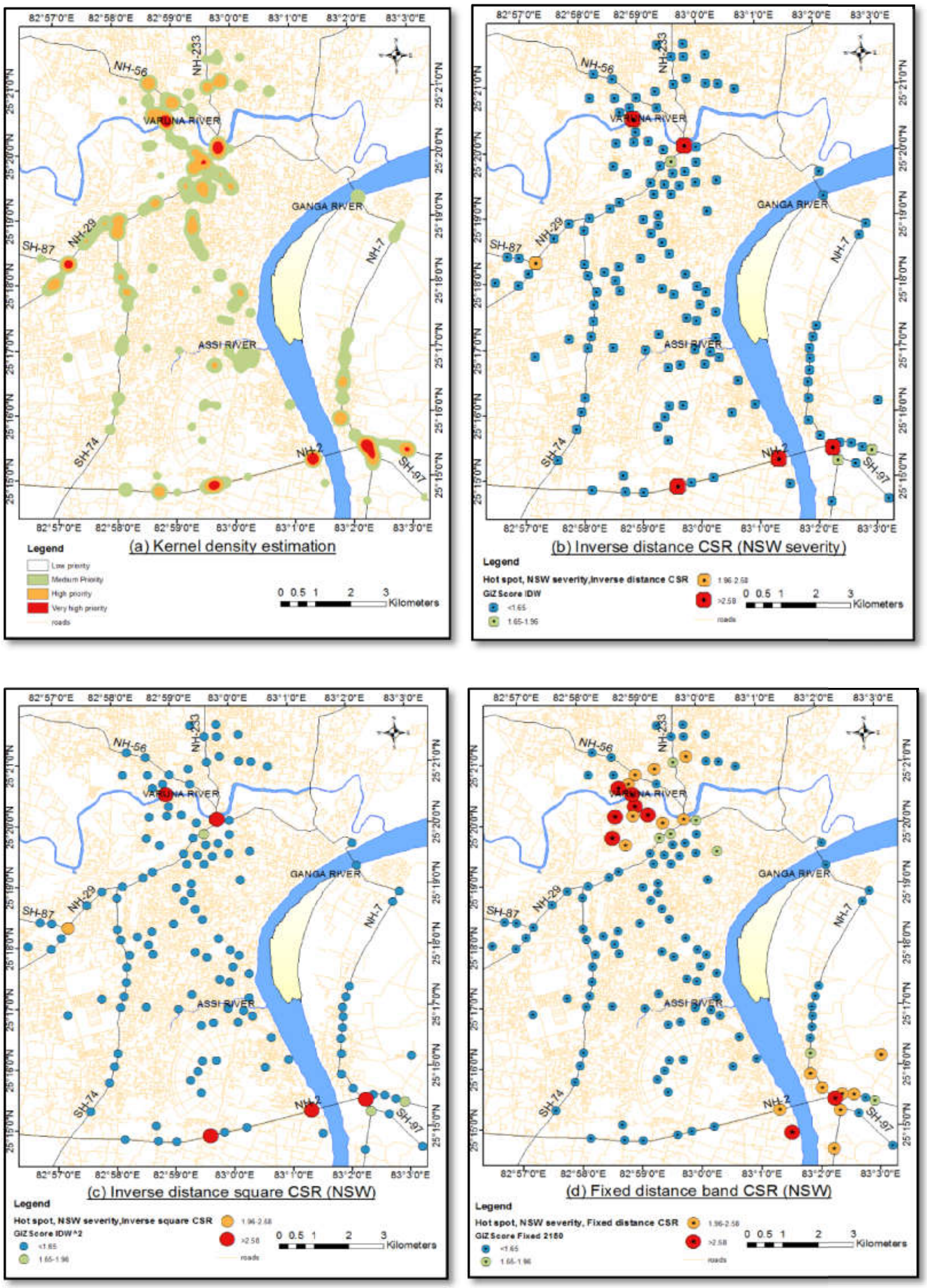


Figure 5: Hot spot identification using K and Gi* statistic for three CSR and employing NSW severity.

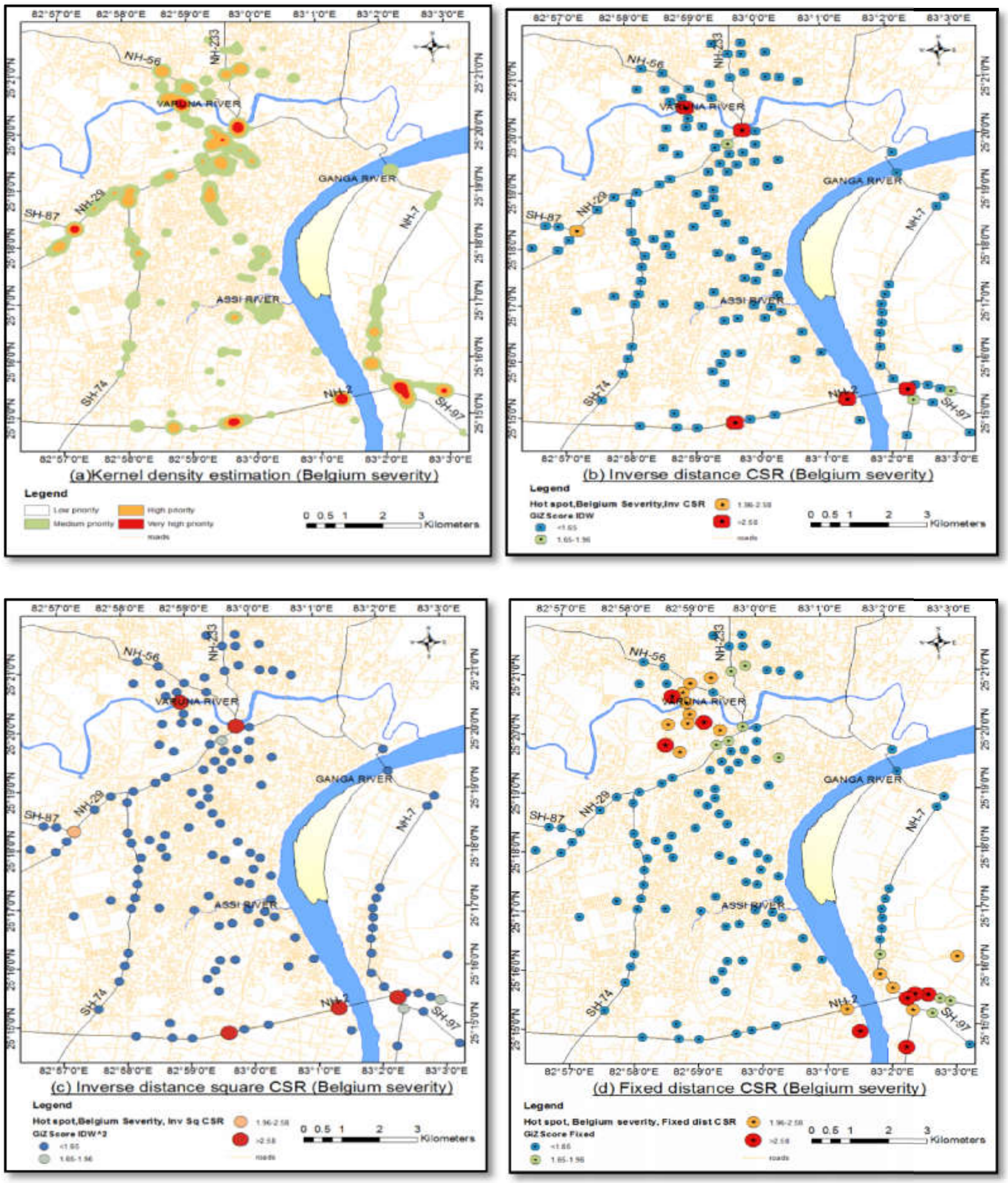


Figure 6: Hot spot identification using K and Gi* statistic for three CSR and employing Belgium severity.

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