GIS-Based Identification of Traffic Incident Hot Spots and Severity Index in Khartoum, Sudan

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Abstract:- Most road traffic accidents (RTA) are fatal or injury-related, particularly in low and moderate-income countries. As a low-income nation, Sudan is significantly impacted by a high rate of traffic accidents, subsequent in numerous fatalities and many individuals suffering severe or permanent injuries, which has direct repercussions for individuals, communities, and governments. This study aimed to identify areas of Khartoum, Sudan, that experience traffic accidents frequently. Geographic Information Systems (GIS) tools have been employed to measure the severity of those accidents from 2020 to 2022. Moreover, the Getis-Ord Gi*, Average of Nearest Neighbor (ANN), and Kernel Density Estimation (KDE) were used to investigate spatial distribution and clustering of traffic accidents. In addition, the study incorporated factors such as the severity of accidents to assess better the risks associated with roads. The results revealed significant clustering patterns of incidents with a high severity indicator in specific locations in the study area, characterized by traffic law violations and inadequate infrastructure in particular zones. Moreover, the ANN approach underscored a statistically significant clustering pattern with a P-value less than 1.0. This emphasized that accidents were spatially concentrated rather than randomly distributed. Therefore, the stability of this clustering throughout the investigation underscores the significance of executing long-term interventions in these high-risk zones.

Keywords: *Road Traffic Accidents, GIS, Kernel Density Estimation, Getis-Ord Gi*, Average Nearest Neighbor, Accident Severity, Khartoum.*

1. Introduction

Road traffic accidents (RTA) are the most significant cause of death among young people worldwide, and they are expected to rank seventh by 2030. Moreover, Traffic accidents endanger people's lives, which are more common in low-income countries due to inadequate road safety measures [1]. These accidents not only cause economic losses but also have an impact on a country's GDP. As a result, research on the economic factors associated with traffic accidents has gained considerable attention in recent years. For example, Outay et al. [2] found that areas with lower incomes and educational levels have more traffic accidents. His analysis highlights the need for interventions for specific economic variables, such as driver training programs and regulations enforcement in underdeveloped areas. which emphasizes it is critical to take precautions to prevent mishaps. Hotspots, sometimes called "black spots," are regions on a highway where accident frequency surpasses expected levels at a given significance level [3].

Due to the advancement of roadway transportation and motor vehicles throughout the years, traffic safety hazards have significantly proliferated. The World Health Organization (WHO) mentions that road traffic collisions (RTS) rank as the eighth highest cause of mortality across all age demographics, with the vulnerable group being 5-29-year-old children and adolescents and young adults [4]. Road traffic accident safety officials assess factors to minimize fatalities, identify the root cause of traffic accidents, and pre-describe relevant intervention measures. This study aims to provide the required information on factors to reduce crash occurrences and their consequences.

Owing to the distance factor inherent in road networks, a significant characteristic of road crashes that must be considered in traffic safety studies is the spatial associations of crashes. Spatial analysis investigates crash events and their spatial aspect's correlation geographically. Traffic crashes have two critical geographical data attributes: distribution and re-occurrence. Under the meaning of spatial dependence, the occurrence of an incident will affect the occurrence of another incident located near a previous incident. On the other hand, spatial heterogeneity occurs when the spatial correlation between observables and estimates in the model is heterogeneous by spatial location [5].

GIS has become an essential tool for community health research [6]-[8]. Berhanu et al. conducted a spatial analysis in Addis Ababa to identify traffic accident hotspots and their relationship to health service access and emergency response times. This study shows the need to include traffic safety measures in health planning [9]. Over the last fifty years, GIS has been extensively utilized in road traffic safety research [10],[11]. It uses simple span mapping and visualization to more sophisticated techniques like spatial statistical models and massive dataset analysis. Nowadays, GIS databases contain exact information about the location and characteristics of traffic accidents. GIS software makes acquiring, manipulating, analyzing, and visualizing spatial data easy [12],[13]. Although various evaluations have assessed analytical methodologies, research shows that spatially improved collision analysis provides valuable insights into road safety by highlighting regions of safety concern [14],[15].

Road traffic accidents affect not just individual health but also the well-being of family members, often forcing households into poverty as they deal with the long-term consequences, such as medical treatment costs. Furthermore, these accidents burden national healthcare systems [16],[17]. Low- and middle-income countries endure the most tremendous burden of (RTA). Accounting for nearly 85% of fatalities and 90% of lost life years [18]. Nevertheless, the impact of road traffic accidents could be significantly minimized by implementing preventive measures in areas lacking safety infrastructure [19],[20]. GIS is a crucial and extensive tool for managing traffic safety. Researchers and GIS practitioners have long been intrigued by GIS-enabled spatial analysis of traffic accidents, as it offers insights into identifying hazardous regions, hotspots, and cold spots [21].

A diverse array of conventional statistical models is frequently employed for hotspot detection. Thomas, in 1996, used traditional statistical approaches on collected data of varying segment lengths, noting discrepancies in distribution, and determined that results obtained for one segment may not apply to others. He also noted the significant role of road segment length in the statistical distribution of accident frequency [22]. However, traditional models typically assume constant spatial characteristics of hotspot locations over time, which may not reflect reality. A comprehensive knowledge of the elements affecting traffic accidents, including accident severity and the environmental context, is essential for effective hotspot analysis. [23]. In contrast to conventional methodologies, spatial analysis facilitates the detection of traffic accident trends and offers insights into the fundamental causes of these patterns. [24].

A GIS-based accident analysis enables the modeling of links between spatial phenomena that are challenging or almost unattainable with non-spatial databases. Since the early 1900s, researchers have significantly utilized GIS to geo-code accident sites, create accident pin maps, and execute database queries for analytical purposes. Beyond identifying accident-prone locations by their frequency, accidents can also be ranked based on severity. Various researchers have allocated weight to incidents based on their seriousness. For example, Trivedi et al. [25] proposed weights of 5 for fatal accidents, 3 for grievous accidents, and 1 for minor accidents. Similarly, Luatheb & Tanaboriboon [26] applied weights of 3.0, 1.8, 1.3, and 1.0 for fatal, grievous, minor, and property damage-only accidents, respectively. At the same time, Luathep [27] suggested 125, 9, and 1 weight pertaining to fatal, injury, and property damage-only incidents. Before the advent of GIS, traffic accident analyses relied solely on traditional statistical methods. The introduction of GIS has enhanced the process by offering several capabilities, including managing large volumes of diverse data types, visualizing accident locations, and efficiently conducting spatial analysis to pinpoint hotspots [28]. A recent study conducted by Gautam [29] shows the importance of GIS techniques for identifying traffic accident hotspots, showing how Kernel Density Estimation (KDE) calculations

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can be combined with Getis-Ord Gi* Able to identify and resolve incidents in areas of vulnerability and impact for policy interventions. Another related study by Alkaabi [30] used spatial analysis in the Sultanate of Oman to analyze driving behavior patterns, providing important insights into the relationship between driving habits and accident hotspots. This study examines diverse spatial and statistical techniques utilizing GIS to explore the spatial clustering of traffic accidents and determine high-risk spots within the research area. It includes an example application of KDE, ANN, and Geti-Ord G*.

2. Study Area And Data Collection

The capital and largest metropolitan in the country, Khartoum City, is located at the confluence of the Blue Nile and White Nile rivers, at approximately 15.5007° N and 32.5599° E. This position makes it a critical geographic and economic hub alongside its sister cities, Omdurman and Khartoum Bahri. However, the town encounters considerable road safety difficulties due to rapid urbanization, increasing vehicle numbers, and poor infrastructure. Reckless driving, overcrowded public transport, and lack of traffic law enforcement contribute to frequent accidents. While authorities are working to improve road safety through campaigns and regulations, ongoing congestion, infrastructure, and emergency response issues make accidents a persistent problem. The road traffic accident (RTA) data was obtained from the "General Directorate of Traffic Police." The "Sudan Survey Authority" supplied a map of Khartoum and a road network map, with the research period spanning from 2020 to 2022.

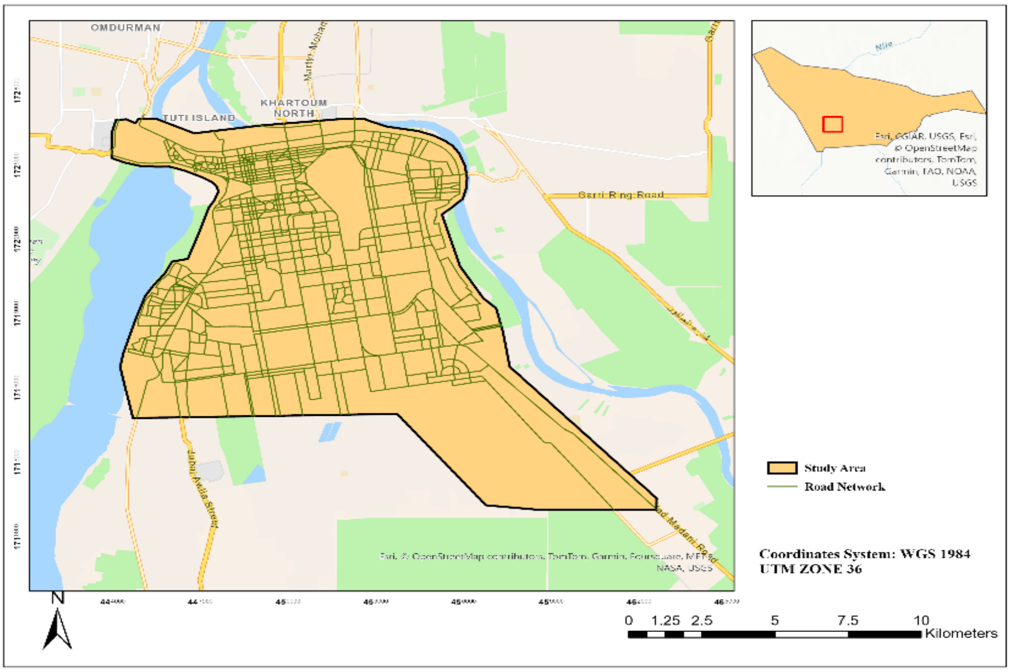

Fig. 1. Study Area

3. Methodology

A. Accident Datasets and Map Preparation

This paper employed ArcGIS Pro for investigation. Khartoum's road network map was imported into ArcGIS Pro and designated as the “roads” shapefile. The imported digital map and data frame in ArcGIS Pro must utilize the identical 'projected coordinate' system. The coordinate system employed in this study is WGS 1984, UTM Zone 36. The accident data from the study area for the past three years (2020-2022) were collected from various departments of Sudan. The accidents were geocoded by assigning Longitude and Latitude coordinates to each location. For each geocoded point, a Feature Identity (FID) is automatically generated as a digit in GIS.

B. Severity Consideration

The study aimed to identify high and low clustering of accident incidents by analyzing crash data. However, it's hard to determine if the clustering is significant without considering the severity of accidents. To do this, the research employed some methods in addition to primary incident data to improve the identification of dangerous places according to the severity of their crashes.

C. Kernel Density Estimation (KDE)

Kernel density is a fundamental spatial analysis technique in GIS, highlighting the boundaries of an event of interest, like accidents. The approach partitions the research area into occupied cells. It smooths accident sites using the kernel's quadratic function movement. [31] The accident point has the highest surface, which drops to zero after a limit. This function assigns values to each cell and totals them by adding their values and dividing them by their number. Each accident is assigned a weight based on its ID number in the kernel density's population field to indicate its importance while computing. This lets the system count accidents and assess their severity. The population field is empty when no severity evaluation is made, and all analysis is done on incident event positions. The kernel estimator equation is below.

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

Equation. (1). Kernel density estimation.

Where (h) refers to the bandwidth, radius, or smoothing factor, while (K) represents the kernel, and f is the estimator of the probability density function. The accuracy of the kernel estimator is influenced by the choice of bandwidth (h), so selecting the appropriate bandwidth is crucial based on the specific goals of the study.

D. Getis-Ord Gi* Statistic

Two main processes were used to identify critical hot spots, collecting event data and mapping clustering with the Getis-Ord Gi* function. [32] This function generates a new output for each accident with a Z score and P value indicating strong clustering. The following equation expresses them.

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij} \, x_j - \bar{X} \sum_{j=1}^{n} w_{ij}}{S \sqrt{\frac{\sum_{j=1}^{n} w_{ij}^2 - \left(\sum_{j=1}^{n} w_{ij}\right)^2}{n-1}}}$$

Equation. (2). The Getis-Ord Gi* Statistic.

Where:

Gi* is the Getis-Ord Gi* statistic for location i

wij = weight of target neighbor pair

xj = severity index at location j

E. Average Nearest Neighbor (ANN)

The "Average Nearest Neighbor" (ANN) analysis is a spatial statistic technique that calculates the proximity to the nearest neighbor of each point. It then measures the measured mean distance compared to the anticipated distance in random distribution. This technique also assists in classifying if a pattern is clustered, dispersed, or random. In the context of accident hotspots, ANN analysis can enable us to discover whether there are areas where accidents tend to occur closer together (clustered), Unspecified (Random), or ununiformly across an area (dispersed) [33]. Hence, it provides helpful information for spatial patterns in road safety planning. The formula for this could be determined by using:

$$R = \frac{D_o}{D_e}$$

Equation. (3). Average Nearest Neighbor.

Where:

R = Nearest neighbor ratio

Do = Measured average distance from each feature to its closest neighbor

De = Anticipated average distance for a stochastic distribution of points, which is given by the formula:

$$D_e = \frac{1}{2\sqrt{\frac{n}{A}}}$$

Equation. (3-1). Expected distance of random points distribution.

Where:

n = Points Number in the study zone

A = Area of the study zone

4. Results and Discussion

The GIS methodology utilized in this study has shown how areas with high road accident potential could be identified on defined parts of the Khartoum Road network. Additionally, it provided an extensive spatial analysis of accident distributions and hotspots using the KDE method and the Getis-Ord Gi* statistic. These methods are essential for understanding accident severity and frequency and provide insights that can be considered while formulating targeted interventions by policymakers and planners.

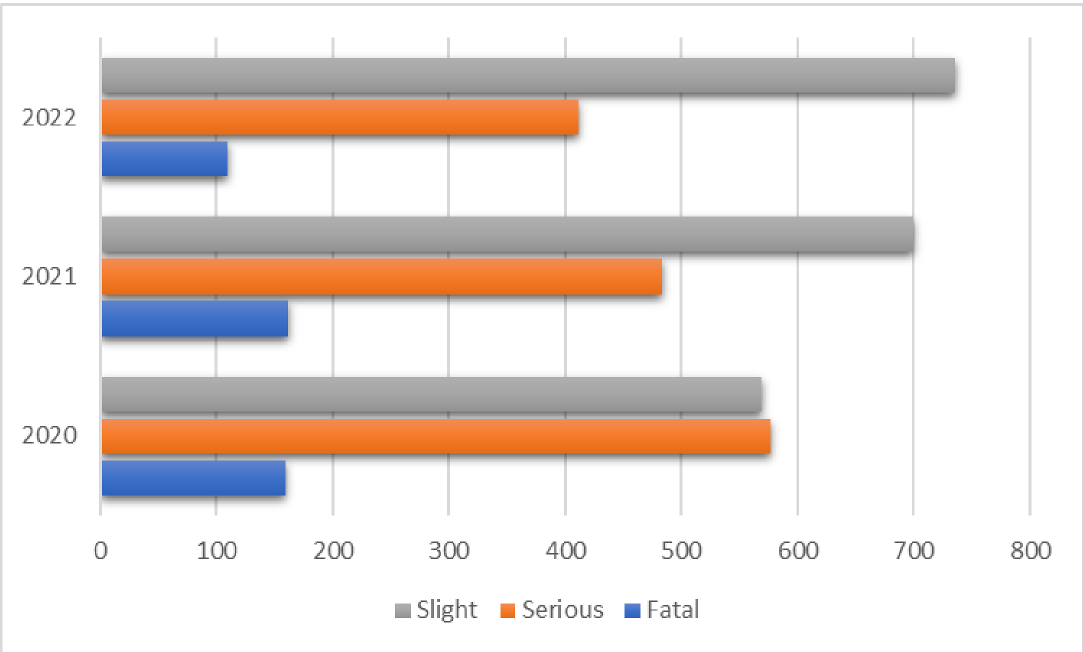

Fig. 2. Accidents severity of the study period.

A focus on ranking hotspots by accident severity is one of the most significant contributions of this study. Prior research has emphasized the incidence of accidents disregarding the severity of each event. Through including severity, the examination offers data that is somewhat more nuanced about the place deaths or serious injuries that need helpful near-term consideration than mere accident counts as shown in (Fig. 2). This agrees with the past research of Mekonnen & Teshager [16]. Dereli & Erdogan et al. [5] have used a weighted system to evaluate accident severity and emphasized that incorporating severity data in geographical models such as KDE can lead to a more informative analysis and have implications for better policy decisions.

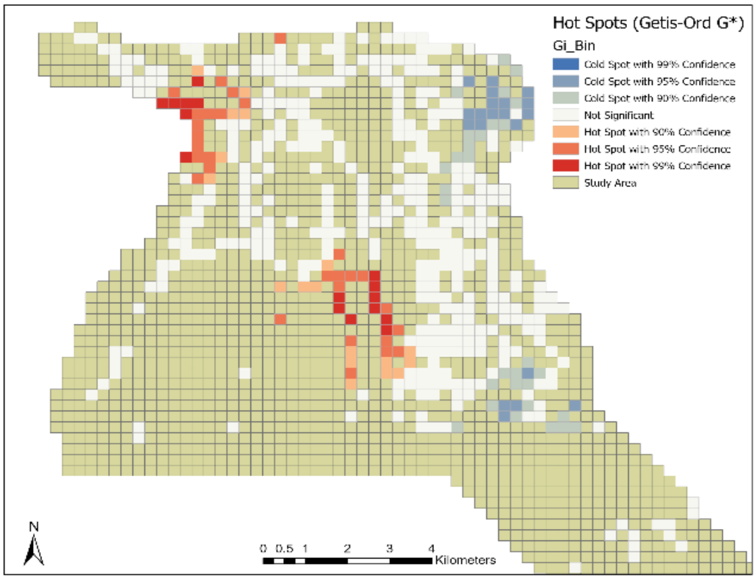

Fig. 3. Hot spots of the year 2020.

KDE was a central part of the methods used in the current study. The KDE provides a clear spatial visualization of accident densities over the Roads Network in Khartoum, as shown in (Fig. 6). This technique is widely applied in spatial analysis, as shown in Zheng et al. [34] and Le Giang et al. [35] Studies. Katicha et al. [36], by including accident severity as a weighting factor, aim to overcome these studies' limitations and ensure that more weight is given to high-severity accidents. Further trials may evolve new bandwidths that range around critical speeds; such results provide information on how well this configuration can identify essential accident zones.

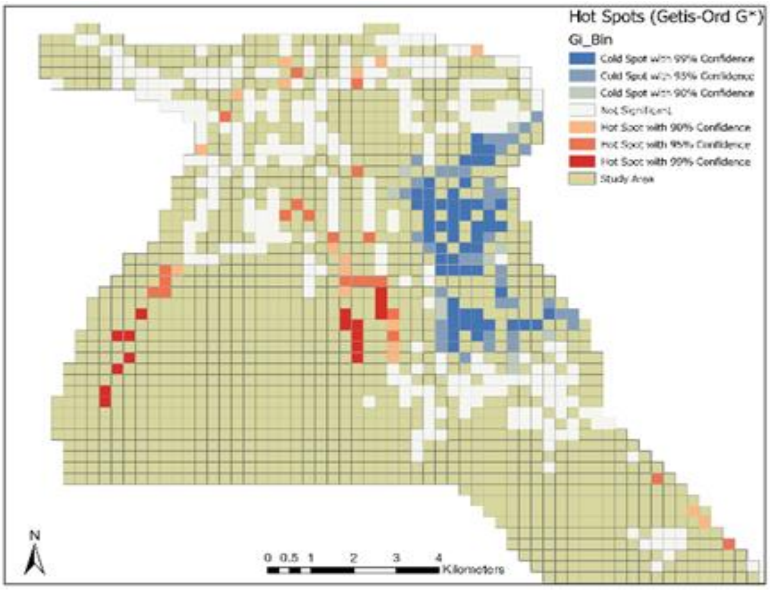

Fig. 4. Hot spots of the year 2021.

The Getis-Ord Gi* statistic further complicates the analysis. On the other hand, the Getis-Ord Gi* function concentrates on statistically significant clusters of high-severity accidents instead of density, which helps to clarify a more nuanced understanding of where risks are vastly over-represented. This approach is also compatible with earlier studies, such as [37]-[39]. Demirel & Erdogan [40] and Truong & Somenahalli [41] have demonstrated the need to detect spatial clusters of higher-risk areas. This way, we can better appreciate the road safety challenges in Khartoum and figure out which areas to target for infrastructure or law enforcement interventions.

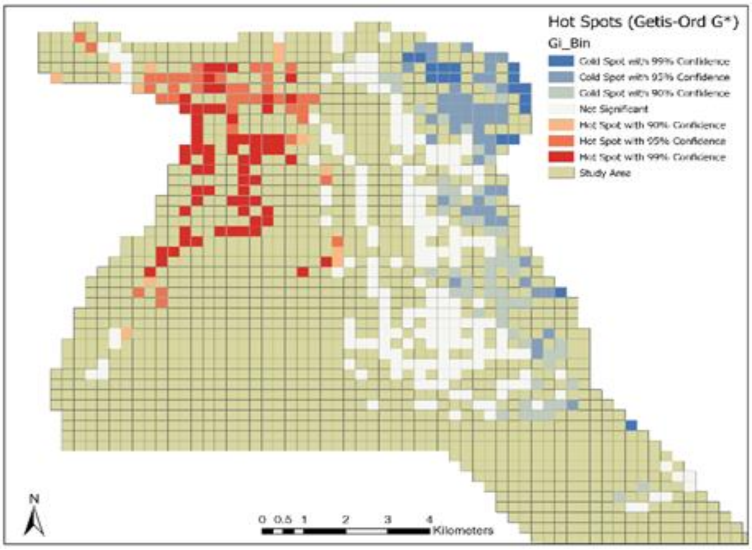

Fig. 5. Hot spots of the year 2022.

The model found that areas identified as accident hotspots through the ANN were correspondingly located in regions with deteriorating infrastructure and overcrowded public transport. The ANN analysis also found a significant clustering pattern with a P-value of less than 1, showing that accidents occur more often close to each other than would be expected by random. Given the z-score of -95.194534, There is a probability of less than 1% that this clustered pattern could arise from random chance (Fig. 7).

The combination of KDE and Getis-Ord Gi* revealed that certain hotspots persisted over the three-year study period (2020–2022), suggesting that these areas are chronically dangerous. The ANN analysis further emphasized that the clustering patterns remained consistent over time (Fig.6 & 8).

Fig. 6. Kernel density result.

The findings of this study are consistent with broader trends observed in other low- and middle-income countries, where rapid urbanization, inadequate infrastructure, and weak traffic law enforcement lead to high rates of road traffic accidents. Erdogan has drawn similar conclusions. [40] and Mekonnen & Teshager [16], highlighting the challenges urban centers face in developing countries. The results show that traffic accidents in Khartoum are concentrated in areas with poor infrastructure, overcrowded public transport, and inadequate traffic control measures. These findings suggest a need for targeted interventions, such as improving road design, expanding pedestrian facilities, and enhancing traffic law enforcement in high-risk areas (Figs. 3, 4, 5).

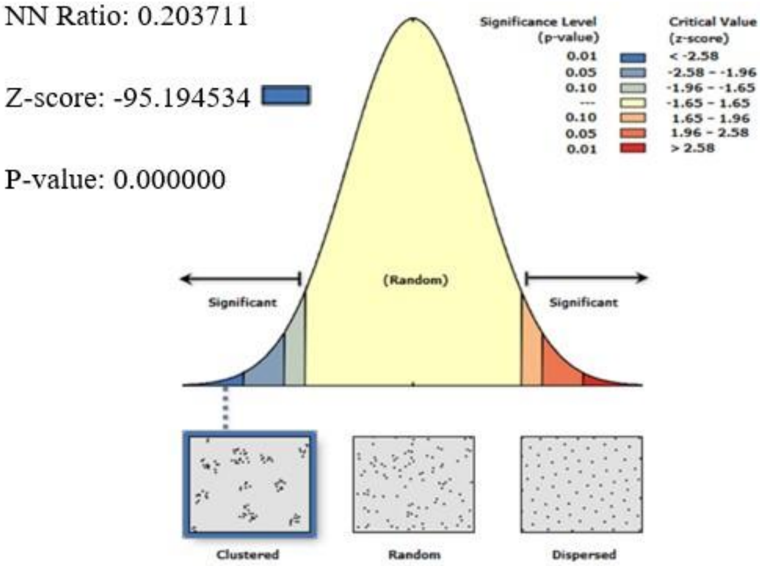

Fig. 7. Average Nearest Neighbor Report.

From a policy perspective, the practical implications of this study are clear. Identifying dangerous road locations through crash severity should guide infrastructure investments and traffic management strategies. For instance, road sections with a high density of severe accidents might benefit from installing Traffic signals, speed cameras, or pedestrian crossings. Moreover, the study highlighted the importance of strengthening traffic law enforcement in areas where reckless driving and over-speeding are prevalent. There should be strict penalties for traffic signal infractions and non-compliance with seat belt usage. These recommendations could be a part of international efforts on road safety, such as the World Health Organization's Decade of Action for Road Safety (2011- 2020), which calls on countries to develop plans targeting road traffic crash reduction.

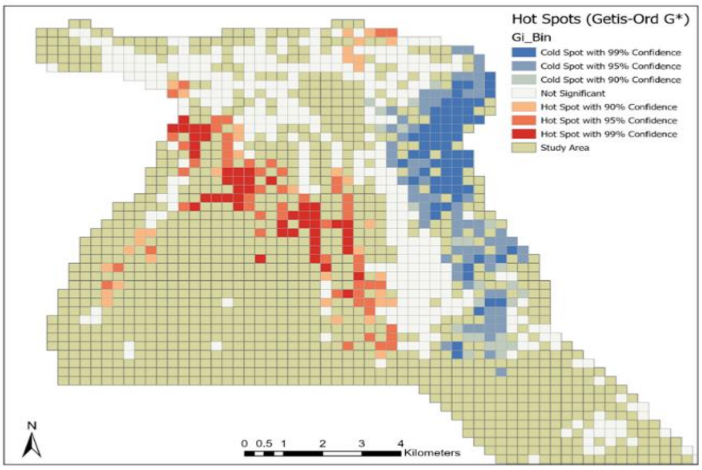

Fig. 8. Hot & Cold spots during the study period severity accident-based

5. Conclusion

The current study highlighted the potential of GIS-based methods in identifying accident black spots with an emphasis on severity. It contributed to road traffic safety by undertaking risk mapping of road accident locations using Kernel Density Estimation (KDE), Average of Nearest Neighbor (ANN), and Getis-Ord Gi* statistic. Furthermore, it provides a comprehensive, evidence-based analysis of road accidents in Khartoum, identifying key locations that need immediate intervention.

The findings also revealed the influence of accident frequency and severity in hotspot identification. Furthermore, this study provided a better overview of road safety problems by integrating severity considerations into the analysis. This can offer better insights for policymakers and practitioners to allocate resources and make decisions. The results indicated that improving the road infrastructure, enforcing traffic laws more effectively, and increasing public awareness are essential to reducing road traffic accidents in Khartoum.

Future work is envisioned to investigate the temporal patterns of accidents to identify factors attributing to the time-dynamic patterns of hotspots. Integrating socio-economic data would provide insight into the causes of accidents and may help develop more effective safety measures. It is also interesting to investigate which types of traffic safety intervention are most effective at reducing crashes in hotspots identified by the proposed framework. The study provides a solid foundation for developing data-driven policies to reduce road traffic accidents and improve public safety in urban environments.

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