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J. Geogr. Inst. Cvijic. 2025, 75(2), pp. 199–216

Original scientific paper

UDC: 551.50-656.1(560)
https://doi.org/10.2298/IJGI241028001G

Received: October 28, 2024
Reviewed: January 29, 2025
Accepted: February 22, 2025

ASSESSMENT OF BLACK ICE RISK LEVELS IN THE CITY CENTER OF ERZURUM (TURKEY) USING GEOSPATIAL DATA

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Abstract: Severe winter conditions, including extended snow cover and frequent frosty days, increase the risk of traffic accidents due to icing, leading to more accidents, even with injuries and fatalities. Erzurum (Eastern Anatolia Region, Turkey), with its harsh winters, stands out as a city requiring attention in this regard. The study focused on Erzurum city center, where the combination of winter weather conditions (October–April) and high traffic volume heightened the accident risk from icing in the period 2017–2022. Accident data from the General Directorate of Security of the Republic of Turkey and weather data from the General Directorate of Meteorology of the Republic of Turkey were analyzed, along with the area's topographical characteristics (slope and aspect). The performed spatio-temporal analysis revealed that most accidents occurred in January (69 cases) and between 17:00 and 00:00 (136 cases). Accidents were linked to specific weather conditions: air temperatures between −11.7 and 0.6 °C, soil temperatures from −4.9 to −0.8 °C, wind intensity of 0 to 1.1 m/s, humidity levels between 81% and 100%, and cloudiness between 6 and 8.9. Hot Spot Analysis identified high-risk locations, including Saray Bosna Avenue, Atatürk Boulevard, and several major junctions. The study also suggested alternative systems to reduce accidents caused by icing on these routes.

Keywords: black ice; traffic accidents; Erzurum; Turkey

1. Introduction

Ice formation on the road surface that is difficult to notice and usually has a transparent appearance is referred to as black ice (Shi & Fu, 2018). The potential for icing on the road surface, contingent on geographical and meteorological parameters exhibiting the aforementioned characteristics, is referred to as black ice risk (Rodman & Williams, n.d.). In Turkey, the probability of this risk is heightened in regions with a harsh continental climate, where frost events are frequent. While the risk of hidden icing may be questioned in the Eastern Anatolia Region, where winters are typically snowy and temperatures drop below 0 °C, this risk may also occur in certain parts of the country where sudden temperature changes are experienced (Atalay, 1992). It can be posited that the harsh continental climate is most

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prevalent in the northern and northeastern regions of the Eastern Anatolia. In these areas, winters are characterized by extreme cold and frequent, severe frosts (Şahin, 2006). The occurrence of frost events is contingent upon sudden temperature changes. It is evident that the most salient feature of the continental climate is the considerable daily and seasonal variation in temperature. The term hydro-meteorological disasters encompasses a range of natural disasters, including extreme temperatures, harsh winter conditions, storms, fog, floods, landslides, avalanches, and waves, as well as frost events (Guha-Sapir et al., 2012). The occurrence of disasters caused by adverse weather conditions raises questions about their spatial implications. Such issues manifest in a number of ways, including disruption to energy connections, an increase in air and water pollution, and a breakdown in transport. Furthermore, traffic accidents are a significant concern in urban areas with high population and vehicle traffic volumes.

In this context, the number of traffic accidents in the city of Erzurum (Eastern Anatolia Region, Turkey) between 2017 and 2022 was 7,896. Of these accidents, 4,785 occurred within the city center, while 3,111 occurred outside of it. Another 373 individuals lost their lives and 14,778 sustained injuries in these incidents (Turkish Statistical Institute, n.d.). The statistics pertaining to road traffic accidents demonstrate that despite the sophisticated transport systems and rigorous regulatory controls that are currently in place, this particular field continues to receive insufficient attention. While the incidence of road traffic accidents is declining in developed countries (Mohammed et al., 2019), the situation in Turkey is showing a consistent upward trend (Özlü et al., 2021). It is evident that traffic accidents represent a significant challenge that requires urgent attention.

A literature review of this topic reveals a lack of scientific studies addressing the spatial dimension of hidden icing detection and risk level determination. Nevertheless, the literature contains studies in which smart road condition sensors are designed to detect the condition of the road surface (Duran & Teke, 2019). At the international level, there are studies on detecting hidden icing. These studies generally include various sensor designs and mechanisms obtained with the help of artificial neural networks to detect icing (Gailius & Jačėnas, 2007; Lee et al., 2022; Liu et al., 2017; Mitas et al., 2011; Tharmakularajah et al., 2020). There are also studies to classify the road condition with the help of video images (Kuehnle & Burghout, 1998). The effect of weather conditions on road safety and traffic accidents is also an area of research (Andrey et al., 2003; Bijleveld & Churchill, 2009; Black & Mote, 2015; Eisenberg, 2004; Nokhandan, 2006). Furthermore, studies have been conducted that examine the spatial patterns of the impact of meteorological conditions on road traffic accidents (Haque et al., 2022; Harirforoush et al., 2019; Khan et al., 2008). In the present studies, the effect of meteorological conditions (rain, fog, snow, etc.) on road traffic accidents has been examined, and the tendency for accidents to cluster has been investigated by means of Hot Spot and Kernel Density Analyses. In contrast to the aforementioned studies, this research addresses the issue of traffic accidents occurring on snowy and icy roads in Erzurum, taking into account the specific challenges posed by the harsh weather conditions. It presents recommendations to mitigate the risk of accidents in this context.

In the context of the study, applications that are currently in use for the detection and prevention of icing have a significant role in analyzing the present situation and conducting future research. Consequently, it is hypothesized that applications such as sensors and intelligent intersections utilized in the domain of smart roads can serve the purpose of the study. Indeed, it is evident that there are numerous application methods involving environmental and road condition sensors that are employed for the purpose of preventing icing. Examples of such applications include the Icing Early Warning System, the Automatic Solution Spraying System, the automatic spraying application used in public transport vehicles, the use of heating with carbon fiber tapes, and the asphalt pavements with electrical conductive properties (Gökdemir, 2013; Joerger & Martinez, 2006; Li et al., 2021; Monsere et al., 2006; Yang et al., 2012).

2. Study area

The study area is situated between 41°08′48″ and 41°20′54″E longitude and 39°49′43″ and 39°57′29″N latitude. In terms of altitude, Erzurum is a city situated at an approximate elevation of 1,900 m a.s.l. The site is situated within the administrative boundaries of Erzurum's metropolitan counties, specifically in the northern district of Yakutiye, the southern district of Palandoken, the western district of Aziziye, and the eastern districts of both Palandoken and Yakutiye. Furthermore, the Erzurum Plain is situated to the north and west, Topdagı Hill and Akyıldırım Mountain are located to the east, and the Palandoken Mountains are located to the south (Figure 1).

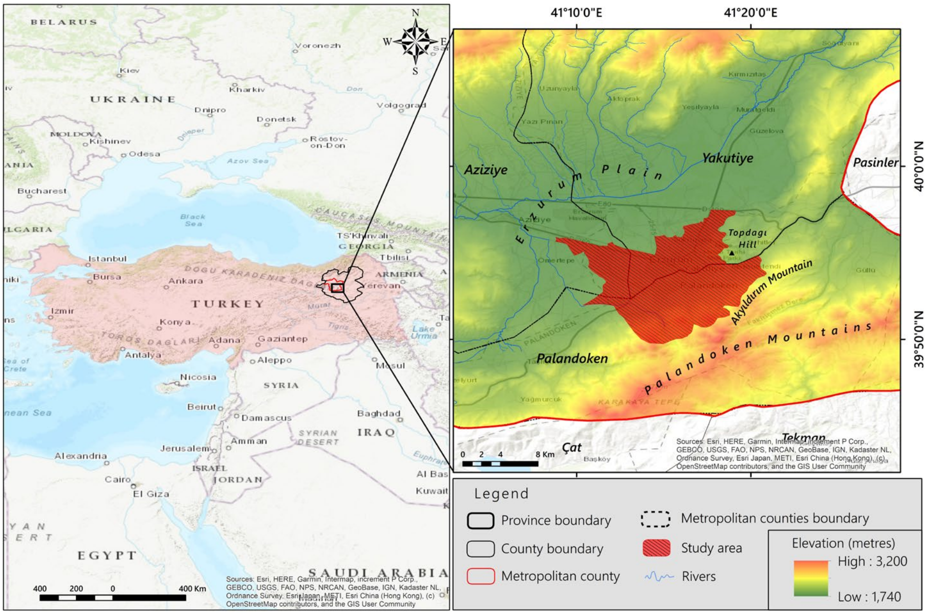

Figure 1. The study area.

The city of Erzurum, which serves as the focus of our study, exhibits the aforementioned harsh continental climate characteristics in the northern and northeastern regions of the Eastern Anatolia. Consequently, the city center of Erzurum experiences frequent frosts and a considerable number of days covered with snow. Snowfall is a possibility in Erzurum and its surrounding area for seven months of the year (Onur, 1961). Furthermore, the average number of days with the lowest temperature below 0 °C in Erzurum is 162.4 (Kaya, 2022).

The mean duration of snow cover on the Erzurum Plain is 120 days (equivalent to four months) per year (Onur, 1961). The data presented herein demonstrate that Erzurum is situated within a geographical region characterized by extremely cold temperatures in comparison to other provinces in Turkey.

A review of the 94-year observation data for Erzurum (1929–2022) reveals an average annual temperature of 5.8 °C. This value indicates that Erzurum is one of the provinces with the lowest average annual temperature in Turkey (General Directorate of Meteorology, n.d.). Similarly, the provinces of Ardahan (3.7 °C) and Kars (4.8 °C) in the northeastern part of Turkey also have relatively low average annual temperatures (General Directorate of Meteorology, n.d.). The primary factors contributing to the low temperatures observed in and around Erzurum are the continental climate and altitude. The city is situated at an altitude of between 1,760 and 2,060 m a.s.l. (Orhan & Güney, 2023), which results in low humidity and air density. This causes daytime heat to return to space rather than being retained on the surface at night (Kaya, 2022). The climatic characteristics of Erzurum and the city's dense urban fabric, particularly when coupled with high levels of vehicle traffic, have been observed to have a detrimental impact on transportation, especially in the context of adverse weather conditions such as heavy snowfall and icing. In order to identify potential solutions to these issues, the Erzurum city center was selected as the primary study area.

3. Material and method

To evaluate the potential for hidden icing and related accidents in the Erzurum city center, a detailed analysis was conducted on the frequency and severity of traffic accidents occurring on snowy and icy roads. A review of past accidents provides insights into the types of incidents that occur and the risks associated with icy conditions. The study employed two datasets.

The first dataset comprised information on road traffic accidents. The data from the General Directorate of Security Traffic Department for the period 2017–2022 comprised information on road conditions (snowy or icy), accident timing, and coordinates (General Directorate of Security of the Republic of Turkey, 2023). However, the dataset is limited to accidents involving injuries or fatalities, thereby underscoring the necessity for comprehensive accident reporting in future research. Meteorological data were collected from the General Directorate of Meteorology, covering the period 2017–2022, included measurements of temperature, humidity, cloud cover, soil temperature, and wind speed (General Directorate of Meteorology of the Republic of Turkey, 2023). These parameters were subjected to analysis in order to ascertain their role in accidents occurring on icy roads.

A frequency analysis was conducted to evaluate the meteorological conditions prevailing at the time of the accidents. The number of frequency groups was determined by applying the logarithm to the data points, and the data ranges were divided into classes for detailed analysis. This approach facilitates a more profound comprehension of the risks associated with accidents under particular meteorological circumstances.

The study employed a quantitative methodology to analyze traffic accidents in Erzurum city center, with a particular focus on both relational and spatial dimensions. The relationship between the distribution of winter accidents and the phenomenon of hidden icing was subjected to comprehensive examination. The integration of spatial data, including slope, aspect, and climate, with accident data enabled the identification of high-risk areas for icing.

The study employed a range of key methods and techniques, including mapping and spatial analysis. The locations of accidents were mapped using ArcMap 10.x (Environmental Systems Research Institute, 2016), utilizing coordinate data from the General Directorate of Security of the Republic of Turkey. Digital elevation data with a resolution of 12.5 m, derived from ALOS PALSAR (Alaska Satellite Facility Data Search, n.d.), were employed to generate aspect and slope maps, which facilitated the identification of areas susceptible to icing based on solar radiation and terrain characteristics. The identification of high-risk routes was achieved through the utilization of spatial mapping techniques such as Kernel Density and Hot Spot Analysis, while temporal patterns in accidents were analyzed based on date and time data. Additionally, meteorological value ranges linked to high accident frequency were determined. The aforementioned analyses enabled the temporal and spatial dimensions of accidents to be associated with climate data, and the meteorological value ranges and locations that pose an accident risk due to icing in the study area to be determined. A Kernel Density Analysis was conducted to evaluate the concentration of accidents, with injury counts used as a weighting factor (Environmental Systems Research Institute, n.d.). This analysis quantified the density of accident occurrences, thereby highlighting high-risk zones. This is calculated in accordance with Equations 1 and 2 provided below (Sheather, 2004; Silverman, 1998):

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

$$K\,(y) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{y^2}{2}\right) \quad (2)$$

In Equation 1, $\hat{f}_h(x)$ denotes the density of the data set at point x; n signifies the total number of data points in the data set; h represents the width of the Kernel function; X_i denotes the i-th (X_1, X_2, ..., X_n) data point in the data set; $K\,(u)$ signifies the contribution of the data points according to their distance from x; and $(x - X_i)/h$ denotes the normalized distance given the Kernel function. In the context of Equation 2, $K\,(y)$ denotes the value of the Kernel function at point y; $1/\sqrt{2\pi}$ signifies the normalization constant in the Gaussian distribution; exp denotes the natural exponential function; $-y^2/2$ is the exponent of the exponential function; and y is the normalized distance.

In addition to Kernel Density Analysis, the accident dataset was subjected to a Getis-Ord Gi* Hot Spot Analysis (Getis & Ord, 1992). The analysis yielded determinations of locations posing risk according to the levels of significance. The results of the Hot Spot Analysis indicate the clustering characteristics of the points obtained according to the p (probability) and y (standard deviation) values, as calculated using the Getis-Ord-Gi* statistic for each feature in the dataset. The significance level of a feature is calculated in accordance with the p and z values, and hot or cold spots are defined in relation to the confidence intervals. It is insufficient for a point to have a high value in order for it to be classified as a significant hot spot. For a given point to possess the requisite features, it must be situated in proximity to other points exhibiting elevated values. The aforementioned analysis is calculated in accordance with Equations 3, 4, and 5 provided below (Environmental Systems Research Institute, n.d.; Getis & Ord, 1992):

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j} \right)^2 \right]}{n-1}}} \tag{3}$$

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{4}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - \overline{X}^2} \tag{5}$$

In the context of Equation 3, the Getis-Ord Gi* statistic for the i-th spatial unit is defined as G_i^*; the total number of spatial units in the dataset, denoted by n; the observation or value of the j-th spatial unit x_j; the relationship between the i-th and j-th spatial units $w_{i,j}$; the arithmetic mean of the dataset $\overline{X}$; and the standard deviation of the dataset S. In Equation 4, $\overline{X}$ denotes the arithmetic mean of the data; $\sum_{j=1}^{n} x_j$ signifies the sum of the data; n is the number of observations in the dataset. In Equation 5, S is the standard deviation of the dataset; $\sum_{j=1}^{n} x_j^2$ is the sum of the squares of the data; the mean of the squares of the data is $\sum_{j=1}^{n} x_j^2/n$; and the square of the arithmetic mean X^2.

4. Results and discussion

4.1. Temporal analysis of accidents

The data pertaining to accidents (in the period 2017–2022) demonstrated fluctuations over the years, exhibiting a cyclical pattern of increase and decrease, with the exception of 2022. The precipitous decline in accidents between 2019 and 2020 can be attributed to the reduction in vehicle traffic that occurred during the SARS-CoV-2 pandemic. A correlation was observed between accidents and injuries, as evidenced by the analysis of the graphs created using the data on these two parameters (Figure 2A). The highest discrepancy was recorded in 2017, with 70 injuries, while the lowest number of injuries was observed in 2020, with 26 cases. This aligns with the impact of the pandemic on traffic patterns.

The distribution of accidents by month demonstrates that the majority occurred in January (69), December (49), February (36), and March (23), while the lowest number was recorded in November (8), April (5), and October (1) (Figure 2B). This is consistent with the site's climatic conditions, as accidents typically begin in October when temperatures drop below 0 °C and continue until April. The highest number of injuries was recorded in January (127), while October (1) and April (6) had the lowest.

The data on accidents demonstrates that 44% of such incidents occurred on Wednesdays and Fridays, while the lowest numbers were recorded on Sundays (19), Mondays (19), and Tuesdays (20). The incidence of accidents was observed to be lower at weekends and at the outset of the week. Additionally, the highest numbers of individuals who sustained injuries were recorded on Wednesdays and Fridays, with 75 and 62 cases, respectively. However, the highest average number of injuries per accident was recorded on

Sundays (2.3). The lowest number of injuries was recorded on Tuesday and Monday, with 32 and 34 cases, respectively (Figure 2C).

The majority of accidents in the study area occurred between 17:00 and 00:00, accounting for 47% of the total. The second-highest number of accidents occurred during the morning hours (08:00–10:00), accounting for 26% of the total with 48 incidents. The lowest number of accidents occurred between midnight and sunrise (07:00), with only 19 accidents (10% of the total). These findings indicate that solar radiation has a direct impact on accident patterns. Additionally, work entry and exit hours likely contribute to traffic density and accidents. The highest number of injuries occurred at 20:00 (39) and 09:00 (30), while the lowest were at 05:00 (1), 03:00 (2), 04:00 (2), and 14:00 (2) (Figure 2D).

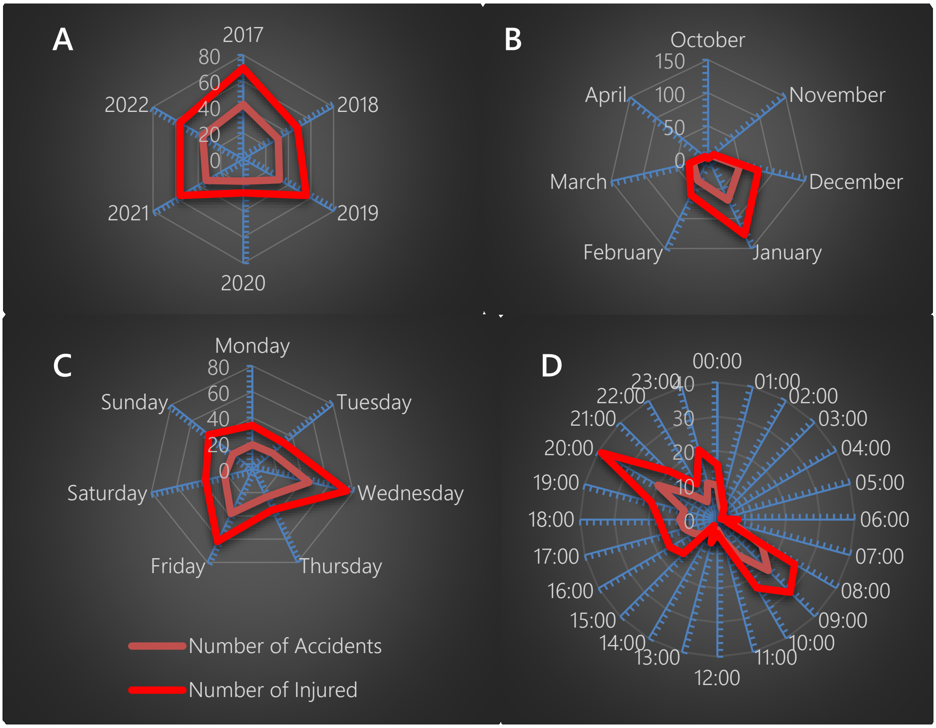

Figure 2. Distribution of traffic accidents and the number of individuals injured by A) years, B) months, C) days, and D) hours.

Note. The data presented were prepared using information from the *Traffic Department, Traffic Accident Data* [Unpublished raw data], by General Directorate of Security of the Republic of Turkey, 2023.

A frequency analysis was conducted on the pertinent meteorological data to ascertain the frequency of accidents in the study area within specific data value intervals. The findings of this analysis are presented in the following tables, which aim to elucidate the results obtained through this analysis. The results demonstrated that traffic accidents were concentrated in meteorological value ranges of −11.7 to 0.6 °C of air temperature (88.8%), −4.9 to −0.8 °C soil temperature (71.6%), 0 to 1.1 m/s wind intensity (71.1%), 81 to 100% relative humidity (56.7%), and 6 to 8.9 (8 octa) cloudiness (60.4%; Tables 1, 2, 3, 4, and 5).

Table 1. Hourly air temperature (°C) frequency values of accidents occurred in the study area

Number of classes	Sub class	Upper class	Class value	Frequency	Rate (%)
1	−17.9	−14.9	−16.4	1	0.5
2	−14.8	−11.8	−13.3	7	3.7
3	−11.7	−8.7	−10.2	28	15.0
4	−8.6	−5.6	−7.1	30	16.0
5	−5.5	−2.5	−4	59	31.6
6	−2.4	0.6	−0.9	49	26.2
7	0.7	3.7	2.2	8	4.3
8	3.8	6.8	5.3	4	2.1
9	6.9	9.9	8.4	1	0.5

Table 2. Hourly soil temperature (°C) frequency values of the accidents occurring in the study area

Number of classes	Sub class	Upper class	Class value	Frequency	Rate (%)
1	−7	−5	−6	7	3.7
2	−4.9	−2.9	−3.9	44	23.5
3	−2.8	−0.8	−1.8	90	48.1
4	−0.7	1.3	0.3	36	19.3
5	1.4	3.4	2.4	9	4.8
6	3.5	5.5	4.5	0	0.0
7	5.6	7.6	6.6	0	0.0
8	7.7	9.7	8.7	0	0.0
9	9.8	11.8	10.8	1	0.5

Table 3. Hourly wind intensity (m/s) frequency values of the accidents occurring in the study area

Number of classes	Sub class	Upper class	Class value	Frequency	Rate (%)
1	0	0.5	0.25	76	40.6
2	0.6	1.1	0.85	57	30.5
3	1.2	1.7	1.45	15	8.0
4	1.8	2.3	2.05	18	9.6
5	2.4	2.9	2.65	4	2.1
6	3	3.5	3.25	9	4.8
7	3.6	4.1	3.85	6	3.2
8	4.2	4.7	4.45	2	1.1

Table 4. Hourly relative humidity (%) frequency values of the accidents occurring in the study area

Number of classes	Sub class	Upper class	Class value	Frequency	Rate (%)
1	51	55	53	8	4.3
2	56	60	58	7	3.7
3	61	65	63	16	8.6
4	66	70	68	18	9.6
5	71	75	73	17	9.1
6	76	80	78	15	8.0
7	81	85	83	31	16.6
8	86	90	88	23	12.3
9	91	95	93	37	19.8
10	96	100	98	15	8.0

Table 5. Hourly cloudiness (8 octa) frequency values of the accidents occurring in the study area

Number of Classes	Sub class	Upper class	Class value	Frequency	Rate (%)
1	0	0.9	0.45	34	18.2
2	1	1.9	1.45	1	0.5
3	2	2.9	2.45	10	5.3
4	3	3.9	3.45	7	3.7
5	4	4.9	4.45	8	4.3
6	5	5.9	5.45	14	7.5
7	6	6.9	6.45	30	16.0
8	7	7.9	7.45	67	35.8
9	8	8.9	8.45	16	8.6

Note. Tables 1, 2, 3, 4, and 5 were prepared by utilizing the data based on *Meteorological Observation Data* [Unpublished raw data], by General Directorate of Meteorology of the Republic of Turkey, 2023 and *Traffic Department, Traffic Accident Data* [Unpublished raw data], by General Directorate of Security of the Republic of Turkey, 2023.

The analysis of meteorological data is a crucial element in the identification of incidents resulting from icing. It is, however, possible that the related accidents may have occurred as a result of a number of factors other than icing, such as fog, for example. It is therefore proposed that an analysis of repeated accidents on icy and snowy road surfaces on the same day will yield more accurate results. In order to elucidate the relationship between accidents caused by icing and meteorological data, the hourly weather values of accidents (four or more) occurring on the same day were subjected to analysis.

The dataset comprising repeated accidents on the same day encompasses incidents that occurred on the following dates: February 11, 2017, March 1, 2018, February 27, 2019, March 18, 2020. On the relevant days, a total of 17 accidents occurred, with five on 18 March, 2020 and four on each of the other three days. It was determined that the related accidents were concentrated in the meteorological value ranges of 0 to −8 °C air temperature (88%), −1.8 to −3.4 °C soil temperature (70%), 1.0 to 3.1 m/s wind intensity (70%), 89 to 99 % relative humidity (88%), and 6 to 7 cloudiness (82%). Furthermore, an examination of the daily graphical representation of the meteorological data values on the days when the accidents were concentrated (with the exception of the accidents on February 11, 2017) revealed that traffic accidents occurred following a sudden decrease in air temperature values (Figure 3) when relative humidity exceeded the threshold value of 80%, wind intensity reached 0.5 m/s, and cloudiness reached 6 (8 octa), and when the 10 cm soil temperature was below −0.3 °C.

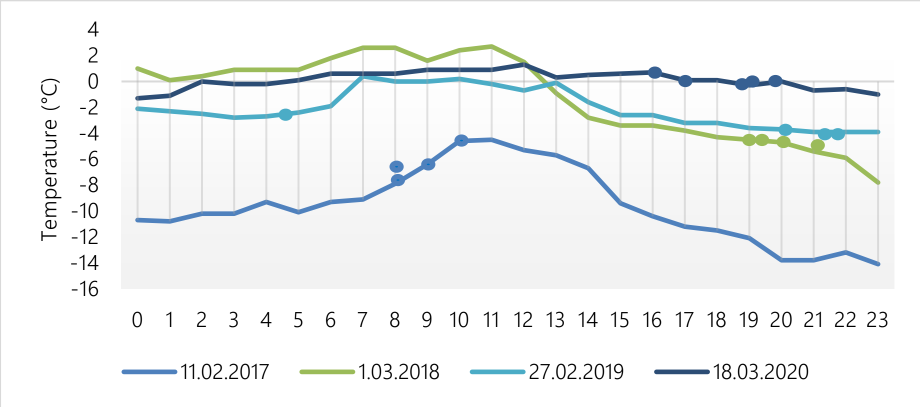

Figure 3. Hourly air temperature (°C) graph on the days when accidents are concentrated (the presence of circles in the graph lines is indicative of traffic accidents).
Note. Prepared by utilizing the data based on *Meteorological Observation Data* [Unpublished raw data], by General Directorate of Meteorology of the Republic of Turkey, 2023 and *Traffic Department, Traffic Accident Data* [Unpublished raw data], by General Directorate of Security of the Republic of Turkey, 2023.

4.2. Spatial analysis of accidents

A statistical analysis of accident data on snowy and icy road surfaces between 2017 and 2022 reveals a concentration of incidents in the central area of the study area (Figure 4), particularly in the vicinity of the Central Business Area, which is characterized by high levels of business activity and mobility. A Kernel Density Analysis, weighted by the number of injuries, identified three areas of elevated risk. The most significant of these is situated in the center of the study area, encompassing the majority of the Muratpasa Neighborhood, with the western part of Rabia Ana Neighborhood also identified as a risk area (Figure 5). Additionally, the junction of Abdurrahman Gazi Road Avenue and Erzurum-Ağrı Transit highway (E80), as well as Org. Esref Bitlis Boulevard, are identified as high-risk locations. The moderate-risk areas include University Junction, City Hospital Junction, Yaren Street, Kazım Karabekir Stadium Junction, Airport Road in the vicinity of the Recep Tayyip Erdoğan Fairground, and Prof. Dr. Ihsan Dogramacı Boulevard in the Dadaskent District. Furthermore, it is notable that a considerable number of accidents occurred on Refik Saydam Avenue (six incidents) and Cat Road Avenue (four incidents).

It is also pertinent to highlight the vulnerability of routes such as the Erzurum-Erzincan Highway (Dadaşkent Road) and Erzurum-Bingöl Highway (Refik Saydam and Cat Road Avenue) to the effects of wind-induced icing. These routes are devoid of the construction elements that would otherwise prevent the effects of high winds. It can, therefore, be stated that the risk of icing is high on these routes on days and hours when wind frequency and intensity are high, and weather conditions are favorable for icing.

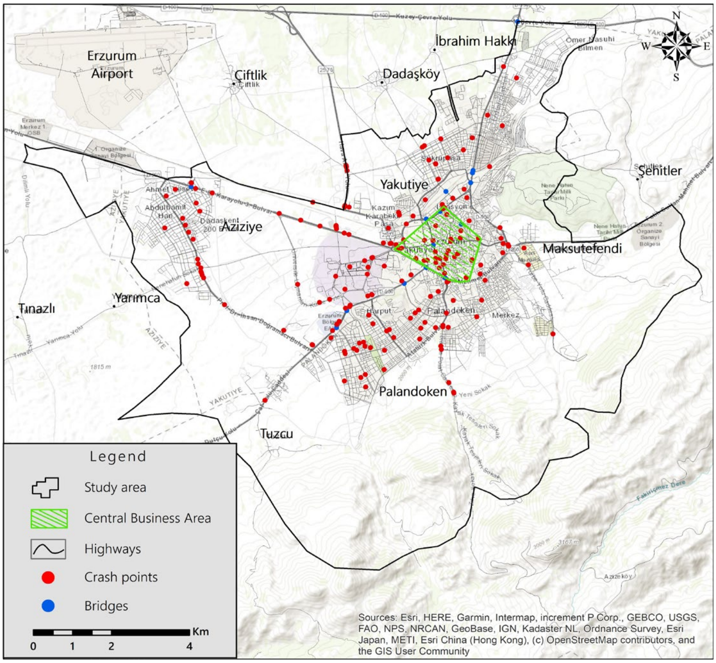

Figure 4. Distribution of accidents occurring in the study area.

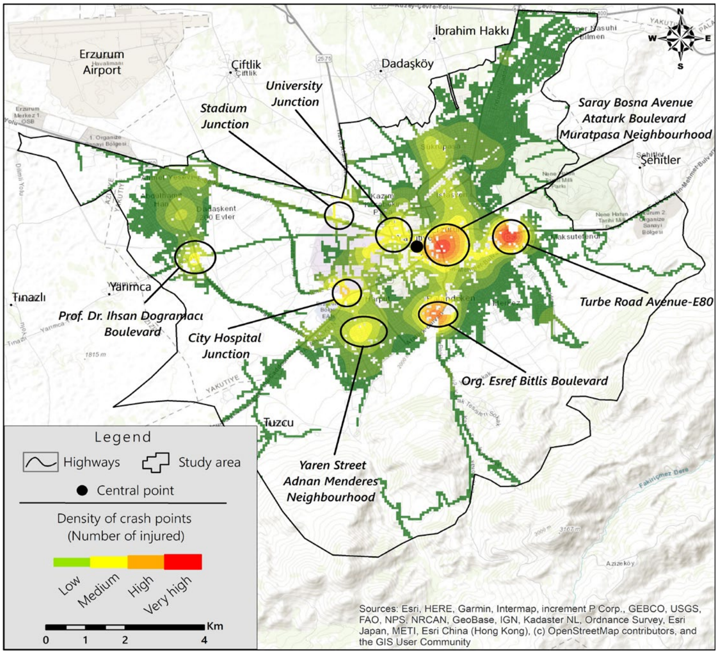

Figure 5. Kernel Density Analysis of accidents occurring in the study area.

A Hot Spot Analysis (Getis-Ord Gi*) of the accidents occurring in the study area reveals that the junctions of Airport Road (in front of the Recep Tayyip Erdoğan Fairground and Mehmet Sekmen Avenue-Airport Road Junction) fall within the 95% confidence interval. The remaining hotspots are located on Erzurum-Erzincan Highway (Dadaskent Road), specifically at the Kazım Karabekir Stadium junction and the junction connecting Ipekyolu Avenue and Dadaskent Road. Finally, the junction point of Somunoglu Avenue with the secondary road connecting to Erzurum Metropolitan Municipality Public Works Construction Site is identified as a hotspot (Figure 6). Furthermore, the 90% confidence interval identifies additional hotspots for accidents, namely: the junctions of Org. Selahattin Demircioglu Avenue with Fairground Road and Kazım Karabekir Street, as well as the junction linking Ipekyolu Avenue and City Hospital Road, showed a significant concentration of accidents.

It is imperative to consider the slope values of the transport axes as a significant factor influencing the accident risk level. As the slope values of highways increase, the friction force between vehicle tires and the road surface will decrease further, thereby reducing the driver's ability to control the vehicle. Upon examination of the slope values in the study area, it can be observed that the roads connecting to Gazi Muhtar Pasa Avenue from the east in Kurtulus Neighborhood (Dag District), Demiryolu Ustu Street and the roads in the vicinity (Sehitler), Osmangazi Avenue, and Fabrikaonu Street in Hilalkent District exhibit high slopes (Figure 7). Furthermore, Ibrahim Polat Avenue (Palandoken Road), Abdurrahman Gazi Road Avenue (Turbe Road), Tuzcu Neighborhood Road, Mevlâna Avenue, Zeynep Street (Adnan Menderes Neighborhood), 3rd Hacı Ahmet Street, and Dere Street (Muratpasa Neighborhood) also represent transport axes with high slopes.

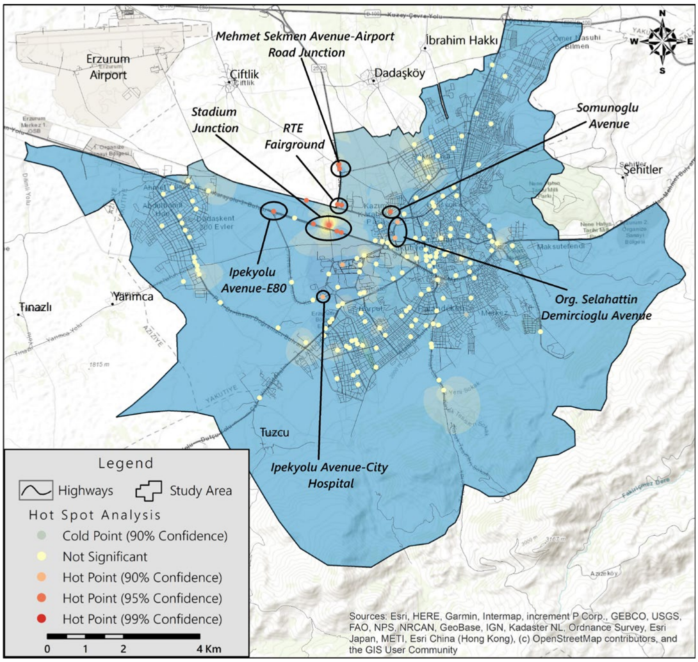

Figure 6. Hot Spot Analysis of accidents occurring in the study area.

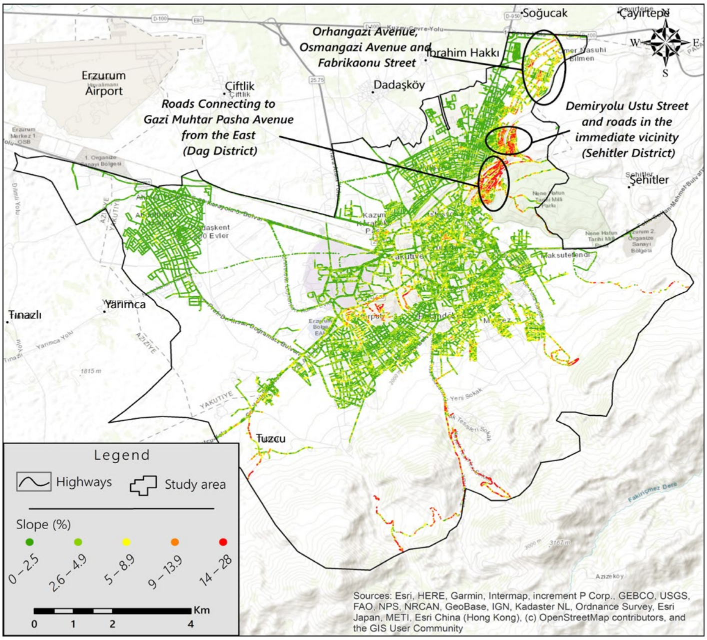

Figure 7. Slope map of highways in the study area.

The aspect ratio has a direct impact on the duration of sunbathing and the intensity of radiation. In this context, human factors can also be identified as a significant influencing factor in the duration of sunbathing. Nevertheless, further detailed research is required in order to gain a fuller understanding of this topic. Accordingly, in order to provide a general impression of the site, human factors were excluded from the aspect analysis, with the focus instead being on the morphological features.

Upon analysis of the aspect status of the transport axes within the study area, it becomes evident that the majority of these axes are oriented toward the north (Figure 8). It can thus be concluded that the site is unable to benefit from solar radiation in an effective manner. It should be noted, however, that there are also some transport axes oriented toward the south. These roads comprise the transport networks on the southern slopes of the hilly areas, as well as some roads in the Dadaskent District and Zeynep Street, and immediate vicinity. It is evident that the south-facing slopes of the hilly areas in Gaziler and Sehitler District can effectively benefit from solar radiation. Furthermore, areas with slope values approaching zero also exhibit effective solar radiation benefits relative to other areas. Transport networks exhibiting the aforementioned characteristics are present in selected areas of Dadaskent and Hilalkent.

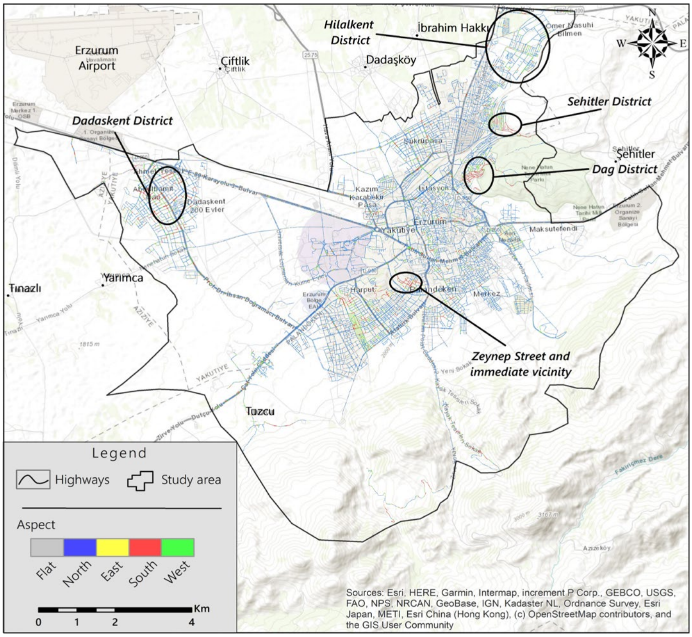

Figure 8. Aspect map of the highways in the study area.

The southerly orientation of the view on the transport axes will result in increased insolation time on the roads, with temperature values on these roads being relatively above average. It is therefore essential to include an analysis of the aspect status of the roads in the study area within the scope of the study.

In addition to these analyses, in order for the study to be solution-oriented, a number of anti-icing systems were considered as tools for decreasing black ice risk. These include the Automatic Solution Spraying System, the conductive heating cable system, and the use of heating with carbon fiber tapes, the automatic spraying application used in public transport vehicles, asphalt pavements with electrical conductive properties and an icing early warning system (Joerger & Martinez, 2006; Monsere et al., 2006; Yang et al., 2012). Given the complexity of the research problem, the findings of this study could inform specific aspects of the issue.

5. Conclusion

In light of the climatic and geographical characteristics of Erzurum city center, it can be concluded that the environment is highly conducive to accidents that may occur due to icing. Erzurum is one of the settlements situated at the highest altitude in the Eastern Anatolia Region. In addition to its elevation, Erzurum is a settlement with long and harsh winter conditions in terms of climate characteristics. It is crucial to examine the accidents that have occurred during the winter season on snowy and icy road surfaces in order to ascertain the regions and routes with a high risk level within the scope of this study. Once the regions and routes have been identified, it is essential to conduct comprehensive studies in order to achieve the objectives of the study and to prevent accidents. The monthly and hourly distribution of the accidents reveals a notable concentration of incidents occurring at specific times and on specific days. In particular, January (69) and 17:00–00:00, and 8:00–10:00 (136) hours warrant further investigation as a potential temporal black spot.

A frequency analysis of the hourly meteorological data of the accidents revealed that the majority of accidents occurred in the following value ranges: air temperature between −11.7 and 0.6 °C (88.8%), soil temperature between −4.9 and −0.8 °C (71.6%), wind intensity between 0 to 1.1 m/s (71.1%), relative humidity between 81 and 100% (56.7%), and cloudiness between 6 and 8.9 (60.4%). Furthermore, it can be stated that the majority of accidents occurred within the following value ranges: air temperature 0 to −8 °C (88%), soil temperature −1.8 to −3.4 °C (70%), wind intensity 1.0 to 3.1 m/s (70%), relative humidity 89 to 99% (88%), and cloudiness 6 to 7 (82%). These value ranges were identified on the days when accidents were concentrated. Furthermore, an examination of the temperature graph for the days on which accidents occurred revealed that the majority of these incidents took place in the period following a sudden decline in temperature. The aforementioned value ranges may be employed as meteorological criteria for the prediction of accident risk. The data may be employed to facilitate risk prediction and to inform the design of subsequent studies.

According to the spatial analysis of accidents, the daily traffic load of high accident risk junctions exceeds 20,000 vehicles. This shows that there is a linear relationship between traffic density and accident occurrence, and that higher accident rates are associated with areas with dense business centers and increased mobility. Consequently, these routes and locations should be given the highest priority for accident prevention.

In order to ascertain the risk levels of accidents that may occur as a result of icing, it is essential to consider the impact of slope and aspect conditions. It is evident that the aspect condition plays a pivotal role in differentiating the solar radiation efficiency of transport axes, which in turn affects the temperature values observed on the ground. The condition of the slope has a significant impact on the driver's ability to control the vehicle, particularly in the event of ice formation on the surface. Except for the south-facing slopes of hilly areas in Gaziler and Sehitler District and the roads in some parts of Dadaskent and Hilalkent District with slope values close to zero, it can be said that the solar radiation efficiency of other traffic axes in the study area is low. The axes with high traffic volume and high road gradient have a high potential for traffic accidents with icing. It is essential to take these roads into account in the precautionary phase.

Today various intelligent transport systems and anti-icing technologies can be used both nationally and internationally to prevent the accumulation of snow and ice. Based on these methods and their applicability to Erzurum city center, the proposed solution can reduce accident risks by establishing a joint information-sharing center between Erzurum Metropolitan Municipality and the General Directorate of Meteorology. In this center, hourly weather forecast data will be automatically compared with risk value ranges from meteorological data, generating pre-icing risk forecasts. If icing risk is detected, the system will automatically activate spraying devices installed on public transport vehicles and other public service vehicles operating in risk areas.

Another proposed solution involves installing electrically conductive cables beneath the pavement along tire tracks. This system, powered by solar energy panels installed in identified risk areas, will activate automatically when icing risk is high, providing a sustainable and energy-efficient method to mitigate accidents. Both proposals utilize data from the General Directorate of Meteorology to predict and manage icing risks, with the goal of significantly reducing accidents caused by icy road conditions.

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