

A GIS Tool for Modelling the Effects of Gasoline Station Explosions in Urban Areas

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Abstract

Urban regions are under increasing pressure due to the economic, social, and environmental domains with a steady upward trend in the motor vehicle numbers. Consequently, the demand for liquid fuel oil rises, necessitating gasoline station construction both inside and outside cities. Gasoline stations remain more dangerous even with the adoption of contemporary methods for storing petroleum products and stringent construction and operation guidelines. Furthermore, they pose a risk of hazardous fire and explosion to both humans and buildings. A Geographic Information System (GIS) tool has been developed to model the impacts of gasoline station explosions in urban areas. The tool visualizes relevant variables, such as size of the fireball, danger zone of possible self-emitting combustion, impacted zone of the spilled gasoline combustion, zones of human injuries ranging from 1st degree burns to painful sensations on the skin and mucous membranes, and zones of building damage ranging from total destruction to minor damage. Apart from the danger buffer visualization, affected buildings are extracted, and queries are presented to extract the key statistics. The current study applies the developed strategy to gasoline station network in Tashkent, Uzbekistan, as a case study, to assure model applicability. The study produced encouraging results when assessing station explosion scenarios and displaying danger, human injury, and building damage zones. The model has the advantage of assessing a large collection of gasoline stations automatically, saving time and effort for emergency management while analysing large datasets with hundreds of stations and thousands of buildings in real operation.

Keywords

GIS, gasoline station explosion, urban areas, emergency management

1 Introduction

Recently, natural and man-made disasters are both becoming more frequent and severe due to the noticeable acceleration of human actions such as urbanization and inadequate infrastructure [1, 2]. Disaster management deals with the mitigation of the human, material, economic or environmental impacts during and after catastrophic events. Nowadays, Geographic Information Systems (GIS) provide essential tools for the assessment of disaster risks, enhancing disaster preparedness, and designing and guiding response and recovery efforts considering the capability of integrating spatial data with advanced analytical tools.

Man-made disasters, as viewed by the International Federation of Red Cross and Red Crescent Societies (IFRC) [3] are events that cause major damage, disruption, or fatality as a result of human actions, carelessness, technical emergencies, or complicated circumstances. This can include environmental degradation, pollution, or accidents (e.g., industrial, technological, and transportation sectors typically involve the production, usage, or transfer of hazardous materials like fuel) [1]. Public fuel stations have seen an increase in fire accidents over the past few years, which have been attributed to various risk factors, including the improper use of mobile phones during

fueling, inadequate maintenance of vehicles, and defective fuel dispensing systems [4]. Fires at fuel stations not only threaten the station infrastructure but also pose serious risks to vehicles on-site and nearby structures, including residential buildings [5].

The occurrence of fire is fundamentally governed by the presence of three essential components: heat, oxygen, and fuel. At a gasoline station, oxygen is always present, while fuel (gasoline) vapor is released during refueling of vehicles and storing fuels [6, 7]. Potential heat sources include vehicle engines, hot exhaust systems, electrostatic discharge from communication devices, or intentional acts of arson.

As a possible source of an industrial disaster, the network of gasoline stations belongs to the critical infrastructure in every municipality. As a result, the emergency management authorities in all countries have strict restrictions in place to prevent accidents and carry out rescue operations in the event of an accident. For the emergency services, adequate knowledge of the location and storage capacity of gasoline stations is essential to plan fire safety procedures. Vehicle fuels are divided into various types: liquid fuels such as gasoline, liquefied fuels, and compressed gases. Gasoline vehicles present a main source of danger during the refilling process or during fuel storage [4]. Liquid fuels produce explosive atmospheres while being transported, stored, or filled. The causes of these situations include human error, equipment malfunctions, vehicle issues, and static electricity [8].

The present study investigates the gasoline station network of Tashkent, Uzbekistan. The aim of the study is to develop a GIS tool to support emergency service activities. Such a tool can provide the decision-makers with the relevant information for emergency management. Model outcomes are crucial for disaster response efforts and urban planning concerns by defining safety categories around the gasoline stations. In the event of a real incident, GIS aids to plan rescue efforts using dynamic queries or show the expected effects of particular actions using static queries.

As for achieving a reliable GIS tool, modelling the scale and the impacts of the petrol station explosion is fundamental. The literature covers several methodologies; Aouad et al. [9] have applied the Sedov–Taylor model (based on the combination of the methods of Sedov [10] and Taylor [11, 12] to generate the fireball of the 2020 Beirut explosion and calculate the shockwave radius as a function of time). Sedov–Taylor method is valid in the region where the shock wave can displace a relevant mass of air, resulting in the pressure differential across the shock being high compared to the ambient background pressure [13].

Lobato Bajo et al. [14] have used the Trinitrotoluene (TNT) equivalency explosion model to estimate the impacts of the Texas refinery gasoline explosion (Texas City, TX, USA on March 23, 2005). The overpressure developed at specified distances is calculated and converted into the equivalent mass of TNT. The TNT approach has several advantages, including the accuracy and simplicity of assessing damages in a remote area. Nowadays, the FLame ACceleration Simulator (FLACS) software is widely used in industrial safety and explosion risk management, providing a tool for the appropriate use of a set of fundamental governing equations of fluid dynamics, including mass, momentum and energy equations [15, 16]. Wang et al. [17], Yang et al. [18] have also used FLACS for modelling the process of liquefied petroleum gas release and explosion for the case of an actual expressway accident of an LPG tank trailer. The method uses the Favre-averaged transport equations with a finite volume method [19].

The model has been applied as a case study in Tashkent, Uzbekistan, due to the data accessibility and the familiarity with the fuel filling systems and rules. Furthermore, the model's findings are quite generalizable and applicable to a wide range of countries and urban regions. Three main concepts demonstrate how the framework can be applied in different urban areas:

1. Making use of an opensource QGIS plugin with the relevant code.
2. In this effort, OSM's free building data, available for the whole world, is used.
3. Standard information from gas stations is analyzed in the study, including the station's geolocation, the type of gasoline, and the tank volume.

Since this study offers a GIS tool for Tashkent, the impact of an incident was quantified considering local (Uzbek) regulations. The current risk management legislation and requirements in Uzbekistan depend on the reasoning, formalization, and parameterization of the prior Soviet regulations, hence the modelling is based on post-Soviet literature [20, 21]. The pros and cons of the Uzbek official method were not discussed in comparison to other methods but was adopted as it reflects the considerations of the Uzbek stakeholders and policymakers.

2 Modelling of gasoline station explosion

The capacity of the gasoline tanks at each station is a known input data. Accordingly, the maximal storage capacity can be used to model an explosion event, which is certainly a worst-case scenario, however, only the primer effects are considered

in this modelling, while none of the secondary effects are considered. The characteristics of an explosion event are studied taking into account the following properties:

1. radius of the fireball;
2. radius of risky area, i.e., where the gasoline-air mixture is above the risk level;
3. radius of human injury zones, i.e., where the heat radiation reaches certain empirical thresholds identified with different levels of human injuries;
4. radius of building damage zones, i.e., where the rate of heat spread reaches the empirical thresholds of different forms for building damages.

2.1 Modelling the fireball size

Initially, the gasoline mass inside the tank is determined. Using the Uzbek [20, 21], Russian [22], and Belarus [23] standards, the mass is calculated considering the density of the gasoline, $\rho_g = 725 \text{ kg/m}^3$ at 15°C temperature:

$$m = V \cdot \rho_g, \quad (1)$$

where ρ_g is the density of the gasoline (unit: kg/m^3), V is the volume (unit: $\text{m}^3 = 10^3 \text{ L}$), and m is the mass (unit: kg). Then, the effective radius of the fireball, R_s is determined in m unit by the following empirical formula [13, 14]:

$$R_s = 2.665 \cdot m^{0.327}. \quad (2)$$

2.2 Calculating the size of the 'danger zone'

The term 'risky area', or 'danger zone' refers to the zone of self-emitting combustion in this study. Such a case happens when the gasoline leaks into the open air. Spilled gasoline forms a mixture of gasoline vapor and air, which may be combusted at a high temperature in case the concentration of gasoline vapor in the air exceeds a critical level.

The effect of a tank leakage is modelled when the gasoline is spilled over an area around the gasoline station. Firstly, the contaminated zone is determined i.e., the effective diameter of the spillage, then the zone of self-emitting combustion, where the gasoline vapor concentration in the air is above the critical level, and self-emitting combustion may occur. Self-emitting zone is modelled considering the Lower Flammability Limit (LFL) and Lower Concentration Limit (LCL) of the flame spread of the gasoline vapor. LFL is the lowest vapor concentration that supports a self-emitting flame when mixed with air. Below the LFL, there is not enough gasoline to support combustion, as the mixture of gasoline and air is too weak, and no exacerbation will occur [24].

The self-emitting combustion zone is modelled assuming no wind conditions, accordingly, the spread of the air-gas mixture is considered to be isotropic, achieving the same rate of mixture at a certain distance from the exploded tank location. Safety considerations are addressed when modelling the affected area to compensate for this simplification (see Eq. (10) later).

For the LFL estimation, the widely used method was applied [21, 23]. The radius of the 'danger zone' is calculated as:

$$R = 3.1501 \sqrt{K} \left(\frac{P}{\text{LCL}} \right)^{0.813} \left(\frac{m_v}{\rho_0 \cdot P} \right)^{0.333}, \quad (3)$$

where R is the radius in m unit, $K = T/3600 \text{ s}$ is a unitless coefficient with T being the duration of the flammable liquid spilling onto the open surface, P is the saturation vapor pressure (unit: kPa), LCL is the lower concentration limit of flame spread of flammable liquids and vapors (in percentage), m_v is the mass of gasoline vapor spilling on the open surface during the time of complete vaporization but not exceeding 3600 s (unit: kg), and ρ_0 is the vapor density of the LFL at standard temperature and atmospheric pressure.

As for the actual values of the variables of Eq. (3), the duration of the spill is typically set to $T = 3600 \text{ s}$, resulting in $K = 1$, the saturation vapor pressure for gasoline, P is 66.7 kPa, and the lower concentration limit of flame spread, LCL is 2.5% in the referred studies [25, 26]. The mass of gasoline vapor, m_v is determined by:

$$m_v = F \cdot W \cdot T, \quad (4)$$

where W is the evaporation intensity (unit: $\text{kg m}^{-2} \text{ s}^{-1}$), and F is the area (unit: m^2) would be covered by the stored amount of gasoline spilled on a horizontal surface [13, 15], calculated as:

$$F = 0.15 V. \quad (5)$$

In Eq. (5), the constant is not unitless, but it is $0.15 \text{ m}^2/\text{L}$ to convert the volume of gasoline into liters to surface in m^2 . Then, the effective diameter of the spillage is gained simply by:

$$d = \sqrt{\frac{4 F}{\pi}}. \quad (6)$$

The next variable in Eq. (4), W is the evaporation rate of unheated liquids (unit: $\text{kg}^{-1} \text{ s}^{-1}$), determined in the official procedure [13–15], which has been derived from laboratory experiments:

$$W = 10^{-6} \sqrt{M} \cdot P, \quad (7)$$

where M is the molar mass (unit: g/mol). For the present study, molar mass values of 98.2 g/mol and 114.0 g/mol were used for the octane-92 and the octane-95 gasoline respectively, in accordance with the values used in literature [13–15].

Some references suggest using only the portion of the vapor mass in Eq. (3), which is involved in the explosion [23]. So, based on the amount of total vapor mass m_v , the portion involved in the explosion m_{ve} can be determined by Eq. (8):

$$m_{ve} = 2.21 \cdot 10^{-8} \cdot Q \cdot m_v, \quad (8)$$

where Q is the specific heat of combustion of gasoline vapor in kJ/kg with a value of $4.73 \cdot 10^7$ kJ/kg for the gasoline.

Finally, the vapor density ρ_0 , the last term in Eq. (3), is determined by:

$$\rho_0 = \frac{M}{V_0(1 + 0.00367 t)}, \quad (9)$$

where V_0 is the molar volume ($22.413 \text{ m}^3 \cdot \text{kmol}^{-1}$) for gasoline; t refers to the reference air temperature indicating either the maximum air temperature that is achieved in this region or the maximum air temperature that occur in accordance with the technological regulations, taking into account the possibility of temperature increase in the event of an emergency – the higher value should be chosen. If it is not possible to determine such indicators, it can be set to 61 °C.

Then, the radius of the impacted zone, R_{impact} , where the impact of the combustion of spilled gasoline, by forming a mixture of gasoline vapor and air in the open air and combusting at a high temperature, is considered to be influential, is determined as [21]:

$$R_{\text{impact}} = 1.2 R. \quad (10)$$

2.3 Determining the heat radiation

Two relevant methods for determining heat radiation were found in the literature. A method, applied by MES [23], is deriving the heat radiation considering several local in-situ properties, such as the temperature outside, the ignition temperature of the fireball, or the temperature of the surface of the irradiated material. These are case-sensitive parameters being not feasible for general simulation, therefore the use of this method is rejected.

The other method, described in Gordon et al. [13] and Lobato Bajo et al. [14], calculates first the effective radius of the fireball, R_s as it is explained by Eqs. (1) and (2). By assuming a roughly spherical fireball, the height of

the center of the fireball can roughly be approximated by the effective radius:

$$H = R_s. \quad (11)$$

Knowing the geometrical parameters of the fireball, two coefficients can be calculated as a function of the distance from the fireball. These are the so-called angular coefficients of the radiation (F_q):

$$F_q = \frac{H/2R_s + 0.5}{4\left(\left(H/2R_s + 0.5\right)^2 + \left(r/2R_s\right)^2\right)^{1.5}} = \frac{1}{4\left(1 + \left(r/2R_s\right)^2\right)^{1.5}}, \quad (12)$$

and the so-called atmospheric transmission coefficient (τ), which reads:

$$\tau = \exp\left(-7.0 \cdot 10^{-4} \left(\sqrt{r^2 + H^2} - R_s\right)\right), \quad (13)$$

where r refers to the distance from the center of the fireball in meters. The used coefficients are calculated for the certain size of a fireball, depending on the volume and type of the flammable liquid, at variable distances, and used as a free parameter. Then the heat radiation, q is determined as:

$$q = E_f \cdot F_q \cdot \tau, \quad (14)$$

where E_f is the average surface density of the flame heat dissipation (unit: $\text{kW} \cdot \text{m}^{-2}$), which is set to $E_f = 450 \text{ kW/m}^2$ considering the considerations of [21].

2.4 Estimating human-injury zones and building damage zones

The thresholds of human injury categories (Table 1), defined by Timofeeva [27], are adopted for the present study.

The thresholds of building damage categories (Table 2), defined by MCHS [22], are also used for this study.

3 Representations in GIS

3.1 Study area

The proposed model has been applied on Tashkent City, the capital of Uzbekistan, as the most populous city in the

Table 1 Impact of heat radiation on humans

Level	Type of injury	Threshold of heat radiation (kW/m ²)
1	1 st degree burns	49
2	2 nd degree burns	27.4
3	3 rd degree burns	9.6
4	Painful sensations on the skin and mucous membranes	1.4

Table 2 Impact of heat radiation on buildings

Level	Type of damage	Threshold of heat radiation (kW/m ²)
1	Total destruction of buildings	100
2	50% destruction of buildings	53
3	Medium damage to buildings	28
4	Moderate damage to buildings (damage to internal partitions, frames, doors, etc.)	12
5	Pressure wave damage to humans	5
6	Minor damage (part of glazing broken)	3

Central Asian region (Fig. 1) [28]. The city covers an area of 630 km² with more than 3 million people and a population density of 4,816 people/km². Tashkent is a megapolis with an average population density comparable to the city of Chicago. The city is among the most developed cities of the region with a Human Development Index (HDI) of 0.814 in 2022, which is labelled to be "very high", being the No. 4 highest HDI in Central Asia behind the most populated regions of Kazakhstan: Almaty (0.831), Karaganda Region (0.820) and North Region (0.816) [29]. Accordingly, Tashkent city is quite "motorized", i.e., the city has a significant car fleet. According to the Statistics Agency under the President of the Republic of Uzbekistan, the number of cars owned by Tashkent residents was 562.1 thousand units as of January 1, 2023. Compared to 2021 (467.2 thousand units), the number increased by more than 20% (94.9 thousand units) reflecting upward trend [30].

3.2 Data used

3.2.1 Gasoline stations

The large number of vehicles is served by an extensive gasoline station network where 156 gasoline stations are enlisted in Tashkent in a business database [31]. For modelling the impact of a gasoline station explosion in Tashkent, the gasoline station locations were downloaded from the Geofabrik free service of OpenStreetMap [32]. For the targeted stations, relevant technical information for the modelling, i.e., capacity of the tank and the type of gasoline (the molar mass), is available for 68 stations (Fig. 2). Modelling the effects of the gasoline station explosion is performed for the defined stations using a proposed GIS tool. The developed tool can easily be adopted to all gasoline stations in the city or any other municipalities in case of interest from the emergency management authority.

3.2.2 Buildings

For modelling how a gasoline station explosion will affect nearby buildings, the Tashkent City building shapefile was downloaded from the Geofabrik free download service of OpenStreetMap (Fig. 3) [32].

3.3 The GIS modelling

3.3.1 Spatial resolution

Building polygon characteristics at Geofabrik [32] are highly accurate due to the availability of high-resolution aerial images. In well-mapped cities, like Tashkent, buildings can match sub-meter corner-level accuracy matching



Fig. 1 Uzbekistan regional map showing the location of Tashkent City [28]

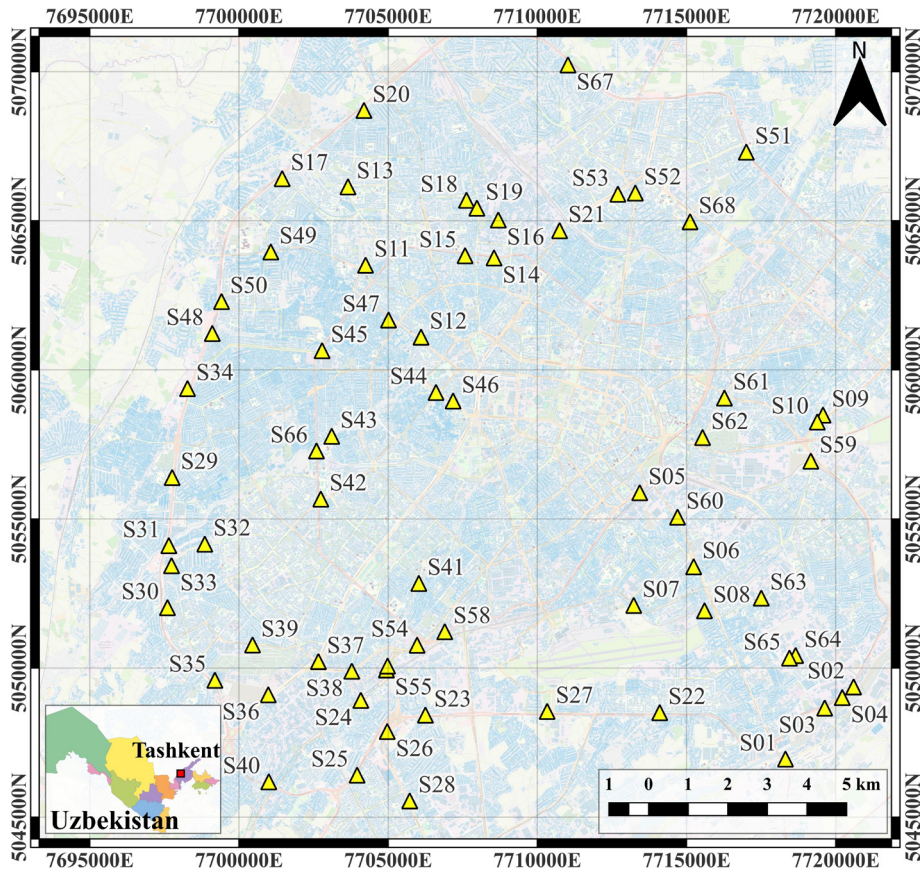


Fig. 2 The locations of the used gasoline stations in Tashkent City

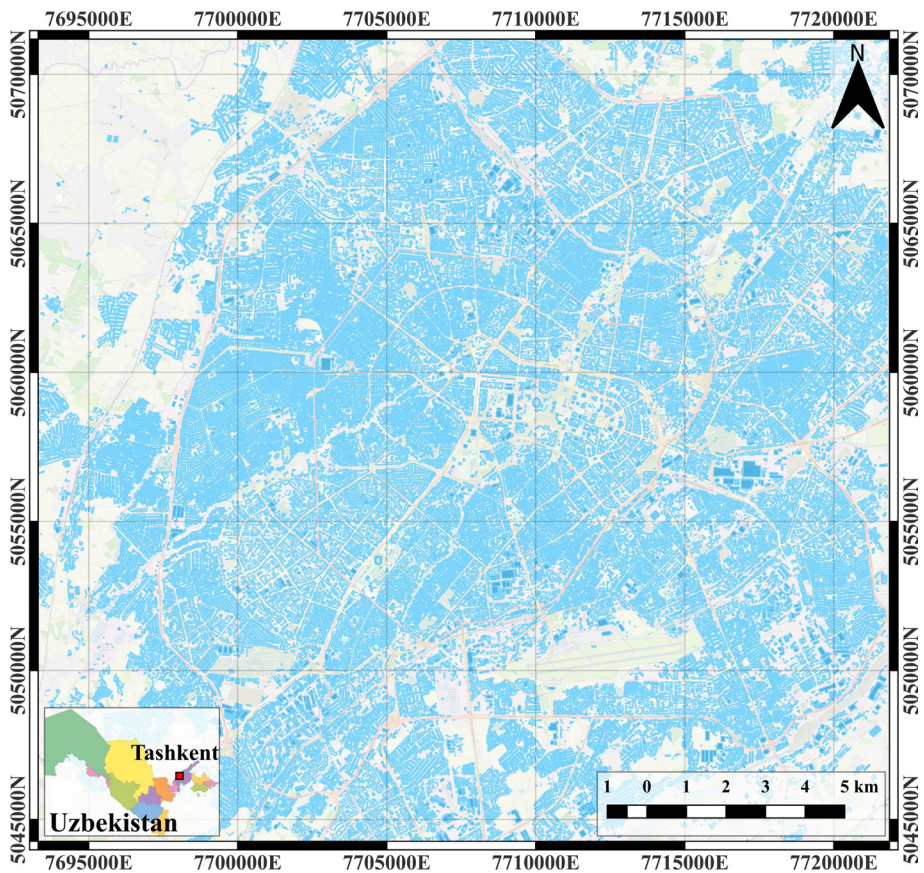


Fig. 3 Building shapefile for Tashkent City

aerial images. The proposed GIS tool integrates the building shapefile with the analyzed data to create buffer zones around petrol stations considering a common Coordinate Reference System (CRS) and including the distance, in length units, between the station and the targeted buildings. The used data are in the projected coordinate system EPSG3857 based on the WGS84 datum as the most common CRS for online maps. Using a common CRS facilitates the generalization of the suggested tool in different study areas.

3.3.2 Modelling workflow

To achieve the model objectives, the following procedures are applied (Fig. 4) and the outcomes are presented. The model loads the station data with station ID, tank volume, molar mass, and geolocation coordinates. Station data are analyzed to calculate the different radii for the effect zones around each station, based on Eqs. (2), (3), (10) and (14) and Tables 1 and 2. Calculated radii are used to plot buffer zones and visualize the affected areas around each station. Using the buffer zones and the building data, the affected buildings could be detected in each danger zone. Finally, the statistics of the extracted buildings are presented based on query by danger zone, query by station, or query building tools. The danger zones are categorized into 3 groups:

1. Explosion danger zones: fireball zone (c.f. Eq. (2)), danger zone (Eq. (3)), impacted zone (Eq. (10)).
2. Human injury zones (Table 1): 1st degree burn zone, 2nd degree burn zone, 3rd degree burn zone, and painful sensations on the skin and mucous membrane zone.
3. Building damage zones (Table 2): total destruction zone, 50% destruction zone, medium damage zone,

moderate damage zone, pressure wave damage zone, and minor damage zone.

3.3.3 Gasoline station explosion modeler

QGIS is an open-source software allows users to browse, edit, visualize, and analyze geographic data in a range of data formats [33]. A QGIS plugin, titled Gasoline Station Explosion Modeller (GSEM), is developed using QGIS Plugin Builder. GSEM (Fig. 5), available with the input datasets at GitHub [34], enables the user to add a base map for exploring the data visually using OSM or ESRI satellite layers and load the shape files needed for the feature extraction process. The station data, in Excel format, contains the station name, tank volume, molar mass, and station coordinates, where the plugin applies the given equations to analyze the explosion scenarios and calculates the radii of the danger zones. Three categories of zones are calculated and plotted on each station: danger zones, human injury zones, and building damage zones. The affected buildings in each zone are extracted through the intersection between the specific layer and the input building layer. The result summary is a generated vector layer containing all the extracted buildings arranged according to station and the related damage zone. Statistics are presented based on station or danger zone to show the number of affected buildings in each danger zone of each station. Moreover, building ID allows the user to access information about the affected building in any danger zones and related station.

4 Results

The proposed model analyses and visualizes the danger zones around each station which reflects the affected areas, extracts the impacted buildings in each zone for emergency aspects, and generates the statistics of the affected buildings. The findings of all stations are displayed on an interactive map, making them accessible to be visualized and examined.

4.1 Interactive map

The interactive map, available at GitHub [35], was created using the Leaflet package. The cartographic base maps include OpenStreetMap (OSM) and ESRI satellite maps. Customized buttons are incorporated to display the spatial layers like the station location and the three categories of danger zones. Additionally, affected buildings identified through the model data analysis are included (Fig. 6). Finally, attribute data are available by clicking the selected spatial object.

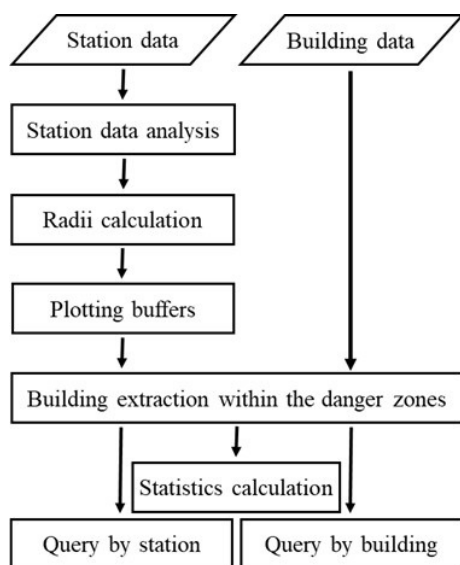


Fig. 4 The model workflow

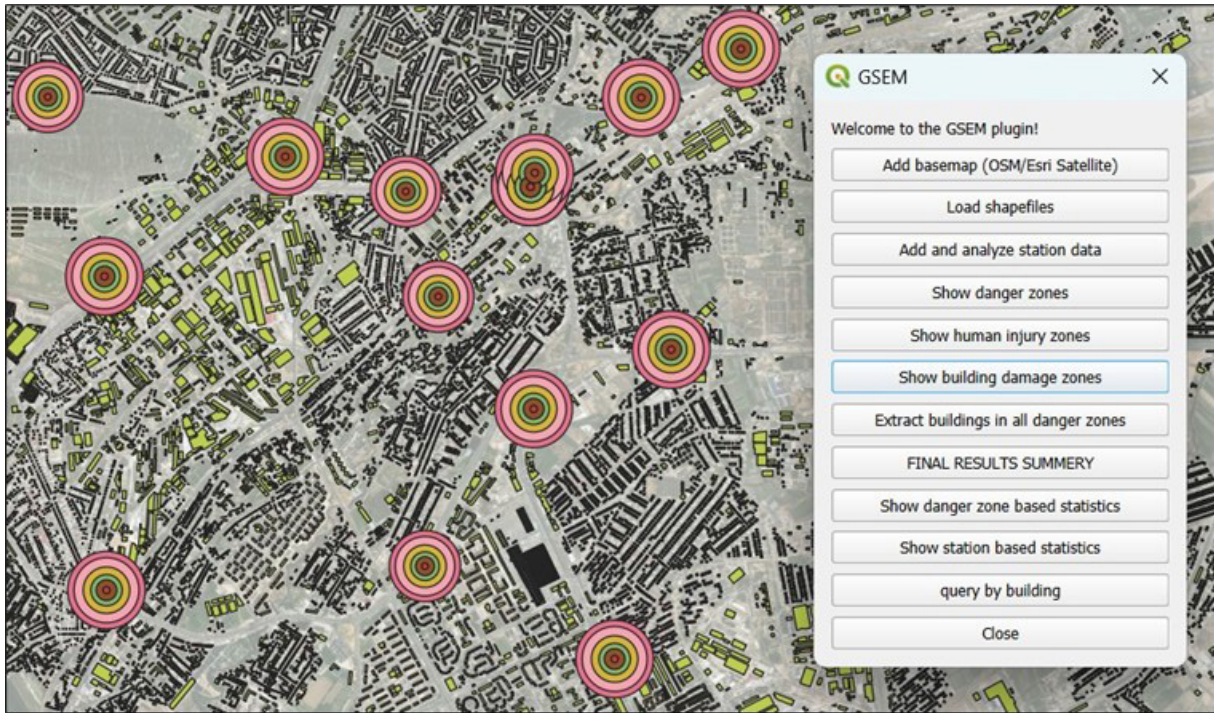


Fig. 5 A screenshot from QGIS software showing the GSEM Plugin

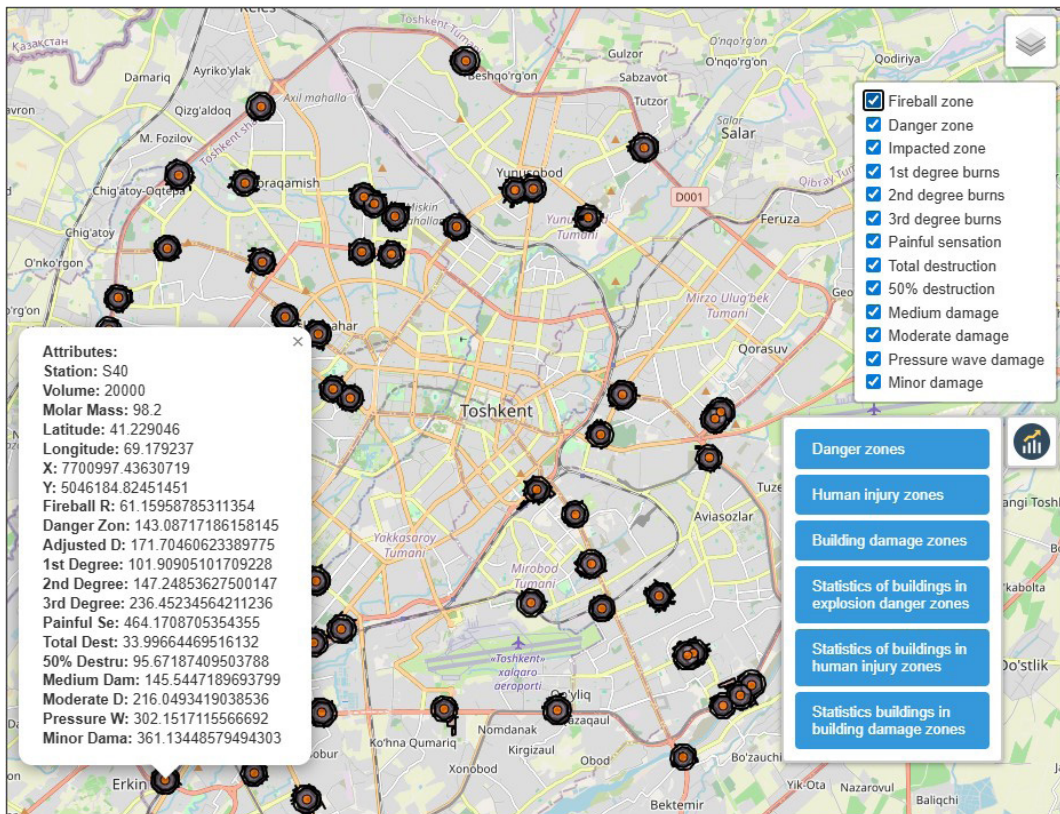


Fig. 6 A screenshot from the interactive map

To verify the model and demonstrate its serviceability and applicability to any similar study area, the outcomes of two stations, Station S01 with a volume of 15,000 L and Station S41 with a volume of 20,000 L, are presented with their danger zones and affected buildings.

4.2 Danger zone visualization

Three danger categories are presented to show the explosion effect (Figs. 7 and 8). The explosion danger zones show the fireball, the danger zone affected directly by the explosion, and the impacted zone, which considers a 20%

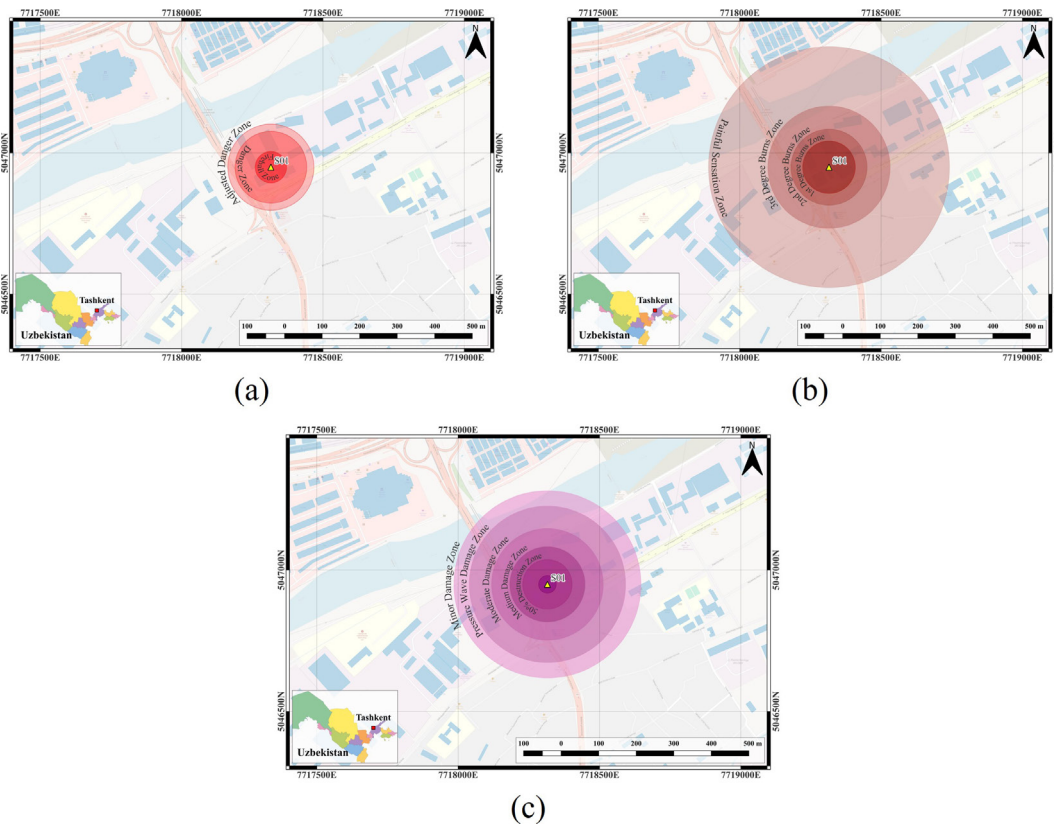


Fig. 7 Explosion danger zones, human injury zones, and building damage zones of Station S01: (a) Explosion danger zone; (b) Human injury zone; (c) Building damage zone

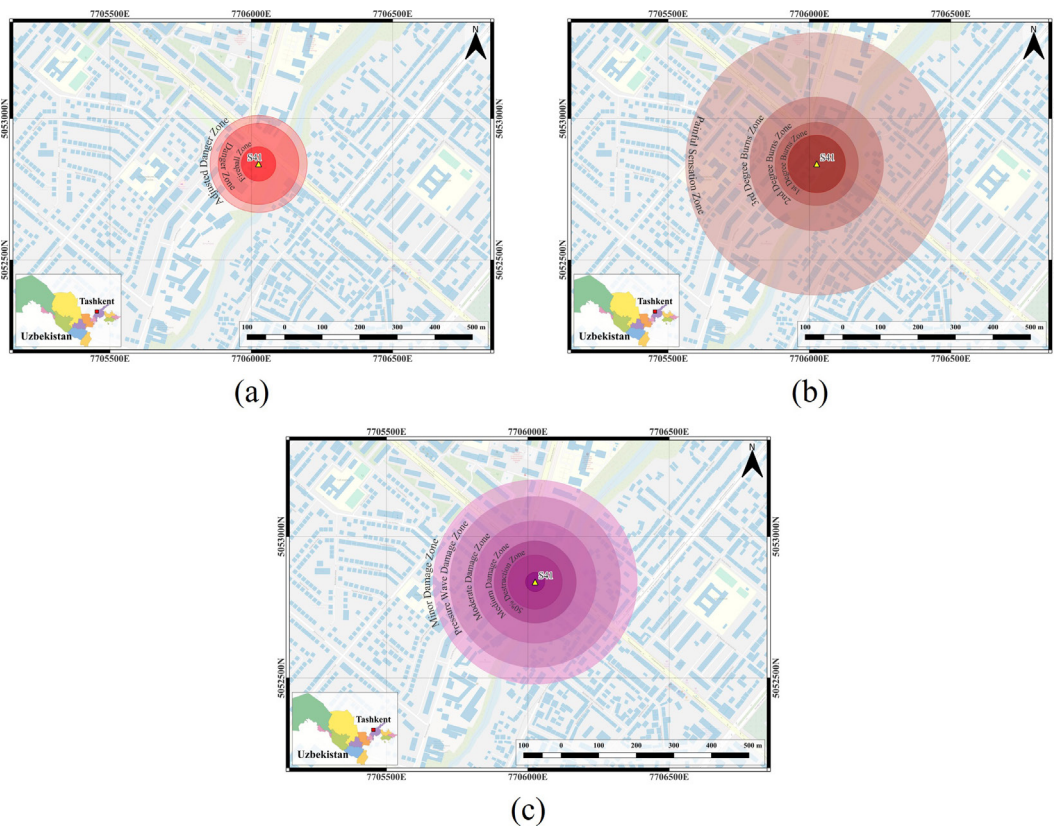


Fig. 8 Explosion danger zones, human injury zones, and building damage zones of Station S41: (a) Explosion danger zone; (b) Human injury zone; (c) Building damage zone

safety factor around the danger zone. The human injury zones show the different levels of harm to humans, starting from the 1st degree burns up to the painful sensations on the skin and mucous membranes. The building damage zones show the possibility of damage degrees could affect the surrounding buildings starting from the total destruction up to the minor damages.

4.3 Affected building extraction

Based on previous incidents, explosions have had serious effects on surrounding buildings. For instance, in 2007, a fuel explosion in Salerno, Italy, destroyed a three-story structure and damaged five more. Leaked gases in Seine-et-Marne, France, in 2002, triggered an explosion that damaged 39 buildings within a 200 m radius [8]. Understanding the anticipated consequences of the explosion is crucial for planning the needed precautions to avoid detrimental effects on individuals and properties [36]. The affected building detection process is applied through the intersection between the created buffer zones for different categories of damage and the building layer. The extracted buildings are presented in separate layers according to the existing damage zone. Affected building extraction is

necessary for emergency activities and decision making during and after the explosion disaster.

4.3.1 Affected buildings in explosion danger zones

Buildings in fireball, danger, and impacted danger zones are extracted (Figs. 9 and 10). Residents of buildings in fireball zones are subjected to fatal exposure due to direct thermal radiation. Buildings, in the danger and impacted danger zones, exist where the impact of the burning of spilled gasoline is deemed influential. Knowing the danger zone corresponding to a building helps manage the required means for appropriate protection and emergency precautions.

4.3.2 Affected buildings in human injury zones

Human injury zones represent the severity of injuries that could occur to humans in buildings placed in these areas (Figs. 11 and 12). Recognizing human injury zones helps to manage the essential aids in the event of an explosion.

4.3.3 Affected buildings in building damage zones

Building damage zones indicate the extent of damage to structures in those areas (Figs. 13 and 14). Buildings

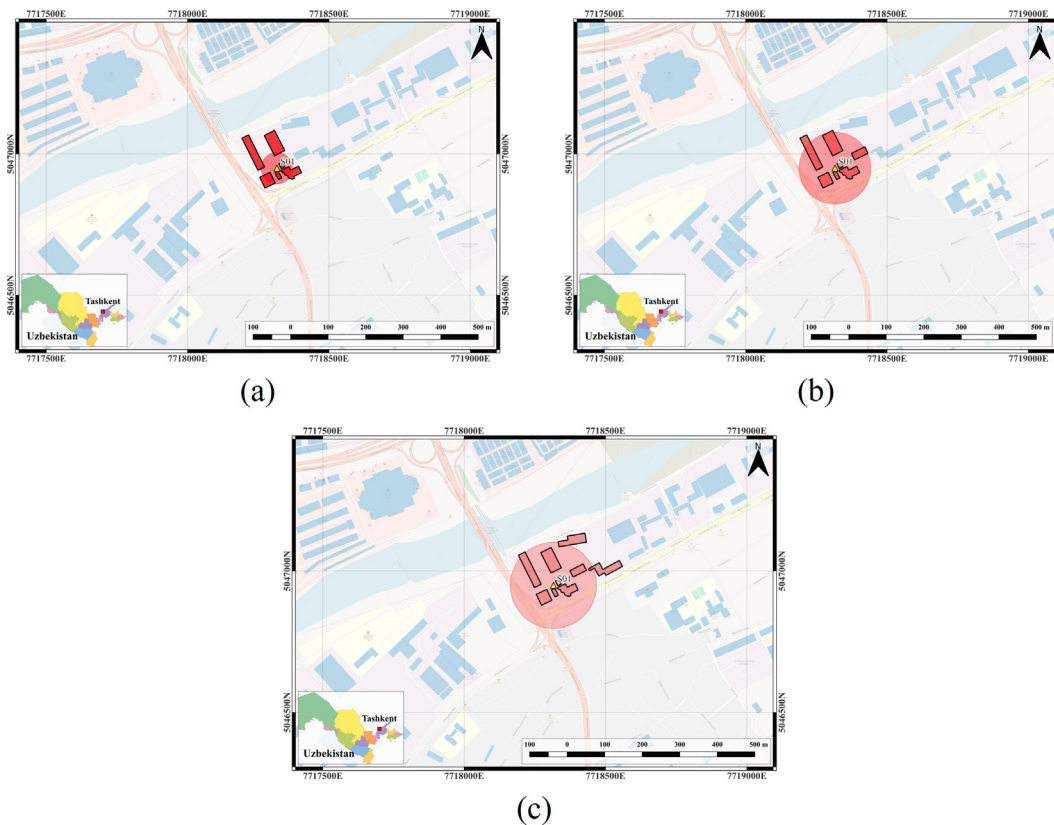


Fig. 9 Affected buildings in explosion danger zones for station S01: (a) Buildings in fireball zone; (b) Buildings in danger zone; (c) Buildings in impacted danger zone

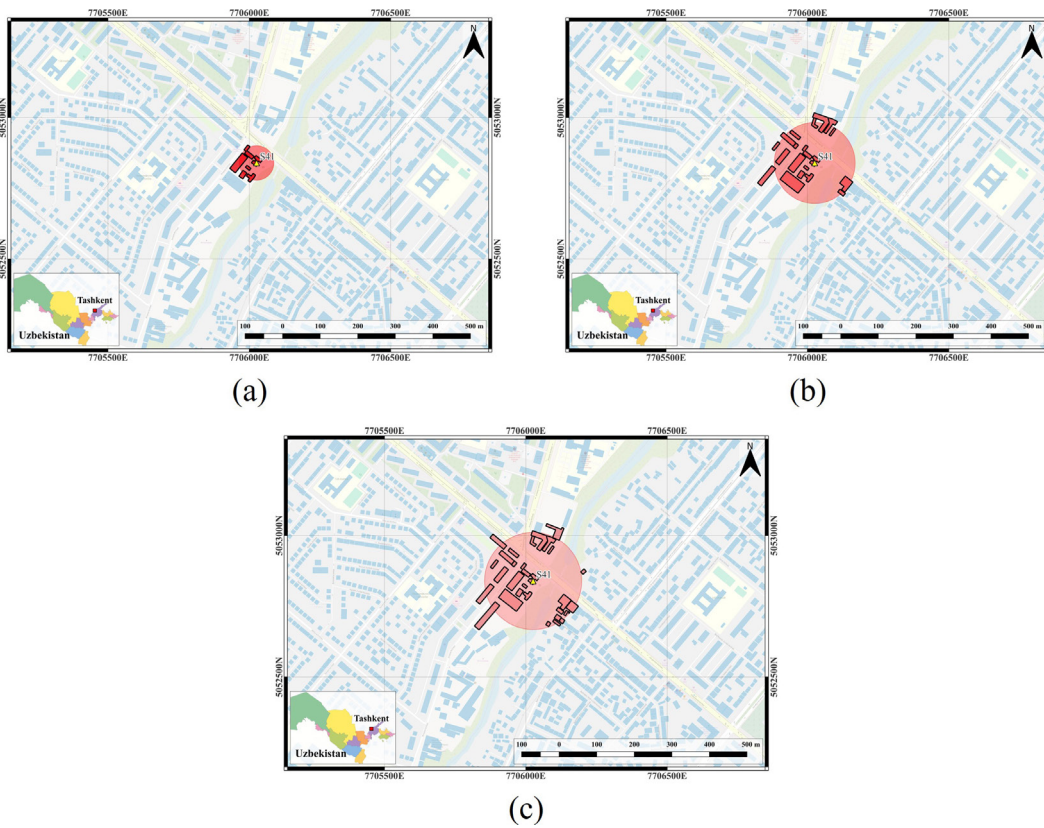


Fig. 10 Affected buildings in explosion danger zones for station S41: (a) Buildings in fireball zone; (b) Buildings in danger zone; (c) Buildings in impacted danger zone

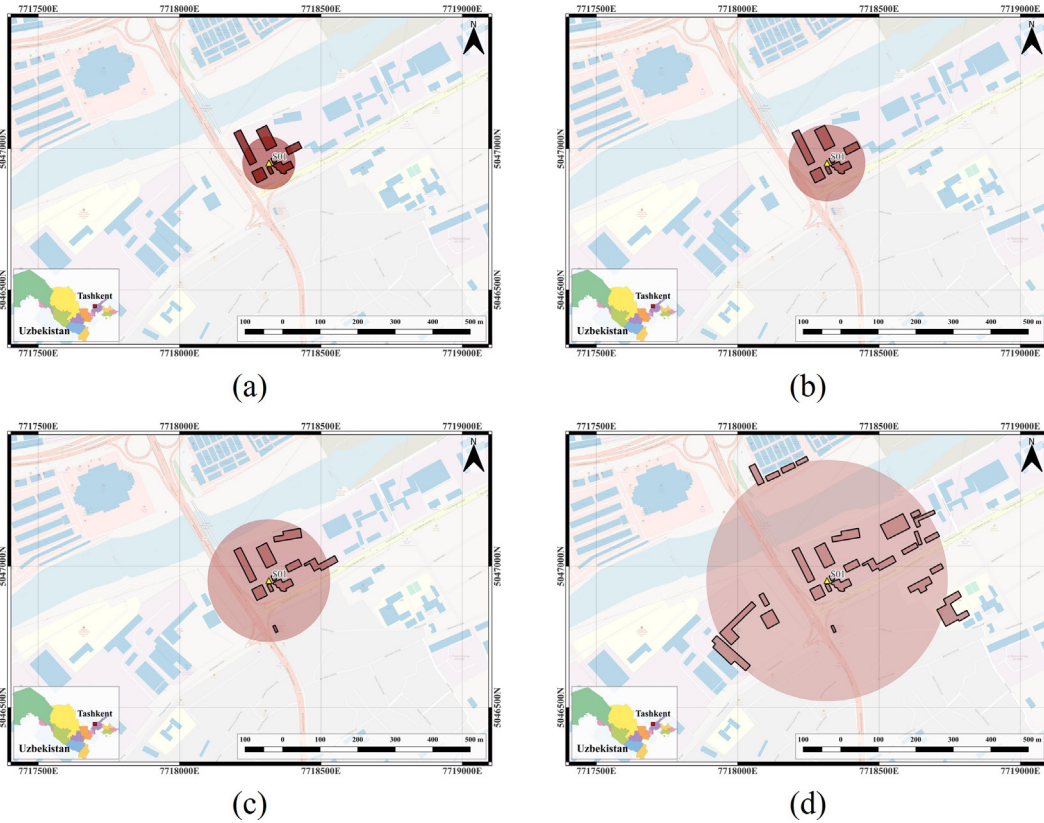


Fig. 11 Affected buildings in human injury zones for station S41: (a) Buildings in 1st degree burns zone; (b) Buildings in 2nd degree burns zone; (c) Buildings in 3rd degree burns zone; (d) Buildings in painful sensations zone

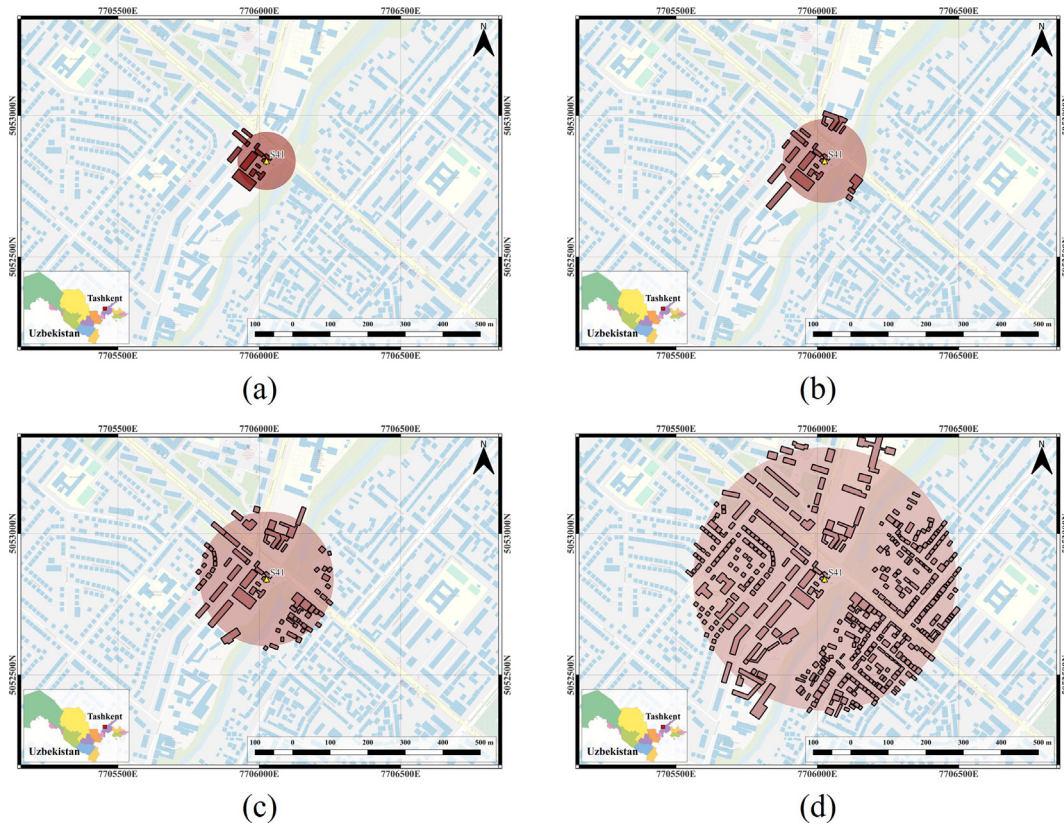


Fig. 12 Affected buildings in human injury zones for station S01: (a) Buildings in 1st degree burns zone; (b) Buildings in 2nd degree burns zone; (c) Buildings in 3rd degree burns zone; (d) Buildings in painful sensations zone

experience six degrees of destruction, ranging from little damage to complete destruction (c.f. Table 2). Assessing the extent of building damage assists in providing adequate civil protection actions before, during and in the aftermath of an incident.

4.4 Statistics

4.4.1 Statistics by station

Statistics give an overview of the affected buildings at each station and provide information for all danger zones. Information is important for urban planning, policy making and updating, and decision-making.

The proposed model generates statistics by station, showing the number of buildings in each danger zone (Figs. 15 to 17).

4.4.2 Overall statistics

Overall statistics for all the stations are presented, showing the number of buildings in each danger zone based on the category (Figs. 18 to 20).

4.5 Query by building

The plugin provides a 'query by building' feature to verify a building, using the building ID provided in the input

building layer, and showing the danger zones where the building exists in, and which station belongs to (Fig. 21).

5 Conclusions

The increase in vehicle registrations is a primary factor contributing to the growing demand for fuels. As for the Association of Southeast Asian Nations (ASEAN) region, the primer economical influence of Asia, Southeast Asia's fuel demand is expected to increase from 4.7 million barrels per day (mb/d) in 2016 to 6.6 mb/d in 2040, according to the New Policies Scenario, requiring safety and risk reduction measures [37]. The study offers key conclusions to be applied for probabilistic explosion risk reduction, safety engineering, and various related research. The relevance of the developed GIS tool is to provide a suitable platform for the challenges of emergency management following gasoline station explosions in urban areas. In addition to the queries already defined, there are many other optional applications that can be explored. Possessing a rescue operations plan is crucial in the case of an explosion. The fastest track to a hospital is an obvious aspect, but there are several other essential criteria, e.g., zones defining where vehicles (including fire trucks and ambulances) cannot enter because they would be exposed to serious fire

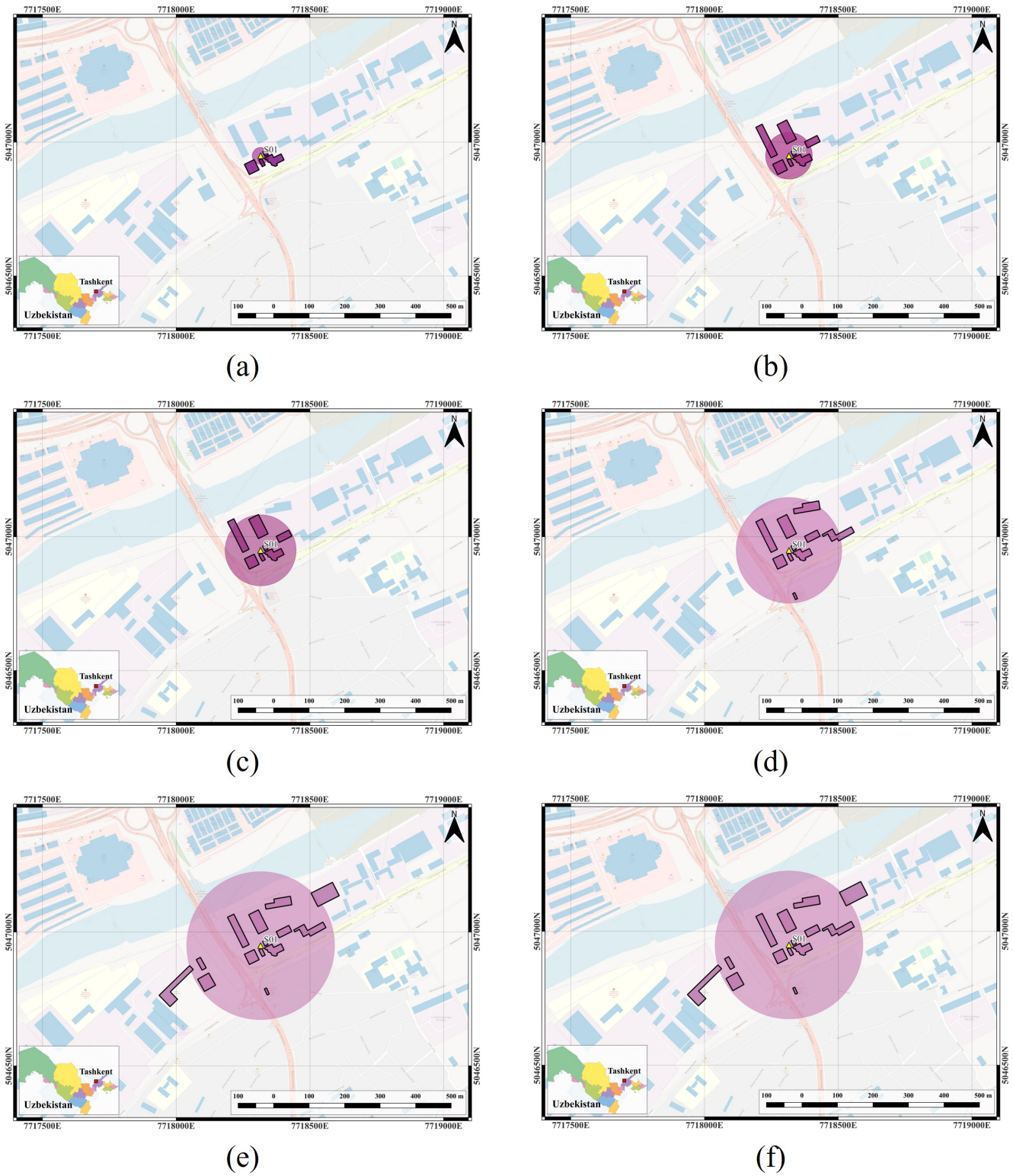


Fig. 13 Affected buildings in building damage zones for station S01: (a) Buildings in total destruction zone; (b) Buildings in 50% destruction zone; (c) Buildings in medium damage zone; (d) Buildings in moderate damage zone; (e) Buildings in pressure wave damage zone; (f) Buildings in minor damage zone

risk. Apart from detecting high-risk areas around existing gas stations, such a GIS tool can be used to train emergency specialists and residents of the most dangerous zones.

In summary, the identified danger zones are crucial for emergency planning and management in the context of international guidance on safety and the local regulatory processes:

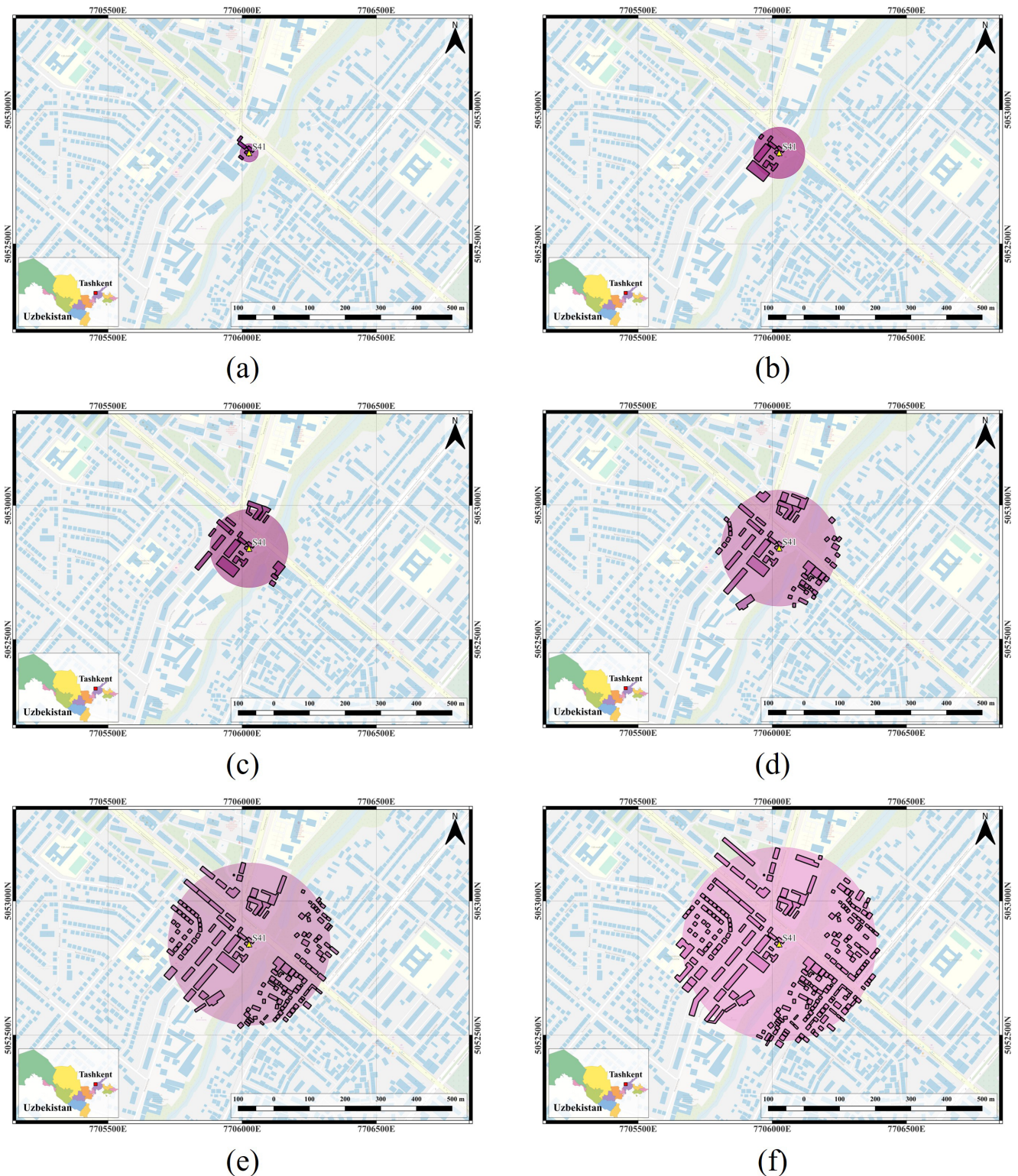


Fig. 14 Affected buildings in building damage zones for station S41: (a) Buildings in total destruction zone; (b) Buildings in 50% destruction zone; (c) Buildings in medium damage zone; (d) Buildings in moderate damage zone; (e) Buildings in pressure wave damage zone; (f) Buildings in minor damage zone

1. Minimizing human casualties: by identifying risk zones, emergency services can prioritize evacuation efforts and allocate resources effectively during emergencies, thus enhancing the safety of residents.
2. Reducing material losses: strategic planning based on risk assessments enables better infrastructure protection, which can significantly minimize damage.

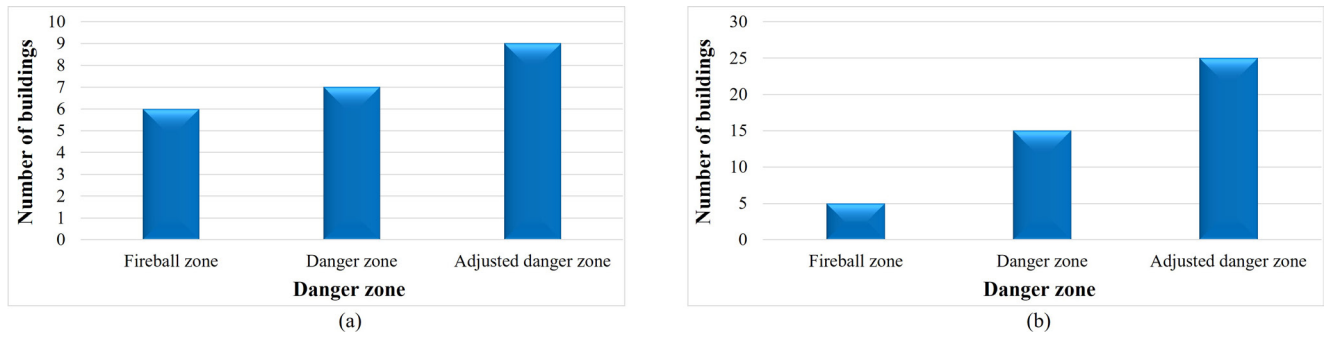


Fig. 15 Statistics of affected buildings in explosion danger zones for: (a) Station S01; (b) Station S41

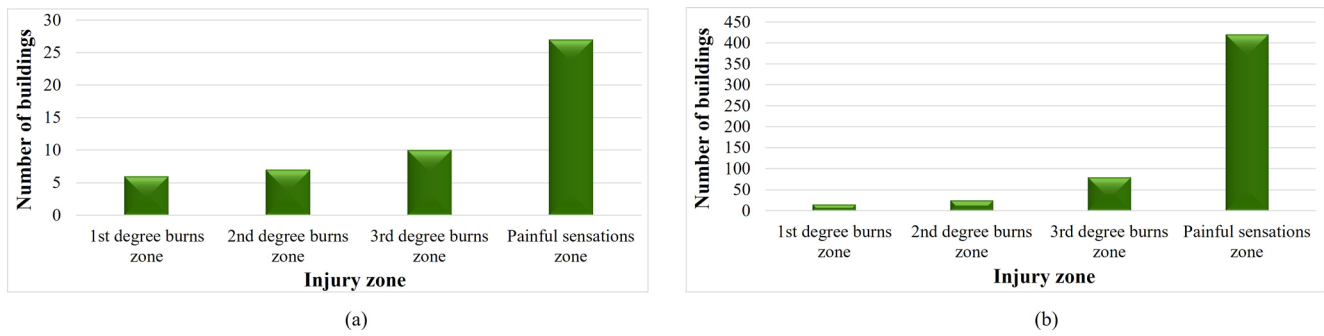


Fig. 16 Statistics of affected buildings in human injury zones for: (a) Station S01; (b) Station S41

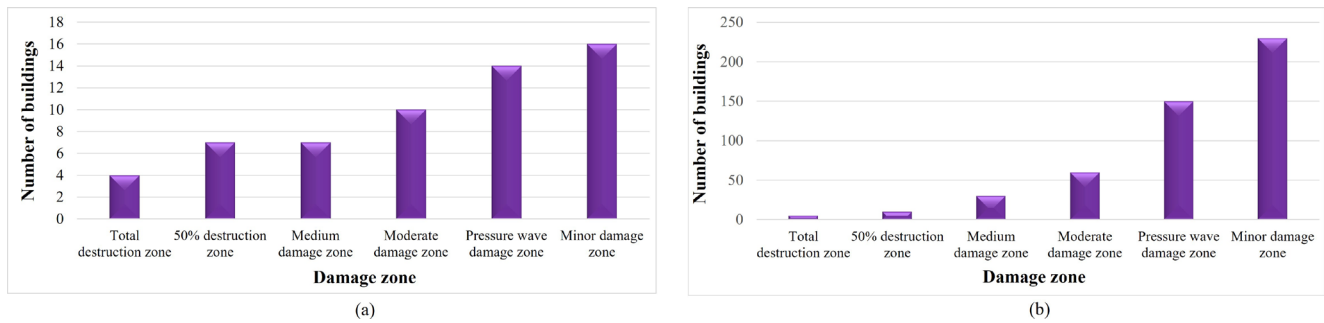


Fig. 17 Statistics of affected buildings in building damage zones for: (a) Station S01; (b) Station S41

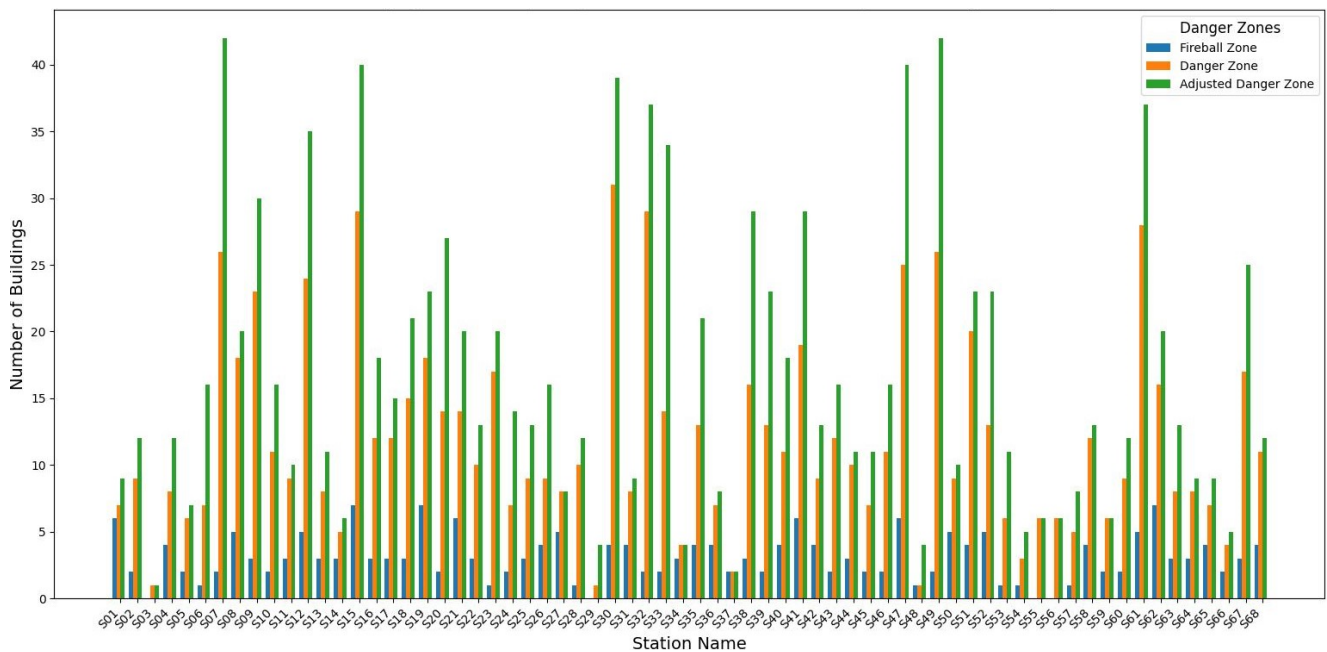


Fig. 18 Statistics of affected buildings in danger zones for all stations

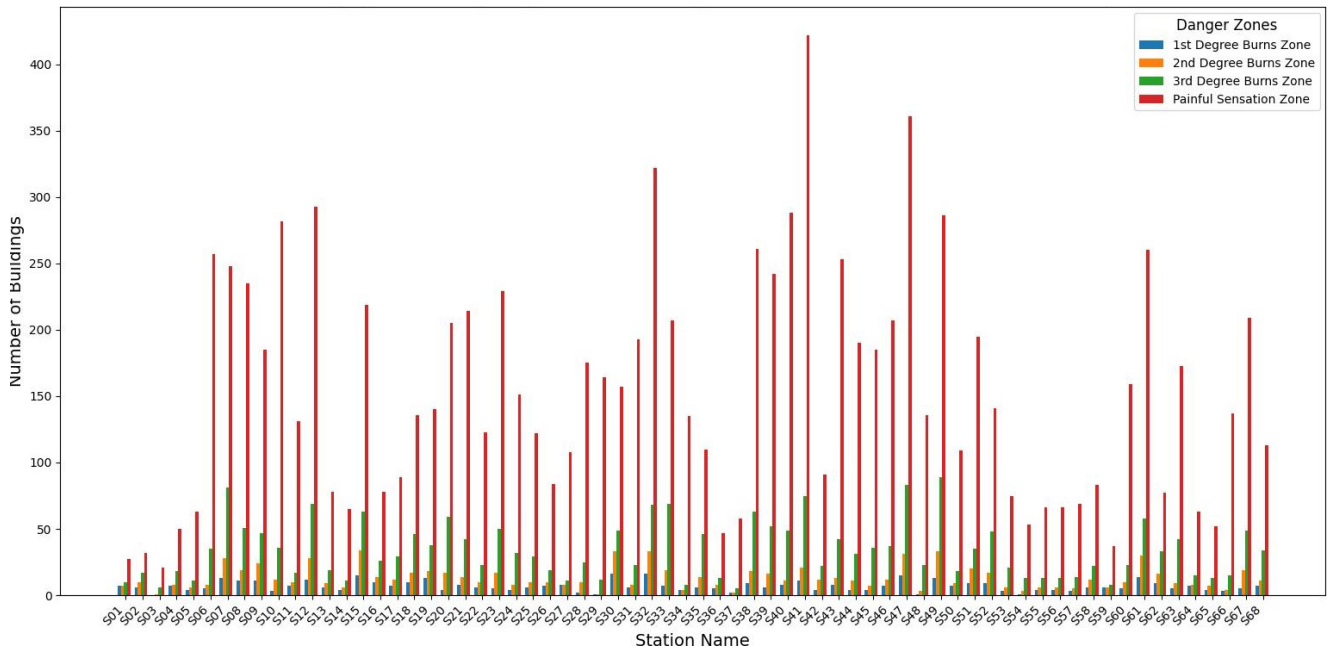


Fig. 19 Statistics of affected buildings in human injury zones for all stations

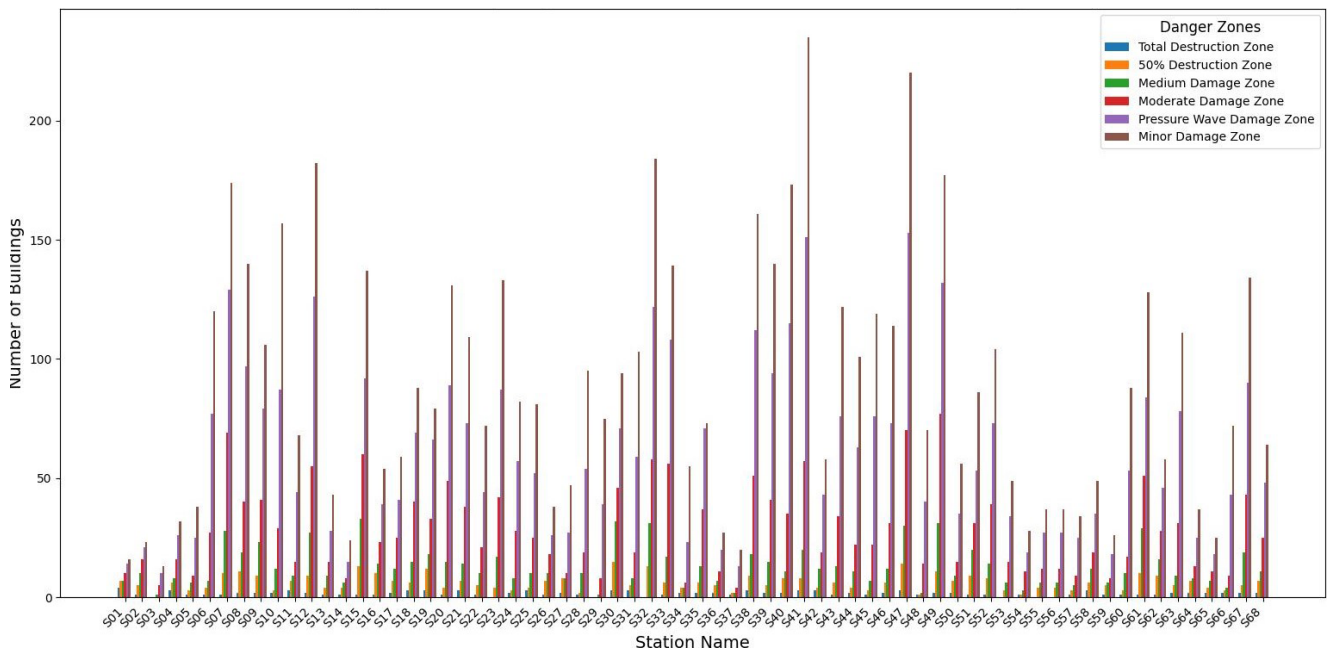


Fig. 20 Statistics of affected buildings in building danger zones for all stations

age to property and essential services during and following disasters.

3. Increase the responsibility of enterprises: industries operating in or nearby vulnerable areas can be held accountable for incorporating safety measures and contingency plans, leading to a more proactive approach to hazard management.
4. Increase public confidence: transparent communication regarding potential threats and safety protocols

fosters trust within the community, encouraging cooperation and adherence to safety measures.

Beyond the significance of emergency management, one should also consider the aspects of official authorisation and urban planning, in which the focus is on the buildings. It might be interesting to query about the danger category of certain buildings which would be a criterion for the permission or refusal of official authorisation for an activity.

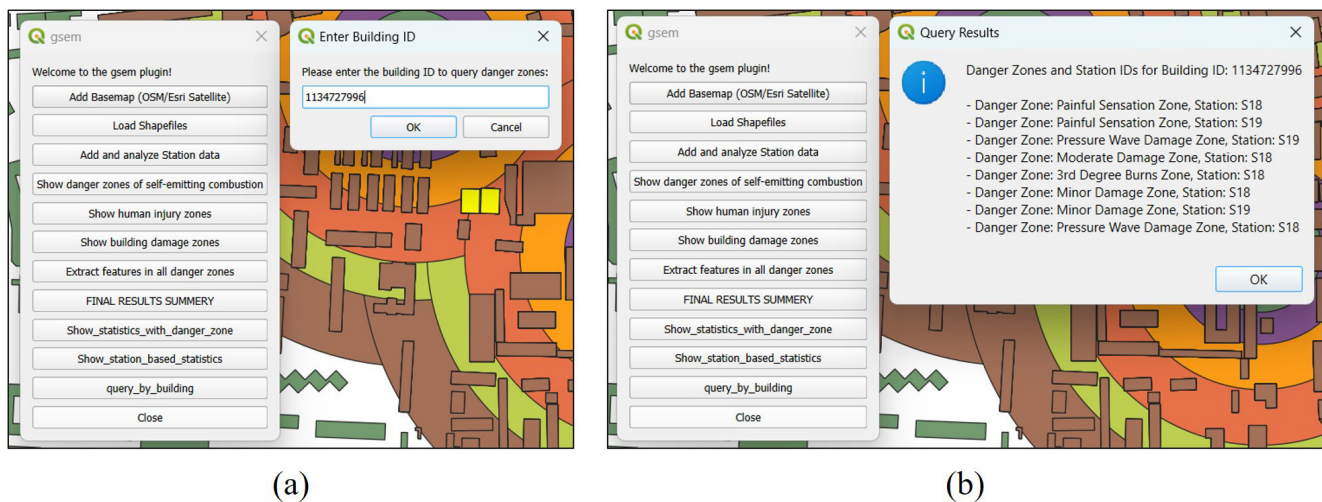


Fig. 21 Querying by building window: (a) Search by building ID; (b) Inquiry outcomes for the required building

Such a way, it would provide a framework to achieve the optimal utility of the building, for an evident example, no activity involving a fire risk would be allowed within the impacted zone (c.f. Eq. (10)). Also, it can be used to identify safe zones for locating high-risk facilities such as oil storage premises, chemical plants, or hazardous material warehouses. Furthermore, during the planning of a future residential area, the location of the future gasoline stations can already be planned by taking into account the safety considerations of the high-priority buildings and institutions.

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