Analysis of ammonium nitrate detonation destruction in Beirut city using geospatial techniques

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Abstract
Applications of geospatial techniques plays an important role in disaster management and mitigation. This study focuses to analyze how can geospatial technology could have been utilized to minimize the destruction created by the Ammonium Nitrate detonation in Beirut city. Firstly, the disaster impacts on the build-up area were demarcated using Google Earth-based survey, Remote Sensing, and ArcGIS applications. According to the analysis, it was identified that the Ammonium Nitrate detonation incident in the Beirut port has extensively damaged the build-up area within a 2 km buffer zone from the explosion. Among them, fully demolished constructions are bounded to a 1 km buffer area while partially damage and less damage to buildings were encompassed within 5 km from the epicenter of the incident. The Quantity Distance Mapping Tool results depicted more as similar results to the results obtained through the aforementioned geospatial techniques in post-disaster impact analysis. Therefore, proper planning to locate built-up areas considering vulnerable places away from the possible disaster-induced location utilizing spatial techniques like Quantity Distance Mapping Tool would be more effective in pre-disaster preparedness as we all live in a hidden catastrophic environment. Thus, lessons learned from this Ammonium Nitrate detonation incident of the Beirut city, especially the importance of risk assessment and adherence to precaution measures are needed in any chemical operation sites as well as chemical storing sites.

Keywords Ammonium nitrate detonation · Build-up · Geospatial · Quantity Distance Mapping

1 Introduction
Chemical-induced incidents by anthropogenic or technological failure events are more often devastative in nowadays. Explosions can inflict injuries on many people at the same time resulting in a higher number of mortality and morbidity [1]. The explosion incident took place in Beirut city which happened on 4th August 2020 with an explosion of a large amount of ammonium nitrate (NH₄NO₃) stored at the port of the city of Beirut in Lebanon can be recognized as a massive catastrophe. This problem was critical as it was happened during the worldwide covid-19 pandemic situation whilst Lebanon also facing a large economic and health crisis. Ammonium nitrate is a crystal-like white solid usually used as a source of nitrogen for agricultural fertilizer and used as an explosive agent in mining [2]. Pure ammonium nitrate is stable, but heat, confinement, contamination, and shock can lead to fire and detonation [3]. The main reason is that the ammonium nitrate is intact with moisture and rocks which will be accelerated the chemical reaction in case of a fire attack. According to the historical pattern of occurrence, most of the ammonium nitrate accidents have been associated with storing issues [2].

Further, improperly manufactured, transported, handled and stored explosive materials, such as ammonium nitrate, are a safety risk to local communities and a security threat to states and societies. The production and consumption of manufactured chemicals continue to spread worldwide, with an increasing spread over developing countries and economies in transition, many of which may have a limited regulatory capacity [4]. As Lebanese authorities reported, the reason behind the Beirut explosion is mainly due to

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improper storage of ammonium nitrate [5]. This was stored unsafely at a warehouse in the Beirut port for almost six years [6]. According to the BBC news page [6], the ammonium nitrate arrived at the Beirut port in 2013, when a Moldovan-flagged cargo vessel made an unscheduled stop there and was then banned from leaving because of a legal dispute over unpaid fees and ship defects. The heads of the port and customs authority complain about their warnings about the danger posed by the ammonium nitrate and as it was repeatedly ignored.

There are many historical records of ammonium nitrate explosions worldwide. Since 1916, there have been at least 30 disasters induced by ammonium nitrate [7]. Beirut city explosion can be recognized as the third large incident throughout the historical timeline concerning the amount of ammonium nitrate explode [8, 9]. According to an expert on blast protection engineering (Andy Tyas), the Beirut explosion can be recognized as one of the biggest non-nuclear explosions in history [10]. As per the records of the European-Mediterranean Seismological Center (EMSC), 240 km (150 miles) away neighboring country island of Cyprus felt an explosion of Beirut city [11].

Deaths, injuries, property damages, and natural environmental deteriorations are the common negative circumstances that come with this kind of disastrous situation. Accordingly, the Texas incident that took place in 1947 with 581 deaths has been recorded as the deadliest ammonium nitrate explosion incident and the Beirut city explosion in the sixth place with 157 death tolls [12]. Furthermore, reports confirmed at least 6500 injuries, 300,000 homeless records, and many missing records [13]. A number of buildings, hospitals, mosques, roads, parks, ships, and many motor vehicles had been affected and damages occurred with this explosion. Also, many lives of workers had been lost while they were engaged with emergency services during that period. According to a list of inveterate fatalities released by the Ministry of Health, at least five nurses had died. Also, around 840 healthcare workers have been diagnosed with respiratory illness [14].

Concerning this devastative incident, the objectives of the current study were to demarcate the affected built-up area in Beirut city and to investigate whether there were taken safeguard measures to avoid possible destruction to the built-up area with the help of the Quantity Distance Mapping Tool. Disaster research allows for advancing existing preparedness, response, and recovery practices [15]. Effective risk reduction needs both systems thinking, and localized vulnerability analysis and mitigation [16]. Within the context of this concern, studies conducted concerning disaster-induced impacts are indeed required to make awareness among relevant authorities and the community to make prior planning and actions to avoid or mitigate impacts of such a situation in the future.

2 Methodology

2.1 Study area

Beirut city is the capital city and the largest city of Lebanon. It is a coastal city located on the Mediterranean coast at the foot of the Lebanon Mountains. The city lies in 33° 52’ 38.2692” North latitudes and 35° 29’ 52.5912” East longitudes. Beirut extends over 19.6 km² of the surface area [17]. Beirut’s climate is characterized by subtropical climatic conditions with cool and temperate in winter and hot and humid in summer [18].

The map of the study area (Beirut city, Lebanon) shows the site of the ammonium nitrate explosion near Beirut port (Fig. 1). A location map has been created using a downloaded shapefile with the help of DIVA-GIS of the entire extent of Lebanon. The open street building map of Beirut city was extracted using the Open Street Map (OSM) software.
Beirut port which is located at the center of the city has a critical role in Beirut’s history [19]. Before the 2020 explosion incident, Beirut port has been damaged during the Lebanese civil wartime as well. The port handles 60% of Lebanon’s imports as well as the storage of its food and medical reserves. The location of the port is closer to a dense residential area [8]. The metro area population of Beirut in 2020 was 2,424,000 [20]. Beirut is a highly populated city in Lebanon and has an urban population density breaching more than 3,500 individuals per square kilometer [21].

2.2 Data Collection and Analysis

2.2.1 Demarcation of affected built-up area in Beirut city

Ammonium nitrate explosion affected spot identification facilitated using Google Earth software. Initially, the area covered within a 10 km radius and 5 km radius from the explosion has been demarcated (Fig. 2). The systematic sampling method has been used as the primary sampling method and therefore, sample buildings were considered radially along 10 degrees intervals from the location of the explosion. As to understand the effect of the explosion radially from the location that the explosion took place, eight sample buildings each up to 5 km and 5 km up to 10 km radially from the explosion location were randomly selected at each 10° from East to S40°W. Thus, two hundred and twenty-four sample buildings were considered from this area. However, it was noted that the sea exists from the West to N50°E from the explosion. Therefore, this extension has not been considered for the sampling process. Also, part of the area between N50°E to East (zone A) and from S40°W to West (zone B) within 10 km from the location of the explosion is covered by the sea. Therefore, only eighty randomly selected buildings from these two zones were considered for the analysis. Based on the sampling method explained above, there were three hundred and four buildings were considered for this study.

As Google Earth is helpful geospatial software that facilitates remote studies, this research study has used the Google Earth Street View option to recognize the status of damages due to the explosion. Google Earth maps and Street View create interesting possibilities for research [22]. Thus, this facility has been utilized in this research. Also, this facility is useful as the majority of images currently captured by the Street View demonstrate near high-definition quality [23].

When analyzing the building damage estimation, destructions of houses and other buildings were considered as highly affected building spots (non-repairable). Partially damaged buildings i.e., damaged walls, damaged roofs, damaged window covers, etc. in buildings marked as medium affected building spots (needed major reparations) while visible damages, i.e., cracks in walls, partially damaged windows, building glasses, and roofs were marked as less affected spots (needed fewer reparations) while no visibility of broken parts of buildings was identified as not affected building spots. Affected zones i.e., severely, moderately, less, and not affected were demarcated according to the distribution of ammonium nitrate detonation affected building spots in each category.

Further to verify the findings, the study used ‘Blast Damage Estimation Tool’ results and ‘Normalized Difference Built-up Index (NDBI)’ calculations. A Blast Damage Estimation is a structured process, utilizing explosives science and explosives engineering, to provide scientific evidence of the potential hazard or risk to individuals and property from direct blast effects [24]. It calculates damages to brick structures when TNT amount and ranges from munition to structure values inserted.

The study used remote sensing and GIS applications to develop NDBI. Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) satellite bands were downloaded from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/) to compare the before and after situation of the built-up area around the Beirut explosion center. Accordingly, Landsat 8 band 5 and band 6 for 21.06.2020 (before the explosion) and 24.08.2020 (after the explosion) were downloaded from the website. As to developing NDBI with Landsat 8 data, it needs only band 5 and band 6. The wavelength for band 5, Near Infrared (NIR) is range between 0.851 and 0.879 μm and the wavelength for band 6, Short-Wave Infrared 1 (SWIR 1) is range between 1.566 and 1.651 μm. Both bands are with 30 m resolution. After downloading the images, image enhancement was performed to increase the clarity and accuracy of feature extraction [25]. During this process, haze reduction under
radiometric corrections in ERDAS IMAGINE 2014 was applied. Otherwise, results may less reliable in the presence of clouds and atmospheric haze [26]. Thereafter, the images were exported to ArcGIS software (version 10.8.1). The Map Algebra option in Spatial Analyst tools in ArcGIS was used to compute NDBI. The formula to calculate NDBI is as follows [27][28].

\[
NDBI = \frac{SWIR_1(band6) - NIR(band5)}{SWIR_1(band6) + NIR(band5)}
\] (1)

Using the formula (1), NDBI was developed to compare before and after the explosion. The NDBI value lies between −1 to +1. The negative value of NDBI represents water bodies whereas the higher value represents built-up areas [27]. Here, demarcated affected zone KML files were exported to ArcGIS and observed whether there are any built-up area changes per demarcated affected zones in Google Earth Pro. Google Earth-based survey and NDBI computation were very supportive as remote geospatial analysis methods. In Google Earth-based survey, though there was a combination of systematic and random sampling for building selection for the analysis still there are missing points. Anyways, selected sample points can say about the real status of damage, whether it is in the non-repairable state or a medium affected state, etc. There are no missing records in the NDBI calculation. Though it can indicate density differences in the comparison of before and after the incident, spot wise level of damage is hardly visible. Blast Damage Estimation Tool provides, an experimental level picture and thus it can use to verify results.

2.2.2 Investigate whether there were taken safeguard measures to avoid possible destructions to the built-up area: application of Quantity Distance Mapping Tool

There are three classes of explosive materials, i.e., high explosives, low explosives, and blasting agents. Ammonium nitrate is belonging to the blasting agent category [29]. Therefore, relevant authorities should have taken safeguard measures to reduce risks in case of an explosion. To investigate the status of beforehand preparedness for sudden catastrophe ‘Quantity Distance Mapping Tool’ was used as a technique. This beforehand preparedness means actions taken before a disaster takes place.

In Quantity Distance Mapping, the rules are known as Quantity-Distance (Q-D) criteria and are based on the approach derived from the Hopkinson-Cranz Scaling Law, which is further modified by a range of coefficients. It is the basis of much of the work on the estimation of appropriate quantity and separation distances [30]. The zonal demarcation is an automatic process when we enter TNT (Trinitrotoluene) value and select hazard division. Trinitrotoluene (TNT), a pale yellow, solid organic nitrogen compound used chiefly as an explosive, is prepared by step-wise nitration of toluene [31]. In the Beirut explosion, the warehouse ignited ~2,750 tons of ammonium nitrate [8, 9]. Thus, the explosion is equivalent to ~1,100 tons of TNT (1,100,000 kg). When a mass explosion occurs affecting almost the entire load instantaneously it is belonging to hazard division 1.1 [32, 33]. Therefore, inserting those values in the Quantity Distance Mapping Tool, vulnerable building distance, inhabited building distance, and public traffic route distance (medium density) were computed. Thereafter, we could investigate whether the buildings and routes have located in a safer area from the possible impact in case of the explosion.

3 Results and discussion

3.1 Demarcate affected built-up area in Beirut city

When accidental events occur in the chemicals’ production, storage, transportation, or other processes, they often lead to multiple domino effects and may spawn serious consequences of mass casualties, property losses, and environmental pollution [34]. Demarcation of the sphere of influence of ammonium nitrate detonation incident on the built-up environment was one of the main objectives of this particular study. Although obviously there may be associated death records, other infrastructure demolitions, and environmental pollution as well. Generally, the severity of the impact depends on many factors including, when and where the event had taken place, the number of people in the area, material in the area of the explosion, and the type of explosion (i.e., nuclear, mechanical, or chemical), how far the victim is from the explosion, and etc. [1]. In this study, the level of destruction was considered a key factor in demarcating affected zones.

Ammonium nitrate detonation affected area in Beirut city is attached to Lebanon West-central area. In Fig. 3, totally collapsed sample buildings are in the area colored in red. According to the distribution of ammonium nitrate detonation affected buildings, it can be generalized that the severely affected building is fallen within 1 km of the explosion center. Hundred and forty-meter detonation craters were created at the epicenter has been destroyed adjacent warehouses and deeply damaged grain silo which was leading to food and economic crisis in the country [35]. The majority of the buildings within 1 to 2 km from the explosion are moderately affected with partially damaged buildings while buildings between 2 and 3 km from the explosion are less affected. Also, it was noted that buildings that are
located more than 3 km away from the explosion are not affected by ammonium nitrate detonation. Therefore, the severity of the building affected by this hazard can be generalized as shown in Fig. 3.

From the total number of samples considered in this study 3% (9 buildings) is belongs to this severely affected category, 18% (54 buildings) for moderately affected, 15% (47 buildings) for less affected, and 64% (194 buildings) for not affected category. Severely affected buildings are totally collapsed buildings (non-repairable). Except two, buildings out of 9 buildings which were severely affected category are multi-storied buildings. The built-up area within 1 km distance from the explosion center before and after the explosion is shown in Fig. 4.

As described in the methodology, moderately affected buildings needed major reparations. Out of a total number of 54 buildings marked as moderately affected, 32 were shown at least two combined damages i.e., damaged walls and damaged roofs or damaged walls and damaged window covers, etc. Thus, a 2 km buffer zone from the site of the explosion can be demarcated as an area with extensively damaged buildings. Building spots that needed fewer reparations i.e., cracks in walls, partially damaged windows, building glasses, and roofs which were marked as less affected areas.

International Ammunition Technical Guidelines have introduced ‘Blast Damage Estimation Tool’, which provides simple empirical correlations of explosion consequences from the detonation of a certain amount of explosives at distances of concern: degree of damage to brick structures and windows, blast-related injury levels, and maximum affected range by ground vibration [26]. When enters the TNT amount range from munition to structure, calculations for damages to brick structures at distance in meters (m) of concern are shown in Table 1. According to the results of the Blast Damage Estimation Tool, uninhabitable buildings are located within and around 2000 m distance from the detonation center.
Table 1  Calculations of possible damages to brick structures from the detonation of ~1,100 tons of explosives (TNT) at distances of concern

| Damage to Brick Structures                                | Distance (m) |
|-----------------------------------------------------------|--------------|
| Houses completely demolished                               | 495.49       |
| Houses badly damaged, beyond repair, require demolition    | 732.92       |
| Houses rendered uninhabitable can be repaired with exten   | 1280.02      |
| Houses rendered uninhabitable can be repaired reasonably quickly | 2198.75     |
| Houses rendered uninhabitable can be repaired reasonably quickly | 4397.51     |

As described in the methodology, NDBI calculation was performed to further verify the results obtained through the remote survey with Google Earth applications. Using these techniques urban land cover has been mapped automatically using satellite imagery and it has broadly grouped into two general types: (1) based on the classification of the input data, including pixel- and object-based classifications, and (2) based on directly segmenting the indices, such as this NDBI [36]. NDBI highlights urban areas where there is a higher reflectance in the shortwave-infrared (SWIR) region, compared to the near-infrared (NIR) region [37]. As the NDBI value lies between −1 to +1 and the higher value represents built-up areas [27], the red shades of Fig. 5 are the areas with a value above 0 up to 1.

When it compares the before and after changes to the built-up area, the NDBI values ranges for before the incident is from –0.131730854 (min) to 0.121518098 (max). NDBI values range from −0.216438234 (min) to 0.101496726 (max) after the explosion. Though it is possible to exist remnants after the collapses, there is a change compared to the previous status. It is clear that the built-up area within the 1 km buffer zone has been reduced to a lesser extent; the highly-dense area of 298.51 sq. km has been reduced up to 59.23 sq. km after the explosion incident.

A: Before the explosion (21.06.2020) B: After the explosion (24.08.2020).

3.2 Investigate whether there were taken safeguard measures to avoid possible destruction to the built-up area

Many States use rules based on the explosives, their quantity, and the distance from the explosive to where people are at risk [30]. According to the amount of Ammonium Nitrate stored in the Beirut port and considering the hazard category, distances should have been maintained to prevent potential explosion incidents. As Quantity Distance Mapping Tool results, three circle areas (Fig. 6), public traffic route distance (medium density) from the potential explosion site should be away from 1520 m distance (away from the green circle area), inhabited building distance from the...
potential explosion site should be away from 2300 m distance (away from the yellow circle area), and vulnerable building distance from the potential explosion site should be away from 4580 m distance (away from the purple circle area) (Fig. 6).

According to the outdoor magazines in which blasting agents in quantities of more than 50 pounds are stored must be located no closer to inhabited buildings, passenger railways, or public highways [29]. However, it is visible that the authorities have not followed those guidelines as beforehand measures in the Beirut incident, i.e., locate vulnerable places away from the explosive site or locate explosive materials away from the vulnerable places. When it examines the situation before the explosion with Google Earth Pro historic maps, public traffic routes are visible within the 1520 m zone. The highway in front of the Beirut port is one of the busiest highways, named Charles Helou. Also, the Charles Malek highway runs within this risk zone.

The term “inhabited building” defines any building regularly occupied in whole or in part as a habitation for human beings, or any church, schoolhouse, railroad station, store, or other structure where people are accustomed to assembling, except any building occupied in connection with the manufacture, transportation, storage, or use of explosive materials [38]. When it is examining the situation within the risk zone for inhabited buildings, dense residential areas, i.e., Gemmayzeh, Mar Mikhael, and Rmeil, and many others are situated within the risk zone for inhabited buildings. Also, vulnerable buildings, i.e., Beirut governmental hospital, Lebanese hospital, Geitaoui, Roum hospital, Saint George hospital university, and many other high storied vulnerable building structures have been located within the risk zone for vulnerable buildings. Those structures have a high potential of vulnerabilities during ground vibration with the explosive incident. Especially, hospitals are essential for dealing with a disaster, but they are also highly vulnerable installations. Perhaps there are other buildings and installations of equal size and construction in a city, but not as complex from the functional, technological and administrative point of view [39].

According to the Google Earth-based survey, severely affected buildings due to detonation were bounded to 1 km from the explosion center. The affected area is almost similar to the prohibited zone for public traffic routes as per Quantity Distance Mapping Tool results. The public traffic routes exemplify more public space in the area, which is in danger in case of sudden catastrophe. Furthermore, there are inhabited buildings within 2300 m distance from the explosion center which is the prohibited zone for inhabited buildings as per Quantity Distance Mapping Tool results. This area has been affected moderately due to the explosion. As Quantity Distance Mapping Tool demonstrates, vulnerable buildings should locate away 4580 m distance from the explosion center. Anyways, Google Earth-based survey depicts damages on constructions up to 3 km from the explosion center. As there is a connection between real damages and predicted damages, they could have prevented those damages; at least damages on lives if they have applied precautionary measures.

Fig. 6 Distances to public traffic routes, inhabited buildings, and vulnerable buildings as per the amount of TNT and Hazard Division value
4 Conclusions

This study investigated the influence of Ammonium Nitrate detonation incident around the Beirut port and ignorance of safeguard measures that could have been taken to avoid possible destructions in a disaster vulnerable area. According to results obtained through geospatial techniques, completely demolished buildings due to Ammonium Nitrate detonation were located within 1 km from the explosion center and the uninhabitable buildings are located within 2 km from the detonation center. Even though this study covered an area up to 10 km from the detonation center, the affected area has fallen up to about 5 km including moderately destroyed and less damaged buildings. These findings were further clarified using UN Safer Guard Blast Damage Estimation Tool records and NDBI analysis. When analyzing the status of safeguard measures should have been taken to mitigate possible destructions to the built-up area with the help of the Quantity Distance Mapping Tool, public traffic routes with medium density should be located at least at 1,520 m away from the potential explosion site. Further, the minimum distance to inhabited building sites should be 2,300 m away from the explosion site while vulnerable building sites should be located 4,580 m away from the explosion site. According to the analysis, it can be concluded that all the damages to built-up areas, casualties, and injuries were caused by the Ammonium Nitrate detonation due to a lack of preparedness for such incidents. Therefore, this study implies the importance of having a proper and active disaster management plan to avoid this kind of man-made catastrophe in the future.

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