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Article

Earth Observation Data to Support Post-Hazard Damage Assessment: A Case Study of the Appiatse Explosion in Ghana

Naa Dedei Tagoe[1, *], Ebenezer Ashun[2]

[1]Department of Geomatic Engineering, University of Mines and Technology, Tarkwa, Ghana
[2]Department of Environmental and Safety Engineering, University of Mines and Technology, Tarkwa, Ghana

Abstract

On Thursday, January 20, 2022, a motorbike allegedly collided with a truck carrying about 10 tonnes of ammonium nitrate explosives. The explosion caused a blast that created an 18 m diameter crater at the centre of the road and leveled almost the entire village of Appiatse, located in the Prestea Huni Valley District in the Western Region of Ghana. During such disasters, whether natural or anthropogenic, rapid assessment is crucial for an appropriate and effective emergency response. The Appiatse incident resulted in detrimental environmental damage, including the dispersion of particulate matter, dust, soil, and water pollution in the catchment area. Similarly, the high levels of ground vibration caused by the incident resulted in the razing down of most of the structures which were constructs of wattle and daub plastered with concrete. Earth observation (EO) technologies, such as satellite imagery and Unmanned Aerial Vehicle (UAV) data, play a crucial role in disaster management by providing accurate and detailed assessments of damage, enabling effective emergency response and recovery efforts. The impact of the Appiatse explosion was detected by the Enhanced Pollution Management (EPM) EO service, piloted in Ghana, through a time-series analysis. In this research, a damage assessment was carried out using EO data. A collection of Sentinel-2 (10 m resolution) optical satellite images, Synthetic Aperture Radar (SAR) images, and aerial images obtained from a UAV survey (3 cm resolution) were used for the analysis. The damage assessment map of Appiatse provides insights into the extent and severity of the impact, demonstrating the value of integrating various EO data sources for detailed post-hazard damage assessment. The findings from the current research highlight the lack of compliance with the protocols for the transport of hazardous chemicals in Ghana and highlight the need to strictly adhere to safety protocols prescribed by relevant authorities to ensure environmental safety and curb such incidents in the future.

Keywords

Appiatse, Damage Assessment Map, Disaster Preparedness, Earth Observation, Explosion, Hazardous Chemicals

1. Introduction

Mining significantly contributes to government revenues through taxes, royalties, rents, employment creation, technology transfer, and economic resourcefulness. This contribution is expected to increase following recent research by the

*Corresponding author: ndtagoe@umat.edu.gh (Naa Dedei Tagoe)

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UK Government predicting increased metal use in the coming decades [1, 2]. Although the recent decade has recorded a significant decline in mining-related accidents due to strict regulations and better safety practices globally [3-5], mining-related accidents still occur, often with negative consequences for nearby communities. These incidents can leave lasting environmental, social, and economic legacies [6, 7]. The causes of these accidents include human, technical, environmental, and organizational factors [8-11].

Gold mining and most extractive industries have extremely hazardous working conditions, leading to disasters and incidents, of which Ghana is no exception [12-16]. A literature search indicated at least seven mining-related accidents in 2022 alone. These accidents occurred in various countries, including Ghana, highlighting the industry's persistent hazards. The most recent incident includes the explosion of a truck transporting ammonium nitrate mixed with 6% fuel oil (ANFO) to a mining site in Ghana at Appiatse near Bogoso in the Western Region. The explosion resulted in 13 fatalities, injured around 100 people, flattened the rural community, and left a crater roughly 18 m (59 ft) wide (Figure 1a). Figure 1 shows the Appiatse community after the explosion. Figure 2 shows the community before the incident.

Since safety standards are typically only achieved through the demands of worker organizing or regulatory expansion following a major disaster, the government of Ghana, via the Ministry of Land and Natural Resources identified the culprit liable under the Mining Regulation (LI 2177) and imposed hefty fines following a thorough investigation of the incident [17, 18]. Disasters of this nature affect all three dimensions of sustainable development, namely society, economy, and the environment, and simultaneously recording disaster-related losses and impacts on society and the economy [19]. Most significantly, the loss of human lives, bodily injuries, and long-term health issues such as respiratory diseases due to dust exposure are the casualties frequently associated with these mining-related disasters [20-23]. These impacts have been captured and monitored by leading global disaster loss databases, such as DesInventar, the Sendai Monitor, the international disaster database EM-DAT, or reinsurance databases like Sigma of SwissRe or NatCatService of MunichRe [19].

Additionally, the profound psychological impact on survivors and families of victims is often overlooked [24]. At the same time, the hefty financial, legal, and compensation costs imposed on organizations associated with the causes of these disasters are huge. They may be responsible for the uneventful folding of these firms [25]. Economically, accidents result in direct costs like medical expenses and compensation and indirect costs such as productivity losses and legal liabilities [26, 27]. The explosion at Appiatse near Bogoso was a tragic event that had significant implications for the catchment community and the mining industry.

To effectively respond to and mitigate the impacts of such disasters, detailed and timely post-hazard damage assessments are crucial. Earth Observation (EO) technologies, utilizing satellite imagery and remote sensing, have emerged as preferred methods for providing detailed and objective post-hazard damage assessments. EO helps integrate disaster preparedness strategies, enhancing capabilities in preparedness and response. As a result, it significantly reduces losses in lives, livelihoods, health, and the economic, physical, social, cultural, and environmental assets of individuals, businesses, and communities, while also decreasing vulnerability to future hazards [28-30].

By utilizing satellite imagery and other remote sensing technologies, authorities can quickly assess the extent of damage caused by natural or man-made disasters, such as explosions. This paper aims to analyze the causes of the blast, assess its impact on the environment and local population, and propose recommendations for preventing similar incidents in the future. By examining the factors that led to the explosion and its consequences, this study aims to provide valuable insights to improve safety measures in mining operations and in the handling, transportation, storage, and disposal of hazardous chemicals. These occurrences highlight the urgent need for increased safety measures and regulatory enforcement to prevent similar fatalities from occurring in the future.

Integrating EO data into disaster management practices allows authorities to improve their ability to respond effectively to emergencies, allocate resources efficiently, and mitigate the impact of disasters on communities and infrastructure. Analyzing satellite images before and after the incident allows for rapid identification of affected areas, estimation of the severity of damage, and prioritization of response efforts to government monitoring and cooperative inspections to improve mine safety, indicating a proactive approach to avoiding future disasters [31, 32]. Under this premise, this research focuses on the use of EO technologies in the assessment of post-hazard damage using the example of the Appiatse explosion as a case study. The aim is to highlight the effectiveness of EO technologies in disaster assessment and the potential improvements in response and recovery efforts.

Figure 1. *Images of Appiatse after the Explosion - 18 m wide crater which was the location where the truck conveying the explosives exploded. (A), Wattle and Duad plastered with cement sancrete buildings that were destroyed because of the blat (B), (C), (D) Ripped off the roof of building structures in the Appiatse community after the blasting incident of January 20, 2022, (E) and Excavator searching through the rubble during rescue operations and (F) Ripped and destroyed corrugated roofing sheets and household items following the incident.*

Figure 2. *Appiatse community on Google Street View before the incident (January 2020).*

2. Legal Framework Governing the Use of Explosives in the Mining Industry

The mining industry in Ghana is regulated by several laws, some of which specifically address the use of explosives. The primary legal framework includes the Minerals and Mining (Health, Safety, and Technical Regulations, 2012) LI 2182, and the Minerals and Mining (Explosives) Regulations, 2012 (LI 2177). These regulations govern the handling, transportation, storage, and disposal of hazardous chemicals such as cyanide and explosives. They are designed to protect the health and well-being of people, as well as biotic and abiotic factors in the environment, through effective monitoring and control.

2.1. Overview of Policy, Legal and Institutional Framework for the Transport, Storage and Use of Explosives in Ghana

The 1992 Constitution of Ghana offers an extensive policy foundation for the safeguard of the environment. The relevant sections are as follows:

1) Economic Development - Article 36 (9): The State shall take appropriate measures needed to protect and safeguard the national environment for posterity; and shall seek co-operation with other states and bodies for the purposes of protecting the wider international environment for mankind.
2) Economic Development - Article 36 (10): The State shall safeguard the health, safety and welfare of all persons in employment, and shall establish the basis for the full deployment of the creative potential of all Ghanaians.
3) Duties of a Citizen - Article 41 (k): The exercise and enjoyment of rights and freedoms is inseparable from the performance of duties and obligations, and accordingly, it shall be the duty of every citizen to protect and safeguard the environment. The Policy Statement on the Environment requires the State to "take appropriate measures, irrespective of the existing levels of environmental pollution and extent of degradation, to control pollution and the importation and use of potentially toxic chemicals". This expectation from the State requires a more comprehensive policy on toxic substances for the country.

The aim of Ghana's environmental policy is to improve the surroundings, living conditions and the quality of life of the entire citizenry, both present and future. The policy specifically seeks to:

1) Maintain the ecosystems and ecological processes essential for the functioning of the biosphere;
2) Ensure sound management of natural resources and the environment; adequately protect humans, animals and plants, their biological communities and habitats against harmful impacts and destructive practices, and preserve biological diversity;
3) Guide development by quality requirements to prevent, reduce, and as far as possible, eliminate pollution and nuisances;
4) Integrate environmental considerations in sectoral, structural and socio-economic planning at the national, regional, district and grass root levels;
5) Seek common solutions to environmental problems in

West Africa, Africa and the world at large.

2.2. The Explosives Act 350 of 1970 and the Minerals and Mining Act (703) of 2006

The Explosives Act, 1970 (Act 350) is the primary legislation regulating the use of explosives in Ghana. The Act outlines the procedures for the acquisition, possession, and use of explosives, including those used in the mining industry. The objectives of the Act include ensuring the safe use of explosives, preventing unauthorized access, and protecting the public from potential dangers. Similarly, the Minerals and Mining (Explosives) Regulations, 2012 (LI 2177), serves as the primary regulation governing the transportation, storage, and usage of explosives in the mining industry in Ghana. This regulation outlines various provisions, including regulatory oversight, explosives operating plans, risk and security assessments, emergency response plans, and sanctions for non-compliance. However, the Appiatse explosion exposed weaknesses and lapses in the safety controls of the mining sector, necessitating immediate measures to address these issues. The Minerals Commission is the regulatory body responsible for implementing this regulation. Table 1 presents the key applications of the 2012 Minerals and Mining law regarding the transport, storage, and usage of explosives across numerous mining sites in Ghana.

Table 1. *Key Applications of the 2012 Minerals and Mining Law (LI 2177) for the Transport, Storage, and Usage of Explosives in Ghanaian Mining Site.*

Key Aspect	Regulation
Application:	The regulations apply to the conveyance, storage, possession, manufacture, and use of explosives for mining, quarrying, and civil works, including substances used for the manufacture of explosives
Regulatory Oversight:	The Chief Inspector of Mines acts as the chief inspector of explosives, and inspectors of mines serve as inspectors of explosives for administering and enforcing these regulations.
Explosives Operating Plans:	An explosives manager must submit operating plans for storage, transport, manufacture, use, dealership, and blasting firm operations to the Chief Inspector of Explosives for approval. Any variations must be approved before implementation.
Risk and Security Assessments:	An explosives manager must conduct a risk assessment of the entire explosive operation, develop a security plan, and appoint a competent person to oversee security.
Emergency Response Plans:	An emergency response plan must be drawn for the transportation of explosives and activated during emergencies.
Notification and Approval for Transport:	Entities must notify the Chief Inspector 48 hours before transporting explosives, detailing the type and quantity.
Vehicle Requirements:	Vehicles transporting explosives must be approved and exhibit specific safety features, such as earthing chains, red flags with the letter "E," and danger signs.
Police Escort:	Explosives transport must be escorted by police, maintaining a convoy distance of at least 50 m between vehicles.
Accident Procedures:	In case of an accident, the transporter must implement the approved emergency plan and secure the accident scene.
Sanctions for Non-Compliance:	Penalties include fines and imprisonment for failing to submit required plans, not adhering to regulations, and other breaches.

3. Materials and Methods

3.1. Study Area

Appiatse is a small community near the city of Bogoso, located in the Prestea Huni Valley District of the Western Region in Ghana. It is located approximately on 5°34'54" N latitude and 2°00'30" W longitude. Appiatse experiences a tropical climate with distinct wet and dry seasons. It has an average daily temperature ranging from 24℃ to 30℃. The wet season, which spans from April to October. The dry season, from November to March, is characterized by lower humidity and less precipitation. The economy of Appiatse is predominantly driven by mining, agriculture, and small-scale trading. Mining operations, both large-scale and artisanal, are significant sources of employment and revenue for the community. Due to extensive mining activities in the Prestea Huni Valley District and neighboring districts, the use of heavy-duty trucks to transport mine waste and hazardous chemicals is prevalent.

3.2. Dataset

The EO data used for the damage assessment comprised pre-event and post-event information. The data included Sentinel-1 SAR and Sentinel-2 optical images, which provided detailed radar-based information about the surface structure and high-resolution multi-spectral information about the land cover, respectively, before and after the event.

High-resolution UAV images provided precise, localized information on damage to infrastructure and the environment. A Digital Elevation Model (DEM) was generated from the UAV images, offering a 3D representation of the terrain to understand topographical changes and quantify morphological alterations such as crater depths. Another source of DEM used in this research was derived from Shuttle Radar Topography Mission (SRTM) data.

Table 2 shows the specifications of the EO data used, including the date of acquisition, spatial resolution, and data type.

Table 2. Details of EO Dataset.

Time	Date	EO Data	Type	Spatial Resolution
Pre-event	22/12 2021	Sentinel-2	Optical	10 m
Post-event	11/01/2022	Sentinel-1	SAR	20 m
	21/01/2022	Sentinel-2	Optical	10 m
	21 01/2022	UAV	Optical	3 cm
	23/01/2022	Sentinel-1	SAR	20 m
	23/01/2022	Capella	SAR	35 cm
Other		SRTM	DEM	30 m

3.3. Automatic Detection of Terrain Changes from the Explosion

Due to terrain changes caused by the explosion, an early warning alert was made available through the Enhanced Pollution Monitoring (EPM) customised remote sensing-based service developed by Sarmap for environmental monitoring [33]. This customised service was first piloted in Ghana in 2017 to monitor artisanal and small-scale mining activities. Figure 3 shows the workflow of the customised service. Data collection and analysis for change detection in the EPM remote sensing-based service are fully automated.

A typical change detection within this service is often done using coherence time series analysis. The procedure for change detection involves three broad steps: data acquisition, pre-processing of SAR data, and detecting terrain changes. Data acquisition is done on a continuous basis, where a series of SAR images (e.g., Sentinel-1) over the area of interest are collected. This provides the necessary temporal coverage to monitor changes over time.

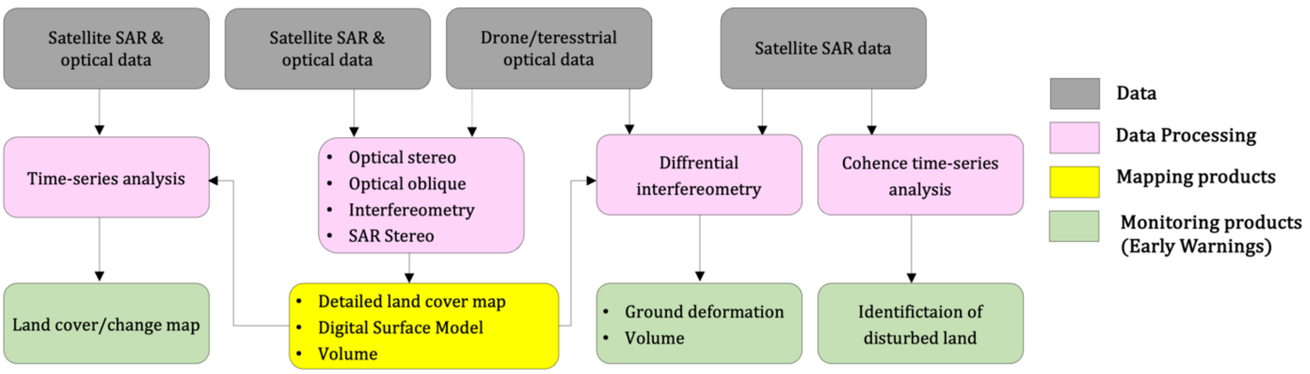

Figure 3. Workflow of the Enhanced Pollution Monitoring Remote Sensing-Based Service (modified after EPM [33]).

During the pre-processing of SAR data, radiometric calibration is applied to ensure that the SAR data is corrected for sensor-specific biases, standardizing the pixel values for accurate comparison across images. This is followed by geometric correction (geocoding) to convert the SAR images into a map coordinate system by applying a range-Doppler approach [34]. Detecting terrain changes involves several steps: co-registration, interferogram generation, coherence calculation, and change detection analysis. Co-registration ensures that sequential images are precisely aligned in the time series to a sub-pixel level, ensuring that each pixel corresponds to the same ground location across the sequence of images. An interferogram is generated by computing the phase difference between pairs of SAR images acquired at different times to detect changes in the terrain. This involves estimating the relative shifts between a reference and a slave image and interpolating the slave image to account for the estimated shifts. Coherence calculation is then performed to measure the similarity between image pairs. This helps in identifying changes and maintaining consistent monitoring over time. The coherence values range between 0 and 1, with 1 indicating high coherence (no change) and 0 indicating low coherence (significant change). These values indicate the quality of the phase correlation between two sequential SAR images and serve as a measure of change in the terrain. This is followed by coherence time series analysis, where temporal changes in coherence for each pixel are analyzed. This step is necessary to detect trends and areas where coherence has significantly decreased or changed, indicating potential terrain changes or disturbances. Change detection is then carried out to identify areas with significant coherence changes over time. This is necessary to understand specific events or shifts within the monitored area. When significant changes are detected, an alert is triggered.

3.4. Processing Orthophotos of Post-Event from UAV Data

The UAV images were processed using photogrammetric techniques based on Structure from Motion (SfM) and the Dense Multi-view Stereo (MVS) pipeline [35, 36]. Figure 4 shows the workflow for the SfM and MVS pipelines. Following the acquisition of overlapping images (80% forward overlap and 70% sidelap) from a UAV, the SfM pipeline was used for automated image orientation and generation of a sparse 3D point cloud of the scene. This procedure involves feature extraction, feature matching, and outlier detection. During feature extraction, a feature-matching algorithm utilising Scale Invariant Feature Transform (SIFT) was employed to extract salient features from image pairs, which were subsequently matched [37, 38].

The Random Sample Consensus (RANSAC) algorithm was then used to remove outliers from the dataset [39]. Simultaneous resection and intersection were used to estimate both the 3D coordinates of object points and the camera positions. Bundle adjustment optimises the 3D structure and camera parameters to achieve the best fit for all observations. During the MVS pipeline, additional conjugate points are extracted based on the sparse 3D point cloud of the scene. Depth information for each point is calculated, resulting in a dense point cloud that provides a more accurate and detailed representation of natural and man-made features.

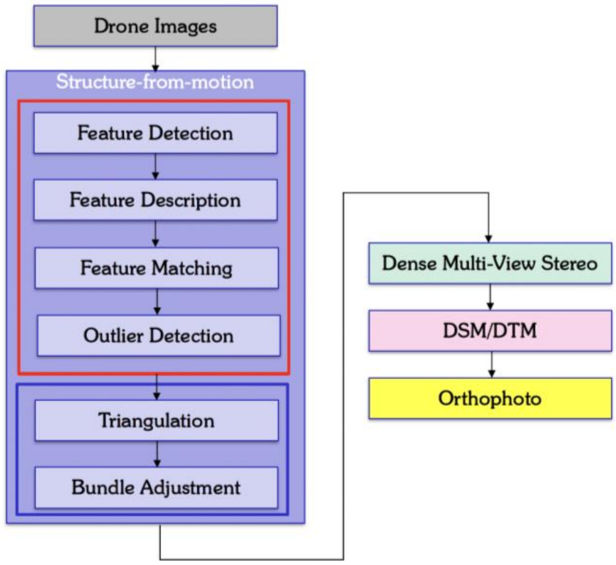

Figure 4. *Processing of UAV based on Structure from Motion and Dense Multi-view Stereo pipelines.*

3.5. Processing Damage Assessment Maps from SAR Data

Based on the alert following the Appiatse explosion, this research conducted a damage assessment using intensity changes derived from Sentinel-1 images collected before and after the event. The sentinel-1 images were first pre-processed and co-registered. Intensity images were extracted and calibrated from the Sentinel-1 data for both the pre-event (Ipre) image and post-event (Ipost) periods. The methodology involved computing the difference in intensity values (ΔI= Ipre - Ipost) to identify areas with significant changes, employing appropriate thresholding techniques. These intensity changes were then classified into different damage levels. The extent and severity of the damage caused by the explosion were visualized using maps and overlays, facilitating interpretation of the impact. Terrain data from Capella images were also integrated to enhance the visualization of the damage extent and severity depiction. Orthophoto and Google Maps images were used for visual inspection and post-event validation. Figure 5 illustrates the workflow for post-hazard damage assessment.

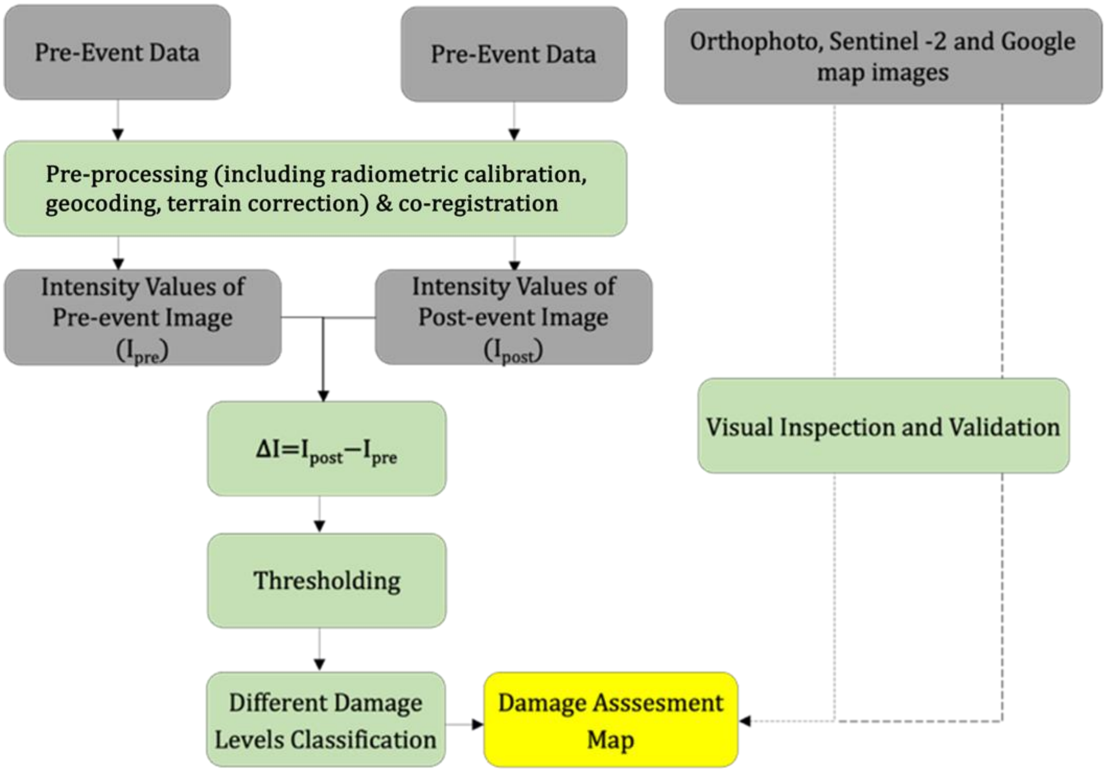

Figure 5. *Workflow for post- hazard damage assessment.*

4. Results and Discussions

Following the alert from the EPM remote sensing service, a visual inspection was conducted to assess the extent of the damage caused by the explosion, including the affected buildings and infrastructure. Figure 6a shows a 10 m Sentinel-2 optical image of Appiatse before the event, with the area of interest (AOI) highlighted in yellow. Figure 6b depicts the same AOI highlighted in yellow after the event, clearly revealing the impact of the explosion, especially on the road networks.

Figure 7a presents a 20 m spatial resolution Sentinel-1 SAR image of Appiatse, with the AOI highlighted in yellow before the event. Figure 7b also shows the AOI after the event, similarly, highlighted in yellow. The explosion's impact is evident within the AOI, particularly noticeable from changes in the grayscale levels of various feature types.

To evaluate the extent of the disaster caused by the explosion, various tools were utilized, including an orthophoto, a 3D model, a Digital Surface Model (DSM), and a damage assessment map. These tools collectively provide detailed insights into the impact of the explosion on the affected area.

Figure 8a and 8b show the DSM and orthophoto superimposed on Sentinel-2 images. Figure 9 illustrates a realistic 3D model of the Appiatse Community, highlighting the crater and the widespread destruction caused by the blast. Numerous buildings were destroyed, particularly concentrated around the explosion's epicentre where a large crater was observed, demonstrating the scale of the blast. Precise measurements indicated a crater diameter of 18 m, providing critical data to understand the explosion's impact on the local terrain. These models also help to identify variations in elevation and structural deformations across the affected area. The damage assessment map, derived from Sentinel-1 SAR images (illustrated in Figure 5), is depicted in Figure 10. This map categorises the extent of destruction into four level: *fully destroyed, destroyed and largely collapsed, strongly damaged lightly damaged*. Such classification is pivotal for prioritising emergency response efforts, enabling targeted interventions based on the severity of damage observed. Areas with destroyed buildings, partially damaged structures, and those unaffected can be clearly delineated to facilitate the efficient allocation of resources for recovery and reconstruction efforts.

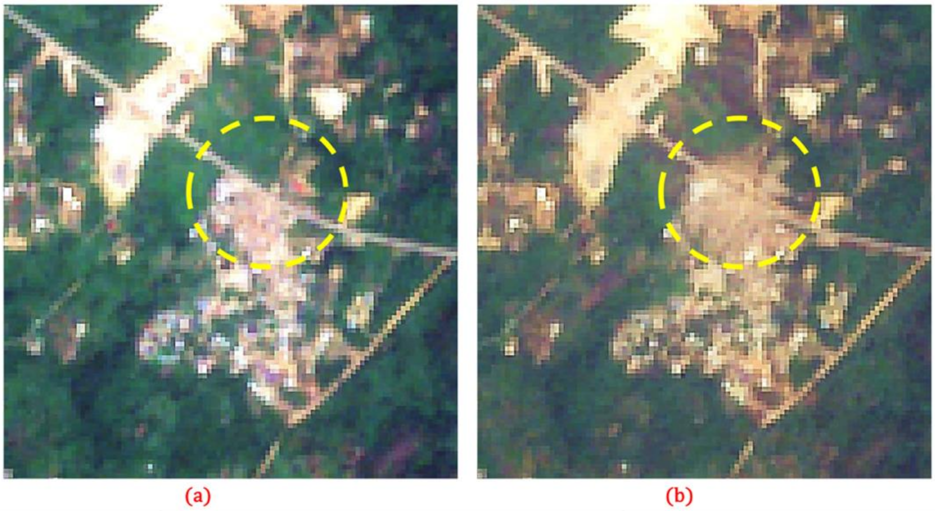

Figure 6. *Sentinel-2 optical images of Appiatse at 10 m spatial resolution. (a) The area of interest (AOI) is highlighted in yellow before the event. (b) The AOI after the event.*

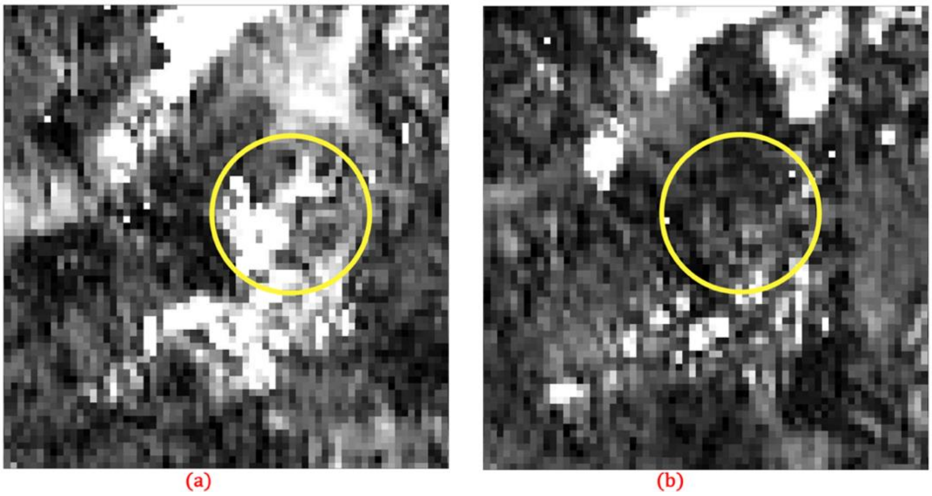

Figure 7. *Sentinel-1 SAR images of Appiatse at 20 m spatial resolution. (a) The area of interest (AOI) is highlighted in yellow before the event. (b) The AOI after the event.*

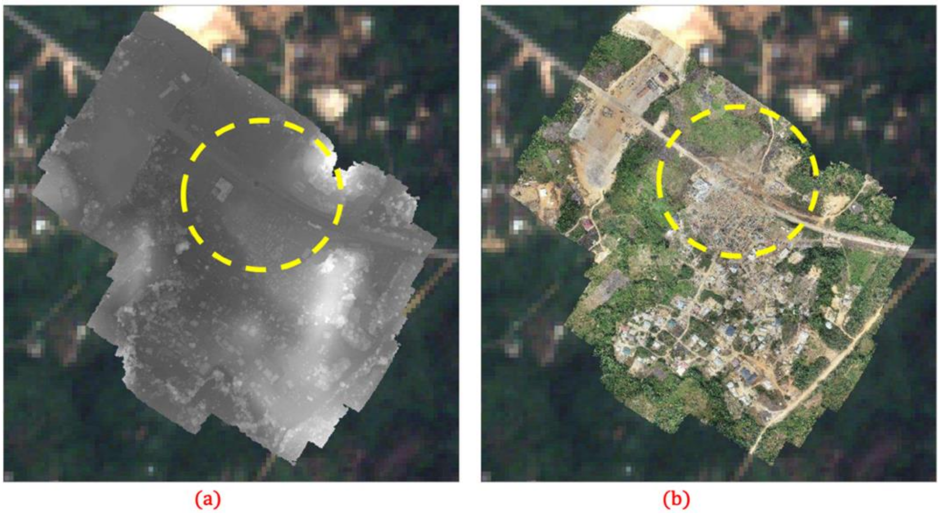

Figure 8. *DSM (a) and Orthophoto overlaid on Sentinel 2 images.*

Figure 9. *3D model of Appiatse Community showing the crater and the entire destruction caused by the blast incident.*

5. Environmental and Safety Implications of the Explosion Incident

Ghana's Environmental Protection Law (Act 490) together with Minerals and Mining Law (Act 703) imposes a duty of care and responsibility on a mining company to protect its surroundings and catchment communities against ground vibration resulting from their mining operations. Additionally, the impact of these ground vibrations generated from blasting activities on people and buildings within the 500 m radius from the point of blast needs to be evaluated to ensure safety and structural stability. However, effective protection is possible only if the actual level of the blasting impact is known because it is recorded and the data submitted to the Minerals Commission for compliance monitoring because when blasting vibration exceeds the safe allowable value, it can cause engineering disasters such as landslides, structural deformation, fracture and even collapse of buildings (structures), structural instability of underground works, and foundation sinking [40-42].

Unfortunately, the deadly incident at Appiatse, Ghana, which occurred because of the explosion of a 40 ft container truck conveying (10000 kg) of explosives, (Ammonium Nitrate Fuel Oil) had significant environmental effects on the surrounding area. The Ghana Minerals and Mining (Explosives) Regulations, 2012 were breached by the incident that occurred on January 20, 2022.

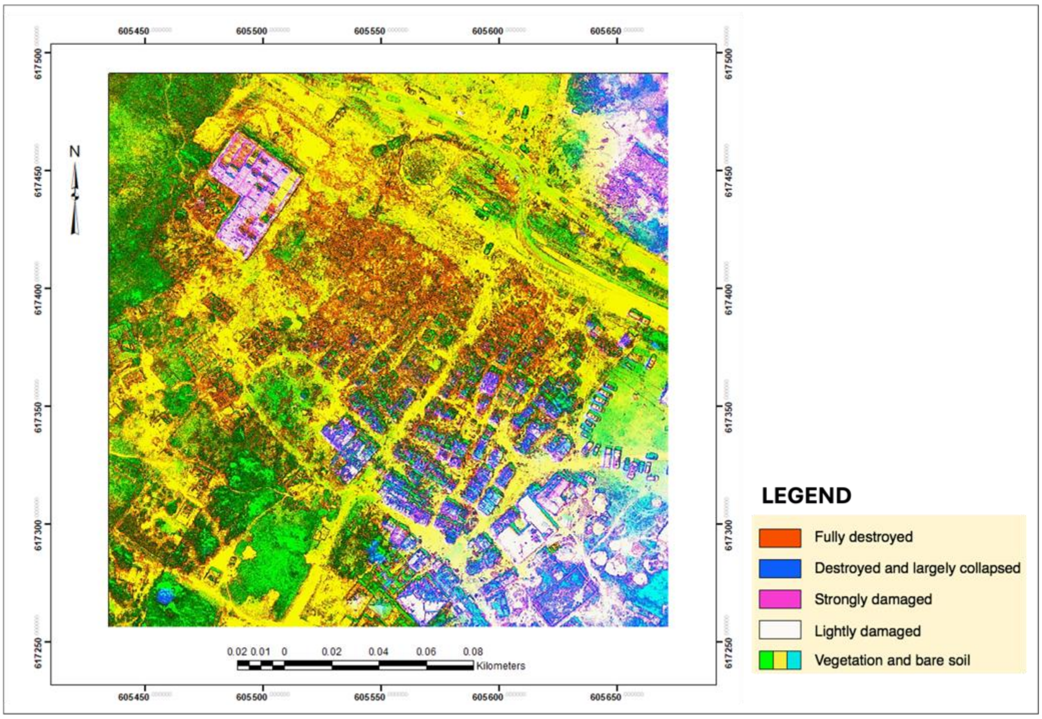

Figure 10. *Damage analysis map generated for the Appiatse ammonium nitrate explosion incident.*

Blasting events induces detrimental effects on the environment, such as flyrock, dust, fumes, and air overpressure and noise while ground vibrations and airblast beyond the blast site are strongly dependent on charge weight per delay, confinement, and distance [40, 42-44]. The Appiatse explosion resulted in the release of toxic chemicals and pollutants into the environment and left the whole community littered with debris generated by the blast event. These environmental effects can have long-lasting consequences on the ecosystem, wildlife, and human health in the catchment area of the blast.

The explosion released a significant number of toxic substances into the air, soil, and surrounding water bodies, posing a serious threat to the local ecosystem and the health of the residents [45]. The Appiatse explosion likely dispersed a variety of heavy metals and other hazardous materials throughout the area, which could have devastating consequences for local agricultural productivity because Heavy metals/metalloids cannot be easily degraded and are continuously being deposited into soil, water, and sediment, causing pollution [46-48]. The resulting impact of this development on agriculture cannot be overstated as soil contamination from spilled chemicals or debris could affect agricultural lands in the area, potentially impacting crop yields and food security for local communities where this deadly explosion occurred. The destruction caused by the explosion resulted in habitat loss for local flora and fauna. The blast site itself was likely stripped of vegetation and disrupted ecosystems, displacing wildlife populations and altering natural habitats. The long-term recovery of these ecosystems may be challenging and require extensive restoration efforts to mitigate the environmental impact of the disaster.

Apart from soil pollution, the deadly explosion in Appiatse resulted in a significant release of particulate matter and harmful gases into the atmosphere. This is because the blast involved the burning of various materials, including plastics, fuel, and construction materials, all of which emit harmful substances when burned [49, 50]. Gases created by detonating explosives and blasting agents which may contain reaction products that pose a health or environment hazard [51-53]. Small amounts of toxic reaction products will, however, be formed because of deviations from oxygen balance, incomplete reaction, or secondary reactions with the atmospheric air [51, 54, 55].

Due to incomplete reaction of the explosive and subsequent reactions with the surrounding air, other reaction products will always be present, and some of these are toxic if the concentration becomes high enough. The primary toxic fumes produced are carbon monoxide (CO), nitrous oxide (NO), and nitric oxide (NO2). The total content of the latter two is often jointly called the NOx content. The dispersion of particulate matter (PM), a mixture of solid particles and liquid droplets found in the air was the immediate result of the explosion. These particles which come in different sizes, and those smaller than 10 micrometers (PM10) and 2.5 micrometers (PM2.5) are particularly harmful as they can penetrate deep into the lungs and cause serious health problems [56-60].

The explosion would have released a significant amount of PM10 and PM2.5 into the air, leading to a deterioration in air quality. Additionally, the burning of materials would have released harmful gases such as nitrogen oxides (NOx), sulfur dioxide (SO_2), and volatile organic compounds (VOCs) into the atmosphere. These gases can react with other substances in the air to form harmful pollutants, such as ozone and particulate matter, further exacerbating air quality issues [61, 62]. The resultant effect of the release of these diverse air pollutants into Appiatse community and its immediate environment has the potential causing a wide range of health problems for the inhabitants who inhaled the noxious gases that emanated from the blast. For example, exposure to particulate matter can lead to respiratory problems such as asthma, bronchitis, and emphysema. Additionally, exposure to harmful gases such as NOx, SO_2, and VOCs can lead to a range of health problems, including respiratory issues, headaches, dizziness, and nausea [58, 63, 64]. Furthermore, exposure to heavy metals and other hazardous substances via breathing can lead to a range of health problems, including neurological damage, kidney damage, and cancer [58, 63, 64]. The pollution risks associated with this devastating explosion at Appiatse can lead to a high prevalence of skin diseases, numbness in the palms, and respiratory problems among the affected population.

The explosion at Appiatse could also have significant effects on water quality in the surrounding area. This is because the blast would have likely resulted in the release of hazardous substances into the environment, which could eventually make their way into water bodies. Blasting adversely affects groundwater when soluble substances from detonators and explosives that are not fully combusted permeate groundwater [65]. It may cause short-term turbidity and long-term changes to incumbent wells due to the expansion of fractures from loss of lateral confinement [66, 67]. There are cases reported in the literature on groundwater contamination, including elevated nitrate levels and turbidity [66]. These metals are particularly harmful to aquatic life and can accumulate in the food chain, leading to serious health effects for both animals and humans [68-70]. Additionally, the blast could have resulted in the release of petroleum products and other hazardous substances into the environment. These substances can contaminate water bodies, making them unsafe for both human consumption and aquatic life [68-70].

The explosion which was caused by the ignition of a mixture of ANFO. The detonation of this the huge volumes of explosive (10000kg) conveyed by the truck mixture produced a shock wave with a higher frequency and intensity that radiated outwards from the source, causing the structural damage observed (Figure 1). When an explosive detonates, it releases an enormous amount of energy in the form of gases, pressure, heat, and stress waves [71], causing the surrounding rock mass to develop cracks and get displaced. About 20–30% of the explosive energy released is utilized to fragment and throw the material [11], while the remaining 70–80% generates undesirable outcomes [72]. The undesirable outcomes include airblast/air overpressure, ground vibration, flyrock, noise, heat, fumes/dust, and backbreak. It should be noted that heat, which is a part of the undesirable outcomes, does not necessarily produce adverse effects; it is the portion of the released energy that is not fully utilized in breaking the rock mass [65]. The damage level depends on factors such as type, condition and age of the structure, foundation, frequency of the vibrations, etc. The problem becomes even more with structures like religious monuments, schools, hospitals and other socially important buildings and historically important buildings that are older in age and not stable.

Ground vibrations originating from a blasting event enter a structure at the foundation or ground level and air blast through the roof or building sides. As a result, the part of the house above ground shakes or otherwise responds [73, 74]. In the present case, the blast event caused significant ground vibration which was clearly felt in all the surrounding communities including Bogoso and Wassa Akropong in the Western Region of Ghana. An observation that was corroborated by all witnesses we interviewed on the incident scene and the catchment area. Air blast is an undesirable and unavoidable output of blasting that propagates as a compression wave in air [71, 74, 75]. Air blast damage and annoyance may be influenced by factors such as blast design, weather, field characteristics, and human response [43, 76, 77]. The explosion resulted in the destruction of approximately 500-600 buildings, including residential and commercial structures in Appiatse (Figure 1B, C, D, E, and F). This accounts for almost all the buildings in the community, leaving all the inhabitants of the community displaced after the incident. The blast wave from the explosion caused various types of damage to structures. An examination of the incident scene revealed that the broken and shattered glasses, destruction to primary structures, unstable partitions and beams, damaged/collapsed ceilings, debris underfoot, and shreds of glass embedded in human beings who were unable to escape the blast (Figure 1 B, C, D, and F).

The impact of blasting vibration depends not only on the size and strength of the vibrating load, but also on the structure and foundation form of the building (structure) itself. This observation was since majority of the damaged houses were wattle and daud which were plastered with sandcrete. The makeup and architecture of these buildings which lacked both a concrete foundation and aprons rendered them susceptible to collapse due to the lack or weak foundation on which these structures were built. Furthermore, the risks of electrocution were heightened following the exposure to live electricity service lines which were not disconnected. The overpressure generated by the explosion caused windows to shatter and doors to be blown off their hinges while flying debris resulting from the explosion propelled debris at high velocities, causing damage to nearby structures. The collapse of buildings resulted in the entrapment of individuals [78].

6. Conclusions

Transporting dangerous products by road or rail is one of the potential sources of accidents. In the present study, a truck carrying ANFO smashed into a motorcycle, caught fire, and accelerated the self-sustaining degradation of the hydrocarbon-fuel AN mixture until it exploded at Appiatse. The Appiatse explosion in Ghana underscored the devastating impact of mining-related accidents on communities and the environment. The extensive damage to buildings and infrastructure demonstrates the urgent need for stricter safety measures in the transport of explosives.

The use of orthophoto, 3D models, DSMs, and damage map in the post-hazard damage assessment of Appiatse highlights the vital role of EO data in disaster response and management. Orthophotos provide a clear visual representation of the extent of damage, offering immediate insight into the affected areas, while 3D models and DSM offer detailed quantitative data, enabling a thorough evaluation of the explosion's impact severity by measuring parameters such as crater depth and building damage. Additionally, damage maps categorize the extent of destruction, prioritizing emergency response efforts and guiding targeted interventions. These integrated tools, if incorporated into future post-damage protocols, would play a crucial role in supporting humanitarian and governmental efforts, particularly evident in the immediate aftermath of the incident in Appiatse. By incorporating post-hazard damage assessment with disaster preparedness efforts, organizations like NADMO can develop and implement effective measures to reduce disaster risk and enhance community resilience.

The paper explores the policy, legal, and institutional framework governing the transport, storage, and use of explosives in Ghana, emphasizing the environmental and safety implications highlighted by the Appiatse explosion incident. While these events are catastrophic, they are common and preventable. The failure to prevent them is often because security officials focus on the specifics of each disaster rather than considering the similarities between them. Furthermore, to mitigate and improve hazardous materials transportation risks and impacts on communities near transportation routes, it is essential to estimate potential impact areas, considering risk factors related to cargo size, road conditions, and time of day. These factors can provide additional criteria to ensure compliance with established policies and laws.

Further research on such explosions should explore and implement advanced predictive modeling techniques to assess the risks associated with transporting hazardous materials within mining communities. It should focus on machine learning algorithms and big data analytics to predict potential accidents based on various risk factors.

Abbreviations

ANFO	Ammonium Nitrate Mixed Fuel Oil
CO	Carbon Monoxide
DEM	Digital Elevation Model
DSM	Digital Surface Model
EM-DAT	Emergency Events Database
EO	Earth Observation
EPM	Enhanced Pollution Management
LI	Legislative Instruments
MVS	Multi-view Stereo
NADMO	National Disaster Management Organization
NO	Nitrous Oxide
NO_2	Nitric Oxide
PM	Particulate Matter
RANSAC	Random Sample Consensus
SAR	Synthetic Aperture Radar
SfM	Structure from Motion
SIFT	Scale Invariant Feature Transform
SO_2	Sulfur Dioxide
SRTM	Shuttle Radar Topography Mission
UAV	Unmanned Aerial Vehicle
VOCs	Volatile Organic Compounds

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Author Contributions

Naa Dedei Tagoe: Conceptualization, Data curation, Methodology, Investigation, Software, Validation, Visualization, Resources, Writing – original draft, Writing – review & editing

Ebenezer Ashun: Formal Analysis, Methodology, Data curation, Investigation, Validation, Resources, Writing – original draft, Writing – review & editing

Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Otto, J., Andrews, C., Cawood, F., Doggett, M., Guj, P., Stermole, F., Stermole, J. and Tilton, J., Mining Royalties: A Global Study of Their Impact on Investors, Government, and Civil Society. (2006) World Bank Publications. https://doi.org/10.1596/978-0-8213-6302-1

[2] F. Calvão, C. Ankenbrand, M. A. F. Ros-Tonen, M. D. Beevers, Extractive industries and human security: An overview, Extr Ind Soc 8 (2021) 101007. https://doi.org/10.1016/J.EXIS.2021.101007

[3] T. Joe-Asare, E. Stemn, N. Amegbey, Causal and contributing factors of accidents in the Ghanaian mining industry, Saf Sci 159 (2023) 106036. https://doi.org/10.1016/J.SSCI.2022.106036

[4] S. Noraishah Ismail, A. Ramli, H. Abdul Aziz, Research trends in mining accidents study: A systematic literature review, Saf Sci 143 (2021). https://doi.org/10.1016/J.SSCI.2021.105438

[5] A. Zhu, Q. Wang, H. Liu, H. Zhu, Y. Lei, Correlational analysis of occupational accidents and the safety policies in the Chinese coal mining industry from 2008 to 2021, Scientific Reports 2024 14:1 14 (2024) 1–13. https://doi.org/10.1038/s41598-024-54241-3

[6] D. P. Edwards, W. F. Laurance, Preventing tropical mining disasters, Science (1979) 350 (2015) 1482. https://doi.org/10.1126/SCIENCE.350.6267.1482-C/ASSET/52CD9D11-0BEA-40C2-A515-597B4B027D5E/ASSETS/SCIENCE.350.6267.1482-C.FP.PNG

[7] L. C. Garcia, D. B. Ribeiro, F. De Oliveira Roque, J. M. Ochoa-Quintero, W. F. Laurance, Brazil's worst mining disaster: Corporations must be compelled to pay the actual environmental costs: Corporations, Ecological Applications 27 (2017) 5–9. https://doi.org/10.1002/EAP.1461/EPDF

[8] M. M. Ajith, A. K. Ghosh, J. Jansz, Risk Factors for the Number of Sustained Injuries in Artisanal and Small-Scale Mining Operation, Saf Health Work 11 (2020) 50–60. https://doi.org/10.1016/J.SHAW.2020.01.001

[9] L. S. Friedman, K. S. Almberg, R. A. Cohen, Injuries associated with long working hours among employees in the US mining industry: risk factors and adverse outcomes, Occup Environ Med 76 (2019) 389–395. https://doi.org/10.1136/OEMED-2018-105558

[10] D. Komljenovic, G. Loiselle, M. Kumral, Organization: A new focus on mine safety improvement in a complex operational and business environment, Int J Min Sci Technol 27 (2017) 617–625. https://doi.org/10.1016/J.IJMST.2017.05.006

[11] E. J. Tetzlaff, K. A. Goggins, A. L. Pegoraro, S. C. Dorman, V. Pakalnis, T. R. Eger, Safety Culture: A Retrospective Analysis of Occupational Health and Safety Mining Reports, Saf Health Work 12 (2021) 201–208. https://doi.org/10.1016/J.SHAW.2020.12.001

[12] F. Arthur, W. Agyemang-Duah, R. M. Gyasi, J. Y. Yeboah, E. Otieku, Nexus between Artisanal and Small-Scale Gold Mining and Livelihood in Prestea Mining Region, Ghana, Geography Journal 2016 (2016) 1605427. https://doi.org/10.1155/2016/1605427

[13] F. Calvão, C. E. A. Mcdonald, M. Bolay, Cobalt mining and the corporate outsourcing of responsibility in the Democratic Republic of Congo, Extr Ind Soc 8 (2021) 100884. https://doi.org/10.1016/J.EXIS.2021.02.004

[14] E. K. Nakua, E. Owusu-Dabo, S. Newton, K. Adofo, E. Otupiri, P. Donkor, C. Mock, Occupational injury burden among gold miners in Ghana, Int J Inj Contr Saf Promot 26 (2019) 329–335. https://doi.org/10.1080/17457300.2018.1515232

[15] M. A. F. Ros-Tonen, J. J. Aggrey, D. P. Somuah, M. Derkyi, Human insecurities in gold mining: A systematic review of evidence from Ghana, Extr Ind Soc 8 (2021) 100951. https://doi.org/10.1016/J.EXIS.2021.100951

[16] T. Schrecker, A. E. Birn, M. Aguilera, How extractive industries affect health: Political economy underpinnings and pathways, Health Place 52 (2018) 135–147. https://doi.org/10.1016/J.HEALTHPLACE.2018.05.005

[17] D. Rosner, G. Markowitz, A Short History of Occupational Safety and Health in the United States, Am J Public Health 110 (2020) 622. https://doi.org/10.2105/AJPH.2020.305581

[18] G. Sorensen, J. T. Dennerlein, S. E. Peters, E. L. Sabbath, E. L. Kelly, G. R. Wagner, The future of research on work, safety, health and wellbeing: A guiding conceptual framework, Soc Sci Med 269 (2021) 113593. https://doi.org/10.1016/J.SOCSCIMED.2020.113593

[19] Y. Walz, S. Janzen, L. Narvaez, A. Ortiz-Vargas, J. Woelki, N. Doswald, Z. Sebesvari, Disaster-related losses of ecosystems and their services. Why and how do losses matter for disaster risk reduction?, International Journal of Disaster Risk Reduction 63 (2021) 102425. https://doi.org/10.1016/J.IJDRR.2021.102425

[20] J. A. Entwistle, A. S. Hursthouse, P. A. Marinho Reis, A. G. Stewart, Metalliferous Mine Dust: Human Health Impacts and the Potential Determinants of Disease in Mining Communities, Curr Pollut Rep 5 (2019) 67–83. https://doi.org/10.1007/S40726-019-00108-5/TABLES/2

[21] S. Mavroulis, M. Mavrouli, E. Lekkas, A. Tsakris, Managing Earthquake Debris: Environmental Issues, Health Impacts, and Risk Reduction Measures, Environments 2023, Vol. 10, Page 192 10 (2023) 192. https://doi.org/10.3390/ENVIRONMENTS10110192

[22] J. Tian, Y. Wang, S. Gao, Analysis of Mining-Related Injuries in Chinese Coal Mines and Related Risk Factors: A Statistical Research Study Based on a Meta-Analysis, International Journal of Environmental Research and Public Health 2022, Vol. 19, Page 16249 19 (2022) 16249. https://doi.org/10.3390/IJERPH192316249

[23] L. Yang, G. E. Birhane, J. Zhu, J. Geng, Mining Employees Safety and the Application of Information Technology in Coal Mining: Review, Front Public Health 9 (2021) 709987. https://doi.org/10.3389/FPUBH.2021.709987/BIBTEX

[24] I. of M. (US) C. on R. to the P. C. of Terrorism, A. S. Butler, A. M. Panzer, L. R. Goldfrank, Understanding the Psychological Consequences of Traumatic Events, Disasters, and Terrorism, (2003). https://www.ncbi.nlm.nih.gov/books/NBK221638/ (accessed June 26, 2024).

[25] S. D. Sugarman, Roles of Government in Compensating Disaster Victims, (n.d.).

[26] M. Battaglia, M. Frey, E. Passetti, Accidents at Work and Costs Analysis: A Field Study in a Large Italian Company, Ind Health 52 (2014) 354. https://doi.org/10.2486/INDHEALTH.2013-0168

[27] E. Tompa, A. Mofidi, S. van den Heuvel, T. van Bree, F. Michaelsen, Y. Jung, L. Porsch, M. van Emmerik, Economic burden of work injuries and diseases: a framework and application in five European Union countries, BMC Public Health 21 (2021). https://doi.org/10.1186/S12889-020-10050-7

[28] K. E. Joyce, K. C. Wright, S. V. Samsonov, V. G. Ambrosia, K. E. Joyce, K. C. Wright, S. V. Samsonov, V. G. Ambrosia, Remote sensing and the disaster management cycle, Advances in Geoscience and Remote Sensing (2009). https://doi.org/10.5772/8341

[29] G. Le Cozannet, M. Kervyn, S. Russo, C. Ifejika Speranza, P. Ferrier, M. Foumelis, T. Lopez, H. Modaressi, Space-Based Earth Observations for Disaster Risk Management, Surv Geophys 41 (2020) 1209–1235. https://doi.org/10.1007/S10712-020-09586-5/FIGURES/4

[30] S. Tilon, F. Nex, N. Kerle, G. Vosselman, Post-Disaster Building Damage Detection from Earth Observation Imagery Using Unsupervised and Transferable Anomaly Detecting Generative Adversarial Networks, Remote Sensing 2020, Vol. 12, Page 4193 12 (2020) 4193. https://doi.org/10.3390/RS12244193

[31] J. A. Bullock, G. D. Haddow, D. P. Coppola, Mitigation, Prevention, and Preparedness, Introduction to Homeland Security (2013) 435. https://doi.org/10.1016/B978-0-12-415802-3.00010-5

[32] S. M. H. S. Rezvani, M. J. Falcão, D. Komljenovic, N. M. de Almeida, A Systematic Literature Review on Urban Resilience Enabled with Asset and Disaster Risk Management Approaches and GIS-Based Decision Support Tools, Applied Sciences 2023, Vol. 13, Page 2223 13 (2023) 2223. https://doi.org/10.3390/APP13042223

[33] Enhanced Pollution Monitoring (EPM) - sarmap, (n.d.). https://www.sarmap.ch/index.php/enhanced-pollution-monitoring-epm/ (accessed June 28, 2024).

[34] C. Werner, T. Strozzi, U. Wegmüller, A. Wiesmann, SAR geocoding and multi-sensor image registration, International Geoscience and Remote Sensing Symposium (IGARSS) 2 (2002) 902–904. https://doi.org/10.1109/IGARSS.2002.1025723

[35] Y. Furukawa, C. Hernández, Multi-View Stereo, Foundations and Trends® in Computer Graphics and Vision 9 (2015) 1–148. https://doi.org/10.1561/0600000052

[36] A. Torresani, F. Remondino, VIDEOGRAMMETRY VS PHOTOGRAMMETRY for HERITAGE 3D RECONSTRUCTION, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives 42 (2019) 1157–1162. https://doi.org/10.5194/ISPRS-ARCHIVES-XLII-2-W15-1157-2019

[37] D. G. Lowe, Object recognition from local scale-invariant features, Proceedings of the IEEE International Conference on Computer Vision 2 (1999) 1150–1157. https://doi.org/10.1109/ICCV.1999.790410

[38] M. Brown, D. G. Lowe, Recognising panoramas, Proceedings of the IEEE International Conference on Computer Vision 2 (2003) 1218–1225. https://doi.org/10.1109/ICCV.2003.1238630

[39] R. C. Holies, M. A. Fischler, A RANSAC-BASED APPROACH TO MODEL FITTING AND ITS APPLICATION TO FINDING CYLINDERS IN RANGE DATA *, (n.d.).

[40] Z. Wang, Y. Jiang, X. Shao, C. Liu, On-site measurement and environmental impact of vibration caused by construction of double-shield TBM tunnel in urban subway, Sci Rep 13 (2023) 17689. https://doi.org/10.1038/S41598-023-45089-0

[41] K. Wu, Y. Zheng, S. Li, J. Sun, Y. Han, D. Hao, Vibration response law of existing buildings affected by subway tunnel boring machine excavation, Tunnelling and Underground Space Technology 120 (2022) 104318. https://doi.org/10.1016/J.TUST.2021.104318

[42] W. Yang, Z. Fang, J. Wang, D. Chen, Y. Zhang, X. Ba, Review on Vibration Monitoring and Its Application during Shield Tunnel Construction Period, Buildings 2024, Vol. 14, Page 1066 14 (2024) 1066. https://doi.org/10.3390/BUILDINGS14041066

[43] M. Aloui, Ground Vibrations and Air Blast Effects Induced by Blasting in Open Pit Mines: Case of Metlaoui Mining Basin, Southwestern Tunisia, J Geol Geophys 5 (2016) 247. https://doi.org/10.4172/2381-8719.1000247

[44] E. Kabwe, Y. Wang, E. Kabwe, Y. Wang, Airblast and Ground Vibration Monitoring at Chimiwungo Pit, Geomaterials 6 (2015) 28–38. https://doi.org/10.4236/GM.2016.61003

[45] B. O. Afum, A. F. B. Opoku, B. O. Afum, A. F. B. Opoku, Protecting Mining Environments from Blasting through Impact Prediction Studies, Journal of Geoscience and Environment Protection 6 (2018) 121–132. https://doi.org/10.4236/GEP.2018.65011

[46] O. Dagdag, T. W. Quadri, R. Haldhar, S. C. Kim, W. Daoudi, E. Berdimurodov, E. D. Akpan, E. E. Ebenso, An Overview of Heavy Metal Pollution and Control, ACS Symposium Series 1456 (2023) 3–24. https://doi.org/10.1021/BK-2023-1456.CH001/ASSET/IMAGES/LARGE/BK-2023-00191M_G007.JPEG

[47] A. Haghighizadeh, O. Rajabi, A. Nezarat, Z. Hajyani, M. Haghmohammadi, S. Hedayatikhah, S. D. Asl, A. Aghababai Beni, Comprehensive analysis of heavy metal soil contamination in mining Environments: Impacts, monitoring Techniques, and remediation strategies, Arabian Journal of Chemistry 17 (2024) 105777. https://doi.org/10.1016/J.ARABJC.2024.105777

[48] I. Sánchez-Castro, L. Molina, M. Á. Prieto-Fernández, A. Segura, Past, present and future trends in the remediation of heavy-metal contaminated soil - Remediation techniques applied in real soil-contamination events, Heliyon 9 (2023) e16692. https://doi.org/10.1016/J.HELIYON.2023.E16692

[49] M. Barbuta, R. D. Bucur, S. M. Cimpeanu, G. Paraschiv, D. Bucur, M. Barbuta, R. D. Bucur, S. M. Cimpeanu, G. Paraschiv, D. Bucur, Wastes in Building Materials Industry, Agroecology (2015). https://doi.org/10.5772/59933

[50] G. Pathak, M. Nichter, A. Hardon, E. Moyer, A. Latkar, J. Simbaya, D. Pakasi, E. Taqueban, J. Love, Plastic pollution and the open burning of plastic wastes, Global Environmental Change 80 (2023) 102648. https://doi.org/10.1016/J.GLOENVCHA.2023.102648

[51] S. Brochu, D. Valcartier, Assessment of ANFO on the environment Defence R&D Canada-Valcartier, (2010).

[52] R. J. Mainiero, J. H. R. Iii, M. L. Harris, M. J. Sapko, Behavior of Nitrogen Oxides in the Product Gases from Explosive Detonations, (n.d.).

[53] N. Wetp, Protecting Yourself While Responding to Chemical Incidents Safety and Health Awareness for Responders to Chemical Incidents, (2009). http://www.nti.org/e_research/e3_89.html (accessed June 26, 2024).

[54] Rock Blasting and Explosives Engineering - Per-Anders Persson, Roger Holmberg, Jaimin Lee - Google Books, (n.d.). https://books.google.com.gh/books?id=sdLO5HESJwgC&pg=PA387&lpg=PA387&dq=Gases+created+by+detonating+explosives+and+blasting+agents+which+may+contain+reaction+products+that+pose+a+health+or+environment+hazard&source=bl&ots=-WDC5VwTd8&sig=ACfU3U0KMr9Pqiavc880cbMbw3LcIyfeYw&hl=en&sa=X&ved=2ahUKEwiZzbLF3vmGAxVsQEEAHQJXBlo4HhDoAXoECAcQAw#v=onepage&q=Gases%20created%20by%20detonating%20explosives%20and%20blasting%20agents%20which%20may%20contain%20reaction%20products%20that%20pose%20a%20health%20or%20environment%20hazard&f=false (accessed June 26, 2024).

[55] N. R. C. (US) C. on H. E. of W. Incineration, Environmental Transport and Exposure Pathways of Substances Emitted from Incineration Facilities, (2000). https://www.ncbi.nlm.nih.gov/books/NBK233615/ (accessed June 26, 2024).

[56] S. Ahmad, B. Zeb, A. Ditta, K. Alam, U. Shahid, A. U. Shah, I. Ahmad, A. Alasmari, M. Sakran, M. Alqurashi, Morphological, Mineralogical, and Biochemical Characteristics of Particulate Matter in Three Size Fractions (PM10, PM2.5, and PM1) in the Urban Environment, ACS Omega 8 (2023) 31661–31674. https://doi.org/10.1021/ACSOMEGA.3C01667/ASSET/IMAGES/LARGE/AO3C01667_0014.JPEG

[57] D. M. Cocârţă, M. Prodana, I. Demetrescu, P. E. M. Lungu, A. C. Didilescu, Indoor Air Pollution with Fine Particles and Implications for Workers' Health in Dental Offices: A Brief Review, Sustainability 2021, Vol. 13, Page 599 13 (2021) 599. https://doi.org/10.3390/SU13020599

[58] I. Manisalidis, E. Stavropoulou, A. Stavropoulos, E. Bezirtzoglou, Environmental and Health Impacts of Air Pollution: A Review, Front Public Health 8 (2020) 14. https://doi.org/10.3389/FPUBH.2020.00014

[59] A. P. Mitra, C. Sharma, Indian aerosols: Present status, Chemosphere 49 (2002) 1175–1190. https://doi.org/10.1016/S0045-6535(02)00247-3

[60] P. Thangavel, D. Park, Y. C. Lee, Recent Insights into Particulate Matter (PM2.5)-Mediated Toxicity in Humans: An Overview, Int J Environ Res Public Health 19 (2022). https://doi.org/10.3390/IJERPH19127511

[61] S. S. Kalender, G. B. Alkan, Air Pollution, Handbook of Environmental Materials Management (2019) 149–166. https://doi.org/10.1007/978-3-319-73645-7_77

[62] H. M. Tran, F. J. Tsai, Y. L. Lee, J. H. Chang, L. Te Chang, T. Y. Chang, K. F. Chung, H. P. Kuo, K. Y. Lee, K. J. Chuang, H. C. Chuang, The impact of air pollution on respiratory diseases in an era of climate change: A review of the current evidence, Science of The Total Environment 898 (2023) 166340. https://doi.org/10.1016/J.SCITOTENV.2023.166340

[63] G. Adamkiewicz, J. Liddie, J. M. Gaffin, The Respiratory Risks of Ambient/Outdoor Air Pollution, Clin Chest Med 41 (2020) 809. https://doi.org/10.1016/J.CCM.2020.08.013

[64] P. Kumar, A. B. Singh, T. Arora, S. Singh, R. Singh, Critical review on emerging health effects associated with the indoor air quality and its sustainable management, Science of The Total Environment 872 (2023) 162163. https://doi.org/10.1016/J.SCITOTENV.2023.162163

[65] N. K. Dumakor-Dupey, S. Arya, A. Jha, Advances in Blast-Induced Impact Prediction—A Review of Machine Learning Applications, Minerals 2021, Vol. 11, Page 601 11 (2021) 601. https://doi.org/10.3390/MIN11060601

[66] J. Hawkins, Impacts of Blasting on Domestic Water Wells Workshop on Mountaintop Mining Effects on Groundwater, (2000).

[67] T. M. Keevin, G. L. Hempen, THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS WITH METHODS TO MITIGATE IMPACTS, (1997).

[68] W. S. Chan, J. Routh, C. Luo, M. Dario, Y. Miao, D. Luo, L. Wei, Metal accumulations in aquatic organisms and health risks in an acid mine-affected site in South China, Environ Geochem Health 43 (2021) 4415–4440. https://doi.org/10.1007/S10653-021-00923-0/FIGURES/7

[69] M. Zaynab, R. Al-Yahyai, A. Ameen, Y. Sharif, L. Ali, M. Fatima, K. A. Khan, S. Li, Health and environmental effects of heavy metals, J King Saud Univ Sci 34 (2022) 101653. https://doi.org/10.1016/J.JKSUS.2021.101653

[70] S. Mitra, A. J. Chakraborty, A. M. Tareq, T. Bin Emran, F. Nainu, A. Khusro, A. M. Idris, M. U. Khandaker, H. Osman, F. A. Alhumaydhi, J. Simal-Gandara, Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity, J King Saud Univ Sci 34 (2022) 101865. https://doi.org/10.1016/J.JKSUS.2022.101865

[71] A. Arthur, Application of a Laser Distance Sensor in the Measurement of Stemming Height, (n.d.) 1–11.

[72] S. Murmu, P. Maheshwari, H. K. Verma, Empirical and probabilistic analysis of blast-induced ground vibrations, International Journal of Rock Mechanics and Mining Sciences 103 (2018) 267–274. https://doi.org/10.1016/J.IJRMMS.2018.01.038

[73] M. Grobbelaar, T. Molea, R. Durrheim, Measurement of air and ground vibrations produced by explosions situated on the Earth's surface, The Journal of the Southern African Institute of Mining and Metallurgy 120 (2020). https://doi.org/10.17159/2411

[74] Y. Ren, S. Xi, Y. Yang, T. Wan, H. Wang, K. Zhao, Structural vibration characteristics of the historical building in a nearby blasting test, Front Earth Sci (Lausanne) 11 (2023) 1304354. https://doi.org/10.3389/FEART.2023.1304354/BIBTEX

[75] J. Yang, Z. Liu, K. Liu, X. Li, S. Ma, Z. Yan, Study on the blasting damage of prestressed rock-like specimens with different coupling mediums, Int J Impact Eng 181 (2023) 104758. https://doi.org/10.1016/J.IJIMPENG.2023.104758

[76] A. K. Raina, A. Haldar, A. K. Chakraborty, P. B. Choudhury, M. Ramulu, C. Bandyopadhyay, Human response to blast-induced vibration and air-overpressure: An Indian scenario, Bulletin of Engineering Geology and the Environment 63 (2004) 209–214. https://doi.org/10.1007/S10064-004-0228-7

[77] X. Zhou, X. Zhang, L. Wang, H. Feng, C. Cai, X. Zeng, X. Ou, Propagation characteristics and prediction of airblast overpressure outside tunnel: a case study, Scientific Reports 2022 12:1 12 (2022) 1–14. https://doi.org/10.1038/s41598-022-24917-9

[78] M. R. Jorolemon, R. A. Lopez, D. M. Krywko, Blast Injuries, StatPearls (2023). https://www.ncbi.nlm.nih.gov/books/NBK430914/ (accessed June 26, 2024).

Biography

Naa Dedei Tagoe is a Senior Lecturer in the Department of Geomatic Engineering at the University of Mines and Technology (UMaT). She completed her PhD studies in Geomatic at the University of Cape Town, South Africa, and her Master's degree at the Stuttgart University of Applied Sciences, Germany. Her research interests include the application of geospatial tools and technologies, namely Photogrammetry, GIS, Remote Sensing, GeoAI, and Digital Twin, for environmental monitoring and climate change to promote environmental sustainability. Additionally, she focuses on the intersection between gender and climate vulnerability, as well as heritage documentation and preservation.

Ebenezer Ashun is a Lecturer in the Department of Environmental and Safety Engineering at the University of Mines and Technology (UMaT). His research interests include environmental contamination and risk assessment from persistent organic pollutants (POPs), pesticides, pharmaceutical and personal care products (PPCPs), toxic metals, and other xenobiotics. He has conducted extensive work on monitoring and remediating these pollutants in air, water, and soil media. Additionally, he specializes in community participation initiatives and environmental quality monitoring.

Research Field

Naa Dedei Tagoe: Geospatial Tools and Technologies, Environmental Monitoring and Climate Change, Gender and Climate

Vulnerability, Cultural Heritage Documentation and Preservation, Mining Impact Assessment, Photogrammetry and UAV Applications, Land Administration and Property Systems

Ebenezer Ashun: Environmental Quality Monitoring, Bioremediation, Risks Assessments, and Contaminant Behavior Analysis and Modelling, Water Resources Management