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Original Article

Consequence Modeling and Analysis of Benzene leakage and explosion from a poorly sited gas station in the City of Douala, Cameroon

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ABSTRACT

Introduction: Benzene has long been recognized as highly carcinogenic and the most cytotoxic of all air pollutants released by gas stations. Although several studies have been conducted on accidents in the process industry, very little work has been directed toward the modeling of risks caused by the leakage and explosion of toxic substances in gas stations. This knowledge could aid in predicting the vapor concentration inside gas station office buildings and neighboring infrastructures and in developing corresponding safety measures. The purpose of this study was, therefore, to model the consequences of Benzene dispersion following leakage and explosion from gas stations, taking the city of Douala, Cameroon as an example.

Methods: Based on the measured vent emission and meteorological data, the Areal Location of Hazardous Atmosphere (ALOHA v.5.4.7) model was used to predict the hazard radius of leakage and dispersion of benzene from a tank in different seasons. The maps of the toxic and flammable vapor cloud of benzene, evaporation rate from a puddle, and the concentration of toxic and flammable vapor cloud inside and outside of the station were prepared with the aid of MARPLOT and Google Earth software.

Results: The results showed that the maximum average sustained release rate of benzene from a tank was 26 kilograms per minute, with an estimated total amount released of 1,340 kilograms per 60 minutes in the dry season. The puddle spread to a diameter of 19.8 meters. The predicted threat zone distance from the station in the dry season, as compared to the rainy season, had an increase in radius of 12, 20, and 83m for the red, orange, and yellow zones, respectively. The worst hazard level extends primarily in the downwind direction and is predicted to be 31 meters in the rainy season in all directions, covering parts of the adjacent settlements and social infrastructure.

Conclusion: The potential scenarios of benzene dispersion from a poorly sited gas station in the city of Douala have been modeled and the threat zones estimated. Nearby residences and social infrastructures are significantly exposed, with the predicted threat zones being more hazardous for the employees of the gas station. Further research looking at the impact of combined consequences of gasoline emissions may help determine whether the combined effects of benzene with other chemicals are cumulative or synergistic.

Keywords: ALOHA, Benzene, Douala, MARPLOT, Poorly sited Gas station

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Introduction

Benzene has long been recognized as a carcinogenic substance, and research has shown that it is one of the most cytotoxic of all the air pollutants released by gas stations and other petrochemical plants. Ambient air at gasoline stations contains volatile organic compounds from fuel vapors and combustions from vehicle engines, including those of benzene, toluene, ethylbenzene, and xylene (BTEX). Other sources of chronic unburned fuel release at gas stations are fuel storage and dispensing: vapor release through the storage tank's vent pipe and vapor emissions from the evaporation of spilled fuel. However small the amount of unburned fuel lost during vehicle refueling and fuel storage might be, the cumulative release of fuel to the environment can be substantial if large amounts of fuel are dispensed at gas stations. The average benzene content of gasoline has been approximately 1%–3% (and up to 5%) in the United States,[1] and 3%–5% in European countries.[2] Recent research shows that gas stations emit ten times the amount of benzene previously recorded.[3]

Concerns about gasoline's health and environmental hazards extend beyond academia, science, and regulation. Benzene exposure has been linked to several blood cancers,[4] including acute myeloid leukemia and acute nonlymphocytic leukemia. Studies in South Korea have found some differences in the median outdoor and indoor concentrations of benzene (9.9 and 6.0 g/m^3 or about 3.1 and 1.9 ppb respectively) at a variety of residences neighboring gas stations. The median indoor concentrations were higher at these sites, reaching 13.1 and 16.5 g/m^3 respectively (about 4.1 and 5.2 ppb, respectively). Another study discovered that benzene and other gasoline vapor releases from service stations can be distinguished from traffic emissions as far as 75 meters away from service stations and that the contribution of service stations to ambient benzene is less significant in high traffic density areas.[5]

The EPA's Toxic Chemical Substance Declaration System reported a dimethyl benzene leak at an unnamed plant in November 2009, a phosgene leak at a chemical complex in December 2009, and a leak at a water purification plant in a chemical complex in December 2009.[6] These leaks had caused physical ailments in the surrounding communities, necessitating medical attention. In light of recent events, if petrochemical plant operators had predicted the magnitude of the impact, it would have facilitated pre-rescue preparations and reduced the extent of the toxic gas's impact on the residents.[7] This raises the question of the consequences of potential benzene dispersion following leakages and explosions from storage devices in gas stations, especially as most of these stations are widely distributed in residential areas and very close to social infrastructures. Predicting the fluid behavior after release and its emissions into the environment is critical for estimating the consequences and potential injuries, as well as being aware of the maximum safe radius of fire, explosion, and toxic substance emissions. Furthermore, it can be extremely useful in dealing with accidents and emergencies.[8]

Several other studies have modeled the consequences of fire, explosion, and toxic dispersion by using different modeling tools such as PHAST (Process, Hazard, Analysis, Software Tool),[9] ALOHA (Areal Locations of Hazardous Atmospheres, U.S. Protection Agency),[10] GIS software,[11] and FLACS (Flame Acceleration Software) modeling programs.[12] Each formal method is founded on a specific mathematical theory. However, researchers, for example,[13] have demonstrated the significance of systematic and analytical methods such as the Bowtie method in shaping the relationship between hazards and their consequences.[14] The Bowtie method has been used to analyze process accidents in refineries,[15] as well as to model the propagation of natural gas leaks. Whether qualitative or quantitative, the method is a useful tool for determining the causes of events as well as specifying critical tasks to ensure the integrity and effectiveness of ongoing controls. However, as a standalone piece of software, it is limited in terms of hazard modeling and simulation.

Previous other studies at the Cameroon level on this topic are rare and the few that exist have either focused on the consequences of exposure to benzene contamination,[16] or the compliance of gas stations sitting with existing regulations.[17] Though implicit to functional recovery, consequence analysis and modeling has never been a focus for local researchers. Added to the necessity of implementing emergency response planning in this area, this gap overlooks the consequences of benzene leakage from tanks at gas stations and other hydrocarbons storage areas. With these explanations, the purpose of this study was to use the ALOHA (Areal Locations of Hazardous Atmospheres) model has been chosen to simulate the scales of impact (threat zones) in the event of benzene release/ dispersion following leakages and explosion from a storage device and to observe the safety measures required using one of the poorly sited gas stations in the city of Douala, Cameroon as an example. Two failure scenarios were considered:

- A sudden catastrophic failure leading to a Boiling Liquid Expanding Vapor Explosion (BLEVE); and
- A leak leading to a flash fire or a vapor cloud explosion.

The approach consisted in entering source information at a level of concern (LOC) and mapping the footprint on a map to show potential offsite receptors (e.g., schools, roads) using a combination of software (ALOHA, MARPLOT, and Google Earth). The research could be useful in identifying and improving key performance indicators in the areas of health, safety, and the environment.

Methods

The study area is situated on the Wouri estuary, 30 kilometers from the Atlantic Ocean and not far from the Equator, between 4° and 4° 10' North latitude and 9° 35' and 9° 80' East longitude. It is Cameroon's economic hub as well as the country's first city. It is governed by the Douala Urban Community and contains 20,220 hectares. Five urban municipalities (also known as districts) and one rural municipality form the urban community of Douala.[18] (Fig.1)

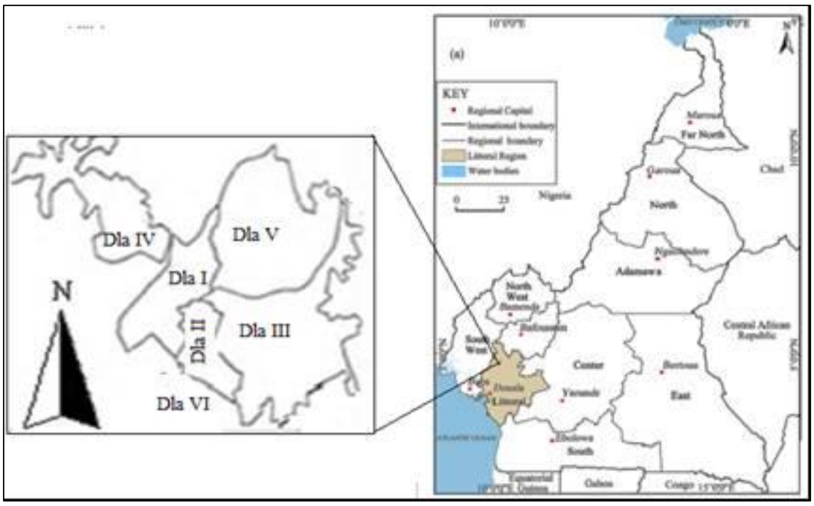


Figure 1: Location of the study area (DLA: Douala)

Douala was chosen for this study because it is the largest city in Cameroon, but also because, it is the commercial and economic capital of Cameroon and the entire CEMAC region comprising Gabon, Congo, Chad, Equatorial Guinea, Central African Republic, and Cameroon. Consequently, any hazard may impact serious economic and environmental loss on the entire region. Douala is also an industrial city and one of the fastest developing urban areas in Africa and ranks first at the national level. According to current estimates from the Douala city council, the population of the municipality is estimated to at 5,000,000 people with an average growth rate of 4.8%. The mean annual rainfall is about 36000.mm, while the mean annual temperature varies between 240C in the rainy season, to about 330C in the dry season. Relative humidity varies between 75 to 100%.

In a previous study,[19] we found that of the one hundred and fifty-two (152) gas stations unevenly distributed all over the city of Douala, eighty (80) are poorly sited, that is, their locations do not comply with the dictates of existing regulations. These stations have common characteristics in terms of size, products, embedded in human settlements, at close distances (< 400m) from schools, markets, and other social infrastructures, and climatic (weather) conditions. Hence, Total Bonaberi1 (Fig. 2), was conveniently selected for this study. This gas station, like other poorly sited gas stations, is less than 7m from an always busy-traffic congested major road (Route du Lycee), neighboring many residences, public and private nurseries, primary, secondary, and high schools, and other social infrastructures. Additionally, people typically spend 15 min to 1 hour at this station.

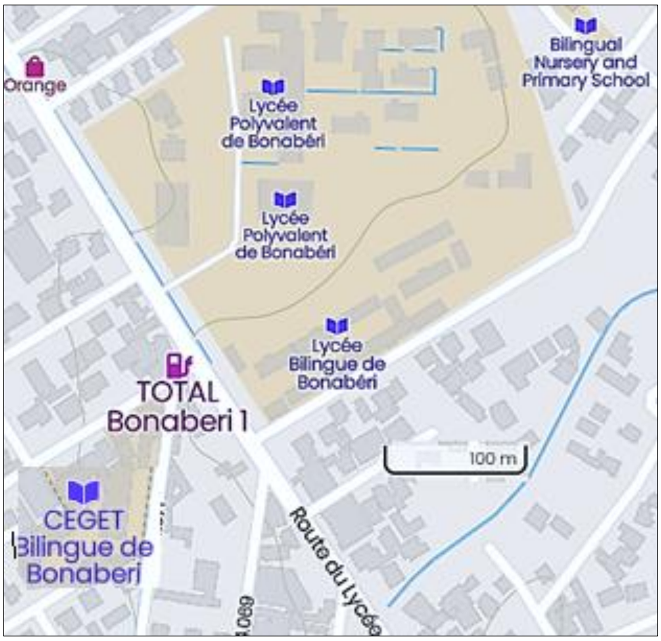
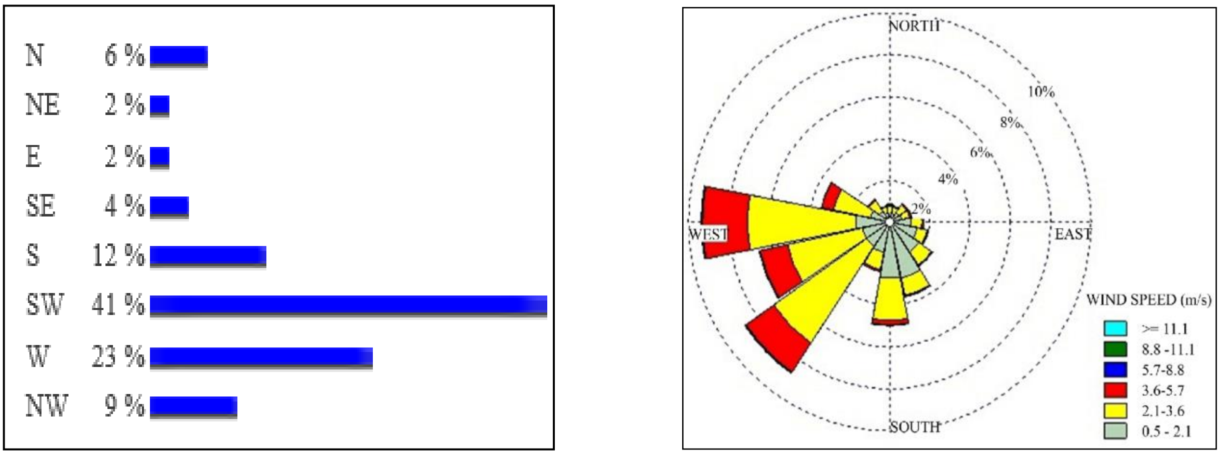


Figure 2: Total Bonaberi1 gas station

Data Collection

Between December 2020 and January 2021, data were gathered. There was a site walk-through observation, followed by document analysis. Site data (source location and tank geometric information), atmospheric data (temperature, humidity, wind direction and speed, topography, and other meteorological parameters) were gathered

- Atmospheric data: One of the random parameters impacting the dispersion behavior of a leak event is the weather. To account for changing meteorological circumstances over time, leak occurrences should be recreated under various weather settings. Weather data were obtained from field investigations. The wind rose (Fig 3) for Douala shows how many hours per year the wind blows from the indicated direction. Example SW: Wind is blowing from South-West (SW) to North-East (NE).
- Chemical data: For the model to run, the hazardous material released, as well as its physical and chemical properties were specified. The chemical properties released ultimately determined the shape, magnitude, and severity of the plume. The HazMat site was used as a chemical data provider in this study.[20] The data includes product identification, the nature of the danger, physical and chemical properties, security instructions, transportation conditions, etc.



(a) Wind-force per Day (Jan. 2000 – Dec. 2021) (b) Wind rose for the Douala city

Figure 3: Wind rose derived from both the agency for Aerial Navigation Safety in Africa and Madagascar (ASECNA) and National Oceanic and Atmospheric Administration (NOAA) data for the period of 2008-2012.[18]

- Source data: For this type of data, the exact source characteristics such as geometric properties, storage capacity, and so on were described. This type of information was gathered in this study through field visits and interviews with HSE and engineering experts at gas stations.

A recapitulation of the data collected is summarized as shown in Table 1.

Table 1: Data for the configurations of the release scenario for the seasonal simulations

Parameters	**Season**	
	Dry	Rainy
Air temperature (°C)	33.7	24
Relative humidity (%)	80	95
Wind speed (m/s)	2.8	3.5
Wind direction	SW (225)	SW (225)
Elevation of wind speed measurement (m)	4	4
Atmospheric stability class	E	D
Cloud cover (0–10)	7	7
Total volume released (m^3)	500	500
Model of release	Heavy gas	Heavy gas
Total duration (min)	60	60

Data Analysis

The study employs two scenarios:

- Modeling the domain of benzene toxic vapor cloud formation
- Modeling the domain of benzene flammable vapor cloud formation

It is supposed that the benzene leakage is caused by the creation of a hole with a diameter of 100 mm in the iron wall of a vertical cylindrical tank with a capacity of 5000 liters, in which petroleum products are stored. The benzene storage in the tank is equal to the ambient temperature (25 °C).

In addition to creating maps, the concentration of benzene toxic and flammable vapor cloud in the office building's indoor and outdoor areas was estimated. The American Institute of Chemical Engineers (AIChE) and Det Norske Veritas (DNV) Institute proposed a conventional approach to modeling and assessing the consequences in the chemical process, oil, gas, and transportation industries.[21]

To determine the domain of flammable and toxic vapor cloud Levels of Concern (LOCs), two main criteria were used:

1. The Lower Explosive Limit (LEL): the minimum concentration of a gas or vapor in the air which

can cause a fire in the presence of an ignition source (spark, hear, etc.) and is expressed as the volume percentage of flammable gas in the air.[22] Based on this criterion, we adopted the LOC level for two levels of benzene as stated below.[23]

(1) a concentration of 7200 ppm benzene equivalent to LEL of 60%. In this case, extreme safety precautions against explosion are considered, and,

(2) a concentration of 1200 ppm benzene, equivalent to LEL of 10%. In this case, safety precautions against explosion are considered.

2. Acute Exposure Guideline Levels (AEGLs). AEGLs used in this study are classified into three levels.
    - Level 1: AEGL-1 is the airborne concentration (in ppm or mg/m^3) of a substance above which the general population is expected to experience significant discomfort and irritation. The effects, however, are not disabling and are transient and reversible (AEGL-1 (60 min): 52 ppm).
    - Level 2: Susceptible individuals may experience adverse and severe effects, as well as irreversible effects, at this concentration. People may lose their ability to escape in this case (AEGL-2 (60 min): 800 ppm). AEGL-2 is the airborne concentration of a substance (expressed as ppm or mg/m^3) above which it is predicted that the general population will suffer irreversible or other serious, long-term adverse health effects.
    - Level 3: People may lose their lives at this concentration, or exposure at this concentration may be fatal (AEGL-3 (60 min): 4000 ppm). The airborne concentration of a substance (expressed in parts per million or milligrams per cubic meter) above which the general population is expected to experience life-threatening health effects or death is referred to as AEGL-3.

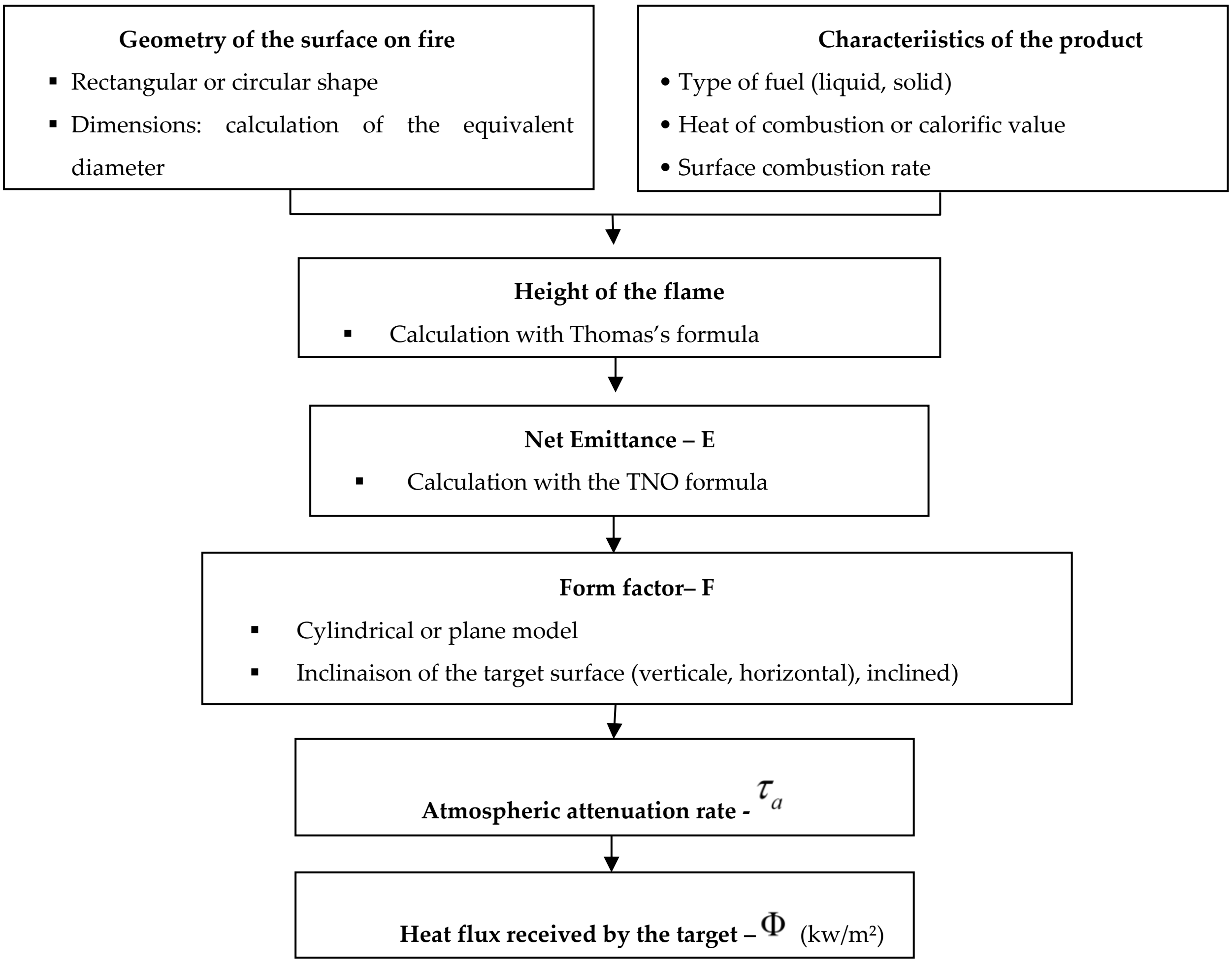


Figure 4: Principle of the method for calculating the thermal effects of fire

ALOHA software (Version 5.4.7), which has been built upon the Gaussian dispersion model of continuous, buoyant air pollution flumes,[25] was then used to model the dispersion maps of benzene toxic and flammable vapor cloud, determination of Max Average Sustained Release Rate averaged over a minute or more, the total amount released, and diameter of the evaporating puddle following the Wiekema's TNO model.[26] (Fig. 4)

The source emission time may vary between limits of one minute to one hour.[27] ALOHA employs solid flame models to compute thermal radiation hazards from bleve fireballs, jet fires, and pool fires. In these three scenarios, the incident radiant heat flux, ϕ(kW/m^2), emitted from a surface is computed, as follows:

$$\phi = E.F.\tau_a$$

Where E is the surface emissive power (kWm^{-2}), F is the geometric view factor, and τ_a is the atmospheric transmissivity. The severity of injuries and the extent of damage caused by thermal radiation from a fire is determined by the intensity of the incident radiation as well as the duration of exposure to that level of heat flux. Because fireballs last only a few seconds, the duration of exposure is commonly set to be the same as the duration of the fireball. ALOHA® threat zone estimates were displayed on a map using the Mapping Application for Response, Planning, and Local Operational Tasks (MARPLOT) software.

The ALOHA model of dispersion is a free application provided by NOAA (National Oceanic and Atmospheric Administration) of the United States and EPA (Environmental Protection Agency) and it is the tool for the assessment of toxic gas cloud threat zones recommended by the USEPA. The model is capable of simulating the dispersion model for over 900 chemicals and is primarily used in the simulation of accidental release of hazardous substances,[28] and the dispersion of chemical vapor.

The ALOHA software was used for this analysis because of its friendly graphical user interface, and because it helps analysts and planners/decision-makers to carefully visualize what may happen.[29] ALOHA can predict source strength for four general classes of chemical releases, or sources:

- Direct. An instantaneous or continuous release of chemical vapors into the air from a single point. This is the only option that allows for an elevated release.
- Puddle. A puddle of constant area, containing either a non-boiling or boiling liquid.
- Tank. A cylindrical or a spherical tank at ground level with a single hole or leaking valve. Tank contents may escape directly into the atmosphere or first form a spreading evaporating pool.
- Gas pipeline. A pressurized pipe containing gas is either connected to a very large reservoir or unconnected to any storage vessel.

The first three classes were considered in this study. Furthermore, ALOHA employs Levels of Concern (LOC) to address the impact of toxic air plumes, fires, and explosions on human populations. For inhalation hazards, ALOHA's LOCs are concentrations of airborne chemicals associated with adverse health effects. It uses two separate dispersion models including the Gaussian plume model,[30] and the heavy gases model,[31] for heavy gases like benzene.

After determining the model for estimating gas dispersion, ALOHA plots the points a concentration higher than Level of Concern, which is used to assess the flammable and toxicity threat of a chemical release.[32] The model assumes that all the combustion energy present in the flammable part of the cloud contributes to the explosion. If the characteristic explosion length is calculated, the blast parameters, such as peak pressure and the duration of the positive pressure phase at a certain distance from the center of the hemisphere are derived from the blast chart.

Results

The study was conducted to simulate the consequence modeling due to toxic materials dispersion from poorly sited gas stations in the city of Douala, Cameroon. In the first scenario considering gas leak, gas station information, and atmospheric information, the outcomes of a gas leak and emissions from the tank are modeled. The predicted averaged release rate during the hour after the release revealed that the release of benzene from the tank and evaporation from the puddle for up to 60 minutes had a decreasing trend and direction in both seasons (Fig.5).

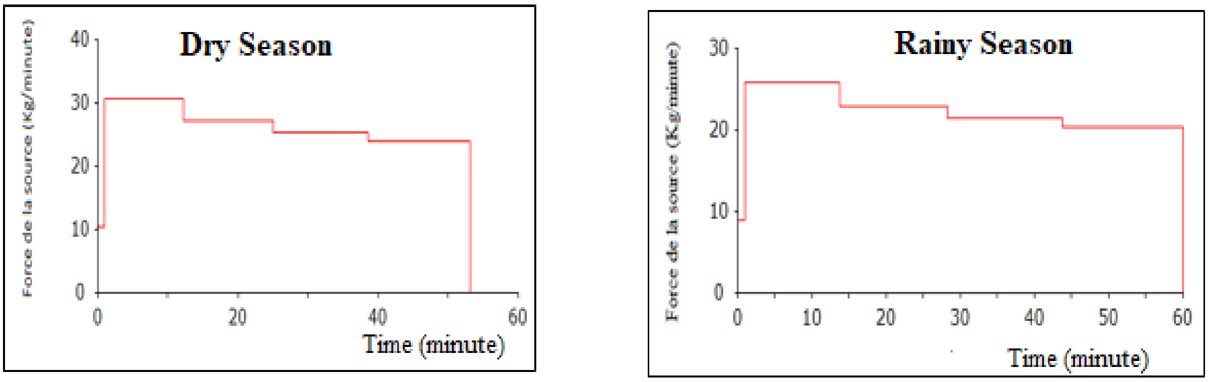
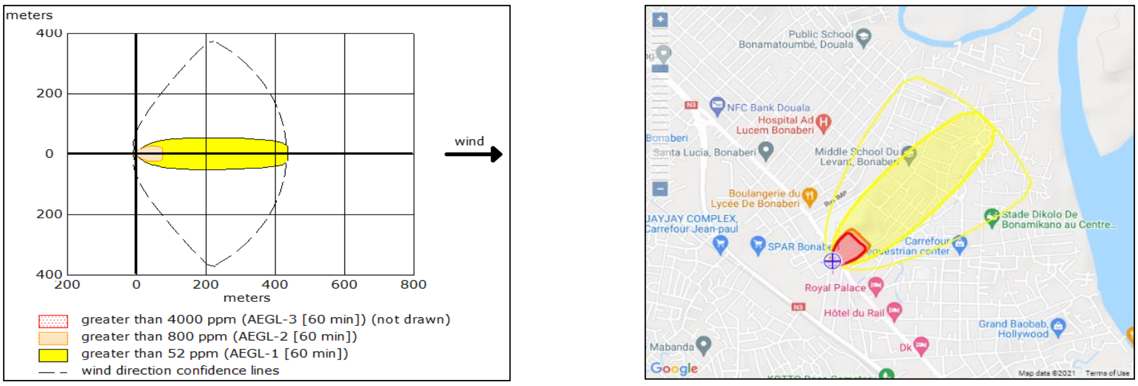
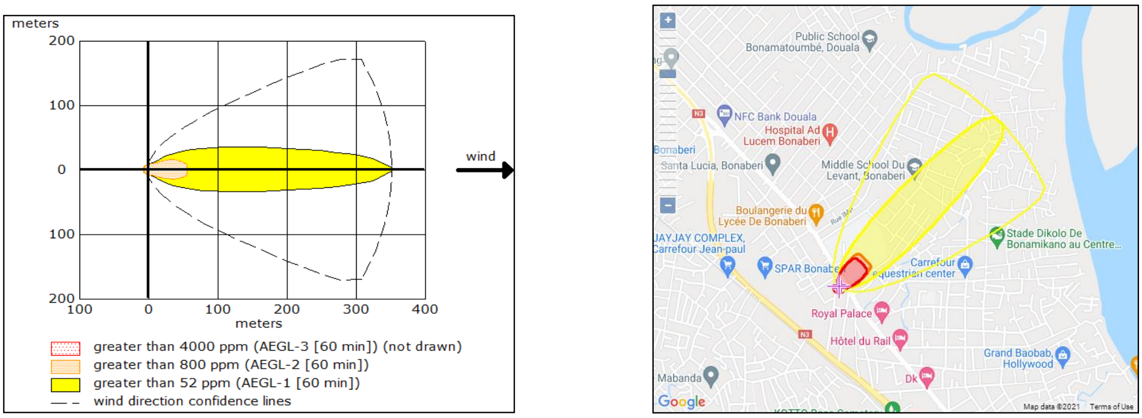


Figure 5: Predicted averaged release rate during the hour after which the release begins

According to ALOHA, the release of vapor into the atmosphere lasts approximately 53 minutes, with a maximum amount of vapor released at any one time of 30.6 kilograms per minute (maximum average sustained release rate). In our study, the evaporation rate of benzene from the puddle formed in the dry season was lower (wind speed of 2.8 m/s, temperature 33.7°C, vapor pressure of the liquid at ambient temperature of 0.12 atm, ambient saturation concentration of 184,216 ppm or 11.9%) than in the rainy season (wind speed of.3.5 m/s, temperature 24°C, vapor pressure of the liquid at ambient temperature of 0.18 atm, ambient saturation concentration of 119,261 ppm or 18.4%). The results related to the domain of formation of the benzene toxic vapor cloud (threat zone) at different distances from the tank in dry and rainy seasons, together with potentially affected areas are shown in Fig.6.



(a) Threat zones in the dry season (b) Potential affected areas in the dry season



(c) Threat zones in the rainy season (d) Potential affected areas in the rainy season

Figure 6: Modeling and simulation of the domain of threat zones (a and c), and potentially affected areas (b and d) due to the formation of the benzene flammable vapor cloud at different distances from the tank per season

We observe from figure that, although the toxic vapor threat zone did cover a few sensitive areas with a dense population (the main road that is often traffic-congested and full of students in the morning and afternoon), it could potentially affect surrounding residential areas and school (Government bilingual high school Bonaberi) with a denser population with a change in wind direction in different seasons.

Based on the findings, the threat zone for benzene toxic vapor clouds in the dry and rainy seasons was divided into three layers red, orange, and yellow. The red zone in both seasons represents AEGL-3, which had an exposure concentration of 4000 ppm and was dispersed to 19 and 31 m from the tank, respectively; the orange zone represents AEGL-2, which had an exposure concentration of 800 ppm and was dispersed to 56 and 76 m from the tank, respectively. Ground-level benzene concentrations may exceed the ERPG-2 level within this zone. People may experience serious health effects or have their ability to escape impaired at concentrations above the ERPG-2 level (if they are exposed for about an hour). Finally, the yellow zone represents AEGL-1, which had an exposure concentration of 52 ppm and was dispersed up to 353 m and 436 m from the tank, respectively, during both seasons.

The maximum average sustained release rate was estimated at 26 kilograms/min (averaged over a minute or more), with an estimated total amount of released being 1,340 kilograms. The puddle spread to a diameter of 19.8 meters. The potential consequences of benzene toxic vapor cloud concentrations at different points and times of exposure in the office and outdoor in both seasons vary considerably in the downwind direction (Fig. 7).

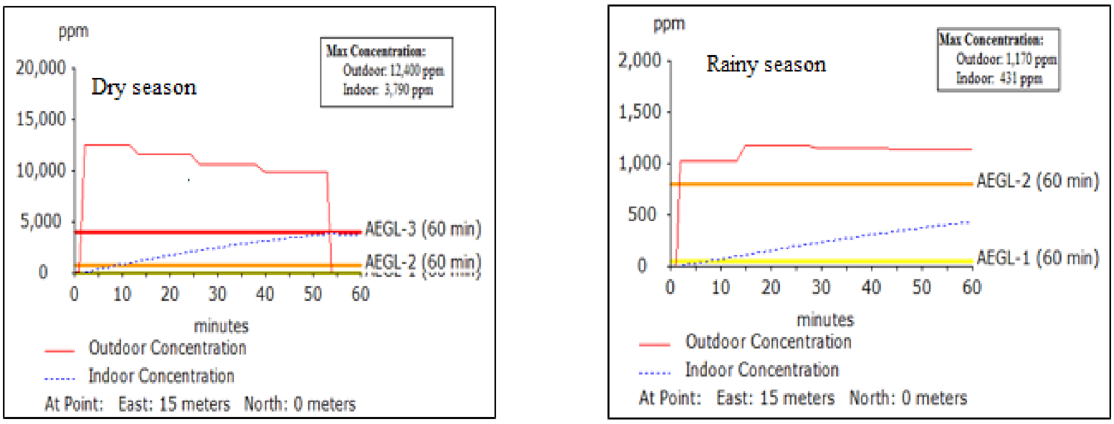


Figure 7: Concentration Estimates at a point of vapor cloud as a function of time in the office building and outdoor

We infer from the figure that, while both AEGL-3 and AEGL-2 levels are likely to be attained at about 54 minutes after the release in the dry season, no such phenomenon is likely to occur in the rainy season. The concentration of benzene flammable vapor cloud in office buildings did not exceed the standard of 10LEL in both seasons. However, the concentration of benzene flammable vapor cloud in the area outside the office building 5 minutes after the start of the accident exceeded the 10% LEL standard. Further, at a point 35mN (across the road from, Government Bilingual High School, Bonaberi), and 35mE of the station, the concentration of benzene toxic vapor cloud exceeded the AEGL-2 standard (800 ppm) only in the dry season after 40 minutes of the accident but was not the case in the rainy season (Fig 8).

In our modeling, ALOHA estimates that the pool fire would last just under 2 and half minutes. The maximum flame length was 25 meters, and the burn duration was about 3 minutes, with a maximum burn rate of 727 kilograms/min. The release followed a decreasing trend in both seasons. The total amount of material burned was1393 kilograms. The chemical escaped as a liquid and formed a burning puddle. The puddle spread to a diameter of 13.5 meters. The increase in burn rate for the first minute and a half could be attributed to the growing puddle size as the chemical continues to leak from the tank (Fig. 9).

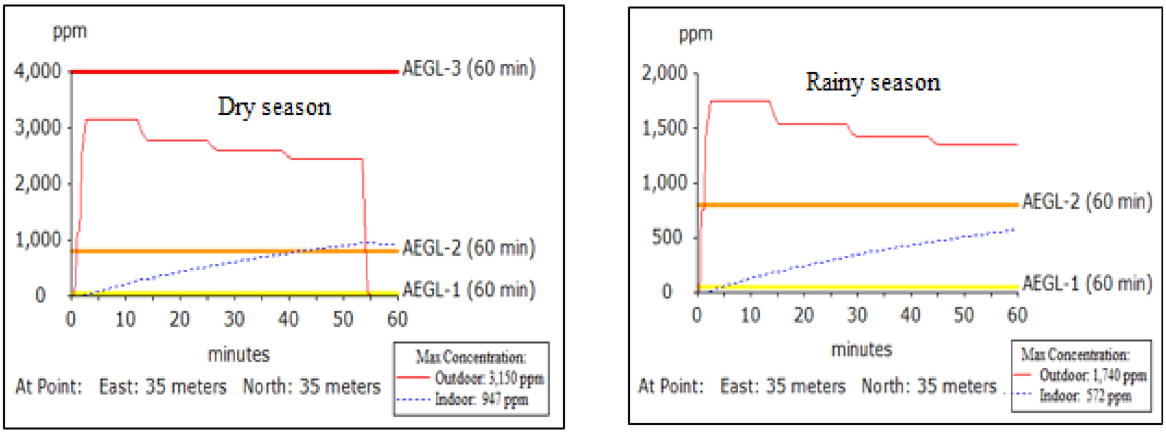
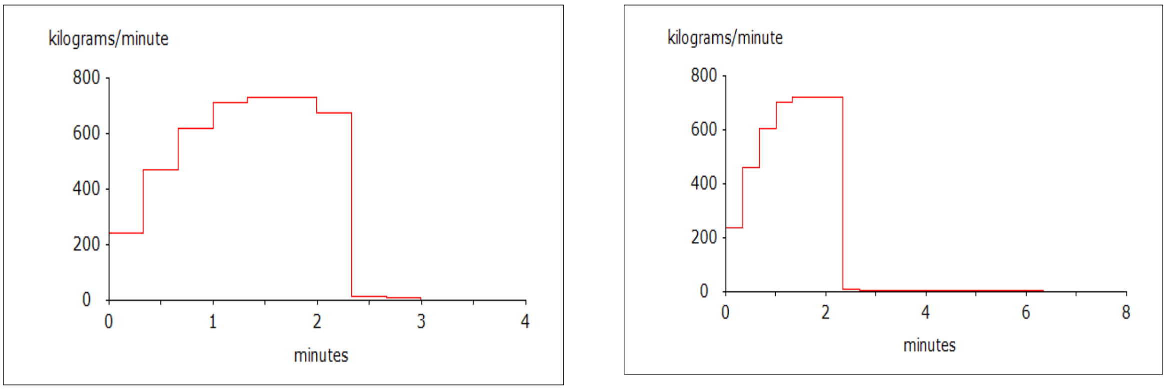


Figure 8: Concentration estimates at a point of vapor cloud as a function of time in & outdoor office building



a

b

Figure 9: Evaporation rate of benzene from the puddle formed in dry (a) and rainy (b) seasons

ALOHA's threat zone estimate for this scenario shows three nearly circular thermal radiation threat zones the red threat zone which represents the worst hazard level, and the orange and yellow threat zones which represent areas of decreasing hazard for both seasons (Fig. 10 a & b).

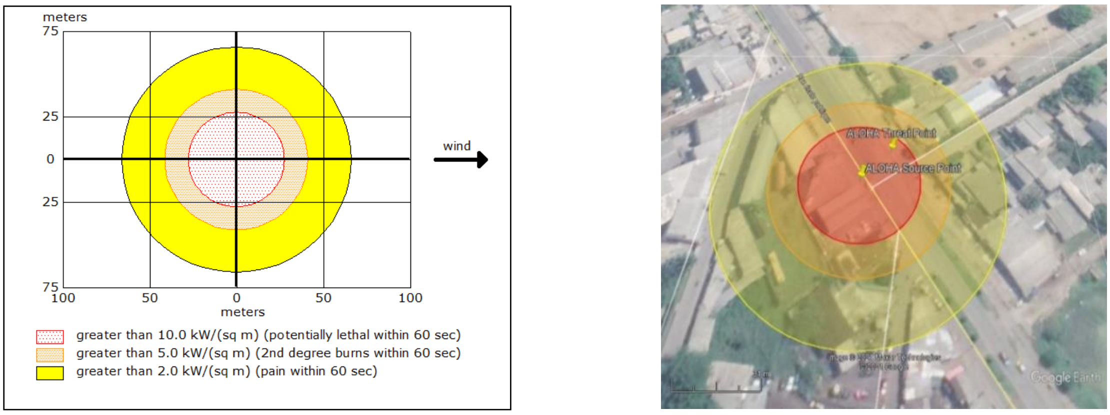


Figure 10a: Thermal radiation threat zone from pool fire in the the dry season

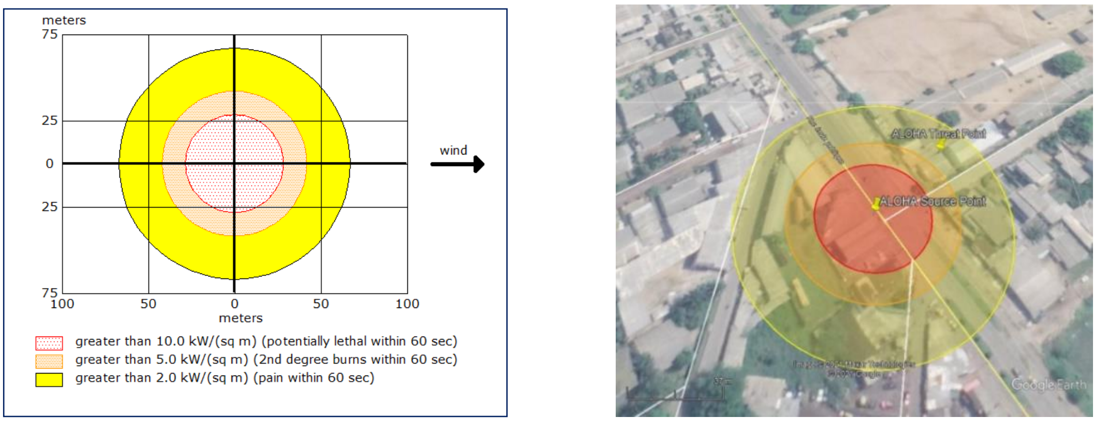
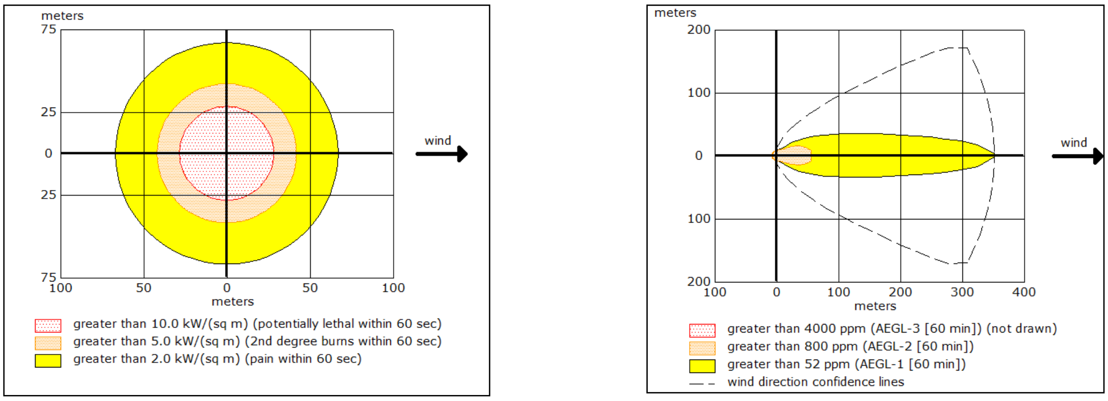
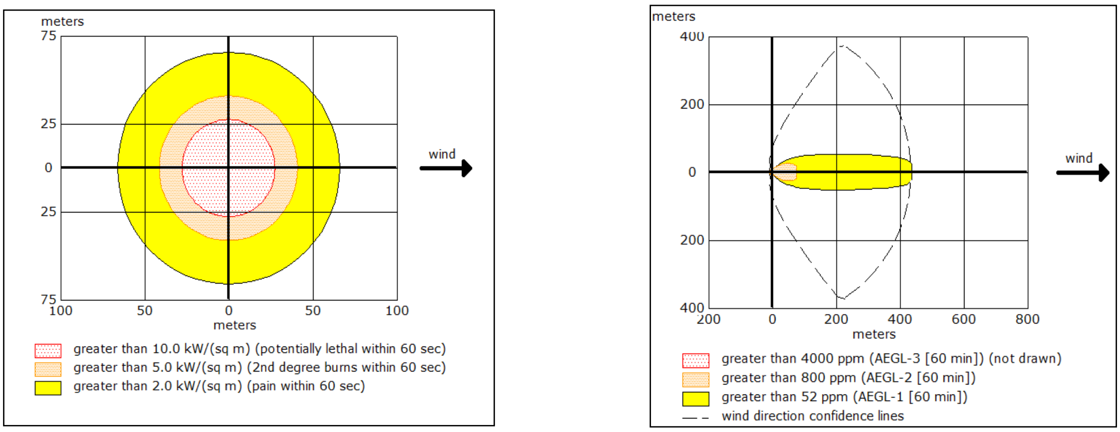


Figure 10b Thermal radiation threat zone from pool fire in the rainy season

The thermal radiation threat extends a little farther in the downwind direction. In both seasons, the red threat zone was estimated to extend 28 meters (10.0 kW/(sq m) = potentially lethal within 60 seconds) downwind. In the dry season, the orange threat zone extends only about 41 meters (5.0 kW/(sq m) =2nd-degree burns within 60 sec), and in the rainy season, it extends 42 meters in the upwind direction. This slight difference exists probably because the wind tilts the flames in the downwind direction, leading to a greater thermal radiation threat in that direction. The origins (0, 0) on both figures represent the center of the puddle. ALOHA estimates that the red toxic threat zone - the worst hazard level extends primarily in the downwind direction, predicted to extend roughly 31 meters (4000 ppm = AEGL-3 [60 min]) in the dry season, and 19 meters (4000 ppm = AEGL-3 [60 min]) in the rainy season respectively in all directions and a little farther in the downwind direction (Fig 11).



Rainy season pool of fire Rainy season toxic dispersion



Dry season pool of fire Dry season toxic dispersion

Figure 11: Comparison of the threat zone estimates from both of the scenarios in dry and rainy seasons

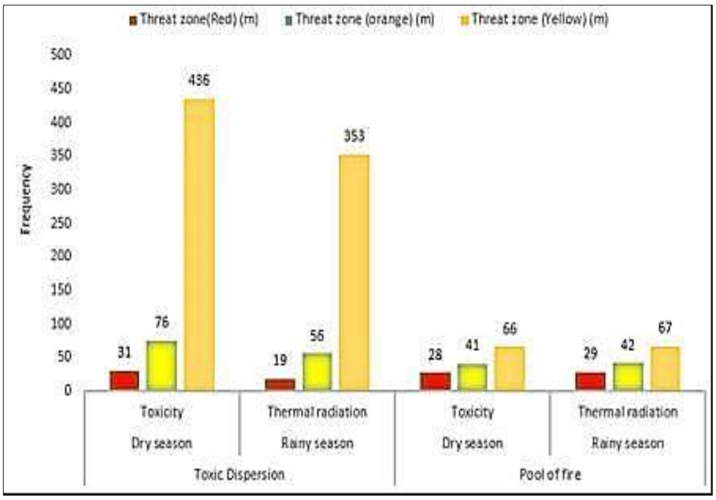


Figure 12: Summary of threat distances from the Text Summary screens

The toxic threat is confined primarily to the area downwind of the release, and even though the thermal radiation threat occurs in all directions is shifted downwind from the origin. The threat distances from both scenarios are summarized as follows (Fig 12).

If operators of petrochemical plants had performed the environmental survey at the initial stage of hazard and simulated the pattern of toxic vapor dispersion using the ALOHA model by plugging in various measurements, the statistics from the simulation would not only serve as a useful reference for rescue operations but also as a basis to notify residents in the affected areas to take necessary safety precautions to ensure the safety of their lives and properties. Considering the threat zone of the toxic vapor cloud, presenting some control strategies for the prevention of human casualties and equipment damage is essential. The most important safety measures to prevent damage to the area are as follows (Table 2).

Table 2: Recommendations based on the results obtained from both scenarios

ID	Prevention barriers	Limitations	Action steps for improvement
1	Operation procedures	Operation procedures are not updated	Regularly review and update operation procedures; establish Management of Change (MOC) procedure
2	Emergency management	No emergency plan to indicate emergency evacuation routes; no oil spill emergency supplies	Need for emergency plan and procedures that will be regularly reviewed and updated; consider emergency procedure updates in the MOC procedure; ensure that first aid equipment and medicine are available per actual needs; ensure that oil spill emergency supplies are in place; conduct desktop exercise once a week and practice once a month
3	Staff training	Insufficient staff ability; insufficient staff training	Develop post-appraisal system; develop training program and plan
4	Routine inspection and monitoring	No specific monitoring plan	Regular foundation settlement assessment
5	Security system	Only one gathering place is set for emergencies; inadequate persons on duty at night	Add an alternative gathering place; increase the site staff on duty at night; strengthen site supervision
6	Fire extinguishing system	Only two fire water tanks of 1500m^3 are available; the quality of fire water is poor	Check fire extinguishers and fire hydrants once a month; add alternative water supply source for fires; forming support groups like firefighting teams in the threat zone in different seasons, ensure that quantity and quality of water conform to the requirements for fire protection; assess the

			effectiveness of fire fighting in case of a large pool fire in an oil transfer pump area
7	Human inspection	Inadequate staff	Periodic inspection in a fixed route
8	Alarm and emergency shutoff	No control system of combustible gas detectors in the central control room; no broadcasting system	Install an acousto-optic alarm system and broadcasting system in threat zones and teaching the personnel how to deal with such situations, providing emergency telephone lines and communication devices for better coordination with the adjacent industries and habitations, and preparing a response plan for emergencies can reduce the harmful impacts of toxic and dangerous substance release.

Discussion

This study was performed on 152 gas stations in the city of Douala and showed that over half of the gas stations were exposed to varying fire risk scenarios. Two failure scenarios were considered: a sudden catastrophic failure leading to a Boiling Liquid Expanding Vapor Explosion (BLEVE); and, a leak leading to a flash fire or a vapor cloud explosion. Both scenarios were considered for both the dry and rainy season inorder to express an opinon on the season that could be riskier to decicion makers.

In the fisrt scenario, the consequences of benzene puddle formed in the dry season due to evaporation were higher (wind speed of 2.8 m/s, temperature 33.7°C, vapor pressure of the liquid at ambient temperature of 0.12 atm, ambient saturation concentration of 184,216 ppm or 11.9%) than in the rainy season (wind speed of.3.5 m/s, temperature 24°C, vapor pressure of the liquid at ambient temperature of 0.18 atm, ambient saturation concentration of 119,261 ppm or 18.4%). Our results suggests that wind speed and atmospheric stability are the primary factors that influence dispersion. Previous research also asserted that air movements can move, disperse, or trap a pollutant cloud.[33] Atmospheric stability is a measure of the mixing or turbulence in the atmosphere, which depends on the amount of solar radiation heating the air near the ground.[34] The dry season corresponds to stability class the slightly stable class, E, while the rainy season corresponds to class D: Neutral (Adiabatic), normally occurs with moderate to dim sunshine, cloudy conditions, and at night, with wind speeds > 3 m/s.[35] Because the topography of Douala is generally flat, the puddle would spread out until it becomes very thin in the dry season with the lesser stable class.

High incoming solar radiation (as would occur on sunny days) and low wind speeds characterize unstable/neutral conditions (e.g. stability class D) and result in high levels of buoyant turbulence. Under such unstable conditions, the air temperature of the atmosphere near the earth’s surface declines rapidly with elevation. Warm parcels of air near the surface travel a long distance upward before cooling to the temperature of the air around it. As warmer air rises, the cooler air that is displaced sinks downward. Large-scale, convective motions develop that provide substantial vertical mixing. On the other hand, stable atmospheric conditions (e.g., stability class E), corresponding to the dry season, can occur on clear nights with low wind speeds. The smaller atmospheric temperature gradient that occurs with stable atmospheric conditions limits upward convection and reduces vertical mixing. In this case, ALOHA might have overestimated the real puddle size and evaporation rate given that it assumes a perfectly flat surface which is not the case in the city of Douala. If the puddle were constrained by small depressions in the ground, it would not spread out as far because the liquid flowing away from the tank would fill up the depressions in the ground, and would then be smaller in the area and deeper at a slower rate and it would take longer to completely evaporate.

The predicted threat zone distance from the tank and /or the station in the dry season, as compared to the rainy season, had an increase in radius of 12, 20, and 83m for the red, orange, and yellow zones, respectively. The variation between seasons suggests that meteorology might be influencing dispersion. This hypothesis correlates with the work of,[36] who concluded that wind speed and atmospheric stability are the primary factors that influence dispersion. Atmospheric stability is a measure of the mixing or turbulence in the atmosphere, which depends on the intensity of solar radiation heating the air near the ground.[37] In this study, the stability classes were D and E in the dry and rainy seasons, respectively. The study's findings revealed that the rate of spread of heavy gases is much higher in an unstable atmosphere than in a more stable atmosphere because airflow movement in the axis perpendicular to the ground is low and the pollutant spreads more in the horizontal axis.[38] As a result, dry-season stability increases the dispersion distance of benzene toxic vapor clouds.

For a low-wind release, the cloud will meander a lot, and we will be unsure of the snakelike path that the cloud will take. Because of the smaller expected cloud meander at high wind speeds, the dashed lines will be close to the footprint. Plume meander refers to the variation of the location of the plume centerline (i.e., plume swings back and forth), due to turbulent velocity fluctuations. The magnitude of the plume meander effect on the time-averaged centerline concentration is a function of averaging time. The time-averaging effect on plume meander dispersion is generally accounted for by the Gifford algebraic expression that relates the horizontal dispersion coefficient (δ_y) for the averaging time of interest (t_a) to a known reference horizontal dispersion coefficient (δ_y, ref) that is associated with a reference averaging time (t_a, ref).[39] This phenomenon was observed during both seasons. However, in the case of low winds, which are more prone to cloud meandering, the area of the dashed lines is a complete circle with a radius equal to the footprint length, indicating that the wind could shift and blow the cloud in any direction. This condition was more prevalent during the dry season than during the rainy season. In Douala, the prevailing wind directions in both seasons are SW, W, ENE, and ESE. However, the direction with the strongest wind speed in both seasons is the SW. For this reason, the approximate direction of the benzene toxic vapor cloud in both seasons was SW. We agree with,[40] that, in general, the prevailing wind direction plays a decisive role in the movement of the benzene toxic vapor cloud. In general, there are two ideal classes of sources: One is an instantaneous source, where the pollutant is released into the atmosphere all at once. The other type of release is a continuous source, where the material is released at an approximately steady rate for a longer period.

ALOHA considers continuous releases lasting up to 60 minutes. Other studies,[6] for example,6 found that benzene and other gasoline vapor releases from service stations can be discerned from traffic emissions as far as 75 m from service stations and that the contribution of service stations to ambient benzene is less important in areas of high traffic density. This is probably because vehicle exhaust is usually the most abundant volatile organic compound (VOC) in urban areas, often followed by gasoline vapor emissions from fuel handling and vehicle operation.

From the foregoing, it appears that the exposures to benzene and other components of refueling vapors and spills experienced by these populations vary based on several factors, including the size and capacity of the refueling station, spatial variation in pollutant concentrations in ambient air, climate, meteorological conditions, time spent at varying locations of the service station, changing on-site activity patterns, physiological characteristics, and the use of vapor recovery and other pollution prevention technologies. Employees at service stations (such as pump attendants, on-site mechanics, garage workers, etc.) are among those with the greatest exposure to benzene originating from gas stations.[41] According to,[42] these receptors spend the most time on site (potentially reflecting approximately 40 h per week, for decades) and intermittently spend time where vapors from the pump are at their highest concentrations, with benzene concentrations measuring between 30 and 230 ppb in the breathing zone. Whether this is significantly affecting the physiological and biochemical processes of humans (which in turn may indirectly affect the productivity potential of the enterprise) or the increased benzene in the atmosphere is directly affecting the output of workers is difficult to ascertain from this study.

Conclusion

The consequence analysis of potential benzene dispersion following leakages and explosion from storage devices in gas stations in the city of Douala has been modeled in the above discussion. The approach is comparable to other heuristic methods. In some cases, it can be considered as a real-time and reliable detection approach, and offers a strong potential for better understanding and investigating of the environment, especially in regions such as sub-Saharan Africa, where existing petrol station databases are uncommon and often unreliable. Nearby residences and social infrastructures are significantly exposed, with the predicted threat zone being more hazardous for the employees of the gas station. The comparison shows that potential risks could be higher in the dry season than in the rainy season. The results trigger the need for local governments to inculcate the interest of the resident population and employees of petrol stations as a core concern in projects that directly affect local ecosystems. An advantage of this algorithm is that cartography of potential threat zones is provided together with empirical results. The results can be used to help manage facility risks by considering decisions such as siting buildings and specifying appropriate protection against overpressure, thermal radiation, and gas ingress, locating fire and gas detectors and fire hydrants, land use planning restrictions on development around facilities, and emergency response planning. The results could also be applied to other institutions such as airports, local fuel companies, power plants, and large manufacturing facilities such as automobiles and steel plants that also have bulk storage of flammable and combustible liquids. Implementing a risk management system that could evaluate the main causes and consequences of explosions in gas stations, focusing on the identification of prevention and mitigation barriers that could/should be applied by management to avoid and/or mitigate the consequences of explosions caused by gas or fuel leaks, can help achieve more realistic results. In addition, further research on the impact of combined consequences of gasoline emissions could help determine whether the combined effects of benzene with other chemicals are cumulative or synergistic.

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