# Accidental Release of Chlorine and Population Vulnerability Mapping using GIS and ALOHA

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**Abstract: For any type of hazard, either industrial or natural, one of the major elements at risk is the population in the hazard site. For responding and mitigating to such hazards, knowledge of the size and distributions of the human population in an area is essential. As chemical hazards are unpredictable and often devastating, conceptual framework and methods must be developed to help the decision makers and emergency personal to identify the areas that are likely to be affected as well as the characteristics of the population residing in the area. The present study focuses on the population vulnerability assessment associated with the atmospheric release of chlorine. The application of two software programmes, ALOHA (Areal Locations of Hazardous Atmospheres) and GIS (Geographical Information System) are incorporated in this study to assess the vulnerable population. This study identified the possible spatial extent of chlorine releases and estimated the vulnerable population coming under the impacted area.A modified method of Dasymetric mapping and Areal interpolation method is used in this study to estimate the vulnerable population. It has been estimated that the chlorine release likely to be resulted in a highly vulnerable situation by severely affecting more than 2000 people as the peripheries of the chemical installations are populated with permanent residents, mainly the industrial workers. The study also shows how GIS's analysis application can be useful in the chemical disaster management, and how the chemical dispersion model can be integrated with GIS applications to estimate the risk associated with the accidental release of hazardous chemicals.**

**Key Words: Chlorine release, Population vulnerability, GIS, ALOHA, Hazardous chemical**

## I. INTRODUCTION

Chemical disasters are the unintentional release of hazardous substances under certain circumstances that could harm human health and the environment. After the most serious disaster occurred in India, the Methyl Isocyanate (MIC) released in vapor and liquid form from the Union Carbon Plant in Bhopal, 1984 (Mehta et al., 1990; Mishra et al., 2009), more and more public attention has been paid to chemical emergency prevention and planning. Studies described the inadequacies of the responsible agencies during the Bhopal gas tragedy (Dinham&Sarangi, 2002; Khare,1990; Bowonder, 1987; Howland,1986). As an aftermath of the incident, UNEP initiated a worldwide program, Awareness and Preparedness for Emergencies at Local Level (APELL), in 1988 in order to prevent such disasters from recurring (Jover and Pavia, 1991). To prepare the nation to mitigate such accidents, national, state and district level emergency preparedness framework has been enforced by the Government of India as envisaged in Disaster Management Act, 2005. Manufacture, Storage and Import of Hazardous Chemical (MSIHC) Rules, 1989 and Chemical Accident (Emergency Planning, Preparedness, and Response) Rules, 1996 are the two sets of regulations that primarily handles chemical accidents in India, administered through Ministry of Environment and Forest, for the safety of workers as well as the nearby population outside the industry (Gupta, 2006). A multisectoral approach is required to reduce the occurrence and effects of industrial disasters (Sena and Michael, 2006).

Chlorine is one of the most common hazardous chemicals reported in an accidental release that has resulted in death, injury and evacuation (Kirk et al., 1994). India has witnessed countless industrial accidents involving the release of chlorine. Chlorine gas released from Haji Bunder hazardous cargo warehouse in the Mumbai Port Trust (MPT) in 2010 (Jones et al., 2010; Sharma et al., 2010), leakage from Kanoria Chemicals Industrial Ltd. (Uttar Pradesh) in 2006, from ruptured tank cars in Graniteville, South Carolina, in 2005, Chemplast accident (Tamil Nadu) in 2004, Orient Paper Mill (Madhya Pradesh) accident in 2003and GACL accident (Vadodara, Gujarat) in 2002 are some of the incidents happened in the recent past. For reducing the injuries, causalities, and death, it is necessary to assess the human vulnerability in the vicinity of the industries (Fatemi et al., 2017). For responding and mitigating such environmental hazards, the knowledge of the size and distributions of the human population in an area is essential (Liu, 2003).

In contrast to the traditional mathematical models, to assess the risk associated with the chemical release and asses the vulnerable population, the present study uses consequential modelling with the help of computer software. Many of the past studies uses merely the population density in an area to assess the vulnerable population. This kind of assessment does not give a clear idea about the exact location of the populated areas in an impact zone, and when it is depicted through a map, even the uninhabited area may be highlighted as an inhabited area. To solve this problem, this study adopted a more realistic depiction of population distribution method, called the Dasymetric mapping method. The method has already applied in the vulnerability analysis of ammonia in the industrial area(Anjana, 2018), and this study is the part of the same.

By incorporating two software programmes, ALOHA and GIS, a method is demonstrated through this study for assessing the vulnerable population during chemical release. It is expected that the methods used in this study will be very beneficial for the emergency responders for dealing with accidents in the limited time.

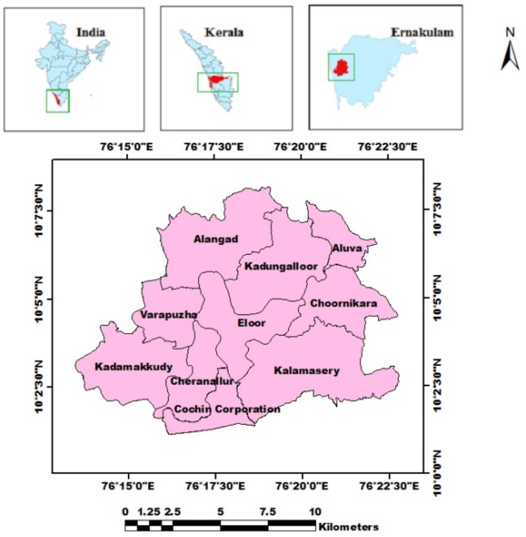
### *1.1. chlorine Storage and dangers involved therein*

Chlorine, a yellow-green gas, is easily recognizable with an intense pungent smell in its natural state, and with a molecular weight of 70.9 making it more than twice as heavy as air (Watt, 2002). Chlorine has a normal boiling point of -340C and is, therefore, a gas, but it is frequently handled as liquid gas under pressure (Mannan, 2005). Chlorine is slightly soluble in water, approximately 1 percent at 9.40C. Above this, its solubility decreases with rising in temperature up to the boiling point of water at which it is completely insoluble (Indian standard, 1997). Though chlorine is neither explosive nor flammable, it is almost as efficient an oxidizer as oxygen. Therefore, when mixed with chlorine any ordinary combustible or very flammable materials may become explosive (Routley, 1991). The significant hazard associated with chlorine is its inhalation by the people or animals (Bennett et al., 1982). Chlorine is classified as both toxic and poisonous. The threshold limit value (TLV) of chlorine is 1ppm and 35 ppm for a short period is considered to be dangerous. Chlorine can be smelt at a concentration of about 1/2 ppm or less so that persons exposed normally try to escape (Ruj&Chatterjee, 2012). Its long term occupational exposure standard is 0.5 ppm. Many organic materials react with chlorine explosively, and at higher temperatures many metals will burn in chlorine (Mannan, 2005).

Liquid chlorine in a ruptured tank during an accident is expected to volatilize rapidly, forming a greenish-yellow cloud of chlorine gas, which remains in the lower atmosphere, as it is heavier than air. From the source of release,these gas cloud can be carried several miles away. Various case studies have been reported on the release of chlorine from storage facilities (Yu et al., 2009; Gangopadhyay et al., 2005; Tseng et al., 2008). LOCATION DETAILS OF CHLORINE STORAGE FACILITY IN INDUSTRIAL AREA

The chlorine storage facility is located at 10004’29” N latitude and 76018’12” E longitude of Eloor Municipality, Ernakulam, Kerala. It is an industrial area north of Kochi and an island of 13.23 km2 formed between two tributaries of the river Periyar. According to the international environmental group Greenpeace (2003), the industrial belt of Eloor in Kerala is one of the world’s “top toxic hot spots.” Though this region is an industrial area, it has a unique ecosystem and a large number of people are residing in the surroundings of the industries.

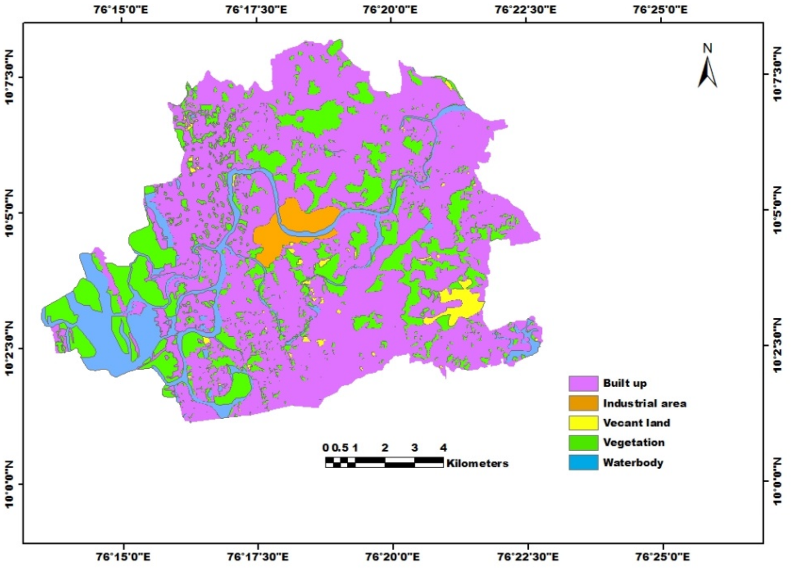
Though the installation is located in Eloor municipal area, in case of a chemical disaster, depending on the weather condition and other influencing factors of the gas leak, the chemical may spread into the neighbouring area depending on the wind direction. Therefore, based on the area likely to be affected by the release of chlorine, Eloor municipality and adjoining areas were taken into account in this study.The location is given in the Map 1.



Map 1: Location map of the study area

Around 322,121 people are residing in and around the Eloor industrial area and the Cochin Corporation along with contributing 601,574 people. The area covers 197 wards, and the population number of wards is ranging from 645 to 9274.

The LULC classification of the study area shown in Map 2 gives a clear idea of the land use pattern near the chemical installation of chlorine. The classification shows that 64% of the land is covered by human residences and other buildings. Both of these together are considered as a populated area in the study. When only populated area (built up area) is taken into account, the population density in the area may be about 2465 people / km2. Industries are located at only 2% of the total area. Water resources are available in 9 % of the total land and the remaining are vegetation (23%). Vacant land covers only 2%.



Map 2: LULC classification of the study area

## II. MATERIALS AND METHODS

Population vulnerability in an area due to chemical release depends upon various factors such as population density around the plant, hazardous nature of the released chemical, spatial extent and direction of the chemical released and proximity of the population to the hazard site. To attain the objectives of the study, two software programmes,ALOHA and ArcGIS, haves been aided by incorporating all the above information.

### 2.1 *Modeling of chemical release using ALOHA*

ALOHA is the air hazard program in the CAMEO software suite, developed and supported by the Emergency Response Division (ERD)in collaboration with the office of Emergency Management of the Environmental Protection Agency (EPA). ALOHA is widely used to simulate the airborne release of hazardous chemicals.

After gathering the required information, consequence analysis of the chlorine releases was carried out using the air dispersion model ALOHA. Consequence analysis, which includes the performance of air dispersion modeling of identified accidental release scenarios of hazardous chemicals into the atmosphere is essential to assess the severity of risk (Spellman, 1997), and it is one of the vital parts of determining the magnitude of Emergency Response Plan.ALOHA uses Gaussian Dispersion Model to estimate the atmospheric dispersion of gas clouds (NOAA and U. S. EPA, 2007).The data used to model Gaussian dispersion of chlorinein ALOHA is detailed below.

The performance of the consequence analysis and its results depend upon the accuracy of the information provided as input. For this purpose, various data, regarding the handling of hazardous chemicals, their storage condition, quantities, dimensions of the storage tank, weather condition, etc., were collected from the concerned departments.Basic data fed into the ALOHA model and the assumptions taken for modeling the chemical release are the following.

### *2.1.1 Properties of chlorine*

ALOHA's database includes a chemical library that dealswith the properties of the hazardous chemical. To model the atmospheric release of chlorine, the characteristics taken into consideration are physical state (Gas at ambient condition), Boiling point (-34.05°C), melting point (-101°C), Molecular weight (70.0g/mol), Gaseous density (3.213 kg/m3(About two and half times as dense as air), Solubility in water (slightly soluble), Expansion Ratio (450-500), etc.

### *2.1.2 Atmospheric condition*

Atmospheric conditions such as wind speed and stability largely influence the affected area of toxic, flammable, and explosive gas clouds (Canepa et al., 2000). The core factor in ALOHA's dispersion model is the stability classification. Since turbulence intensity cannot be measured directly, correlations are sought to indicate stability class as a function of readily measurable variables (Woodward, 1998). As it is difficult to measure the stability, Pasquill (1961) proposed a scheme in order to estimate the stability classes, which are dependent on wind speed and solar insolation during the day and cloud cover during the night. Paquill-Gifford's stability classes include six classes from the stable to unstable decided by the wind speed, solar radiation and cloud cover.

As it is impossible to predict when the accident can occur, in the present study, four hypothetical scenarios are selected - Scenario I, Scenario II, Scenario III and Scenario IV representing the Night, Morning, Afternoon and Evening respectively. The atmospheric variables taken into consideration are temperature, wind speed and humidity at the above-mentioned times, characteristic to the geographical location of Kochi. The average value of each of these variables respective to time, was taken by referring the site meteorological data collected from the weather monitoring stations operating in the City under Indian Meteorological Department (IMD). ALOHA determine the stability classes corresponding to the given weather conditions, where solar insolation and wind speed are the primary determining factor. Information on date, time, location, and cloud cover is used to determine the solar insolation in ALOHA (NOAA andU. S EPA, 2007). The values of atmospheric variables and stability class used in the modeling are given in Table 1.

Table 1: Atmospheric Variables used in Modeling.

| **Atmospheric Variables** | **Time of day** | | | |
|---|---|---|---|---|
| | **Scenario I Night (00.00)** | **Scenario II Morning (06.00)** | **Scenario III Afternoon (12.00)** | **Scenario IV Evening (05.30)** |
| Temperature | 24°C | 27°C | 32°C | 29°C |
| Humidity | 85% | 68% | 60% | 76% |
| Wind speed | 1 m/s | 1.5 m/s | 3.6 m/s | 3.3 m/s |
| Stability class | E | D | B | C |

### *2.1.3 Source Information*

The source is the vessel or pool from which a hazardous chemical is released into the atmosphere. Chlorine is liquefied and stored in a horizontal cylindrical tank with 7.31 m length and 2.8 m diameter. A partial pressure of 3kg/cm2 and temperature of -5°C are maintained in the storage tank.It is assumed that chemicals are leaking through a short pipe or valve of a storage tank which is used to transfer the chemical from the tank. In the case of selection of the size of the valve, through which a chemical is released into the atmosphere, different methodologies were used in different studies. Regardless of pipe size, some analysts use 2 inches and 4 inches diameter and, in some studies, it ranges from too small (0.2 inches) to large (6 inches) (AIChe/CCPS, 2000). In this study to understand the probability of risk of the chlorine releases the assumption taken is that the chemicals released through 2-inch diameter pipe connections. The valve opening was assumed beneath the liquid level. In a liquefied gas vessel, an open valve beneath the liquid level is potentially more serious than if it is placed in the gas space, as the mass flow rate is greater (Carson, 2002).

### *2.2 Population Vulnerability Assessment*

The methodology used to estimate the demographic composition of a population which can be affected by accidental releases of hazardous chemicals is an important element in the evaluation of consequences of serious accidents (Brzozowska, 2016). A modified method suitable for the study area of Dasymetric mapping and Areal interpolation method (Chakraborty& Armstrong, 1996) is used in this study to estimate the vulnerable population with the aid if GIS software Arc GIS 10.4.

### *2.3 Dasymetric Mapping and Areal Interpolation Method*

Many of the past studies use merely the population density in an area to assess the vulnerable population. This kind of assessment does not give a clear idea about the exact location of the densely populated areas in an impact zone. To solve this problem, this study adopted a more realistic depiction of population distribution method; called Dasymetric mapping method. The output of dasymetric mapping calculate the population for each Landuse-landcover cell.A dasymetric map depicts quantitative areal data using boundaries that divide the mapped area into zones of relative homogeneity and portraying the underlying statistical surface (Eicher&. Brewer, 2001). The term areal interpolation means transferring information from one set of boundaries to another (Goodchild& Lam, 1980; Lam, 1983) or from one set of spatial units to another. Area weighted interpolation, a simplest type of areal interpolation, is used here to calculate the vulnerable population

Several GIS databases were required to assess the community vulnerability including census data of each ward, ward boundaries andlanduse-landcover (LULC) characteristics of the area. The ancillary information of LULC is extracted from remote sensing images and Google Earth. The ward boundary maps of Panchayaths and Municipal areas were used for the identification of the wards within the studyarea.

After building the required layers, the spatial analytical capabilities of GIS tools such as overlay, extraction, zonal applications, reclassification, raster calculation, etc. helped to generate a population distribution map. In conversion tool, vector to raster conversion and in analyst tool, extract, overlay, and proximity, all were the unavoidable analytical tools in dasymetric mapping. Based on the methodology given by Holloway et al. (1997) and Mennis (2003), initially, LULC database was prepared and classified into five different classes such as built up, industrial area, vegetation, vacant land and water body. These classes were reclassified by giving values to each, based on the occurrence of population. The built up and industrial area is considered as highly populated, vegetation and vacant land is very less populated and the water body is considered as an uninhabited area in this reclassification. Population counts were correlated with these reclassified LULC classes to generate population distribution raster surfaces. The resulting raster surfaces and their attributes were then used to estimate the vulnerable population.

After preparing all the input information, to calculate the population for each LULC cell (pixel), a modified equation of Holloway et al. (1997) was used.

$P = ((RA^{*} (PA/PA))^{*} N/E) / AT$

Where,

'P' is the population of the cell,
'RA' is the relative density of a cell within LULC type A,
'PA' is the proportion of LULC type A in the ward
'N' is the actual population of ward
'E' is the expected population of ward calculated using relative densities.
'E' equals the sum of the products of relative density and the proportion of each LULC type in each ward.
AT is the total number of cells in the ward.

PA / PA, which cancels each other out, is to calculate the unit area in the grid-based dasymetric mapping. The output population estimated was not for each mapping unit (LULC type), but for each cell. The size of the cell was obtained from ArcMap and divide the area of the ward by cell size to get the value of AT.
Of the four scenarios modelled, only the worst case (a scenario which shows the largest impacted distance) was taken into account to assess the vulnerable population.The result of the modeling of chlorine releases by ALOHA in the form of a plume footprintcould be integrated directly with ArcGIS, and plume analysis was also done as part of estimating the vulnerable population. When the plume footprints overlaid on the GIS database layers, the shape of the footprint did not coincide with ward boundaries and LULC boundaries. In such cases, the areal interpolation method helps to compute the population within the plume footprint. The areal-weighting method is a straight forward algorithm for performing areal interpolation (Goodchild& Lam, 1980). The population within each threat zone plume footprint can be expressed as:

$$\mathbf{Pop} = \sum_{i=0}^{n} P_i + \sum_{j=0}^{m} (P_j * a_j' / a_j)$$

Where,

***n***: number of wards entirely enclosed by the footprint (whose boundaries may not coincide with the impact zone boundary)

***Pi*** : population of a ward entirely enclosed by the footprint.
$i$ = 0,1,2,3…………., n

***m*** : number of wards partially contained within the footprint (whose geographical boundaries do not exactly coincide with the footprint boundary)

**Pj** : population of the ward partially contained the footprint;
$j$ = 0,1,2,….., m

***aj***: total area of populated region of partially contained wards (calculated from the GIS laduse classification layer)

***aj'*** : area of populated region of partially contained wards that is enclosed within the footprint;

Though the degree to which the population is vulnerable to hazards depends upon the individual's character (health, age) and social factors (wealth, housing characteristics, etc.) (Cutter et al., 2000), this study gives more priority to the geographical proximity of the population to the potential source of the hazard. So, all the individuals coming within the hazardous zone are given equal priority.

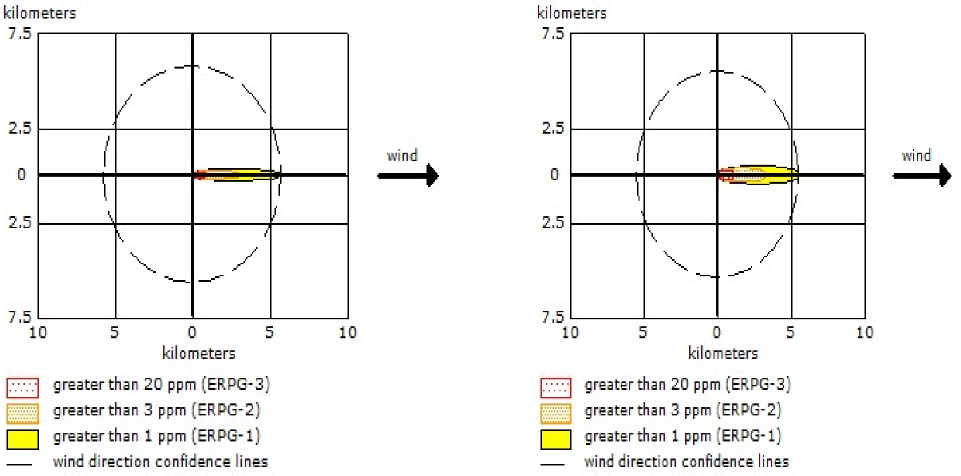
## III. RESULTS AND DISCUSSION

### *3.1 Consequence analysis of the toxic impact of chlorine*

The major impact associated with the large scale release of chlorine is its toxic inhalation hazard. ALOHA employs Levels of Concern (LOCs) to indicate the impact of toxic air plumes. LOCs for chlorine is given in Table 2.Here, in this study ERPGs (Emergency Response Planning Guidelines) are used for LOCs to anticipate health effects from exposure to certain airborne chemical concentrations. Figure 1 shows the graphical representation of the result of the modeling of chlorine release. The model depicted the impacted area in the form of threat zones, and the area within the threat zone is the region where the ground level concentration of the chemical exceeds the limit or threshold concentration.

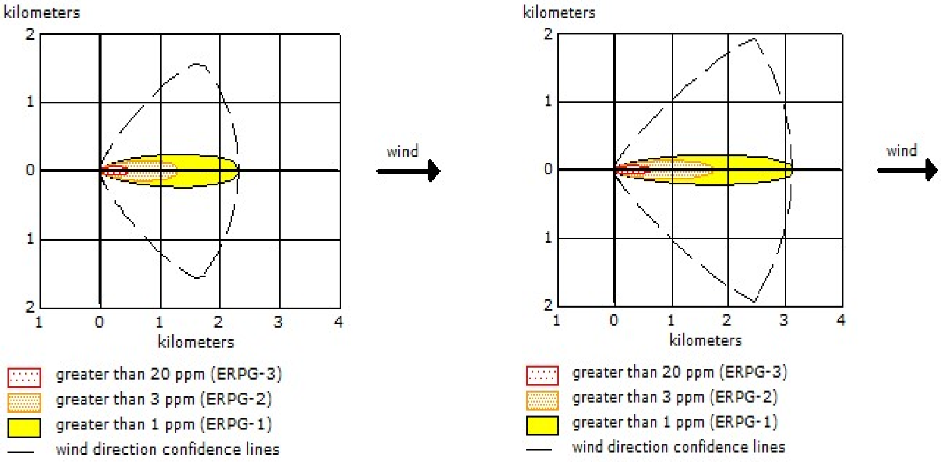
**Table 2:** LOCs taken for modelling the Toxic Inhalation Hazard affected area of Chlorine

| Threat modelled | Threat zones | Concentration of the chemical | Effect on people |
|---|---|---|---|
| ChlorineToxicity | Red (ERPG-3) | >20 ppm | Life threatening health effect |
| | Orange (ERPG-2) | >3 ppm | Serious health effect |
| | Yellow (ERPG-3) | >1 ppm | Transient adverse health effect |



**Scenario I (Night)**

**Scenario II (Morning)**



**Scenario III (Afternoon)**

**Scenario IV (Evening)**

Figure 1: Toxic Inhalation Impact affected distance of Chlorine under different Atmospheric Conditions

Toxic inhalation hazard affected distance of chlorine or the extent of threat zones in each scenario is given in Table 3. The largest dispersed extent, 5.8 km from the source is observed for the scenario I and its red, orange, and yellow zones distance are 1.1 km, 3.2 km and 5.8 km respectively. The release rate of the chemical estimated is 41 kg/ min and the amount of chemical released during one hour is 2,454 kg. It is observed that, of the four scenarios modeled, considering different atmospheric conditions, the night time conditions take the hazardous gas clouds to a larger distance than the other times of a day. The shortest hazardous distance is observed during the mid-day. Meteorological conditions such as wind speed and stability, representing the amount of atmospheric turbulence, are likely to have a definite influence on the overall hazardous distances. If the air is more turbulent, it causes quick dilution of toxic clouds. Stability class is at its peak during mid-day due to larger solar radiation. Under this condition (unstable conditions), because the pollutants are soon diluted, the hazardous gas clouds will not travel to a larger distance as far as it is expected under stable conditions. The largest impacted area estimated under night time conditions (scenario I) is considered as the worst-case scenario and further analysis in this study is based on this worst-case scenario.

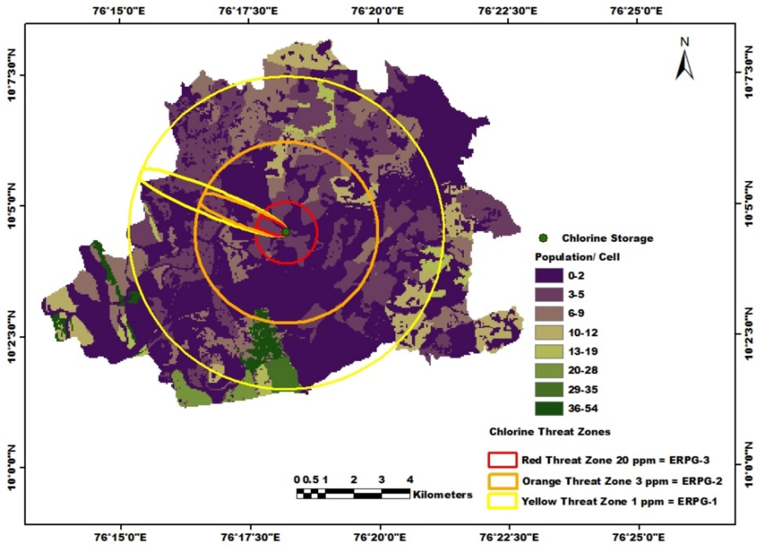
Table 3: Toxic Inhalation Hazard affected distance of Chlorine under different Atmospheric Conditions.

| **Threat zone** | **Scenario I (Night)** | **Scenario II (Morning)** | **Scenario III (After noon)** | **Scenario IV (Evening)** |
|---|---|---|---|---|
| Red | 1.1km | 908 m | 481m | 642m |
| orange | 3.2 km | 3.2 km | 1.3km | 1.8km |
| yellow | 5.8 km | 5.5 km | 2.3km | 3.1km |

### *3.2 Population Vulnerability of Chlorine Release*

The modeling result indicates that in the worst case scenario, the most hazardous concentration of chlorine as indicated by the red threat zone may extend up to a distance of 1.1 km from the source depending on the release conditions. The lesser hazard concentration zones, orange and yellow, may extend up to a distance of 3.2 km and 5.5 km from the source of release. The red, orange and yellow circles indicate the wind confidence line, as the wind changes its direction. As the modeling is done by considering the wind direction from ESE, the threat zone direction in the map is in the NW direction.

Map 3 shows the population distribution in the area with overlaid threat zones of chlorine release. The wind direction may change with time. Therefore, population vulnerability is assessed in all directions around the chlorine installation. Population vulnerability assessment indicates that (Table 4) within the most dangerous red zone, in the NE and NW direction there is no public population. As this zone is covered by the industrial areas, the workers of the industries need to take immediate protective measures. But this red zone is vulnerable in SE and SW directions, which includes nearly 1200 and 360 people respectively. But, a large number of people comewithin the orange and yellow threat zones.It is indicated that when the wind direction changes, high variability can be seen in the vulnerable population. Within the orange threat zone, a higher number of populations is seen in the NE direction and less population in the SE direction, whereas in the case of the yellow threat zone, a higher number is observed in the SW direction. However, when considering the total number of population (including all the three threat zones), the SW direction contains the highest population.



Map 3: Population Distribution Map with overlaid Threat Zones of Chlorine Release

Table 4: Number of People likely to be affected around the Storage Facility of chlorine

| **Threat Zone** | **Population likely to be affected in different directions around the Storage Facility** | | | | **Expected impact on people** |
|---|---|---|---|---|---|
| | **NE** | **SE** | **SW** | **NW** | |
| **Red** | Workers of the industry | 1200 | 360 | Workers of the industry | Life threatening health effect |
| **Orange** | 15221 | 11332 | 12804 | 14294 | Serious health effect |
| **Yellow** | 23522 | 18793 | 32338 | 22053 | Transient adverse health effect |

Note: NE- North East; SE- South East; SW-South West; NW- North West

Larger the dispersed area, the larger will be the impacted population. In the study area, chlorine release will beresulted in a highly vulnerable situation as the peripheries of the chemical installations are populated with permanent residents, mainly the industrial workers. Therefore, even a small scale release of chemical may cause high risk.

From the resulting population vulnerability map emergency management personnel can easily understand at a glance where the population is concentrated within the threat zone of chemical release and its related attribute can provide the exact number of populations in the area, which needs immediate and subsequent evacuations. Such population vulnerability maps will be very useful information during evacuation procedures.

Knowledge of the spatial distribution of population, as well as the vulnerable population, can help to be better prepared for accidental chemical releases and to develop appropriate mitigation strategies to reduce the risks for the area under consideration.

## Conclusion

An attempt has been made in this study to estimate the atmospheric dispersion of chlorine and population vulnerability. The study showed that the varying atmospheric conditions largely influence the dispersion of chlorine gas clouds in the atmosphere. The highest dispersed area observed in the study at night time ismainly because of the stable atmospheric condition. Not only the atmospheric conditions, but also the characteristics of the chemical, its storage condition, and nature of leakage, all influence the dispersed area of chlorine.As it is not possible to relocate the industries to other safer places, the only precautions we can take is to be prepared to prevent and reduce theimpact. No generally applicable rule can be applied to understand the influence of atmosphere on gas dispersion because the intensity of the variables changes not only with the time but also with the season. Considering this, through the present study an attempt is made to assess the vulnerability using the spatial data with the help of GIS and the model ALOHA. The study proves that for providing timely accurate answers to geographical queries during an emergency situation, GIS applications are uniquely helpful. The consequence analysis using computer software, ALOHA, used in this study found that it can easily be run by entering accurate data. Hence, it can be useful even at the time of the accident. Moreover, it provides an intuitive visualization of the impacted area. Identifying areas that are most vulnerable to hazard has immense value in all the stages of chemical disaster management.A good insight can be provided by these types of studies to the decision makers to identify the possible threat zone, formed from chemical hazards like toxic release.

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