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RESEARCH ARTICLE

Modelling the Chlorine Dispersion from Hypothetical Leak in Kasigui Water Treatment Plant

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Abstract The dispersion of a hypothetical chlorine leak from the Kasigui water treatment plant was modeled using the Areal Locations of Hazardous Atmospheres (ALOHA) software. Meteorological data, including wind speed, direction, and time, were obtained from the local weather station through the Malaysian Meteorological Department for the simulation. The effect of wind conditions on the chlorine dispersion was evaluated using both the Gaussian plume and heavy gas models. The local concentration and threat zones were mapped using the Mapping Application for Response, Planning, and Local Operational Tasks (MARPLOT) software, with the aid of OpenStreetMap. The results showed that the residential areas surrounding the plant, including Taman Kasigui, Taman Desa Manis Kasigui, Kg Kibabaig, Kg Tuavon, Kg Nampasan, the Sabah Cultural Center, Jabatan Pertanian Penampang, the Penampang District Council, and Kg Dabak, were affected by a dangerous chlorine dispersion, as indicated by 60 minutes Acute Exposure Guidelines Level 3 (AEGL-3) (>20 ppm). Suitable safety evacuation routes were proposed to reduce the risk of exposure to hazardous gas. The findings from this work are useful for understanding the risks of chlorine gas dispersion around the Kasigui water treatment plant.

Keywords: Chlorine dispersion, emergency response, safety evacuation route, modelling, monsoon season.

Introduction

Chlorine, a commonly used water treatment chemical, is essential for disinfection, as it eliminates germs and pollutants. While its effectiveness is acknowledged, challenges arise, such as the formation of disinfection by-products and the need for careful handling and storage (Dyson, 1961). Chlorine is also widely utilized in the manufacture of numerous chemicals, including solvents, insecticides, and polymers, as well as being a common disinfectant in water treatment and swimming pools. Despite its uses, chlorine is a dangerous substance that may trigger serious health problems if not handled appropriately. Inhalation of chlorine gas can irritate the respiratory system, resulting in coughing, wheezing, and shortness of breath (CDC, 2018). Prolonged exposure to high chlorine concentrations can cause lung damage and, in severe cases, pulmonary edema. Chlorine gas can also irritate the skin and eyes, and exposure to high doses can result in chemical burns. The detection threshold for the odor of chlorine is as low as 3.5 ppm, and exposure to 1000 ppm of chlorine gas can be fatal after only a few deep breaths. Higher levels of chlorine exposure have been observed to cause more severe effects in humans, including mild irritation of the mucous membranes at concentrations of 1 to 3 ppm, and symptoms like chest pain, vomiting, difficulty breathing, and coughing at concentrations of 30 ppm. At even higher concentrations of 46 to 60 ppm, chlorine exposure can lead to toxic pneumonitis and pulmonary edema (National Center for Biotechnology Information, 2023). Chlorine gas leaks pose dangers to human health, residential areas, and the environment. The consequences of a chlorine leak can be severe, as evidenced by past leak incidents.

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Chlorine leakage incidents have occurred worldwide, resulting in numerous deaths and injuries, and posing a significant threat to human health and the environment. Several notable chlorine gas leak incidents have occurred in recent years. On June 27, 2022, a chlorine gas leak in Aqaba, Jordan, resulted in 14 deaths and over 300 injuries when a tank fell from a crane (Palacios *et al*., 2024). In Malaysia, a leak at the Malay-Sino Chemical Industries factory in 2016 was caused by a ruptured ferric acid tank, leading to several injuries (Nasa, 2016). More recently, on November 29, 2023, a chlorine leak in Pegagau, Sabah, occurred when an excavator ruptured a tank, exposing six workers to the gas. Another leak in Kota Belud, Sabah, in 2017 was stopped without injuries (Goh, 2017). A similar incident in Kuala Krai, Kelantan, in 1997, led to 79 people being evaluated for respiratory distress, with 20 hospitalized. These incidents underscore the dangers of chemical exposure and the need for strict safety protocols (Toyos, 2023). It is clear from these recent incidents that chlorine leaks can seriously affect both plant workers and nearby residents. The Kasigui Water Treatment Plant, located near Donggongon town in Penampang, Sabah, was initially built relatively far from residential areas. However, due to the urbanization of Donggongon, more residential and public buildings have been developed in the vicinity of the plant. No study is currently available on chlorine dispersion in the Donggongon area or around the Kasigui Water Treatment Plant. Therefore, the risk of chlorine leaks from the Kasigui Water Treatment Plant is a concern, as chlorine is used and stored at the plant. It is also important to develop a suitable safety evacuation plan in the event of accidental chlorine leaks.

Wind speed significantly affects gas dispersion, with higher speeds promoting faster dispersal and lower concentrations, while low speeds lead to gas accumulation near the source (Xin *et al*., 2021). Wind direction also influences gas distribution, and tools like wind roses are used to visualize wind patterns and pollutant transport (Chakrabarti, 2016). Malaysia's weather is defined by two distinct monsoon seasons: the southwest monsoon, occurring from late May to September, and the northeast monsoon, which runs from November to March. The inter-monsoon occurs in April and October (Law *et al*., 2019). Studies by Erain *et al*. (2017), Law *et al*. (2019), and Sudarsan *et al*. (2016) concluded that seasonal changes in wind speed and direction affect pollutant plume dispersion and risk zones. Therefore, this study includes atmospheric stability, wind speed, and direction in the chlorine gas dispersion modeling.

ALOHA is commonly used by several researchers to predict chlorine gas dispersion and to evaluate its consequences (Chehrazi *et al*., 2024; Tseng *et al*., 2012; Bagheri *et al*., 2020; Horng *et al*., 2005; Ilić *et al*., 2018; Jeong and Baik, 2018). A comparison of ALOHA with other software, such as SLAB, RMP*Comp, and numerical calculations, was made by Horng *et al*. (2005) and Chehrazi *et al*. (2024), who concluded that ALOHA offers more practical advantages for real-time assessments and emergency response due to its user-friendly interface and accessibility. In their assessment of toxic chemical releases, Tseng *et al*. (2012) found that ALOHA provided good predictions of toxic chemical dispersion and its threat zones, which are helpful for risk assessment and emergency planning. Bagheri *et al*. (2020), who evaluated chlorine dispersion from a water treatment plant, also found that ALOHA is useful for predicting chlorine dispersion, especially in identifying high-risk zones, thus enabling emergency planning and rapid response measures in the event of accidental chlorine leaks. Jeong and Baik (2018) and Ilić *et al*. (2018) studied chlorine leaks from chemical plants and chlorine stations. They reported that ALOHA can predict the potential risks posed by chlorine leaks, particularly to local residents. They emphasized that ALOHA's predictions are useful for developing effective safety measures and risk mitigation strategies, including evacuation plans. In conclusion, ALOHA provides good predictions of chlorine dispersion, which allow for the estimation of threat zones and are useful in emergency evacuation planning. Law *et al*. (2019) employed the ALOHA model to simulate gas dispersion and investigate the effects of variables such as wind speed, direction, and atmospheric stability on dispersion patterns in the industrial area of Gebeng. They reported that in the case of relatively flat surface terrain, ALOHA's predictions are similar to those of CFD simulations. Therefore, since the surface terrain in the Donggongon town area is mainly flat, ALOHA can be used to predict chlorine gas dispersion with acceptable accuracy. ALOHA allows for the prediction of chlorine gas dispersion, which can be mapped using MARPLOT on OpenStreetMap to determine the threat zones. According to the Emergency Response Planning Guidelines (ERPGs), locations affected by chlorine concentrations at AEGL-2 and above require evacuation. Consequently, an emergency evacuation route for Donggongon town, in the event of accidental chlorine leakage from the Kasigui water treatment plant, is proposed based on the modeling results.

Methodology

Meteorological Data

The meteorological data on temperature, humidity, wind speed, and direction were obtained from the Malaysian Meteorological Department. Data was collected from the closest weather station to the area of interest, which was the Kota Kinabalu station, covering the period from January to December 2022. The meteorological data were subdivided according to the two monsoon seasons: the Southwest and Northeast monsoon seasons. The first and second inter-monsoon transitions were also considered. A wind rose plot of the wind direction and speed was generated using Origin 2024 software.

Modelling of Chlorine Gas Dispersion

The modeling of chlorine dispersion was performed using ALOHA 5.4.7. This model is designed to estimate chemical dispersion in the event of an accidental release, using information on the specified site, period, atmospheric stability, wind speed, wind direction, temperature, humidity, chemical properties, leakage source, and chemical release rate. ALOHA's chemical database contains about 700 pure chemicals, including chlorine (NOAA, 2024; Law and Gimbun, 2020). Chlorine was selected from ALOHA's chemical database and was treated as a non-reactive chemical. The chemical dispersion was modeled using dispersion models such as the Gaussian and heavy gas dispersion models. In this work, the heavy gas dispersion model was chosen for downwind dispersion since chlorine is denser than air. ALOHA accounts for gravitational forces, in which the dispersion of heavy gas is influenced by wind and atmospheric turbulence.

The hypothetical chlorine leak in this work originates from a horizontal chlorine cylinder tank. The source of the chlorine leak is a single-story building that houses two large cylinders of liquid chlorine, and the leak is assumed to occur over a duration of one hour. The quantity of chlorine gas leaked is based on the size of the chlorine gas tank, which weighs about 500 kg. The leak is assumed to originate from a malfunctioning gas valve or connector with an opening diameter of 1 cm, assuming the valve or pipe is not completely broken. An analysis of leak source diameters of 0.5 cm and 1 cm is also conducted to assess their effect on the AEGL distance. The liquefied chlorine is stored at ambient temperature. The maximum average sustained release rate of chlorine at 500 kg/h was assumed based on the amount of chlorine stored. The concentration of the plume is calculated using the heavy gas dispersion model following Colenbrander (1980) with atmospheric stability class following Briggs (1973). The threat zone analysis was set based on chlorine concentrations of AEGL-1 (>0.05 ppm), where individuals may feel discomfort, AEGL-2 (>2 ppm), which may cause long-term adverse health effects, and AEGL-3 (>20 ppm), which poses a life-threatening risk.

ALOHA is considered valid for use in this work because the Kasigui water treatment plant, located near Donggongon town, is situated on primarily flat terrain. The wind data were obtained from a continuous air quality monitoring station at Kota Kinabalu Airport, located approximately 7 km from the Kasigui water treatment plant. The wind direction around Donggongon town is influenced by the northeast monsoon (November to March) and the southwest monsoon (mid-May to September), with two inter-monsoon periods, typically around March-April and October-November. However, only one month is designated as an inter-monsoon period, i.e., April and October, since changes in monsoon seasons typically occur at the end of March or mid-November. To ensure this study covers a wide range of conditions, the three most frequent wind directions for each month were analyzed. Temperature and humidity were set between 31–32.8°C and 75–90%, respectively, based on the monthly average data from the meteorological department. Based on the temperature, humidity, and wind speed, ALOHA determines atmospheric stability according to Pasquill's classification (Crowl & Louvar, 2001). The urban dispersion parameters (Vallero, 2019) were used in this work since Donggongon town is an urban area.

Mapping of Threat Zone and Evacuation Route

The source point in this work is the Kasigui water treatment plant, located at coordinates 5.916251, 116.110824 (Figure 1). It is clear from the map that Kasigui water treatment plant is surrounded by residential area, which may be affected in the event of accidental chlorine leak. ALOHA modeling was used to predict the chlorine dispersion, while MARPLOT (Mapping Application for Response, Planning, and Local Operational Tasks), which uses actual maps, was employed to generate a threat zone map. Based on the threat zone mapping obtained from MARPLOT, appropriate evacuation routes to suitable evacuation centers, such as public halls or schools, were proposed. In the event of a chlorine leak, an emergency school holiday in the area could be declared to reduce public exposure to chlorine gas. Therefore, schools can also serve as evacuation points.

The evacuation routes were proposed according to two criteria: using existing roads available in the area and avoiding any potential areas affected by the chlorine plumes. Several suitable evacuation locations were identified in the event of a chlorine gas leak from the Kasigui water treatment plant, as shown in Table 1. All the proposed evacuation points are not affected by chlorine dispersion at AEGL-2 and AEGL-3 levels in any scenario or wind condition.

Table 1. Proposed evacuation point

No	Evacuation point	Distance (km)
1	Dewan Raya Kg Mogoputi	3.2
2	Nagasiba hall	4.0
3	KDCA hall	3.3
4	Nosoob Baru community center	5.2
5	St Anthony national school	4.9
6	GKC Sabah	3.6
7	Dewan Paroki Sacred Heart	3.8
8	Dewan Pagansakan	3.9
9	Dewan Raya Kg Ramayah	4.6

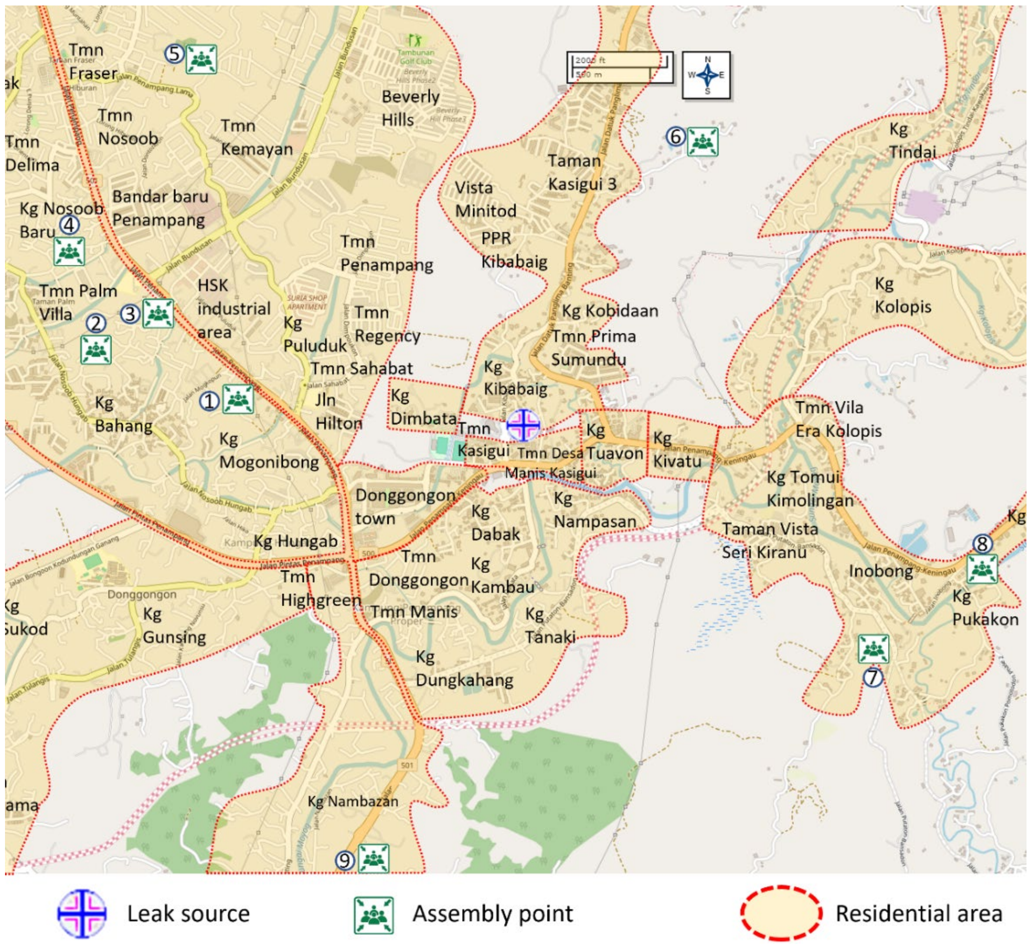

Figure 1. Map indicating the location of Kasigui water treatment plant and designated evacuation points in Donggongon Sabah

Results and Discussion

Meteorological Data

Malaysia's weather is influenced by two distinct monsoon seasons: the southwest monsoon, occurring from late May to September, and the northeast monsoon, from November to March. Wind rose plots were generated for each month in 2022 based on wind speed and direction data obtained from the Malaysian Meteorology Department. Figure 2 shows wind rose plots for each month during the northeast monsoon and the first inter-monsoon in April. The transition to the northeast monsoon typically occurs after mid-November, so the wind direction in November does not feature much of the northern wind. In November, the prevalent wind directions are west-northeast (13.3%), east-southeast (16.7%), and west

(13.3%). In December, south-southwest (22.8%), east-southeast (13.0%), and north (13.0%) emerge as the three wind directions with the highest percentages. The prevailing wind directions with the highest percentages among the eight directions are north (36.0%), east (13.0%), and north-northwest (13.0%) in January. In February, the dominant wind directions are north (32.5%), north-northeast (18.0%), and east-northeast (11.0%). In March, the predominant wind directions are from the southwest (9.8%), west-northwest (13.0%), and north (16.1%). It can be observed that wind direction in March starts to shift southeast as the monsoon season begins transitioning at the end of March. The prevailing wind directions in April for the first inter-monsoon are as follows: northwest, accounting for 16.8%, and east-southeast and south-southwest, both representing 13.2% frequency.

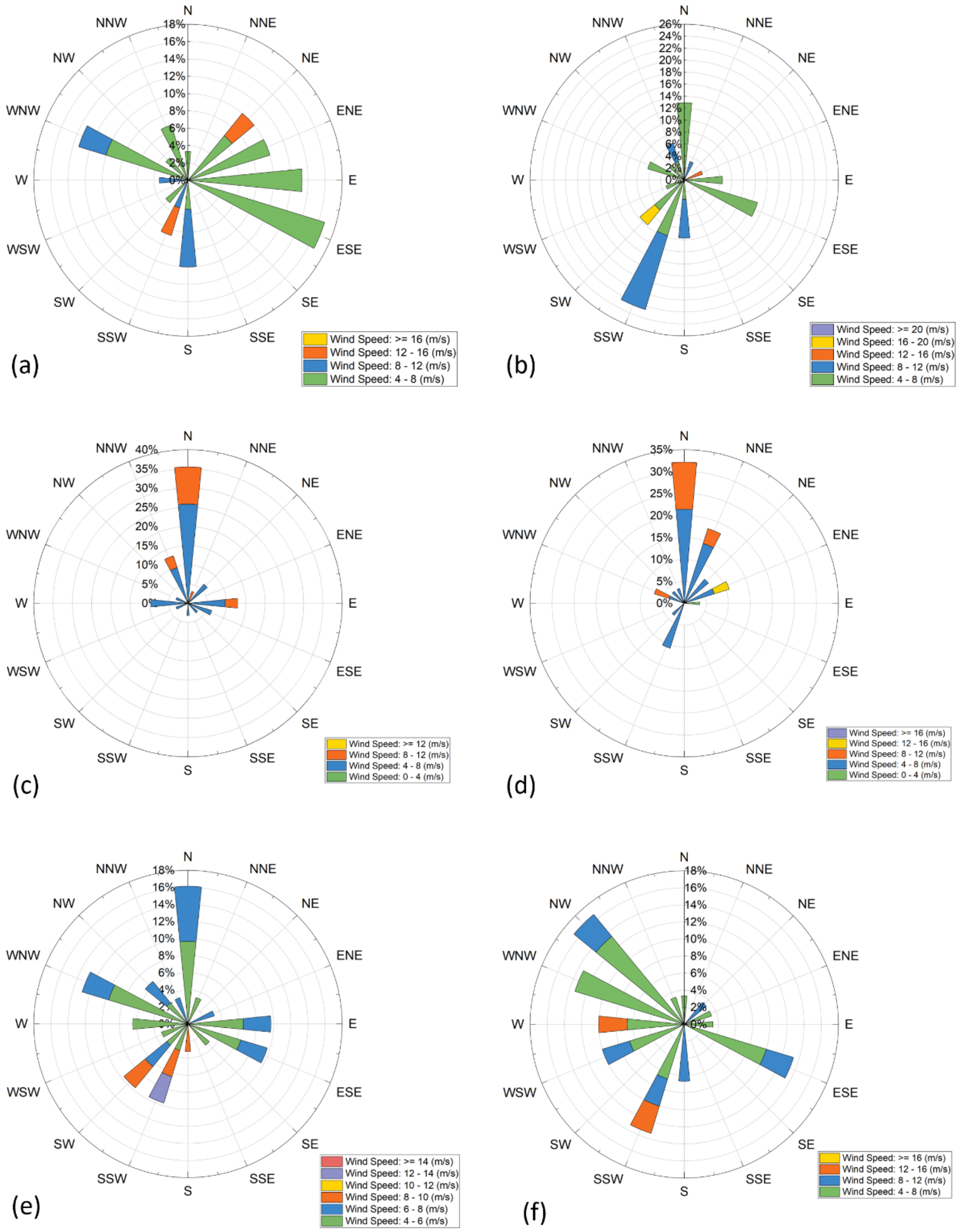

Figure 2. Windrose monthly plots for northeast monsoon and 1st inter-monsoon. (a) November, (b) December, (c) January, (d) February, (e) March, (f) April

Figure 3 shows monthly wind rose plots for the southwest monsoon and the second inter-monsoon in October. The predominant wind directions in May are east (22.6%), northwest (12.9%), and west-northwest (12.9%). In June, the prevailing wind directions include east-southeast (13.2%), south-southwest (23.3%), and west (10.0%). In July, the primary wind directions are east (16.1%), west (16.1%), and southwest (9.8%). In August, the dominant wind directions consist of northwest, east, and south-southwest, each with a frequency of 16.1%. In September, the most frequent wind directions are southwest (23.3%), south-southwest (13.3%), and east-southeast (16.1%). During the second inter-monsoon, the three most frequently occurring wind directions in October are south-southwest (22.5%), southwest (16.2%), and west-northwest (16.2%).

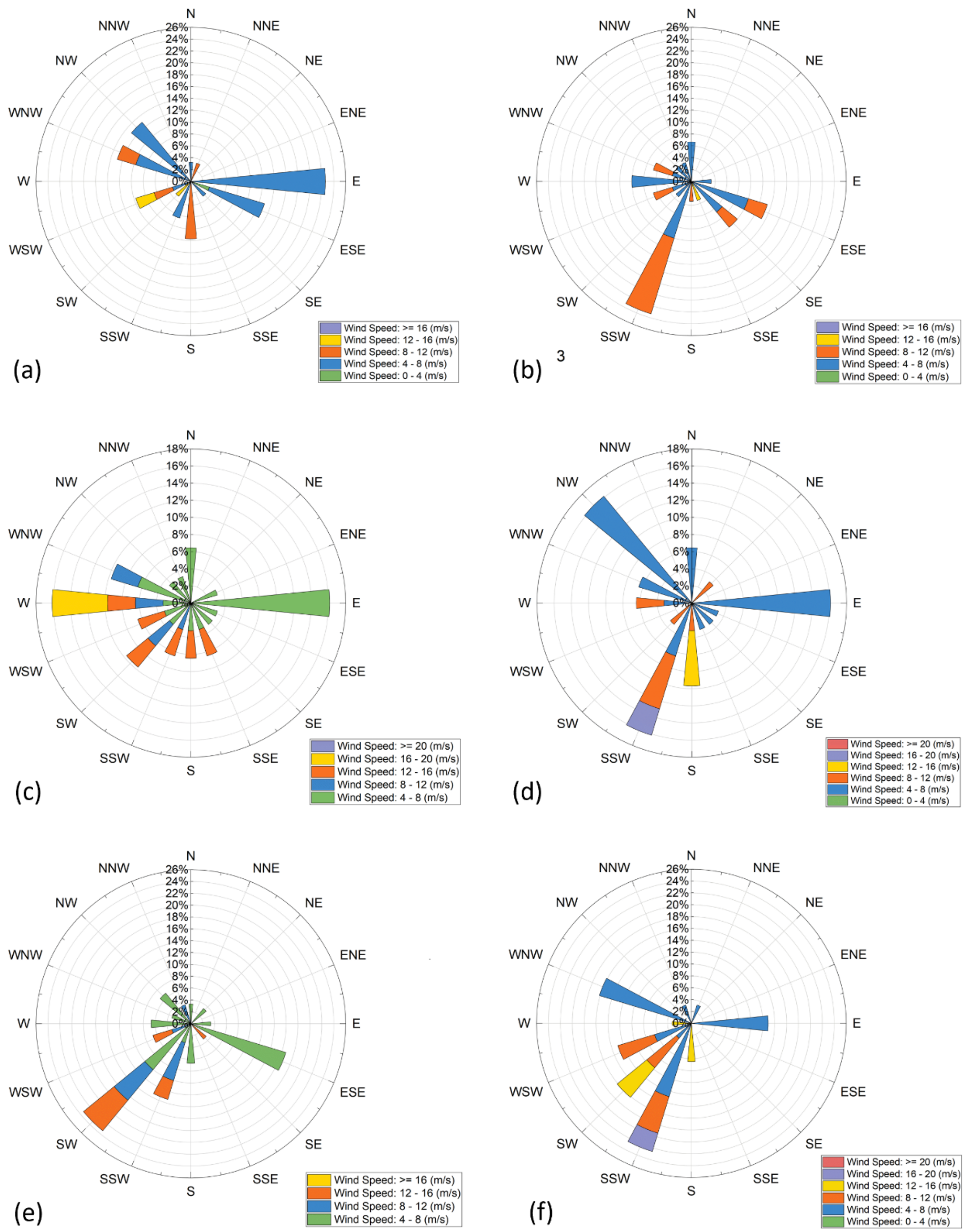

Figure 3. Windrose monthly plots for southwest monsoon and 2nd inter-monsoon. (a) May, (b) June, (c) July, (d) August, (e) September, (f) October

ALOHA analysis was performed by considering the three most prevalent wind speeds and directions in each month. Table 2 presents a summary of the meteorological data used to calculate chlorine dispersion using ALOHA software. The threat zone was then plotted in MARPLOT to accurately map the danger to local households and businesses. MARPLOT can use a basemap from Google Maps, Esri Streets, Esri Satellite, Esri Physical, or OpenStreetMap. In this work, the OpenStreetMap basemap was used to generate the threat zone plot. Predicted threat zones from the three most prevailing wind directions in each month were then combined to map the most probable threat zone for each month. Accordingly, suitable evacuation routes for each month were proposed. The evacuation sites in this work are either public halls or schools, as these buildings are accessible to the public during emergencies. Public halls or schools are also often used as evacuation points during flooding emergencies.

Data on wind direction and speed, as well as average humidity from the Malaysia Meteorological Department, was not differentiated between day and night. However, temperature data is available for both day and night. Temperature may affect gas density and buoyancy, atmospheric stability, as well as evaporation and vapor pressure, and may therefore influence chlorine dispersion. Chlorine dispersion during the months of November (Northeast monsoon) and June (Southeast monsoon) was studied to understand the differences between day and night-time dispersion.

Table 2. Summary of the meteorological data

Season	Month	Temperature (°C) Day	Night	Humidity (%)	Average wind speed (m/s)	Direction	Prevalence (%)
Northeast monsoon	November	31.8	23.6	89	8.27	ESE	16.7
					6.25	WNW	13.3
					5.99	E	13.3
	December	31.0	23.4	86	8.55	SSW	22.8
					5.55	ESE	13.0
					7.96	N	13.0
	January	31.3	23.9	81	7.45	N	36.0
					6.5	E	13.0
					7.63	NNW	13.0
	February	31.5	23.7	76	7.69	N	32.5
					5.78	NNE	18.0
					8.03	ENE	11.0
	March	31.5	24.0	75	7.82	SW	9.8
					5.20	WNW	13.0
					6.15	N	16.1
1st inter-monsoon	April	32.1	24.0	81	6.26	NW	16.8
					7.07	ESE	13.2
					11.65	SSW	13.2
Southeast monsoon	May	32.8	24.7	89	5.72	E	22.6
					5.32	NW	12.9
					9.22	WNW	12.9
	June	32.1	24.1	88	6.73	ESE	13.2
					6.68	SSW	23.3
					6.85	W	10.0
	July	32.4	23.8	87	5.36	E	16.1
					10.70	W	16.1
					10.68	SW	9.8
	August	32.4	23.7	89	5.43	NW	16.1
					6.08	E	16.1
					10.56	SSW	16.1
	September	31.4	23.7	89	9.89	SW	23.3
					9.89	SSW	13.3
					8.26	ESE	16.8
2nd inter-monsoon	October	31.6	24.1	90	9.92	SW	16.2
					9.24	SSW	22.5
					6.98	WNW	16.2

Chlorine Dispersion and Evacuation Routes

The threat zone is classified according to 60-minute Acute Exposure Guideline Levels (AEGLs), where AEGL-1 is >0.2 ppm, AEGL-2 is >2 ppm, and AEGL-3 is life-threatening at >20 ppm. The area affected by AEGL-1 is indicated by yellow, while the areas affected by AEGL-2 and AEGL-3 are indicated by orange and red, respectively. According to NOAA (2024), areas with chlorine gas concentrations of AEGL-2 and AEGL-3 require safety evacuation, while areas affected by AEGL-1 do not require evacuation unless an individual has a medical condition that may worsen due to chlorine exposure. Typically, babies and elderly individuals are evacuated from areas affected by AEGL-1 as a precaution. Therefore, in this work, evacuation routes are indicated for all areas affected by AEGL-1, AEGL-2, and AEGL-3, even though AEGL-1 does not mandate evacuation. According to NOAA (2024), AEGL-1 represents a concentration where individuals may experience discomfort, irritation, or certain asymptomatic nonsensory effects, which are temporary and reversible upon cessation of exposure. AEGL-2 represents a concentration where individuals may suffer irreversible or long-lasting adverse health effects or have impaired ability to escape. AEGL-3 represents a concentration where individuals may face life-threatening health effects or death.

Figure 4 shows the effect of chlorine leak source size on the threat zone at a wind speed of 6 m/s, a temperature of 31.6°C, and a humidity of 89%. It was found that the AEGL-2 distance increased significantly when the leak source doubled from 0.5 cm to 1 cm. For a 0.5 cm leak source, the AEGL-2 extended to a distance of about 0.9 km, while for a 1 cm leak source, the AEGL-2 reached approximately 1.4 km. In this hypothetical leak incident analysis, the leak source is assumed to be 1 cm, since it represents a worst-case scenario.

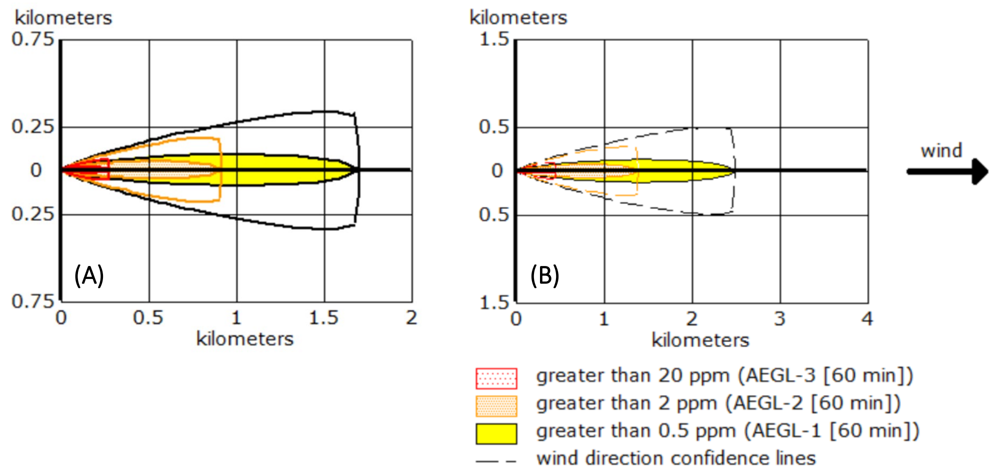

Figure 4. Comparison of leak source size and AEGL distance. A) 0.5 cm, B) 1 cm

Figure 5 shows the difference between chlorine dispersion during the day and at night in the months of November and June. It was found that the affected area is greater during the daytime. Therefore, a detailed analysis is only performed for the worst-case chlorine leak scenario during the day. This analysis may have limitations, as wind direction data specific to day or night is not available. Instead, the wind data used in this analysis is time-averaged over a 24-hour period. Similarly, the humidity data is averaged over the entire day, with no separate information for day or night. Despite these data limitations, the purpose of this study is to predict the worst-case scenario. Based on the available meteorological data, chlorine dispersion during the day appears worse than at night. This is due to the effect of temperature on several factors, such as gas density and buoyancy, atmospheric stability, and evaporation and vapor pressure. It was found that the temperature changes from 31.8°C during the day to 23.6°C at night do not affect atmospheric stability in November, as it remains classified under stability class D. Similar observation was found for the month of June. Temperature affects chlorine liquid release from the tank, as lower temperatures at night slow the evaporation process, thereby reducing the rate of gas release. ALOHA models heavy gases like chlorine, which tend to settle close to the ground due to their density. Temperature also affects the density difference between the chlorine gas and the surrounding air. At night, lower temperatures increase the density of chlorine gas and decrease its buoyancy, which may cause the gas to remain close to the ground, reducing the distance it can travel. While temperature inversion may occur at night, it is less likely in tropical regions, especially under high-humidity conditions. In tropical areas, temperature inversion at night is often associated with high-altitude regions that can trap cooler air near the surface. The Kasigui water treatment plant is located on flat terrain, averaging about 5 meters above sea level, in a high-humidity, tropical climate. Therefore, temperature inversion is not considered in this study.

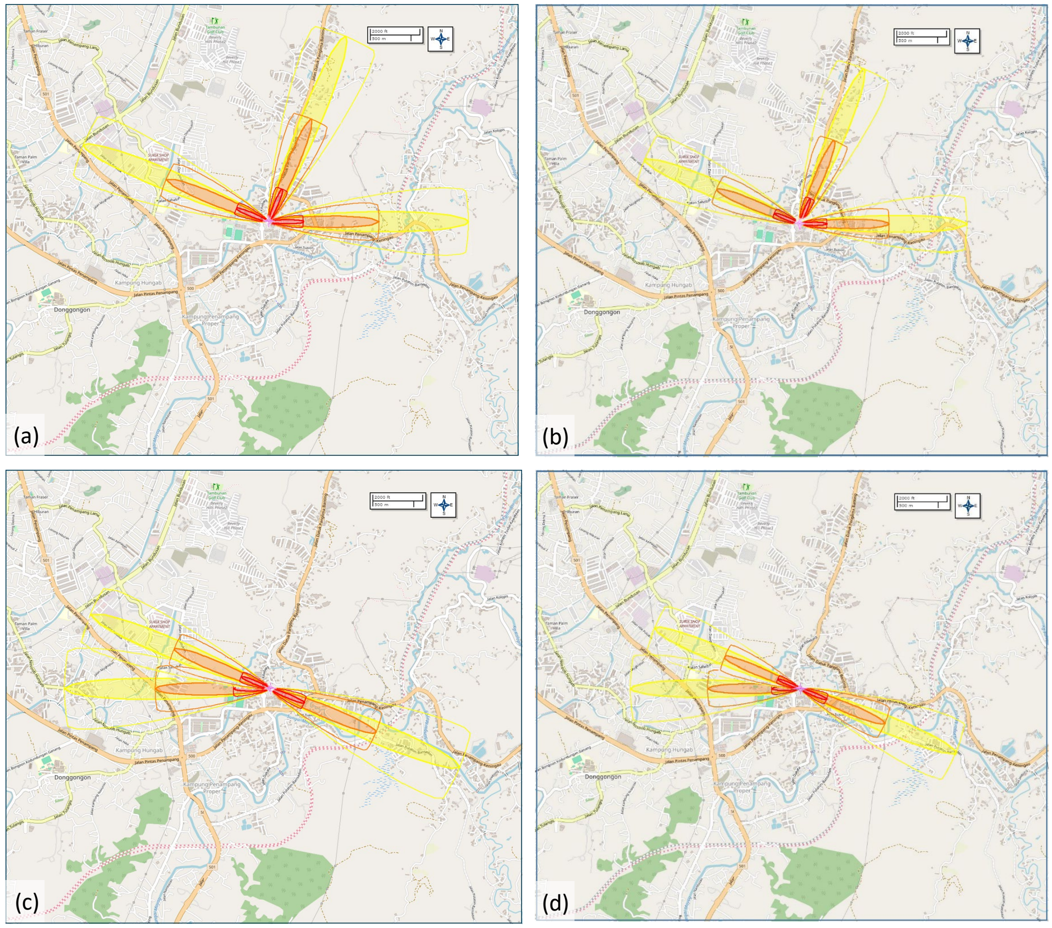

Figure 5. Comparison of chlorine dispersion during the day and night in June and November. a) June daytime, b) June nighttime, c) November daytime, d) November nighttime

Figure 6 shows the threat zone map of chlorine during the northeast monsoon season and the first inter-monsoon. While, the summary of the affected areas and evacuation points for each month is provided in Table 3. The evacuation routes consider two main criteria: utilizing existing roads for practicality and efficiency, and strategically planning routes to avoid potentially affected areas, ensuring resident safety (Gai & Deng, 2022). Residents can seek refuge during emergencies at suitable evacuation centers such as public halls and schools (Yoo & Choi, 2019). Nine assembly points are proposed at distances ranging from 3.2 to 5.2 km from the leak source, ensuring extensive coverage and facilitating an organized evacuation response in the event of a chlorine gas leak. There are several public halls near the Kasigui water treatment plant, such as Dewan Huguan Siou and Dewan Kebudayaan Penampang, which were not designated for safety evacuation due to their proximity (approximately 500 m) to the leak source. In the event of an accidental chlorine leak, these halls would be affected by the AEGL-3 plume.

The AEGL-3 chlorine plume extends from 0.39 to 0.5 km from the source during the northeast monsoon season. Places in close proximity to the leak source and downwind are affected by the life-threatening chlorine plume (>20 ppm). The areas affected by the AEGL-3 plume include Kg Kibabaig, Taman Kasigui, the Sabah Cultural Centre, Kg Dabak, Taman Desa Manis Kasigui, the northern part of Kg Nampasan, as well as the offices around Penampang District Council and Jabatan Pertanian Penampang. In the event of a chlorine gas leak, individuals in these locations must be evacuated immediately. The AEGL-2 chlorine plume disperses up to 1.5 km downwind during the northeast monsoon season. Areas affected by the AEGL-2 plume include Taman Regency, Kg Tuavon, Kg Kivatu, Jalan Hilton, Kg Tomui Kimolingan, Taman Prima Sumundu, Kg Dabak, Kg Kambau, Kg Kobidaan, Kg Tanaki, Kg Nampasan, Donggongon town, and the industrial area around HYF Corporate. Meanwhile, the AEGL-1 plume disperses up to 2.7 km due to the northeast monsoon wind, affecting HSK Industrial Area, Kg Puluduk, Taman Vista Seri Kiranu, Inobong, Kg Mogonibong, Kg Tanaki, Kg Dungkahang, Kilang Mee Tien Hock, Kg Hungab, the northern part of Kg Nambazan, Kg Kimolingan, and Kg Kobidaan.

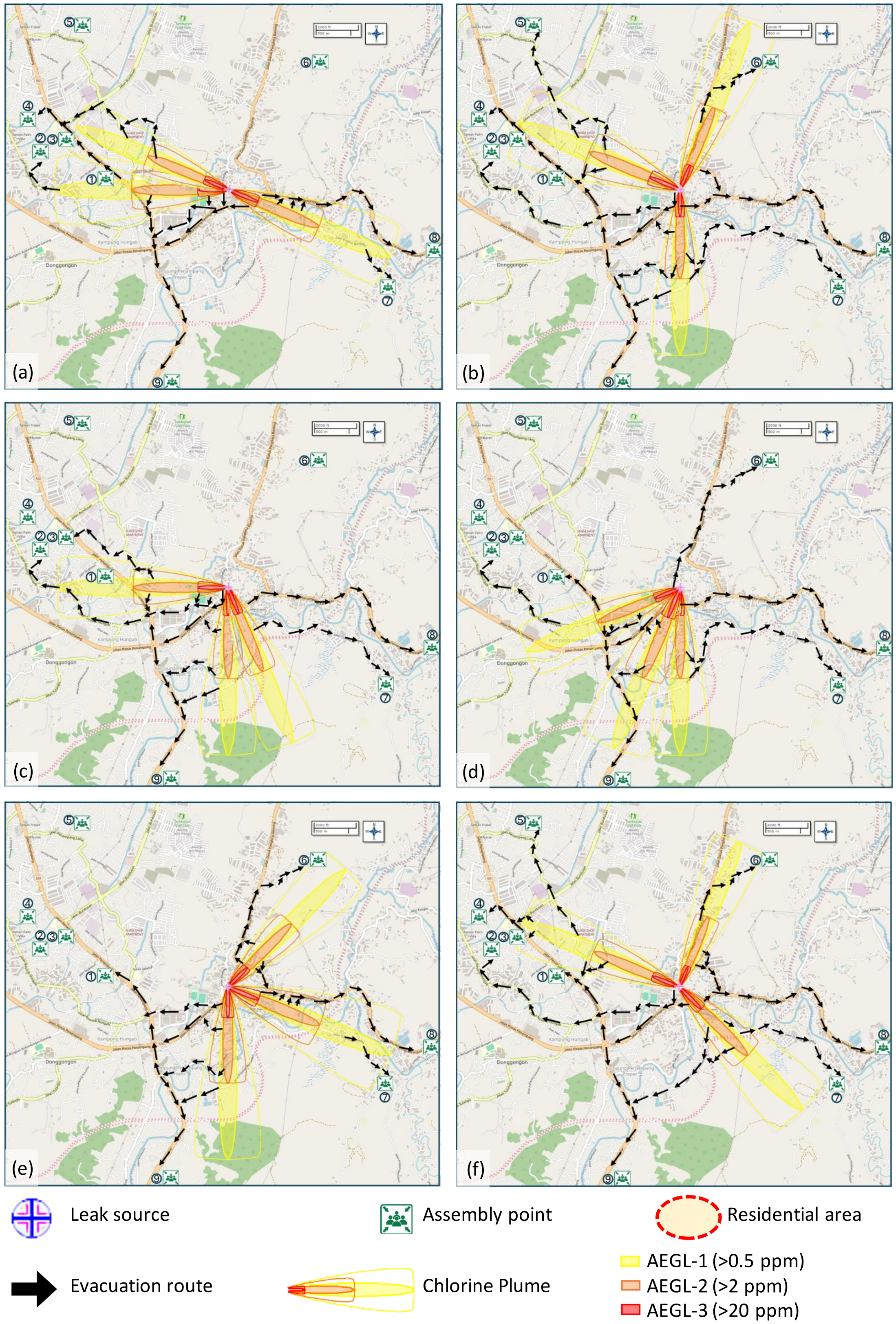

Figure 6. Prediction of chlorine dispersion and proposed evacuation routes during northeast monsoon and 1st inter-monsoon. (a) November, (b) December, (c) January, (d) February, (e) March, (f) April

The suitable evacuation sites during the northeast monsoon season include Dewan Raya Kg Ramayah, Dewan Paroki Sacred Heart, Dewan Pagansakan, GKC Sabah, Nagasiba Hall, KDCA Hall, Dewan Raya Kg Mogoputi, Nosoob Baru Community Center, and St. Anthony National School. The nearest evacuation point should be used whenever possible; however, the capacity of each evacuation site is limited. In such instances, evacuation sites further from the leak source may be utilized. Main roads or highways should be used as evacuation routes whenever possible, as they often consist of wider, multilane roads that can ease and speed up the evacuation effort. Suitable evacuation routes include Jalan Penampang-Tambunan, Penampang-Papar Old Highway, Jalan Datuk Panglima Banting, Jalan Bundusan, Jalan HSK Puluduk, Jalan Penampang, Jalan Inobong Putaton Bansadon, and Jalan Nosoob Hungab. It should be noted that the evacuation route to Dewan Raya Kg Ramayah may briefly be exposed to the AEGL-1 chlorine plume at Jalan Penampang-Papar in February. However, brief exposure to the AEGL-1 chlorine plume is unlikely to impair individuals' ability to escape, as chlorine at 0.5 ppm may cause only minor discomfort without adverse health effects.

Figure 6(f) shows the chlorine dispersion during the first inter-monsoon in April. In April, the AEGL-3 plume extends up to 0.42 km, while the AEGL-2 and AEGL-1 plumes disperse up to 1.40 km and 2.60 km, respectively. The areas affected by the AEGL-3 chlorine plume include Kg Kibabaig, the Sabah Cultural Centre, and Taman Desa Manis Kasigui. Meanwhile, most parts of Kg Kibabaig, Taman Prima Sumundu, Taman Regency, Kg Nampasan, Taman Sahabat, and Kg Kobidaan are affected by the AEGL-2 chlorine plume. Both the HSK Industrial Centre and Kg Puluduk are affected by the AEGL-1 plume. The suitable evacuation sites in April are Dewan Raya Kg Mogoputi, Dewan Raya Kg Ramayah, GKC Sabah, Dewan Pagansakan, and Dewan Paroki Sacred Heart. Additional evacuation sites that can be used are Nagasiba Hall, KDCA Hall, and Nosoob Baru Community Center. Nevertheless, these locations are at a slightly greater distance from the areas affected by the AEGL-2 and AEGL-3 plumes. However, vulnerable individuals, such as babies, the elderly, and those with respiratory issues, may need to be evacuated from areas affected by the AEGL-1 chlorine plume. Therefore, these additional evacuation sites may be utilized in such cases. The evacuation routes include Jalan Penampang-Tambunan, Jalan Datuk Panglima Banting, Jalan Penampang, Jalan Inobong Putaton Bansadon, and Jalan Nosoob Hungab.

Figure 7 shows the threat zone map of chlorine during the southwest monsoon season and the second inter-monsoon. The southwest monsoon dispersed the chlorine plume, with the AEGL-3 concentration extending up to 0.49 km, while the AEGL-2 and AEGL-1 plumes reached distances of 1.50 km and approximately 2.70 km, respectively. The areas affected by the AEGL-3 plume during the southwest monsoon season include the Sabah Cultural Centre, Taman Desa Manis Kasigui, Penampang District Council, Jabatan Pertanian Penampang, Kg Kibabaig, and Taman Kasigui. Meanwhile, the AEGL-2 plume affects Jalan Hilton, Kg Nampasan, Kg Tuavon, Kg Kivatu, Kg Dimbata, Taman Prima Sumundu, Taman Sahabat, and Taman Regency. Individuals in Kg Mogonibong, Kg Nampasan, Taman Villa Era Kolopis, Kg Puluduk, HSK Industrial Area, Taman Vista Sari Kiranu, Kg Kimolingan, and the western part of Inobong may experience discomfort as they are affected by the AEGL-1 chlorine plume.

The suitable evacuation routes during the southwest monsoon season are Jalan Penampang-Tambunan, Penampang-Papar Old Highway, Jalan Datuk Panglima Banting, Jalan Bundusan, Jalan HSK Puluduk, Jalan Penampang, Jalan Inobong Putaton Bansadon, and Jalan Nosoob Hungab. The suitable evacuation sites during the southwest monsoon season are Dewan Raya Kg Ramayah, Dewan Paroki Sacred Heart, Dewan Pagansakan, GKC Sabah, Nagasiba Hall, KDCA Hall, Dewan Raya Kg Mogoputi, and Nosoob Baru Community Center.

The chlorine dispersion during the second inter-monsoon month in October is shown in Figure 7(f). The AEGL-3 plume extended to 0.37 km, while the AEGL-2 and AEGL-1 plumes dispersed up to 1.20 km and over 2.60 km, respectively. The areas affected by the AEGL-3 plume include Kg Kibabaig and Taman Desa Manis Kasigui. Meanwhile, the AEGL-2 plume affects Taman Prima Sumundu, Kg Tuavon, Kg Kobidaan, Kilang Mee Tien Hock, and Kg Kivatu. Taman Vista Seri Kiranu and the western part of Inobong are affected by the AEGL-1 plume. The suitable evacuation sites in October are Dewan Raya Kg Mogoputi, Dewan Raya Kg Ramayah, GKC Sabah, Dewan Pagansakan, and Dewan Paroki Sacred Heart. The evacuation routes are Jalan Penampang-Tambunan, Jalan Datuk Panglima Banting, Jalan Penampang, and Jalan Inobong Putaton Bansadon.

Table 3. Monthly list of affected area by chlorine plume and evacuation point

Month	Affected area		Evacuation point
January	AEGL-3	Sabah cultural centre, Penampang district council, Taman Desa Manis Kasigui, Jabatan pertanian Penampang, Kg Dabak (northern)	Dewan Raya Kg Ramayah Dewan Pagansakan Dewan Paroki Sacred Heart Nagasiba Hall St. Anthony National School
	AEGL-2	Kg Nampasan, Kg Dabak, Jalan Hilton, Kg Kambau, Kg Tanaki (northern)	
	AEGL-1	Kg Mogonibong, Kg Tanaki	
February	AEGL-3	Taman Desa Manis Kasigui, Kg Dabak, Taman Kasigui	Dewan Raya Kg Mogoputi Dewan Pagansakan Dewan Paroki Sacred Heart Nagasiba Hall, GKC Sabah
	AEGL-2	Kg Dabak, Kg Kambau, Donggongon town	
	AEGL-1	Kg Tanaki, Kg Dungkahang, Kg Hungab, Kg Nambazan	
March	AEGL-3	Kg Kibabaig, Taman Kasigui, Kg Dabak	Dewan Raya Kg Ramayah Dewan Pagansakan Dewan Paroki Sacred Heart Dewan Raya Kg Mogoputi GKC Sabah
	AEGL-2	Taman Prima Sumundu, Kg Tuavon, Kg Kivatu, Kg Dabak, Kg Tanaki, HYF corporate	
	AEGL-1	Taman Vista Sari Kiranu, Kg Kimolingan, Inobong, Kg Tanaki, Kg Kobidaan	
April	AEGL-3	Kg Kibabaig, Sabah cultural centre, Taman Desa Manis Kasigui	Dewan Raya Kg Ramayah Dewan Pagansakan Dewan Paroki Sacred Heart Dewan Raya Kg Mogoputi GKC Sabah
	AEGL-2	Kg Kibabaig, Taman Prima Sumundu, Taman Regency, Kg Nampasan, Taman Sahabat, Kg Kobidaan	
	AEGL-1	HSK Industrial Centre, Kg Puluduk	
May	AEGL-3	Sabah cultural centre, Taman Desa Manis Kasigui, Kg Tuavon, Jabatan pertanian Penampang, Penampang distric council	Dewan Raya Kg Ramayah Dewan Pagansakan Dewan Paroki Sacred Heart Nagasiba Hall, KDCA Hall
	AEGL-2	Jalan Hiltton, Kg Nampasan, Kg Tuavon, Kg Kivatu, Kg Dimbata	
	AEGL-1	Kg Mogonibong, Kg Nampasan, Taman Vista Sari Kiranu, Kg Kimolingan, Inobong	
June	AEGL-3	Sabah cultural centre, Kg Kibabaig	Dewan Raya Kg Mogoputi Dewan Pagansakan, KDCA Hall Dewan Paroki Sacred Heart Nosoob Baru Community Center
	AEGL-2	Taman Regency, Kg Kibabaig, Taman Prima Sumundu, Taman Sahabat, Kg Tuavon, Kg Kivatu	
	AEGL-1	HSK Industrial Centre, Kg Puluduk, Taman Vila Era Kolopis	
July	AEGL-3	Kg Kibabaig, Sabah cultural centre	Dewan Pagansakan, KDCA Hall Dewan Paroki Sacred Heart Dewan Raya Kg Ramayah Nagasiba Hall, GKC Sabah Nosoob Baru Community Center
	AEGL-2	Kg Tuavon, Kg Kivatu, Jalan Hilton, Taman Prima Sumundu	
	AEGL-1	Taman Vila Era Kolopis, Kg Mogonibong,	
August	AEGL-3	Kg Kibabaig, Sabah cultural centre, Taman Kasigui	Dewan Pagansakan, KDCA Hall Dewan Paroki Sacred Heart Dewan Raya Kg Ramayah Nagasiba Hall, GKC Sabah Nosoob Baru Community Center
	AEGL-2	Taman Prima Sumundu, Jalan Hilton, Kg Nampasan	
	AEGL-1	Kg Mogonibong	
September	AEGL-3	Kg Kibabaig, Sabah Cultural Center	Dewan Pagansakan, KDCA Hall Dewan Raya Kg Mogoputi Nagasiba Hall, GKC Sabah Nosoob Baru Community Center
	AEGL-2	Taman Prima Sumundu, Taman Regency	
	AEGL-1	HSK industrial area, Kg Puluduk	
October	AEGL-3	Kg Kibabaig, Taman Desa Manis Kasigui	Dewan Raya Kg Ramayah Dewan Pagansakan, GKC Sabah Dewan Paroki Sacred Heart Dewan Raya Kg Mogoputi
	AEGL-2	Taman Prima Sumundu, Kg Tuavon, Kg Kivatu, Kg Kobidaan, Kilang mee Tien Hock	
	AEGL-1	Taman Vista Seri Kiranu, Inobong	
November	AEGL-3	Kg Kibabaig, Tmn Kasigui, Sabah cultural centre, Jabatan pertanian Penampang, Penampang distric council	Dewan Raya Kg Ramayah Dewan Pagansakan Dewan Paroki Sacred Heart
	AEGL-2	Taman Regency, Kg Tuavon, Kg Kivatu, Jalan Hilton	
	AEGL-1	HSK industrial area, Kg Puluduk, Taman Vista Seri Kiranu, Inobong, Kg Mogonibong	
December	AEGL-3	Kg Kibabaig, Taman Desa Manis Kasigui, Kg Dabak	Dewan Pagansakan, KDCA Hall Dewan Paroki Sacred Heart Dewan Raya Kg Ramayah Dewan Raya Kg Mogoputi Nagasiba Hall, GKC Sabah Nosoob Baru Community Center St. Anthony National School
	AEGL-2	Taman Prima Sumundu, Tmn Regency, Kg Dabak, Kg Kambau, Kg Kobidaan, Kg Tanaki	
	AEGL-1	HSK industrial area, Kg Puluduk, Kg Tanaki, Kg Dungkahang, Kilang mee Tien Hock	

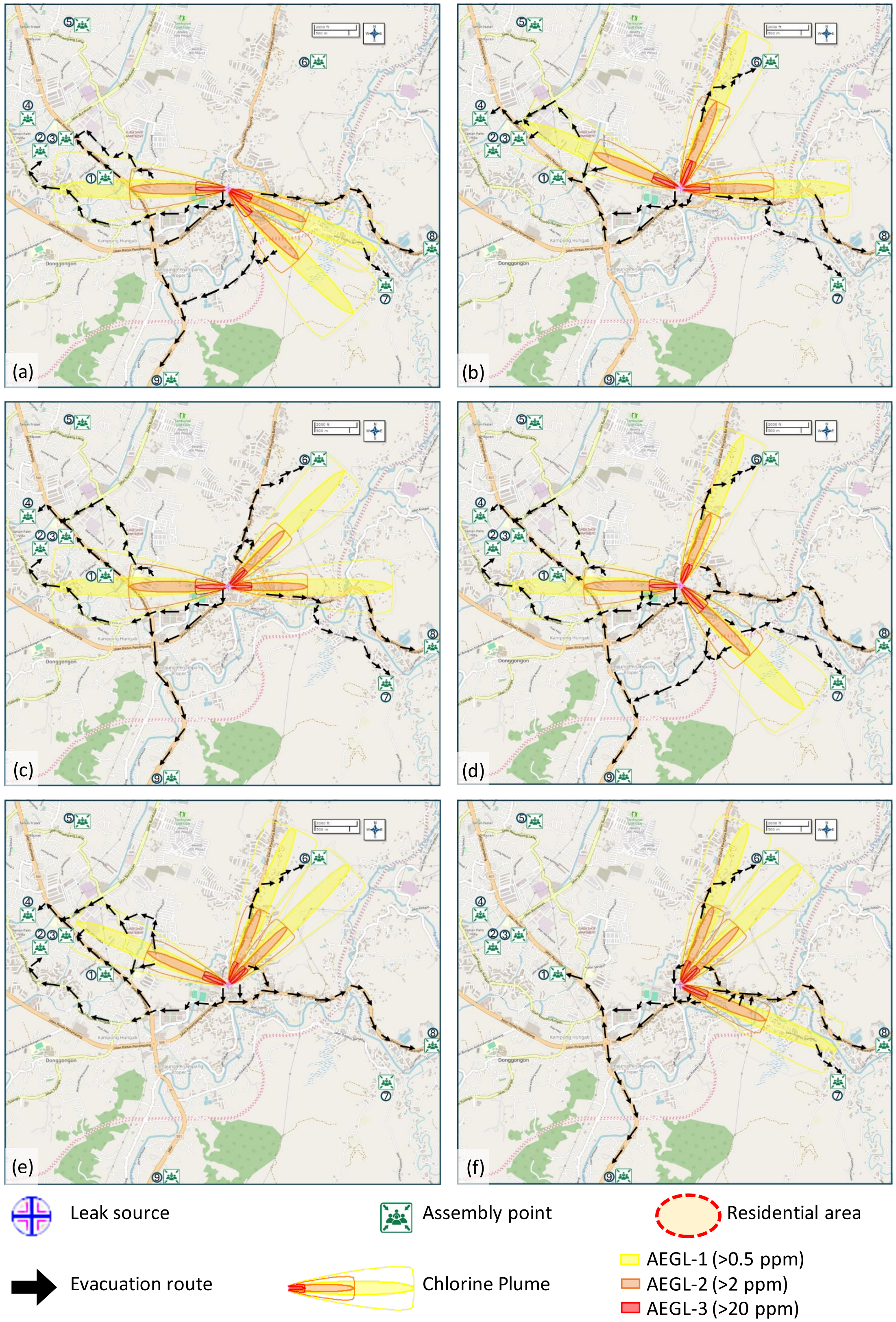

Figure 7. Prediction of chlorine dispersion and evacuation routes during southwest monsoon and 2nd inter-monsoon. (a) May, (b) June, (c) July, (d) August, (e) September, (f) October

Conclusions

A successful risk assessment of chlorine leak dispersion around the Kasigui water treatment plant was conducted using the ALOHA heavy gas dispersion model. The leak source was found to have a significant effect on the distance of the threat zones. Doubling the leak source from 0.5 to 1 cm increased the threat zone distance by about 55%. In the case studied in this work, the worst-case scenario occurs during the daytime. The findings indicate that chlorine dispersion is influenced by wind speed and direction. The areas affected by life-threatening chlorine plumes at AEGL-3 >20 ppm include Kg Kibabaig, Taman Desa Manis Kasigui, Taman Kasigui, Sabah Cultural Center, Jabatan Pertanian Penampang, Penampang Distric Council, Kg Nampasan, Kg Tuavon, and Kg Dabak. Suitable evacuation points are Dewan Pagansakan, KDCA Hall, Dewan Paroki Sacred Heart, Dewan Raya Kg Ramayah, Dewan Raya Kg Mogoputi, Nagasiba Hall, GKC Sabah, Nosoob Baru Community Center, and St. Anthony National School. The results of this work are valid for the immediate vicinity of the Kasigui water treatment plant, where the surface terrain is mostly flat, but may not be accurate when applied to other areas. This assessment is valuable for predicting hazardous zones and potential impact areas in the event of an accidental chlorine leak. Additionally, it offers guidance for identifying safe emergency evacuation routes.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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