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Accidental benzene release risk assessment in an urban area using an atmospheric dispersion model

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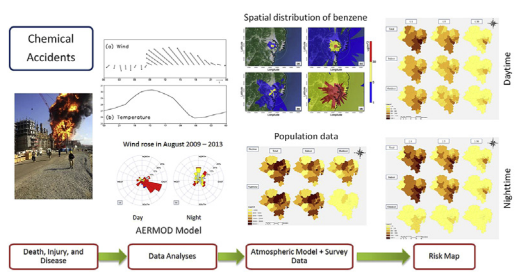
HIGHLIGHTS

- Risk assessment of atmospheric dispersion of toxic chemicals in the urban area.
- Characteristic patterns of atmospheric dispersion in the anthroposphere
- Risk maps based on multiple AERMOD simulations and indoor and outdoor populations.
- Quite different risk depending on the meteorological condition and population.
- Risk needs to be assessed by chemical concentration and population.

GRAPHICAL ABSTRACT



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ABSTRACT

This study applied the American Meteorological Society and Environmental Protection Agency Regulatory Model (AERMOD) to assess the risk caused by an accidental release and dispersion of the toxic chemical benzene in the vicinity of a highly populated urban area. The modeling domain encompasses the Korean megacity of Ulsan, which includes two national industrial complexes and is characterized by a complex coastal terrain. Multiple AERMOD simulations were conducted for an assumed emission scenario using background wind data from August between 2009 and 2013. The series of experiments produced the spatial accident probability patterns for different concentration levels during daytime and nighttime scenarios based on the corresponding dominant wind patterns. This study further quantifies the potential accident risk based on the number of affected individuals by combining the accident probability with the indoor and outdoor population estimates. The chemical gas dispersion characteristics depend on various local meteorological conditions, such as the land-sea breeze direction, which alternates between daytime and nighttime, and the atmospheric stability. The results reveal that benzene dispersion affects a much larger area during the nighttime owing to the presence of a nocturnal stable boundary layer with significant temperature stratification. The affected area is smaller during the daytime owing to decreased stability and enhanced vertical mixing in the boundary layer. The results include a high degree of uncertainty during the nighttime owing to weak wind speeds and the lack of a prevailing wind direction, which impact the vulnerable area. However, vulnerable areas are more effectively identified during the daytime, when more consistent meteorological conditions exist. However, the

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potential risk becomes much lower during the nighttime owing to a substantial reduction of the outdoor population.

1. Introduction

Most metropolitan cities worldwide suffer from serious air quality degradation (Baklanov et al., 2016). Rapid industrialization and urbanization represent major reasons for air quality degradation, resulting in increased air pollutant emissions due to transportation and in energy production and consumption due to industrial activities. These negative environmental impacts are often concentrated in or near densely populated areas. The United Nations (UN) reported that 54% of the world population lived in urban areas in 2014, which is projected to increase to 66% by 2050 (UNWUP, 2014). Urbanization and the associated air quality impacts have become an active research area. Many studies have been conducted to examine the short-term and long-term effects of air pollution on human health in metropolitan areas. Hang et al. (2015) investigated the adverse health impacts caused by nitrogen compounds in major urban areas of South Korea. Gurjar et al. (2010) assessed the health risks, mortality and morbidity caused by sulfur dioxide, nitrogen and total suspended particles in megacities.

Growing concerns exist regarding the accidental release of hazardous materials and explosions in or near megacities. These events can cause more serious short-term health effect and immediate casualties. The Union Carbide pesticide plant accident in Bhopal, India is one well known example. At least 40 tons of the highly toxic methyl isocyanate gas and a number of other poisonous gases were released on the evening of December 2, 1984. Death toll estimates vary from 3800 to 16,000, but the current death toll suggests that 15,000 people have been killed because of the accident, both immediately and over time. After 30 years, toxic material remains in the local environment and many of those who were exposed to the gas have given birth to physically and mentally disabled children (Edward, 2005). A series of massive explosions in the port of Tianjin, China represent another urban accident. The explosions killed 173 people and injured 797 more on August 12–15, 2015. In addition, the explosions caused as much as $1.5 billion USD in damages, making the event the most costly disaster in China in recent years (Huang and Zhang, 2015).

According to the statistical summary from the Korea Research Institute of Chemical Technology (http://eng.me.go.kr/), over 70 chemical accidental events occurred in Korea from 2010 to 2013. These events are associated with various types of carcinogenic chemical compounds, including benzene, hydrochloric acid, ammonia and others (http://stat.me.go.kr/). Such accidents not only kill and injure industrial complex workers but also affect the surrounding residential areas. A notorious accident occurred in Gumi, South Korea on September 27, 2012. Approximately eight tons of highly toxic hydrogen fluoride gas was released from the Hube Global chemical plant. The leak killed 5 workers and injured at least 18 people. The gas spread to the adjacent residential area where 3200 people were treated for nausea, chest pain, rashes and sore eyes after inhaling toxic fumes. The leak also damaged crops and livestock. These sudden hazardous material releases are more likely to instantly kill people and affect nearby urban residential areas (Lim and Lee, 2012; Park, 2013).

Accidental toxic chemical releases and dispersion are now included in urban planning risk assessments owing to growing awareness among policy-making agencies. One proposal seeks to establish the Emergency Alert Systems (EASs) throughout the city (Tseng et al., 2008; Lee et al., 2015). However, high-density monitoring network construction and maintenance can be costly, specifically networks that observe the atmospheric dispersion of hazardous chemicals. Therefore, researchers increasingly utilize various numerical models, which can provide the toxic gas dispersion estimates in near real time (Marcelo et al., 2003; Holmes and Morawska, 2006). These estimates save time during the decision-making and action or evacuation processes. For example, the first all-evacuation order was issued by the municipal office 3 and a half hours after the Gumi accident. However, the order was too late to effectively rescue people and prevent damages. Therefore, the American Meteorological Society and U.S. Environmental Protection Agency Regulatory Model (AERMOD) is applied in this study (Perry et al., 2005).

The AERMOD model has been used in numerous studies, including dispersion analyses for various pollutants, such as PM_{10}, $PM_{2.5}$, NO_x, SO_2, mercury and others (Kanyanee et al., 2011; Kakosimos et al., 2011; Nicole et al., 2011, Hasson et al., 2013; Hadlocon et al., 2015; etc.). AERMOD has also been compared to other models, including the California Puff Model (CALPUFF) and the Atmospheric Dispersion Modeling System (ADMS) (Andler et al., 2012; Dmitry et al., 2013; Arthur, 2014; Mark et al., 2015; Dmitry et al., 2016), and integrated with the Weather Research and Forecasting (WRF) model to analyze the sensitivity to metrological conditions associated with PM_{10} dispersion calculations (Amit et al., 2007). In addition, AERMOD was used to conduct a health risk assessment of coal-fired power plant emissions, including the carcinogenic and non-carcinogenic health risk associated with both short-term and long-term exposure (Mutahharah et al., 2014).

This study investigates the effects of such accidents on human health based on long-term, multiple dispersion simulation statistics in a region. These statistics can identify high risk potential areas, providing useful information for policy makers and local stakeholders. Ulsan, South Korea is selected as a case study because it is one of the fastest growing urban areas in the nation. The UN estimates that 82% of the South Korean population lives in urban areas (UNWUP, 2014). Benzene is selected as a representative chemical because this represents a first class carcinogenic chemical that is produced in Ulsan industrial complexes. However, the generalized modeling framework utilized in this study can also be used to assess various other applications and gases. The assumed scenario for the accidental benzene release is based on information from past accidents in South Korea.

Long-term simulation statistics are required to create a risk map. Multiple AERMOD simulations were conducted based on different background winds, which were observed at the Ulsan weather station. The benzene concentration 1 h after the emission (i.e., 1-h concentration) and the frequency exceeding a threshold concentration value have been averaged to obtain the spatial distribution of the potential risk method. This method differs from those described in other AERMOD studies (Mutahharah et al., 2014; Silverman et al., 2007) in which only the peak maximum value of 1-h concentration is used for the risk assessment of a given location. The short-term atmospheric dispersion of toxic strongly depends on wind variations and atmospheric stability. Ulsan is located in the coastal region and has a complex terrain. The terrain creates complicated local circulation patterns, including land-sea breeze and mountain-valley