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Air Pollution Directional Risk Assessment for Siting a Landfill

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ABSTRACT

Air pollution directional risk (APDR) is an essential factor to be assessed when selecting an appropriate landfill site. Because air pollutants generated from a landfill are diffused and transported by wind in different directions and speeds, areas surrounding the landfill will be subject to different associated risks, depending on their relative position from the landfill. This study assesses potential APDRs imposed from a candidate landfill site on its adjacent areas on the basis of the pollutant distribution simulated by a dispersion model, wind directions and speeds from meteorological monitoring data, and population density. A pollutant distribution map layer was created using a geographic information system and layered onto a population density map to obtain an APDR map layer. The risk map layer was then used in this study to evaluate the suitability of a candidate site for placing a landfill. The efficacy of the proposed procedure was demonstrated for a siting problem in central Taiwan, Republic of China.

INTRODUCTION

Despite the availability of various alternatives, landfilling remains an essential disposal method for municipal solid waste (MSW). However, new landfill sites are extremely difficult to obtain because of increasing land costs and the NIMBY (not in my back yard) consensus from the general public.^{1,2} Regulations for construction of landfills have become quite restrictive because of increased understanding of their significant environmental impact. Landfill siting is now a sensitive environmental issue, particularly for a densely populated island such as Taiwan.

Choosing a suitable location for placing a landfill requires evaluation of potential air pollution impact. A landfill can emit pollutants such as methane and volatile organic compounds, although soil covering is generally

applied on the top of landfilled waste to reduce emissions. The odors from a landfill also pose significant impacts on its neighboring population. Furthermore, occasional fires in landfills increase the emission of organic pollutants.³ These pollutants can significantly affect human health and the environment. Lindberg et al.⁴ indicated that methylated mercury species have been detected in gas generated from a municipal waste landfill as a result of fluorescent lights, batteries, electrical switches, and thermometers being landfilled, despite recommendations that these wastes should be avoided. To protect the health of the population, an appropriate landfill site should not impose a significant air pollution impact on its adjacent downwind area.

Because air pollutants are transported by wind, wind direction determines the direction pollutants are carried to, and wind speed determines how far the pollutants can be diffused. As Thanh and Lefevre⁵ pointed out, wind speed and direction strongly influence the level of health impacts because of air pollution at varied locations. Although landfill sites are usually located in areas of low population density, air pollutants generated by the landfill can be transported by wind to affect downwind areas with high population density.

Different locations have different meteorological characteristics with different wind direction and speed patterns. Wind directions and speeds are not constant over time, and are generally subject to seasonal or temporal variation. To analyze air pollution risk, a windrose plot analyzing wind direction and speed patterns is generally prepared. The windrose plot displays the distribution of wind speeds in different directions. The prevailing wind direction is the direction with the highest frequency of occurrence. However, in many cases nonprevailing wind directions may also have significant distant diffusion and cause significant impact on high population density areas. Assessing air pollution risk on the basis of the prevailing wind direction only may thus be inappropriate. Even with the same emission rate, different wind directions and speeds will cause different air pollutant impacts on downwind areas. This study therefore assesses the potential air pollution directional risk (APDR) posed by a candidate landfill site. There are several other methods available for assessing the potential risk induced by a landfill. For example, Macleod et al.⁶ developed a risk screening approach for assessing human exposures to air pollution control residues released from landfills. Butt and Oduyemi⁷ developed a holistic computer model of 12

IMPLICATIONS

For evaluating the suitability of a candidate landfill site, this study proposed a method to estimate APDR on the basis of population density and a simulated spatial pollution distribution. A site located in an area with low population density may still induce high APDR in its downwind areas, and the direction with the highest APDR may not occur in the prevailing wind direction. Thus, siting decisions based on the prevailing wind direction alone may be misleading. The proposed APDR is expected to improve the quality of siting decisions, although it should not be the sole factor considered in making a final determination of a siting.

modules to carry out concentration assessment for evaluating landfill risk. However, although quite comprehensive, these methods are not suitable for use in a siting analysis. In general, siting requires analysis of various factors. As risk assessment is just one consideration, albeit important, it is not appropriate to use a complex or expensive method during the siting stage. The proposed APDR, although simple, is capable of assessing the potential directional risk caused by a landfill site.

To estimate the potential risk from a landfill, it is necessary to know the spatial pollution distribution. For instance, Sengupta et al.⁸ used air pollution data to create an air quality map, which was combined with a land-use map to produce an air quality index map. A population pressure map, based on population density and population growth data, is then overlaid with the air quality index map to find out the pollutant risk zones. The impact of air pollution on any location can be assessed by analyzing the population in conjunction with the air pollution concentration at that location.⁹ Beer and Ricci¹⁰ also considered the population pattern and concentration distribution for evaluating the risk. An air quality model, ISCST3,¹¹ was thus applied to simulate air pollutant concentration distribution at areas surrounding a candidate landfill site. The proposed APDR was then calculated by multiplying the simulated concentration by the population density. Population density data were obtained from a census database. Meteorological observation data were available only for the few locations containing monitoring stations. Meteorological data for all other locations were estimated using the Draxler method¹² according to the data collected at closest monitoring stations.

Landfill-siting analysis requires processing of a significant amount of spatial information to evaluate various environmental, social, economic, and engineering factors. Because collecting and analyzing this spatial data is time consuming and tedious, in recent years a computerized geographical information system (GIS) has often been implemented to facilitate siting-related tasks.^{13–20} A GIS can process digital map layers of pollutant and population density distributions, provides analysis functions for implementing map layer computation, and presents a georeferenced illustration of analytical results. ArcView²¹ is the GIS used in this study to process and create various map layers to facilitate landfill-siting analyses.

The following sections describe the proposed method for assessing the potential APDR imposed by a candidate landfill site on its adjacent areas on the basis of the simulated pollutant distribution, wind direction and speed patterns, and population density. Overlaying a population density map onto a pollutant distribution map layer created using a GIS formed an APDR map layer. This APDR map layer was then used to evaluate the suitability of a candidate landfill site. A case study for a local landfill-siting problem in central Taiwan, Republic of China, was implemented to demonstrate the efficacy of the proposed method.

METHODOLOGY

A landfill site should be situated at a location with minimal APDR to protect the health of the surrounding population. A risk estimate primarily based on the prevailing

wind direction is not appropriate, especially in areas of significant seasonal wind direction variation. Consequently, this study assesses the APDR on the basis of wind directions and speeds, population density, and the pollution concentration distribution simulated by the ISCST3¹¹ dispersion model. The suitability of a candidate site can be then evaluated based on its estimated APDR value. The procedure for implementing the proposed APDR assessment is illustrated in Figure 1, and each step of the procedure is detailed as follows.

Preliminary Screening

Various criteria were adopted to preliminarily screen out areas that were obviously inappropriate for constructing a landfill on the basis of environmental, sociocultural, and engineering/economic factors. Map layers for environmental, sociocultural, and engineering/economic factors were thus prepared by ArcView.²¹ The cell size of these map layers is 500 × 500 m. This prescreening process (e.g., see Kao et al.¹³) can eliminate many inappropriate locations within the siting area, thereby minimizing further siting analysis and reducing analysis time.

Wind Direction and Speed Estimation

Completion of this study requires temporal and spatial wind direction and wind speed data for candidate sites. However, most candidate sites do not have a meteorological observation station in their immediate vicinity to provide this data. Therefore, wind directions and speeds must be based on the data collected from neighboring observation stations. Two kinds of methods are available to perform such an estimation: diagnostic methods and prognostic methods.²² Prognostic methods are too complex and expensive to apply to this siting problem. Instead, this study used a practical diagnostic method known as the DRAXLER method.¹² The DRAXLER method estimates the wind directions and speeds at a location according to its distance from observation stations. Hourly meteorological data were collected from several observation stations, and wind directions of N (north), north-northeast (NNE), northeast (NE), east-northeast (ENE), E (east), east-southeast (ESE), southeast (SE), south-southeast (SSE), S (south), south-southwest

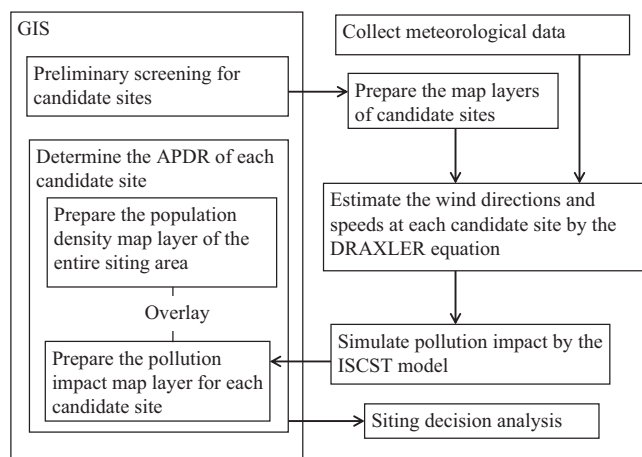


Figure 1. The procedure of the proposed APDR assessment.

(SSW), southwest (SW), west-southwest (WSW), W (west), west-northwest (WNW), northwest (NW), and north-northwest (NNW) were recorded. Wind speeds below 0.51 m/sec were regarded as a calm wind. Wind directions and speeds were estimated by the following DRAXLER equation:

$$(u_s, v_s)_{ij} = \frac{\sum_k \frac{\alpha_s}{r_{sk}^2} \cdot (u_k, v_k)}{\sum_k \frac{\alpha_s}{r_{sk}^2}} \quad (1)$$

where u_s and v_s are the E and N vector components of the wind direction to be estimated at the grid point $s_{(i,j)}$; u_k and v_k are the E and N vector components of the wind direction observed at station k ; r_{sk} is the distance from grid point $s_{(i,j)}$ to the observation station; α_s is a weighting parameter, $\alpha_s = 1 - 0.5 \sin \Psi_s$; and Ψ_s is the angle, in degrees, between the observed wind direction and the line connecting grid point $s_{(i,j)}$ and observation station k .

Pollution Impact on the Vicinity

To determine the APDR, it is important to assess the potential impact of pollution on the vicinity of a candidate site. A spatial pollution distribution was therefore simulated using the ISCST3 model.¹¹ The area adjacent to the candidate site was divided into several receptor zones. As shown in Figure 2, the center of a receptor zone is located in one of 16 directions, consistent with the directions used for drawing a windrose plot. The area of a receptor zone spans 11.25° either side of the centerline, connecting the center and the candidate site. The distance between each receptor zone and the candidate site is a multiple of 500 m, as illustrated in Figure 2. A typical emission rate was applied to each candidate site to estimate the average monthly pollutant concentration for each simulated location. This monthly average was then used to compute the risk, as described below.

APDR

The proposed APDR of a receptor zone was computed by multiplying the population in the zone by the pollutant concentration simulated at the center of the zone. The

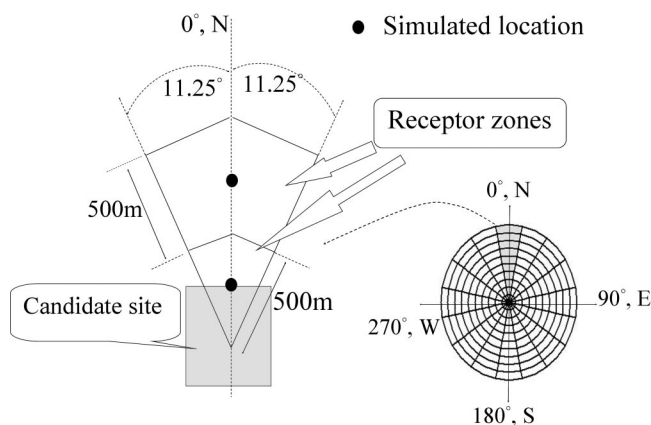


Figure 2. Pollution concentrations simulated in different directions and locations.

computation was performed using the spatial calculation function in a GIS, ArcView.²¹ Two map layers were prepared for pollutant concentrations at all simulated locations and population densities for all map cells, respectively. The size for each map cell is 100×100 m. A GIS map calculation function was then applied to multiply the pollution concentration map layer by the population density map layer and the logarithm function was used to obtain a new map layer for APDR values at all map cells. The APDR map layer could then be used to assess the suitability of a candidate site.

CASE STUDY

The siting area for this study includes the three counties of Howlong, Shihwu, and Tong-Shiiiau of Miaoli Prefecture in central Taiwan, Republic of China. A regional landfill is desired for the three counties. The size of the study area is approximately 224.7 km^2 . Various GIS map layers and related information were collected for the study area. The average population density is 402 capita/ km^2 , whereas the maximum is 14,746 capita/ km^2 and the minimum is 16 capita/ km^2 . Although selecting a landfill site in an area with low population density can decrease the risk, transportation costs may be significantly increased. It is therefore a challenge to site a landfill at a considerable distance from an area of significant population density variation. Different locations have different population densities and wind direction and speed patterns. Therefore, the scope of the impact posed by air pollutants emitted from a landfill is also different for different locations and directions. Further analysis is thus required to assess the suitability of each candidate site by the proposed APDR.

Preliminary Screening

Before applying the proposed method to estimate APDR, various raster-based geo-referenced map layers were collected and prepared. These layers include fault zones, rivers, road networks, water resources and groundwater protection areas, historical sites, and land slope.¹³ According to the collected criteria, a landfill site is restricted from the following sensitive areas:

- Environmental Factors: groundwater protection areas; water source, water quality, and water quantity conservation districts; buffer zones close to a stream (a 180-m buffer zone was set); natural ecology conservation districts; fault and unstable areas (a 60-m buffer zone was set); and the 100-yr flood plain.
- Sociocultural Factors: urban areas (a 150-m buffer zone was set), cultural and historic sites (a 350-m buffer zone was set), and national parks.
- Engineering and Economic Factors: areas distant from accessible roads (an acceptable distance of 1100 m was set) and land slopes greater than 25%.

Various map layers were collected and prepared based on the criteria listed above. Map layer analysis functions provided by a GIS, ArcView,²¹ were applied to process these digital map layers to eliminate the areas that are inappropriate to be a landfill site. Figure 3 illustrates the

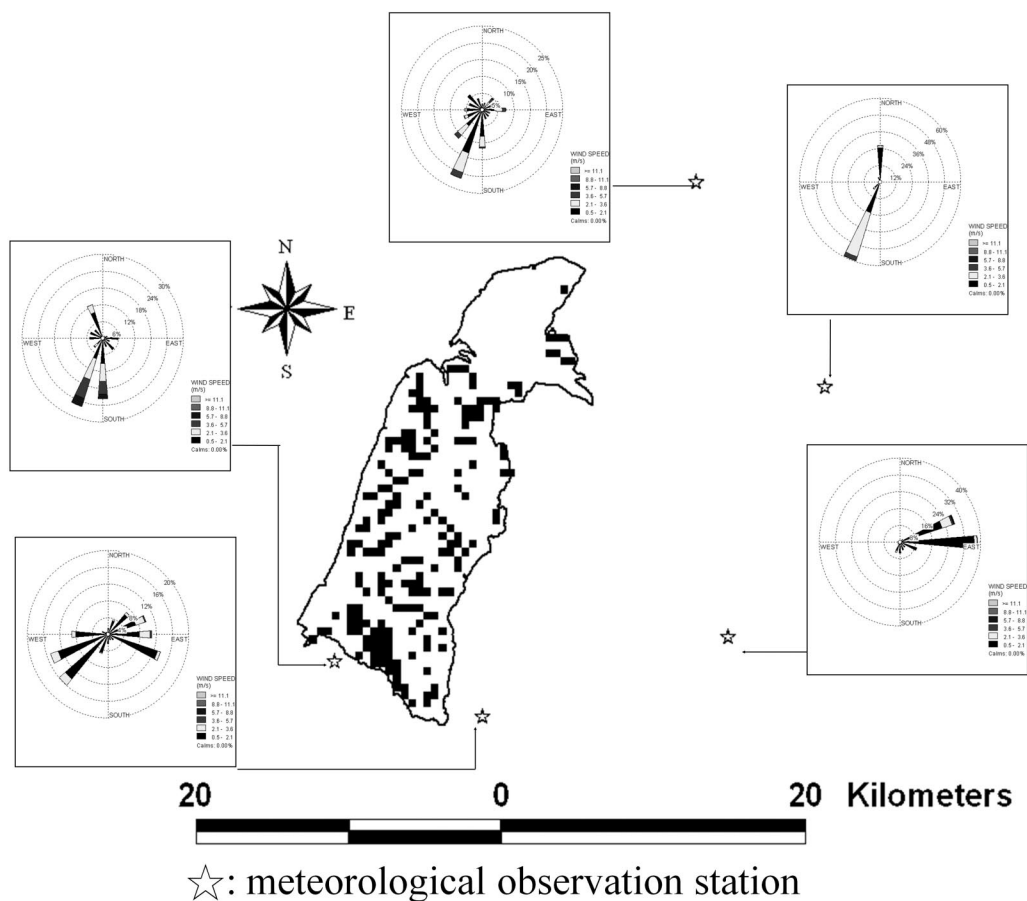


Figure 3. Map layer of the 194 candidate sites remaining after the preliminary screening process, and the locations and associated windroses for five meteorological observation stations in the study area.

194 sites remaining after this preliminary screening process. Although the prescreening process screens out a large unsuitable portion of the siting area, further analysis is required to determine the most suitable site. Seven candidate sites, as illustrated in Figure 4, have been selected to demonstrate the proposed method.

Population Density Map Layer

A population density map layer for the study area, as shown in Figure 4, was prepared to determine the proposed APDR. The cell size of this map layer is 100×100 m and the unit of population density is capita/10,000 m², (equivalent to 100 capita/km²). The maximum population density is 777 capita/10,000 m² and the minimum is only one capita/10,000 m². Approximately 5% of the area has a population density over 17 capita/10,000 m²; approximately 30% between 4 and 10 capita/10,000 m²; 36.5% between 2 and 3 capita/10,000m²; and 13.5% 1 capita/10,000 m².

In general, placing a landfill at a location with low population density is preferred. However, Taiwan is a heavily populated country and it is difficult to find a location that is far away from residential areas. For candidate sites located at areas with similar population density, a method is desired to make a further decision. The proposed directional risk is thus applied herein to facilitate landfill-siting analysis.

Wind Direction and Speed Estimation

There are five meteorological observation stations surrounding the study area. Windrose plots for each station are illustrated in Figure 3. The prevailing wind directions for these stations are SW for one station, SSW for three stations, and E for one station. As previously mentioned, the DRAXLER method¹² was used to estimate wind directions and speeds at seven candidate sites and the associated windrose plots were drawn by the WRPLOT View,²³ as shown in Figure 4. This study defines calm as the wind speed under 0.51 m/sec, as used by Rama Krishna.²⁴ As listed in Table 1, the range for wind directions mainly spans over [90° 270°]. Therefore, the pollutants are rarely diffused towards the N area of the sites. Table 1 also lists the average wind speed in each direction at candidate sites. A significant variation of wind speeds can be observed from the list.

Pollutant Distribution Simulation

The pollutant distribution for each site was simulated using the ISCST3¹¹ model. In this study, the emission rate at each site is assumed to be 0.018 mg/(s · m²), a typical average emission rate measured from 2- to 3-yr-old local landfill sites.²⁵ If required, a different emission rate can be applied, and a particular pollutant can be specified. However, there is generally no need to do so because siting is

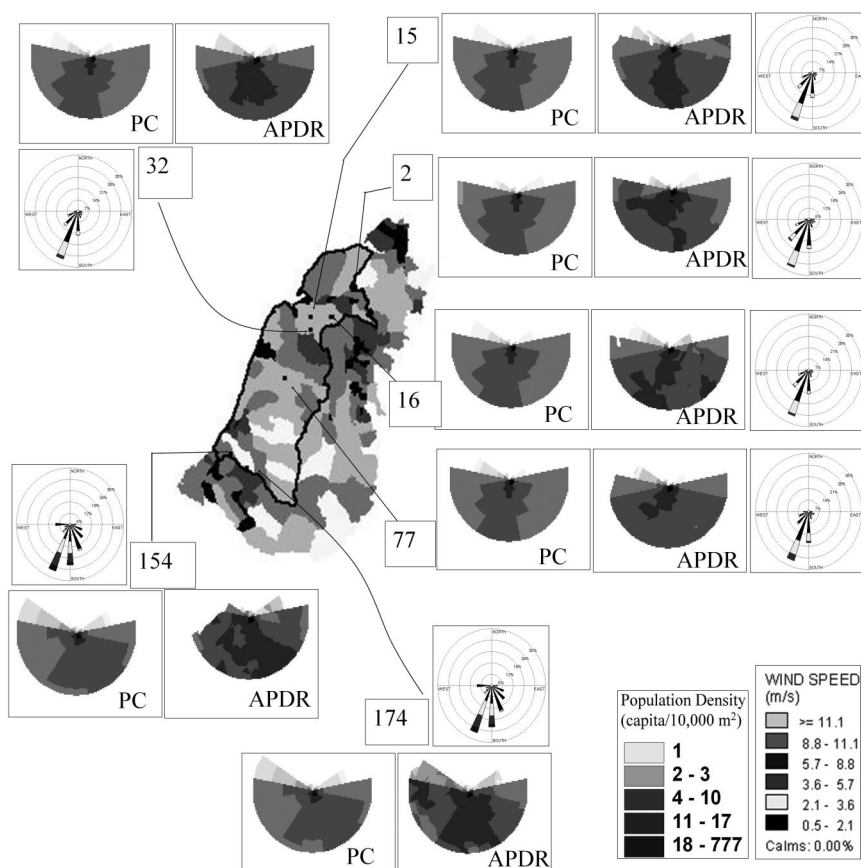


Figure 4. The population density map layer for the study area, and the pollutant concentration (PC), APDR distribution, and windrose diagrams for each candidate site.

primarily based on a relative comparison among candidate sites. The simulation region is a circular area of radius of 5 km that surrounds each candidate site. The simulation results are converted into GIS pollutant distribution map layers, as illustrated in Figure 4. The darker area indicates the area with higher pollutant concentration and vice versa. It can be observed that, for sites 154 and 174, the directions of high concentration are not the same as the direction of prevailing wind because the dispersion of pollutant is also influenced by wind speed. The

direction with high pollutant concentration generally occurs at a low mean speed, such as the SSE direction for sites 2, 15, 16, 32, and 77. However, low mean speed is not the only factor to affect the simulated pollution distribution. The occurrence frequency is also essential. For example, the direction W of sites 2, 15, 16, 32, and 77 has a low mean speed and low occurrence frequency, and, as illustrated in Figure 4, the areas with high pollutant concentration are obviously smaller than those with high occurrence frequency, such as sites

Table 1. Mean wind speeds and frequencies estimated by using the DRAXLER method¹² in different wind directions for each candidate landfill site.

Wind Direction	Mean Value of the Wind Speed (m/sec) and Frequency						
	Site Number						
	2	15	16	32	77	154	174
78.75–101.25 (E)	1.21 (379)	1.09 (318)	1.10 (314)	1.02 (318)	1.05 (267)	1.11 (300)	1.11 (299)
101.25–123.75 (ESE)	0.83 (467)	0.80 (400)	0.76 (438)	0.8 (389)	0.88 (435)	1.01 (630)	1.00 (630)
123.75–146.25 (SE)	0.69 (462)	0.68(435)	0.67(448)	0.68 (474)	0.75 (381)	1.04 (846)	1.01 (851)
146.25–168.75 (SSE)	0.69 (631)	0.67 (617)	0.68 (595)	0.68 (569)	0.73 (542)	1.16 (1306)	1.12 (1292)
168.75–191.25 (S)	1.12 (1634)	1.24 (1588)	1.16(1550)	1.28 (1542)	1.59 (1873)	2.80(1896)	2.70 (1906)
191.25–213.75 (SSW)	1.67 (2553)	1.69 (2996)	1.61 (2923)	1.68 (3055)	1.85 (3014)	3.24 (2291)	3.16 (2290)
213.75–236.25 (SW)	1.59 (1498)	1.27 (1301)	1.31 (1413)	1.19 (1301)	1.03 (1156)	1.67 (481)	1.65 (481)
236.25–258.75 (WSW)	1.27 (849)	1.16 (785)	1.17 (784)	1.13 (789)	1.07 (722)	1.04 (293)	1.04 (293)
258.75–281.25 (W)	1.07 (287)	1.00 (320)	1.05 (295)	1.00 (323)	0.95 (370)	1.03 (717)	1.03 (718)

Notes: Wind frequency values are given in parentheses.

Table 2. The APDR values in different wind directions for each candidate landfill site.

Wind Direction	APDR						
	Site Number						
	2	15	16	32	77	154	174
78.75–101.25 (E)	6.821	6.456	6.578	6.267	6.412	7.222	6.543
101.25–123.75 (ESE)	8.469	7.993	7.860	7.833	7.990	8.368	7.647
123.75–146.25 (SE)	8.600	8.126	8.122	8.749	8.110	8.552	7.993
146.25–168.75 (SSE)	8.756	8.249	8.097	8.851	8.211	8.817	8.141
168.75–191.25 (S)	8.761	8.305	8.147	8.833	8.184	8.560	8.558
191.25–213.75 (SSW)	8.353	7.928	7.814	8.258	7.807	8.098	8.051
213.75–236.25 (SW)	7.924	7.443	7.433	7.775	7.418	7.945	7.668
236.25–258.75 (WSW)	8.135	7.130	7.116	7.496	7.175	7.972	7.805
258.75–281.25 (W)	6.771	6.335	6.200	6.387	6.384	7.496	8.092

154. On the other hand, similar reasons can be applied to explain why the area with high pollution concentration does not occur in the prevailing wind direction for sites 2, 15, 16, 32, 77, and 174. For example, the prevailing wind direction for site 154 is the SSW direction, but the direction with high pollutant concentration is in the SE direction because the mean speed is higher in the SSW. If wind speeds in the prevailing direction are frequently high, the emitted pollutant will be effectively dispersed and hence the impact on the direction will be minimized.

APDR

The APDR estimated in this study is equal to the population density multiplied by pollutant concentration for the receptor zones located in each wind direction. Figure 4 displays the logarithmic annual APDR plot for each site. The darker area implies higher risk and vice versa. Table 2 lists the APDR values of all candidate sites. As listed in the table and illustrated in Figure 4, the direction of high pollutant concentration is not always consistent with the direction of high risk. This is because the population densities of receptor zones vary significantly in different directions. For example, for site 2, the direction with high pollutant concentration is pointed towards the SSW, but the high APDR direction is instead pointed S. The pollutant concentrations simulated for sites 15 and 32 are similar in the direction of SSW, whereas the APDR values in that direction are higher for site 32 than for site 15. In comparison, the pollutant concentrations simulated for site 154 are lower than those for site 16, but the APDR values for site 154 are higher than those for site 16 because their population densities at receptor zones are significantly different. A decision made primarily based on pollution distribution may thus be inappropriate, and therefore the proposed APDR can be used to enhance the quality of a siting decision.

CONCLUSIONS

Suitable landfill sites should have low potential impact to the environment and human health. This study thus proposed an APDR siting factor for assessing the suitability of a candidate site. The pollution concentration estimated at receptor zones in the prevailing wind direction is not

always the highest concentration. This is because the distribution of wind speeds may vary with directions, causing significant variation in the APDRs in different wind directions. The direction with high pollution distribution may be different from the direction with high APDR because of the population distribution. The correct positioning of a landfill is at a site with relatively low APDR for its vicinity. The proposed APDR siting factor is expected to enhance the quality of site selection for landfill construction.

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