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Research article

Evaluating the impact of odors from the 1955 landfills in China using a bottom-up approach

Bofeng Cai [a, **], Jinnan Wang [a, ***], Ying Long [b, c, *], Wanxin Li [d], Jianguo Liu [e], Zhe Ni [e], Xin Bo [f], Dong Li [g], Jianghao Wang [h], Xuejing Chen [e], Qingxian Gao [i], Lixiao Zhang [j]

[a] *Center for Climate Change and Environmental Policy, Chinese Academy for Environmental Planning, Beijing 100012, China*
[b] *Beijing Key Lab of Capital Spatial Planning and Studies, Beijing 100084, China*
[c] *Beijing Institute of City Planning, Beijing 100045, China*
[d] *Department of Public Policy, City University of Hong Kong, Hong Kong, China*
[e] *School of Environment, Tsinghua University, Beijing 100084, China*
[f] *Appraisal Center for Environment and Engineering, Beijing 100012, China*
[g] *China Academy of Urban Planning and Design, Beijing 100044, China*
[h] *LREIS, Institute of Geographic Sciences & Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*
[i] *Chinese Research Academy of Environmental Sciences, Beijing 100012, China*
[j] *School of Environment, Beijing Normal University, Beijing 100875, China*

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ABSTRACT

Landfill odors have created a major concern for the Chinese public. Based on the combination of a first order decay (FOD) model and a ground-level point source Gaussian dispersion model, the impacts from odors emitted from the 1955 landfills in China are evaluated in this paper. Our bottom-up approach uses basic data related to each landfill to achieve a more accurate and comprehensive understanding of impact of landfill odors. Results reveal that the average radius of impact of landfill odors in China is 796 m, while most landfills (46.85%) are within the range of 400–1000 m, in line with the results from previous studies. The total land area impacted by odors has reached 837,476 ha, accounting for 0.09% of China's land territory. Guangdong and Sichuan provinces have the largest land areas impacted by odors, while Tibet Autonomous Region and Tianjin Municipality have the smallest. According to the CALPUFF (California Puff) model and an analysis of social big data, the overall uncertainty of our calculation of the range of odor impacts is roughly −32.88% to 32.67%. This type of study is essential for gaining an accurate and detailed estimation of the affected human population and will prove valuable for addressing the current Not In My Back Yard (NIMBY) challenge in China.

1. Introduction

With increases in population, urbanization, and living standards, the municipal solid waste (MSW) produced in China has increased continually. In 2012, the harmless disposal rate of MSW reached 84.80%, of which 72.55% went to landfills. Neighborhoods in the proximity of MSW landfills are often burdened with a series of adverse consequences that result from solid waste disposal. One of the major impacts is the unpleasant odors generated from the decomposition of waste. The high moisture content (40–60%) and high content of easily degradable organic waste (50–70%) within the MSW of China often lead to serious landfill gas (LFG) fugitive emissions and air pollution in the form of undesirable odors. The landfill odor problem is an important and highly debated environmental concern of the Chinese public, and it is also the main reason for the public complaints lodged against landfilling. Based on the records of the environmental protection hotline “12369” in 2013, 25 complaint cases were related to landfill odors, which accounted for 1.5% of all cases processed that year (Environment Complaint Center, 2015). Considering that China only had approximately 2000 landfills at that time while industrial enterprises numbered in the millions as well as the fact that air, soil, and water pollution are also severe in China, landfill odors accounted for a disproportionally high percentage of public complaints. This indicates the severity of the problem and a high level of public

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[*] Corresponding author. Beijing Key Lab of Capital Spatial Planning and Studies, Beijing Institute of City Planning, Beijing, China.
[**] Corresponding author.
[***] Corresponding author.
E-mail addresses: caibofeng@gmail.com (B. Cai), wangjn@caep.org.cn (J. Wang), longying1980@gmail.com, longying0522@sina.com (Y. Long).

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concern about landfill odors. Given these conditions, an accurate and comprehensive understanding of the impacts of landfill odors in China is essential for solving the Not In My Back Yard (NIMBY) issue related to waste management facilities. Providing basic data for improving solutions and policies is therefore a priority. Understanding the effects of landfill odors is also valuable for the identification of locations and the spatial optimization of new landfills (Leão et al., 2004). However, previous research related to the impact of landfill odors in China has simply focused on case studies. A more accurate and comprehensive evaluation of the impact range of landfill odors at national level is greatly needed. In this study, we adopt a bottom-up approach that ensures the accuracy of our calculations and provides full coverage of landfills in China. To our knowledge, this is the first study that evaluates the spatial range of the impacts of odors from each landfill in China.

2. A review and assessment of the impact range of landfill odors

Because odors from landfills can have an obvious influence within a certain range, studying and determining the range of those impacts is important. Studies have shown that sulfides were the main compounds causing landfill-generated odors and that many other complex trace substances also contributed to those odors (Allen et al., 1997; Ding et al., 2012; Duan et al., 2014; Kim et al., 2005; Sarkar et al., 2003; Scheutz and Kjeldsen, 2003; Young and Parker, 1983; Ji, 2011). Governments regulate siting of landfills by specifying the minimum distance between landfill sites and residential areas. The European Union Council Directive 1999/31/EC of 26 April 1999 states that decisions on landfill siting should consider the distance to residential and recreation areas and the Directive proposed a minimum distance of 500 m. However, the final version of the Directive does not specify a minimum distance but only broadly states that an unspecified minimum distance should be taken into consideration. British Columbia's environmental protection bureau requires that the minimum distance from a landfill to residential areas, schools, and hotels should be more than 300 m (British Columbia Ministry of Environment (1993)). The government of South Australia states that the safe distance from landfills to residential areas should be at least 500 m to prevent the influence of landfill gases (South Australia Environment Protection Authority, 2007). The State of Victoria in Australia (2010) requires that the safe protection distance from landfills to buildings should be 500 m. Hasan et al. (2009) reviewed the safe distance of landfills and demonstrated that the distance between landfills to urbanized areas should be at least 500–2000 m. Úbeda et al. (2010) used two methods, simple and commercial Gaussian atmospheric dispersion models, to assess the range of the impact of odors of a landfill in Valencia, Spain. Tagaris et al. (2003) studied CH_4 concentrations from the Lemonou landfill in Greece via a CALPUFF (California Puff) model. Tagaris et al. (2012) thought that the concentration of CH_4 could be representative of most landfill odor gases, and thus the range of effects could be calculated by a dispersion model. Guarriello et al. (2007) recognized H_2S as the main landfill gas producing undesirable odors and that CH_4 could also be used to evaluate the range of impacts from landfill odors. Figueroa (2006) studied the range of impacts from landfill odor of a landfill in Seminole, FL, USA, and they found that an H_2S could be perceived at distances of 800–1200 m away from the landfill.

China has also issued a series of technical specifications and planning guidelines to regulate the impact of landfills on the general public. The Standard for pollution control on the landfill site of municipal solid waste (GB 16889-2008) states that the location of landfills and their distances to the surrounding population should be decided by an assessment of environmental effects. The Urban environmental sanitation planning specification (GB50337-2003) states the minimum distances required to separate MSW landfills from cities and residential areas. The Domestic waste sanitary landfill technology specification (CJJ17-2004) asserts that landfills should not be built within 500 m of residential areas or drinking water sources for humans and animals. Researchers in China have also evaluated the range of the impacts of odors from landfills based on theoretical analyses and field measurements. Yan et al. (2008) and Li et al. (2010) calculated the size of buffers needed around landfills to protect human health at different scales. Lu et al. (2009) studied the range and the diffusion of landfill odor pollutants and their impacts on the surrounding residential areas, showing that the range and diffusion of odor pollutants from large-scale landfills would exceed 500 m.

Table 1 summarizes the size of buffers around landfills required to protect human health based on current regulations and academic research from Chinese and international sources. The results ranged from 500 m to 1000 m. Furthermore, the evaluation subject in these previous studies was either a single landfill or a macro-analysis on landfills which had limited coverage or the final results lacked good accuracy. Thus, a determination of odor emissions and range of their impacts from the bottom-up via incorporating site-specific conditions and local meteorological patterns related to each landfill is greatly needed.

3. Methods and data

We focused on 1955 landfills, including both 1057 sanitary landfills and 898 open dump sites. This represents almost all the landfills in China. A FOD model was used to calculate the odor emissions, and a ground-level source Gaussian dispersion model (hereafter, Gaussian dispersion model) was applied to calculate the diffusion of odor gas around each landfill. The bottom-up research model has several advantages: (1) In contrast with research at the national and regional level, this method calculates a specific landfill odor impact distance for each landfill, which can reflect the differences between landfills; (2) This work ensures that the basic information of each landfill (including waste composition, annual and total landfill amount, and management levels) and the calculation model (FOD model and Gaussian dispersion model) used herein were consistent with those used in single case studies; (3) This study covers almost all the landfills in China with detailed information on each landfill.

In this research, olfactory threshold is the base data used to determine the range of the impacts of odors, and it is defined as the critical point when the odors could be perceived by people. Although landfill odors contain many harmful substances, inhaling the odors does not necessarily cause harmful health consequences, but it can certainly cause unpleasant emotions.

In view of the range of the impacts of landfill odors, the main research method is based on physical models and the olfactory threshold. In addition to the landfill itself, the centralized transportation around the landfills is also an important odor source. Moreover, the impacts of odors are greatly influenced by the subjective feelings of individuals, and the results from the Gaussian dispersion model may underestimate the range of the impacts of odors to a certain extent. Thus, the CALPUFF model and social media data were used to assess the overall uncertainty in the results of Gaussian dispersion model.

3.1. Calculation method of odor gas emission

H_2S is the main landfill odor gas (Ding et al., 2012; Duan et al., 2014; Kim et al., 2005; Sarkar et al., 2003; Ji, 2011; Qiang et al., 2014). We chose H_2S as the representative odor gas, which is the

Table 1
Comparison of buffers around landfills required to protect human health.

Classification		Effect/health protection distances of landfills	Notes
Global	Regulations	500 m	British Columbia, Canada (1993)
		500 m	South Australia, Australia (2007)
		500 m	The State of Victoria in Australia (2010)
	Academic research	500–2000 m	Hasan et al. (2009)
		1100 m–3300 m	Úbeda et al. (2010)
		300 m was the critical point for CH_4 concentration change, and after 300 m CH_4 concentration began to drop slowly	Tagaris et al. (2003);
		800–1200 m	Figueroa (2006)
Domestic	Regulations	More than 5, 2, and 0.5 km from urbanized areas of large and medium cities, small cities, and residential areas, respectively.	Urban environmental sanitation planning specification-(GB50337-2003)
		More than 500 m from residential areas or water sources for human and animals	Domestic waste sanitary landfill technology specification (CJJ17-2004)
	Academic research	Small size landfills:500–800 m, medium landfills:800–1000 m, large-scale landfills:1000–1500 m;	Yan et al. (2008)
		Small landfills:800 m, medium landfills:1500 m, large landfills:2000 m	Li and Li (2010)
		Odor intensity was 0 after 1500 m	Huang et al. (2009)
		500 m	Hong et al. (1994)
		>500 m	Lu et al. (2009)

standard method in the landfill odor literature. The H_2S emissions from landfills were calculated according to CH_4 concentration, since the volume ratio of H_2S to CH_4 is relatively stable. CH_4 concentration is approximately 50%, and H_2S concentration is approximately 36 ppm of total landfill gases (IPCC, 2006; U. S. EPA, 2005; Huang et al., 2009). The CH_4 emission from landfills was calculated by the FOD model (a detailed description of this model can be found in the Supplementary file) recommended by the IPCC, which is the commonly used method for calculating CH_4 emissions from landfills and is also used by the U.S. EPA (2013) to establish the inventory of CH_4 emissions from landfills. Cai's research (Cai et al., 2014) has determined CH_4 emission factors of landfills in different regions and at different scales, and they calculated the CH_4 emission of each landfill in China for 2007. We applied the basic data and emission factors from the Cai research (Cai et al., 2014) and combined the data from our investigation and the updated information of China's landfills in 2012 to study CH_4 emissions and determine H_2S emissions.

3.2. Gaussian dispersion model

The Gaussian dispersion model is used internationally as the core model to analyze landfill odor diffusion (Figueroa, 2006; Guarriello, 2007; Tagaris et al., 2012; Úbeda et al., 2010; Ji, 2011). It can be expressed as follows:

$$C(x, y, z, 0) = \frac{q}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_y^2}\right)\right] \tag{1}$$

If we only take the range of the impacts of odors into consideration, regardless of horizontal directivity and vertical diffusion, then we can define y = z = 0, the formula becomes as follows:

$$C(x) = \frac{q}{\pi u \sigma_y(x) \sigma_z(x)} \tag{2}$$

$$q = q_{CH_4} \times \left(V_{H_2S}/V_{CH_4}\right)/(34/16) \tag{3}$$

This simplified model regards odor emission sources from landfill as a ground-level point source (Guarriello, 2007; Zhang et al., 2012, 2005), and the results represent the odor gas concentration in axial direction. $C(x)$ refers to the odor gas concentration; q refers to the emission intensity of odor gas, g/s (grams per second); σ_y and σ_z are functions of distance$x$, which represent the horizontal and vertical diffusion parameters, respectively (see the specific functional forms in Hao et al., 2010); and u refers to the speed of wind, m/s. The olfactory threshold of H_2S is used as the concentration at diffusion terminal. q_{CH_4} is the emission intensity of CH_4 and is calculated according to the method described in section 3.1; V_{H_2S}/V_{CH_4} is the volume ratio of H_2S to CH_4 in landfill and the data are described in section 3.1. The “34” and “16” in Equation (3) are the molecular weights of H_2S and CH_4, respectively. u is set as the average annual wind speed at the landfill location. There are 6 atmospheric stability scenarios in the Gaussian dispersion model (detailed information regarding these six atmospheric conditions can be found in the Supplementary file), representing different diffusion processes under 6 different atmospheric conditions. Based on the principle of conservative calculation, we calculated all 6 atmospheric stability conditions under the corresponding wind speed of each landfill and chose the maximum value as the impact radius of landfill odor.

The olfactory threshold of H_2S from landfills was determined to be approximately 0.5–1 ppb (Parker et al., 2002). Nagata's (2003) results showed that the value was 0.41 ppb (0. 62 $\mu g/m^3$), and this value has been widely recognized and cited. The WHO air quality guidelines of the European Union (WHO Regional Office for Europe, 2000) report that the perception concentration of H_2S is 0.2–2.0 $\mu g/m^3$ and that the maximum value should not exceed 7 $\mu g/m^3$. The 0.41 ppb used herein is also within the range of European Union regulations.

3.3. CALPUFF model

The CALPUFF model is one of the most popular models for evaluation of landfill odors (Capelli et al., 2013; Davoli et al., 2010; Ranzato et al., 2012; Sironi et al., 2010). A detailed description of this model can be found in the Supplementary file. It is also one of the three models recommended by the national guidelines of China (Environmental impact assessment technical guideline: atmospheric environment (HJ2.2-2008)). Furthermore, results from the CALPUFF model are relatively accurate and precise. Therefore, the CALPUFF model was applied to simulate the odor dispersion of selected landfills, and its results were used to verify the results of the Gaussian dispersion model. There are some issues that need to be addressed when choosing landfills, including (1) Considering large landfills, whose modeled results will have an significant effect on the total impact ranges at provincial and national levels; (2) Taking landform into account by using the DEM (Digital Elevation Model) data for calculation, since some landfills in China lie in mountainous areas while the Gaussian dispersion model cannot reflect the influence of landform on odor diffusion; (3) Including landfills in different regions into consideration.

3.4. Analysis of social media data

Although physical modeling is the mainstream method to study the range of impacts of landfill odors, landfills cannot be completely characterized as simple point sources. Normally, there are many other odor sources, such as transportation and temporary storage (Lu et al., 2013). Sometimes the odor sources could act as large-scale non-point sources, especially for landfills with low management levels. According to field surveys and expert opinion, centralized transportation around the landfills could be an important landfill odor source, but this factor cannot be reflected in the landfill odor diffusion model. Moreover, the impacts of odors are greatly influenced by one's subjective feelings. The odor perception of different populations could be significantly different, and odors could affect emotions instead of directly affecting health. Therefore, the impacts of landfill odors are more than a physical issue. It involves the physical and psychological conditions of individuals as well as other factors. In order to further analyze the range of the impacts of landfill odors, we conducted text analysis on large sets of microblogs from Sina Weibo (a popular social media site in China, similar to Twitter) and news reports to identify complaints about landfill odors.

First, we identified all the microblogs with geographical coordinates and selected those containing the words “landfill” and “odors.” The selected microblogs were then assessed individually to make sure they actually reflected landfill odor impacts. The distance from where the microblog was submitted to the nearest landfill was set as the odor impact range of that landfill. For data from news reports, we selected those containing the specific odor impact distance and specific landfill. These data from social media and news reports were then compared with the results from our physical models.

It should be noted that the distance determined by this method might be smaller than the actual affected range of landfill odor, so the data could underestimate the actual influence range of landfill odors to a certain extent.

3.5. Data

We collected and processed data from 1955 landfills in China. Our data are mostly from provincial environmental protection bureaus, with a few large landfills investigated by our research group. The site-specific dataset for each landfill includes geographic coordinates (latitude and longitude), administrative properties, detailed address, annual and total amount of landfilled waste, and management levels. Data quality was checked by cross verification (logical analysis between different indicators). Some abnormal values were identified and revised after the field investigation.

The emission factors of the FOD model were obtained from field survey and lab analysis results from the Chinese Academy for Environmental Planning and Tsinghua University. The detailed information can be obtained from the literature (Cai et al., 2014), in which China was divided into 7 regions according to their different climate features, economic levels, and living habits. Then, the emission factors of landfills from different regions were further divided to three categories according to landfill size, i.e., type I (>5 million m^3), type II (2 million–5 million m^3), and type III (<2 million m^3). The final emission factors were multi-dimensional matrices for different regions and different landfill sizes. The meteorological data of 1 km grid data in 1951–2000 were obtained from the Data Sharing Infrastructure of Earth System Science.

We used the Sina microblog (weibo) platform as a source of big data. The data, including location information, was obtained through their official API. Landfill odor impacts are more obvious in the summer since high temperature, low air pressure, and high levels of biodegradable components in MSW are inductive to stronger odor generation and emissions. Thus, we used Sina microblogs published in July for analysis. There were 16,952,472 microblogs with identifiable location and further semantic analysis targeted 3181 microblogs related to landfills. We then confirmed these items individually and found that 24 of them were about the impacts of landfill odors. In addition, we obtained 57 pieces of online news reporting regarding landfill odors, of which 3 had specific information about the source and range of the impacts of landfill odors. Thus, the media data achieved 27 items in total.

4. Results and analysis

4.1. Odor gas emissions from landfills

Based on the results of the FOD model and the specific parameters of each landfill in China, the H_2S emissions from landfills in 2012 totaled 226.62 tons (Fig. 1 and Table 2). The average emissions per landfill were 115.92 kg. The results show that landfills in eastern coastal provinces had higher H_2S emissions. For example, landfills in Guangdong and Zhejiang had the highest H_2S emissions, while those in Hainan and Tibet had the lowest H_2S emissions. Overall, H_2S emissions are greatly influenced by factors including total and annual amount of landfilled waste, MSW components, and management levels.

4.2. Range of the impacts of odors of landfills

We calculated the range of the impacts of odors from Chinese landfills based on the Gaussian dispersion model. The histogram of the impact distances for landfills in China (Fig. 2) shows that the average distance of impacts was 796 m, the impact distances of most landfills (46.85%) was approximately 400–1000 m; and only a few landfills (0.15%) had an impact distance exceeding 10 km.

Based on our statistical analysis, the average distances from the nearest urban built areas to landfills with design capacity of 3–4 million and over 5 million m^3 are both under 5 km, lower than the required minimum distance (5 km) for the urbanized areas of large and medium cities stated in the Planning Guidelines for Urban Hygiene Facilities (GB50337-2003).

The distances of the impact of odors differs for each landfill based on each landfill's properties, including total and current amount of landfilled waste, waste composition, management level, geographic location, and meteorological conditions. Results showed that the total spatial area affected by landfills reached 837,476 ha, accounting for 0.09% of China's land territory. Table 2 shows the affected area for each province. Guangdong and Sichuan provinces had the largest affected area, while Tibet and Tianjin had the smallest affected area.

We analyzed landfill odor emissions and the range of impacts (Fig. 3). The linear relation is not good, especially when the odor emissions are large. When the emissions were lower than 100 kg, the range of impacts was below 100 ha with limited variation. The range of the impacts of odors manifested two different trends when the odor emission was in the higher range of 100–1000 kg. The range of impacts increased rapidly with increasing odor emissions in some landfills; however, the range of impacts increased slowly with increasing odor emissions in other landfills. This indicates that the range of odor impacts of a specific landfill was influenced by the diffusion model, meteorological factors, and other factors and that these effects do not have a simple linear relation with the rate of odor emissions.

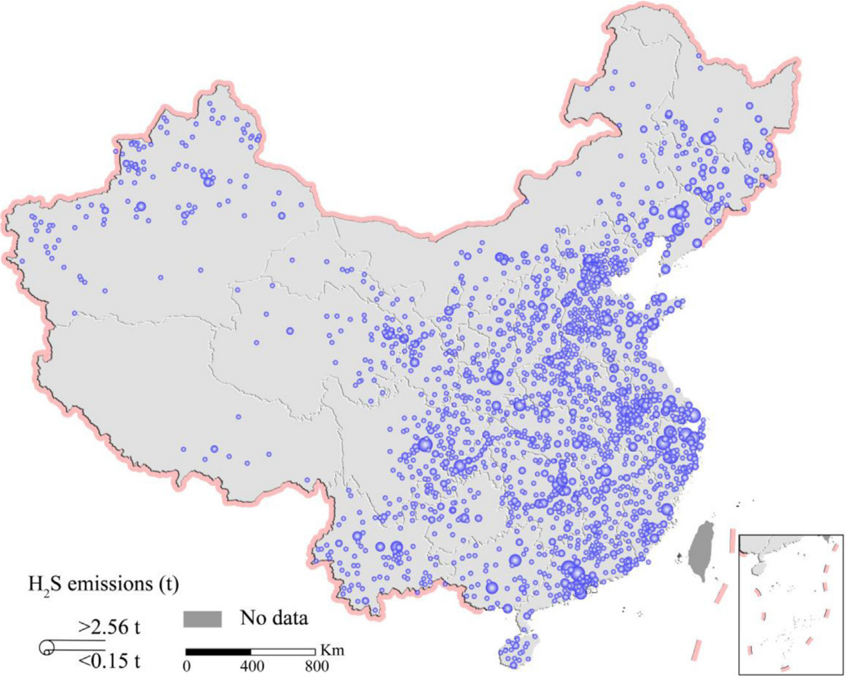

Fig. 1. The H_2S emissions from each landfill in China for 2012.

4.3. *Analysis of the range of the impacts of odors of selected landfills*

We chose six landfills to analyze. These landfills had a relatively large range of impacts and were in the vicinity of residential areas. Fig. 4 shows that a wide range of residential areas were located west of the Gaoantun Landfill in Beijing, and the nearest residential area was within only 486 m. This proximity had caused many odor nuisance for local residents in recent years. The Baoding Landfill lies to the east of the urbanized area of Baoding City and is surrounded by dense human settlements. The nearest residential area is within only 645 m of the landfill; in addition, the range of impacts of the Baoding Landfill covers the majority of the urbanized area of eastern Baoding. The Mianyang Landfill is located in a mountainous area that is very close to Mianyang Airport, and the range of the effects of odors covers part of Fucheng District of Mianyang. For the Nanjing Tianjingwa Landfill, many residential areas are located to the east within the Pukou District, as close as 940 m. The northern part of the Taizhou Landfill in the city of Tianshui is near the urbanized area of the Taizhou District, and the range of the impacts of

Table 2
Landfill odor emissions and ranges of impacts in each provinces of China.

Provinces	H_2S emissions (kg)	Range of impacts (ha)
Beijing	8537	14391
Tianjin	2425	1410
Hebei	6961	28055
Shanxi	4944	12733
Inner Mongolia	5259	5646
Liaoning	10353	21735
Jilin	6757	17464
Heilongjiang	5513	6546
Shanghai	11164	45086
Jiangsu	10543	21964
Zhejiang	19901	61268
Anhui	8726	19227
Fujian	4689	15465
Jiangxi	8170	41356
Shandong	11602	6962
Henan	7166	25983
Hubei	7094	48234
Hunan	10650	58136
Guangdong	27749	112203
Guangxi	4909	14934
Hainan	849	3337
Chongqing	4816	30963
Sichuan	8929	78245
Guizhou	3158	14529
Yunnan	5565	23344
Tibet	347	1634
Shaanxi	6404	47321
Gansu	3523	27379
Qinghai	2334	5575
Ningxia	1328	7712
Xinjiang	6258	18639
Total	226623	837476

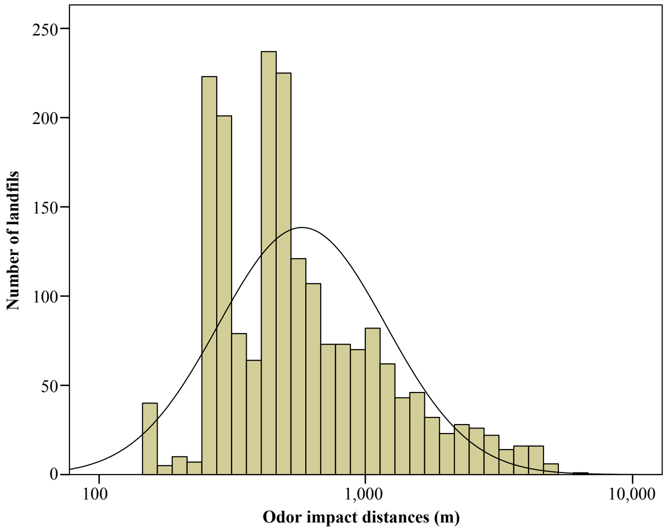

Fig. 2. Histogram of impact distances of odors for landfills of China.

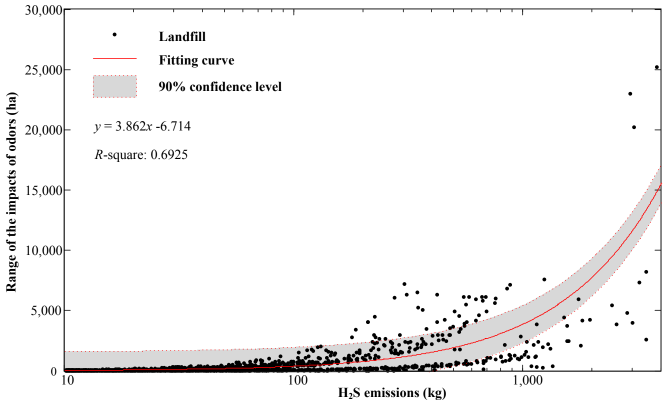

Fig. 3. Correlation analysis of amounts of landfill odor emissions and the range of their impacts.

odors covers the eastern part of the Taizhou urbanized area. The Xi'an Jiangcungou Landfill is located in a rural part of Baqiao District of the city of Xi'an. The main area affected by the landfill is the village of Jiangcun, and is as close as 329 m from the landfill.

4.4. Uncertainty analysis based on the CALPUFF model

We chose landfills with detailed meteorological data available to calculate the range of the impacts of odors based on the CALPUFF model. We then compared and checked these results against those from the Gaussian dispersion model. Nine landfills were identified, including Liulitun (Beijing), Laogang (Shanghai), Maiyuan (Nanchang), Xingfeng (Guangzhou), Xiaping (Shenzhen), Changshengqiao (Chongqing), Chengdu (Chengdu), Jiangcungou (Xi'an), and Shenjiagou (Xining) landfills. Fig. 5 shows calculated and compared ranges of the impacts of odors from the CALPUFF model and from the Gaussian dispersion model. Generally speaking, the results of these two models were consistent. However, because the

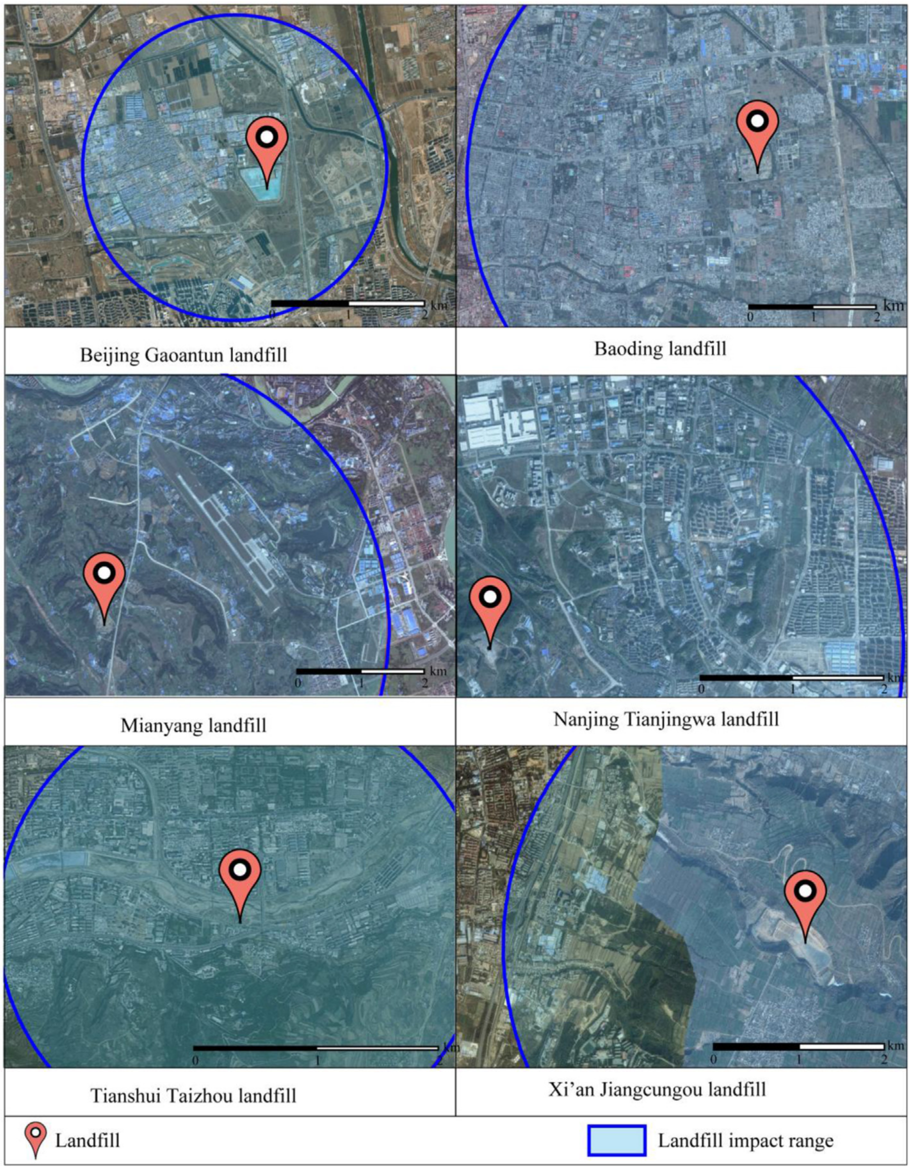

Fig. 4. The range of impacts from odors of selected landfills.

CALPUFF model took many more factors into consideration, such as topography, land use, and hourly weather conditions, the results obtained can reflect more detailed spatial differences that cannot be shown using only the Gaussian dispersion model.

A quantitative analysis and comparison of the spatial range of the impacts of odors given by the CALPUFF and Gaussian dispersion models were also conducted. The results provided by CALPUFF were lower than those from the Gaussian dispersion model, except for results from the Xingfeng (Guangzhou) and Chengdu landfills. The Shenjiagou (Xining) and Xiaping (Shenzhen) landfills show relatively large discrepancies between the two models, with results from the Gaussian dispersion model that were 136.93% and 55.98% higher than those from the CALPUFF model, respectively. The range of the impacts of odors from the Liulitun (Beijing) landfill show the lowest discrepancy between the two models (11.04%). The Xingfeng (Guangzhou), Chengdu, and Changshengqiao (Chongqing) landfills are all located in areas with complex terrain. The results of the CALPUFF model for the first two of these landfills are higher than those from the Gaussian dispersion model, while the Changshengqiao (Chongqing) landfill shows the opposite result. This indicates that topographical factors have complex effects on odor dispersion. If we assume that results of the CALPUFF model are reliable, then we can use them to evaluate the uncertainty of the Gaussian dispersion model. Overall, the results from the Gaussian dispersion model are on average 32.88% larger than those from the CALPUFF model.

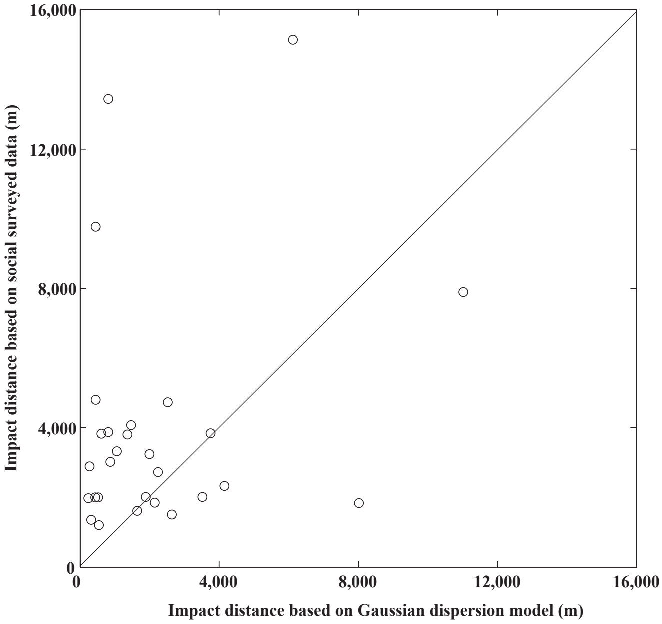

Fig. 6. Comparison of the range of the impacts of odors between the results of the Gaussian dispersion model and surveyed data.

4.5. Uncertainty analysis based on social data

Fig. 6 compares the results of the social media survey data and those of the Gaussian dispersion model. The comparison illustrates that most of the social media survey results show the impacts of landfill odors cover a greater area than the ranges determined by theoretical calculation, which confirms the viewpoint presented in this study. That is, the actual range of the impacts usually cover a

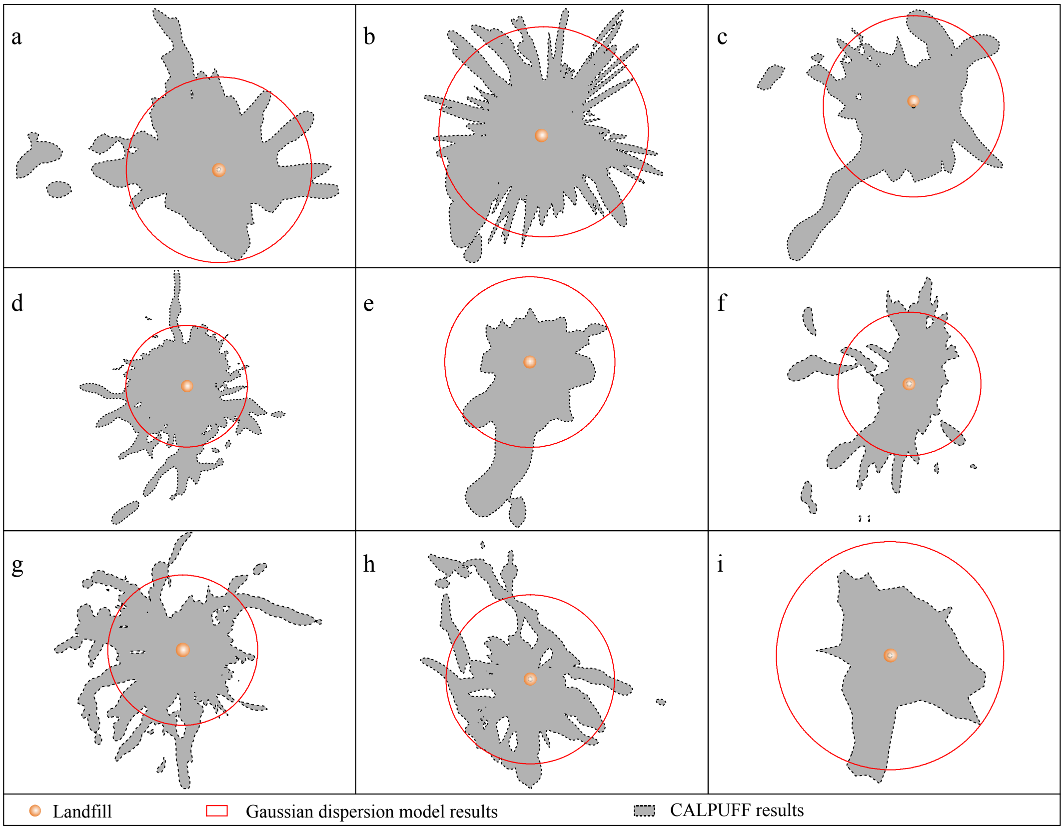

Fig. 5. Comparison of the simulated results between the CALPUFF and Gaussian dispersion models. Landfill names (and locations): (a) Liulitun (Beijing); (b) Laogang (Shanghai); (c) Maiyuan (Nanchang); (d) Xingfeng (Guangzhou); (e) Xiaping (Shenzhen); (f) Changshengqiao (Chongqing); (g) Chengdu (Chengdu); (h) Jiangcungou (Xi'an); (i) Shenjiagou (Xining).

greater area than the theoretical calculations, because of a series of reasons, such as transportation, temporary storage, field operations, and landfill mismanagement. Generally speaking, the range of the impacts calculated from the Gaussian dispersion model of the 27 landfills was 32.67% lower than the results from the social media survey.

5. Conclusions and discussion

Although landfills directly serve the public, their construction and operation have negative impacts on residents living nearby, especially the obvious impact of landfill odors. The NIMBY syndrome for landfills has emerged as a serious issue worldwide. In this paper, we calculated the odor emissions of 1955 landfills in China based on the FOD model and obtained the range of the impacts of odors based on the Gaussian dispersion model. The average distance that landfill odors had an impact in China was 796 m, and the total area affected by odors reached 837,476 ha. The CALPUFF model and social media survey data were applied to verify the calculated range of the effects. The results from the CALPUFF model show that the Gaussian dispersion model overestimates the impact area by 32.88%, while the results from the analysis of social media data (microblog) and news reports indicate that the theoretical modeling may underestimate the impact area by 32.67%. Hence, the uncertainty of the spatial extent of the range of impacts calculation is −32.88% to 32.67%. For odor impacts from landfills, Guangdong and Sichuan provinces have the largest affected area, while Tibet and Tianjin have the smallest affected area. Overall, range of impacts increases with odor emissions. Based on our analysis of selected landfills, large residential areas are within the range of the impacts of odors. The results of our bottom-up model provide fundamental data related to the accurate and detailed estimation of affected population and will be valuable for landfill management as well as for proper odor control in China. Therefore, our results can help target landfills that need policy attention the most and can further inform solutions addressing NIMBY syndrome in China.

This research has some limitations that should be improved: (1) the Gaussian dispersion model does not consider terrain related factors, which will influence the diffusion of odors. However according to the calculations and comparison of nine selected landfills using the CALPUFF model, terrain factors do not show an obvious effect on the range of the impacts of odors from landfills. This may indicate that terrain influences are insignificant given the current spatial resolution of available data and the spatial extent of the impacts of landfill odors; (2) although H_2S is the main component of odorous gases, other odoriferous gases still have impacts. Our method ignored other odoriferous gases, and thus underestimated the odor impacts.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.09.009.

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