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Landfills in Jiangsu province, China, and potential threats for public health: Leachate appraisal and spatial analysis using geographic information system and remote sensing

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ABSTRACT

Waste disposal is of growing environmental and public health concern in China where landfilling is the predominant method of disposal. The assessment of potential health hazards posed by existing landfills requires sound information, and processing of a significant amount of spatial data. Geographical information system (GIS) and remote sensing (RS) are valuable tools for assessing health impacts due to landfills. The aims of this study were: (i) to analyze the leachate and gas emissions from landfills used for domestic waste disposal in a metropolitan area of Jiangsu province, China, (ii) to investigate remotely-sensed environmental features in close proximity to landfills, and (iii) to evaluate the compliance of their location and leachate quality with the relevant national regulations. We randomly selected five landfills in the metropolitan areas of Wuxi and Suzhou city, Jiangsu province, established a GIS database and examined whether data were in compliance with national environmental and public health regulations. The leachates of the sampled landfills contained heavy metals (Pb, As, Cr^{6+} and Hg) and organic compounds in concentrations considered harmful to human health. Measured methane concentrations on landfill surfaces were low. Spatial analysis of the location of landfills with regard to distance from major water bodies, sensible infrastructure and environmental conditions according to current national legislation resulted in the rejection of four of the five sites as inappropriate for landfills. Our results call for rigorous evaluation of the spatial location of landfills in China that must take into consideration environmental and public health criteria.

1. Introduction

Over the last two decades, the national economy of China has grown at an annual rate of approximately 10%. In parallel to the economic expansion, there has been an exponential growth of the amount of solid waste to be disposed. In 2002, the total quantity of municipal solid waste (MSW) was estimated at 136.5 million tons. The respective quantities for industrial solid waste (ISW) and hazardous waste (HW) were 945 million tons and 10 million tons, respectively. The recorded quantity of disposed MSW in the same year was 74 million tons. Approximately, 90% was disposed in landfills, whereas the remaining 10% was incinerated or composted in the 651 licensed waste disposal facilities for MSW across China (Huang et al., 2006). In 2004, solid waste output in China had already surpassed that of the United States, and the predicted annual MSW quantity in China for the year 2030 is 480 million tons. The environmental, financial and social impacts of waste disposal in China are significant (World Bank, 2005). It is conceivable that health impacts are considerable, but there is a paucity of epidemiological investigations to address and quantify this issue. A recent survey carried out by the State Environmental Protection Administration (SEPA) of China revealed that landfills account for 88% of all urban waste management facilities and accommodate 94% of the urban waste collected. However, only 10–30% of these facilities are managed in accordance with national standards regulating waste disposal in landfills (Nie et al., 2004; Wang and Nie, 2001).

The disposal of poisonous materials in non-specialized landfills and without proper pretreatment may lead to the pollution of the environment by toxic emissions and threaten the health of local communities. For example, contaminated storm water can seep into the underlying groundwater. The decomposition of organic waste in landfills may also lead to the formation of hazardous gases such as methane (CH_4) and volatile organic compounds (VOC). Such "landfill gases" contribute to the greenhouse effect and they can cause explosions if trapped in buildings (Macleod et al., 2006; Palmer et al., 2005). There is considerable concern

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about the adverse health effects due to leachates and landfill gases. A recent analysis, for example, found an association between the location of landfills and the risk of congenital anomalies (Kloppenborg et al., 2005). In response, countries put forward national standards and laws to regulate and enforce the spatial location and safe management of landfills. These regulations take into account, among other issues, the toxic properties of deposited substances, the potential for the contamination of drinking water supplies, adverse effects on sensitive ecosystems and aesthetic, security and operational considerations.

China has issued a series of laws and regulations on waste disposal including the siting and operation of landfills, such as the "Atmospheric Pollution Prevention and Control Law", the "Management Methods for the Prevention and Control of Environmental Pollution from Tailings", and the "Solid Waste Pollution Control Law". The latter was issued in 1995 and specifies comprehensive prevention and control measures for solid waste landfills (Huang et al., 2006; Inanc et al., 2004; World Bank, 2005).

Various competing interests must be considered when evaluating existing and selecting new landfill sites (Calvo et al., 2005). Empirical studies and practical experience have shown the utility of geographical information system (GIS) and remote sensing (RS) technologies in this process (Dewidar, 2002; Eihoz, 2006; Eiselt, 2007; Gemitzi et al., 2007; Ghose et al., 2006; Kontos et al., 2003; Kwarteng and Al-Enezi, 2004; Tarhan and Ünlü, 2005; Vuppala et al., 2006). These technologies facilitate the collection, management and visualization of relevant data in a spatially-explicit manner, and thus greatly enhance the evidence-based, objective evaluation of available data and the assessment of potential environmental and health hazards.

The aim of this study was to investigate a random sample of MSW landfills in the metropolitan areas of Wuxi and Suzhou city, Jiangsu province. This province has experienced rapid economic development and urbanization, and the number of landfills has increased significantly. Since the location and management of landfills may not comply with national regulations, landfills could compromise the health of local residents (Wang et al., 2005; Xi et al., 2003). Remotely-sensed environmental data and data on inorganic and organic compounds in leachates and gases were incorporated into a GIS platform. Spatial analysis was carried out with an emphasis on potential hazards for human health and the environment.

2. Materials and methods

2.1. Study area and selection of study sites

The study was carried out in the metropolitan areas of Wuxi and Suzhou city, located on the southern banks of the Yangtze River in Jiangsu province, eastern China. The area has a subtropical oceanic monsoon climate with abundant rainfall. The fertile alluvial plain is crossed by a dense network of rivers and artificial canals. There are a number of lakes, the largest of which is Taihu Lake in the southwest. Considering the administrative boundaries, the surface areas of Wuxi and Suzhou city are 4786 and 8488 km^2, respectively. The estimated populations of the two cities are 7.1 million and 12.5 million, respectively. As a result of the rapid growth of the local economy and the profound changes in the lifestyle of its people, a massive increase in the amount of solid waste has occurred. There are an estimated 80 landfills in this area, most of which are operated under the direction of counties or townships. A recent study concluded that most of the solid waste produced in this area is indeed deposited in landfills, and that the facilities are rapidly approaching their operational limits (Wang et al., 2005). We recorded the active landfills in the study area, identified their official classification and then selected five facilities at random, constraining our selection to one large provincial-level landfill, two medium county-level landfills and two small township-level landfills.

2.2. Ground-based data collection

The exact location of the selected landfills was recorded using a hand-held global positional system (GPS) receiver (Map 76, Garmin Inc., Olathe, USA).

At every landfill site, samples of landfill leachates were obtained from collection holes or ponds, and transferred to a nearby laboratory and analyzed according to a SEPA guideline entitled "Technical Specifications and Requirements for Monitoring Surface Water and Wastewater" (SEPA of China, 2002). In brief, chemical oxygen demand (COD) was quantified using potassium dichromate ($K_2Cr_2O_7$). The 5-day biochemical oxygen demand (BOD5) was assessed via the oxygen consumption of bacteria breaking down organic matter in the sample over a 5-day period under standardized conditions. The concentration of ammonium (NH_4–N) was measured by Nessler's reagent photometry. The concentrations of heavy metals (i.e., lead [Pb], arsenic [As], chrome [Cr^{6+}] and mercury [Hg]), volatile phenol and coliform bacteria were assessed using the standard examination methods specified by the Standardization Administration of China (SAC) (SAC, 1985). The emission of methane (CH_4) from the landfills was evaluated on the surface of the landfills using a digital methane measuring device (9000D, Jingchen Hongchen Co. Ltd. Jingchen, China).

2.3. Digital maps, satellite images and spatial dataset

Twenty map layers containing, among others, information about topography, wetlands, surface water, settlements and transportation corridors in the study area were obtained from a commercially available digital map of Jiangsu province at a scale of 1:10,000 (edition 2003). Additional data were derived from hard-copy maps by scanning and digitizing the relevant information using ArcGIS 9.0 (ESRI; Redlands, CA, USA). The slopes within the study area were obtained from a digital elevation model (DEM) downloaded from the US Geological Survey website (USGS, www.usgs.gov). A Landsat 7 Enhanced Thematic Mapper Plus (ETM+) image, acquired on 26 July 2002, was obtained from the China Remote Sensing Satellite Ground Station (China RSGS). The Landsat 7 ETM + satellite is equipped with multispectral radiometers and provides high-resolution images of the earth's surface at the visible, near-infrared, short-wave infrared, and thermal infrared frequency bands. The nominal pixel resolution is 30 m in the six visible, near and short-wave infrared bands. In addition, the ETM + provides a panchromatic band with a resolution of 15 m. A subscene of the satellite image containing the study area was resampled using the subset image module of ERDAS 8.6 (Leica Geosystems, Atlanta, GA, USA) and geometrically corrected to the UTM projection. The coefficients of the linear transformation equations used for transformation were obtained by linear regression employing several control points across the study area that were derived from the 1:10,000 digital topographic map. Subsequently, a root mean square error (RMSE) evaluation was performed to assess the image-to-map accuracy. The RMSEs for the transformed image and standardized maps were smaller than 1 pixel. The resolution of the multispectral image was further enhanced using the 15 m panchromatic band and the principal component method of the spatial enhancement module of ERDAS 8.6, resulting in colored high-resolution images.

2.4. Environmental features derived from remotely-sensed imagery

The environmental features considered in the current study consisted of the land surface temperature (LST), the normalized difference vegetation index (NDVI) and clay minerals index (CMI). Justification for selecting these environmental features is as follows. The difference in LST between actual landfill sites and surrounding areas is correlated to some extent with the speed and extent of biodegradation in the landfilled material and the release of landfill gases (Kwarteng and Al-Enezi, 2004). The NDVI is widely and extensively used in vegetation analyses due to its ability to highlight differences in the plant cover that are not readily visible otherwise. A common assumption is that the NDVI also correlates with the water content in the soil. A key structure of landfills is barrier systems that contain leachates and prevent the dissipation of biogases (Zheng and Zhao, 2000). Clay is commonly used to seal off landfills, thus preventing contaminated water and other liquids from reaching water bodies and infiltrating the groundwater (Edil, 2003). The CMI can be calculated based on remotely-sensed data, allowing the assessment of the clay concentration in the surface cover.

We obtained LST estimates by converting the thermal band covering the wavelengths of 10.40–12.50 μm using the following formula (Li et al., 2004; Weng et al., 2004):

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)},$$

where T is the effective temperature at the sensor, measured in Kelvin, K_1 and K_2 denote calibration constants ($K_1 = 666.09$ W/(m^2 sr μm); $K_2 = 1282.71$ K), L_λ is a spectral radiance (measured in W/(m^2 sr μm)) defined as follows: $L_\lambda = ((L_{\max} - L_{\min})/DN_{\max})^* DN + L_{\min}$, with $L_{\min/\max}$ = spectral radiance, scaled to $DN_{\min/\max}$, $DN_{\min/\max}$ = minimum/maximum DN (DN is the quantized calibrated pixel value).

With regard to the NDVI, we used the following formula from ERDAS 8.6 (ERDAS, 1999):

$$\text{NDVI} = \frac{\text{Near-infrared} - \text{red}}{\text{Near-infrared} + \text{red}}.$$

The CMI was calculated in ERDAS 8.6 employing the following formula (Carranza and Hale, 2002; ERDAS, 1999):

$$\text{Clay minerals index} = \frac{\text{band 5}}{\text{band 7}}.$$

2.5. *GIS analysis and suitability assessment of the study area for landfills*

All data were imported into a GIS database, and six different buffer zones around landfill centroids were considered: (i) <500 m, (ii) 500–1000 m, (iii) 1001–2000 m, (iv) 2001–3000 m, (v) 3001–4000 m, and (vi) 4001–5000 m. The smallest buffer zones (<500 m) were assigned the contamination levels measured in the leachates because they approximately correspond to the actual size of a typical landfill in China. Subsequently, the distance between landfills and surrounding bodies of open water (rivers, canals and lakes) was calculated.

The previously mentioned environmental features (i.e., LST, NDVI and CMI) were evaluated for the different buffer zones separately by zonal statistics, using the analysis of variance (ANOVA) function in SPSS 11.0 (Chicago, USA).

The characteristics of the study area were investigated using relevant data derived from ground maps and by RS, and the suitability of the area for landfills was determined based on the selection criteria mentioned below. Subsequently, the location of the five selected landfills was compared with the suitability map. All spatially-explicit analyses were carried out using the spatial analyst module of ArcGIS 9.0.

The criteria used to determine potentially suitable locations for landfills were derived from the following two SEPA guidelines: (i) "Standard for Pollution Control from Landfill Sites for Domestic Waste" (SEPA of China, 1997), and (ii) "Pollution Control Standard for Hazardous Waste Landfills" (SEPA of China, 2001). The two documents list a set of constraints and suitability conditions for the location of landfills. The constraints consider issues related to proximity to ecological features and the built environment (e.g., nature reserves, open water bodies, soil permeability and soil type, land use and land cover, roads, residential areas and accessibility for delivery of waste (for details, see Appendix A).

Considering the criteria mentioned in the national standard for the selection of landfill sites and the available data of our study area, we selected the following criteria for the suitability analysis: proximity of open water bodies, residential areas, roads, airports, and protected areas, and the slope of the terrain. Straight-line distances between the landfills and the considered ecological and man-made structures were calculated and the slopes in the vicinity of landfills were derived from the DEM. The resulting data were reclassified. Reclassification is a method to replace values based on new information and to grouping values together to facilitate the analysis. All raster points of the individual maps were assigned a value between 1 and 10, representing their suitability for the construction and operation of a landfill in reference to the specific condition. For example, a point in the vicinity of a water body or residential area would be assigned a value of one, because it is highly unsuitable as a landfill site. However, a point close to a major road would get a value of 10 due to its convenient accessibility. Next, the variables were assigned individual weights to represent their perceived importance for landfill siting. The weights were determined according to previously published examples: the weights of distance to open water bodies, residential areas, roads, airports, protected areas and slope were 0.4, 0.3, 0.1, 0.1, 0.05, and 0.05, respectively (Cai and Cha, 2004; Mahini and Gholamalifard, 2006). The combination of these different criteria and data resulted in an output dataset where the summary value of each pixel indicated its suitability for landfill construction, with higher scores indicating better qualification. Areas with pixel scores above the median of all pixels, namely, with pixel scores >5 were tentatively identified as suitable for landfill construction.

3. Results

Fig. 1 shows the location of the five selected landfills in Jiangsu province and the extent of the different buffer zones around them, depicted against the background of the Landsat 7 satellite image (RGB: 543). All of the landfills are located close to the shore of the Yangtze River or the Taihu Lake, with two of the 4 km buffer zones overlapping the boundaries of Taihu Lake.

The results of the chemical analysis of the leachates and the gas measurements are summarized in Table 1. Currently used concentration thresholds for the classification of leachates from landfills in China are shown in Table 2.

None of the investigated leachate samples complied with all limit values for the lowest quality standard, i.e., class 5. At the level of individual contaminants, the picture was more complex. When considering lead (Pb) concentration, only one landfill (Badu) qualified better than class IV according to existing guidelines in China, i.e., the measured Pb concentration of 0.034 mg/l was below the class IV level (⩽0.05 mg/l). In two landfills (Pingwang and Miaogang), the measured Pb concentrations exceeded the limits of class V (>0.1 mg/l). Arsenic (As) was found in a lower concentration than the class III cut-off value (⩽0.05 mg/l) in the leachate of Taohuashan. The As concentration in Pingwang exceeded all limits. The measured chrome (Cr^{6+}) concentrations were above the upper limit of class V (0.01 mg/l) at all sites. Mercury (Hg) was found in the

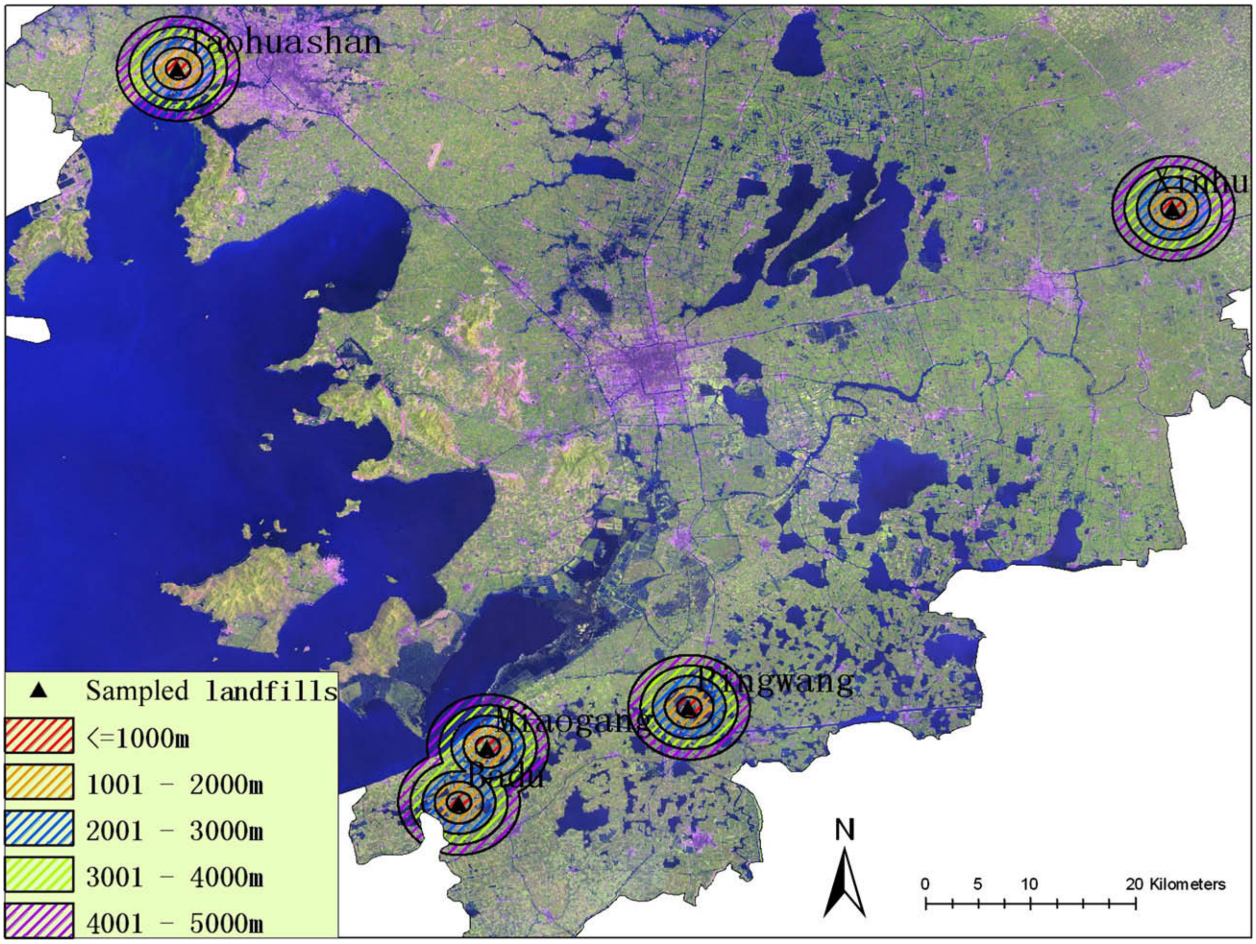

Fig. 1. Location of the study area and the five investigated landfills, including buffer zones, in Jiangsu province, China. Background: Landsat 7 satellite image (RGB: 543).

Table 1
Chemical analysis of the leachate and additional parameters measured at five different landfills in Jiangsu province, China

Name of landfill	Classifi-cation	pH	Lead (Pb, mg/l)	Arsenic (As, mg/l)	Chrome (Cr^{6+}, mg/l)	Mercury (Hg, mg/l)	Volatile phenol (mg/l)	Coliform bacteria (CFU/l)	COD (mg/l)	BOD5 (mg/l)	NH_4–N (mg/l)	Methane (CH_4; %)	
												Covered by soil	Without cover
Pingwang	Township-level	8.4	0.195	0.113	0.086	0.000467	12.5	>160 000	925.8	330	94	0.05	0.06
Badu	County-level	7.7	0.034	0.0778	0.132	<0.000 093	0.4	7 000	226.3	73	4	0.05	0.05
Taohuashan	Large provincial-level	6.7	0.098	0.0327	0.064	0.00467	3.4	>160 000	3760.6	1100	860	0.04	0.07
Xinhu	County-level	8.4	0.098	0.0649	0.11	0.000 93	0.088	500	3 296.3	210	88	0.04	0.04
Miaogang	Township-level	8.0	0.179	0.0649	0.11	0.000561	0.11	500	4 426.3	390	200	0.04	0.07

BOD5: 5-Day biological oxygen demand.
CFU: Colony forming units.
COD: Chemical oxygen demand.

run-off water of Badu in medium concentrations (class III, $\leqslant$0.0001 mg/l), while exceeding the maximum limit in Taohuashan. The concentration of volatile phenol qualified only Xinhu for class V ($\leqslant$0.1 mg/l). The density of coliform bacteria was up to class II standard in the samples from Xinhu and Miaogang ($\leqslant$2000 bacteria/l), but exceeded the limit for class V in Pingwang and Taohuashan. The measured values for COD, BOD5 and NH_4-N were within acceptable limits in Pingwang and Badu (COD), all landfills except Taohuashan (BOD5), and in Badu (NH_4–N), respectively. The measured concentrations of methane (CH_4) did not reach the limit values for fire or explosion risk at any site. In summary, the limit values for qualification for the lowest quality standard, i.e., class V, were exceeded for two (Badu) to seven (Taohuashan) of the nine investigated contaminants.

The LST, NDVI and CMI in the different buffer zones around the selected landfills and the ANOVA results are presented in Table 3. In general, the LST, NDVI and CMI showed an inverse relationship to the distance from landfills, but only the decrease in the NDVI and the CMI were significant ($P < 0.05$). The NDVI and the CMI were low around Xinhu and Pingwang but the CMI was very high in the area of the Taohuashan landfill.

Fig. 2 shows potentially suitable areas for the construction and operation of landfills in the study area, according to our decision matrix detailed before. Fig. 3 depicts the location of

Table 2
Limit concentrations for the classification of leachate from landfills in China (SEPA of China, 2002)

Substance	Class I	Class II	Class III	Class IV	Class V
Lead (Pb; mg/l) ⩽	0.01	0.05	0.05	0.05	0.1
Arsenic (As; mg/l) ⩽	0.05	0.05	0.05	0.1	0.1
Chrome (Cr^{6+}; mg/l) ⩽	0.001	0.005	0.005	0.005	0.01
Mercury (Hg; mg/l) ⩽	0.00005	0.00005	0.0001	0.001	0.001
Volatile Phenol (mg/l) ⩽	0.002	0.002	0.005	0.01	0.1
Coliform bacteria (CFU/l) ⩽	200	2000	10 000	20 000	40 000
COD (mg/l) ⩽	100	300	1000	n.a.	n.a.
BOD5 (mg/l) ⩽	30	150	600	n.a.	n.a.
NH_4–N (mg/l) ⩽	15	25	n.a.	n.a.	n.a.

BOD5: 5-Day biological oxygen demand.
CFU: Colony forming units.
COD: Chemical oxygen demand.
n.a.: Not applicable.

the five landfills studied in this manuscript, in relation to the potentially suitable areas for landfills. Most of these areas are located close to cities and major transportation corridors, but at some distance from open water bodies. Four out of the five investigated landfills are located outside the area deemed appropriate for such facilities.

4. Discussion

Waste disposal is a significant environmental challenge that China is facing in the wake of its unprecedented economic development. There is growing awareness of the threats to the natural environment and human health that are associated with inadequate waste disposal (Huang et al., 2006; World Bank, 2005). Here, we focused our analysis on five selected landfills in Jiangsu province. The landfills were mapped using a hand-held GPS device, gas emissions were measured on the spot, leachates were analyzed for various contaminants, and key environmental features were derived by RS.

Our laboratory investigations revealed that none of the analyzed samples complied with the national regulations of China and the limit values specified therein. Remotely-sensed data and information from existing digital maps showed that the five selected landfills were located rather close to open water bodies, and clearly indicated humid conditions in the areas surrounding the landfills. Longitudinal monitoring of leachates and groundwater quality is required at all sites, and is of particular importance at sites with a low CMI value, i.e., Xinhu and Pingwang.

We employed an integrated GIS approach to process the available data, and to analyze and query the established database for spatial relationships. Using an elaborate decision matrix for site selection, we were able to determine and map the suitability of the location of the investigated landfills. To that end, the study area was tentatively classified into areas that are potentially suitable for the construction and operation of landfills, and areas that should be avoided. There are myriad of factors governing the selection of landfill sites. In the present investigation, we strictly adhered to the national criteria set forth in China. We considered the impact of different factors on the suitability of a particular setting by weighing the considered factors, but we are well aware that the attributed weights can be challenged. For example, the distance to open water bodies was given the highest weight, since the contamination of these water bodies would jeopardize the provision of drinking water. Leaching of toxic substances into drinking water supplies is probably the most direct and the most severe adverse effect of landfills on human health. It was exactly this criterion which lead to the rejection of the siting of four of the five landfills studied here. However, the identification of suit-

Table 3
LST, NDVI and clay minerals index measured at five different landfills in Jiangsu province, China

Buffer zones (m)	Land surface temperature (°C)							Normalized difference vegetation index							Clay minerals index						
	Pingwang	Xinhu	Taohuashan	Badu	Miaogang	Mean	SD	Pingwang	Xinhu	Taohuashan	Badu	Miaogang	Mean	SD	Pingwang	Xinhu	Taohuashan	Badu	Miaogang	Mean	SD
Landfills	30.5	30.2	30.5	30.5	30.5	30.4	0.146	0.161	0.170	0.195	0.222	0.083	0.166	0.052	1.244	1.224	1.257	1.145	1.272	1.228	0.050
<1000	30.4	30.2	30.5	30.5	30.5	30.4	0.130	0.167	0.127	0.182	0.191	0.104	0.154	0.037	1.219	1.212	1.200	1.155	1.271	1.211	0.042
1000–2000	30.2	30.2	30.5	30.4	30.5	30.4	0.134	0.132	0.087	0.150	0.143	0.096	0.121	0.029	1.174	1.179	1.136	1.147	1.226	1.173[a]	0.035
2001–3000	30.2	30.2	30.5	30.4b		30.3	0.143	0.062	0.110	0.055	0.106b		0.083[a]	0.029	1.129	1.114	1.189	1.120[b]		1.138[a]	0.035
3001–4000	30.2	30.2	30.4	30.4b		30.3	0.137	0.052	0.073	0.052	0.108b		0.071[a]	0.026	1.135	1.098	1.123	1.109[b]		1.116[a]	0.016
4001–5000	30.2	30.2	30.4	30.3b		30.3	0.122	0.054	0.051	0.049	0.071b		0.056[a]	0.010	1.097	1.097	1.101	1.111[b]		1.101[a]	0.007
F-value	–	–	–	–		–	0.946	–	–	–	–		–	7.943	–	–	–	–		–	9.556
P-value	–	–	–	–		–	0.470	–	–	–	–		–	0.0002	–	–	–	–		–	0.0001

[a] Significant difference between landfill and buffer zone ($P < 0.05$).
[b] The 2001–3000, 3001–4000, 4001–5000 m buffer zone of Badu and Miaogang landfill overlapped, the indicated value is the average.

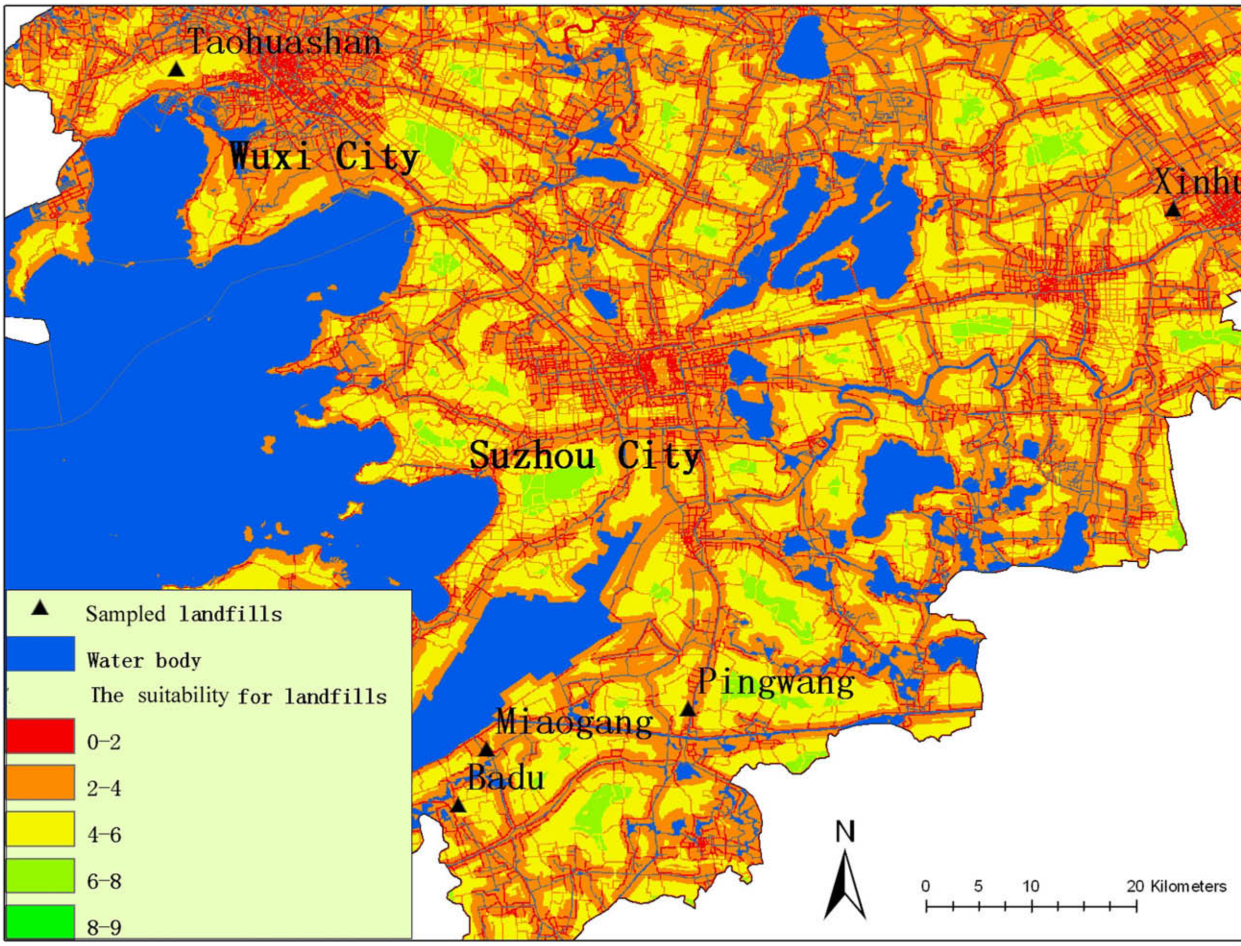

Fig. 2. Suitability map of the study area around Wuxi and Suzhou city, Jiangsu province for landfill construction considering geological, hydrological, geographical and land use characteristics. Higher values indicate higher suitability.

able areas without further ground-based geotechnical and hydrogeological analyses is of limited relevance. Political and economic constraints were also not considered. Nevertheless, the proposed method constrained the potentially suitable area quite considerably and could therefore be used to focus further investigations to certain areas at an early stage of a study to identify potential landfill sites, thus accelerating the process of landfill site identification. Also, health impact assessment, coupled with environmental and social impact assessments, should become integral parts right from the onset of the planning and decision making process on where and how to construct and operate future landfills in China (Kemm et al., 2004).

Usually, it is not possible to directly identify landfills on readily available satellite images. However, the consistently elevated LST at landfill sites indicates that this remotely-sensed environmental feature holds promise for the identification of landfills. The increased LST is probably due to the decay of organic materials which can also lead to the spontaneous ignition and combustion of the deposited materials (Crutcher et al., 1982). In this study, the LST was found to be only moderately elevated. In fact, the measured methane (CH_4) concentrations were below 1%, indicating decomposition under aerobic conditions and rapid dissipation of heat and gases (Prakash et al., 1997; Zhang et al., 1998). The NDVI was consistently higher at the actual landfill sites and in their immediate vicinity than in their more distant surroundings. Since the NDVI is closely correlated with the plant cover, wetness and the stabilization of landfills (Carranza and Hale, 2002; Komiya et al., 2006; Weng et al., 2004), we speculate that this might indicate higher wetness in the surroundings of the investigated landfills and stabilized conditions at the actual landfill sites. Contaminated leachates or run-off water from the landfills could reach these wet areas and pollute them as well as connected water bodies downstream and in the ground. This again emphasizes the need for close monitoring of contaminants in these areas. The analysis of the leachate samples for heavy metals, organic contaminants, coliform bacteria and NH_4–N showed that none of the samples complied with even the lowest acceptable quality standards and that limit values were exceeded for two to seven of the nine considered contaminants, depending on the site. Of particular concern are the high concentrations of heavy metals, NH_4–N and coliform bacteria. The considered contaminants not only pose direct threats to drinking water supplies but also render the water unsuitable for irrigation and aquaculture due to the problem of bio-accumulation of heavy metals and hygiene issues associated with coliform bacteria.

The five selected landfills in Jiangsu province exhibit a considerable risk for public health and the natural environment. It is conceivable that the situation is similar in other parts of Jiangsu and elsewhere in China. Possible remedies include the closure and clean-up of unsafe facilities and their relocation to well-maintained landfills at more suitable locations that comply with all relevant regulations. Another option is the increased use of incinerators built according to the highest international standards for emissions.

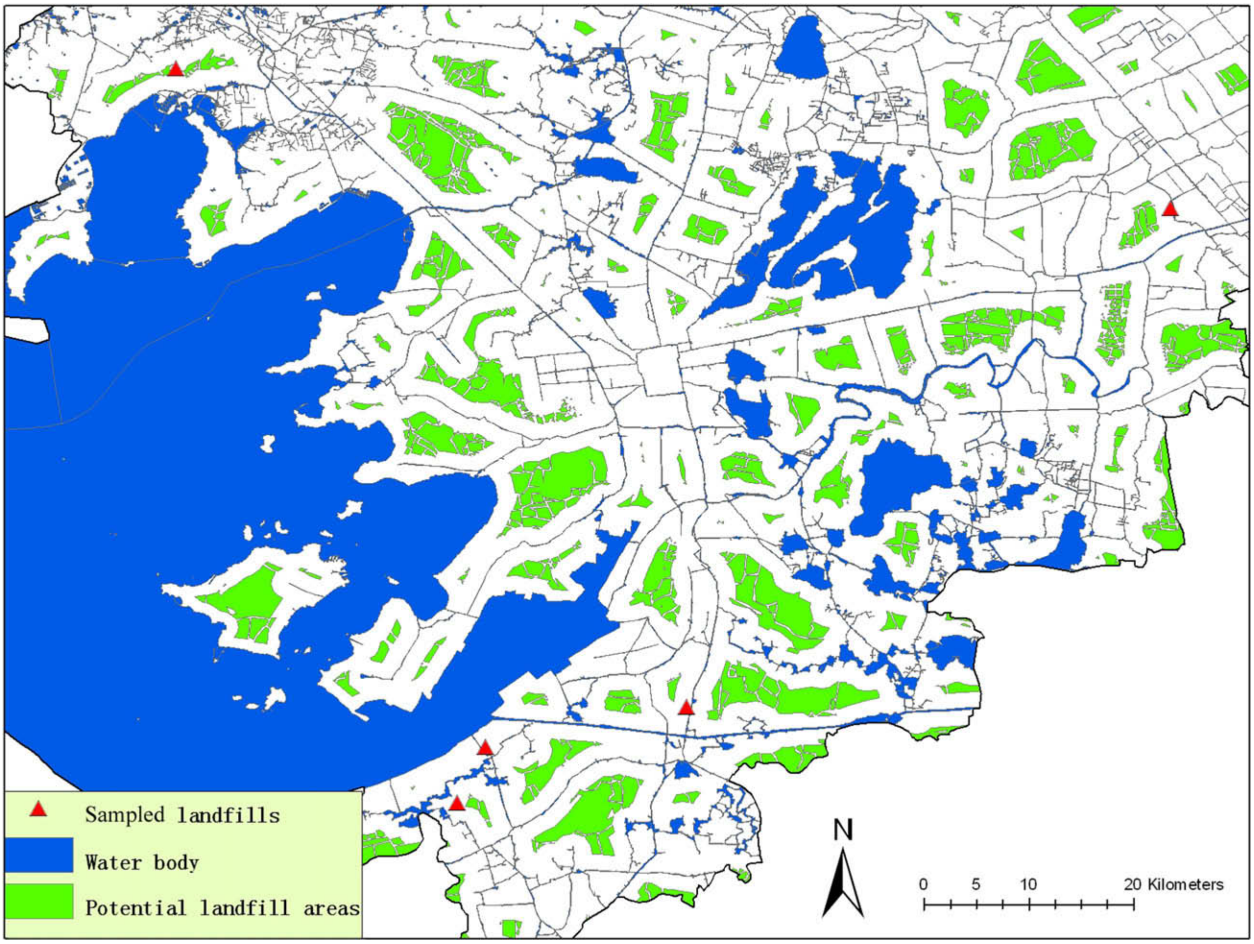

Fig. 3. Identified areas around Wuxi and Suzhou city in Jiangsu province which are potentially suitable for landfill construction considering geological, hydrological, geographical and land use characteristics. Cut-off: median suitability value.

5. Conclusions

The critical appraisal of the spatial location and risks posed to the natural environment and human health due to landfills and other man-made ecological transformations requires comprehensive and sound databases that take into consideration local conditions and the possible hazards exhibited by the unit, integration of legal, political and scientific requirements, and sound judgment. The collected data need to be put into perspective and evaluated in their entirety. Understanding such processes is complex and often time consuming, but progress made with GIS and RS technologies, as well as health impact assessment, can facilitate and expedite an evidence-based evaluation. These tools are particularly helpful for predicting potential health risks, and hence for putting into place sound mitigation measures, and for the establishment of locally-adapted monitoring and surveillance platforms.

The landfill leachate analysis clearly indicated that the concentrations of different substances exceed the acceptable threshold values and are thus potentially harmful to human health and the natural environment. The study also showed that the investigated landfills are located rather close to water bodies, suggesting that environmental and health considerations were not the major drivers at the time the landfill sites were selected and operations started. Available digital maps, remotely-sensed data and GIS-based analyses can facilitate the monitoring of existing landfills, as well as the identification of potentially suitable locations for new facilities in Jiangsu province. The establishment of GIS databases also offers the potential to carry out further analyses covering additional issues.

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Appendix A

Requirements for landfill sites according to the national standards for landfills (SEPA of China, 2001, 2002):

(1) The selection of landfill sites should be done in accordance with the national and local development plan. The sites should be located in a stable region that is not likely to be affected by natural forces or human activities.
(2) Landfill sites should not be located in urban, industrial or agricultural planning and development zones, agricultural or natural protection zones, scenic resorts, historic (archaeo-

logical) sites, drinking water resources protection zones, water supply zones, mineral resources reservations or other zones requiring special protection.

(3) Landfill sites should be at least 3000 m away from airports and military bases.

(4) The boundary of landfill sites should be over 800 m away from residential areas and it should be ensured that under the local meteorological conditions, the odor nuisance of landfills does not affect nearby residential areas.

(5) The distance between landfill sites and surface water bodies should be at least 150 m.

(6) The establishment of landfills should be avoided in the following zones: earthquake zones; tsunami-prone areas; marshlands and basins; regions of rapid movement of the earth's crust, areas with karst or caves, abandoned mining areas or collapse-prone areas above mines, regions with collapse, talus, landslides and torrents; regions with shifting sand dunes, unstable alluvial fans and gullies; regions with highly compressive sullage, turf and mollisol; and other regions that may pose a danger to the landfill.

(7) The landfill should be large enough for usage over 10 or more years after its construction.

(8) Landfills should be located in areas that are served by appropriate transportation infrastructure, be close to the source of the deposited materials, enjoy low construction and operation costs, and be generally favorable to the regular operation of a landfill site.

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