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Quantification of regional leachate variance from municipal solid waste landfills in China

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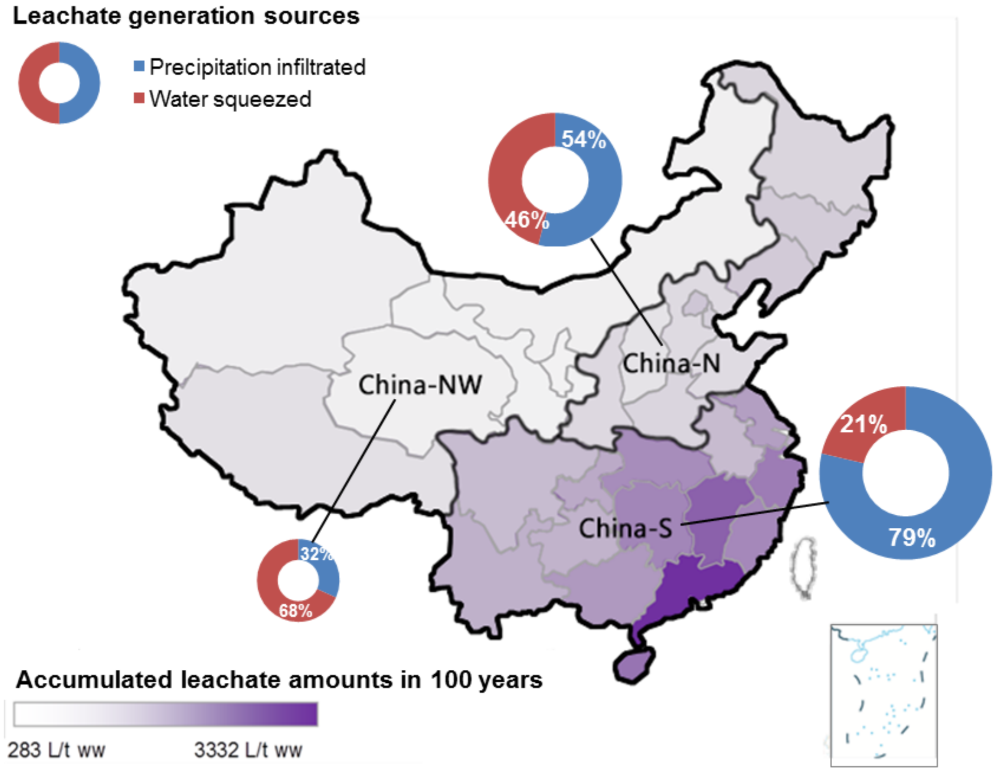
Abstract

The quantity of leachate is crucial when assessing pollution emanating from municipal landfills. In most cases, existing leachate quantification measures only take into account one source – precipitation, which resulted in serious underestimation in China due to its waste properties: high moisture contents. To overcome this problem, a new estimation method was established considering two sources: 1) precipitation infiltrated throughout waste layers, which was simulated with the HELP model, 2) water squeezed out of the waste itself, which was theoretically calculated using actual data of Chinese waste. The two sources depended on climate conditions and waste characteristics, respectively, which both varied in different regions. In this study, 31 Chinese cities were investigated and classified into three geographic regions according to landfill leachate generation performance: northwestern China (China-NW) with semi-arid and temperate climate and waste moisture content of about 46.0%, northern China (China-N) with semi-humid and temperate climate and waste moisture content of about 58.2%, and southern China (China-S) with humid and sub-tropical/tropical climate and waste moisture content of about 58.2%. In China-NW, accumulated leachate amounts were very low and mainly the result of waste degradation, implying on-site spraying/irrigation or recirculation may be an economic approach to treatment. In China-N, water squeezed out of waste by compaction totaled 22−45% of overall leachate amounts in the first 40 years, so decreasing the initial moisture content of waste arriving at landfills could reduce leachate generation. In China-S, the leachate generated by infiltrated precipitation after HDPE geomembranes in top cover started failing, contributed more than 60% of the overall amounts over 100 years of landfilling. Therefore, the quality and placing of HDPE geomembranes in the top cover should be controlled strictly for the purpose of mitigation leachate generation.

Graphical abstract



Keywords

Municipal solid waste, leachate generation, hydrological modeling, precipitation infiltration, waste water squeezing, regional variation

1. Introduction

Due to its economic advantages, landfilling is still the most dominant treatment method used worldwide for municipal solid waste (MSW), especially in developing countries such as China (National Bureau of Statistics of China, 2012). Leachate from MSW landfills is a threat to the quality of groundwater and surface waters (Kelly, 1976; Mor et al., 2006; Reinhard et al., 1984). Even though a series of leachate control systems may be installed in a landfill site, their performance is associated significantly with the amount of leachate generated, which is often underestimated in landfills in China (Lan et al., 2012) and results in an increased water head above the liner system, due to insufficient design capacities for collection and treatment. Subsequently, the high water level in a landfill body may lead potentially to leaching into the surrounding area and cause landfill instability. In addition, as the content of organic fractions in Chinese MSWs is usually high, the storage of water in a landfill may encourage the accumulation of acid and delay the arrival of the methanogenic phase, thereby making the landfill an “acid tomb” (He, 2009). In an “acid tomb”, decaying carbon in the waste is most likely to be transferred into leachate rather than released as landfill gas, which aggravates the pollution loads and limits the energy recovery potential. Therefore, it is important to establish a leachate quantification method suitable for MSW landfills in China, to be able to control landfill pollution.

In addition to the control of leachate contamination, estimating landfill leachate quantities is also important in life cycle assessments (LCAs) of landfilling technology, as leachate is the origin of one of the most serious local environmental impacts. In LCA modelling for decision support, environmental impacts are normally modelled as the impact caused by one unit of waste (Banar et al., 2009; Cherubini et al., 2009; Hong et al., 2010), e.g. one tonne of waste or the waste generated in a defined geographical region in a given time (e.g. 1 year). This type of LCA modelling of landfill is often used for comparisons with other technologies (incineration, composting, etc.). However, existing methods in previous research (ElFadel et al., 1997) and in the Chinese national standards for landfill construction (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2013) were developed mainly to estimate leachate amounts generated from the entire landfill and with all the waste buried, in order to design leachate collection and treatment systems. In addition, most of the conventional LCA models (specific waste LCA models the exception (Gentil et al., 2010)) estimate the leachate quantities with default values without considering spatial and temporal variations. However, leachate generation amounts in different regions could vary a great deal, due to different climate conditions, waste properties.

Landfill leachate quantification is traditionally modeled based on water balance principles by summing the amounts of water entering the landfill and subtracting the amounts of water consumed by degradation and lost as water vapour (Blakey, 1992; ElFadel et al., 1997; Kjeldsen and Beaven, 2011). Accordingly, several mathematical models have been developed, in which Hydrologic Evaluation of Landfill Performance (HELP) model is most widely used for hydrological modeling of precipitation (Schroeder et al., 1994). The validation of existing HELP models were conducted for cover systems in tested field (Berger, 2015), which indicated that "the sum of measured lateral drainage and liner leakage is close to the sum of the corresponding simulated values" (overestimation by HELP model for 1.4% of the precipitation). However, the HELP model was questioned for leachate quantification in recent years because it neglected the water balance of waste, which was proved to be important processes during leachate generation. For instance, Komilis and Athiniotou (2014), Pantini et al. (2014) and Sao Mateus et al. (2012) established their own water budget models and demonstrated that water which leached out by waste compression and biodegradation contributed to the leachate amounts to a large extent. In China, researchers (Lan, et al. 2012; Yang, 2012b) widely believed that the failure to include water leaching out from waste itself in the Chinese national standard (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2013) was the main reason for the underestimation of leachate generation amounts in landfills.

In this study, an estimation approach for leachate generation per tonne of waste landfilled in China is developed. The influences of waste properties, climate conditions and top cover types on leachate generation are investigated, and regional values are suggested accordingly. Finally, suggestions are provided, to mitigate the leachate amounts in different geographic regions of China.

2. Data Sources and Model Assumptions

The water balance approach of a landfill used in this study is shown schematically in **Figure 1**. Leachate generated from MSW landfills can be divided into two sources: (1) precipitation infiltrated throughout waste layers (PI), which occurs in all types of landfill and lasts for the whole lifetime of the landfill, and (2) water squeezed out of waste itself by gravity and compaction, as well as degradation (WS), which occurs in the landfills receiving dumped waste with a high moisture and organics content. It should be notice that although water storage occurred in a real landfill, it was not considered in our simulation, as it is just the temporary situation for leachate in a long time scale (e.g. 100 years in this study). The amount of leachate can be calculated using **eq.1**. More details for each of the two parts can be found in Section 2.1 and Section 2.2.

$$L=PI+WS \tag{1}$$

where L is the sum total of leachate generation. L, PI and WS are leachate quantities in litres per tonne of landfilled waste wet weight, $\mathrm{L \cdot t^{-1}ww}$.

In order to verify the reliability of the leachate quantification method developed by this study, actual amounts of leachate – as measured in several landfill sites – were obtained and compared with the estimated values.

2.1 Infiltration from precipitation

Leachate generated from infiltrated precipitation can be calculated by **eq.2**, which was established according mass balance theory.

$$PI=\sum_{c}^{n}\frac{P\times(I_c/100)\times t_c}{\rho\times h} \tag{2}$$

where P is precipitation at a locality, at $\mathrm{mm \cdot year^{-1}}$; c means the top cover type in a landfill; I_c is the ratio of precipitation infiltrated throughout waste layers with the top cover type of c, in % terms; t_c is the time period a top cover type of c is utilised, in years; ρ represents waste density in landfill, at $\mathrm{t \cdot m^{-3}}$; h is the waste height in the landfill, in metres.

A generic landfill was established to calculate the amount of leachate associated with precipitation over a 100 year period after landfilling. In the landfill, a uniform height of 20 m of waste was assumed to be buried. After landfilling, waste density changed along with time due to compaction and degradation. The density of fresh waste and old waste were set as 0.8 and 1.3 $t \cdot m^{-3}$, respectively (Qu et al., 2005). According to current Chinese national standards (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2013), four top cover types were investigated: daily cover (DC), intermediate cover (IC), unplanted final cover (UFC) and planted final cover (PFC). Based on a field survey by Ecobalance Inc. (1999), the timescales for the four types of top cover were set as follows: during the first 2 years after landfilling, the proportion of DC decreased from 100% to 0%, whilst IC increased from 0% to 100%; during 3-10 years after landfilling, the proportion of IC decreased from 100% to 0%, whilst UFC increased from 0% to 100%; over 10 years after landfilling, the top covers of the landfill were entirely set as PFC. The tensile strength of HDPE geomembranes decreases with its ageing, which may induce defects and influence the infiltration process. Accordingly, PFC were separated into two stages, i.e. with intact HDPE geomembranes (PFC-I) and with defective HDPE geomembranes (PFC-D). The service lifetime of HDPE geomembranes was likely more than 40 years according to Rowe (2011). To simulate the worst situation, PFC-I was assumed to be converted into PFC-D after 40 years of landfilling in this study.

The infiltration ratios of precipitation ending up as leachate (I_c) are critical parameters for calculating PI, which are closely associated with regional climate conditions and landfill structures. In current Chinese national standard (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2013), I_c are provided but are experience factors lacking practical verification. In this study, the specific I_c under typical climate conditions with five different landfill top covers were obtained using the HELP model (Schroeder et al., 1994) (Visual HELP 2.2 was used in this study) by assessing the fates of precipitation in a landfill, namely evapotranspiration, runoff, collected leachate (i.e. leachate collected by the lateral drainage layers in the bottom liner system) and fugitive leachate (i.e. leachate percolated through the lowest layer of the bottom liner system). Considering the spatial variations in China, 31 locations were simulated, and each landfill was calculated using one city's weather parameters (one city per province, to represent China overall; the locations are shown in **Figure 2**, (the main weather data are shown in **Figure S1 in Supporting Information**). For each location, five different sets of data were calculated – each one with different landfill structures, as shown in **Table 1**. Buried waste and material properties are summarised in **Table S1** and **Table S2** in Supporting Information, respectively. Note that the initial moisture content (IMC) of the waste was set to the same as field capacity because water squeezed from waste was discussed as the other source of leachate generation (i.e. WS). For the purpose of minimising temporal uncertainties of climate conditions for the parameter I_c, accumulated leachate amounts over 100 years were obtained and divided by accumulated precipitation. To test for the robustness of the results, analyses of the critical parameters, i.e. runoff area factor, high-density polyethylene (HDPE) geomembrane defects, and HDPE geomembrane placement quality, were also performed, as shown in **Table S3**.

2.2 Squeezed water from waste

MSW landfilled in Western countries is believed to have the potential capacity to absorb water (Kjeldsen and Beaven, 2011), because its IMC is lower than the initial field capacity (IFC). Without considering the influence of precipitation and degradation, Zornberg et al. (1999) summarised the free liquid generation mechanism in three stages as a result of waste compression (the first three stages of waste with low IMC in **Figure 3**). Unlike waste in Western countries, the IMC of MSW in most Chinese regions is higher than the IFC. This means that when waste is unloaded at landfills, the extra liquid contained therein will drain away as a result of gravity. After mechanical compaction, followed by waste placement, the field capacity of the waste will decrease to a lower level, which is herein referred to as "field capacity after compaction" (FCC). Next, waste will decompose in the landfill body, during which time the field capacity of waste is reduced due to the decrease in dry matter of organic containing fractions. Finally, the "field capacity of aged waste" (FCA) is reached representing the final status of waste in landfills. Accordingly, waste undergoes four stages in total (see Stages "I/II/III/IV" in **Figure 3**) during landfilling. The differences between leachate mechanisms for waste with low and high IMCs are seen primarily between Stages I and II.

The first two processes (i.e. the two "compaction" processes for waste with low IMC and "gravity" and "compaction" processes for waste with high IMC) usually occur in weeks or months after waste is landfilled, during which waste decomposition is of minor importance and dry matter content of the waste remain relatively unchanged. For the sake of uniformity, the combined amount of leachate generated by those two processes, namely water squeezed by compaction and gravity (WS_C), could be calculated as the difference between the IMC and FCC (**eq. 3**).

$$WS_C = IDM \times (IMC_{DM}/100 - FCC_{DM}/100) \times 1000 \tag{3}$$

where WS_C is the amounts of water squeezed by compaction and gravity from 1 tonne of raw waste, with a unit of $L \cdot t^{-1}$ww; IDM represents the initial dry matter weight in 1 tonne of raw waste, which could be calculated as $IDM=1-IMC/100$ with a unit of $t \cdot t^{-1}$ww; IMC_{DM} is the initial moisture content based on the weight of dry matter, calculated by $IMC_{DM} = \frac{IMC}{1 - IMC/100}$ with a unit of % of DM; FCC_{DM} is field capacity after compaction based on the weight of dry matter, calculated by $FCC_{DM} = \frac{FCC}{1 - FCC/100}$ with a unit of % of DM; IMC and FCC are with the unit of % of wet weight and 1000 is the constant used to convert the unit from tonne to litre, $L \cdot t^{-1}$.

The degradation process usually last for years depending on landfill conditions and the fractional composition of the waste. In this stage, water is lost in two ways, one is via the degradation process itself and released as vapour in the landfill gas;

the remainder is released as leachate. For the former, the water loss was about 12.3 $L{\cdot}t^{-1}$ww according to the following estimations: 100 m^3 of landfill gas were generated per tonne of typical Chinese MSW (Yang et al., 2013); 0.1 L of water was used for degradation (Burton et al., 2004) and 0.023 L of water was released as water vapour (at a temperature of 20^{o}C) (Kjeldsen and Beaven, 2011) for 1 m^3 of landfill gas. These figures were negligible in comparison to the entire water loss during degradation, which is supported by Athinoitou et al. (2012). Therefore, leachate generation during degradation process, namely water squeezed by degradation (WS_D), could be represented as the decrease of field capacity (or water holding capacity) calculated using **eq.4**.

$$WS_D = (IDM \times FCC_{DM} / 100 - DMA \times FCA_{DM} / 100) \times 1000 \tag{4}$$

where WS_D is the amounts of water squeezed by degradation from 1 tonne of raw waste, with a unit of $L{\cdot}t^{-1}$ww; *DMA* represents the dry matter weight of aged waste remaining from 1 tonne of raw waste, calculated by $DMA = \sum_i [IDM_i \times (1 - DR_i/100)]$ with a unit of $t{\cdot}t^{-1}$ww. With regard to degradation levels, waste fraction compositions could be divided into three groups represented by *i*: fast degradable (i.e. food waste), slow degradable (i.e. paper, wood and textile) and non-degradable (i.e. plastics, metal, slag and glass). IDM_i is the initial dry matter weight of waste fraction *i* in 1 tonne of raw waste, with a unit of $t{\cdot}t^{-1}$ww. DR_i represents the extent of degradation in relation to the three groups above, with a unit of % of wet weight. FCA_{DM} is the field capacity of aged waste on a dry basis, calculated by $FCA_{DM} = \frac{FCA}{1 - FCA/100}$ with a unit of % of DM.

Waste properties used for the simulation of WS were summarised from a literature review (**Table S4** in Supporting Information), including 1) initial moisture contents and composition fractions of MSWs in 16 Chinese cities (locations can be found in **Figure 2**) and 2) moisture contents of individual waste fractions in 10 of the aforementioned cities, which were used to calculate the dry basis distributions of the waste fraction groups. According to the regional location of those cities, the average values for IMCs of MSW, and the dry basis distribution of three waste fraction groups (i.e. fast, slowly and non-degradable), were calculated for China-NW, China-N and China-S (**Table 2**), respectively. The degradation extents (DR_i) for fast degradable, slowly degradable and non-degradable fractions of the MSW were assumed to be 84%, 39% and 0%, respectively, according to the study carried out by Barlaz (1998), where optimised anaerobic degradation processes were simulated individually for different degradable waste components.

In terms of MSW field capacity, a number of studies have been conducted on the relevance between compression and the field capacity of MSW (**Table S5** in Supporting Information). As the bulk density of waste varies along with compression, the correlation between field capacities (FC) and bulk densities (BD) can be obtained through linear regression (**Figure S3** in Supporting Information) with the fitting equation of $FC=(59.6\pm2.5)-(12.9\pm2.3)\times BD$. According to Chinese industrial standards (Ministry of Construction Development of the People's Republic of China, 2007), the bulk density of waste prior to the final top cover should be higher than 0.8 $t\cdot m^{-3}$, with the help of daily and final compaction. Thus, field capacity after the compaction (FCC) of MSW in a Chinese landfill can be calculated as 49.3±4.4% on the basis of regression. As no recommended bulk density or generic field capacity of waste after degradation were given in the literature, the field capacity of aged waste (FCA) was considered as the lowest value in the linear regression range, which was 39.0±6.2%.

3. Results and Discussion

3.1 Quantification of leachate generated by infiltrated precipitation

Figure 4 presents the infiltration ratios of precipitation ending up as leachate (I_c, shortened as infiltration ratios) in 31 Chinese cities' landfills with the five types of top cover. Considering the profiles of both infiltration ratios and geographic locations (**Figure 5**), the 31 cities can be classified into three groups: (1) cities with annual precipitations of less than 400 mm, representing those located in north-western China (China-NW), (2) cities with annual precipitations between 400 and 800 mm, located in northern China (China-N), and (3) cities with annual precipitations of more than 800 mm, located in southern China (China-S). The three geographic regions have different climate conditions: China-NW is semi-arid and temperate, China-N is semi-humid and temperate and China-S is humid with a sub-tropical/tropical climate.

The infiltration ratios in the three geographic regions were calculated as the average values of the cities in specific regions (**Table 3**). In China-NW, infiltration ratios in this respect were generally lower than the values in China-N and China-S. Moreover, the variation extents of the infiltration ratios among different top cover types were smaller than those in China-N and China-S. Taking Lanzhou as an example (**Figure S2** in Supporting Information), the above phenomenon can be explained by the fact that most of the precipitation was lost by evapotranspiration, due to low relative humidity and high solar radiation. In China-N and China-S, 30.7% and 43.1% of precipitation would end up as leachate when DC are utilised in landfills, respectively, which is obviously higher than in China-NW. If IC is installed instead of DC, the infiltration ratios would decrease by around 10−24% in China-N and in China-S. UFC and PFC-I induced an additional 54−79% reduction for infiltration ratios in China-N, whilst the mitigation rates were as high as 84−95% in China-S. In contrast to the situations in China-N and China-S, landfills in China-NW with PFC-I as the top cover cause lower infiltration ratios than those with UFC indicating the importance of vegetation for mitigating leachate generation in China-NW. For the PFC-D, the infiltration ratios were 1.6−4.5 times and 5.8−13 times higher than those for PFC-I in China-N and China-S, respectively. These figures imply that the installation and maintenance of HDPE geomembranes in landfills are important to mitigate leachate formation in China-N and China-S, and the mitigation effort was more effective in China-S than in China-N, directly correlated to the precipitation level.

According to current Chinese national standards (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2013), infiltration ratios were suggested for landfills covered by DC, IC and final covers. With regards to DC and IC, regional specific values were given on the basis of annual precipitations (**Table 3**). By contrast with the values simulated in this study, the infiltration ratios in China-NW (or the locations with the annual precipitation ≤ 400 mm) were significantly higher in the Chinese national standard, which might overestimate the leachate quantities in China-NW. The infiltration ratios for the landfills with PFC-D in China-S were higher than the suggested values for final covers in the Chinese national standard. Since the placement and maintenance process for HDPE geomembranes have not been strictly operated so far, PFC-D may be common in many Chinese landfills. If a landfill site located in China-S was designed according to Chinese national standard, leachate generated from infiltrated precipitation would be underestimated due to the missing distinction of PFC-D from final covers.

Sensitivity analyses of the primary parameters used in HELP modelling are shown in **Table S3**, assessing the influence of runoff area factor (i.e. 0%, 50% and 100%), HDPE geomembrane defects (2, 20 and 200 defects ha^{-1}), and HDPE geomembrane placement quality (i.e. good, poor and bad/worst case). The impact of runoff area factor on leachate generation ratio was insignificant except for the situations with IC, where the infiltration rate fell from as high as 42% to 15% in China-S. Regarding practical experience in landfill construction performance, an artificial gradient was usually first created when the final cover was established. Hence, a runoff area factor of 0% was used in the cases of DC and IC, and the runoff area factor were set as 100% with the top cover types of UFC, PFC-I and PFC-D. HDPE geomembranes with 20 $holes{\cdot}ha^{-1}$ performed similarly to those with 200 $holes{\cdot}ha^{-1}$ in China-N and China-NW, whereas the infiltration doubled in China-S when going to 200 holes·ha^{-1}. To simulate the worst situations, we set the defect densities of HDPE geomembrane for PFC-D to 200 holes·ha^{-1}. It should be noted that the infiltration ratios with the defect densities of 20 and 200 holes·ha^{-1} were significantly higher than the values suggested in the current Chinese national standard. The placement quality of HDPE geomembrane affected the infiltration ratio significantly for landfills with the top cover types of UFC and PFC-I. However, considering the practical installation conditions of HDPE geomembrane in most landfills in China, "poor" status wasset for all the profiles.

3.2 Quantification of leachate generated by water squeezed out of the waste

On the basis of **eq. 3** and **eq. 4**, WS_C and WS_D were calculated for the cities for which it was possible to obtain waste properties (**Table S4**, Supporting Information) and the results are presented in **Table 4**. The regional specific values for the three geographical regions were calculated by applying the average waste property values in **Table 2.** For cities located in China-NW, landfilled waste may not drain away water during the compaction process, due to the low initial moisture content being below field capacity, while approximately 256 L of water can leach out for 1 tonne of raw waste during complete degradation. Conversely for China-N and China-S, 175 L of water would leach due to the compaction, and an additional 250L of water due to the degradation of the waste, showing the importance of including the squeezed water. There were just small differences between the regionals specific values for China-N and China-S, but there was a large regional variation in China-S (i.e. 62-349 L·t^{-1}ww for WS_C and 206-283 L·t^{-1}ww for WS_D), which could be due to diverse living habits and climate conditions in the cites located in China-S and subsequent various waste properties.

3.3 Accumulated leachate amounts generated over 100 years

The accumulated leachate amounts over 100 years for one tonne of MSW landfilled in the 31 cities are presented in **Figure 6**. To illustrate temporal distribution, PI was allocated to four time periods with relevant top cover types, i.e.

1 and 2 years (with top cover DC and IC), 3-10 years (with top cover IC and UFC), 11-40 years (with top cover PFC-I) and 41-100 years (with top cover PFC-D). As for WS_C and WS_D, the city specific values could be used for the cities shown in **Table 4**, whilst the regional specific values were used for the other cities. The temporal distributions of WS_C and WS_D were not available due to the definition of **eq.3** and **eq.4**.

In China-NW, leachate accumulated over 100 years was less than 600 $L \cdot t^{-1}$ww, of which WS_D made the dominant contribution. As degradation occurs over a long time after initial landfilling (usually in years), depending on the degradation condition in the specific landfill site, the management of WS_D is difficult. Leachate quantities from PI were insignificant, as it may be absorbed by waste during compaction (WS_C). Therefore, it may be unnecessary to construct leachate treatment facilities in a landfill site in China-NW. The most economical solution may be to drain leachate into nearby municipal wastewater treatment plants, spray/irrigate leachate on landfill surface or recirculate the leachate into the waste layers.

In the case of China-N, leachates generated from WS were significant, accounting for 40−63% of the overall amounts over 100 years. Considering WS_C, the values (22−45%) were significantly higher than those of PI (15−25%) in the first 40 years. This implies that decreasing the initial moisture content of landfilled waste could be an effective approach to reducing leachate generation in China-N cities, especially at the beginning of landfilling. One of the approaches employed to mitigate waste moisture content could be avoiding food waste being disposed of in landfills, which is being tested in Shanghai (Shanghai Municipal People's Government, 2014) and Guangzhou (Guangzhou Municipal People's Government, 2011) and can be extended to the cities in China-N.

In China-S, the amounts of leachate from each individual source were higher than in China-N. Long-term (i.e. after 40 years of landfilling) generation potential could be a severe problem, since leachate generated during this period contributed more than 60% of the overall amounts as a result of the ageing HDPE geomembranes in the top cover. This is worsened as the ageing of HDPE geomembranes in the liner system occurred at the same time or earlier, which led to more migration of leachate into groundwater. For example, 4−8% of the generated leachate after 40 years of landfilling could be released if this was the case (data were calculated by HELP modelling but are not included in this paper). Therefore, in China-S, the quality of HDPE geomembranes, either through manufacturing or placement, must be controlled strictly, in order to reduce leachate generation and release.

3.4 Comparison with actual data in practical landfills

To evaluate its reliability, the landfill leachate quantification method established in this study was applied to 20 real-world landfill sites (considered as “estimated” results) where on-site measured leachate amounts (considered as “actual” values) were available. The estimated values and the actual values were not the same by definition. The estimated values meant the accumulated leachate of one tonne of waste generated in the operating period from the first year to the year of gathering data (named “testing year”). The actual values represented the transient leachate amounts generated by waste with different ages in the landfill at the testing year. To achieve a data format consistent with the estimated values (i.e. leachate amounts generated by one tonne of waste), actual leachate amounts were computed by dividing the measured yearly leachate quantities by yearly waste disposal amounts in the testing year. In the case of estimated results, PI was computed as the accumulated values during operating period, whilst WS represented the overall amounts during the entire lifetime of the landfill (considered as 100 years). Since some locations of the 20 real-world landfills were not included in the 31 cities discussed above, the parameters of the cities located in the same province were utilised for estimation.

The comparison between the estimated results and the actual values is shown in **Table 5**. The actual values indicated that leachate amounts generated in landfills located at China-S were significantly higher than those located at China-N and China-NW with similar operating period, which confirmed the findings in **Figure 6**. In all of the 20 landfill sites investigated in this study, actual leachate amounts were higher than the estimated values of PI, which only accounted for precipitation associated leachate. This highlights the necessity of including squeezed water out of waste (WS) when estimating landfill leachate quantities in China. For the landfills located in China-N and China-NW, as well as those located in China-S with an operating period of more than 3 years, the estimated values of PI+WS were higher than the actual leachate amounts. This was reliable as the estimated WS represents the overall values during the entire lifetime of the landfill rather than the accumulated values during the operating period. In the case of the landfills located in China-S with an operating period of up to 3 years, this estimation method frequently underestimated leachate amounts, even taking WS into account. This may be attributed to the underestimation of I_c in the first years after landfilling assuming DC and IC were operated following the instructions of Chinese national standard. However, this assumption may not always be true. The failure of effective DC and IC could induce higher I_c, especially in China-S where precipitation amounts were extremely high. Since on-site measurements of leachate quantities (actual values) were rare in China, the statistical reliability for the above conclusions was limited by sample size. Therefore, validating the reliability of this method should be repeated as new actual data is made available.

4. Conclusion

In this study, a leachate quantification method was established for MSW landfilling in China. Two leachate sources were calculated separately in this method, which were precipitation infiltrated throughout waste layers (PI) and water squeezed out of waste itself (WS). By utilising this method, leachate amounts generated from one tonne of MSW, landfilled for 100 years, were estimated for 31 cities located all over China. According to the results, Chinese cities were grouped into three geographic regions based on climate conditions, which were China-NW (northwestern China), China-N (northern China) and China-S (southern China).

The contribution of WS to overall leachate quantities were significant, especially for the cities located in China-N. Therefore, WS is a non-ignorable part when quantifying leachate amounts in China. This could also be possible for other countries where the initial moisture contents of MSW were higher than the landfill field capacity. From the aspect of leachate mitigation, avoiding food waste being disposed of in landfills could be an effective approach in China-N.

In China-NW, leachate quantities were significantly lower than those in other regions. Therefore, it may be unnecessary to construct leachate treatment facilities in a landfill site in China-NW. The possible solution may be to drain leachate into nearby municipal wastewater treatment plants, spray/irrigate leachate on landfill surface or recirculate the leachate into the waste layers. Another finding requiring special attention was that, the infiltration ratios of precipitation ending up as leachate for China-NW suggested by the current Chinese national standard were higher than the values obtained in this study. This may lead to the overestimation of leachate quantity in China-NW by utilising the current Chinese national standard.

In China-S, leachate generation was aggravated dramatically after 40 years landfilling because of the increased defects for HDPE geomembranes in top cover layers. Since the placement and maintenance process for HDPE geomembranes have not been strictly operated so far, defective HDPE geomembranes may occur frequently in many Chinese landfills. However, this was not taken into account in the current Chinese national standard, which may lead to underestimation of the precipitation-associated leachate amounts (as “PI” in this study). In addition, the quality of HDPE geomembranes, either through manufacturing or placement, must be controlled strictly in China-S in order to limit leachate generation amounts effectively.

Acknowledgement

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Tables

Table 1 Setup parameters for the five datasets used in the HELP simulations [a].

Landfill cover types	Top cover structures [b]	Top cover slope	Runoff area factor	Vegetation class	HDPE geomembranes defects [c]	HDPE geomembrane placement quality	Waste layer	Bottom liner systems [a]
1) Daily Cover (DC)	22.5 cm of loamy sand soil	0%	0%	Bare soil	2 ha^{-1}	poor	10 m of crude waste 10m of aged waste	30 cm of gravel 1.5 mm of HDPE geomembrane 30 cm of gravel 1.5 mm of HDPE geomembrane 30 cm of moderately compacted clay
2) Intermediate Cover (IC)	30 cm of clay	0%	0%	Bare soil	2 ha^{-1}	poor	5 m of crude waste 15 m of aged waste	
3) Unplanted Final Cover (UFC)	60 cm of loamy soil 30 cm of gravel 1.0 mm of HDPE geomembrane 25 cm of clay	5% (60m)[d]	100%	Bare soil	2 ha^{-1}	poor	20 m of aged waste	
4) Planted Final Cover – Intact (PFC-I)	Well-planted grass 60 cm of loamy soil 30 cm of gravel 1.0 mm of HDPE geomembrane 25 cm of clay	5% (60m)	100%	Good stand of grass	2 ha^{-1}	poor	20 m of aged waste	
5) Planted Final Cover – Defective (PFC-D)	Well-planted grass 60 cm of loamy soil 30 cm of gravel 1.0 mm of HDPE geomembrane	5% (60m)	100%	Good stand of grass	200 ha^{-1}	poor	20 m of aged waste	

25 cm of clay

[a] Evaporative zone depth was set to the Visual HELP default values for each location.

[b] Referring to Ministry of Housing and Urban-Rural Development of the People's Republic of China (2013). In this standard, geotextiles should be installed above and beneath the HDPE geomembrane for protection. As the geotextiles impact hardly on water percolation and drainage compared with other layers, geotextiles layers were not stated here for simplification. Additionally, this standard recommended two kinds of bottom liner systems, i.e. single liner system and double liner system. In this study, double liner system was utilised.

[c] HDPE geomembrane defects represents two kinds of defects: pinhole density and installation defects density (see Table S2). In this study, the two kinds of defects were set to the same value and were described as one uniform term “HDPE geomembrane defects” for the sake of simplification. The values of “HDPE geomembrane defects” were set for the HDPE geomembranes liner in the top covers in the case of UFC, PFC-I and PFC-D, and in the bottom liner systems in all the five cases.

[d] Data in parentheses represent the slope length of the landfill top cover..

Table 2 Relevant waste properties in three geographical regions in China[a].

	China-NW	China-N	China-S
Initial moisture contents (% of ww)	(n=3)[b]	(n=5)[b]	(n=8)[b]
	46.0±1.5	58.2±4.1	58.2±4.6
Dry basis distributions (% of DM)		(n=3)[b]	(n=7)[b]
Fast degradable	37.9±6.1[c]	37.9±6.1	43.9±4.1
Slowly degradable	25.1±5.2[c]	25.1±5.2	16.3±6.5
Non-degradable	37.0±45.8[c]	37.0±45.8	39.8±7.7

[a] Data in this table were calculated on basis of data in Table S4, Supporting information

[b] The numbers of datasets used to obtain the values.

[c] The values refer to those in China-N due to a lack of data for China-NW.

Table 3 Infiltration ratios of precipitation ending up as leachate in three Chinese geographic areas (unit: %)

	This study			Chinese national standard [b]		
	China-NW[a]	China-N[a]	China-S[a]	AP[c]<400mm	400≤AP<800mm	AP≥800mm
Daily Cover (DC)	15.0±6.3	30.7±6.2	43.1±6.9	40−55[d]	50−70[d]	70−80[d]
Intermediate Cover (IC)	14.4±6.8	25.5±5.8	36.6±6.6	16−33[e]	20−42[e]	28−48[e]
Unplanted Final Cover (UFC)	6.8±2.5	7.3±0.6	3.9±0.7	10−20		
Planted Final Cover-Intact (PFC-I)	5.1±2.4	7.3±0.5	3.9±0.7			
Planted Final Cover-Defective (PFC-D)	6.9±5.7	23.5±6.5	35.8±6.1			

[a] Annual precipitations in the cities located at China-NW, China-N and China-S were in the ranges of 178−429 mm, 415−631 mm, and 886−1832 mm, respectively

[b] Referring to Ministry of Housing and Urban-Rural Development of the People's Republic of China (2013).

[c] AP represents "annual precipitation".

[d] The infiltration ratios of precipitation ending up as leachate for landfills with DC are the suggestions for waste with organic matter content less than 70%.

[e] The infiltration ratios of precipitation ending up as leachate for landfills with IC are not given in the standard, but are suggested as 40−60% of the values for DC.

Table 4 Squeezed water from landfilled waste in Chinese cities due to gravity and compaction (WS_C) and waste degradation (WS_D)

Geographical regions	Cities	WS_C ($L \cdot t^{-1}$ww)	WS_D ($L \cdot t^{-1}$ww)	WS ($L \cdot t^{-1}$ww)
China-NW	Lanzhou	-99	--	--
	Urumqi	-45	--	--
	Lhasa	-51	--	--
	Regional specific[a]	**−65**	**321**	**256**
China-N	Harbin	108	--	--
	Beijing	276	212	488
	Qingdao	131	--	--
	Shenyang	247	220	467
	Tianjin	111	283	394
	Regional specific[a]	**175**	**247**	**423**
China-S	Hefei	62	283	345
	Wuhan	82	266	348
	Chengdu	158	276	434
	Chongqing	349	206	555
	Shanghai	185	259	444
	Suzhou	225	--	--
	Hangzhou	143	259	401
	Shenzhen	205	232	438
	Regional specific [a]	**176**	**252**	**429**

a The regional specific values were calculated by applying the average waste property values in **Table 2.**

Table 5 Comparison of the actual and estimated leachate generation amounts in practical landfill sites

Number	Regions	City (Landfill site)	Operating period (years)	Actual values ($L\cdot t^{-1}ww$)	Estimated values ($L\cdot t^{-1}ww$)		Reference for actual values	City with the parameters referred for estimated values
					PI[a]	PI+WS[b]		
1	China-NW	Yi'ning	5	70	8.2	284	(Lan, 2012)	Urumqi
2	China-N	Beijing (Liulitun)	3	400	30	518	(Li et al., 2009)	Beijing
3	China-N	Beijing (Beishenshu)	11	167	70	558	(Li et al., 2009)	Beijing
4	China-N	Beijing (Anding)	3	490	30	518	(Lan, 2012)	Beijing
5	China-N	Tangshan (Jianzigu)	2	280	13	440	(Lan, 2012)	Shijiazhuang
6	China-N	Xi'an (Jiangcungou)	8	230	37	464	(Lan, 2012)	Xi'an
7	China-S	Suzhou (Qizishan)	1	830	20	498	(Lan, 2012)	Suzhou
8	China-S	Changzhou	8	380	110	588	(Lan, 2012)	Suzhou
9	China-S	Shanghai (Laogang)	5	400	77	521	(Lan, 2012)	Shanghai
10	China-S	Ningbo (Yinzhou)	4	400	105	507	(Lan, 2012)	Hangzhou
11	China-S	Lishui (Wulinggen)	2	950	60	462	(Lan, 2012)	Hangzhou
12	China-S	Nanchang (Maiyuan)	14	320	225	653	(Lan, 2012)	Nanchang
13	China-S	Changsha (Qiaoyi)	8	290	144	573	(Yang, 2012a)	Changsha
14	China-S	Guiyang (Gaoyan)	10	190	102	475	(Lan, 2012)	Guiyang
15	China-S	Chongqing (Changshengqiao)	3	800	85	640	(He et al., 2007)	Chongqing
16	China-S	Chengdu (Chang'an)	18	400	113	547	(Lan, 2012)	Chengdu
17	China-S	Kunming (Xijiao)	5	154	78	507	(Wu, 2007)	Kunming
18	China-S	Guangzhou (Xingfeng)	10	330	287	725	(Lan, 2012)	Shenzhen
19	China-S	Shenzhen (Xiaping)	15	454	299	736	(Shenzhen Habitation and Environmental	Shenzhen

							Committee, 2013)	
20	China-S	Jiangmen (Datuicheshan)	7	356	243	680	(Zhang et al., 2009)	Shenzhen

[a] Leachate generation amounts estimated by the method established in this study, but only accounting for one source, i.e. “PI” representing. precipitation infiltrated throughout waste layers.

[b] Leachate generation amounts estimated by the method established in this study, accounting for both sources, i.e. “PI” representing precipitation infiltrated throughout waste layers and “WS” representing water squeezed out of waste itself.

Figures

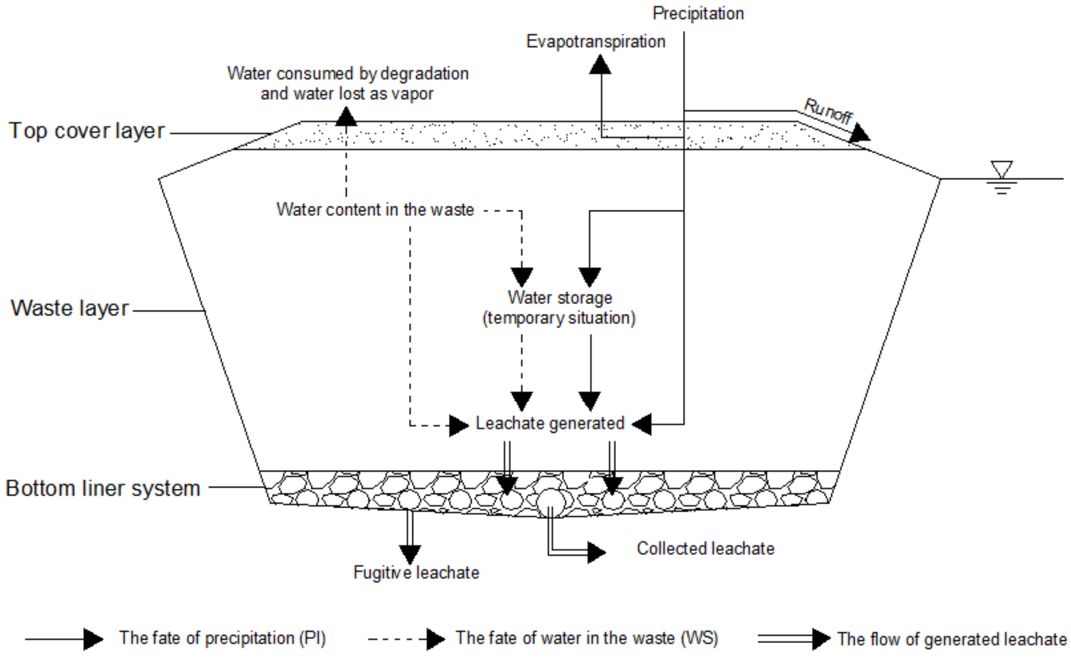

Figure 1 Schematic diagram of the water balance of a simulated landfill

Figure 2 Cities where leachate generation by precipitation infiltration was simulated (red dots) and where waste compositions were obtained (blue circles)

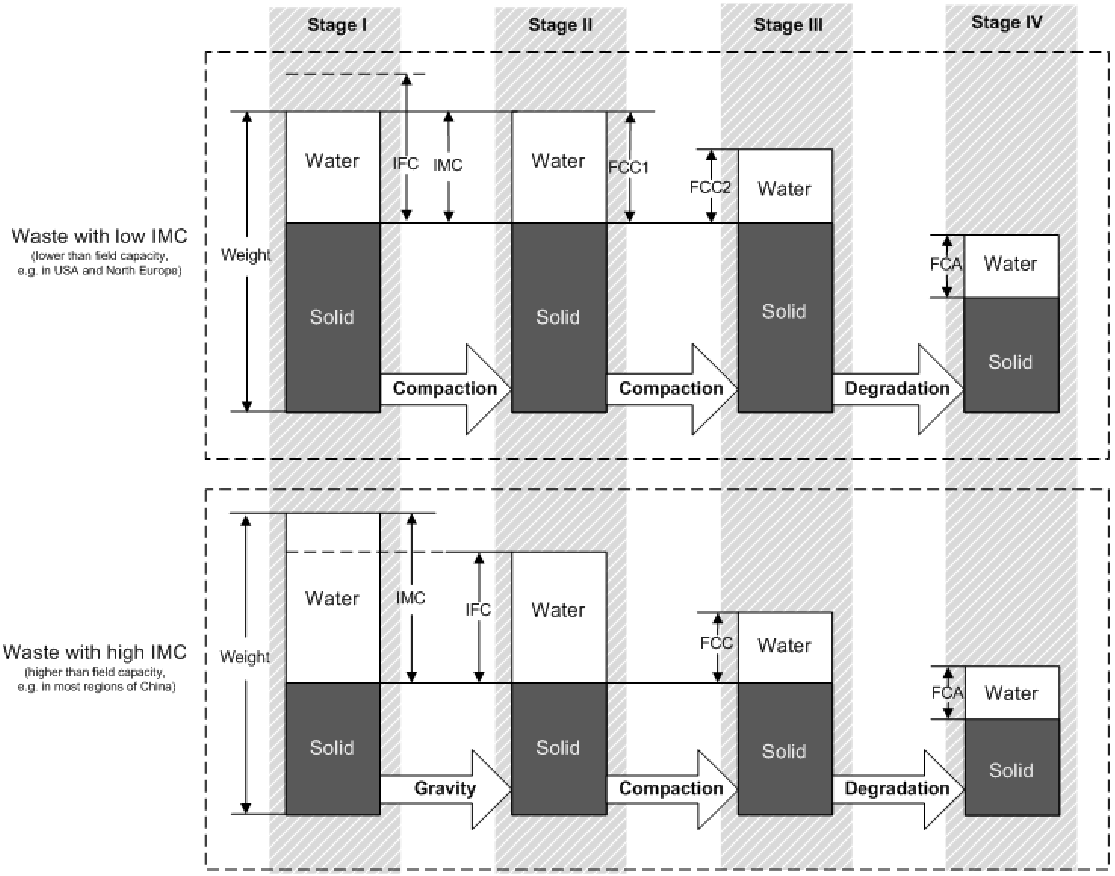

Figure 3 Schematic fate of water originally contained in waste during landfilling (IMC, Initial Moisture Content; IFC, Initial Field Capacity; FCC, Field Capacity after Compaction; FCA, Field Capacity of Aged waste. Stage I: The status of waste arriving at the landfill. Stage II: The status of waste when filled capacity is reduced to the same as the “IMC” through the compaction of waste with low IMC. The status of waste when its moisture content is reduced to the same as “IFC” by gravity for waste with high IMC; Stage III: The status of waste with the greatest physical compaction in the landfill body. Stage IV: The status of waste after complete degradation).

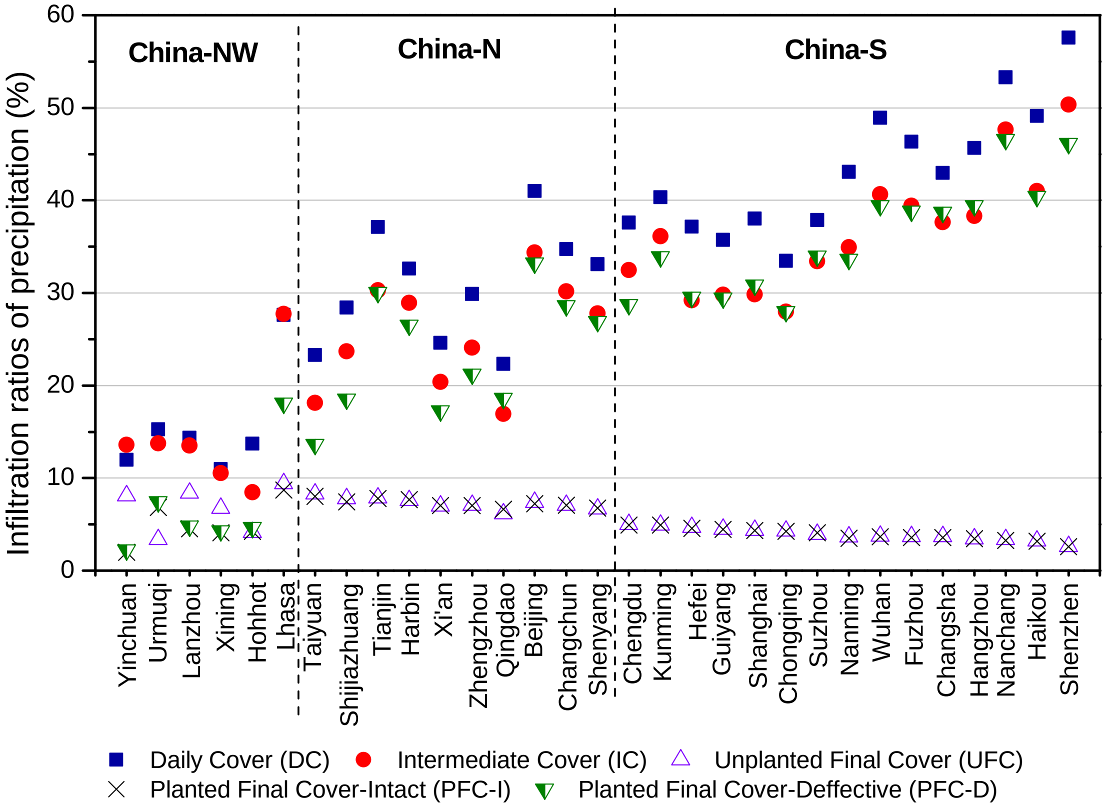

Figure 4 The infiltration ratios of precipitation ending up as leachate in 31 Chinese cities

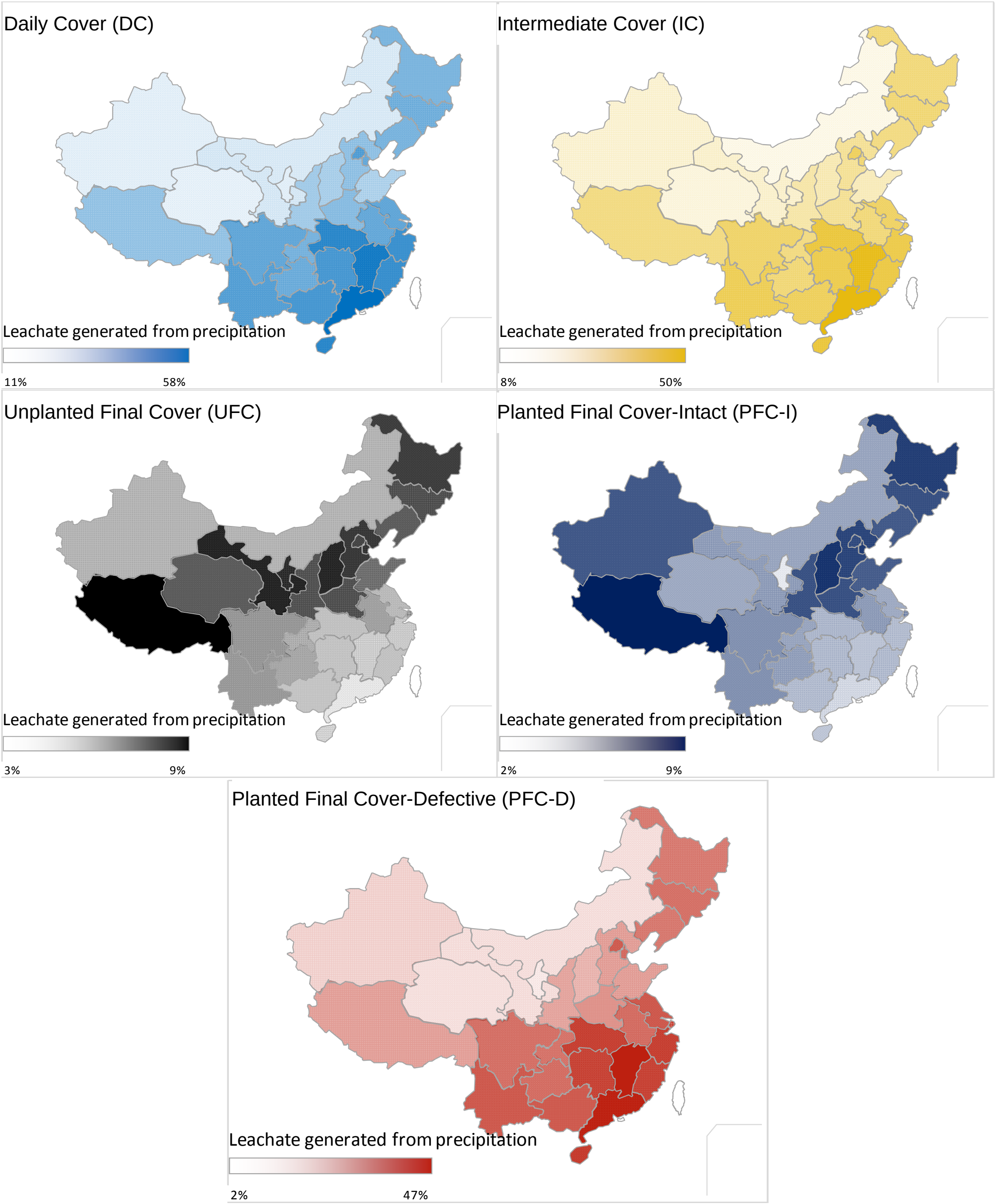

Figure 5 Geographic distributions of the infiltration ratios of precipitation ending up as leachate in China

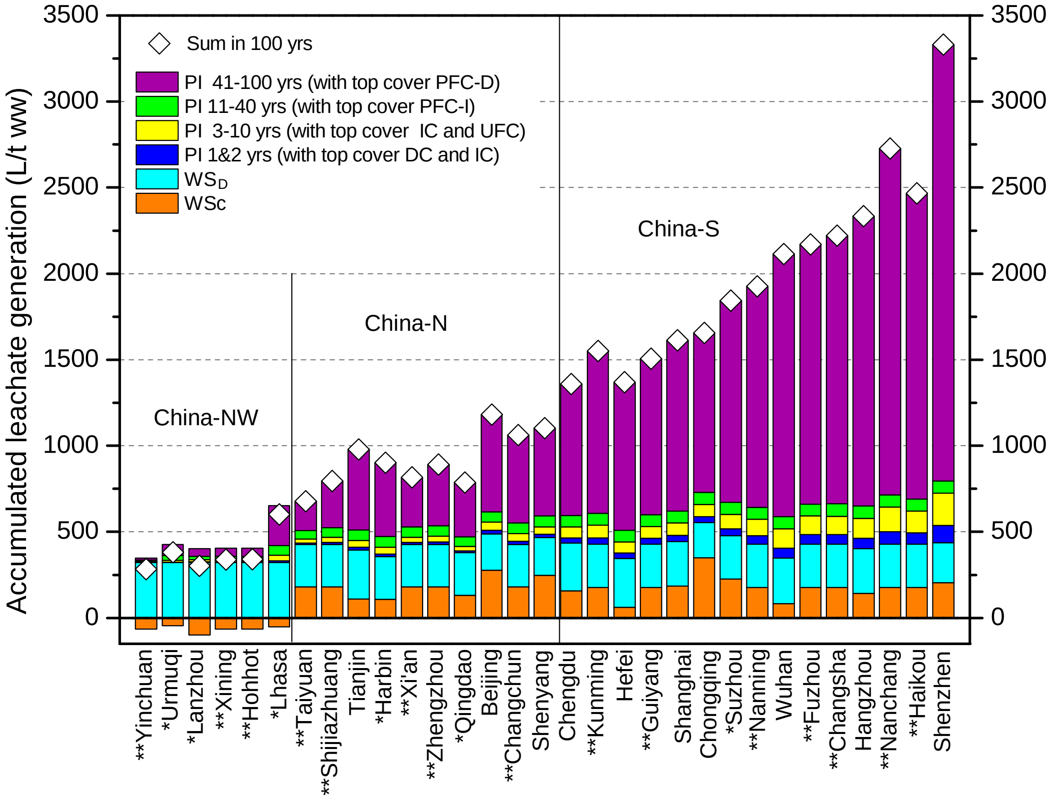

Figure 6 Accumulated leachate from different sources over 100 years. (For cities with "**" in front of their names, we used the average values of WS_C and WS_D for the relevant geographic regions. For cities with "*" in front of their names, we used the average values of WS_D for the relevant geographic regions.).

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Supplementary material

Tables

Table S1 Specific parameters for Chinese waste

	Fresh waste	Old waste	Reference
Total porosity ($v\cdot v^{-1}$)	0.80	0.70	(Cao, 2007)
Saturated hydraulic conductivity ($cm\cdot s^{-1}$)	1.45×10^{-3} [a]	3.1×10^{-4} [a]	(Qu et al., 2005)
Field capacity ($w\cdot w^{-1}$)	0.45	0.30	(Ministry of Housing and Urban-Rural Development of the people's republic of China, 2012)
Wilting point ($v\cdot v^{-1}$)	0.077	0.077	Default value in HELP model (Schroeder et al., 1994)
Initial moisture content ($w\cdot w^{-1}$)	0.45	0.30	Same as field capacity [b]

[a] Median values of the six results for fresh waste and 3-year-old waste excavated from the Laogang landfill site, respectively.

[b] In this section, no absorption or leaking of water by the landfilled waste was considered.

Table S2 Parameters of the materials used in the HELP model

	Loamy sand soil	Loamy soil	Clay	Moderately compacted clay	Gravel	HDPE geomembrane
Total porosity ($v \cdot v^{-1}$)	0.437	0.463	0.475	0.451	0.397	--
Field capacity ($v \cdot v^{-1}$)	0.105	0.232	0.378	0.419	0.032	--
Wilting point ($v \cdot v^{-1}$)	0.047	0.116	0.265	0.332	0.013	--
Saturated hydraulic conductivity ($cm \cdot s^{-1}$)	1.7×10^{-3}	3.7×10^{-4}	1.7×10^{-5}	6.8×10^{-7}	0.3	1×10^{-11} [a]
Pinhole density (ha^{-1})	--	--	--	--	--	2/200 [b]
Installation defects (ha^{-1})	--	--	--	--	--	2/200 [b]
Placement quality	--	--	--	--	--	poor
Utilisation	As the barrier layer in the daily top cover	As the plant layer in the final covers	As the barrier layer in the intermediate top cover	As the barrier layer in the final covers and in the bottom liner system	As the drainage layers in the final covers and in the bottom liner system	As the geomembrane liner in the final covers and in the bottom liner system

[a] Referring to (Ministry of Construction of the People's Republic of China, 2006).

[b] The pinhole density and installation defect density of HDPE geomembranes were set to the same value, and were described as HDPE geomembrane defects in Table 1. The pinhole density and installation defect density were set to 2 ha^{-1} during service life (the first 40 years) as default values in the Visual HELP model. However, after service life (in the last 60 years), the value will increase due to the ageing of HDPE geomembranes. According to the sensitivity analyses (see Table S3), HDPE geomembranes with defects between 20 and 200 $\cdot ha^{-1}$ will induce similar leachate generation. To represent the worst situation in respect to aged HDPE geomembranes in this paper, the highest value 200 $\cdot ha^{-1}$ was chosen.

Table S3 Sensitivity analyses of the parameters used in the HELP model

	Infiltration ratios of precipitation ending up as leachate				
	Daily Cover (DC)	Intermediate Cover (IC)	Unplanted Final Cover (UFC)	Planted Final Cover-Intact (PFC-I)	Planted Final Cover-Defective (PFC-D)
1. Runoff area factor					
			Lanzhou (China-NW)		
0%	14.3%*	13.5%*	9.9%	4.6%	4.8%
50%	14.3%	10.9%	9.1%	4.5%	4.8%
100%	14.3%	9.2%	8.4%*	4.5%*	4.8%*
			Beijing (China-N)		
0%	41.0%*	34.4%*	8.5%	8.4%	35.0%
50%	41.0%	20.1%	7.5%	7.3%	34.1%
100%	41.0%	12.0%	7.4%*	7.2%*	33.2%*
			Shenzhen (China-S)		
0%	49.6%*	42.1%*	3.6%	3.6%	42.8%
50%	49.6%	24.5%	3.1%	3.0%	41.7%
100%	49.6%	14.9%	3.1%*	3.0%*	40.7%*
2. HDPE geomembrane defects					
			Lanzhou (China-NW)		
2 ha^{-1}				4.5%*	
20 ha^{-1}				4.8%	
200 ha^{-1}				4.8%	
			Beijing (China-N)		
2 ha^{-1}				7.2%*	

	Infiltration ratios of precipitation ending up as leachate				
	Daily Cover (DC)	Intermediate Cover (IC)	Unplanted Final Cover (UFC)	Planted Final Cover-Intact (PFC-I)	Planted Final Cover-Defective (PFC-D)
20 ha^{-1}				29.0%	
200 ha^{-1}				33.2%	
			Shenzhen (China-S)		
2 ha^{-1}				3.0%*	
20 ha^{-1}				21.7%	
200 ha^{-1}				40.7%	
3. HDPE geomembrane placement quality					
			Lanzhou (China-NW)		
good	14.3%	13.6%	3.0%	2.4%	4.5%
poor	14.3%*	13.5%*	8.4%*	4.5%*	4.8%*
bad/worst case [a]	14.3%	13.5%	8.8%	4.8%	4.8%
			Beijing (China-N)		
good	41.0%	34.4%	1.8%	1.8%	31.8%
poor	41.0%*	34.4%*	7.4%*	7.2%*	33.2%*
bad/worst case [a]	41.0%	34.4%	19.2%	33.1%	33.4%
			Shenzhen (China-S)		
good	49.6%	42.1%	0.7%	0.7%	30.6%
poor	49.6%*	42.1%*	3.1%*	3.0%*	40.7%*
bad/worst case [a]	49.6%	42.1%	22.8%	37.9%	40.9%

* These values are the results in the baseline scenario.

[a] In the Visual HELP online help, this status is called “bad placement quality”. While it is called “worst case” in the user’s manual. To avoid misunderstanding, these two terms are both shown here.

Table S4 Initial moisture content and fraction compositions of municipal solid waste in 16 Chinese cities

Regions	Cities	Initial moisture contents, IMC (% of ww)	Fraction compositions (% of ww)[a]								Reference
			Food wastes	Papers	Plastics	Wood	Textiles	Slags	Glass	Metals	
China-NW	Lanzhou	44.3	36.5	9.7	11.3	1.4	2.1	37.8	0.9	0.2	(Ji, 2007)
China-NW	Urumqi	47.0	76.0	2.4	5.4	2.5	4.2	6.4	2.4	0.8	(Shao et al., 2009)
China-NW	Lhasa	46.7	57.0	6.0	12.0	14.0	7.0	3.0	0.0	1.0	(Jiang et al., 2009)
China-N	Harbin	54.8	44.8	13.4	3.3	0.0	4.7	24.5	6.6	2.7	(Xie, 2009)
China-N	Beijing	63.3	66.2(82)	10.9(29)	13.1(33)	3.3(22)	1.2(22)	3.9(12)	1.0(NA)	0.4(NA)	(Wang and Wang, 2013)
China-N	Qingdao	56.0	69.0	9.5	8.4	2.3	3.0	6.8	2.2	0.9	(Jiang et al., 2011)
China-N	Shenyang	61.8	60.4(72)	7.9(32)	12.9(NA)	2.5(28)	3.6(44)	5.3(25)	5.4(NA)	2.1(NA)	(Gao et al., 2007; Ma, 2010)
China-N	Tianjin	55.0	56.9(65)	15.3(48)	16.9(44)	1.6(40)	3.9(47)	2.9(14)	1.6(2)	0.7(9)	(He et al., 2010)
China-S	Hefei	52.3	61.5(64)	1.9(61)	11.4(33)	0.9(27)	2.1(36)	21.7(34)	0.6(NA)	0.0	(Jin, 2006)
China-S	Wuhan	53.5	55.3(66)	1.5(43)	4.5(49)	8.3(49)	0.0	27.3(36)	2.0(NA)	1.1(NA)	(Li, 2010)
China-S	Chengdu	55.2	65.7(68)	13(32)	12(14)	0.88(55)	2.5(92)	2.1(57)	0.8(55)	2.9(55)	(Huang and Liu, 2012)
China-S	Chongqing	58.7	53.7(76)	13.6(68)	16.3(59)	4.9(73)	6.2(66)	0.0(NA)	3.8(13)	1.1(5)	(Huang et al., 2003)
China-S	Shanghai	60.9	63.8(71)	11.1(36)	17.2(43)	1.1(48)	2.6(37)	1.1(25)	2.7(11)	0.4(7)	(Zhang et al., 2009)
China-S	Suzhou	60.7	62.6	10.9	18.6	0.9	4.2	0.7	2.0	0.2	(He et al., 2008)
China-S	Hangzhou	56.5	64.5(71)	6.7(26)	10.1(13)	0.1(27)	1.2(43)	15.1(49)	2.0(0)	0.3(2)	(Zhuang et al., 2008)
China-S	Shenzhen	49.9	51.6(64)	17.2(32)	21.8(52)	3.9(48)	2.7(48)	0.8(1)	2.1(2)	0.42(4)	(Shenzhen Environmental Sanitary Management

Department, 2011)

“NA” represents “not available.” [a] Values in parentheses represent the moisture content of the specific waste fractions in % of wet weight.

Table S5 Summarisation for the field capacities of waste in the existing literature

Waste types used for testing	Initial bulk density ($t \cdot m^{-3}$)	Initial moisture content (% of wet weight)	Bulk density at field capacity ($t \cdot m^{-3}$)	Field capacity (% wet weight)	Reference
4000 m^3 crude MSW	0.66	25%	NA	31.8% [a, b]	(Campbell, 1982; Kjeldsen and Beaven, 2011)
4000 m^3 crude MSW	0.95	25%	NA	28.0% [a, b]	(Campbell, 1982; Kjeldsen and Beaven, 2011)
4000 m^3 crude MSW	1.00	25%	NA	26.8% [a, b]	(Campbell, 1982; Kjeldsen and Beaven, 2011)
6 m^3 crude MSW	0.40	15%	NA	36.6% [a, b]	(Campbell, 1982; Kjeldsen and Beaven, 2011)
8 m^3 pulverised MSW	NA	40%	NA	51.0% [a]	(Kjeldsen and Beaven, 2011; Robinson et al., 1981)
6 m^3 crude MSW	0.5	35%	0.71 [a]	54.4%	(Kinman et al., 1982; Kjeldsen and Beaven, 2011)
0.2 m^3 pulverised MSW	0.76	26%	0.98 [a]	42.6% [a]	(Blakey, 1982; Kjeldsen and Beaven, 2011)
Indoor lysimeter crude MSW	0.33	15% [a]	0.62 [a]	54.6% [a]	(Fungarioli and Steiner, 1979; Kjeldsen and Beaven, 2011)
9 m^3 and 18 m^3 crude MSW	0.33	56% [a]	0.45 [a]	68.0% [a]	(Kjeldsen and Beaven, 2011; Rovers and Farquhar, 1973)
0.2 m^3 drums 17-year-old MSW	0.96	32%	1.07 [a]	38.6%	(Holmes, 1980; Kjeldsen and

					Beaven, 2011)
0.2 m^3 drums 17-year-old MSW	0.64	32%	0.84 [a]	47.6%	(Holmes, 1980; Kjeldsen and Beaven, 2011)
4 tonnes of crude domestic refuse	0.49	34%	0.79−1.16 [a]	50.3%−38.2% (n=9)	(Beaven, 1999)
2.4 tonnes of pulverised MSW	0.36	29%	0.55−0.94 [a]	52.8%−35.8% (n=10)	(Beaven, 1999)
6.5 tonnes of 20-year-old waste	0.91	42%	1.09−1.43 [a]	42.9%−33.6% (n=9)	(Beaven, 1999)
0.11 m^3 of fresh waste	0.2−0.5	12.5%	0.36−0.85 [a]	51.2%−48.5% (n=3) [a]	(de Velasquez et al., 2003)
0.14 m^3 of fresh waste	0.2−0.5	21.3%	0.6−0.61 [a]	74%−35.5% (n=3) [a]	(de Velasquez et al., 2003)
0.18 m^3 of fresh waste	0.2−0.5	16.5%	0.54−1.06 [a]	45.7%−35.5% (n=3) [a]	(de Velasquez et al., 2003)
0.13 m^3 of fresh waste	NA	NA	0.98−1.23 [a]	59.4%−44.3% (n=6)	(Lan, 2012)
0.13 m^3 of 0.5-year-old waste	NA	NA	1.09−1.30 [a]	53.8%−43.5% (n=6)	(Lan, 2012)
0.13 m^3 of 2-year-old waste	NA	NA	1.02−1.23 [a]	5.05%−41.4% (n=6)	(Lan, 2012)
0.13 m^3 of 3-year-old waste	NA	NA	1.04−1.10 [a]	51.5%−38.2% (n=6)	(Lan, 2012)
0.13 m^3 6-year-old waste	NA	NA	1.08−1.42 [a]	64.8%−36.9% (n=7)	(Lan, 2012)
Fresh waste with 90% paper and cardboard	NA	NA	1.01−1.72 [a]	69.7%−54.5% (n=5) [a, c]	(Blight et al., 1992)
Various kinds of fresh waste	NA	NA	0.85−1.56 [a]	59%−45% (n=11) [a]	(Blight et al., 1992)
Various kinds of 1-year-old waste	NA	NA	0.93−1.62 [a]	44%−34% (n=15) [a]	(Blight et al., 1992)
Various kinds of 1-year-old waste	NA	NA	0.79−1.62 [a]	48%−36% (n=17) [a]	(Blight et al., 1992)
0.04 m^3 of old waste	NA	NA	0.88−1.18 [a]	60.2%−40.5% (n=4)	(Zornberg et al., 1999)

[a] These data were not originally present in the literature but calculated by the authors from other existing parameters.

[b] Field capacity is calculated based on primary absorptive capacity, which is not the same as others based on total absorptive capacity. Therefore, these data are not used in the regression in Figure S5.

[c] As waste with 90% paper and cardboard is not the typical MSW, these field capacities are not used in the regression in Figure S5.

Figures

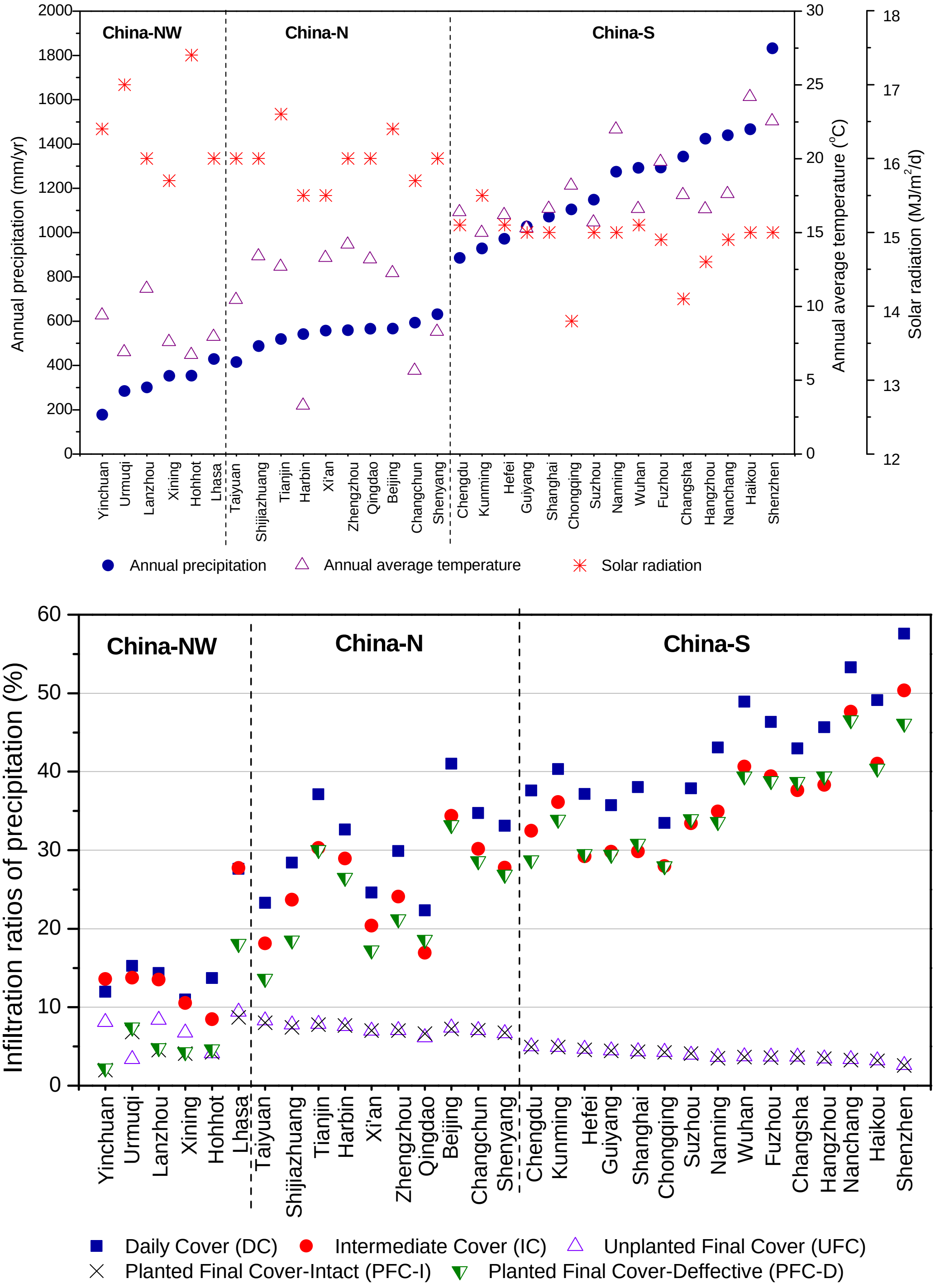
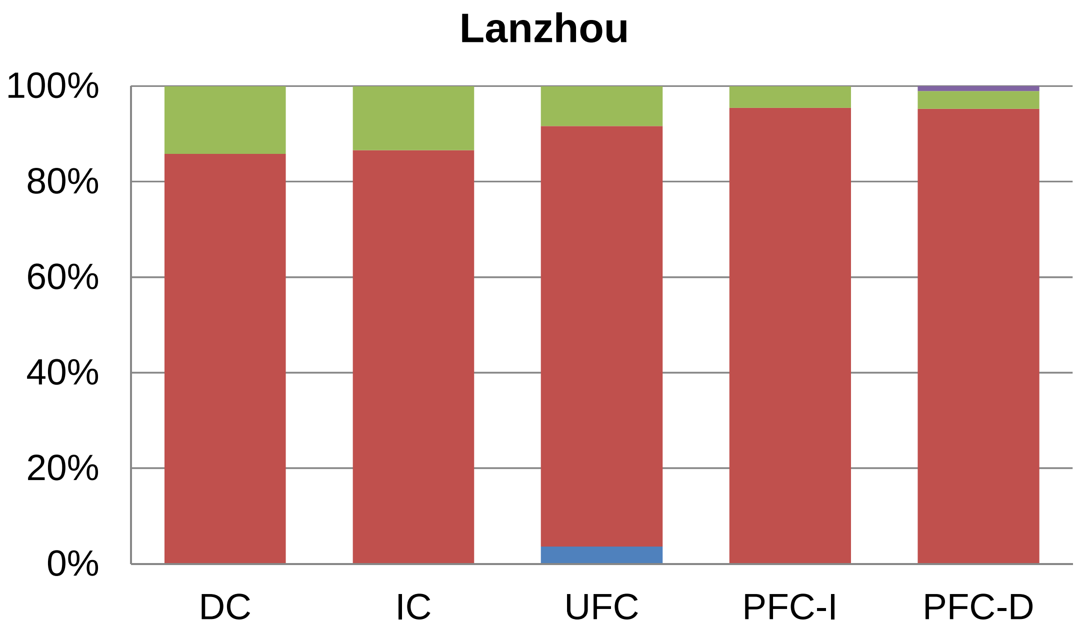
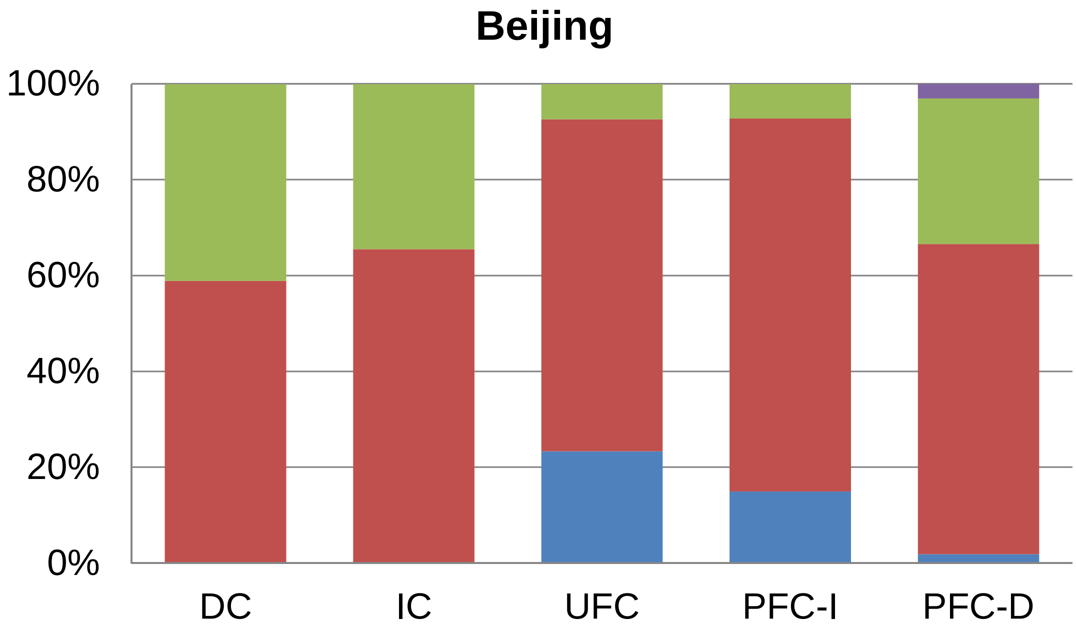


Figure S1 Weather parameters used in the HELP simulations and the infiltration ratios of precipitation ending up as leachate in 31 Chinese cities

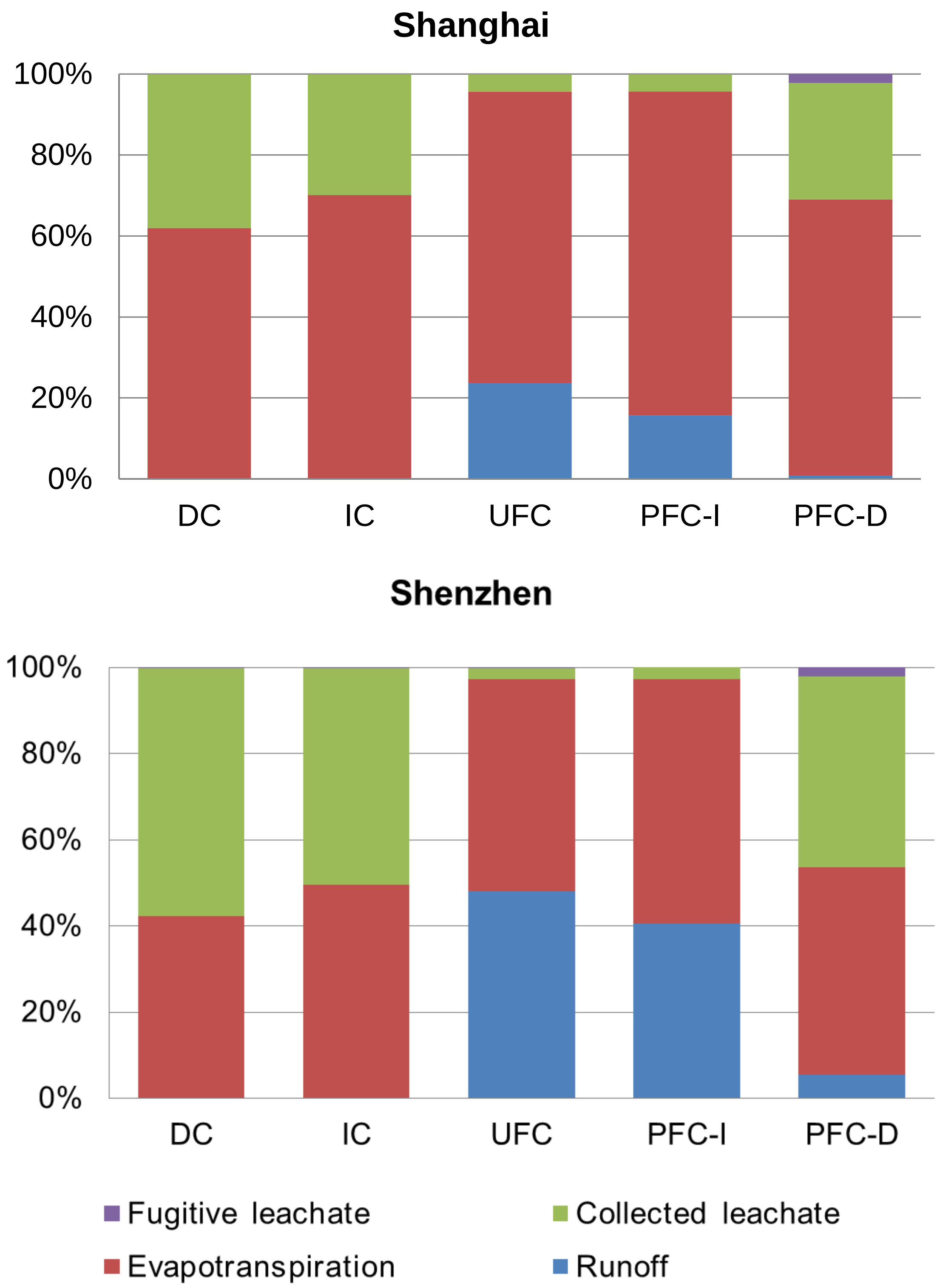
(The weather data was created by the Weather Generator included in Visual HELP. The weather data of Harbin, Changchun, Chongqing and Changsha were not available in Weather Generator, the closest cities’ weather datasets were used instead for calculation (i.e. Shenyang for Harbin and Changchun, Jinfushan for Chongqing, Yueyang for Changsha). However, the average monthly rainfall and average monthly temperature of the closest cities’ weather datasets were replaced by the four cities’ own parameters based on 30 years’ data sources supplied by China Meteorological Administration.)



(a) China-NW



(b) China-N



(c) China-S

Figure S2 Average yearly water balances in percent of precipitation at landfill sites under five types of top cover for the three Chinese geographic regions

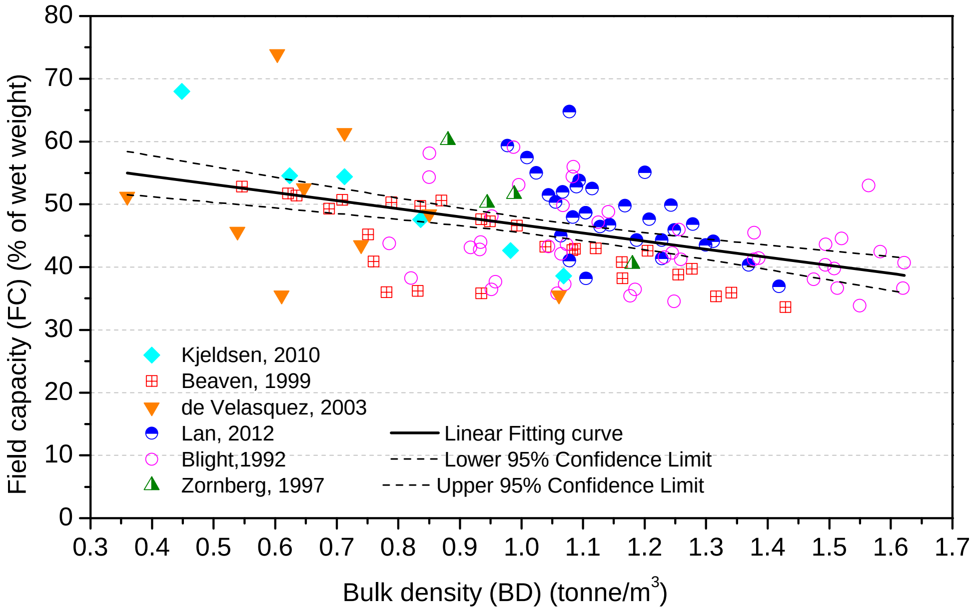


Figure S3 Linear fitting of field capacity and bulk density for municipal solid waste.

The fitting equation is FC= (59.6±2.5)−(12.9±2.3)×BD.

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