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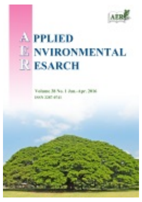

Estimation of Leachate Generated from Zimbabwe's Municipal Solid Wastes (MSW) Landfills using a Simple Stochastic Water Balance Model

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Abstract

Landfilling remains the predominant component in the waste management hierarchy of most developing nations. The adoption of emerging waste management technologies and the use of recycling or composting is still in its infancy. Among several inadequacies of current waste management practices in Zimbabwe is the absence of sanitary disposal of municipal solid waste (MSW) in landfills. As a result, the leachate generation rate and leachate characteristics are not routinely monitored. Such information is essential when assessing the impact of leachate on ground and surface water or a facility to which the leachate can be conveyed. Indiscriminate disposal of MSW at unsanitary dumpsites poses a double threat as the discharge of hazardous leachate to potable water sources and emissions of toxic odours leads to further environmental degradation. Poor waste management practices are compounded by a lack of financial resources and technical capabilities. The financial incapacitation of local authorities is reflected in the fact that there are no reliable statistics on MSW generation and disposal. This lack of comprehensive data has hampered the quantification of MSW and resultant leachate. Therefore, the objectives of this study are twofold. First, we seek to predict the annual quantity of landfilled MSW, and secondly to quantify the leachate flow from Zimbabwe's landfills. Both were achieved through the use of probability models and a stochastic water balance method supported by 10,000 Monte Carlo iterations. The calculated 90% confidence interval indicates that 13-16 million metric tonnes of MSW have been landfilled, with about 41-128 million m3 of leachate released since 1980. This is equivalent to a mean of 414,212 metric tonnes/yr of landfilled MSW and 2.2 million m^3/yr. of leachate generated, respectively.

Keywords: Water balance; Monte Carlo; Leachate; Zimbabwe; MSW; Probability model

Introduction

Landlocked and situated in the southern hemisphere, Zimbabwe is a country troubled by environmental degradation due to poor waste management. With a total land area of 390,757 km^2, the nation is bordered by Mozambique, South Africa, Botswana, and Zambia to the east, south, west and north, respectively. Zimbabwe's population reached 7.7 million in 1982 according to census data. The country's first 10 million was reached in 1992 with the 15-million mark surpassed in 2015. The urban population has grown from 1.6 to 5.2 million between 1980 and 2016 [1-2], presenting many emerging challenges for local authorities who have inadequate capacity to effectively handle the solid waste generated. This has been compounded by an ailing economy which saw a sharp decline in GDP per capita between 1980 and 2009 [3]. Local authorities lack adequate infrastructure, financing and labour, among other factors. These complexities have adversely affected the waste management system which is characterized by low collection efficiencies, high crude tipping rates, on-site burning of waste, and the buildup of garbage in drainage systems, waterways, and streets [4]. Landfills are pre-dominantly used for final MSW disposal albeit without the necessary leachate collection systems at most sites. Nearly 98% of these landfills are not sanitary [5] but are open dumps, as little to no final cover is applied. One of the largest dumps is Pomona located in the capital city as shown in Figure 1. Reports of groundwater contamination have been verified by rising levels of trace elements such as lead, mainly due to the unconfined leachate entering potable water sources from nearby landfills [6-8].

A quick survey of the scientific literature reveals that few attempts have been made to quantify the leachate discharged from Zimbabwe's landfills, the intricacies of which are magnified by the lack of a historical solid waste database. This has hampered the quantification of the amount of MSW landfilled and leachate generated. Reports that have been trickling in since the early 2000s have focused on Zimbabwe's solid waste composition, energy potential, its impact and possible solutions and technological remedies to challenges encountered in the sector [4-6, 9-30]. Due to a lack of field monitoring data to evaluate seepage from the existing landfills and limited studies on the estimation of leachate generation from Zimbabwe's landfills, this study will bridge a gap for other environmental studies. This paper could help in the investigation of groundwater vulnerability in the vicinity of landfills and to estimate the cost of remediation or setting-up of landfill leachate collection systems.

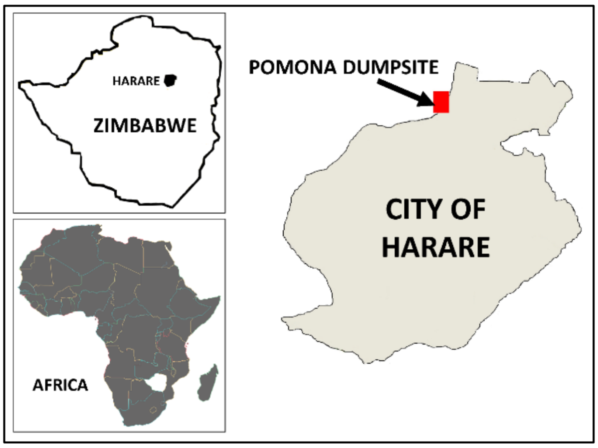

Figure 1 Maps showing location of Pomona dumpsite in Harare. The city of Harare is the largest in terms of population size and area. The city is located at 17.8° S, 31.0° E. on the north-east side, on the outskirts of Harare, Pomona municipal landfill is neither lined nor covered daily.

Approaches to predicting leachate generation categorically fall into either of the following five groups: the water balance method, computer modeling- water balance method combinations, empirical equations, mathematical models and direct infiltration measurements [31]. Zimbabwe is classified as a semi-arid country with at least 85% of the country receiving no more than 800 mm of rain annually. Furthermore, rainfall is concentrated between November and March [32]. Precipitation can thus be expected to contribute to leachate generation as landfills are of inferior design. The Water Balance Method (WBM) adopted in this study allows a relatively simple computation compared to other methods. WBM is particularly appropriate for landfills in which a relatively high permeable layer of soil is used as final cover. Water infiltration and leaching are drastically reduced when a synthetic membrane is used as a covering. Despite extensive use of WBM, field verification revealed significant margins of error between predicted and actual leachate quantities [31]. Too often, minimal account is taken of the uncertainty surrounding the spatial and temporal heterogeneity that characterizes the leachate generation process when approximations are made. The limitations of conventional prediction techniques emanate from their deterministic nature. This makes these models insensitive to uncertainty. The objective of this study is therefore to introduce a stochastic approach to the quantification of MSW generated and subsequent leachate generated from Zimbabwe's landfills. This will be achieved through the use of probability models supported by 10,000 Monte Carlo simulations.

Materials and methods

A WBM model was developed on a spreadsheet equipped with Palisade's @Risk software [33], a risk analysis plugin capable of performing Monte Carlo simulations. The Monte Carlo method is deployed when an approximate solution to a mathematical problem that is difficult to solve analytically is required. Typically, experimentation would be time-consuming, costly, or unfeasible for such a problem. The problem may contain elements that exhibit chance in their behavior. The idea behind these simulations is to generate values for uncertain elements in the model (the inputs) through random sampling. The basic steps involve modelling a system as a series of probability density functions (PDFs), repeatedly sampling from the PDFs and analyzing the outcomes [34-35]. The greater the number of runs the greater the confidence in the result. Since statistical sampling experiments are performed on a computer, time and resource savings can be attained as @Risk eliminates the need to run, test, and present several spreadsheets. In simple terms (Eq. 1) WBM states:

$$L = P - RO - ET - \Delta S - G \qquad \text{(Eq. 1)}$$

where L = post closure leachate volume per unit surface area of landfill (mm), P = volume of precipitation per unit surface area of landfill (mm), ET = volume lost through evapotranspiration per unit surface area of landfill (mm), RO = volume of surface runoff per unit surface area of landfill (mm), ΔS = gain in moisture storage within soil and waste in a unit volume of landfill (mm) and G = volume of water consumed in landfill gas formation per unit surface area of landfill (mm)

The determination of these parameters is outlined in the following subsections.

1) Prediction of MSW generated and landfilled

Total MSW generated from 1980 to 2015 was estimated using historical urban population data provided by the World Bank and per capita MSW generation data. The latter was estimated by first defining a probability distribution using @RISK's built-in distribution fitting feature on reported per capita generation values shown in Table 1. The annual quantity of landfilled MSW was determined by multi-plying together the following terms by 365: total population, rate of urbanization, per capita MSW generation (probability distribution function) and collection efficiency (probability distribution function).

A variation of a triangular distribution, called Trigen in @RISK [36] was used to model the collection efficiency defined by Trigen (a, b, c, p, q). The parameters represent the following: a is the practical minimum, b the most likely value, c the practical maximum value, p is the probability that the parameter value could be below a and q is the probability that the parameter value could be below c. Collection efficiencies dropped from at least 80% (in the mid-1990s) to as low as 30% in the mid-2000s [16]. Other reports cite the efficiency between 50 and 85% [5, 27, 29]. Therefore for this study, Trigen (0.3, 0.75, 0.8, 0.1, 0.9) was assumed.

Table 1 Reported MSW waste generation rates for Zimbabwe (Africa)

MSW generation rate (kg/capita/day)	Reference
0.70	[37]
0.50	[38]
0.50	[28]
0.53	[39]
0.31	[40]
0.50	[27]
0.79	[41]
0.29	[42]
0.53	[29]
0.44	[43]
0.60	[44]
0.42	[5]
0.64	[45]
0.70	[46]

2) Estimation of evapotranspiration

Thorntwainte's equation below was used to estimate ET. This is an indirect way of determining ET and the use of this equation which is inherently simple gives justifiable good results [47]. Direct methods of measuring ET are often expensive, highly demanding in terms of accuracy of measurement and require well-trained researchers. Other indirect methods (empirical or semi-empirical equations) are only valid under specific climatic conditions and sites [48]. The complexity of alternative models or direct methods does not translate into more accurate results hence the choice of this equation. Instead of deterministic values for the terms in Eq. 2, probability distribution models defined from historical rainfall, temperature patterns and daylight hours were used. Akaike's Information Criterion (AIC) determined the best fitting distribution model.

$$\mathrm{PET} = 16 \times \left(\frac{\mathrm{L}}{12}\right) \times \left(\frac{\mathrm{N}}{30}\right) \times \left(\frac{10\mathrm{T}\alpha}{\mathrm{I}}\right)^{\alpha} \qquad \text{(Eq. 2)}$$

where PET is the estimated potential evaporation (mm/month), Tα is the average daily temperature of the month being calculated (°C), N is the number of days in the month being calculated, L is the average day length of the month being calculated (hours), $\alpha = (6.75 \times 10^{-7}) \times I^3 - (7.71 \times 10^{-5}) \times I^2 + (1.792 \times 10^{-2}) \times I + 0.49239$ where $\mathrm{I} = \sum_{i=1}^{12} \left(\frac{\mathrm{T_{ai}}}{5}\right)^{1.514}$ is the heat index which depends on the 12 monthly mean temperature $\mathrm{T_{ai}}$ ET was estimated by assuming a uniform distribution, with limits 0 < ET < PET. ET is unpredictable but is always less than or equal to PET.

3) Estimation of runoff and volume of water consumed during landfill gas formation

Typically, runoff coefficients range from 0.05 to 0.75 [49] hence a uniform distribution was assumed between these values. Ehrig's and Cossu et al. equations [50] below were used to estimate G. The mass of water consumed per m^3 of landfill gas produced (W) is given by

$$\mathrm{W} = \frac{(4a-b-2c+3d) \times (\frac{18}{4}) \times 1000}{(12a+b+16c+14d) \times G_e} \qquad \text{(Eq. 3)}$$

where Ge is the total gas quantity in m^3/tonne of MSW ($C_aH_bO_cN_d$) given by Ge = 1.868 × C × (0.014 T+0.28). C is the Total Organic Content (TOC) (kg/tonne of MSW) and T is temperature in °C. An approximate chemical formula was calculated for MSW using typical ultimate analysis data and Zimbabwe MSW composition data reported by [9-10, 12, 14-19, 51-54]. G was then calculated by dividing volume of water consumed by landfill surface area as shown in Eq. 4.

Uniform distributions for depth and landfilled-MSW density were used with of limits 3-6 m and 534-1,000 kg/m^3 respectively.

The following assumptions were made in developing the model: the only source of infiltration is precipitation falling directly on the surface area of landfill, groundwater does not enter the landfill, all water movement through the landfill is vertically downward, leachate re-cycling or co-disposal of liquid do not take place and the landfill is at field capacity at the start of calculations. Meteorological data are site specific, but due to unavailability of landfill site data, weather bureau data were used in line with common practice [49].

Results and discussion

Results from 10,000 iterations are shown in Figures 2-4. The trend in MSW generation from 1980-2015 depicted in Figure 2 shows that the quantity of MSW has been increasing steadily. The black region represents the 5-95 percentile and the grey depicts the 25-75 percentile for the simulations. The mean is the most-likely estimate of MSW generation. As shown in Figure 3(b), on average, about 291,259-540,037 tonnes/yr of MSW has been landfilled since 1980. This amounts to roughly 13-16 million tonnes of MSW in total since 1980. Using deterministic models, roughly 989,000 tonnes and 490,000 tonnes were generated and landfilled in 2012 according to a study by [29]. Analysis of reported values reveals an average composition of 32.4% putrescibles, 16.2% plastics, 8.6% miscellaneous, 19.9% paper and cardboard, 6.9% metals, 4.0% glass and ceramics, 2.1% leather and rubber, 3.1% textiles, 4.1%-yard waste and 4.5% wood.

Reported MSW generation per capita (kg/capita/day) figures follow a normal distribution with μ and σ of 0.53 and 0.14 respectively. The calculated molecular formula in this study is $C_{617}H_{1718}O_{620}N_{18}Cl_{7}$ and landfill gas (CO_2 and CH_4) quantity generated, Ge, is 81.8 m^3/tonne of MSW. Previously [29] reported 66.7 Nm^3 CH_4/tonne MSW being generated.

$$\text{Landfill surface area} = \frac{1}{\text{depth of landfill (m)}} \times \frac{\text{landfilled}-\text{MSW (tonnes)}}{\text{density of waste (tonnes/ m}^3)} \qquad \text{(Eq. 4)}$$

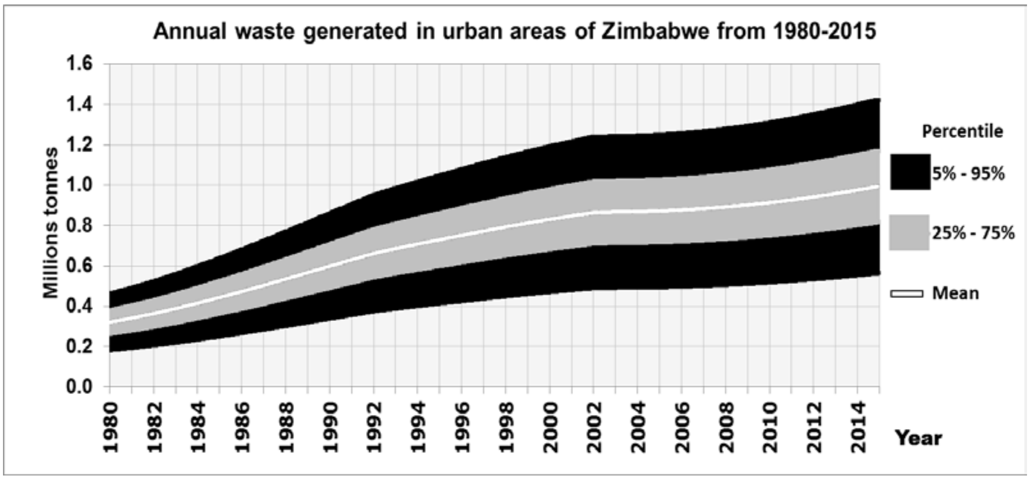

Figure 2 Summary trend for annual MSW generated.

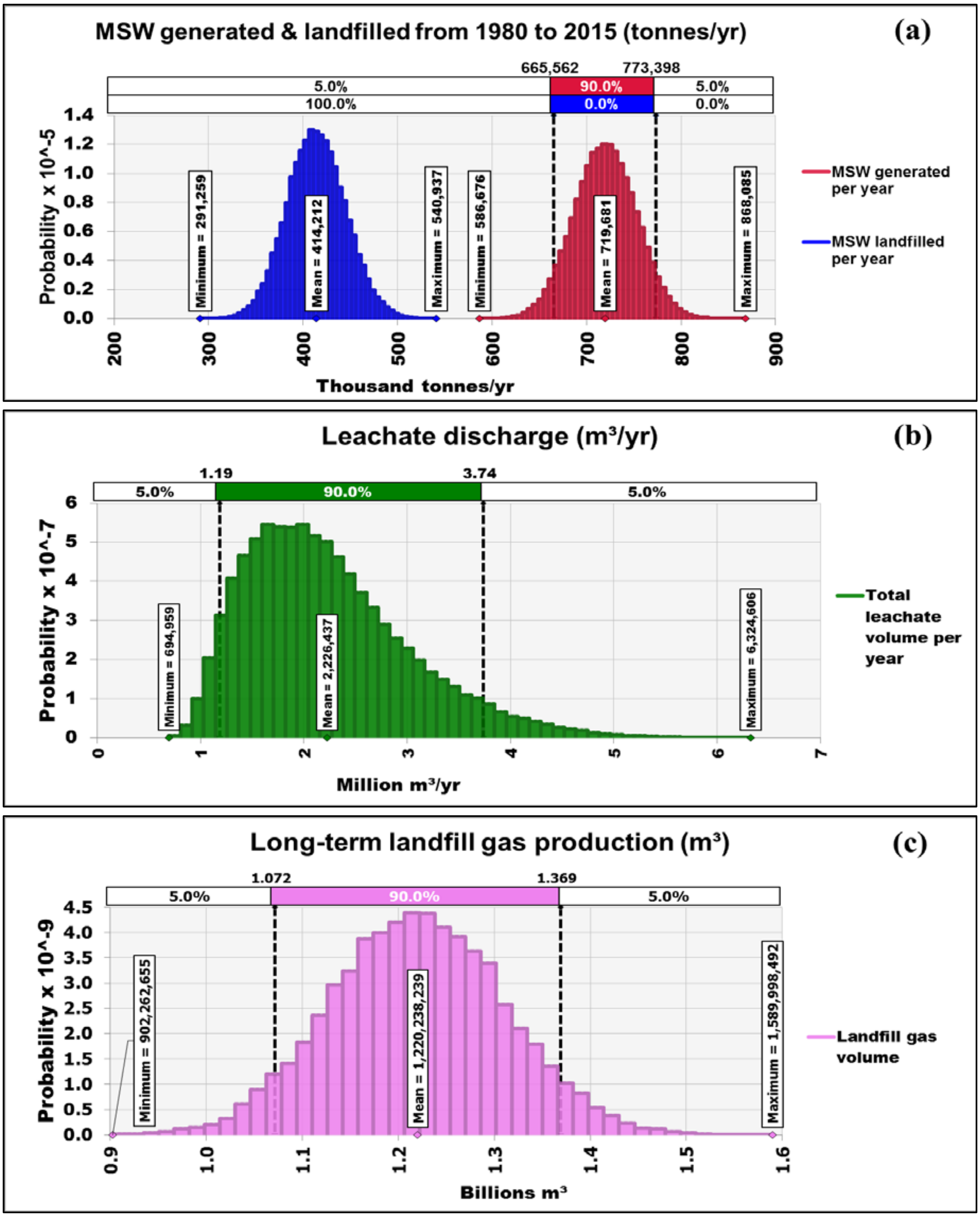

Figure 3 Distribution probability of a) average generated and landfilled MSW b) leachate volume c) landfill gas production.

Calculated TOC and W are 74.7 kg/tonne of MSW and 1.24 kg water/m^3 of landfill gas. At a 90% confidence interval, 1.07-1.37 billion m^3 of landfill gas can potentially be released. Since most landfill sites are open dumps (where aerobic conditions prevail), the predominate gas emitted is likely to be carbon dioxide. The volume of leachate generated is 1.19-3.74 million m^3/yr at a 90% confidence level as shown in Figure 3(b). This amounts to about 41-128 million m^3 of leachate discharge in total since 1980. The high variability of leachate produced from the landfills can be attributed to the variation inherent to leachate generation which relies on hydrologic and climatic influences.

In another study, the average leachate volume discharged from a landfill in Harare (capital city) during the period 1983 to 2014 was estimated to be 94,486 m^3/yr [55].

There are at least 20 official dumpsites corresponding to each urban settlement in Zimbabwe and countless illegal sites, hence the confidence in the estimates presented here. There is also reasonable agreement with the rule of thumb approach of assuming 0.2-1.0 m^3 of leachate being generated for each cubic meter of waste landfilled [56]. Figure 4 is a cumulative distribution of the stochastic water balance. At a 90% confidence level, 381-571 mm per year of leachate is discharged as shown in Figure 4. ET lies between 390-707 mm. The average annual ET in neighboring South Africa was estimated to be 303 mm [57] for 2000-2012 using a different technique. This falls well within the range shown in Figure 4. The stochastic WBM methodology for estimating leachate volumes avoids the limitations of most empirical models, fundamentally flawed by their deterministic nature. Most of the data required in WBM is stochastic or poorly defined (temperature, heat index, precipitation, runoff coefficients). Therefore, the use of deterministic models and techniques must be treated with caution.

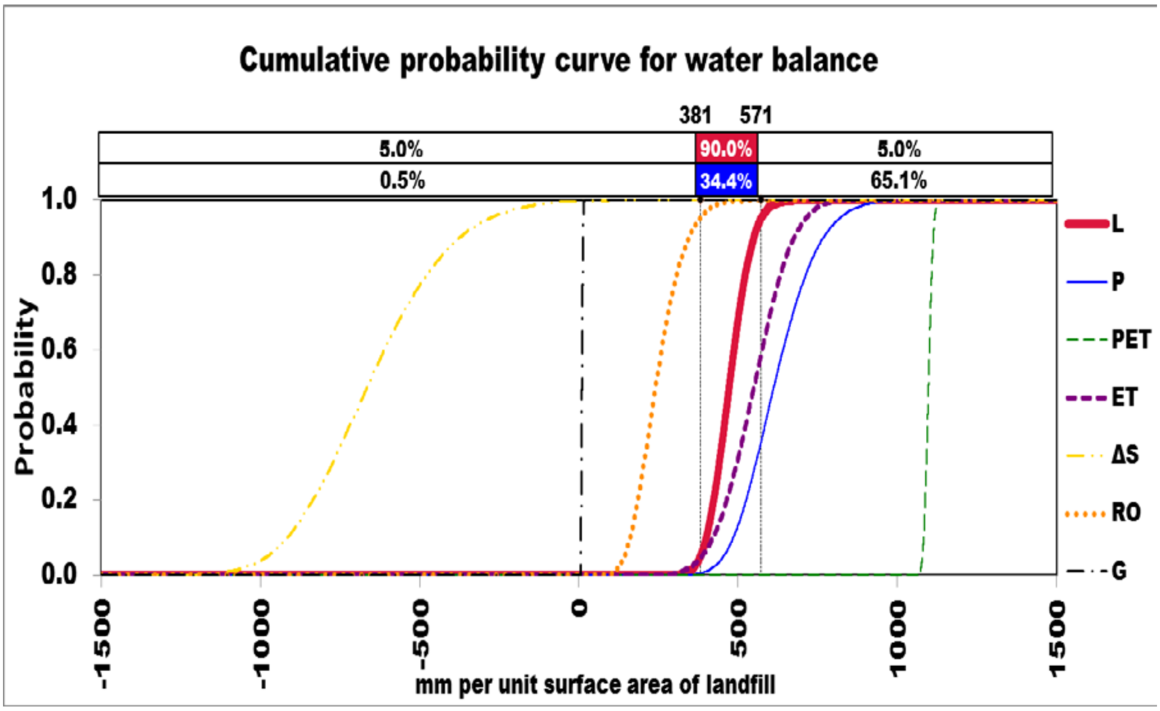

Figure 4 Cumulative probability distribution for annual water balance.

Conclusion

Using Monte Carlo simulations, 13-16 million metric tonnes of MSW have been landfilled since 1980. At a 90% confidence interval, the leachate discharged from landfills is 1.19-3.74 million m^3/yr or about 41-128 million m^3 in total since 1980. It is necessary to stress that this article is an initial approximation. This study could be used in the preliminary design of leachate control systems or to assess the impact of leachate on the environment. There is limited field data on the characteristics of landfill leachate in Zimbabwe, therefore, gathering of such data is highly recommended for future work.

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