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Probabilistic Description of Runoff and Leachate Volumes from Open Windrow Composting Sites

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ABSTRACT. Stormwater runoff generated from open windrow composting sites is often heavily polluted. Detention ponds are typically constructed to contain and treat runoff from these sites. For the proper sizing of detention ponds, runoff volumes from composting sites under rainfall events of different magnitudes need to be estimated. A conceptual rainfall-runoff model that captures the key hydrologic and hydraulic processes is developed in this paper for open window composting sites. Based on this model, closed-form mathematical equations are derived for the purpose of estimating the average volume of runoff per rainfall event, runoff with different return periods, and average leachate runoff from open windrow composting sites with impermeable pads. Example calculations not only demonstrate the capabilities of these equations but also illustrate the effects of regional climatic differences on runoff and leachate volumes.

Keywords: rainwater, solid waste management, composting, stormwater management, probabilistic methods

1. Introduction

Composting of organic type municipal and agricultural wastes is an effective means of managing these solid waste streams. The vast majority of composting sites employ open windrow composting techniques in which wastes are stacked in piles that can be arranged in long parallel rows or windrows. The compost piles are exposed to the atmosphere for aeration. The windrows may have rectangular, trapezoidal, or triangular cross sections, depending largely on the characteristics of composting materials and the equipment used for operation. The heights of the windrows range from 1 to 2 meters and the widths of the windrows are about 4 meters (Haug, 1980; Ge et al., 2006); the exact dimensions are mainly a function of the feedstock and the machine used for turning the piles.

The windrow system has been used successfully for composting a wide variety of organic wastes, including urban refuse, logging and wood manufacturing residues, agricultural crop residuals, food wastes, and manure. The infeed to a composting facility may be shredded or grinded and mixed with other composting materials (e.g., manure, or recycled compost product) for better moisture control and composting characteristics (Wiles, 1977; Haug, 1980). In large systems, windrows are turned at regular intervals by mechanical equipment (Haug, 1980). Regular turning or other ways of agitation are used to ensure complete aeration and uniform distribution of heat and moisture throughout the pile volume. Although the system uses large areas of land, it is relatively low in cost because of the productivity of the mechanical equipment and the location of composting sites in relatively remote areas (Haug, 1980).

Precipitation comes into contact with composting materials and entrains particles from the composting pad, making the runoff high in suspended solids and other attached or dissolved pollutants. Stormwater runoff from composting sites is therefore unsuitable for direct release into receiving waters (Richard and Chadsey, 1990; Cole, 1994). Many regulatory agencies thus require that runoff from open windrow facilities be collected in a stormwater detention pond for treatment prior to release into the natural environment (USEPA, 1994). Figure 1 illustrates schematically an open windrow composting site and the relevant hydrologic processes.

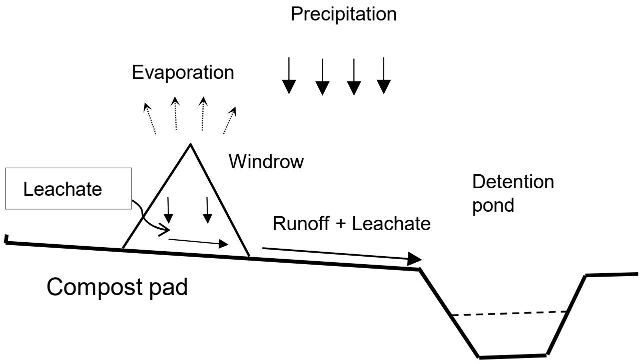

Figure 1. Schematic of an open windrow composting site.

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The rainfall-runoff relationship of open windrow composting sites needs to be better understood for the proper sizing of these detention ponds. Depending on the shape of the windrow, the nature and the state of the composting material, compost windrows can shed precipitation, absorb precipitation, or act as a reservoir and detain precipitation (Krogmann and Woyczechowski, 2000; Wilson et al., 2004). In addition, the high temperatures generated during composting may result in an increased rate of evaporation of moisture from the pile during inter-event dry periods. Proper modeling of all these processes is necessary for the better estimation of runoff and leachate from composting sites.

Although the quantity of runoff generated from composting sites has not been well studied, many jurisdictions (e.g., New York State, the State of Georgia, the Province of British Columbia) still provide specific guidance on how to size detention ponds for the treatment of runoff from composting sites (Kalaba et al., 2007). In its draft guideline, the Ontario Ministry of the Environment (OMOE) requires that a site water management plan be prepared for any proposed composting sites (OMOE, 2009). In the plan, the expected quantities of stormwater and leachate, and the timing of the peak generation of each must be determined. The draft guideline also requires the determination of the need for active treatment and disposal of collected stormwater runoff and leachate. However, the draft guideline does not provide detailed guidance on how to estimate the volumes of runoff and leachate.

Methods for estimating runoff from composting sites reported in the literature or prescribed by regulations are largely design event based (Kalaba et al., 2007), similar to the design storm approach used for estimating flood peaks. Since design storms were developed for the estimation of flood peaks not runoff volumes, use of them to estimate runoff volumes of different return periods would produce highly unreliable results. As noted by Kalaba et al. (2007), there is no consensus about what constitutes an appropriate design rainfall event for a compost facility, resulting in considerable uncertainty about the proper sizing of detention ponds.

Developed in this paper are analytical equations that may be used to estimate the average runoff volume generated from a composting site per rainfall event, the annual or seasonal total runoff volume generated from a composting site, and the runoff event volume from a composting site for a specific return period. The average leachate runoff per rainfall event can also be estimated analytically. The exponentially distributed rainfall event characteristics as described in Adams and Papa (2000) are assumed to apply for the location of interest. These exponential distributions form the foundation of the equations derived in this paper and are briefly reviewed in the next section.

2. Probabilistic Models of Local Rainfall Characteristics

An event-based approach of statistically analyzing local precipitation records which is different from what is used in the conventional design storm approach is described in detail by Adams and Papa (2000). The starting point of the event-based approach is the division of rainfall records that are continuous in time into discrete rainfall events. The criterion for distinguishing between events is a minimum time period without rainfall, referred to as the minimum inter-event time definition (IETD). Rainfall periods separated by a time interval longer than or equal to the selected IETD are considered as separate rainfall events. With the selection of a suitable IETD, a continuous rainfall time series is divided into discrete events and the characteristics of each event can then be determined.

Each rainfall event is characterized by its rainfall depth (v), duration (t), and inter-event time (b) to the subsequent rainfall event. A historical rainfall record can be viewed as a time series comprised of the three characteristics. Frequency analyses on the sample values of v, t and b can be conducted to prepare histograms and fit marginal probability distribution functions. The annual or seasonal total number of storm events for each year can also be determined. Several earlier studies have shown that exponential probability density functions (PDF) often fit the v, t and b histograms satisfactorily (Eagleson, 1972, 1978; Adams et al., 1986; Guo and Adams, 1998; Guo, 2001; Guo and Baetz, 2007; Guo et al., 2009; etc.).

To ensure the statistical independence of successive events, a suitable IETD may be selected following the strategy for formulating and testing Poisson partial duration models suggested by Cruise and Arora (1990). With an exponentially distributed inter-event time b, the occurrence of storm events can be approximated as a Poisson process if the duration of event t is much smaller than b (Restrepo-Posada and Eagleson, 1982). Selection of different IETD values will result in different number of rainfall events every year. If the occurrence of these events is Poissonian, the numbers of events occurring during each consecutive year must follow the Poisson distribution. The test suggested by Cruise and Arora (1990), which was first proposed by Cunnane (1979), relies on the well-known fact that the mean and variance of the Poisson distribution are equal. Therefore, if the ratio $r = Var[n] / E[n]$ is formed for the annual number of event series, where n is the annual number of events, $Var[\bullet]$ and $E[\bullet]$ are the variance and expectation operations, respectively; r should approach unity as the selected IETD is increased. Therefore, a statistical test may be devised for r based on the approximation that the factor $(N\text{-}1)r$ is χ^2 distributed with $(N - 1)$ degrees of freedom (Cunnane, 1979), where N is the number of years of record. The critical values can thus be determined for selected levels of significance (Cruise and Arora, 1990).

For illustration purposes, we selected Toronto, Halifax, and Calgary as our example locations. The Toronto data are from the Yonge Street station (AES #6158350) and cover the years from 1939 to 1998 (with 1940, 1956 ~ 1958 missing). The Halifax data are from the Shearwater station (AES #8205 090) and stretch from 1956 to 1998 with 1957 and 1992 missing. The Calgary data are from the Calgary International Airport station (AES #3031093) and include years from 1960 to 1999. For each year, we analyzed the non-winter months or rainfall year only with snowfall excluded. For Halifax and Toronto, the rainfall years are expected to be from April 1 through October 31; for Calgary, the rainfall years are expected to be from April 30 through October 1. Since small rainfall events (1 ~ 2 mm) usually do not generate any runoff, to improve the goodness-of-fit between the theoretical exponential distributions and observed relative frequencies, it may be desirable to have small events censored from the rainfall event series.

The detailed rainfall analysis results for Toronto, Halifax, and Calgary are reported in Li (2008), Guo et al. (2009), and Mikalson (2011), respectively. It was shown that an IETD of 9 hours is suitable for all three locations, and censoring out events with volumes less than or equal to 1 mm improves the goodness-of-fit for all three locations. The resulting statistics for the three locations and the exponential distribution functions are listed in Table 1.

The event-based definitions and the exponential distribution functions form the basis of probabilistic models of local rainfall characteristics. In this paper, for the development of analytical equations, the event-based probabilistic model of local rainfall characteristics is incorporated into the stochastic analysis of runoff generation from open windrow composting sites. The exponential distributions for rainfall event characteristics as given in Table 1 are assumed to be appropriate for the location of interest, with the understanding that the goodness-of-fit may be better for some locations than others. According to the method of moments, the values of the three distribution parameters ζ, λ, and ψ may be estimated from $\bar{v}$, $\bar{t}$ and $\bar{b}$ respectively; where $\bar{v}$ is the average event depth, $\bar{t}$ is the average event duration, and $\bar{b}$ is the average inter-event time determined from a specific rainfall record.

If local rainfall data are not available or statistical analysis of local rainfall data is not feasible, rainfall statistics reported in previous publications may be used as approximate local values. For locations throughout Canada, the values of the parameters may be found in Adams and Papa (2000); for locations throughout the United States, they can be found in Wanielista and Yousef (1993), Driscoll et al. (1989), or U.S. Environmental Protection Agency (1986).

3. Conceptual Rainfall-Runoff Model for Composting Sites with Impervious Pads

Most open windrow composting operations are located on an impervious surface of asphalt or concrete (Kalaba et al., 2007). A concrete slab flooring with provision for forced aeration of the windrows is also provided to improve operational characteristics under wet weather conditions (Haug, 1980). The site is usually slightly graded to enable good drainage of the composting pad. For most cases, steps are also taken to ensure that only water from the compost pad enters into a treatment pond and that rainfall that does not land on the pad is routed away from the pond. As a result of these design measures, a compost pad can be modeled as an individual catchment comprised of two types of surfaces: bare pad and pad areas covered by compost windrows.

In calculating the total runoff resulting from the input of a rainfall event, a compost pad can be divided into impervious and pervious areas. Impervious areas are those not covered by windrow piles, the input rainfall is totally converted to runoff after filling the impervious area depression storage (denoted as S_{di}, in mm). Thus, runoff event volume generated from these areas (denoted as v_{ri}, in mm) can be calculated as:

$$v_{ri} = \begin{cases} 0, & v \le S_{di} \\ v - S_{di}, & v > S_{di} \end{cases} \qquad (1)$$

where v is the total rainfall volume or depth (mm) of the input rainfall event.

For pervious areas or areas covered by windrow piles, the input rainfall may be shed away by the windrow or fill the void spaces of the windrow pile. We denote the maximum amount of rain water that can be absorbed by windrow piles as S_m. After rainfall fills S_m, the remaining water will run off from the pad. The units of S_{di} and S_m are mm of water over the respective impervious and pervious areas. The bulky nature of some composting materials may cause part of the absorbed water to quickly seep downward through the pores and leak out at the toe of the pile. For estimating runoff volume, this fraction of absorbed water is combined with the fraction that is shed away and immediately becomes runoff. Therefore, S_m is here with more accurately defined as the maximum amount of rain water that can be absorbed and held by the composting material without immediate release. This definition is equivalent to the definition of field capacity for soils.

The rate of rain water absorption by windrow piles can be very high because of the large hydraulic conductivity of bulk materials. Thus, absorption of rain water can be assumed to be instant upon the contact of the rain drop with the pile. For each rainfall event, the maximum amount of rain water that can be absorbed by the windrow piles may be different because of different preceding conditions. To simplify the rainfall-runoff model, we assume that the maximum amount of rain water that can be absorbed by the windrow pile for each rainfall event is the same, equaling the average maximum amount of rain water that can be absorbed per rainfall event. This average is denoted as S_{ma}. Similar to S_m, S_{ma} is the rain water that can be absorbed and held by the composting material without immediate release. The runoff volume from the windrow covered areas (v_{rp} in mm) resulting from the input of a rainfall event can then be calculated as:

$$v_{rp} = \begin{cases} 0, & v \le S_{ma} \\ v - S_{ma}, & v > S_{ma} \end{cases} \qquad (2)$$

The total runoff (in mm over the composting pad) is the area-weighted summation of runoff from the impervious and windrow covered portions of the composting pad. Since window piles sit on the same impervious pad areas, S_{di} is less than S_{ma} because S_{ma} should in fact be the sum of S_{di} and the absorption amount provided by the windrow piles. For simplification in notation, S_{di} is included in S_{ma} and water held in depression areas underneath windrow piles is assumed to behave

Table 1. Probabilistic Model of Local Rainfall Characteristics

Rainfall Event Characteristic	Exponential Probability Density Function	Parameter Value for Toronto	Parameter Value for Halifax	Parameter Value for Calgary
Depth, v (mm)	$f_V(v) = \zeta \exp(-\zeta v)$	$\zeta = 0.09754$	$\zeta = 0.06925$	$\zeta = 0.1160$
Duration, t (h)	$f_T(t) = \lambda \exp(-\lambda t)$	$\lambda = 0.1092$	$\lambda = 0.09105$	$\lambda = 0.0980$
Inter-event Time, b (h)	$f_B(b) = \psi \exp(-\psi b)$	$\psi = 0.00966$	$\psi = 0.1034$	$\psi = 0.0071$

similarly as water held inside the piles. If the fraction of the composting pad area not covered by windrow piles is h (i.e., bare pad surface fraction), then in determining the total runoff volume the area weight for the pad area not covered by windrow piles is h, and that for the areas covered by windrow piles is $(1 - h)$. The total runoff from the composting site resulting from a rainfall event with volume v is denoted as v_r and $v_r = [hv_{ri} + (1-h)v_{rp}]$ where v_{ri} and v_{rp} are as expressed in Equations (1) and (2) respectively. When v is less than or equal to S_{di}, according to Equations (1) and (2), both v_{ri} and v_{rp} are zero, so $v_r = 0$. When $S_{di} < v \le S_{ma}$, $v_{ri} = v - S_{di}$ and $v_{rp} = 0$, therefore, $v_r = h(v - S_{di})$. When $v > S_{ma}$, $v_{ri} = v - S_{di}$ and $v_{rp} = v - S_{ma}$, therefore $v_r = h(v - S_{di}) + (1 - h)(v - S_{ma}) = v - hS_{di} - (1 - h)S_{ma}$. Summarizing the above, the conceptual rainfall-runoff model for a composting site can be expressed as:

$$v_r = hv_{ri} + (1-h)v_{rp} = \begin{cases} 0, & v \le S_{di} \\ h(v - S_{di}), & S_{di} < v \le S_{ma} \\ v - hS_{di} - (1-h)S_{ma}, & v > S_{ma} \end{cases} \tag{3}$$

where v_r is the runoff event volume (in mm over the pad area) resulting from a rainfall event with volume v.

4. Probabilistic Transformation from Rainfall to Runoff

Equation (3) describes the functional relationship between dependent random variable v_r and the independent random variable v. In the following, the probability distribution of v_r is derived according to the derived probability distribution theory (Adams and Papa, 2000) and the functional relationship described in Equation (3). The cumulative distribution function (CDF) of v_r is determined separately for v_r values in the three ranges as indicated in Equation (3). First, when the input rainfall volume is less than S_{di}, no runoff will be generated. The probability per rainfall event that the resulting runoff volume is zero is given by:

$$P[v_r = 0] = \int_0^{S_{di}} \zeta \exp(-\zeta v)dv = 1 - \exp(-\zeta S_{di})$$

Secondly, when runoff volume is small and solely derived from the impervious areas of the pad (i.e., when $S_{di} < v < S_{ma}$), the volume of runoff will always be less than $h(S_{ma} - S_{di})$. The probability of v_r being less than a given value v_o, where v_o is greater than zero but less than or equal to $h(S_{ma} - S_{di})$, is found by integrating the PDF of v over the region of $S_{di} < v < v_o / h + S_{di}$:

$$P[v_r \le v_o] = \int_{S_{di}}^{\frac{v_o}{h} + S_{di}} \zeta \exp(-\zeta v)dv + P[v_r = 0] = 1 - \exp(-\zeta S_{di} - \frac{\zeta}{h}v_o),\ 0 < v_o \le h(S_{ma} - S_{di}) .$$

At the upper limit of $v_o = h(S_{ma} - S_{di})$, the above equation becomes:

$$P[v_r \le h(S_{ma} - S_{di})] = 1 - \exp(-\zeta S_{ma}) .$$

Thirdly, when v is greater than S_{ma}, areas covered by windrow piles may also contribute runoff. Under this condition, the runoff volume will always be greater than or equal to $h(S_{ma} - S_{di})$. For a given v_o value falling in this range [i.e., when $v_o > h(S_{ma} - S_{di})$], the probability of v_r being less than or equal to v_o is:

$$P[v_r \le v_o] = \int_{S_{ma}}^{v_o + hS_{di} + (1-h)S_{ma}} \zeta \exp(-\zeta v)dv + P[v_r \le h(S_{ma} - S_{di})]$$
$$= 1 - \exp\{-\zeta[hS_{di} + (1-h)S_{ma} + v_o]\}$$

Summarizing the above expressions for the three ranges of v_r values and replacing v_o with v_r to represent any specific runoff event volume of interest, the CDF of runoff event volume is determined as:

$$F_{V_R}(v_r) = \begin{cases} 1 - \exp(-\zeta S_{di}), & v_r = 0 \\ 1 - \exp(-\zeta S_{di} - \frac{\zeta}{h}v_r), & 0 < v_r \le h(S_{ma} - S_{di}) \\ 1 - \exp\{-\zeta[hS_{di} + (1-h)S_{ma} + v_r]\}, & v_r > h(S_{ma} - S_{di}) \end{cases} \tag{4}$$

The PDF of runoff event volume is determined by taking the derivative of the CDF with respect to v_r:

$$f_{V_R}(v_r) = \begin{cases} [1 - \exp(-\zeta S_{di})]\delta(0), & v_r = 0 \\ \frac{\zeta}{h}\exp(-\zeta S_{di} - \frac{\zeta}{h}v_r), & 0 < v_r \le h(S_{ma} - S_{di}) \\ \zeta \exp\{-\zeta[hS_{di} + (1-h)S_{ma} + v_r]\}, & v_r > h(S_{ma} - S_{di}) \end{cases} \tag{5}$$

In Equation (5), $\delta(0)$ is the Dirac delta function used to indicate that there is an impulse probability at $v_r = 0$. The expected value of the runoff event volume per rainfall event can be found as follows:

$$\mathrm{E}(v_r) = \int_0^{\infty} v_r f_{V_R}(v_r) dv_r = \frac{h}{\zeta}\exp(-\zeta S_{di}) + \frac{(1-h)}{\zeta}\exp(-\zeta S_{ma}) \tag{6}$$

The average annual runoff volume is simply the product of $\mathrm{E}(v_r)$ and θ, where θ is the average annual number of rainfall events. The probability per rainfall event that the generated runoff volume is greater than v_r is denoted as $G_{V_R}(v_r)$. This probability is also referred to as the exceedance probability of runoff event volume and can be calculated as $G_{V_R}(v_r) = 1 - F_{V_R}(v_r)$, therefore:

$$G_{V_R}(v_r) = \begin{cases} \exp(-\zeta S_{di}), & v_r = 0 \\ \exp(-\zeta S_{di} - \frac{\zeta}{h} v_r), & 0 < v_r \le h(S_{ma} - S_{di}) \\ \exp\left\{-\zeta\left[hS_{di} + (1-h)S_{ma} + v_r\right]\right\}, & v_r > h(S_{ma} - S_{di}) \end{cases} \tag{7}$$

Conversion from exceedance probability per rainfall event to return period is as follows:

$$T_R = \frac{1}{\theta G_{V_R}(v_r)} \tag{8}$$

In Equation (8), T_R is the return period (in years) of runoff event volume v_r; θ is the average annual number of rainfall events.

5. Estimation of the Average Maximum Absorption by Windrow Piles

In the formulation of the conceptual rainfall-runoff model, the maximum absorption that a windrow pile can take under each rainfall event is assumed to be the same, equalling the average maximum absorption denoted as S_{ma}. In reality, the windrow piles may have different absorption capabilities under each rainfall event due to different weather conditions prior to the specific rainfall event. For some rainfall events, the actual maximum absorptions are larger than S_{ma}; for some others, they are less than S_{ma}. If a value larger than S_{ma} is taken as the maximum absorption for each rainfall event, the number of events with runoff volumes underestimated will be greater than the number of events with runoff volumes overestimated, thus the total runoff volume would likely be underestimated; similarly if a value less than S_{ma} is taken as the maximum absorption for each rainfall event, the total runoff volume would likely be overestimated. Therefore, assuming that the maximum absorption for each rainfall event equals S_{ma} would result in the most accurate estimation of the total runoff volume and also the expected value of runoff event volume using Equation (6). For larger events, the difference between the rainfall volume actually absorbed by windrow piles and calculated with the S_{ma} assumption would be relatively small in comparison to the rainfall volume itself. As a result, the loss of accuracy in estimating runoff volume resulting from larger rainfall events would be relatively small with the assumption of equal maximum absorption for every rainfall event. Since it is the larger events that affect the sizing of detention ponds the most, the use of average maximum absorption for each event is justifiable for detention pond analysis. When using the design event or design storm-based approach for estimating runoff from composting sites, similar assumptions about the conditions of the site at the start of the design event (referred to as the antecedent conditions) also need to be made.

S_{ma} should be estimated based on a long-term water balance analysis. The long-term water balance requires that the total amount of rain water absorbed by the windrow piles should equal the total amount leached or evaporated from the piles plus the total amount consumed inside the piles as a result of the biological/chemical processes occurring in the compost. Let the total rate of depletion of water (which equals the sum of the leaching rate, evaporation rate, and consumption rate, production of water as a result of aerobic digestion is counted as negative consumptions) be R_d (mm/hr) and assuming that it remains constant during inter-event times, the maximum long-term total depletion of water from the windrow piles can be estimated as ($N \cdot R_d \cdot \bar{b}$), where N is the total number of rainfall events and inter-event times during the long term, and $\bar{b}$ is the average duration of inter-event times (hr). ($N \cdot R_d \cdot \bar{b}$) is the maximum long-term total depletion because depletion of absorbed water may not last for the entire duration of some inter-event times when all the absorbed water is depleted before the ends of these inter-event times. The maximum total amount of rain water absorbed by the windrow piles is ($N \cdot S_{ma}$). This is also the maximum total amount because some small rainfall events may not have enough water to fill S_{ma}.

An approximate long-term water balance may be achieved by letting $N \cdot R_d \cdot \bar{b} = N \cdot S_{ma}$, i.e., $S_{ma} = R_d \cdot \bar{b}$. However, the windrow piles have a maximum absorption of S_m provided by the total void spaces of the waste materials and held against quick release by these materials, therefore S_{ma} cannot exceed S_m. The above considerations may be summarized as:

$$S_{ma} = \begin{cases} R_d \bar{b}, & R_d \bar{b} \le S_m \\ S_m, & R_d \bar{b} > S_m \end{cases} \tag{9}$$

Although Equation (9) still only gives an approximate estimate of S_{ma}, it at least prevents high inaccuracies for the following two types of extreme cases. One type is when the average amount of depletion during inter-event times is extremely low due to the specific characteristics of windrow piles and/or the local weather conditions (i.e., locations with extremely small $\bar{b}$); the second type is when S_m is extremely high in relation to the local weather conditions. With S_{ma} estimated using Equation (9), subsequent calculations using Equations (5) through (8) should be accurate enough for planning and preliminary estimation purposes even under the two types of extreme cases.

A more accurate approach for estimating S_{ma} is to treat the maximum absorption of the windrow piles at the beginning of each rainfall event as a random variable, to find the PDF of this random variable considering the dynamic, event-by-event water balance of the windrow piles, and then to determine the expected value of this random variable. This expected value should be taken as the value of S_{ma}. However, what we found is that the resulting PDF cannot be expressed in closed-form analytical equations and numerical integration is needed in order to determine the expected value. That is why the above-described approximate way of estimating S_{ma} is suggested.

6. Estimation of Leachate Runoff

As mentioned earlier, some absorbed rain water can leak through the windrow piles and drain from the toes of the piles (Krogmann and Woyczechowski, 2000; Wilson et al., 2004). The runoff volume v_r calculated by Equation (3) includes the portion that is shed, leaked and drained quickly from the toes during rainfall events but does not include the portion slowly leached and drained after rainfall events during inter-event times. Since there is no way to differentiate between runoff shed by (or leaked through) windrow piles during rainfall events, only runoff occurred during inter-event times is referred to as leachate runoff and counted separately.

Runoff event volume v_r as defined and used earlier can be treated as the complete runoff event volume resulting from a rainfall event due to the following two considerations. First, the amount of leachate runoff occurring during inter-event times must be, on average, less than S_{ma} and therefore may constitute only a small portion of the total event runoff under large rainfall events. Second, after a rainfall event, compost mass in most cases detains rain water and releases it slowly over a period of 1 to 2 days (Wilson et al., 2004). Thus, leachate runoff behaves similarly as baseflows in small streams. There may be no need to consider leachate runoff for the sizing of detention ponds for the majority of cases. However, for cases where S_{ma} is large as compared to the average volume of input rainfall events, there may be a need to add the leachate runoff to the runoff event volume v_r.

Denoting the rates of leaching, evaporation and consumption (or production) of water during inter-event times as R_l, R_e, and R_c, respectively; the sum of R_l, R_e, and R_c is therefore R_d. For processes dominated by aerobic digestion, R_c will be a negative value. These rates are all measured in mm/h per unit area covered by windrow piles. A random rainfall event and its subsequent inter-event time may be examined to estimate the mean event and annual average leachate runoff volume. The amount of rain water absorbed by the window piles from the input of a random rainfall event is

$$ABS = \begin{cases} v, & v \le S_{ma} \\ S_{ma}, & v > S_{ma} \end{cases} \tag{10}$$

where ABS is also measured in mm of water per unit windrow-covered areas. The mean of ABS per rainfall event can be found as:

$$\overline{ABS} = \int_0^{S_{ma}} v\zeta \exp(-\zeta v)dv + \int_{S_{ma}}^{\infty} S_{ma}\zeta \exp(-\zeta v)dv$$
$$= \frac{1}{\zeta}\left[1 - \exp(-\zeta S_{ma})\right]$$

Since S_{ma} is estimated based on the long-term water balance of the windrow pile, $\overline{ABS}$ should also be equal to the mean of water depleted during the subsequent inter-event time following the random rainfall event. Because leaching, evaporation, and consumption or production of water largely start and end at the same times during each inter-event period, the mean duration D (hrs) within an inter-event period when the three depletion processes occur can be estimated as:

$$D = \frac{\overline{ABS}}{R_l + R_e + R_c} = \frac{1 - \exp(-\zeta S_{ma})}{\zeta\left(R_l + R_e + R_c\right)}$$

Therefore, the mean leachate runoff volume $E(v_l)$ per inter-event time is:

$$E\left(v_l\right) = R_l D\left(1 - h\right) = \frac{R_l\left[1 - \exp(-\zeta S_{ma})\right]\left(1 - h\right)}{\zeta\left(R_l + R_e + R_c\right)} \tag{11}$$

In the above, $R_l D$ is leachate measured in mm of water per unit windrow-covered area, it is converted to mm of water per unit of the entire pad area by multiplying with $(1 - h)$. The annual average leachate runoff volume (mm of water over the entire pad area) can be calculated as the product of θ and $E(v_l)$.

7. Example Calculations

7.1. Hypothetical Cases Demonstrating the Applicability and Robustness of the Approach

Some example calculations were performed using hypothetical values of h, S_{di}, S_m, R_l, R_e, and R_c. The results are summarized in Tables 2 through 4 and Figures 2, 3 and 4. For cases presented in Tables 2 through 4, h and S_{di} were kept constant (0.5 and 1.0 mm respectively) because their impact is obvious. The values of R_c were kept at zero because R_c's impact on runoff and leachate is the same as that of R_e; therefore, examination of the impact of R_e alone is enough. Three groups of cases are included in each table. In the first group, the values of S_m were changed from small to large, while the values of other parameters remain unchanged. In the second group, the values of R_l were changed from low to high, while the values of other parameters remain unchanged. In the third group, the values of R_e were changed from small to large, while the other parameters maintain their values taken for the corresponding cases in the second group. In Tables 2 through 4, R_d is calculated as the sum of R_l, R_e, and R_c, whereas S_{ma}, $E(v_r)$ and $E(v_l)$ are cal-

Table 2. Example Calculations Illustrating the Effects of S_m, S_l and R_e in Toronto

S_m (mm)	R_l (mm/h)	R_e (mm/h)	R_d (mm/h)	S_{ma} (mm)	$E(v_r)$ (mm)	$E(v_l)$ (mm)	$E(v_r) + E(v_l)$ (mm)
10.0	0.200	0.000	0.200	10.0	6.58	3.19	9.78
20.0	0.200	0.000	0.200	20.0	5.38	4.40	9.78
30.0	0.200	0.000	0.200	20.7	5.33	4.45	9.78
40.0	0.200	0.000	0.200	20.7	5.33	4.45	9.78
20.0	0.000	0.000	0.000	0.0	9.78	0.00	9.78
20.0	0.002	0.000	0.002	0.2	9.67	0.10	9.78
20.0	0.010	0.000	0.010	1.0	9.28	0.49	9.78
20.0	0.500	0.000	0.500	20.0	5.38	4.40	9.78
20.0	0.900	0.000	0.900	20.0	5.38	4.40	9.78
20.0	0.000	0.000	0.000	0.0	9.78	0.00	9.78
20.0	0.002	0.100	0.102	10.6	6.48	0.06	6.54
20.0	0.010	0.200	0.210	20.0	5.38	0.21	5.59
20.0	0.500	2.000	2.500	20.0	5.38	0.88	6.26
20.0	0.900	3.000	3.900	20.0	5.38	1.01	6.39

Table 3. Example Calculations Illustrating the Effects of S_m, S_l and R_e in Halifax

S_m (mm)	R_l (mm/h)	R_e (mm/h)	R_d (mm/h)	S_{ma} (mm)	$E(v_r)$ (mm)	$E(v_l)$ (mm)	$E(v_r) + E(v_l)$ (mm)
10.0	0.200	0.000	0.200	10.0	10.35	3.61	13.96
20.0	0.200	0.000	0.200	19.3	8.63	5.33	13.96
30.0	0.200	0.000	0.200	19.3	8.63	5.33	13.96
40.0	0.200	0.000	0.200	19.3	8.63	5.33	13.96
20.0	0.000	0.000	0.000	0.0	13.96	0.00	13.96
20.0	0.002	0.000	0.002	0.2	13.86	0.10	13.96
20.0	0.010	0.000	0.010	1.0	13.49	0.47	13.96
20.0	0.500	0.000	0.500	20.0	8.54	5.41	13.96
20.0	0.900	0.000	0.900	20.0	8.54	5.41	13.96
20.0	0.000	0.010	0.010	1.0	13.49	0.00	13.49
20.0	0.002	0.040	0.042	4.1	12.19	0.08	12.27
20.0	0.010	0.080	0.090	8.7	10.69	0.36	11.05
20.0	0.500	0.090	0.590	20.0	8.54	4.59	13.13
20.0	0.900	0.100	1.000	20.0	8.54	4.87	13.42

culated using Equations (9), (6), and (11), respectively.

The first group of cases in Table 2 shows that when other parameters remain constant, an increase in S_m results in a decrease in $E(v_r)$ but an increase in $E(v_l)$. This is because increase in S_m results in more rainfall being absorbed by the compost, and less rainfall becomes runoff. During inter-event times, absorbed rainfall leaches out and becomes leachate. Therefore, the higher the S_m, the larger the $E(v_l)$. Since R_e and R_c were kept zero in the first group of cases, absorbed water can only be depleted through leaching, therefore, the sum of $E(v_r)$ and $E(v_l)$ remains constant equalling the part of rainfall that is not lost through depression storage of the impervious areas. Results of this group also show that when S_m increases from 30 mm and up, the corresponding S_{ma} does not increase any further. For cases with S_m of 30 mm and up, the depletion of water from the compost between rainfall events is controlled by other factors (i.e., rate of depletion, time available for depletion, absorbed water available for depletion) and not by S_m any more; and the entire storage space provided by the compost is not fully utilized for the storage of rainfall during the majority of events. That is why, on average, the actual void space used in the absorption of rainfall is less than S_m and reaches a plateau as S_m increases further.

The impact of R_d on runoff and leachate is further illustrated by the second group of calculations in Table 2. When other parameters remain constant, increase in R_l (consequently increase in R_d) results in a decrease in $E(v_r)$ but an increase in $E(v_l)$. These can also be explained by relevant hydrological processes. More obvious is that with the same S_m of 20 mm, the increase of R_d from 0 mm/h to 0.9 mm/h results in an increase from 0 to 20 mm of the actual average maximum absorption (S_{ma}). Again, the sums of $E(v_r)$ and $E(v_l)$ are the same for all the cases because evaporation and consumption/production rates are both assumed to be zero.

The third group of calculations in Table 2 demonstrates that, when R_e values were added to the corresponding cases in the second group, the values of $E(v_r)$ decrease and the values of $E(v_l)$ increase. This is because the addition of R_e causes more water in the compost to be depleted during inter-event periods and thus a higher S_{ma} value even though the S_m values

Table 4. Example Calculations Illustrating the Effects of S_m, S_l and R_e in Calgary

S_m (mm)	R_l (mm/h)	R_e (mm/h)	R_d (mm/h)	S_{ma} (mm)	E(v_r) (mm)	E(v_l) (mm)	E(v_r) + E(v_l) (mm)
10.0	0.200	0.000	0.200	10.0	5.19	2.96	8.15
20.0	0.200	0.000	0.200	20.0	4.26	3.89	8.15
30.0	0.200	0.000	0.200	28.2	4.00	4.15	8.15
40.0	0.200	0.000	0.200	28.2	4.00	4.15	8.15
20.0	0.000	0.000	0.000	0.0	8.15	0.00	8.15
20.0	0.002	0.000	0.002	0.3	8.01	0.14	8.15
20.0	0.010	0.000	0.010	1.4	7.50	0.65	8.15
20.0	0.500	0.000	0.500	20.0	4.26	3.89	8.15
20.0	0.900	0.000	0.900	20.0	4.26	3.89	8.15
20.0	0.000	0.010	0.010	1.4	7.50	0.00	7.50
20.0	0.002	0.040	0.042	5.9	6.01	0.10	6.11
20.0	0.010	0.080	0.090	12.7	4.83	0.37	5.20
20.0	0.500	0.090	0.590	20.0	4.26	3.29	7.56
20.0	0.900	0.100	1.000	20.0	4.26	3.50	7.76

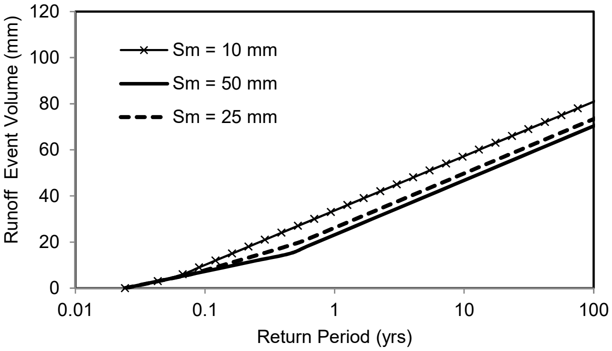

Figure 2. Runoff event volume versus return period for cases with different S_m values in Toronto with $h = 0.5$, $S_{di} = 1$ mm, $R_l = 0.2$ mm/h, $R_e = 0.1$ mm/h, and $R_c = 0.0$.

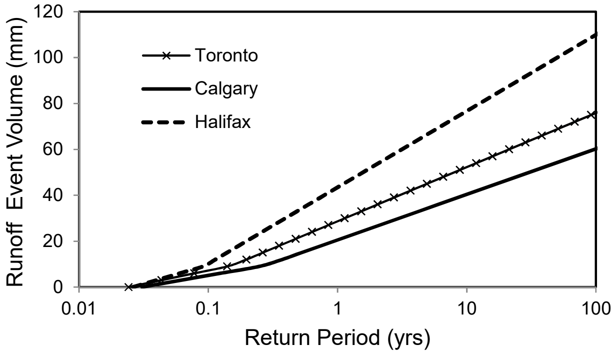

Figure 3. Runoff event volume versus return period for cases at three different Locations ($S_m = 20$ mm, $h = 0.5$, $S_{di} = 1$ mm, $R_l = 0.1$ mm/h, $R_e = 0.1$ mm/h, and $R_c = 0.0$).

are the same as the ones with $R_e = 0$. Higher S_{ma} values decrease E(v_r) but increase E(v_l) because more absorbed water is available to become leachate.

Results in Tables 3 and 4 follow similar patterns as those in Table 2. However, the corresponding values of E(v_r) and E(v_l) in Table 3 are higher than those in Table 2; and the corresponding values of E(v_r) and E(v_l) in Table 4 are lower than those in Table 2. These results reflect the climate differences between the three locations. The main climate difference is that the average rainfall event volume is the highest in Halifax and lowest in Calgary.

Figure 2 shows how runoff event volumes for different return periods change with S_m for a composting site located in Toronto. In obtaining the three curves in Figure 2, all the other parameters keep their respective constant values, namely, $h = 0.5$, $S_{di} = 1$ mm, $R_l = 0.2$ mm/h, $R_e = 0.1$ mm/h, and $R_c = 0.0$. For composting sites where the windrow pile is high and S_m is large, runoff event volume is smaller for the same return period. But when S_m exceeds a certain amount (e.g., from 25 mm on in the case in Figure 2), a further increase in its value will not significantly decrease runoff event volume. As explained previously, this is because the value of S_{ma} is also affected by the rate of depletion of absorbed water and climatic factors; above a certain level, further increase in S_m does not always translate to increase in S_{ma}, and it is the value of S_{ma}, not S_m, that affects the relationship between runoff event volume and return period.

For a specific case where $h = 0.5$, $S_m = 20$ mm, $S_{di} = 1$ mm, $R_l = 0.1$ mm/h, $R_e = 0.1$ mm/h, and $R_c = 0.0$, Figure 3 shows its runoff event volume versus return period relationship when it is located in Toronto, Halifax, or Calgary. It can be seen that for the same return period, the runoff event volume from the composting site would be the largest if it is located in Halifax, and smallest if is located in Calgary. The differences get larger with the increase in return period. This is a direct result of the climatic differences between the three locations.

The effect of h on runoff event volume is illustrated in Figure 4 where three curves for three different levels of h are constructed for a site in Toronto with parameters other than h kept at the same values. As shown in Figure 4, the same increment in h values resulted in largely the same vertical distance between the three curves. This is as expected because the effect of h on runoff event volume is linear (Equation (3)) and not affected by climate or the change in other parameter values.

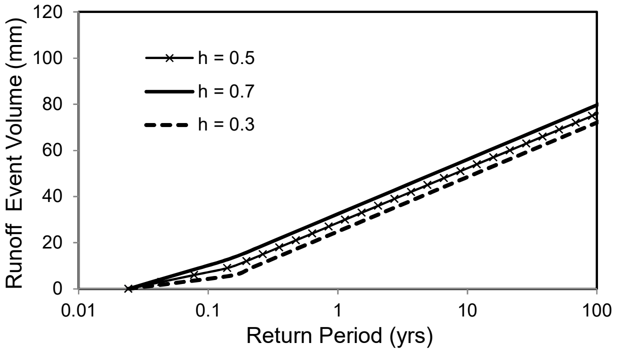

Figure 4. Runoff event volume versus return period for cases with different *h* values in Toronto (S_m = 20 mm, S_{di} = 1 mm, R_l = 0.1 mm/h, R_e = 0.1 mm/h, and R_c = 0.0).

7.2. Real Cases Verifying the Event-Based Rainfall-Runoff Model

The above example calculations show that the derived equations provide reasonable estimates of the average volume of runoff per rainfall event [E(v_r)], runoff with different return periods, and average leachate runoff [E(v_l)] from composting sites with a wide range of different characteristics. For a specific site, long-term measured values of rainfall and runoff need to be available in order to determine its E(v_r), runoff with different return periods, and E(v_l) directly from observed data. Our literature review indicated that no long-term measurement of rainfall and runoff was conducted so far for any composting site. We have found only two sites (Kalaba et al., 2007; Webber et al., 2010) where a few individual rainfall/run- off events were monitored. From these limited data, E(v_r), run- off with different return periods and E(v_l) cannot be directly estimated. In the future, long-term monitoring needs to be conducted in order to directly verify the accuracy of our derived equations.

As the acceptability of the exponential distributions of rainfall event characteristics for various locations has been verified already in previous studies (e.g., Guo and Adams, 1998; Adams and Papa, 2000; Guo, 2001; Guo and Baetz, 2007), and the analytical equations for calculating E(v_r), runoff with different return periods and E(v_l) are all derived based on these exponential distributions and the event-based rainfall-runoff model [i.e., Equation (3)], if Equation (3) can provide reasonably accurate estimation of runoff volumes from individual rainfall events, then E(v_r), runoff with different return periods and E(v_l) calculated using the derived equations are expected to be quite accurate as well. Thus, in the following, we will verify the accuracy of Equation (3) using observed data from individual rainfall events.

Webber et al. (2010) measured runoff from an experimental composting site resulting from six rainfall events. Data contained in Webber et al. (2010) is more complete than those contained in Kalaba et al. (2007), that is why data contained in Webber et al. (2010) is used in this study. The composting pad studied by Webber et al. (2010) is 0.13 hectares in size and is comprised of fly ash compacted with heavy equipment and graded to approximately 2% in slope to augment drainage. The pad was used for windrow composting of livestock manure materials and is located in Ames, central Iowa, the United States. Fly ash is a byproduct derived from combustion of bituminous coal at power generating stations. The composting pad made of fly ash was observed to crack and slough off the pad surface during the experimental period (Webber et al., 2010). Cracks in the fly ash pad increased preferential flow pathways and infiltration losses of rainfall. Since pad areas covered by windrow piles were subjected to a lesser degree of damage during the experimental period, it was found that rainfall losses over areas covered by windrow piles are less than that over bare pad areas.

The pervious nature of the fly ash composting pad can actually be modeled using Equation (1) as well, although Equation (1) was originally written for impervious pads. This is because with S_{di} replaced by S_{ma}, Equation (1) is the same as Equation (2) whereas Equation (2) was written for windrow covered areas which are essentially pervious. So with S_{di} defined and calculated for pervious pad the same way as we defined S_{ma} for windrow-covered areas, Equation (1) can also be used for bare pad areas which are pervious. In order to use Equation (3) which calculates the area-weighted summation of runoff from bare pad and windrow-covered areas, all we need to do to ensure the applicability of Equation (3) for pervious pad cases is to compare S_{di} and S_{ma} instead of taking S_{di} as always less than S_{ma} as a default. For pervious pad cases, if S_{di} is still less than or equal to S_{ma}, Equation (3) still applies and nothing needs to be changed. If $S_{di} > S_{ma}$, we may treat windrow-covered areas as impervious areas (since it is indeed less permeable than bare pad areas) and rename S_{ma} as S_{di}; the bare pad areas can be treated as if it is windrow-covered areas of a composting site with impervious pad, its original S_{di} is renamed as S_{ma}. The *h* value should also be calculated according to this change of designations of impervious and windrow-covered areas, then Equation (3) and all subsequent equations remain valid for cases where the composting pad is pervious and the maximum rainfall infiltration/storage loss from the bare pad areas is larger than that from the windrow-covered areas.

For the case study, no measurement was available that can be used to directly estimate the values of S_{di} and S_{ma}. In modeling the runoff generation over the composting site, Webber et al. (2010) used the USDA NRCS runoff curve number (*CN*) method (Fangmeier et al., 2006). Different *CN* values for bare pad and windrow-covered areas were estimated and verified by Webber et al. (2010). Based on the definition of *CN*, the corresponding maximum soil moisture storage deficit at the time runoff begins (in mm) can be calculated as:

$$S_D = \frac{25,400 - 254CN}{CN} \tag{12}$$

In calculating the total rainfall losses, the NRCS method usually estimates the initial abstraction as $0.2S_D$ (Fangmeier et al., 2006). The total rainfall losses from an individual rainfall

Table 5. Example Calculations Verifying the Accuracy of the Event-Based Rainfall-Runoff Model

Event ID	Rainfall depth (mm)	Windrow area CN/S_{di} (mm)	Fly ash pad area CN/S_{ma} (mm)	Equation (3) estimated runoff (liter)	Observed runoff (liter)	Relative difference between estimation and observation (%)
W1, W2	35, 81	93/19	84/48	4978	5032	-1.1
W3	61	93/19	88.6/33	3631	3661	-0.82
D1, D2	46, 33	91/25	86/41	718	686	4.7
D3	46	92/22	86/41	749	744	0.62

event is thus $1.2S_D$. Therefore, on a rainfall event-by-event basis, it is equivalent to say that the S_{ma} (or S_{di}) as required by Equation (2) (or Equation (1) if S_{di} is calculated) is approximately equal to $1.2S_D$ where S_D can be calculated using Equation (12). Equation (3) can then be used for cases where the CN values are assigned/estimated for composting pad areas. Table 5 shows the event IDs of the six rainfall events monitored by Webber et al. (2010), their rainfall event volume, the estimated S_{di} and S_{ma} values, as well as Equation (3) predicted and observed runoff volumes. As explained earlier, since the originally estimated S_{di} is greater than S_{ma}, they were renamed in Table 5. The value of h was calculated based on measurements and the revised designation of impervious and windrow-covered areas.

In Table 5, Events W1 and W2 are combined together and have the same CN values. This is because W1 and W2 were used for calibration and W3 was used for validation in the study of Webber et al. (2010) and they did not report separately the results for W1 and W2, only a total runoff volume from W1 and W2 was reported. Results for Events D1, D2 and D3 were reported the same way in Webber et al. (2010). Due to differences in antecedent conditions, the CN values are different for different events; nevertheless, the exact CN value for each individual event was not reported in Webber et al. (2010), only ranges of values were reported separately for bare pad and windrow-covered areas. The CN values listed in Table 5 are selected from within the reported ranges of values. With these CN values, the corresponding S_{di} and S_{ma} values are calculated using Equation (12). Based on the directly calculated h and the estimated S_{di} and S_{ma} values, Equation (3) is then used to calculate the runoff event volume resulting from each of the six monitored rainfall events. Table 5 shows that Equation (3) estimated runoff event volumes are very close to the observed values. This verifies that the event-based rainfall-runoff model proposed in this study may provide fairly accurate estimates of runoff event volumes.

8. Summary, Conclusions and Future Studies

Derived and tested in this paper are analytical equations describing the probability distribution of runoff event volume and the expected value of leachate volume from open windrow composting sites. Derivation of the analytical equations is based on the following four main assumptions:

1) Exponential probability density functions provide good fits to the histograms obtained from frequency analysis of rainfall event volume, rainfall event duration, and inter-event time.
2) The maximum amount of rain water that can be absorbed by windrow piles during each rainfall event is the same, equaling the average maximum amount of rain water that can be absorbed over the long term per rainfall event (denoted as S_{ma}).
3) S_{ma} can be estimated based on an approximate long-term water balance where the maximum total amount of rain water absorbed by the windrow piles is equal to the maximum total amount of water depleted from the windrow piles.
4) The rates of leaching, evaporation, and consumption of water absorbed by composting materials during inter-event times are constant. For aerobic digestion processes, the rate of production of water inside composting materials is also constant.

Assumption (1) has been evaluated and adopted by many researchers (Eagleson, 1972, 1978; Adams et al., 1986; Guo and Adams, 1998; Adams and Papa, 2000; Guo, 2001; Guo and Baetz, 2007) for many different locations. The maximum amount of rain water that can be absorbed by windrow piles changes from event to event due to varying antecedent conditions. This event-by-event difference is eliminated with the introduction of Assumption (2). Using fixed initial conditions when applying different design storms, Assumption (2) was actually adopted as well when the design storm approach is used to estimate runoff event volumes of different return periods. Assumption (3) provides a way of estimating an approximate, long-term average maximum amount of rain that windrow piles can absorb per rainfall event. This approximate value reduces the inaccuracies introduced by Assumption (2). When used together, Assumptions (2) and (3) would provide as reasonably accurate results as the design storm approach. Frequent turning of the windrow piles as a part of the normal operation makes Assumption (4) acceptable.

The example calculation results illustrate quantitatively the influence of the various composting site characteristics on the generation of runoff and leachate. The physically reasonable results justify the adoption of the simplifying assumptions. Real case comparisons also show that the event-based rainfall-runoff model proposed and used in this study can provide fairly accurate estimates of runoff volumes. With the parameters of a site such as h, S_m, R_l, R_e, and R_c estimated, the analytical equations may serve as a tool to size preliminarily detention ponds for the treatment of runoff from composting sites. In future research, field or lab data may be used for the estimation of some of the parameters (e.g., S_m, R_l, R_e, and R_c), results from some of the analytical equations [e.g., Equations (6) and (11)] may be validated against measured values. Snowmelt generated runoff events can also be investigated in future studies.

Only a limited number of studies have been conducted so far to measure or model the runoff and leachate volumes from open window composting sites. Long-term observed flow data is very difficult to find for any composting site. The equations derived here provide an easy-to-use alternative to continuous simulation of the hydrologic processes associated with the operation of composting sites. More detailed deterministic urban stormwater simulation models are still required for composting sites since continuous simulation results would be theoretically more accurate than both the design storm and the analytical equation results. This is because antecedent conditions for each individual rainfall events are all calculated by the continuous simulation model itself by considering processes occurring during inter-event dry periods. However, both design storm and continuous simulation modeling of composting sites have been hampered by a lack of basic knowledge regarding the rainfall-runoff relationships for compost windrows (Wilson et al., 2004). In the future, the accuracy of the proposed analytical equations can be verified further by comparing with continuous simulation results. For a specific site, sensitivity and uncertainty analyses similar to what we commonly do for deterministic models may be conducted for the probabilistic models in order to quantify the effect of uncertainty of the input parameters on the results of interest.

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