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EVALUATION OF A DROPLET SPRAYING/MISTING SYSTEM TO ENHANCE LEACHATE EVAPORATION AND REDUCE LEACHATE TREATMENT COSTS: A CASE STUDY AT THE THREE RIVERS SOLID WASTE AUTHORITY LANDFILL

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ABSTRACT

Three Rivers Solid Waste Authority (TRSWA) operates a MSW landfill outside Jackson, South Carolina at which leachate is stored in a collection pond then trucked to a local wastewater treatment plant (WWTP) for treatment. This landfill operates a droplet spraying/misting system (referred to as the Lilypad system) to enhance leachate evaporation and ultimately reduce the quantity of leachate in the pond that requires subsequent treatment. Little work investigating the efficacy in using such a system to enhance leachate evaporation has been reported. The overall goal associated with this study was to quantify the amount of evaporation enhanced by the droplet spraying system and evaluate how the economics of the enhanced leachate evaporation compare to hauling leachate to a WWTP. This was accomplished by performing a water balance on the pond, developing a simple model to link leachate evaporation to the droplet spraying system, and performing an economic evaluation of the system. Overall, results from this work indicate the use of a droplet spraying/misting system to enhance leachate evaporation at on-site storage/collection ponds is effective, resulting in between 2.1 to 2.6 times more evaporation than what would occur naturally. In addition, the economic evaluation of this system indicates that operating the Lilypad system at maximum speed/flow for the greatest number of hours results in saving up to 7% of the total cost when compared to no operation of the Lilypad system.

1. INTRODUCTION

Treatment of leachate from municipal solid waste (MSW) landfills is necessary but can often be complicated and costly. Evaporation is a technique that is gaining attention and is commonly used at large-scale facilities in the United States to treat and/or reduce the volume of leachate. Significant leachate evaporation (as much as 90%) generally requires the use of heaters and evaporators, and condensers to collect the resulting condensate. A small volume of concentrated residuals results from this process, which is often treated via reverse osmosis and filtration to achieve high contaminant removals (Birchler et al., 1994; di Maria et al., 2018a; di Palma et al., 2002; Ettala, 1998). Several commercial systems of this type are available. While evaporation rates in such systems are often high, the cost associated with construction and operation of these systems can make such treatment prohibitively expensive (Birchler et al., 1994; Ettala, 1998).

Partial evaporation of leachate contained in on-site storage areas (e.g., ponds or tanks) has the potential to result in sufficient evaporation to significantly reduce overall leachate treatment costs. Although natural evaporation from leachate collection/storage ponds does occur, it is limited and depends on site-specific parameters, such as wind speed, leachate temperature, and pond surface area (Harwell, 2012). Using mechanical means to enhance leachate evaporation has been shown to be advantageous. Benyoucef et al. (2016) created and evaluated the use of a system to enhance evaporation from a small-scale basin. This enhanced evaporation system involved increasing solar radiation absorption, agitation, and aeration (Benyoucef et al., 2016). Results from this work indicated that this sys-

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tem increased evaporation by three to five times in the summer and winter, respectively, and suggests that enhancing evaporation is possible and may be quite advantageous. Several commercial mechanical aerators are available.

The Three Rivers Solid Waste Authority (TRSWA) MSW landfill located in Jackson, South Carolina (USA) produces an average of approximately 152,300 L of leachate per day, which is stored in a collection pond then trucked to a local wastewater treatment plant (WWTP) for treatment. This landfill operates a droplet spraying/misting system to enhance leachate evaporation, ultimately reducing the quantity of leachate in the pond that requires subsequent treatment. Little work investigating the efficacy in using such a system to enhance leachate evaporation has been reported in the peer reviewed or gray literature. The majority of the work investigating evaporation from droplet sprayer systems has focused on evaporation losses from irrigation water. These studies have reported evaporation losses ranging between 2% and 40% of water passing through these systems (Lorenzini, 2002; McLean, 2000; Stambouli et al., 2013; Tarjuelo et al., 2000; Uddin and Murphy, 2020), suggesting such systems do have the potential to promote signification leachate evaporation. The objectives of this study were to:

(1) conduct a water balance on the leachate collection and storage pond to determine the amount of total evaporation occurring;
(2) quantify the amount of evaporation enhanced by the droplet sprayer system;
(3) understand how changes in Lilypad operation (e.g., operational time, basket speed) influence leachate evaporation;
(4) evaluate how enhanced leachate evaporation may influence concentration of the leachate; and
(5) evaluate how the economics of the enhanced leachate evaporation compares to hauling leachate to WWTP.

2. MATERIALS AND METHODS

2.1 Description of the leachate collection and storage pond and evaporation system

Leachate from the TRSWA MSW landfill is collected via a series of leachate collection pipes located in seven active landfill cells and is pumped via six sump pumps into an on-site leachate storage pond. Leachate is stored in this pond until its removal by tanker truck to an off-site WWTP. The leachate pond is trapezoidal, with a bottom base surface area of approximately 21 m^2, a top base surface area of approximately 3,716 m^2, and a maximum depth of 5 m. When full, the leachate pond can hold approximately 10.2 million liters of leachate. The entire pond is lined with a High-Density Polyethylene (HDPE) geomembrane. This liner is trenched into the embankment such that runoff from the surrounding ground surface cannot enter the storage pond. Possible sources of inflow to the pond include flow from the sumps, flow from a condensate line (approximately 19,000 L/month) and precipitation. Possible outflows from the pond include evaporation and removal to trucks for off-site transport to a WWTP.

A Typhoon Lilypad evaporation system (New Waste Concepts, Inc.) that utilizes a droplet spraying/misting approach to enhance evaporation is installed in the leachate pond (see the supplementary material for a figure and pictures illustrating this system). This system consists of 8 nozzle heads, or baskets, mounted on poles located on a dock in the middle of the pond. Leachate is pumped through these baskets and subsequently sprayed, as a fine mist, into the air over the pond surface, promoting leachate evaporation.

The Lilypad data recording system records pond hydraulic data (e.g., flows in and out and pond depth), Lilypad system data (e.g., system run time, flow through the system), and climatological data (e.g., barometric pressure, temperature, rainfall, wind speed) from an on-site weather station every 15 minutes. The Lilypad system currently operates under several site-imposed constraints:

(1) all baskets operate at their maximum speed during the day (13 hours) and operate at 26% of their maximum speed at night.
(2) if the two-minute wind speed (as measured by the Lilypad sensors) during the daytime is 8 km/h or above, the baskets slow to 80% of their maximum speed during the 15-minute interval which data are recorded and if the two-minute wind speed is 16 km/h or above, the baskets slow to 70% of their maximum speed during that recording interval. The nighttime basket speeds are unaffected by the wind speed.
(3) relative humidity readings over 90% trigger speed reductions.

2.2 Determination of actual total evaporation

Estimating total evaporation from the leachate collection pond over the entire 18-month study period (beginning in January 2019 and ending in June 2020) was a goal of this study. Over this period, the depth and surface area of the pond fluctuated, with total pond volumes ranging from approximately 1.9 to 6.8 million L (data shown in the supplementary information).

The actual total evaporation occurring in the leachate collection and storage pond per month was determined by using a water balance approach, as described in Equation (1).

$$E=I-O-\Delta V \quad (1)$$

where E is the actual total monthly evaporation (L), I is the total monthly inflow of leachate to the pond from the sumps, condensate line, and precipitation (L), O is the total monthly outflow from the pond that is trucked to a local wastewater treatment plant (L), and ΔV is the total monthly change in pond volume (L).

All water balances were conducted on a monthly basis. The use of a monthly time-step in water balance applications is supported by studies conducted by Ivezic et al. (2017) and Wang et al. (2011). Wang et al (2011), for example, compared the use of monthly and daily water balance models to simulate runoff in large Australian catchments. Results from their study indicated that the use of monthly water balance models was sufficient if interested in monthly, seasonal, and/or annual runoff volumes or in instances in which daily data are not available. The goal of this study was to determine total evaporation on a monthly-basis over the entire 18-month study period, thus a monthly time step was adequate.

To complete the water balance, data were obtained from either on-site monitoring efforts or published electronic data sources. For some parameters, multiple data sources were available. Therefore, to account for the variability associated with changes in parameter values from each data source, two water balances were conducted. Estimate 1 was calculated using mostly on-site and manually-obtained data, while estimate 2 was calculated using data obtained from a combination of on-site and published electronic data sources (Table 1).

For both estimates (Table 1), the inflow to the pond from the sumps was determined using manual readings from totalizing impeller meters located on each of the sumps. Although this type of device is known to clog, because they were checked daily, any clogging was found early and mitigated quickly. The total gallons entering the pond from each sump were recorded from each meter every morning. The volume of leachate entering the pond each day was calculated as the difference between two successive measurements. It was assumed that the operating time between these measurements was 24 hours. If a daily reading was missed because of a weekend, holiday, and/or lack of personnel, it was assumed the volume entering the pond did so equally between measurements. All daily inflows were summed over the month to yield a total monthly inflow of leachate.

The inflow from the gas condensate line was assumed to remain constant (19,000 L/month) for both estimates. Based on information obtained from landfill personnel, the inflow of gas condensate to the leachate pond remained relatively constant. Daily gas condensate values were summed over the month to yield a total monthly inflow.

The inflow to the pond from precipitation differed between the two estimates. For estimate 1, on-site rain gauges were used to estimate precipitation. The depth of precipitation was determined from the site rain gauge and converted to a volume using the top leachate pond surface area. A different method to measure monthly precipitation was used in the second estimate (estimate 2, Table 1) because of potential errors with on-site rain gauges. For the second estimate, daily precipitation data were taken and averaged from the National Oceanic and Atmospheric Administration (NOAA)'s Climate Data Online tool (https://www.ncdc.noaa.gov/cdo-web/) and the National Air and Space Administration (NASA)'s POWER Data Access Viewer (https://power.larc.nasa.gov/data-access-viewer/) and summed over the month. The NOAA tool does not allow the user to select a specific map location, instead it uses data from individual weather stations. Therefore, the weather station located at Augusta's Bush Field Airport (33.36°, -81.96°) was selected for precipitation from the NOAA tool. This weather station is approximately 21 km from the landfill site. The NASA tool does not have data for individual weather stations, but allows the user to select a specific spot on a map and provides interpolated data for that particular location. Thus, when using the NASA tool, the landfill site (33.26°, -81.735°) was selected. Precipitation data for all sources are provided in the supplementary material.

TABLE 1: Summary of estimate input sources.

Parameter	Estimate 1	Estimate 2[1]
Inflow	Manual readings (on-site, manual)	Manual readings (on-site, manual)
Precipitation	Site rain gauge (on-site, manual)	Average of NOAA and NASA data (published data)
Outflow	WWTP invoicing (on-site, manual)	WWTP invoicing (on-site, manual)
Pond volume	Manual depth readings (on-site, manual)	Lilypad system reported depth readings (on-site, electronically obtained)

[1] *information in parentheses indicates how/where data were obtained*

The method used to estimate the change in pond storage also differed between estimates. For estimate 1, daily manual pond depth measurements were taken by landfill personnel. The monthly change in pond storage was calculated based on manual depth readings taken once at the beginning and once at the end of each month. For estimate 2, the change in pond storage was determined by subtracting the average pond depths recorded by the Typhoon Lilypad evaporation system (New Waste Concepts, Inc.) during the first day of the month and the last day of the month.

The only measured outflow from the pond is leachate leaving to a local WWTP. These volumes were determined based on reported volumes received by the WWTPs. Throughout this study, leachate was taken to two separate WWTPs. At one WWTP, the volume of leachate was determined based on truck weight and leachate specific gravity. At the other WWTP, leachate volume was assumed to be constant for each truckload.

The average of the two evaporation estimates was used as the estimated actual total evaporation at the site. Since both estimates have the potential for some error, averaging the two calculated values was determined to be the most appropriate method of determining an overall actual total evaporation estimate at the pond. Evaporation estimates for each estimate are included in the supplementary material.

2.3 Determination of natural and enhanced evaporation

To determine the impact the Lilypad system had on evaporation from the leachate collection and storage pond, it was important to distinguish between evaporation that occurred as a result of climatological factors alone, assuming no Lilypad system was installed (referred to as natural evaporation, NE), and the enhanced evaporation that resulted from the operation of the Lilypad system (referred to as enhanced evaporation, EE). Together, these components represent the actual total evaporation (TE) from the pond, as described in Equation (2).

$$TE=NE+EE \tag{2}$$

where TE is actual total evaporation (L) observed at the site, NE is the natural evaporation (L), and EE is enhanced evaporation (L).

The natural evaporation from the leachate collection and storage pond was modeled using the US Weather Bureau (USWB) evaporation model (Harwell, 2012). This method uses climatological data (e.g., wind speed, temperature, relative humidity, solar radiation) to estimate daily, depth-based evaporation (cm/day) from the pond. Because not all necessary data for this model is collected by the Lilypad system, data were collected from other published sources.

The daily average site climatological data were taken from an on-site weather station, the National Oceanic and Atmospheric Administration (NOAA)'s Climate Data Online tool (https://www.ncdc.noaa.gov/cdo-web/), and/or the National Air and Space Administration (NASA)'s POWER Data Access Viewer (https://power.larc.nasa.gov/data-access-viewer/) using procedures described previously. Because not all climatological data were available at the previously used weather station, the weather station located at the Aiken Municipal Airport (33.65°, -81.683°) was selected from the NOAA data viewer for relative humidity, wind speed, and ambient temperature (44 km from the site). The actual landfill site (33.26°, -81.735°) location was selected for use in the NASA tool, as described previously.

Data used for the site temperature represent a daily average from the two aforementioned published sources and data collected from the Lilypad system. The wind speed and relative humidity used were daily averages from the NOAA and NASA databases, while the solar radiation data were daily averages taken from the NASA database. Data for all climatological parameters used in this study are shown in the supplementary material. The daily average pond surface area, computed based on pond geometry, was required to convert evaporation measurements obtained from the USWB model to an evaporation volume. The monthly enhanced evaporation resulting from the Lilypad system was determined by subtracting the monthly natural evaporation from the monthly total evaporation (see Equation (2)).

2.4 Development of an empirical model to predict total evaporation

An empirical model linking Lilypad operation with evaporation enhancement was desired. Thus a parameter was developed to relate the actual total evaporation at the site with the operation of the Lilypad system using the basket speed (rpm), percent of time the baskets were operational, and volume of leachate passed through the baskets (L). Basket speed and leachate volume control the size of the droplets expected in the mist and amount of leachate passing through the system. This parameter describes the daily contribution of each basket (BF_i) to enhanced leachate evaporation and is shown in Equation (3).

$$BF_i = (BE) \times \left(\frac{\frac{\sum_{i=1}^{n} BS_i}{n}}{Max.Speed} \right) \times \left(\frac{\sum_{i=1}^{n} BskV_i}{Max.Volume} \right) \tag{3}$$

where the basket operational efficiency (BE) is the fraction of 15-minute intervals per day that the individual basket is operating. The basket speed (BS, rpm) is represented by average daily individual basket values calculated over the number of 15-minute intervals per day, n. The max speed and max volume represent the maximum values achievable per basket. The basket volume (BskV, L) was not reported per basket and was therefore calculated per basket as a percentage of the total volume through the system per day, proportional to the operational efficiency of each basket.

The daily BF for each basket was summed and used to adjust the daily NE to ultimately describe the total predicted daily evaporation (including enhancement from the Lilypad system), as described in Equation (4).

$$TE_{pred} = NE * \left[\left(k * \sum_{i=1}^{b} BF_i \right) + 1 \right] \tag{4}$$

where TE_{pred} is the predicted total daily evaporation (L), NE is the daily natural evaporation determined from the USWB model (L), b represents the number of baskets in operation, and k is a fitting factor. Importantly, using the evaporation relationships previously defined in Equation (1), the enhanced evaporation (EE), defined as the volume of total evaporation due to operation of the Lilypad system, can be determined.

The value of the fitting factor in Equation (4) was determined by using a non-linear least squares regression algorithm in Python (v. 2.7) from functions in the SciPy library. The sum of the squared errors (SSE), root mean squared error (RMSE), and a normalized RMSE (NRMSE) were calculated to evaluate the goodness of the fit for the factor. The SSE was determined using Equation (5), using monthly actual total evaporation (TE_{obs}, see Equation (1)) and the monthly predicted total evaporation (TE_{pred}, see Equation (4)).

$$\text{SSE} = \sum_{i=1}^{n} (TE_{pred,i} - TE_{obs,i})^2 \tag{5}$$

where, $TE_{pred,i}$ represents the predicted total monthly evaporation and $TE_{obs,i}$ represents the calculated actual total monthly evaporation. RMSE, which is an indication of mean distance between predictions and observations, was calculated as shown Equation (6).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (TE_{pred,i} - TE_{obs,i})^2}{n}} \tag{6}$$

where, n represents the number of observations. The NRMSE is the RMSE normalized by the average of the calculated enhanced monthly evaporation values.

3. RESULTS AND DISCUSSION

3.1 Natural evaporation

The calculated monthly depth-based natural evaporation ranges from approximately 7.6 cm/month to approximately 26.7 cm/month (Figure 1), which is similar to reported local pan evaporation data. NOAA (1982) reported monthly pan evaporation data for Blackville, South Carolina (approximately 45 km from the site) that ranged from 5.7 to 18 cm/month. These literature-reported pan evaporation data represent averages of at least 10 years' worth of data taken between 1956-1970 (NOAA, 1982).

As expected, the trend in the calculated monthly depth-based natural evaporation (cm/month, Figure 1) closely followed the climatological conditions of the site. As ambient temperature and solar radiation increased and decreased, so too did the calculated depth-based natural evaporation. Ambient temperature and solar radiation are the most seasonally dependent climatological conditions. Solar radiation generally followed a similar trend to ambient temperature, with the notable exception of March 2020, when solar radiation was much lower than previous months (see data in the supplementary material). This dip in solar radiation corresponded to a dip in the calculated depth-based natural evaporation that month, as shown in Figure 1. While relative humidity and wind speed also influenced the calculated natural evaporation, the changes in these parameters over time were not as pronounced as solar radiation and temperature, and therefore did not cause significant changes in the trend of calculated natural evaporation over time.

The monthly calculated volumetric-based natural evaporation ranged from 113,560 to 378,540 L, with the greatest evaporation occurring from May 2019 to September 2019 (Figure 1). This quantity of natural evaporation was between 3.2% and 11.3% of the average pond volume. This is higher than the evaporation seen by Sakita et al. (2016), who saw 1.6% monthly evaporation from a leachate storage pond located in Japan at a similar latitude (suggesting climate conditions may be somewhat similar). This difference in evaporation is likely because surface area of their pond was much smaller than the pond studied in this work (approximately 10% of the size of this pond) (Sakita et al., 2016). The trend of the calculated volumetric-based natural evaporation differed slightly from the calculated depth-based base evaporation, as illustrated in Figure 1. These differences were mostly due to changes in the pond surface area observed over this time period (pond surface areas can be found in the supplementary information). Evaporative losses are sensitive to pond surface area; smaller areas will result in less evaporation. The influence of pond surface area on evaporation is taken into account in this water balance model. Table 2 contains the total natural evaporation determined to occur at this site.

It is important to note that the use of off-site climatological parameters used to determine the natural evaporation may result in errors. When site climatological readings were used by McJannet et al. (2013), the percent difference between actual and predicted evaporation was 12% compared to 27% when climatological readings from a station just over two miles away were used to calculate predicted evaporation (McJannet et al., 2013). Other errors associated with predicting the natural evaporation may also occur. Because this leachate collection pond is small (surface area is less than 50 acres), air passing over the pond surface may not have sufficient time to reach an equilibrium with the surface of the water, resulting in less accurate evaporation predictions (Condie & Webster, 1997; McJannet et al., 2013; Rosenberry et al., 2007).

TABLE 2: Summary of calculated evaporation at the site over the study period.

Evaporation Type	Based on Actual Data[a]	Based on Model Fit[b]
Total Natural Evaporation (L)[c]	4.03 x 10^6	4.03 x 10^6
Total Evaporation (L)	10.5 x 10^6	8.4 x 10^6

[a] *based on an average of methods 1 and 2 (Table 1)*
[b] *using the model in Equation (4)*
[c] *natural evaporation does not change based on method used to determine total evaporation*

3.2 Actual total evaporation

3.2.1 *Actual Total Evaporation*

As described previously, two actual total evaporation estimates based on slightly different approaches (Table 1) were determined. The average of these estimates was used as the actual total evaporation occurring on-site (data for each estimate are shown in the supplementary materials). Time series data associated with the inflows and outflows from the pond are shown in the supplementary information. The percent difference of the majority of these monthly values was less than 30%. However, during four months, the percent difference was greater than 100%. While some variations in precipitation measurements and

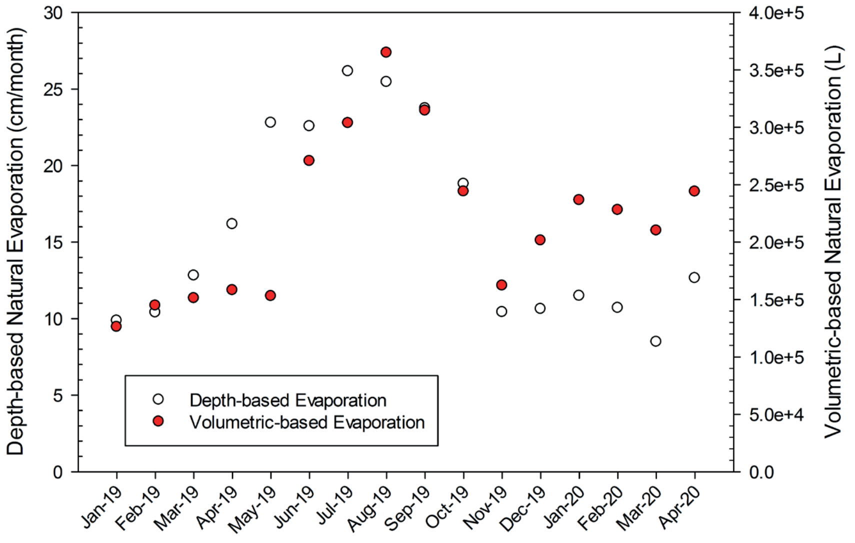

FIGURE 1: Predicted depth- and volume-based natural evaporation.

pond depth likely contribute to these differences, another potential source of error is related to the timing of the pond depth measurement and precipitation accumulation. Because the data for the water balance were recorded as daily totals, it is unknown if the pond depth measurements were taken before or after precipitation accumulated the pond. In months with large differences between the two estimated evaporation volumes, there was a large difference between the site-obtained and published precipitation data and/or there was appreciable precipitation occurring on the first and/or last day of the month, when the pond depth measurement was recorded.

In addition, it is important to note that there is significant monthly oscillation in these evaporation estimates, especially from December 2019 to June 2020, as shown in Figure 2. The exact cause of this oscillating trend is unknown. It is important to note that this trend appears to correlate with changes in pond operation, as shown in Figure 3. Figure 3 shows the total monthly liquid entering and exiting the pond over the study period. In the months with low actual total evaporation (e.g., December 2019 and February 2020), the pond depth was significantly larger at the end of the month than the beginning. In December 2019, for example, the pond was almost 0.61 m deeper at the end of the month than the beginning. Conversely, in the months with large evaporation (e.g., January and March 2020), the pond depth decreased approximately 0.61 m during the month. Corresponding to these observed changes in depth, the volume of leachate entering and exiting the pond changed during these months. From December 2019 to June 2020, the volume of leachate entering and exiting the pond fluctuated more than that observed prior to this period. Pond inflows and outflows from December 2019 to March/April 2020 were

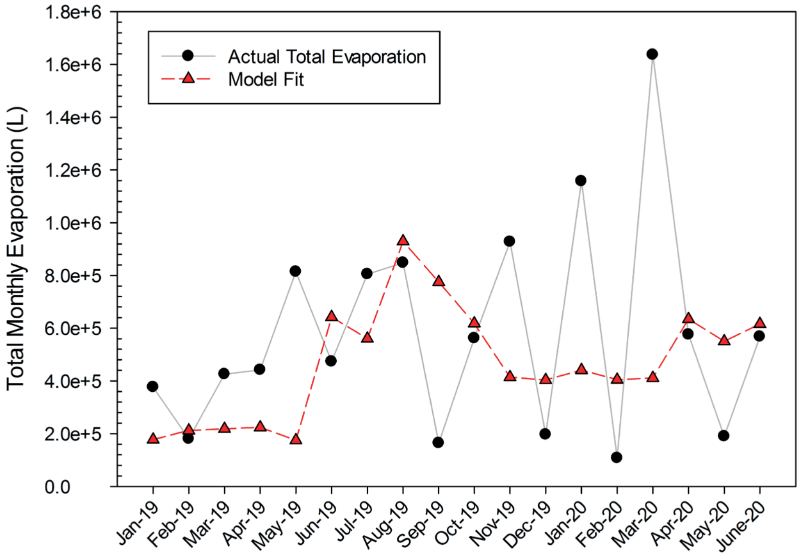

FIGURE 2: Comparison between the actual evaporation and total evaporation model fit. All lines are present to illustrate trends in these data.

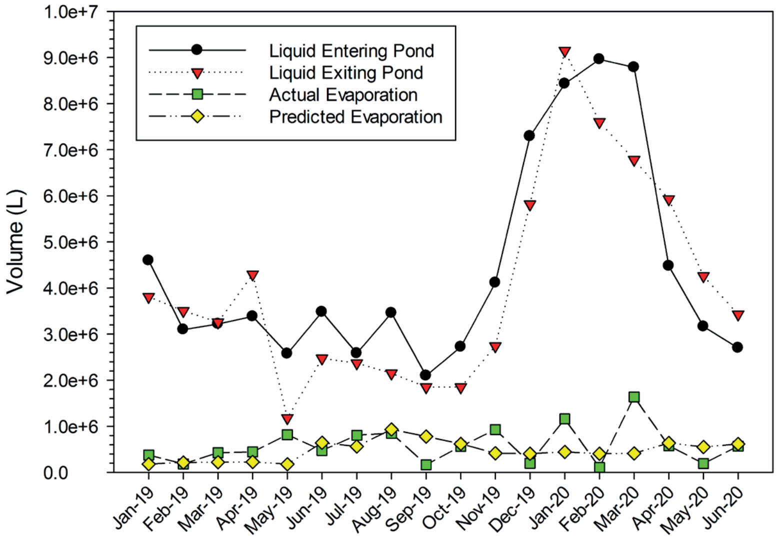

FIGURE 3: Total monthly flows entering and exiting the leachate pond.

higher than seen before this period, and pond inflows and outflows decreased significantly from April to June 2020. The exact cause for these oscillating trends, however, has not been identified.

Using this approach, the total evaporation at the site was determined to be 10.5 x 10^6 L (Table 1). The trend associated with this total evaporation is shown in Figure 3. Based on these data, there does not appear to be a seasonal trend associated with total evaporation.

3.2.2 Total Evaporation Model

The actual evaporation, Lilypad operational information, and the calculated natural evaporation were used to develop an expression to predict total evaporation on the site using Equation (4). The resulting NRMSE associated with the fit was 0.7646. Figure 2 illustrates the fit of the monthly actual total evaporation. Errors associated with the fitted monthly values range from 8% to 130%, suggesting this model should be used cautiously when predicting specific monthly volumes of evaporation. The erratic changes in the actual total evaporation observed from September 2019 to June 2020 are not well represented by this fit and likely contribute to the poor overall fit of these data. The fit to these data does, however, represent an averaging of these highs and lows.

Although monthly estimates appear to differ significantly, it is important to point out that total evaporation volumes do not (Table 2), supporting the use of this model for predicting long-term evaporation. When comparing the total evaporation associated with the model fit to the total actual evaporation over the 18-month study period, the difference was only approximately 22% (Table 2). This observation is consistent with what has been reported previously. McJannet at al. (2013) reported that while daily or monthly predictions may vary more significantly from actual evaporation, long-term variations are less pronounced (McJannet et al., 2013). Overall, these results suggest this model can be used to estimate long-term volumes of leachate evaporated.

3.3 Enhanced evaporation

The volume of leachate evaporated resulting from the Lilypad system was determined by subtracting the monthly natural evaporation from the monthly total evaporation. Results from this analysis are presented in Table 3 and the time series of these data can be found in the supplementary material. Total evaporation as a result of the Lilypad system ranged from 4.4 to 6.8 x 10^6, depending on whether the enhanced evaporation was determined using actual data or was based on the fit of the total evaporation model. These two average values differ by approximately 43%, suggesting that the model developed to predict total evaporation may be used to only provide order of magnitude estimates of total and enhanced evaporation. Monthly enhanced evaporation volumes ranged from 0 to 1.4 x10^6 L, depending on whether the enhanced evaporation was determined using actual data or was based on the fit of the total evaporation model.

TABLE 3: Summary of enhanced evaporation (EE).

	Enhanced Evaporation based on:	
	Site Data	**Model Fit**
Average Monthly EE (L/month)	375,080	243,080
% of NE[a]	167	109
Total EE (L)	6.75 x 10^6	4.38 x 10^6
% Liquid Lost[b]	10.0%	6.5%

[a] *% NE = (Volume EE/Volume NE)*100*
[b] *% Liquid Lost = (Volume EE/Volume of Flow through System)*100*

The trend of enhanced evaporation based on actual data does not result in a defined trend that shows any dependence on season, time of the year, or Lilypad operation (described as BF in Figure 4). The basket factor increases from May 2019 to the end of the study, after which the Lilypad system was under maintenance and subsequently upgraded. The volume of enhanced leachate evaporation using the fit of the total evaporation model, however, does show seasonal dependence, consistent with that reported by others.

Many studies have concluded that air temperature plays a role in the evaporation from sprayed droplet systems. Lorenzini (2002) found that as air temperature increased from 21°C to 27°C, evaporation from a sprinkler system, calculated as difference in volume of water passing through the system and volume of water measured on the ground surface, increased from 4% to 8% (Lorenzini, 2002). When air temperature at the site increased from 21°C to 27°C in this study, there was approximately a 20% increase in predicted enhanced evaporation, a greater increase than that reported by Lorenzini (2002), which is likely due to differences in the studies. In Lorenzini (2002), only one sprinkler head was used and the study period was only 6 minutes.

Overall, these results indicate that the Lilypad system results in the evaporation of an additional 4.4 x 10^6 L (based on the model fit to total evaporation) to 6.8 x 10^6 L (based on site data) of leachate over the project period (18 months), resulting in 109% to 167% more evaporation than could be achieved without the Lilypad system (Table 3). Estimates of evaporation from these systems are often reported as percent of water loss, which is defined as the difference between the amount of water passing through a spray system and the amount of water that ends up on the ground (Mclean et al. 2000). Reported estimates of percent water loss from sprayed droplet evaporation systems range from 2% to 40% (Lorenzini, 2002; McLean, 2000; Ortíz et al., 2009; Stambouli et al., 2013; Tarjuelo et al., 2000; Uddin and Murphy, 2020; Hoque et al., 2010). This large range of water loss likely results from changes in study wind speed, humidity, air temperature, droplet size, sprayer speed, and flow through the system. Overall, the total volume of actual enhanced evaporation was 6.5 to 10.0% of the total volume of water passing through the system over the study period, depending on whether the enhanced evaporation was determined using actual data or was based on the fit of the total evaporation model (Table 3).

3.4 Impact of enhanced evaporation on leachate composition

Concentration of constituents in leachate is a concern during evaporation. To determine the impact enhanced evaporation has on leachate composition, a daily pond concentration factor (CF) was calculated. The CF is defined as the ratio of the volume of the pond as a result of only natural evaporation to the volume of the pond with both natural and enhanced evaporation ocurring. CFs greater than one indicate concentration of the leachate would occur due to enhanced evaporation. The largest daily CF determined during this study period was only 1.02, indicating that any concentration of constituents in the leachate due to evaporation are expected to be negligible. It is important to note that this ratio only accounts for a change in volume and assumes that no other transformation/pathway occurs that modifies pollutant concentration (e.g., ehnaced microbial processes or volatilization). One exception to this, for example, is ammonia. It should be noted that the evaporation system does play a role in changing the ammonia concentrations in the pond. As a result of evaporation, there is likely ammonia that is volatilized. Evaluating ammonia volatilization as a result of the Lilypad system is outside the scope of this paper. More information regrading the fate of ammonia in this syetm may be found in Drafts et al. (2023).

3.5 Understanding the influence of lilypad operation on predicted evaporation

Using the total evaporation model developed in this work (Equation (4)), several hypothetical scenarios were modeled to predict how changes in Lilypad operation may influence total and enhanced evaporation from the pond to develop Lilypad operational strategies. A series of hypothetical scenarios evaluating three operational changes were explored: (1) using temperature and humidity as system shut down criteria (scenario series B) and (2) pump speed/flow variations during the day and night (scenario series C). A base scenario describing how the system is currently operated (scenario A) was also conducted. Details associated with each of these scenarios are included in Table 4.

Specific factors varied in the modeled scenarios were relative humidity, air temperature, basket speed, and basket flow. Relative humidity values were averaged from the NOAA and NASA databases and air temperature values were averaged from NOAA, NASA, and site weather station data, as described previously. Because relative humidity and air temperature were determined via external databases that only reported average daily values, the scenarios were modeled on a daily basis only. Because the model uses daily values, windspeed was not used as an operational constraint. Relative humidity and air temperature

TABLE 4: Scenarios modeled to determine optimal operating conditions.

Scenario Description	Scenario ID	Daytime Basket Speed/ Flow (% of Maximum)	Nighttime Basket Speed/ Flow (% of Maximum)	Temperature Shutdown Point (°C)[a]	Humidity Shutdown Point (%)[b]
Current Conditions	A	100	26	na	90
Evaluate changing shutdown temperature and humidity	B.1	100	26	na	95
	B.2	100	26	na	90
	B.3	100	26	na	85
	B.4	100	26	na	80
	B.5	100	26	1.7	90
	B.6	100	26	7.2	90
	B.7	100	26	12.8	90
	B.8	100	26	18.3	90
	B.9	100	26	23.9	90
Modify basket speed and flow	C.1	100	100	na	90
	C.2	100	75	na	90
	C.3	100	50	na	90
	C.4	100	25	na	90
	C.5	100	12.5	na	90
	C.6	100	0	na	90
	C.7	100	26	na	90
	C.8	75	26	na	90
	C.9	50	26	na	90
	C.10	25	26	na	90
	C.11	12.5	26	na	90
	C.12	0	26	na	90

[a] *if temperatures were lower than this value, the system shutdown*
[b] *if values were higher than this value, the system shutdown*
na = not applicable; criterion does not exist

were modeled as system shutoffs. If the relative humidity or air temperature was above or below, respectively, a specified threshold, the system would be modeled as off for that day, meaning no enhanced evaporation was predicted. Basket speed and basket flow were varied according to each scenario. While basket speed and basket flow are independent of each other, in the scenarios it was assumed that as basket speed was adjusted flow was also proportionally adjusted. These system constraints were then used to determine the basket factor (Equation (3)), which was subsequently used in Equation (4) to predict total evaporation for this site.

3.5.1 Using Temperature and Humidity as System Shutdown Criteria

In scenario series B, different temperature and humidity values were explored as system shutdown criteria, as summarized in Table 4. These conditions were chosen so as to represent conditions at the site. If the humidity is greater or the temperature is less than the stated criteria, the system shuts down. The results from this analysis are presented in Figure 5. As shown, over the ranges investigated for this site, initiating and varying a temperature-related shutdown criterion has a more significant effect on total evaporation than changing the relative humidity system shutdown criterion over the conditions investigated in this study. It is important to note that these changes in shutdown criteria do not significantly alter the predicted total evaporation until extreme values are used as shutdown criteria. When compared to the base case (scenario A), the percent difference in predicted total evaporation is less than 10% when a humidity shutdown criterion of 95%, 90%, or 85% (scenarios B.1, B.2, and B.3, respectively) is instituted or when a shutdown criterion of 1.7°C and 7.2°C (scenarios B.5 and B.6 respectively) is instituted. These results suggest that implementing system shutdown criteria with relatively high humidity or with relatively low temperatures (e.g., Fall and Winter in South Carolina) has the potential to save some energy costs of running the Lilypad system while not resulting in significant changes in evaporation. The most significant decrease in predicted evaporation occurs with a temperature shutdown criterion of 23.9°C (scenario B.9), with a 40% difference in total evaporation when compared to the base case. Therefore, implementing a higher temperature shutdown criterion is not recommended.

3.5.2 Varying Pump Flow and Basket Speed

Another set of scenarios (scenario series C) was modeled to explore the effect of variations in flow through the system (pump flow) and basket speed on evaporation. For each scenario, as described in Table 4, daytime or nighttime speed/flow was varied as a percentage of the maximum operational speed/flow of the Lilypad system, where 100% is the maximum flow possible and 0% is no flow or operation. The first set of scenarios (C.1 – C.6) investigated the influence of changing speed/flow during the night while maintaining the daytime speed/flow at 100% of maximum capacity, while the second set of these scenarios (C.7 – C.12) investigated the influence of changing the flow/speed during the day while maintaining the flow/speed at night at approximately 26% of the maximum capacity. The results from these analyses are presented in Figure 6.

As expected, the scenario (scenario C.1) with the maximum flowrates during the day and night resulted in

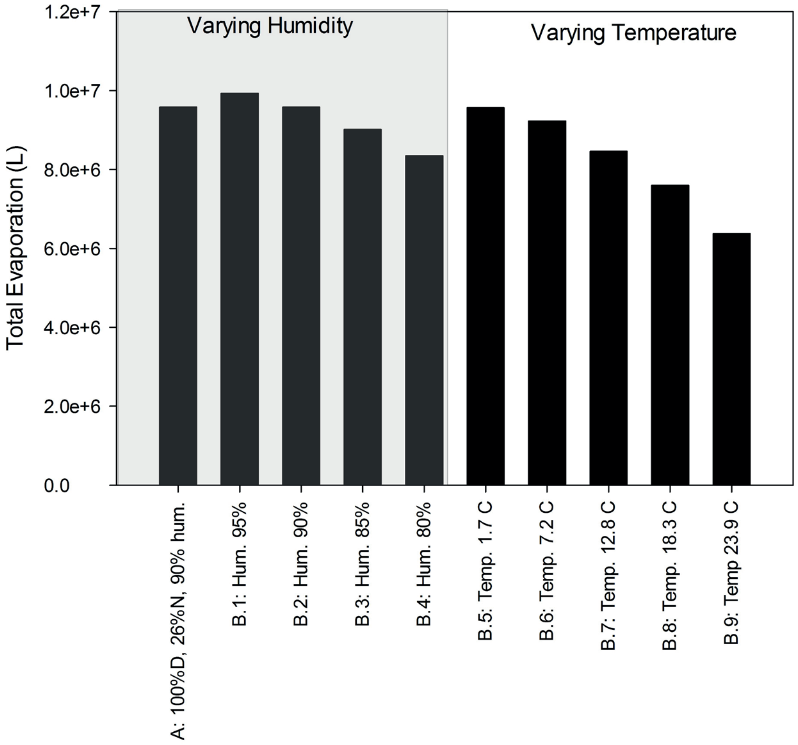

FIGURE 5: Total evaporation predicted over the study period at various humidity and temperature shutdown criteria.

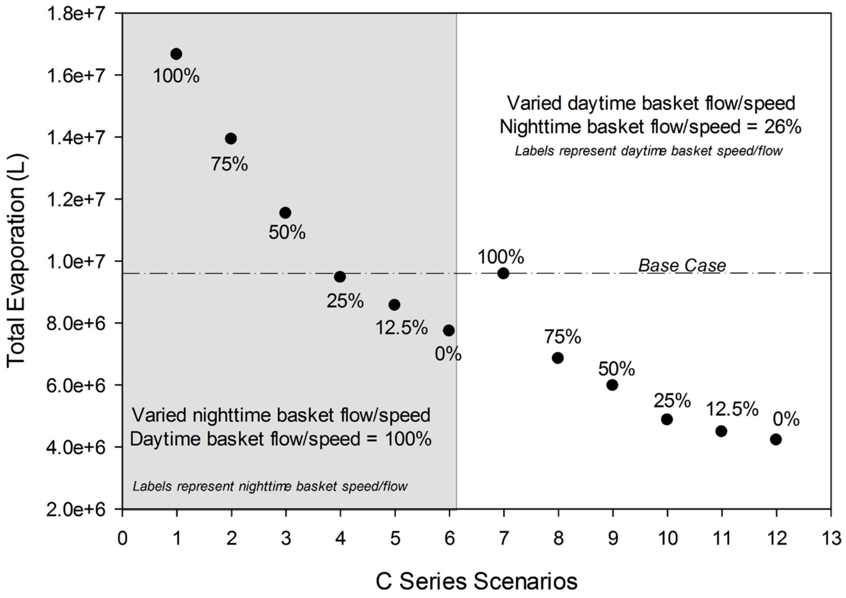

FIGURE 6: Total evaporation for scenarios varying daytime and nighttime speed/flow.

the highest total evaporation values. Varying the system capacity at night while keeping 100% capacity during the day results in significant changes in predicted evaporation, ranging from 16.7 x 10^6 L of predicted total evaporation when the system operates at 100% capacity at night to 7.7 x 10^6 L when the system is completely shut down at night (Figure 5). Operating the system at 100% capacity at night (scenario C.1) results in an 74% increase in total evaporation when compared to the base case. Alternately, increasing nighttime operation to just 50% capacity at night (scenario C.3) results in a 20% increase in total evaporation over the base case. Increasing the nighttime operating capacity from the base case, however, would result in increased electricity costs. If the landfill wished to save on electricity costs, reducing the nighttime capacity from the current 26% to 12.5% results in a reduction of only 10% in total evaporation.

When varying the basket flowrates and speeds during the day (keeping the rates constant at 26% of maximum capacity at night), the predicted total evaporation volumes are always lower than the base case, ranging from 9.6 x 10^6 L when operating 100% during the day (C.7) to 4.2 x 10^6 L when completely shut down during the day (C.12). Reducing daytime operations to 75% (C.8), results in a 29% reduction in total evaporation over the base scenario (A). When no daytime operation occurs (C.12), a negligible amount of enhanced evaporation is predicted over the study period. Therefore, it is recommended that the landfill maintain a 100% capacity during the day as much as feasible given the results observed in this scenario.

3.6 System economic evaluation

A simplified economic model was created to evaluate if and how the enhanced evaporation provided by the Lilypad system contributed to cost savings. This economic model used the total evaporation model developed in this work to estimate the total volume of leachate evaporated by the Lilypad system and therefore not taken to the WWTP for disposal, and also incorporated the capital and operational costs of hauling leachate to a WWTP and running the Lilypad system. A series of assumptions were made to simplify the system and facilitate a cost comparison between hauling and evaporating varied quantities of leachate. Some of the key assumptions are summarized in Table 5. More specific assumptions and costing information can be found in the supplementary materials.

The economic model was first used to estimate costs savings associated with the system as it is currently oper-

TABLE 5: Key assumptions made for the economic analysis.

Assumption	System	Type of Cost
Enhanced evaporation follows that described by the total evaporation model described in Eq. (2) – Eq. (5)	Lilypad System (Leachate Evaporation)	Operational
Two trucks/tanks used	Hauling	Capital
Lilypad system was expanded in 2019	Lilypad System (Leachate Evaporation)	Capital
Leachate is hauled to only 1 WWTP (40 miles roundtrip)	Hauling	Operational
Lilypad system has an 8-year lifespan with average use and 12 year lifespan with low use	Lilypad System (Leachate Evaporation)	Capital
Night-time operation of Lilypad system always at 25% of maximum speed/flow	Lilypad System (Leachate Evaporation)	Operational

ated. Based on the evaporation model, evaporation from the Lilypyad system was estimated contribute to 2.1 to 2.6 times more evaporation and therefore assumed to reduce the need to haul leachate by an equivalent amount. Due to the relatively low operation of the Lilypad system, the current system operates just below the break-even point of system ($712,686) with total costs of $748,276 and $725,550, respectively, resulting in annual cost savings ranging from -5% to -2%. These results indicate more aggressive operation of the Lilypad system is needed to realize appreciable cost savings.

Similar to the evaporation model, the economic model was used to explore the impact of several different operational scenarios on the total cost of removing a specified amount of leachate annually through either hauling or enhanced evaporation. The hypothetical scenarios explored two operational changes: (1) daytime pump speed/flow variations and (2) daily duration of Lilypad operation. To gain an understanding of the impact the Lilypad system has on system economics, the annual cost of leachate removal when operating the Lilypad system under these scenarios was compared to the annual cost of only hauling leachate to a WWTP. In these scenarios, the daytime pump speed/flow was varied as a percentage of the maximum operational speed/flow of the Lilypad system, where 100% is the maximum flow possible and 0% is no flow or operation. For each pump speed/flow value, four operational durations were selected that were representative of possible on-site working conditions (Figure 7). In each of these scenarios, if operational at night, the pump speed/flow remained constant at 25%.

The results from the modeling of these scenarios indicated that running the Lilypad system more frequently will contribute to greater cost savings (see Figure 7 and specific cost data in the supplementary materials). For each scenario, regardless of the total hours the system was operational, operating at 100% speed/flow resulted in the lowest cost (Figure 7). The scenario with the greatest total number of operating hours (16 hours day/8 hours night) resulted in the lowest annual cost of all scenarios. This scenario resulted in an annual savings of 7% when compared to not operating the Lilypad system. Overall, operation of the Lilypad system could contribute to a savings between $1.83 to $0.94 per thousand L of leachate managed. These results suggest that operating the Lilypad system to maximize leachate evaporation can be economically beneficial, despite the upfront capital costs to install the Lilypad system.

The model was also used to evaluate where operation of the Lilypad system was equivalent to the hauling only option (e.g., no Lilypad system in operation), or the break-even point for Lilypad operation. Based on the modeled scenarios the system will break-even between at 25% of maximum speed/flow for all scenarios that include both daytime and nighttime operation (Figure 7). When operation only occurs during the day the breakeven point increased to approximately 50% of maximum speed/flow due to the reduced number of operating hours, indicating nighttime operation is important. Operating at greater speeds/flows at night will both increase leachate evaporation and reduce overall costs, suggesting such an operational approach should be considered.

The economic model was also used to examine the annual costs associated with operating the Lilypad system at different percentages of maximum speed/flow (Figure 8). The annualized capital expense of the Lilypad system was consistently the greatest contribution to the overall annual cost at each percentage of maximum speed/flow. These costs are 58% to 65% of the annual cost depending on the percentage of maximum speed/flow (Figure 8). As the percentage of maximum speed/flow increases, the relative contribution of electricity consumption increased

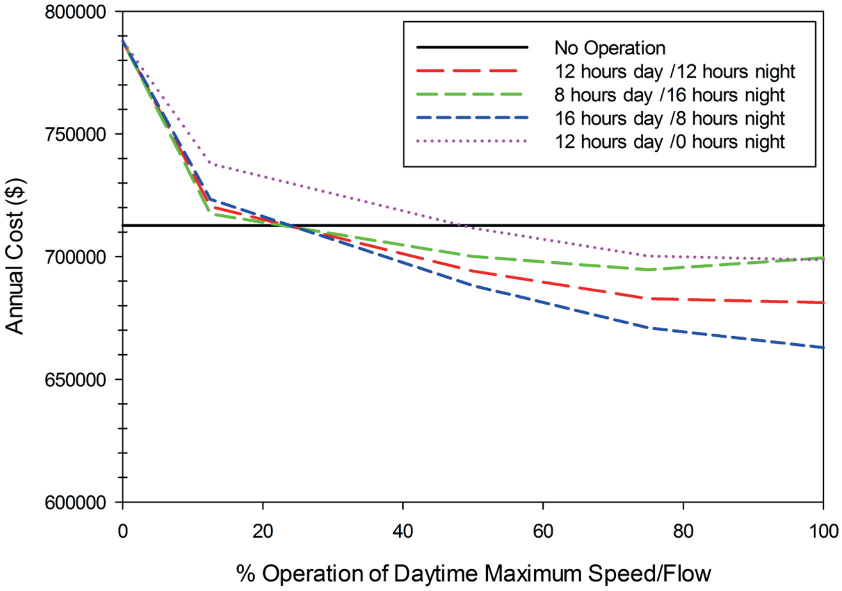

FIGURE 7: Comparison of the annual cost for leachate removal of four Lilypad operational scenarios to no operation of the Lilypad system at TRSWA.

as well. Electricity contributed to 7% to 15% of the annual cost when the Lilypad system was operational with electricity making up a greater portion of the annual cost when operating at a higher speed/flow. Because electricity costs represent a small fraction of the total annual cost, changes in maximum speed/flow can likely be done without being concerned with total costs. Similarly, the costs of maintenance were small at 8 to 14% of the total annual cost. There was a slight increase in maintenance costs as the basket speed/flow decreased due to the assumption that as the equipment was operated less, its life would be extended, resulting incurring more maintenance over the longer lifespan. The annual costs associated with hauling leachate to the WWTP are shown in Figure 9. Unlike the Lilypad system, the annualized capital costs are the smallest portion of the annual cost. The fees charged by the WWTP make up 71% of the total annual leachate hauling costs and the annualized capital expense contribute to 3% of the cost (Figure 9).

When the costs of hauling and evaporation are compared, the absolute and per L costs of hauling are consistently greater than that of evaporation. Hauling contributes to 81 to 90% of the total cost and evaporation contributes to 10 to 19% of the total cost (Figure 10). Due to the fixed costs of hauling, the cost was $0.011 per L regardless of the total volume being managed through hauling or any variation in the maximum speed/flow of the Lilypad system. The cost of hauling is predominantly due to operational expenses including labor and fuel. As the quantity of leachate hauled decreases these operation expenses decrease proportionally contributing to the fixed hauling cost. The cost per L of evaporation varied largely due to the high capital costs compared to the reduced operational efficiencies. The lowest cost for evaporation was $0.008 per L and the greatest

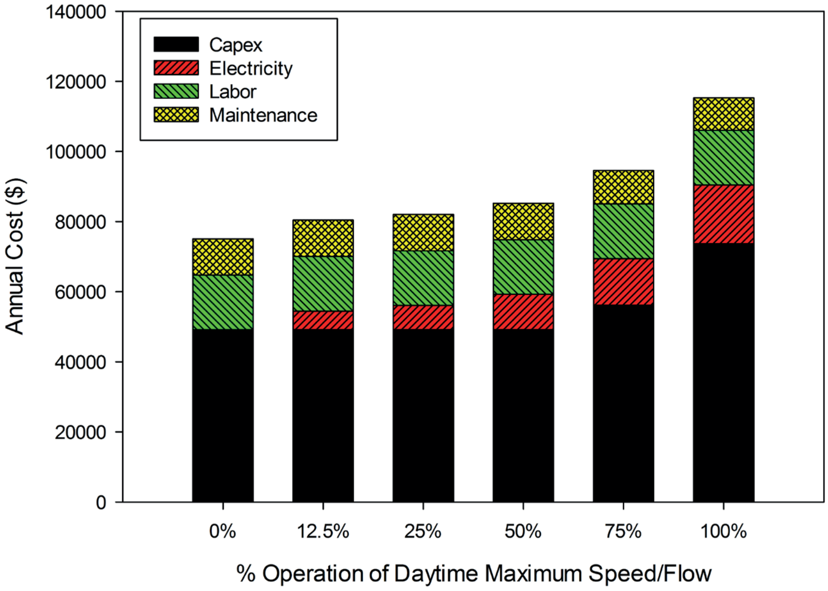

FIGURE 8: Modeled annual cost of operating the Lilypad system at TRSWA for different maximum speed/flow levels.

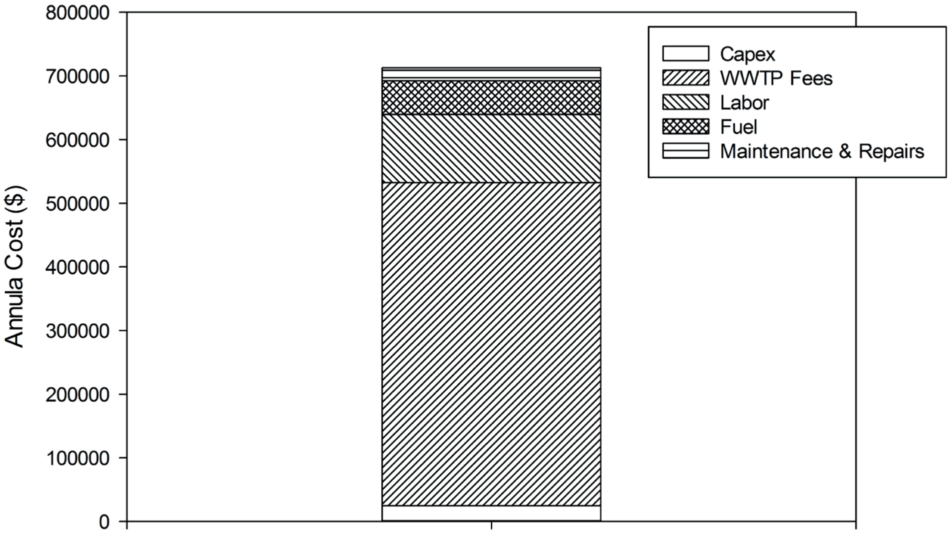

FIGURE 9: Modeled annual cost of hauling leachate from TRSWA to WWTP for disposal.

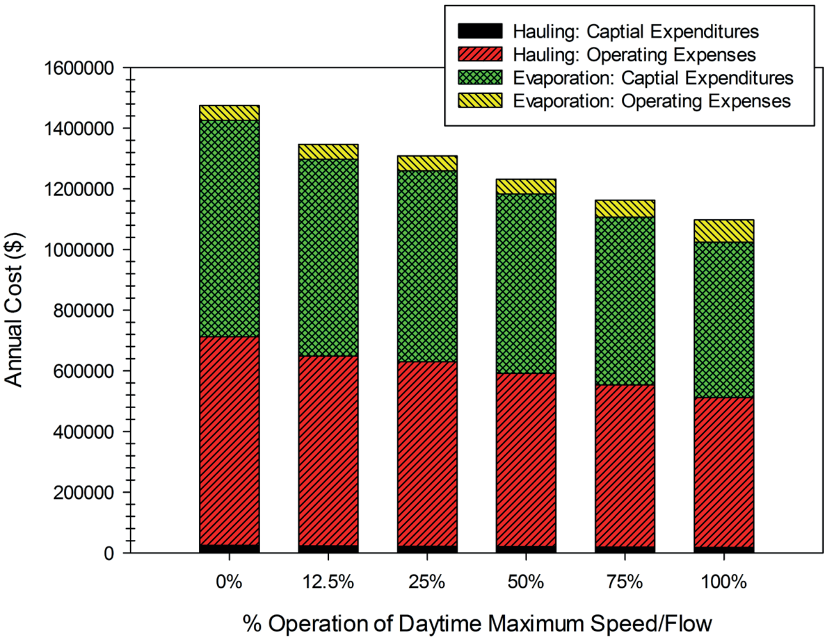

FIGURE 10: Modeled annual costs associated with hauling and evaporation at TRSWA for different maximum speed/flow levels of the Lilypad system.

$0.016 per L. However, the per L cost for evaporation was only greater than hauling costs in 4 of 20 options evaluated.

Considering the cost to haul leachate to a WWTP contributes to the greatest portion of leachate management costs, reducing the quantity of leachate that must be hauled will have the greatest impact on overall cost reduction. Additional cost savings could be realized by minimizing the total quantity of leachate that must be managed either through hauling or enhanced evaporation. For example, maximizing enhanced evaporation could contribute to approximately $36,000 in savings when compared to the lowest modeled runtimes for the Lilypad system. When compared to no Lilypad system, operation at the maximum runtime could result in savings of $49,800.

4. CONCLUSIONS

Overall, results from this work indicate the use of a droplet spraying/misting system to enhance leachate evaporation at on-site storage/collection ponds is effective. Evaporation from the Lilypad system at this site was estimated to range between 2.1 to 2.6 times more evaporation than what would occur naturally. This large volume of evaporated leachate represents a significant quantity of leachate that was not required to be treated; however, the impact on reducing overall leachate treatment costs at this site was minimal and did not contribute to a reduction in cost. In addition, it was shown that although the leachate is evaporating, there is no appreciable concentration of constituents found in the leachate pond. Using the model developed to predict leachate evaporation at this site when using the Lilypad system, several hypothetical operational scenarios were simulated to evaluate how or if changing system operation would influence total evaporation. Results from this portion of the work indicate that if the landfill wished to further increase the amount of leachate evaporated from the pond, increasing the nighttime pump and basket speeds would accomplish this.

The economic evaluation of this system indicates that operating the Lilypad system at maximum speed/flow for the greatest number of hours results in saving up to 7% of the total cost when compared to no operation of the Lilypad system. Based on the modeled scenarios, the system will break-even at 25% of maximum speed/flow for all scenarios that include both daytime and nighttime operation. When operation only occurs during the day, the breakeven point increased to approximately 50% of maximum speed/flow due to the reduced number of operating hours. These results indicate nighttime operation is important. Operating at greater speeds/flows at night will both increase leachate evaporation and reduce overall costs, suggesting such an operational approach should be considered. Considering the fees charged by the WWTP contribute to 71% of the total annual leachate hauling costs, even low operation of the Lilypad system offsets a portion of the WWTP fees lowering the total annual cost.

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