Available Technologies to Approach Zero Leaks

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ABSTRACT
Field-proven technologies are currently available for reducing leakage through installed geomembranes, which are cost effective and non-disruptive to a typical geomembrane construction schedule. These technologies include electrical leak location (ELL) methods and wrinkle management strategies. ELL methods are optimized by employing wrinkle reduction or elimination strategies. A design tool for estimating the effectiveness of ELL technologies, alone or in tandem with wrinkle reduction and elimination, has not previously been presented. This paper takes a deep look at the actual leakage reported through the installed primary geomembrane of double-lined landfills and the equations used to estimate geomembrane leakage. Backed by landfill leakage statistics and case studies, a novel design approach is presented for estimating anticipated leakage after the implementation of the technologies presented. The leakage estimations take into account the limitations of each available technology. With accurate estimations of anticipated leakage, the probability of exceeding a given action leakage rate (ALR) can then be calculated. The probabilities of exceeding a given ALR is presented for the use of the following; a dipole method ELL survey, a bare geomembrane survey followed by a dipole method ELL survey, a bare geomembrane survey followed by dipole method ELL survey where wrinkles have been reduced by 10%, and a bare geomembrane survey followed by a dipole method ELL survey where wrinkles have been eliminated completely. Design guidelines are presented for sites aiming to use the aforementioned technologies to confidently achieve leakage volumes of less than 187 liters per hectare per day (lphd) (20 gpad), 46 lphd (5 gpad), and less than 46 lphd.

1. INTRODUCTION

1.1 Action Leakage Rates

A subsurface water body can only receive a certain amount of contamination before groundwater quality is impacted. The concept of the Action Leakage Rate (ALR) was created in order to set a limit to the amount of leakage allowed from a containment facility. Once the ALR is exceeded, a site must take action to remediate the leakage problem before the site is allowed to continue operations. The establishment of a state or site-specific ALR should address the allowable quantity of contaminant leakage from a containment facility before groundwater is impacted. In the 1990's, the U.S. EPA attempted to establish an ALR for landfills of a few gallons per acre per day (gpad) with this goal in mind (Lee, 1996). Shortly thereafter, a survey of actual leakage through double-lined containment systems by Bonaparte and Gross showed that with the construction practices at the time, it would be technically unfeasible to achieve such a low leakage rate, since actual leakage rates through installed geomembranes were observed to be much higher.

The U.S. EPA does not mandate specific ALRs for various impoundments; rather it requires that individual states establish ALRs for given containment facility types. Environmental regulators in the state of New York understand the correlation between the mandated ALR and the actual leakage that could impact groundwater. New York State requires that municipal solid waste landfills be composed of double composite lining systems. The New York State ALR of 187 lphd (20 gpad) applies to the primary geomembrane. The leakage through the primary geomembrane can be monitored for compliance by the leak detection system. Using the leak detection system flow rate as the driving hydraulic force through the secondary geomembrane, there should be very little flow (less than 1 gpad if any) through the secondary geomembrane, the critical final barrier for groundwater protection. This theory is corroborated by actual monitoring data collected from the pore pressure relief drainage systems installed in about 70% of the landfills in New York State. The monitoring data collected from these comprehensive systems have shown no impact to groundwater quality. For landfills in many of the other forty nine states, most with single composite lining systems, the story is quite different.

1.2 Factors Contributing to Leakage

Many factors can contribute to geomembrane leakage including the number and size of holes, the presence of wrinkles, the depth of waste, the cover system (if in place), the barrier system components, the leachate collection system design, the nature of the barrier system foundation, the nature of the waste and the leachate collection system operation and maintenance (Rowe and Hosney, 2010). By far the biggest factor contributing to leakage are the actual holes in the geomembrane; system design and operation can only mitigate or exacerbate the principal problem of leaks. A comparison of leakage resulting from leaks with intimate contact with the underlying GCL, compared with leakage resulting from leaks on a wrinkle shows that the presence of wrinkles can significantly compound the problem of holes (Rowe and Hosney, 2010). Wrinkles can also increase the probability of creating holes during cover material placement, since even GPS-controlled equipment could catch the peak of a wrinkle, which could be significantly above base grades.

This paper therefore focuses on the technologies for directly avoiding both leaks and wrinkles during the construction phase, since the presence of both leaks and wrinkles work in combination to create the largest risk for exceeding a given ALR throughout the life of a site.

1.3 Leakage Rate Calculations

Probably the most commonly used equation for calculating leakage resulting from a hole in a composite lining system is the Giroud equation (Giroud, 1997). However, this equation is only applicable for leaks maintaining intimate contact with the subgrade material. Although leakage equations for holes on wrinkles have been available for some time, only recently has the field geometries and hydraulic network of wrinkles been extensively quantified (Chappel, 2012, Rowe et al., 2012). The recent evaluations of wrinkle extent and geometries provide the necessary input parameters to apply to the Rowe equation. As installed geomembranes receive solar radiation they begin to expand, resulting in the formation of wrinkles. Evaluations of wrinkles in exposed geomembranes show that up to 30% of the geomembrane area may be covered by hydraulically connected wrinkles (Chappel, 2012). This means that if there is a hole anywhere within that wrinkled area, the network of wrinkles can provide a hydraulic conduit for liquid that has migrated through the geomembrane. For that portion of the geomembrane, the only remaining barrier is the GCL, and the resulting leakage can be several magnitudes greater than a single hole maintaining intimate contact with the GCL. Forensic evaluation has shown that wrinkles do not disappear when the geomembrane is subsequently covered with soil (Koerner and Koerner, 2013). Rather, the wrinkles are entombed in place. Leakage rate calculations must therefore take into account both the leak density and the extent of geomembrane wrinkling.

1.4 Leakage Rate Data

Quantifying actual leakage from the primary geomembrane of existing double-lined landfills provides the most accurate means of assessing actual geomembrane leakage rates. Correlations between theoretical and actual leakage have been performed (Rowe, 2005, Rowe and Hosney 2012), however the hole frequencies used in those studies were based on leaks located by ELL surveys and the data used is over a decade old. It is well documented that liner integrity surveys have difficulty locating leaks in poor contact conditions such as wrinkles, which will bias the published hole frequency statistics (ASTM D7002, ASTM D7703, ASTM D7953 and ASTM D7007). Due to New York State's requirement for double-lined landfills and annual reporting of leakage through the primary geomembrane, actual leakage data can be collected and analyzed. Although this is the most accurate way of obtaining leakage data, it is still prone to inaccuracies due to; leakage caused by condensation and/or vapor diffusion through an intact geomembrane, potential liquid migration to the leak detection layer along the perimeter anchor trenches and measuring frequency.

The required measuring frequency from the leak detection layer varies by state. Although units of gpad are reported, the volumetric leakage measurements are not taken daily. This allows a site to average out any peak values that may have occurred from day to day. Some states allow weekly averaging, while others allow monthly averaging. A weekly average will result in a higher reported maximum leakage rate than a monthly average. New York State allows monthly averaging, so the values published here are certainly a significant underestimation in comparison with states that only allow weekly averaging.

Leakage rate data was analyzed from 122 discrete landfill cells, where no ELL survey was reported to have been performed. It should be noted that the data collected is from New York State for the reporting year 2010, where dipole ELL surveys have been specified for some time. Therefore, most of the leakage data for cells without an ELL survey are from older landfill cells where the waste is now very thick and the cells might even be capped. When older leakage data is investigated, much larger leakage rates are discovered for cells which reported extremely low leakage rates for the reporting year 2010. For example, one cell reported a leakage rate of 1,396 lphd (149.3 gpad) in 1998, but a leakage rate not exceeding 35.5 lphd (3.8 gpad) for any of the reporting years 2006 through 2012. Reviewing data from new cells is typically significantly higher than subsequent years and tends to increase on a downward trend as the cell ages due to the increasing depth of waste. Less liquid is able to migrate through the waste as it gets thicker. Leakage rates for newly constructed cells without a dipole survey performed are therefore not currently available. This data should therefore be considered a considerable underestimation of leakage for newly constructed cells without a dipole survey.

Leakage rate data was analyzed from 60 discrete landfill cells in New York State, where a dipole method ELL survey was performed. The data was collected from reporting years 2006 through 2012.

The average leakage rate for a landfill cell without a dipole survey was calculated to be 124.4 lphd (13.3 gpad). The average leakage rate for a landfill cell with a dipole survey was calculated to be 69.2 lphd (7.4 gpad). Histograms of the leakage data are shown in Figures 1 and 2.

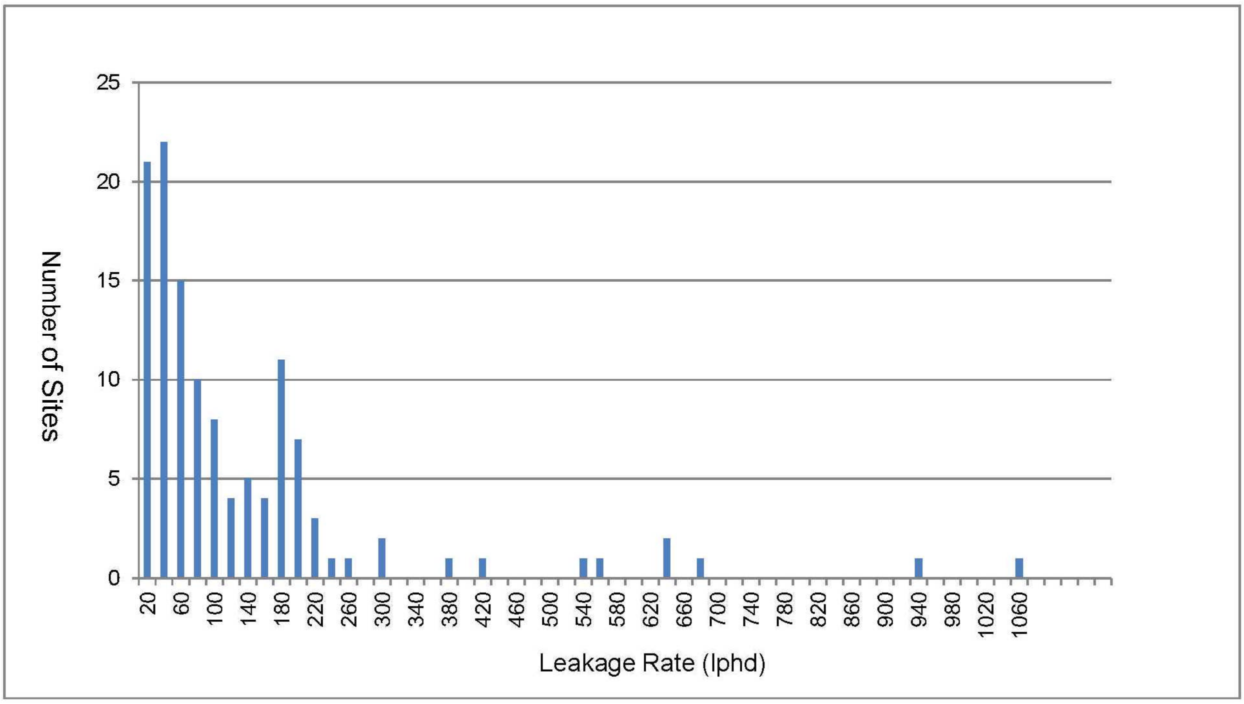

Figure 1. Leakage Rates without ELL survey. Leakage Rate statistics for double-lined landfills in New York State for reporting year 2010; data set from 122 discrete landfill cells, where no ELL survey was reported

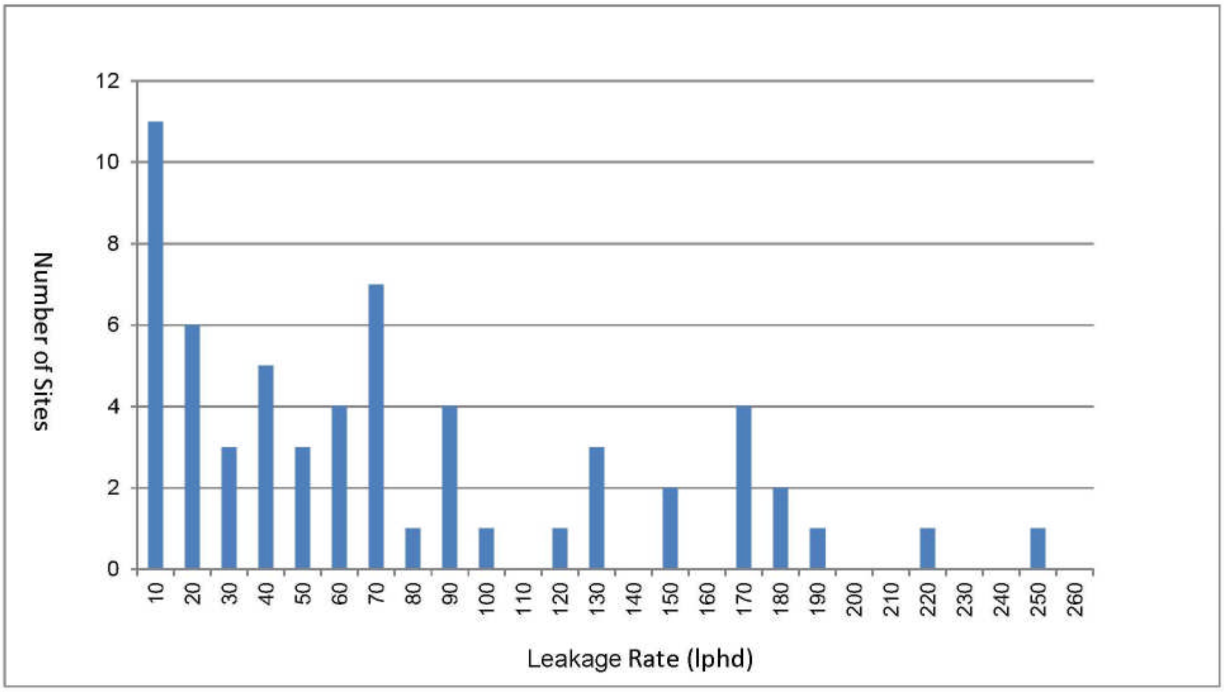

Figure 2. Leakage Rates with dipole ELL survey. Leakage rate statistics for double-lined landfills in New York State for reporting years 2006-2012; data set from 60 discrete landfill cells, where dipole ELL survey was performed as part of construction.

1.5 Available Technologies

The available technologies for reducing leakage presented herein can be economical, effective, and non-disruptive to the rigorous construction schedule of landfill construction. The benefit of each of these technologies in terms of decreasing geomembrane leakage is also quantifiable. The performance of an ELL survey directly locates existing leaks for repair. The reduction in leakage by performing an ELL survey can be deduced by measuring actual leakage through the primary geomembrane for cells with and without an ELL survey. The limitations of ELL technology include the inability to locate a leak on a wrinkle or other poor contact condition. The potential extent of wrinkling is quantifiable through field-scale studies of wrinkle development as a function of increasing geomembrane temperature (Koerner and Koerner, 1995 and Rowe et. al, 2012). The ELL methods can be optimized through wrinkle reduction or elimination strategies. Each technology is discussed in detail below.

ELL surveys for landfill expansions can be divided into two categories; bare geomembrane surveys and soil-covered dipole surveys. The bare geomembrane survey is performed directly after geomembrane installation and can locate the smallest leaks caused during geomembrane installation. The soil-covered dipole survey is then used to locate any leaks created during placement of the cover soil material. The bare geomembrane methods are generally much more sensitive than the soil-covered dipole method. The soil-covered dipole method will not likely find pinholes, knife slices, or other small damage locations created during geomembrane installation. However, most landfills only perform the dipole method for landfill expansions when ELL is required or specified for a site because the most significant damage is typically caused during cover soil placement.

The bare geomembrane methods include the water puddle, water lance and arc testing methods. The water puddle and water lance utilize either a puddle or a stream of water to conduct electricity, as the names imply. The electrical current source is grounded to the subgrade underneath the geomembrane. In the presence of a poor contact condition such as a wrinkle, the water may not be able to travel through the hole and down the underside of the wrinkle to complete the electrical connection with the subgrade. The arc tester does not rely on water to conduct electricity; it imposes a high voltage over the geomembrane and is grounded to the subgrade. However, an electrical arc will not form if the arc tester probe is too far away from the subgrade, as would be the case over a wrinkle. For both methods, effort is made to push down the wrinkles, or the survey is performed at night. However, the risk remains due to the technological limitations of the methods that leaks can be missed on wrinkles and other areas of poor contact.

The soil-covered geomembrane dipole method is similar to the bare geomembrane methods in that a positive voltage is introduced above the geomembrane and grounded to the subgrade beneath the geomembrane. The current source is placed in the soil cover material and current will travel through any leaks in the geomembrane, which have good contact with the subgrade below it. A hole located on a wrinkle entombed in the soil cover simply will not be detected because the electricity will not travel through the air gap created by the wrinkle.

Wrinkle reduction strategies include several techniques, with some of them costly and time-consuming and others much more economic and practical. One of the more labor intensive and time consuming techniques includes the placement of only one geomembrane panel at a time, and then fixing each end with a berm. Another less economic technique is to install a temporary tent, which can be moved over the active placement area, blocking incoming solar radiation during the geomembrane installation process. More practical solutions include limiting the placement of the cover soil to the cool hours of the day and using the “push/accumulate/cut/seam” technique. The option that is the least disruptive to the construction schedule is the use of white geomembrane. White geomembrane can significantly decrease the surface temperature of an exposed geomembrane (Koerner and Koerner, 1995). The lower geomembrane temperature results in a smaller area of the geomembrane covered by wrinkles (Rowe et. al, 2012). The fewer the wrinkles present, the less likely the resulting lining system will contain a hole on a wrinkle that may not be detected by ELL methods.

Wrinkle elimination is extremely difficult to achieve, and may be achieved by using some of the wrinkle reduction strategies discussed in the previous section. However, wrinkles can be “virtually” eliminated through manipulating site conditions or using specialty geosynthetics. These methods are considered “virtual” wrinkle elimination, since the wrinkles are still actually present in the geomembrane; they just no longer pose a limit to ELL surveys. One option is to flood the geomembrane during the performance of the ELL survey. The level of head over the geomembrane must exceed the height of any wrinkles present and the water must fill any voids present underneath the geomembrane. This may or may not be practically achieved in the field. A more reliable option to virtually eliminate the wrinkles is by using conductive-backed geomembrane. Conductive-backed geomembrane is fabricated using the coextrusion process. An electrically insulative HDPE geomembrane is coextruded with an electrically conductive material on the back side as a continuous layer. This results in a conductive layer in intimate contact with the geomembrane. This enables the location of leaks in poor contact conditions such as wrinkles, under the overlap of a fusion weld, or in a location where there is a depression in the subgrade, since the current of the survey is carried by the backside of the geomembrane, removing the need for intimate contact with the subgrade.

2. LEAKAGE RATE DESIGN CALCULATOR

2.1 Calibrating existing equations

Existing equations for estimating leakage through geomembranes caused by holes must be validated for their applicability to large-scale applications. The most realistic leakage rates for actual geomembrane installations are obtained from quantifying the leakage to the leak detection layer, as detailed in Section 1.4. A 2013 case study took this concept one step further and analyzed the leakage from the leak detection layer at a site where dipole surveys were conducted both before and after flooding the primary geomembrane and leak detection layer (Beck, 2014). This allowed for the quantification of leakage through holes located in areas of poor contact. Quantifying the leakage from the leaks that were detected only while the geomembrane was flooded provided evidence that poor contact is an issue for ELL surveys. The case study also allowed for calibrating the Rowe equation in order to arrive at realistic assumptions.

The 2013 case study showed that using the Giroud equation for both good and poor contact between the geomembrane and the GCL, the calculated leakage was over ten times less than the actual leakage recorded. If the holes located are assumed to have been on wrinkles, which would explain why they were not located by the initial dipole survey, the calculated leakage using the Rowe equation fits very well with the actual leakage rate measured from the leak detection layer. The variables used for the Rowe equation in order to match the actual leakage measured included a wrinkle width of 0.31 meters and a wrinkle length of 190 meters. These values are corroborated by field studies of wrinkle formation in large-scale geomembrane installations (Rowe, 2012). Therefore, for a typical geomembrane installation in North America, the Rowe equation should be used to estimate leakage rather than the Giroud equation, which is likely only applicable at sites were extensive measures are taken to create intimate contact.

2.2 Probability Analysis

A probability analysis was introduced by Beck (Beck, 2012) in order to determine the probability of exceeding the New York State ALR when either no ELL survey is performed or a dipole ELL survey is performed. This paper takes that approach further by applying the same statistical analysis to all of the technologies presented in the previous section.

The probability function presented by Beck is as follows:

$$Y(x) = \exp[(-1/\text{mean}) \cdot x] \qquad [1]$$

where Y(x) yields the probability of a leakage rate exceeding a specified ALR, mean is the average leakage rate, and x is the specified ALR.

An excellent correlation is observed in Figures 3 and 4 between the probability function expressed in equation [1] (probability on y-axis of exceeding a given leakage rate on x-axis) and the data analyzed (actual percentage of landfills on y-axis exceeding a given leakage rate on x-axis) for both of the data sets presented in Section 1.4.

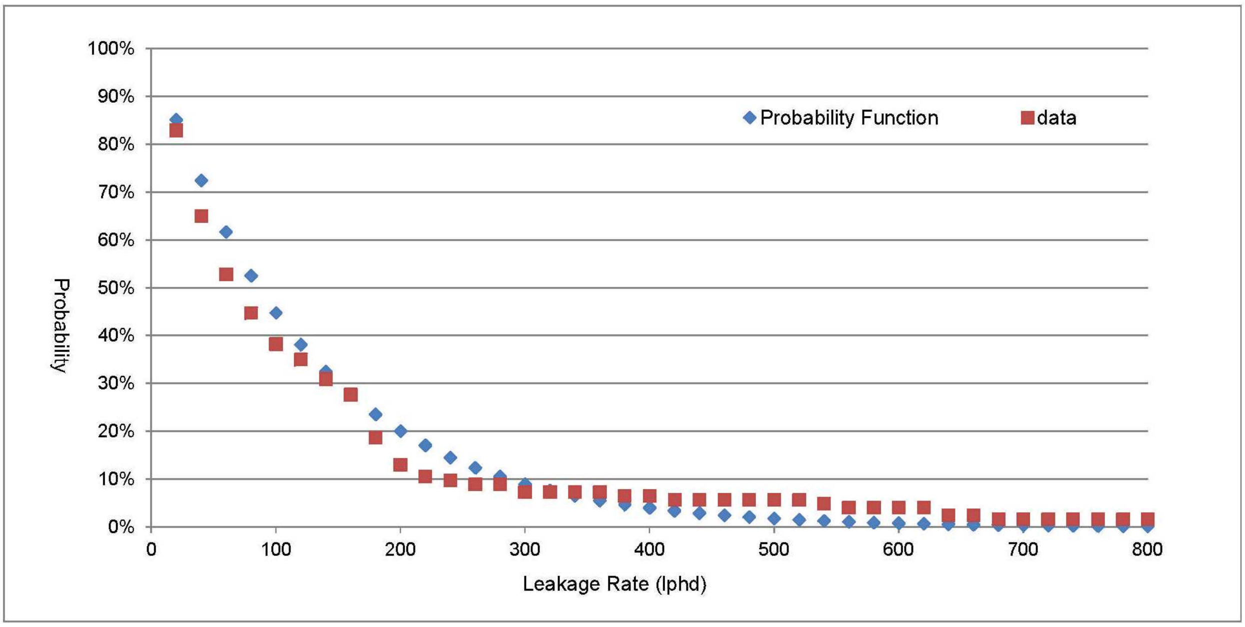

Figure 3: Probability of Exceeding Given Leakage Rate without survey. Probability function plotted along with observed data for double-lined landfills in New York State for reporting year 2010; data set from 122 discrete landfill cells, where no ELL survey was reported.

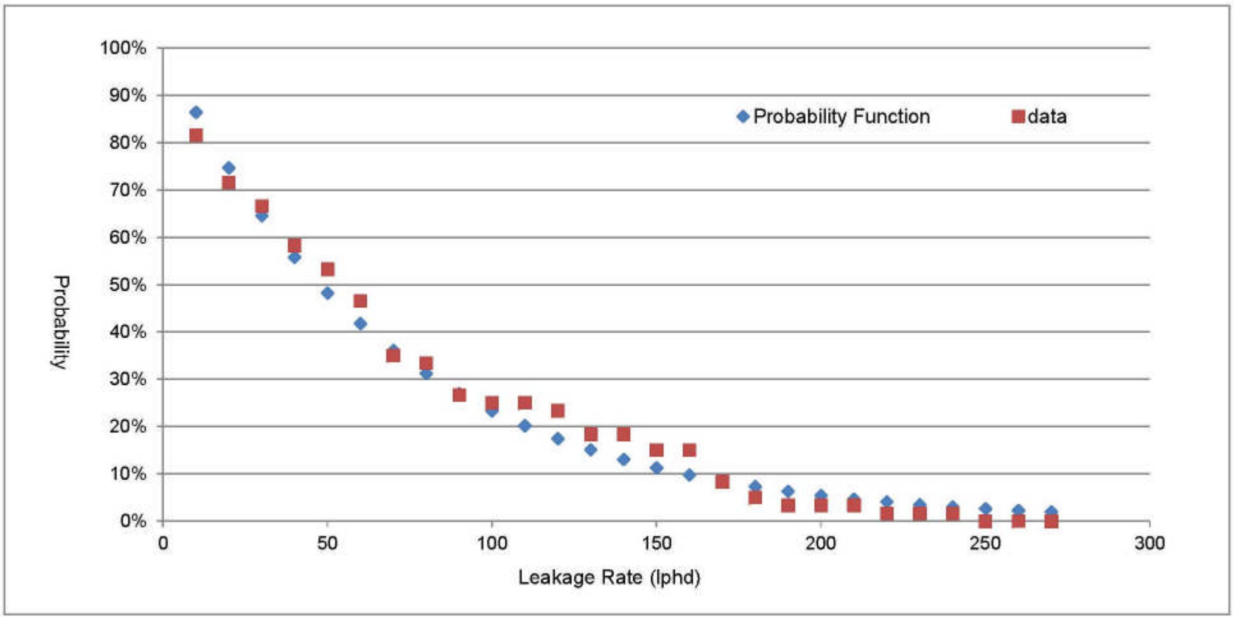

Figure 4: Probability of Exceeding Given Leakage Rate with dipole ELL survey. Probability function plotted along with actual leakage rates observed for double-lined landfills in New York State for reporting years 2006 - 2012; data set from 60 discrete landfill cells, where dipole ELL survey was performed as part of construction.

No leakage data is currently publicly available for landfill cells that have performed a bare geomembrane survey method after geomembrane installation, and then performed a dipole survey after placement of the cover materials. Therefore, some assumptions need to be made. The first assumption is that the probability equation used to create Figures 3 and 4 will be valid for the leakage resulting from the application of the other technologies presented here. This equation requires only the estimated average leakage rate subsequent to applying each technology in order to calculate the probability of exceeding a given ALR. The second assumption is that the ELL methods applied are applied per ASTM standard practices. If an ELL is not performed correctly, it will not locate leaks.

In order to estimate the average leakage rate for a geomembrane subsequent to performing a bare geomembrane survey followed by a soil-covered dipole survey, informed assumptions must be made for the following; leak density and percent of geomembrane covered by wrinkles.

It is inaccurate to make a blanket statement about the typical number of leaks in an installed geomembrane based on published leak statistics, since most of the published studies are now outdated and do not state the complete context of where the statistics came from such as country where the data was taken, whether the construction was new or the survey was on an existing (old) facility, and what ELL method was used to create the statistics. Leak densities can range from zero for new construction with excellent CQA to 75 or more leaks per hectare for older containment facilities or geomembrane construction outside of the U.S. The number of leaks in a given installation will be a function of the skill of the liner installer and the quality of the CQA effort, among other factors including weather that are difficult to predict. An average leak density located in newly constructed geomembrane containment systems in North America when CQA is used as part of construction is approximately 1.2 leaks per ha (0.5 leaks per acre), based on data collected by the author from 46 newly constructed geomembrane-lined containment facilities in North America, which implemented CQA as part of construction, from 2004 through 2010. There are likely more leaks that are not found due to poor contact conditions, so a range of 1.2 to 4.9 leaks per ha (0.5 to 2 holes per acre) was used for the analysis.

The extent of wrinkling can be expressed as a percentage of the total geomembrane area. Rowe provides estimations of wrinkle area as a function of time of day due to fluctuations of the geomembrane temperature (Rowe, 2012). In order to estimate the benefit that wrinkle reduction strategies can provide, the difference in temperature between a black geomembrane and a white geomembrane was analyzed. During the Spring, Summer, and Fall months, the maximum geomembrane temperature difference between a black and a white HDPE geomembrane varies from 25 to 43 °C (Koerner and Koerner, 1995). A temperature difference of 30°C corresponds to a difference in wrinkled area of at least 10% (Rowe, 2012). Therefore, one of the assumptions used for this analysis is that a geomembrane where no wrinkle management has been performed has a wrinkled area of 17%, while a reduced wrinkled area of only 7% can be achieved through moderate wrinkle management strategies. The probability of a hole landing on a wrinkle is assumed to equal the percentage of the area covered by a wrinkle, based upon the assumption that there is equal probability of a hole everywhere throughout the cell. In reality, a location such as the toe of the slope, which is more likely to contain a wrinkle, is also a location more likely to contain a leak, so this approach may underestimate the anticipated leakage.

The Rowe equation was used to calculate leakage resulting from a hole on a wrinkle, using the assumptions arrived upon in the case study described in Section 2.1. The leakage rate per hole on a wrinkle was calculated to be 25.9 lphd (6.85 gpad). The estimated leakage from a geomembrane after applying a bare geomembrane survey was then calculated by multiplying the area covered by wrinkles by the leakage rate per hole and the assumed number of holes per acre. This way, leakage is calculated for only the portion of the geomembrane containing wrinkles, which yields an overall average leakage rate if all of the leaks are located and repaired, except for the ones located within the wrinkled area.

If wrinkles can be completely eliminated, either actually or virtually, and a bare geomembrane survey is performed correctly, followed by a dipole survey after cover soil placement, there should not be any leaks in the geomembrane. Except for liquid generated by condensation or vapor diffusion, there should essentially be no leakage through the geomembrane.

Once the anticipated average leakage is calculated for each of the technologies discussed here, the probability of exceeding a given leakage rate can be calculated by using Equation [1].

3. RESULTS

The probabilities of exceeding typical landfill ALRs of 46.8 lphd (5 gpad) and 187.1 lphd (20 gpad) were calculated for each of the technologies discussed in the previous sections, both alone and in tandem. This was done by using the actual average leakage rate from the leakage data presented in Section 1.4 and when actual data was not available, the average leakage rate was estimated as described in Section 2.2. The results are presented below.

The probability of exceeding an ALR of 46.8 lphd (5 gpad) without applying any of the technologies discussed in this paper was calculated to be 68.7%. The probability of exceeding an ALR of 187.1 lphd (20 gpad) without applying any of the technologies discussed in this paper is calculated to be 22.2%.

The probability of exceeding an ALR of 46.8 lphd (5 gpad) after applying a dipole ELL survey only was calculated to be 50.7%. The probability of exceeding an ALR of 187.1 lphd (20 gpad) after applying a dipole ELL survey only was calculated to be 6.6%. If wrinkle reduction strategies are used, reducing the wrinkled area (and subsequently the average leakage rate) by 10%, the probabilities are decreased to 46.7% and 4.7% for an ALR of 46.8 lphd (5 gpad) and 187.1 lphd (20 gpad), respectively.

For enhanced quality control, a bare geomembrane survey should be performed after geomembrane installation, followed by a dipole survey after placement of the cover material. The probabilities of exceeding both ALRs after applying these measures are presented in Table 2 with three different leak densities and assuming a wrinkled area of 17% and 7% to represent no wrinkle management and moderate wrinkle management, respectively.

Table 2. Summary of Probabilities of exceeding ALR of 46.8 lphd (5 gpad) for both bare geomembrane survey and dipole survey performed and wrinkled area of 17% for leak densities of 1.2, 2.5 and 4.9 leaks per ha (0.5, 1 and 2 leaks per acre).

Leak Density (leaks per ha)	Estimated Leakage (lphd)[1]	Probability of Exceeding ALR
4.9	21.8	11.7%
2.5	10.9	1.37%
1.2	5.45	0.583%

[1] 1 lphd = 0.107 gpad

Table 3. Summary of Probabilities of exceeding ALR of 46.8 lphd (5 gpad) for both bare geomembrane survey and dipole survey performed and wrinkled area of 7% for leak densities of 1.2, 2.5 and 4.9 leaks per ha (0.5, 1 and 2 leaks per acre).

Leak Density (leaks per ha)	Estimated Leakage (gpad)[1]	Probability of Exceeding ALR
4.9	8.98	0.546%
2.5	4.49	2.98×10^{-3}%
1.2	2.24	8.88×10^{-8}%

[1] 1 lphd = 0.107 gpad

Table 4. Summary of Probabilities of exceeding ALR of 187.1 lphd (20 gpad) for both bare geomembrane survey and dipole survey performed and wrinkled area of 17% for leak densities of 1.2, 2.5 and 4.9 leaks per ha (0.5, 1 and 2 leaks per acre).

Leak Density (leaks per ha)	Estimated Leakage (gpad)[1]	Probability of Exceeding ALR
4.9	21.8	0.0187%
2.5	10.9	3.52×10^{-6}%
1.2	5.45	8.88×10^{-13}%

[1] 1 lphd = 0.107 gpad

Table 5. Summary of Probabilities of exceeding ALR of 187.1 lphd (20 gpad) for both bare geomembrane survey and dipole survey performed and wrinkled area of 7% for leak densities of 1.2, 2.5 and 4.9 leaks per ha (0.5, 1 and 2 leaks per acre).

Leak Density (leaks per ha)	Estimated Leakage (gpad)[1]	Probability of Exceeding ALR
4.9	8.98	8.88×10^{-10}%
2.5	4.49	7.89×10^{-19}%
1.2	2.24	6.23×10^{-37}%

[1] 1 lphd = 0.107 gpad

The probability of exceeding both ALRs is essentially zero if wrinkles can be eliminated in tandem with an exposed bare geomembrane survey followed by a dipole survey after cover soil placement (if applicable). This follows from the assumption that the ELL survey is performed per ASTM standard practices and is thus effective and that the wrinkle elimination strategies are effective. It has been reported for sites constructed using these specifications that leakage through the geomembrane is always attributed to faulty pipe penetrations and can be mitigated by a prefabricated pipe penetration design, which allows for spark testing the weld attaching the prefabricated pipe penetration to the geomembrane sheet. In a region of California where the regional water board prescribes double-lined ponds with zero leakage through the primary geomembrane, this is the approach taken, and has been successful.

4. CONCLUSIONS

More accurate methods of calculating anticipated average leakage rates are presented herein, along with a method of applying a probability analysis of exceeding a given ALR with the application of the technologies presented, both alone and in tandem. The tools presented here inform landfill designers, regulators and site owners of the appropriate technologies for the desired level of contaminant containment. These tools can assist design engineers to provide more realistic estimations of landfill leakage in order to adequately assess the potential impact of a proposed landfill expansion on an underlying aquifer. The cost of groundwater remediation and litigation resulting from groundwater contamination far exceeds the cost of minimal forethought and the application of the technologies presented here by many orders of magnitude.

If a site is required to comply with an ALR of 46.8 lphd (5 gpad), it is advisable to employ wrinkle reduction strategies, in tandem with performing both a bare geomembrane survey and a dipole survey after placement of the cover soil. With the application of these technologies, there is less than a 1.0% probability of exceeding the ALR, even in the presence of sub-optimum CQA where the leak density is on the high end of what is typically found for landfills in North America.

If a site is required to comply with an ALR of 187.1 lphd (20 gpad), it is advisable to specify both a bare geomembrane survey and a dipole survey after placement of the cover soil. With these measures, there is less than a 0.1% probability of exceeding the ALR. If only a dipole survey is specified, it is more likely than not that a landfill cell will exceed an ALR of 5 gpad, while the probability of exceeding an ALR of 187.1 lphd (20 gpad) can be as high as 6.6%. This probability is certainly higher if a site is only allowed a weekly averaging of leakage data.

The most conservative approach to minimizing leakage would be the complete elimination of wrinkles, either actually or virtually, and specifying both a bare geomembrane survey during construction and a dipole survey after the cover soil placement. This approach is recommended for any sites requiring a leakage rate of less than 5 gpad. This represents the most technologically feasible way of approaching the goal of zero leakage. This goal is now attainable with the technologies and services available for modern geomembrane construction.

ACKNOWLEDGEMENTS

This study could not have been possible without the cooperation and assistance of Jeff Blum of Weaver Boos Consultants, John Brusa of Barton & Loguidice and Robert Phaneuf, Rick Clarkson, Jamie Lang and Gerard Wagner of the New York State DEC. In addition, Katie Venechuk of the Michigan DEQ and Larry Kamp of D&E Construction generously answered questions about state ALRs and post-spark testing leakage rates, respectively.

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