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Modelling the transport of PFOS from single lined municipal solid waste landfill

R. Kerry Rowe *, Farah B. Barakat

GeoEngineering Centre at Queen's – RMC, Department of Civil Engineering, Queen's University, Kingston, Canada

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ABSTRACT

The contaminant transport of perfluorooctane sulfonate (PFOS) through the base of a municipal solid waste landfill lined by a single composite liner comprised of a geomembrane over a geosynthetic clay liner (GCL) and a 3.75 m-thick attenuation layer underlain by an aquifer is examined. Both pure diffusive transport and advective transport through holed wrinkles are modelled. The peak concentrations of PFOS predicted for the aquifer beneath the landfill are compared to the maximum allowable PFOS concentration established by Australia, Canada, Europe, and various US states. The results show that (a) in most cases with zero leakage and pure diffusive transport, regulatory limits are met; however, (b) if there are holed wrinkles in the geomembrane, the impact is highly dependent on the length of holed wrinkle per hectare, the geomembrane-GCL interface transmissivity, and the GCL hydraulic conductivity. Factors affecting the length of holed wrinkles are discussed. In many of the cases examined, the peak concentrations of PFOS in the aquifer exceed the limits set by the different jurisdictions, indicating that a single composite liner may not be sufficient to contain PFOS acceptable level and recommends that realistic contaminant impact calculations be performed in each specific case.

1. Introduction

Composite liners comprised of a geomembrane (GMB) over a geosynthetic clay liner (GCL; Bouazza, 2002; Li and Rowe, 2020; Meer and Benson, 2007; Mukunoki et al., 2019; Petrov et al., 1997a, 1997b; Petrov and Rowe, 1997; Rowe, 2014, 2016, 2018b; Rowe et al., 2019; Yu et al., 2018, 2020; Yu and El-Zein, 2019; Rowe, 2018a; Scalia et al., 2018) are commonly used for hydraulic containment of landfills (Bouazza, 2002; Rowe, 2005; Chen et al., 2015; Rentz et al., 2016). The liner is intended to act as a barrier to contaminants present in the waste, minimizing transport to groundwater and surface water. Ideally, the geomembrane layer would provide a complete barrier from advective transport of contaminants resulting in diffusion being the most dominant means of transport (August and Tatzky, 1984; Park and Nibras, 1993; Sangam and Rowe, 2001; Rowe et al., 2004; Joo et al., 2005; McWatters and Rowe, 2009a,b, 2010, 2014, 2018; McWatters et al, 2019 Park et al., 2012; DiBattista and Rowe, 2020a,b; DiBattista et al., 2020; Shackelford, 2014; Zhang et al., 1999; Crank, 1979; Divine and Mccray, 2004; Jones and Rowe, 2016). However, that ideal situation is unlikely with a single composite liner since studies have shown that even with good construction quality assurance (CQA), 5 holes/ha may be expected and 20 or more holes/ha with casual CQA (Giroud and Bonaparte, 1989; Giroud, 2016). This raises the questions as to: (a) what is the probability of holes in wrinkles, and (b) how many holed wrinkles are likely to lead to unacceptable impact on groundwater? The answer depends in large part on the critical contaminant and jurisdiction as will be discussed in the rest of this paper.

Perfluorooctane sulfonate (PFOS) is one of the compounds that contribute to a larger group of compounds called per- and polyfluoroalkyl substances (PFAS). Per- and polyfluoroalkyl substances are composed of a carbon chain where some or all of the hydrogen atoms are replaced by fluorine atoms, respectively. They are synthetic chemicals that are extremely strong and stable due to the chemical bond that is developed between the carbon and fluorine atoms which causes them to be very persistent and hard to degrade since these bonds allow them to be resistant to hydrolysis and different degradation mechanisms (e.g., thermal, microbiological and photolytic; Milinovic et al., 2015; Bouazza, 2021). Thus, they attain unique properties which include oil and water resistance resulting in their dominant use in industrial and consumer goods such as treating and protecting textiles including clothes, carpets, and coated paper, and coated food and cardboard packaging or leather products (ATSDR, 2015; CELA, 2019; CONCAWE, 2016; EPA, 2003;

* Corresponding author.
E-mail addresses: kerry.rowe@queensu.ca (R.K. Rowe), 19fb4@queensu.ca (F.B. Barakat).

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EPA, 2017; NTP, 2016; Ahrens, 2011; Cousins et al., 2016). They are also used as industrial surfactants and insecticides (EPA, 2017; Benskin et al., 2012). Due to their persistency and increasing use and thus, presence in the environment, PFAS compounds emerged as contaminants of interest and, PFOS was found to be the most dominant PFAS detected in human blood (ATSDR, 2015; Benskin et al., 2012), EPA, 2015; Lindh et al., 2012; Zeng et al., 2015). In addition, studies have shown evidence that: (a) PFOS is carcinogenic and, (b) there is a relationship between exposure to PFOS and human reproductive and development effects along with elevated cholesterol levels (ATSDR, 2015; EPA, 2016; OECD, 2002; EPA, 2017; Alexander et al., 2003; Alexander and Olsen, 2007; Mandel and Johnson, 1995; Thomford, 2002; Eriksen et al., 2013; Frisbee et al., 2010; Nelson et al., 2010; Apelberg et al., 2007; Chen et al., 2015; Darrow et al., 2013; Maisonet et al., 2012; Washino et al., 2009). Despite these toxic properties, presently there are no specific guidelines regarding the disposal of PFAS. Four different areas are considered major PFAS sources which include lands used for fire training purposes, industrial areas, and the areas crossed by surface water passing over contaminated areas, landfills and landfill leachate, and wastewater treatment facilities including sewage sludge and effluent water (EPA, 2017; ITRC, 2020; Bouazza, 2021; Moody and Field, 2000; Baduel et al., 2017; Cousins et al., 2016; Gallen et al., 2017; Hamid et al., 2018). This paper will focus on the containment of PFOS in landfills using a barrier system comprised of a leachate control layer, a geotextile protection layer, and a composite liner involving a 1.5 mm thick high density polyethylene (HDPE) geomembrane on a 7 mm thick (hydrated under operating stresses which are the stresses applied from the waste and typically exceed 100 kPa except below wrinkles) GCL. The authors are unaware of any published data on the permeation coefficient for PFOS through HDPE geomembranes. On the other hand, data on diffusion of PFOS through linear low density polyethylene (LLDPE) geomembranes has been published (DiBattista et al., 2020). The authors are currently conducting PFAS diffusion tests for HDPE at 23, 35 and 50 °C. After 145 days of PFOS diffusion through a 0.26 mm HDPE GMB, PFOS has only been detected in the receptor at 50 °C which establishes an upper bound to the permeation coefficient for temperatures ≤50 °C of $P_g \leq 6 \times 10^{-16}$ m^2/s. This value is slightly more than the PFOS permeation coefficient of (<) 1.6×10^{-16} m^2/s for 0.1 mm-thick LLDPE at room temperature but less than (<) 27×10^{-16} m^2/s for 0.75 mm-thick LLDPE reported at 50 °C by DiBattista et al. (2020) for LLDPE. A base value of $P_g \sim 6 \times 10^{-16}$ m^2/s will be adopted in this paper but the sensitivity to reasonable uncertainty will be assessed. It is expected that the diffusion coefficients being established from current testing will likely reduce with time as more data becomes available. However, any further reduction in the permeation coefficient for PFAS through HDPE will not change the conclusions of this paper.

Despite the paucity of regulations for the disposal of waste containing PFAS, different jurisdictions have developed regulations and regulatory limits for PFOS to preserve drinking and ground water quality. Australia has a limit of 0.07 μg/L (70 ng/L) for the sum of PFOS and PFHxS (perfluorohexane sulfonic acid) combined and for the purposes of this paper, the concentration of PFOS discussed will represent this sum (NHMRC, 2018). In Canada, Health Canada's drinking water guideline sets the maximum acceptable concentration of PFOS as 0.6 μg/L (600 ng/L) (Canada, Guidelines for Canadian Drinking Water Quality for PFOS and PFOA, 2019), while the province of British Columbia has developed their own regulatory limits of 0.3 μg/L (300 ng/L) (CSR, 2016). The province of Ontario has not developed its own regulatory limits but, based on Ontario Regulations 232/98 and the limits set by Health Canada, the maximum allowable PFOS concentration in the groundwater is calculated to be 0.15 μg/L (150 ng/L) (Canada, 2012; MoE, 1998). Several different states in the United States of America have developed regulations. In this paper, the regulations of four different US states will be considered: Texas, California, Michigan and New York. The regulatory limits of these states were chosen as they represent the maximum, minimum, and median threshold levels developed for the different US states and cover south, west, north and east of the continental US. The maximum allowable concentrations of PFOS in drinking water in Texas, California and Michigan (Table 1) are 0.29 μg/L (290 ng/L), 0.04 μg/L (40 ng/L), and 0.008 μg/L (8 ng/L), respectively (Table 1; AWWA, 2019). Based on currently available information, New York State has adopted a limit of 0.01 μg/L (10 ng/L; New York, 2020) and Europe has a proposed limit of 0.1 μg/L (100 ng/L; EurEau, 2018). For the purposes of this paper, it will be assumed that Europe's proposed limit is accepted (Table 1).

As discussed earlier, if an ideal (impervious to liquid flow) GMB layer was present in a composite liner, diffusion would be the primary mechanism for contaminant transport beneath a landfill. DiBattista et al. (2020) reported partitioning, permeation, and diffusion coefficients for PFOS through a 0.1 mm LLDPE geomembrane at room temperature. Based on this study, the best estimates for PFOS and LLDPE (based on almost 500 days of testing) were: partitioning coefficient, $S_{gf} = 4$, diffusion coefficient, $D_g \leq 4 \times 10^{-17}$ m^2/s, with a permeation coefficient, $P_g \leq 1.6 \times 10^{-16}$ m^2/s with a conservative estimates as: $S_{gf} = 4$, diffusion coefficient, $D_g \leq 6.6 \times 10^{-16}$ m^2/s, with a permeation coefficient, $P_g \leq 2.6 \times 10^{-15}$ m^2/s. The authors are currently conducting similar diffusion tests with HDPE at a range of temperatures (22, 35 and 50 °C) that have now been running long enough to confirm that the P_g estimated for HDPE at typical landfill temperatures between 35 and 50 °C are less than 2.6×10^{-15} m^2/s, with current best estimates of $S_{gf} = 4$, $D_g = 1.5 \times 10^{-16}$ m^2/s, and a permeation coefficient, $P_g = 6.0 \times 10^{-16}$ m^2/s for HDPE.

Geomembranes have a high coefficient of thermal expansion. During the construction of a landfill, if a GMB (including if covered by a geotextile) is exposed to sunlight, it will expand and develop wrinkles. In addition, even if good quality assurance is maintained on site, the geomembrane is most likely going to develop holes. Wrinkles are most likely to be damaged as the cover soil is placed (Gilson-Beck, 2019; Rowe, 2020a). Thus, if holes are present in a wrinkle (referred to herein as a "holed wrinkle"), the wrinkle can act as a pathway for leachate passing through the hole flowing over the entire unstressed area below the wrinkle and then leaking through the unstressed GCL as dictated by Darcy's Law. In addition, the GMB or GCL of a composite liner will not be in perfect direct contact. This results in an interface transmissivity, θ, that defines the resistance to lateral flow between the GMB and GCL layers as it moves away from the holed wrinkle. The flow will extend a lateral distance defined as the wetted distance, a (Rowe, 1998, 2005, 2012), where a is measured from the center of the wrinkle. Thus, when leachate passes through a holed wrinkle, there is downward flow through the unstressed GCL directly beneath the wrinkle as well as lateral flow between the GMB and GCL and downward through the confined GCL out as far as the wetted distance a. The wetted distance is a function of the interface transmissivity, hydraulic conductivity of the GCL and, the differential pressure head acting on the GCL beneath the wrinkle.

Advection (leakage) through the clay liner and soil layers present in the barrier system mostly arises due to the holed wrinkles in the geomembrane. Sorption of PFOS in the waste layers, bentonite of the GCL and soil used for attenuation is investigated. Li et al. (2015) set up batch tests to estimate adsorption of PFOS present in landfill leachate and spiked landfill leachate into bentonite barrier mixtures, and the tests showed that there were very minor changes in the concentrations of PFOS between the control cell and the tests using both permeants. Thus, it was concluded that PFOS does not bind to bentonite. On the other hand, sorption tests reported by Pereira et al. (2018) and Milinovic et al. (2015) showed PFOS sorption to organic soils was relatively high compared to other PFAS's tested due to PFOS's high hydrophobicity and long chain length. Sorption of PFOS in organic soils is highly dependent on the pH, and increased with decreasing pH (Pereira et al., 2018). In addition, it is also directly correlated to the carbon content of the soil (Milinovic et al., 2015). The pH present in landfill leachate is relatively

Table 1
Summary of Regulatory Limits on PFOS Concentration Considered, ratio of maximum landfill concentration to allowable, and PFAS giving the maximum ratio.

Jurisdiction	Australia	Canada	British Columbia	Ontario	Texas	California	Michigan	New York	Europe
Maximum Allowable PFOS Concentration (ng/L)	70	600	300	150	560	40	8	10	100
Ratio peak landfill to maximum allowable PFOS concentration	69	8	16	32	17 (290)	120	600	480	48
Maximum ratio of peak landfill to maximum allowable PFAS concentration**	69	17	17	69	76	345	600	480	48
PFAS giving the highest ratio above	PFOS	PFOA	PFOA	PFOA	PFHxA	PFOA	PFOS	PFOS	PFOS
Peak landfill PFAS concentration considered for contaminant listed above*	4800	3450	3450	3450	7090	3450	4800	4800	4800

* All peak landfill concentrations were obtained from Li (2011).
** The references used to obtain the maximum allowable PFOS concentrations were used to get the maximum allowable PFAS concentrations.

high and typically ranges from about 6 to 8. Thus, sorption in the waste and soil will be at the lower end of the range reported. Sorption of PFOS in the different soils tested by Milinovic et al. was highly variable. Due to the large uncertainty regarding the conditions present within a landfill and the degree of PFOS sorption, sorption was assumed to be negligible in the model considered in this paper.

The primary objectives of this paper are to (i) examine the effectiveness of having a 1.5 mm HDPE GMB layer as a diffusive barrier for PFOS, (ii) examine the effect of different probabilities and lengths of wrinkles with holes and the calculated impacts associated with different probability of leakage, and (iii) identify the circumstances in which PFOS concentrations might be likely to satisfy the different regulatory limits considered in this paper.

2. Background

The liner systems required for modern MSW landfills can vary substantially from one jurisdiction to another depending on the relevant regulations. However, the most commonly used system in a modern landfill is a single composite liner. In some jurisdictions, such as Ontario, a basic single composite liner design such as the one adopted in this paper may be permitted for landfills with up to 139,000 m^3/ha (i.e., an average thickness of waste of up to 13.9 m; MoE, 1998; Canada, 2012) and a double composite liner for MSW landfills with an average waste thickness of 14–38 m (140,000–380,000 m^3/ha), while New York State requires a double liner for all MSW landfills (DEC, 2020).

Considering Fig. 1, the pressure head acting between the GMB and GCL, h, is maximum at the center of the wrinkle and decreases with distance away from the wrinkle (Rowe, 2005, 2012, 2018b). This head on the GCL is typically calculated by using the top of the GCL as datum. If the potentiometric head in the aquifer, h_a, rises to below the GCL (Fig. 1), the wetted distance at which the head h = 0 is a_o (Rowe, 1998; Rowe et al., 2004; Barakat and Rowe, 2020). Along this distance, a_o, the GCL is, to all practical purposes, fully saturated. When h_a is below the GCL, the interface head will continuously decrease until $h \sim -C$ (m), where $C = H_{GCL} + H_{AL} - h_a$ at a wetted distance a (measured from the center of the wrinkle; Fig. 1) where the method used to calculate the distance a_o and a is given in Appendix A (Rowe, 1998; Rowe et al., 2004; Rowe and Abdelrazek, 2019). The subgrade/soil beneath the GCL is expected to be unsaturated with unsaturated downward flow at any distance x where $a_o < x \le a$. Thus, if leachate is to flow through the unsaturated soil, the magnitude of the flow will depend on the current hydraulic conductivity of the soil which is generally less than the saturated hydraulic conductivity with the difference increasing with increasing suctions (Fredlund et al., 2012). Høisæter et al. (2019) examined the leaching of PFAS and PFOS specifically through unsaturated soils, and they showed that unsaturated zones greatly attenuate PFOS, and its mobility is dependent on the infiltration rate or flux passing through the soils. In addition, tests performed by Costanza et al. (2019) showed that the transport of PFOS can be greatly impacted by its accumulation at air-water interfaces in unsaturated soils where the magnitude of PFOS accumulation was said to be directly proportional to the surface area available along these air-water interfaces. As a result, if this area is large enough, PFOS accumulation along it may result in its

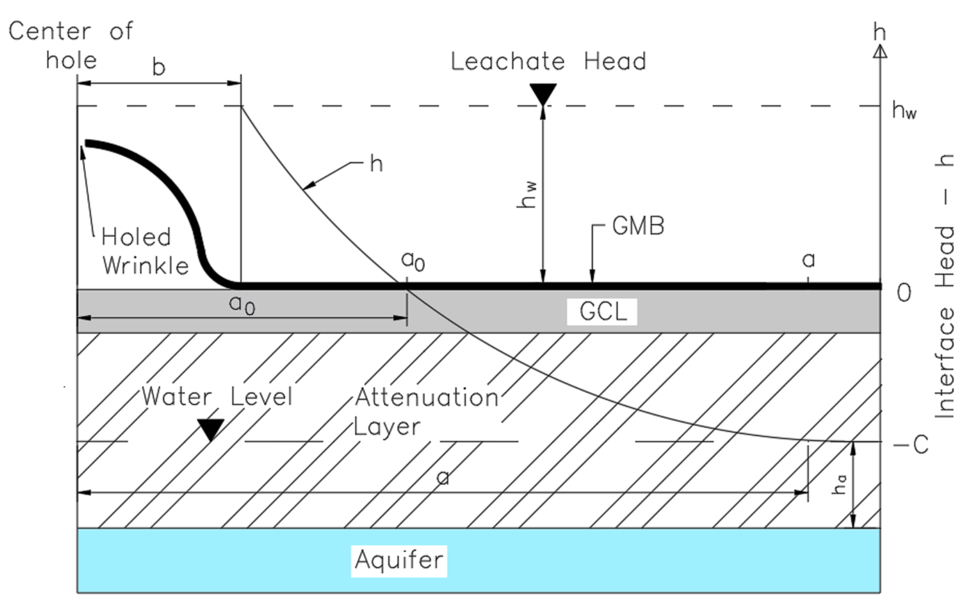

Fig. 1. Schematic showing extent of wetted distance beneath a holed wrinkle.

becoming a long-term source of contamination. Thus, to directly examine the maximum possible (relatively) short-term contamination and remain conservative, in this paper, when calculating the flow developed at the wetted distance a, the hydraulic conductivity of the GCL and subgrade beneath it are assumed to be fully saturated. The bounds of the possible range in leakage can be established using the leakage calculated for $x = a$ and $x = a_o$ in Eq A.7 of Appendix A.

The hydraulic conductivity of the GCL, k_{GCL}, varies depending on the stress applied to the composite liner (Rowe, 2018b). When a holed wrinkle is present, two different hydraulic conductivities must be considered for the GCL when estimating the leakage (Rowe, 1998; Rowe and Abdelrazek, 2019). Where the GMB is in contact with the GCL, the applied stress on the composite liner confines the GCL and k_{GCL} is denoted by k_a. Below the wrinkle, the GCL is unconfined since the applied stresses arch over the wrinkle which typically results in an increase in the magnitude of k_{GCL} along the area directly beneath the wrinkle; this k_{GCL} is denoted by k_b. The leakage, Q, through the wrinkle over a width $2x$ can then be calculated as given in Appendix A, and in this paper that flow is calculated over a width $2a$ (Rowe, 1998; Rowe et al., 2004; Rowe and Abdelrazek, 2019).

3. Problem examined

In this paper, a municipal solid waste (MSW) landfill with a length of 400 m in the direction of underlying groundwater flow is examined. The base of the landfill is lined with a single composite liner comprised of a 1.5 mm-thick HDPE geomembrane, a 7 mm-thick geosynthetic clay liner, over a 3.743 m thick attenuation layer underlain by a 3 m thick aquifer (Fig. 2). The combined thickness of the clay liner and attenuation layer was selected to be in accordance with MoE (1998). The aquifer is assumed to have a horizontal groundwater (Darcy) flux of 1 m/a. This flux was estimated by considering a horizontal gradient of around 0.004 m/m in the sand aquifer from CH2M Hill (2016) and a hydraulic conductivity of sand of 1×10^{-5} m/s. This is a relatively conservative estimate as (a) a much lower value would allow more time for diffusion into the adjacent soil to provide attenuation, and (b) a much higher value would allow more dilution to mitigate the contaminant flux into the aquifer (Rowe et al., 2004). The potentiometric head in the aquifer, $h_a = 3$ m (i.e., 3 m above the top of the aquifer and C = 0.75 m below the GMB). The different variables and base case parameters defining each of the layers are listed in Table 2. Two general scenarios were initially simulated: (i) one with an ideal GMB with no holes, and (ii) one with a composite liner having holed wrinkles/ha running perpendicular to the direction of groundwater flow (Fig. 2).

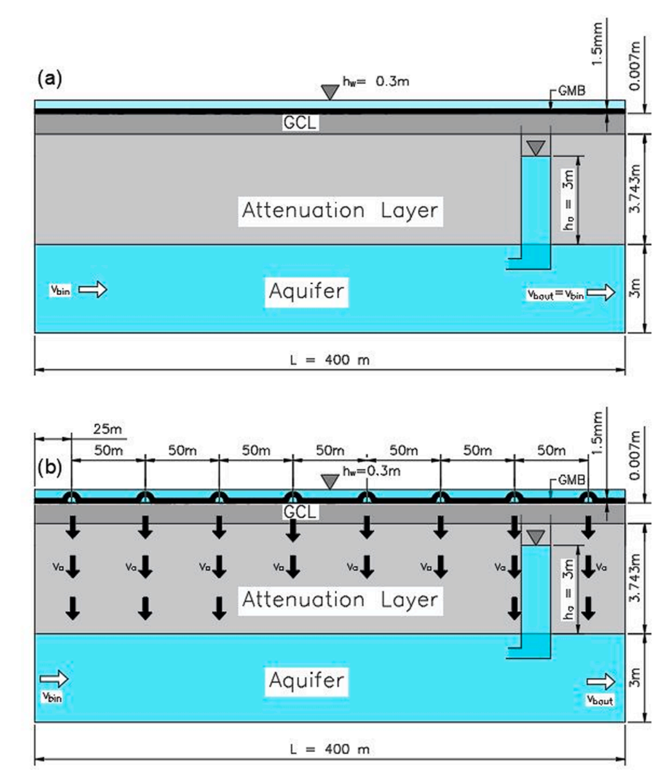

Fig. 2. Schematic of the monofill base and subgrade layers: (a) Case i – No holed wrinkles, (b) Case ii – Holed wrinkles (2 per hectare shown). Not to scale.

The landfill cover was assumed to allow an infiltration rate of 0.15 m/a (minimum permitted by MoE, 1998). The mass of waste (excluding cover soils uncontaminated at the time they were placed) per unit area in the landfill was taken to be 25,000 kg /m^2 (25 t/m^2). The leachate head maintained by the primary leachate collection system, h_w, was 0.3 m. The confining stress applied on the composite liner and GCL was assumed to exceed 100 kPa which is typical for MSW landfills with more than about 11–14 m of waste and for the case considered here, the average applied stress on the base liner, away from wrinkles, was about 250 kPa. To remain conservative, the base case concentration in the leachate was taken to be the maximum concentration of PFOS, c_o = 4800 ng/L (Li, 2011) reported for the jurisdictions being considered in this paper. It is noted that higher values of up to 6000 ng/L (Yan et al., 2015) and 7400 ng/L (Harrad et al., 2019) have been reported for landfills in Ireland and China respectively. Based on the same literature review, the ratio of mass of PFOS to mass of waste, p, was taken to be 1.2 $\times$ 10^{-3} mg/kg. This ratio was calculated by multiplying the annual volume of leachate generated from precipitation by the concentration in the leachate and then dividing this product by the annual tonnage of waste reported by Li (2011). The width of the wrinkles developed, $2b$, was taken to be 0.1 m.

4. Probability of holes in wrinkles in a geomembrane.

Chappel et al. (2012a) performed a detailed study of wrinkles in a HDPE geomembrane for summer construction in Canada. Based on their data, to achieve less than 5% of the area of a geomembrane lined facility as locked-in wrinkles, a geomembrane would need to be covered by a 0.3 m-thick ballast/drainage layer before about 8 AM or after 5 PM. To be less than 10%, it would need to be covered before about 10 AM or after 5 PM. To be less than 20%, it would need to be covered before about 12 noon or after about 3:30 PM. Combining this with the reported 5 holes/ha for good construction and quality assurance to more than 20 holes/ha with casual construction quality assurance, one can assess the probability of a hole in a wrinkle as indicated in Table 3. In fact, as discussed by Rowe (2020a), such probabilistic assessments assume an equal probability anywhere whereas wrinkles act as targets for damage and have a much higher probability of being damaged than

Table 2
Layer Parameters (h_a = 3 m, h_w = 0.3 m, see Fig. 2, and θ = 0.001 m^2/a = 3 $\times$ 10^{-11} m^2/s).

Layer	*Thickness* (m)	k (m/s)		D_e (m^2/a)	n	α – dispersivity (m)
GMB	0.0015	–		(a),(b),(c)	–	–
GCL	0.007	k_a 2 $\times$ 10^{-11}	k_b 2 $\times$ 10^{-10}	0.0012	0.7	0
Attenuation Layer	3.743	1 $\times$ 10^{-7}		0.02	0.3	0.1
Aquifer	3	–		–	0.3	3

(a) Lowest published properties for LLDPE: S_{gf} = 4 and D_g = 4 $\times$ 10^{-17} m^2/s.
(b) Conservative estimated values for LLDPE: S_{gf} = 4 and D_g = 6.6 $\times$ 10^{-16} m^2/s.
(c) GMB base case: Currently available upper bound value for HDPE at 50 °C: P_g = 6 $\times$ 10^{-16} m^2/s (S_{gf} = 4 and D_g = 1.5 $\times$ 10^{-16} m^2/s)

Table 3
Assessment of the probability of a hole in the wrinkle depending on the area below wrinkles and number of holes per hectare.

% of total area below the wrinkles	Probability of a hole in a wrinkle with		
	5 holes/ha	10 holes/ha	20 holes/ha
5	23%	40%	62%
10	41%	65%	88%
15	56%	80%	96%
20	67%	89%	99%
30	83%	97%	>99%

geomembrane that is directly in contact with the GCL; thus, Table 3 represents a minimum probability and the actual probability will be higher.

Research has shown that the wrinkles that are covered may get narrower but did not go away (Stone, 1984; Soong and Koerner, 1998; Gudina and Brachman, 2006; Brachman and Gudina, 2008).

Based on Chappel et al. (2012a,b) and Rowe et al. (2012), the average connected wrinkle lengths and maximum connected wrinkle lengths are given for different proportions of the area covered by wrinkles in Table 4. The average width of a wrinkle is reported to be 0.2–0.23 m over a GCL. Based on the average wrinkle width and connected length, one can infer the number of average wrinkles per hectare as given in Table 4. What the field data, as summarized in Table 4, shows is that as the percentage area covered by wrinkles increases, the intersection between the wrinkles increases and hence the number of individual wrinkles decreases, but the length of the interconnected wrinkles increases. Thus, the time of day that a geomembrane is covered can have a profound effect on the probability of holes intersecting wrinkles as well as on the magnitude of the leakage that will result from those holes since typically the capacity for leakage through a hole is not controlled by the hole itself but by the potential for it to leak out between the geomembrane and the GCL. Based on Canadian conditions, if the HDPE liner was covered between 11AM and 4PM on a sunny day (≥15% of area below wrinkles) and with good CQA (5 holes per hectare) or between 8AM and 5PM with typical CQA (20 holes/ha) then in either case, it is more likely than not that there would be a 200 m holed wrinkle per hectare; this will be explored as a base case.

5. Method of analysis

5.1. Pure diffusion

The first case (Fig. 2a) of only diffusion from a finite source waste disposal facility through a geomembrane with no holes and the underlying layers to the aquifer is relatively simple and was modelled using the finite layer method as initially developed by Rowe and Booker (1984) but with a modification to allow a layer to be a geomembrane with a partitioning coefficient S_{gf} as well as a diffusion coefficient, D_g, (Rowe et al., 2004) as implemented in the program POLLUTEv7 (Rowe and Booker, 2004).

Table 4
Average connected wrinkle length and maximum connected wrinkle length for ranges of total area covered by wrinkles and inferred number of average length connected wrinkles per hectare based on all the data presented in Chappel et al. (2012a,b) and Rowe et al. (2012).

Proportion of total area below the wrinkles	Average (m)	Maximum (m)	Number (–)
≤5%	100	200	≤23
5–10%	200	600	23
10–15%	1200	1800	6
15–20%	2200	2600	4
20–33%	4300	6000	4

5.2. Leakage through holes in wrinkles in a GMB

The second case (Fig. 2b) is much more complicated. This was modelled using the approach for modelling wrinkles using an analytic model, POLLUTE V7 (Rowe and Booker, 2004), published by Rowe and Abdelrazek (2019) to examine the contaminant transport of PFOS beneath the landfill when holed wrinkles were present. The equations they developed to perform the adjustments needed to model the leakage beneath the wrinkles, as slightly adjusted herein, are given in Appendix B. Rowe and Abdelrazek (2019) also compared their approach of using the finite layer analytical approach to a more conventional finite element numerical approach using common and publicly available finite element software (SEEP/W and CTRAN/W, GeoStudio, 2018) and discussed the advantages and disadvantages of the two approaches.

6. Results and discussion

6.1. Pure diffusion – no holes in geomembrane

The case with no holed wrinkles was first examined using PFOS/LLDPE parameters obtained by DiBattista et al. (2020) from almost 500 days of testing of thin 0.1 mm thick LLDPE (the reduced thickness was used to allow faster diffusion) using $S_{gf} = 4$ and $D_g = 4 \times 10^{-17}$ m^2/s. For this case, the peak impact on the aquifer water quality was 9×10^{-5} µg/L = 0.09 ng/L which is almost 100 times below the lowest allowable limit of 8×10^{-3} µg/L (8 ng/L) and does not occur until about 660 years, assuming here that the geomembrane service life exceeds 660 years. The first stage in the service life of HDPE geomembranes in a MSW can range from 10 to 900 years at 40 °C based on Std-OIT depletion, and it is largely dependent on the nature and composition of the HDPE geomembranes used (Rowe et al., 2020). However, the effect of PFAS and PFOS in leachate on the service life of the geomembrane is presently unknown but is the subject of current research at Queen's University.

DiBattista et al. (2020) also performed tests on 0.75 mm thick LLDPE and, likely due to the shorter testing time as well as the greater thickness, obtained an order of magnitude higher upper bound estimate of the diffusion coefficient, $D_g \le 6.6 \times 10^{-16}$ m^2/s. Thus, an analysis was also performed using the, likely very conservative, PFOS/LLDPE diffusion parameters $S_{gf} = 4$ and $D_g = 6.6 \times 10^{-16}$ m^2/s. Here, the peak impact on the aquifer water quality was 2×10^{-3} µg/L = 2 ng/L which is more than 4-fold below the lowest allowable limit of 8×10^{-3} µg/L (8 ng/L) and does not occur until about 350 years (assuming the geomembrane service life exceeds 350 years).

The authors have conducted diffusion tests on HDPE geomembranes and, at 50 °C, the permeation coefficient $P_g \le 6 \times 10^{-16}$ m^2/s. Thus, calculations were performed for corresponding PFOS/HDPE diffusion parameters $S_{gf} = 4$ and $D_g = 1.5 \times 10^{-16}$ m^2/s. For HDPE and these upper bound values of S_{gf} and D_g for MSW landfills ≤ 50 °C, the peak impact on the aquifer water quality was 4.2×10^{-4} µg/L (0.42 ng/L) which is more than 20-fold below the lowest allowable limit of 8×10^{-3} µg/L (8 ng/L) and does not occur until about 425 years (assuming the geomembrane service life exceeds 425 years).

The foregoing results indicate that an intact 1.5 mm HDPE geomembrane is likely to be a very effective diffusion barrier to PFOS and that for the conditions examined if it can be installed and maintained without any holes, it is likely to have an acceptable impact on groundwater quality even by the most stringent requirements if there was an attenuation layer of 3.75 m or more between the geomembrane and the groundwater. Indeed, even if there were no attenuation layer and the receiving aquifer was directly below the liner, the peak impact for the worst-case parameters used above would 1.2 ng/L at 160 years and still below the lowest allowable limit. In short, this analysis indicates that a 1.5 mm thick, completely intact and undamaged HDPE geomembrane would be an outstanding barrier to the escape of PFOS from a MSW landfill containing leachate with PFOS concentrations at levels up to 4800 ng/L considered in this analysis.

However, as previously indicated, even with a very high-quality electrical leak location survey, pin holes are likely to be missed in the exposed geomembrane and larger holes may be missed once it is covered by the drainage layer, and in the absence of an electrical leak location survey but good quality assurance, holes in a wrinkle can be expected as indicated in the next subsection.

6.2. Effect of 200 m of holed wrinkle per hectare.

Following from the earlier discussion, a 200 m long wrinkle per hectare is more likely than not unless there was exceptional construction quality assurance combined with a leak location survey. Thus, the base case to be considered assumes 200 m long wrinkle per hectare corresponding to 8 intersections of holed wrinkles in the geomembrane along the 400 m length in the groundwater flow cross-section being analyzed with the parameters given in Table 2. The leakage calculated to be flowing through and beneath a single holed wrinkle was 13 m^3/a/ha (35 lphd). To put this in context, it is less than the leakage in 76% of primary liners for about 120 landfill cells with a double liner system in New York (based on Gilson-Beck, 2019). For this case (ID: H1–8), the predicted peak PFOS concentration in the aquifer was 110 ng/L at 225 years after landfill development (Table 5). This is below the maximum allowable PFOS limits for Canada and Texas, but, exceeds the threshold limits of Australia, Europe (as proposed), California, New York, and Michigan. Thus, in 60% of the jurisdictions considered in this base case, a single composite liner would not limit contaminant escape to an acceptable value unless there was exceptional construction quality assurance to minimize both wrinkles and holes in wrinkles to the maximum extent practical.

6.3. Effect of interface transmissivity, θ, and GCL hydraulic conductivity, k, on PFOS impact

The calculated impact depends on a number of key variables (Table 2) other than the length of the holed wrinkle and the heads, h_w and h_a. These variables are the interface transmissivity, θ, and GCL hydraulic conductivity, both beneath, k_b, and away from the wrinkle, k_a. The base parameters used represent the best estimates of GCL hydraulic conductivity based on the data reported by Li et al. (2015) for MSW leachate spiked with a combination of perfluoronated compounds were used to permeate bentonite barriers, Bouazza (2021) as previously discussed, and extensive studies conducted by the senior author (e.g., Rowe et al., 2004; Rowe, 2020b) assuming good design and construction quality assurance.

Studies of interface transmissivity have been undertaken by several investigators (Fukuoka, 1986; Brown et al., 1989; Giroud and Bonaparte, 1989; Harpur et al., 1993; Rowe, 1998; Touze-Foltz, 2002; Needham et al., 2004; Rowe and Abdelatty, 2007; Mendes et al., 2010; Rowe and Abdelatty, 2013; Bannour and Touze-Foltz, 2015; Rowe and Hosney, 2015; AbdelRazek and Rowe, 2016, 2017, 2019a,b; AbdelRazek et al., 2016). Most recently, Rowe (2020b), Rowe and Jabin (2021a, 2021b) reported experimental data showing that the geomembrane/GCL interface transmissivity of the composite liner and the hydraulic conductivity of the GCL vary depending on the pressures applied on the liner and, the types of GMB and GCL used. Other factors that can contribute to these two parameters are the permeant used for hydration and nature of the material components of the GCL (Rowe and Jabin, in preparation). Tests performed by Rowe and Jabin (in preparation) estimated transmissivity values that ranged from 0.5 to 0.0002 m^2/a for an applied stress of 100 kPa or higher, with the most likely value being the base case value of 0.001 m^2/a.

Table 5
Results obtained for a range of interface transmissivities, θ (m^2/a) and GCL hydraulic conductivities k_a, in contact with the geomembrane, and k_b, below the wrinkle ($q_o = 0.15$ ($m^3/m^2/a = m/a$), $c_o = 4800$ ng/L, $p = 1.2 \times 10^{-3}$ mg/kg).

Case ID	θ (m^2/a)	k_a (m/s)	k_b (m/s)	Q (lphd)	c_{peak} (ng/L)	Time (yrs)
H1–8	0.001	2×10^{-11}	2×10^{-10}	35	110	220
H2–8	0.01	2×10^{-11}	2×10^{-10}	58	190	215
H3–8	0.1	2×10^{-11}	2×10^{-10}	130	320	160
H4–8	0.001	2×10^{-10}	2×10^{-9}	68	240	170
H3/4–8	0.1	2×10^{-10}	2×10^{-9}	280	810	135

While these case parameters represent the authors' current best estimates, there is also uncertainty and hence a range of values were examined and the implication of reasonable uncertainty on leachate leakage beneath holed wrinkles and thus contaminant transport of PFOS will now be examined.

With respect to the uncertainty regarding interface transmissivity, two simulations were performed with transmissivities [H2–8 ($\theta = 0.01$ m^2/a) and H3–8 ($\theta = 0.1$ m^2/a)] one and two orders of magnitude higher than the base case (best) estimate and the results are given in Table 5.

Relative to the base case (H1–8: $\theta = 0.001$ m^2/a) with leakage, Q, of 35 lphd and the peak PFOS concentration in the aquifer, c_p, of 110 ng/L, increasing θ by one order of magnitude increased Q to 58 lphd and c_p to 190 ng/l (H2–8: $\theta = 0.01$ m^2/a) while increasing θ by two orders of magnitude increased Q to 130 lphd and c_p to 320 ng/L (H3–8: $\theta = 0.1$ m^2/a). For the base case, the requirements of Texas and all of Canada would be satisfied. With an order of magnitude increase in θ, Ontario's requirements would no longer be satisfied, and with a 2 order of magnitude increase in θ, British Columbia's and Texas's requirements would no longer be satisfied. The leakages examined here of 58 lphd and 130 lphd are less than the leakage in 64% and 35% of primary liners for about 120 landfill cells with a double liner system in New York (based on Gilson-Beck, 2019).

Assuming good construction practice but allowing for cation exchange and the effective stress, the most likely hydraulic conductivities for a scrim reinforced thermally treated GCL with high-quality natural sodium bentonite would be $k_a = 2 \times 10^{-11}$ m/s and $k_b = 2 \times 10^{-10}$ m/s. To put these numbers in context, Bouazza (2021) conducted hydraulic conductivity tests at an effective stress of 35 kPa on a GCL with a needle-punched GCL with a scrim reinforced thermally treated carrier geotextile permeated by MSW landfill leachate containing a variety of PFAS, including PFOS, and obtained a hydraulic conductivity of 4×10^{-11} m/s. This is a typical value that might be expected between $k_a = 2 \times 10^{-11}$ m/s at effective stresses $\geq$100 kPa and $k_b = 2 \times 10^{-10}$ m/s at $\sim$0 kPa. If the composite liner is left exposed for a prolonged period of time there is potential for wet dry cycles and/or downslope erosion to increase the hydraulic conductivity by at least one order of magnitude and in a severe cases 2 to 3 orders of magnitude. To assess the impact of the higher GCL hydraulic conductivities, Case H4 – 8 was simulated where both k_a and k_b were increased by one order of magnitude each whilst keeping all other parameters constant. For this case, the leakage and peak impact were 68 lphd and 240 ng/l, satisfying the requirements of Texas and Canada except Ontario.

Lastly, the worst case of increasing θ by 2 orders of magnitude and k_a and k_b by one order of magnitude (Case H3/4–8,) increased the leakage more than 8-fold to $Q = 280$ lphd (less than the leakage in 10% of primary liners for about 120 landfill cells with a double liner system in New York) and c_p more than 7-fold to 810 ng/L which would fail to meet the requirements of any of the jurisdictions being considered. However, this case should be regarded as an extreme case since it combines the highest PFOS initial landfill leachate concentration found in the literature for the jurisdictions under consideration, extremely conservative interface transmissivity for a geomembrane/GCL under an applied stress exceeding 100 kPa, and a very conservative estimate hydraulic conductivity of the GCL.

6.4. Effect of peak PFOS leachate concentration on PFOS contamination

The previous section showed that the parameters defined for case H3/4–8 resulted in the most contamination. Thus, both the base case (best estimate) (H1–8) and worst case (H3/4–8) parameters will be adopted for further analysis from this point onwards. Up to this point, the maximum concentration detected in landfill leachate from the literature for the jurisdictions being considered (c_o = 4800 ng/L) was chosen as the PFOS initial concentration for the simulations. In this section, the mean calculated from three different groupings of published leachate PFOS concentration data for containment facilities (Eggen et al., 2010; Li, 2011; Huset et al., 2011; Benskin et al., 2012; Li et al., 2012; Clarke et al., 2015; Yan et al., 2015; Lang, 2016; Gallen et al., 2018; Harrad et al., 2019; Simmons, 2019) are examined. These three values were: (i) if the data is lognormally distributed then the geometric mean (c_o = 160 ng/L) would be the expected peak leachate value (i.e. 50% of values would be above 50% would be below this value); (ii) if the data is normally distributed then the arithmetic mean (c_o = 740 ng/L) would be the expected peak leachate value; and (iii) if the peak value for each facility is lognormally distributed then the geometric mean (1670 ng/L) would be the expected peak leachate value. These three values are considered because there is still considerable uncertainty regarding the statistical distribution of concentration of PFOS in leachate.

Analyses with an initial PFOS concentration c_o = 160 ng/L gave (Table 6) PFOS c_p = 17 ng/L (B1–8) and 80 ng/L (B3/4–8). Case B1-8 meets the requirements of all jurisdictions considered except Michigan and New York. Case B3/4–8 meets the requirements of all jurisdictions considered except Australia, California, Michigan, and New York.

Similarly, c_o = 740 ng/L gave (Table 6) PFOS c_p = 50 ng/L (C1–8) and 285 ng/L (C3/4–8). Finally, c_o = 1670 ng/L gave (Table 6) PFOS c_p = 75 ng/L (D1–8) and 490 ng/L (D3/4–8). Case C1-8 meets the requirements of all jurisdictions considered except California, Michigan, and New York; Case D1-8 meets the requirements of all jurisdictions considered except Australia, California, Michigan, and New York. Case C3/4–8 meets the requirements of all jurisdictions considered except Australia, Ontario, California, Michigan, and New York. Case D3/4–8 meets the requirements of Canada (excluding British Columbia and Ontario). Thus, the choice of the initial peak concentration in the leachate has a significant impact on the peak concentration in the aquifer, but because of the finite mass of the contaminant ($p = 1.2 \times 10^{-3}$ mg/kg and contaminated soil mass of 25000 kg/m^2 implies 30 mg/m^2 of PFOS) and the infiltration through the cover (0.15 m^3/m^2/a) with the leachate not escaping through the liner being collected and treated, the c_p, is not linearly related to the initial concentration, c_o, as it would be if there were an infinite mass of contaminant.

Table 6
Peak concentration, c_p, in the aquifer for different c_o values (q_o = 0.15 m/a, $p = 1.2 \times 10^{-3}$ mg/kg).

Case ID	c_o (ng/L)	θ (m^2/a)	k_a (m/s)	k_b (m/s)	Q (lphd)	c_{peak} (ng/L)	Time (yrs)
H1–8	4800	0.001	2×10^{-11}	2×10^{-10}	35	110	220
B1–8	160	0.001	2×10^{-11}	2×10^{-10}	35	17	510
C1–8	740	0.001	2×10^{-11}	2×10^{-10}	35	50	345
D1–8	1670	0.001	2×10^{-11}	2×10^{-10}	35	75	280
H3/4–8	4800	0.1	2×10^{-10}	2×10^{-9}	280	810	135
B3/4–8	160	0.1	2×10^{-10}	2×10^{-9}	280	80	245
C3/4–8	740	0.1	2×10^{-10}	2×10^{-9}	280	290	185
D3/4–8	1670	0.1	2×10^{-10}	2×10^{-9}	280	490	160

6.5. Impact of number of holed wrinkles on PFOS contamination

As discussed previously, the number of wrinkles with holes will depend on weather conditions and the time of day that the composite liner is covered. To demonstrate the significant role that can be played simply by the time of day a composite liner is covered, the effect of number of holed wrinkles/ha (0.5, 1, 2, and 4 holed wrinkles/ha) on leakage, Q, and peak impact, c_p, were examined for expected Case H1 and worst Case H3/4 with c_o = 4800 ng/L. Thus, a total of 2, 4, 8, and 16 holed wrinkles in the landfill base intersecting a cross-section parallel to the direction of groundwater flow were considered and the results are given in Table 7.

The results of the simulations performed using H1 parameters (the most likely values of θ, k_a, and k_b) show that even with only 0.5 holed wrinkles/ha (i.e. one 100 m holed wrinkle every 200 m) in the GMB, the threshold limits set by Michigan and New York were exceeded (H1 – 2). When the number of holed wrinkles was increased to 1 holed wrinkles/ha, the simulation results showing the peak concentrations of PFOS detected in the aquifer exceeded California's, Michigan's and New York's allowable limits. At 2 holed wrinkles/ha, c_p surpassed the limits for Australia, Europe, California, Michigan, and New York. At 3 and 4 holed wrinkles/ha, c_p surpassed the limits for Australia, Ontario, Europe, California, Michigan, and New York, but were still acceptable in Canada except for Ontario and Texas.

Using the hydraulic conductivity and interface transmissivity parameters defined for the worst case, H3/4, c_p for only 0.5 holed wrinkles/ha exceeded the limits for Australia, Ontario, Europe, California, Michigan, and New York. At 1 holed wrinkle/ha, British Columbia's and Texas's limits were also exceeded. For 2 or more holed wrinkles/ha, all the limits considered were exceeded (Table 7).

7. Discussion and summary of results

Based on the analyses for a range of leakage values at and the probability of a given leakage being exceeded for the primary liner in over hundred 120 landfill cells with double liners in New York State, Table 8 summarizes the probability of exceeding specific leakages calculated with a single composite liner. The corresponding probability that the impact is less than indicated for a single composite liner for the assumed conditions (q_o = 0.15 (m^3/m^2/a = m/a), c_o = 4800 ng/L, $p = 1.2 \times 10^{-3}$ mg/kg) is also given in Table 8. Fig. 3 shows that the calculated probability of exceeding regulatory limits for a single composite liner and the conditions modelled is about 95% for New York State (but it is not a problem for New York State since they require double liners for all MSW landfills), 90% for California (CA), 85% for Australia, about 80% for Europe (but they generally rely on a thicker attenuation layer so yhe probability is likely lower than 80% but still high), 75% for Ontario (but it is not a problem for Ontario since they require double liners for MSW landfills of the size examined), a little over 50% for British Columbia (BC) and Texas, a little over 20% for Canada excluding Ontario and British Columbia.

The forgoing analysis has demonstrated that none of the cases considered with holes in wrinkles resulted in acceptable peak PFOS concentrations in the states of Michigan or New York for a single composite liner. Thus, since zero, or essentially zero, leakage is an unrealistic expectation for a single composite liner, for the states of Michigan and New York, a double composite liner needs to be installed to have any confidence in maintaining an acceptable impact of PFOS in a MSW landfill for the conditions examined in this paper (as noted previously, New York already requires double lined landfills for municipal solid waste).

A landfill with the same properties as those defined for H1 would meet the groundwater impact requirements of the state of California, for

Table 7
Peak concentrations for different number of wrinkles ($q_o = 0.15$ ($m^3/m^2/a = m/a$),. $c_o = 4800$ ng/L, $p = 1.2 \times 10^{-3}$ mg/kg).

Case ID	N	N/ha	θ (m^2/a)	k_a (m/s)	k_b (m/s)	a (m)	c_{peak} (ng/L)	Time (yrs)
H1 – 2	2	0.5	0.001	2×10^{-11}	2×10^{-10}	3.88	31	255
H1 – 4	4	1	0.001	2×10^{-11}	2×10^{-10}	3.88	58	245
H1–8	8	2	0.001	2×10^{-11}	2×10^{-10}	3.88	110	220
H1-12	12	3	0.001	2×10^{-11}	2×10^{-10}	3.88	178	210
H1 – 16	16	4	0.001	2×10^{-11}	2×10^{-10}	3.88	238	200
H3/4 – 2	2	0.5	0.1	2×10^{-10}	2×10^{-9}	16.6	260	180
H3/4 – 4	4	1	0.1	2×10^{-10}	2×10^{-9}	16.6	520	160
H3/4–8	8	2	0.1	2×10^{-10}	2×10^{-9}	16.6	810	135
H3/4–12	12	3	0.1	2×10^{-10}	2×10^{-9}	16.6	949	100
H3/4 – 16	16	4	0.1	2×10^{-10}	2×10^{-9}	12.5	1200	90

Table 8
Probability of exceeding specific leakages with a single composite liner, the corresponding peak impact for the case considered, and the probability the impact is less then indicated for a single composite liner for the assumed conditions ($q_o = 0.15$ ($m^3/m^2/a = m/a$), $c_o = 4800$ ng/L, $p = 1.2 \times 10^{-3}$ mg/kg).

Leakage (lphd)	Probability of exceeding leakage	c_{peak} (ng/L)	Probability impact is less
0	>99%	8	<1%
9	>90%	30	<10%
18	>88%	60	<12%
35	>76%	110	<24%
53	>67%	180	<33%
71	>57%	260	<43%
140	>30%	520	<70%
280	>10%	810	<90%
430	>6%	950	<94%

municipal solid waste with 30 mg/m^2 (or less PFOS) generating leachate with $c_o \leq 4800$ ng/L, provided that the number of holed wrinkles present along the landfill are limited to one 100 m long holed wrinkles per 200 m of the landfill in the direction of groundwater flow. This is achievable but only with extraordinary construction quality assurance, evening/night covering of the geomembrane, and a very high-quality electrical leak location survey. Even if the PFOS concentration $c_o \leq$ 160 ng/L, only two holed 100 m long wrinkles/ha (H1-8, Table 6) could achieve the groundwater impact limits for California, and only with the most likely geomembrane/GCL parameters. The most likely parameters will not always be realized since the hydraulic conductivity of the GCL is known to be dependent on the type of GCL, its exposure history and hydration, and applied stress (Rowe, 2020b). The interface transmissivity can also be impacted by the normal stress applied on the composite liner. Again, these results are suggesting that a double liner system would be prudent for a MSW landfill in California.

The results obtained from the different cases simulated showed that under the defined base parameters (H-1) and all the PFOS c_o concentrations considered, the peak impacts c_p in the aquifer were acceptable in Australia and Europe for up to 1 holed, 100 m long, wrinkle/ha, in Ontario for up to and including 2 holed wrinkles/ha. For Canada other than in Ontario and Texas, regulatory limits were met for 4 holed wrinkles/ha for the base defined hydraulic conductivity and transmissivity. For the cases with 2 holed wrinkles/ha simulated, as soon as k_a, k_b, or θ was increased by an order of magnitude, the concentrations detected in the aquifer were unacceptable for Australia, Ontario, Europe, California, Michigan, and New York.

If the composite liner utilized is known to have a wide possible range of hydraulic conductivity of the GCL or interface transmissivity, a limit must be set on the background concentration of PFOS present in the waste. For example, when using the parameters defined for the cases identified by H3/4, acceptable PFOS aquifer concentrations were achieved in Ontario when $c_o \leq 160$ ng/L. As in the case of California, it may be possible to construct a single composite liner that would give acceptable impact in Ontario, but it would be very difficult to provide assurance that it was achieved, and it would be prudent to use a double composite liner. Notwithstanding the foregoing, based on the allowable limits of PFOS in groundwater, it would be prudent to dispose of MSW waste in a landfill with a double composite liner in Australia, British Columbia, Ontario, Europe, California, Michigan, Texas and New York state.

For Canada (excluding British Columbia and Ontario), there is a

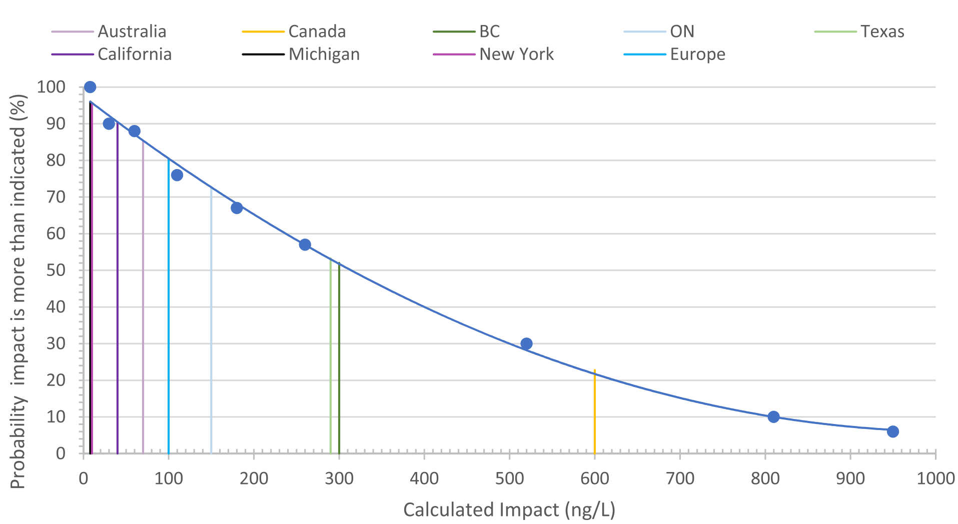

Fig. 3. Calculated probability of exceeding a specific PFOS concentration in aquifer for the conditions examined based on the probability of leakage inferred from Gilson Beck (2019).

reasonable chance that groundwater quality criteria would be met with a single composite liner, which is typically used in landfills, and an attenuation layer of 3.75 m or greater provided that there was good construction quality assurance and an electrical leak location to limit to no more than 200 m of holed wrinkles per hectare, but each situation would need to be examined critically to provide an assurance that this would be indeed true for each specific case.

8. Conclusion

Rowe and Abdelrazek's (2019) approach to modelling contaminant transport through holed wrinkles using a finite layer model was adapted to assess the transport of PFOS from the waste through the base of a MSW landfill with a composite liner comprised of a 1.5 mm thick HDPE GMB over a 7 mm thick GCL, and about a 3.75 m thick attenuation layer above an aquifer. The results obtained from the different simulations were compared to the maximum allowable PFOS limits for groundwater/drinking water in Australia, Canada, Europe, and four of the 10 most populated US states (California, Texas, New York, and Michigan) representing the range of allowable limits in drinking water/groundwater for states with such limits. Based on the parameters examined and the allowable limits in the jurisdictions considered at the time of writing, it is concluded that:

1. A 1.5 mm HDPE geomembrane was an excellent diffusion barrier to PFOS, and if it could be constructed without any holes (zero leakage), it would satisfy the requirements of all jurisdictions considered. However, based on literature cited, it is unreasonable to expect zero leakage with a single composite liner over the contaminating lifespan of a MSW landfill.
2. PFOS threshold limits for Michigan and proposed for New York are sufficiently stringent that analyses involving leakage through the composite liner were exceeded for all cases examined. A double composite liner would likely be required in both jurisdictions.
3. The suitability of a single composite liner for the other jurisdictions considered was dependent on the peak concentration of PFOS in the landfill leachate, the level of construction quality assurance and hence limit on number of holed wrinkles per hectare, geomembrane/GCL interface transmissivity, and GCL hydraulic conductivity. This is especially true for Australia, California, Texas, Ontario, and British Columbia and in those jurisdictions, either a low peak leachate concentration and/or a very high level of construction quality assurance would be required to meet PFOS limits with a single composite liner.
4. Given the sensitivity of impact on reasonable variability in the input parameters relating to contaminant source, geomembrane-GCL properties, and the number of holed wrinkles, this paper has demonstrated that analyses similar to those performed in this paper would be required to provide any assurance of the likely reliability of a single composite liner for containing PFOS in a MSW landfill.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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