Groundwater Quality Monitoring at Lined Landfills: Adequacy of Subtitle D Approaches[1]

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Introduction

It has been recognized for many years that municipal solid waste (MSW) in contact with moisture produces a leachate that contains a myriad chemicals that can be hazardous or otherwise deleterious to the quality of water that could be used for domestic and certain other purposes. The conventional approach for "disposal" of MSW has been to bury it. In an attempt to address the groundwater quality protection issues and at the same time maintain conventional "landfilling" approaches for MSW management, in October 1991 the US EPA (1991) promulgated Subtitle D regulations for the landfilling of MSW. Those regulations specified that as a minimum, MSW landfills shall have a single composite liner, consisting of plastic sheeting (flexible membrane liner - FML) overlying and in contact with two feet of compacted soil-clay with a maximum permeability of $1x10^{-7}$ cm/sec. When such a landfill is closed, i.e., stops receiving wastes, it is to be covered with a low-permeability cover in an attempt to keep the buried wastes dry. The concept is that if no moisture contacts the wastes, no leachate should be generated, and there should be little threat to the quality of groundwater hydraulically connected to the landfill area. Since it is recognized that landfills will generate leachate at least during the active life, leachate collection and removal systems are included; the FML in the composite liner is the key functional component of that system since it serves as the base on which the leachate is transported by gravity to a sump for removal.

In sum, the landfilling approach set forth in Subtitle D is an attempt to create a "dry tomb" in which to store wastes in perpetuity. The containment and other ancillary features of "dry tomb" landfills have been incorporated for the purpose of trying to protect groundwater from adverse impacts of landfill leachate. Realities of the engineered systems of "dry tomb" landfills are, however, that moisture does enter covered landfills; plastic liners commonly have holes in them from the outset of landfilling; the integrity of liner systems deteriorates over time; liner systems are buried beneath hundreds of feet of garbage and are thus not available for inspection and repair/replacement; the leachate collection and removal systems are subject to failure; and the hazardous and deleterious nature of the materials buried in a dry tomb MSW landfill do not in general significantly diminish with the passage of time but rather remain a threat to groundwater quality forever. These issues have been discussed in the technical literature and reviewed elsewhere by the authors (Lee and Jones, 1992a,b; Jones-Lee and Lee, 1993).

Applicants for MSW and industrial "non-hazardous" waste landfills as well as hazardous waste landfills commonly advance a "groundwater protection" scenario that gives the impression

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[1] Reference as Lee, G. F., and Jones-Lee, A., “Groundwater Quality Monitoring at Lined Landfills: Adequacy of Subtitle D Approaches,” Report of G. Fred Lee & Associates, El Macero, CA (1993).

of providing groundwater quality protection even in light of the deficiencies of "dry tomb" landfills. A representative scenario is:

> *When the landfill liners and leachate collection and removal systems fail to prevent leachate from polluting groundwaters, the groundwater monitoring program will detect the pollution before it becomes widespread. Once groundwater pollution is detected, remediation programs can be initiated not only to prevent the spread of the polluted groundwater but also to clean up the polluted groundwater and aquifer to usable condition.*

There are some who go so far as to claim that such an approach is "fail-safe" protection of groundwater quality.

Such scenarios delivered with confidence can be very reassuring to the public and appear to assuage concerns of many regulators about the public health and groundwater resource threats posed by "modern" lined "dry tomb" MSW landfills. However, those provisions do not address the realities of groundwater monitoring programs at lined MSW landfills and their ability to provide assurance of groundwater quality protection, or of the ability to sufficiently remediate leachate-contaminated groundwaters or aquifers.

A typical groundwater monitoring program associated with a lined, "dry tomb" MSW landfill today, and as outlined by Subtitle D, consists of a nominal array of wells, one or two up-groundwater-gradient and several along the down-groundwater-gradient perimeter of the landfill (the "point of compliance"); down-gradient wells are often hundreds to thousands of feet apart. Sampling is often done quarterly after purging several borehole-volumes of water from the wells. A critical review of the ability of a typical and, indeed, even a more extraordinary, conventional groundwater quality monitoring program associated with lined MSW landfills reveals that the number of wells and their spacing and operation are such that the monitoring programs have relatively low probabilities of detecting groundwater pollution by leachate from lined MSW landfills before widespread groundwater pollution has occurred. The inevitable leakage from lined "dry tomb" MSW landfills is likely to be first detected in production wells downgradient of the landfill; by that time, extensive groundwater pollution would have occurred.

The gravity of this situation and the importance of understanding the inadequate "protection" afforded by conventional groundwater monitoring at lined MSW landfills are amplified by the fact that once a groundwater is contaminated by MSW landfill leachate, neither the contaminated water nor the contaminated areas of the aquifer can be "cleaned up" to the point at which they could be used again for domestic water supply purposes (Rowe, 1991; Lee and Jones, 1992a; Jones-Lee and Lee, 1993). The damage to groundwater is due not only to potentially "hazardous" chemicals (Priority Pollutants) (such as lead, cadmium, mercury, and several organic solvents) in municipal solid waste landfill leachate, but also to the conventional and non-conventional pollutants (Jones-Lee and Lee, 1993). "Non-conventional" pollutants are organic chemicals in MSW leachate that have not been specifically identified but are known to be present from determinations of total organic carbon (TOC); they comprise about 95% of the organics in MSW leachate as measured by TOC. Since they are not individually identified in chemical analysis regimens, their characteristics and potential impacts are not known.

Conventional and non-conventional pollutants in municipal solid wastes buried, untreated, in "dry tomb" landfills represent a threat to domestic water supply water quality for thousands of years, effectively forever, as long as they remain in the landfill (Lee and Jones, 1992b; Jones-Lee and Lee, 1993). Therefore, if lined MSW landfills of the type being constructed today are to be located in areas hydraulically connected to groundwater that could ever be used for domestic purposes, it is imperative that landfill leakage monitoring programs be developed that will, in reality, detect leachate-leakage at the earliest possible time and long before groundwater pollution occurs.

Another presumption that is often tacitly incorporated into municipal solid waste landfill monitoring and groundwater quality "protection" scenarios is that groundwater monitoring at municipal and industrial lined "dry tomb" landfills of the type being constructed today and described in Subtitle D will only be required for 30 yrs beyond closure of the landfill. As noted above and discussed by Jones-Lee and Lee (1993), municipal solid wastes contain a wide variety of hazardous heavy metals, inorganic salts, non-degradable organics, and degradable organic residues that can readily render groundwaters un-usable for domestic water supply purposes because of the threats to public health and aesthetic quality, and impacts on plumbing, household fixtures, etc. All of those constituents will be a threat to groundwater quality as long as wastes are present in the landfill. Therefore, the groundwater quality protection and leachate leakage detection systems for a "dry tomb" landfill must be designed and maintained to function in perpetuity.

Regulatory Requirements

In October 1991 US EPA (1991) released the federal minimum requirements for Subtitle D (municipal solid waste) landfills. Those regulations stated with regard to groundwater monitoring,

> *"The ground-water monitoring system must consist of a sufficient number of appropriately located wells able to yield ground-water samples from the uppermost aquifer that represent the quality of background ground water and the quality of ground water passing the relevant point of compliance as specified by the Director of an approved State."*

and

> *"The relevant point of compliance specified by the Director of an approved State shall be no more than 150 meters from the waste management unit boundary and shall be located on land owned by the owner of the MSWLF* [municipal solid waste landfill] *unit."*

As an example of state groundwater monitoring requirements for landfills, the California Water Resources Control Board regulations (WRCB, 1984; 1991) require "detection monitoring"

> *"...to provide the best assurance of the detection of subsequent releases from the waste management unit."* [Article 5 of Chapter 15 (Section 2550.1)]

Further, California regulations require that a sufficient number of monitoring wells be located so that they

> *"...provide for the best assurance of the earliest possible detection of a release from a waste management unit."*

Section 2550.5, Article 5 of Chapter 15 (WRCB, 1991) states with regard to monitoring points and the point of compliance,

> *"(a) For each waste management unit, the regional board shall specify in the waste discharge requirements the point of compliance at which the water quality protection standard of Section 2550.2 of this article applies. The point of compliance is a vertical surface located at the hydraulically downgradient limit of the waste management unit that extends through the uppermost aquifer underlying the unit."*

Those requirements notwithstanding, the typical groundwater monitoring program developed for the purpose of complying with the California (and other states') regulations for waste management units has a low probability of detecting leakage through a landfill liner at the "earliest possible" time as required. In California and elsewhere in the US, groundwater monitoring programs for lined MSW landfills are not based on a critical analytical evaluation of the ability of the monitoring program to comply with such requirements but rather on incorrect assumptions about the nature and movement of leachate from lined municipal solid waste and other landfills and the ability of vertical groundwater monitoring wells to intercept that leakage at the point of compliance.

Issues for Consideration

Nature of Points of Leachate Origin and Horizontal Spread of Leachate-Contaminated Groundwater

A fundamental problem with typical groundwater monitoring programs for landfills described above is that they have been developed from perceptions of leakage from *unlined* landfills without proper consideration for the manner in which *lined* landfills leak and pollute groundwater. Conventional unlined sanitary landfills are expected to leak leachate over a considerable part of the bottom of the landfill. Therefore, even though the lateral spread of a plume of leachate-contaminated groundwater is very limited (Cherry, 1990), the plume of leachate-contaminated groundwater in some types of geological/hydrogeological strata would move downgradient as a wide front downgradient of the unlined landfill (Figure 1). Under those conditions, close well-spacing may not be critical for the detection of groundwater contamination by leachate. However, this is not the character of leakage from lined landfills or movement of leachate-contaminated groundwater.

Some existing MSW landfills and all MSW landfills constructed after October 1993 will include a composite liner composed of a flexible membrane liner (FML) (plastic sheet) and a compacted soil layer below it. While in concept a composite liner can provide greater postponement of leakage than the sum of the two liner components, the true composite character is difficult to achieve in practical applications (Lee and Jones, 1992a). As discussed by Lee and Jones (1992a,c), the initial leakage from such lined facilities occurs at point-sources such as holes, rips, and tears in the FML created at the time of construction or waste deposition. The clay layer beneath the FML is compacted to achieve a prescribed, initial design permeability, which means that even when new, the soil/clay layer will transport leachate. Through Darcy's Law calculations it can be seen that a compacted soil layer provides only a short-term slowing of the leakage of leachate through the liner; one foot of clay compacted to 10^{-7} cm/sec permeability, with one foot of head, will be breached in less than ten years. Workman and Keeble (1989) discussed the time it takes leachate to breach a clay layer used as a liner. There is increasing evidence that in addition to general permeability, such liners leak through imperfections that are created at the time of liner construction. Further, compacted clays used as liners are subject to desiccation cracking, cation exchange shrinking, cracking due to differential settling, impact by chemicals, etc. creating additional points through which leachate can leak, and allowing transport of leachate through the liner at a rate greater than expected based on the design permeability.

Thus, as also discussed by Bumb *et al.* (1988) and Glass *et al.* (1988), the initial leaking of leachate from lined landfills will occur from point sources in the liners, rather than uniformly from the landfill bottom as may be expected from unlined landfills. That fact changes the significance to groundwater monitoring of Cherry's (1990) finding that the lateral spread of a plume of leachate-contaminated groundwater is limited. In a study of the lateral dispersion of leachate plumes from lined landfills, Smyth (1991) of the Waterloo Centre for Groundwater Research, University of Waterloo, reported that a 0.6-m (2-ft)-wide point-source tracer spread laterally to a width of only about 2 m (6 ft) after traveling 65 m (213 ft) in a sand aquifer system. Thus it is clear that leakage from point sources such as holes in liners will move downgradient as narrow "fingers" of leachate (Figure 2) rather than in the traditionally assumed fan-shaped plumes. This means that conventional wells used for monitoring of lined landfills must be placed close enough together at the point of compliance to detect narrow fingers of leachate if the monitoring program is to comply with Subtitle D requirements for the detection of incipient groundwater pollution from waste management unit at the point of compliance.

The typical groundwater monitoring well used today has a four- to eight-inch diameter borehole. Such wells are normally purged prior to the quarterly or so sampling by removal of three to five borehole-volumes of water. Thus the zones of capture for such monitoring wells are on the order of a foot about each well. Since the lateral spread of a finger of leachate-contaminated groundwater from a lined landfill is minimal, monitoring wells that are spaced hundreds of feet apart at the downgradient edge of a lined landfill have a very low probability of detecting the fingers of leachate produced by leaks in the liner system (Figure 2). Those fingers of leachate could travel long distances before groundwater pollution by the landfill is detected.

Parsons and Davis (1992) discussed issues of monitoring well spacing and zones of capture of monitoring wells associated with waste management units. As they discussed and as illustrated in Figure 3, in order to have a high probability of detecting leachate leakage from a waste management unit, the spacing of standard monitoring wells at the point of compliance must be such that zones of capture overlap. Thus, in order to be effective in achieving the groundwater monitoring performance standard of Subtitle D described above, conventional

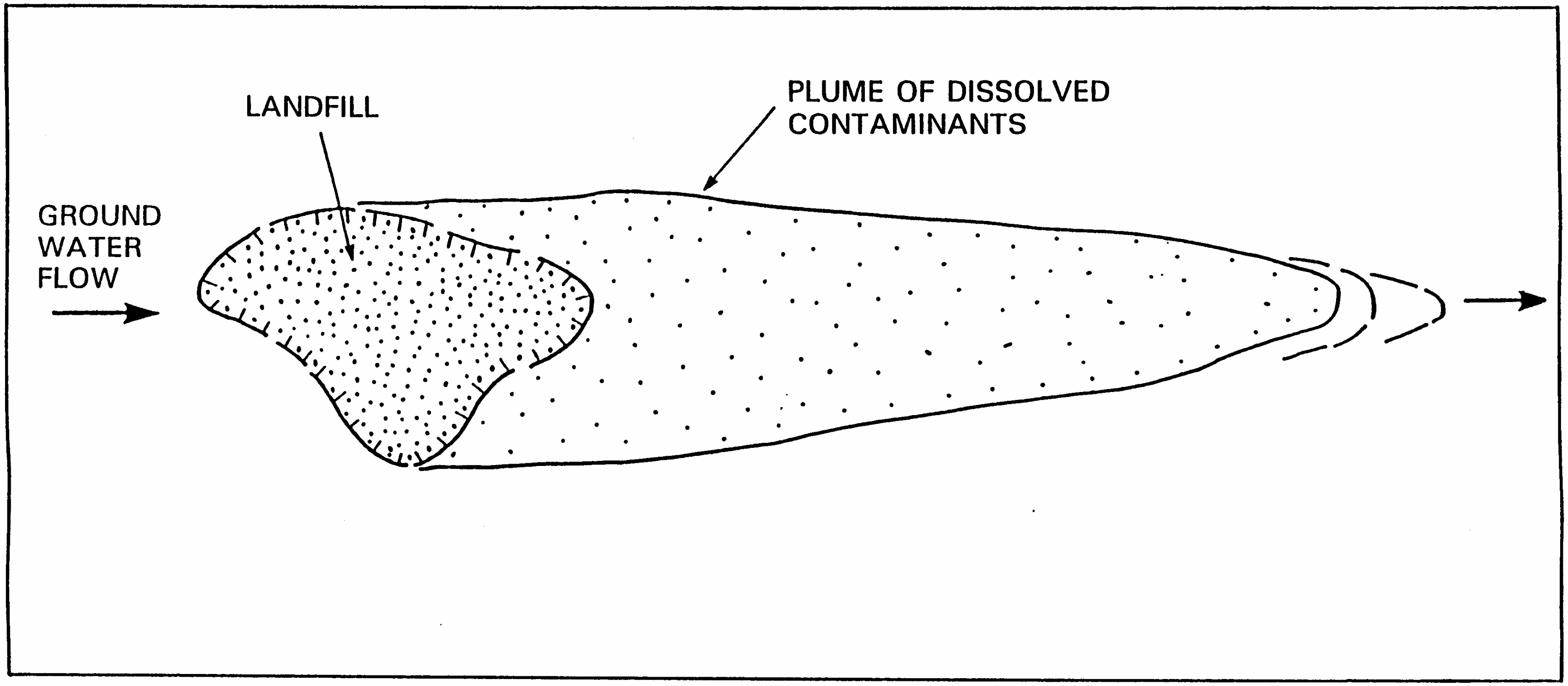

Figure 1. Pattern of Landfill Leakage – Groundwater Contamination – from Unlined Landfills
(after Cherry, 1990)

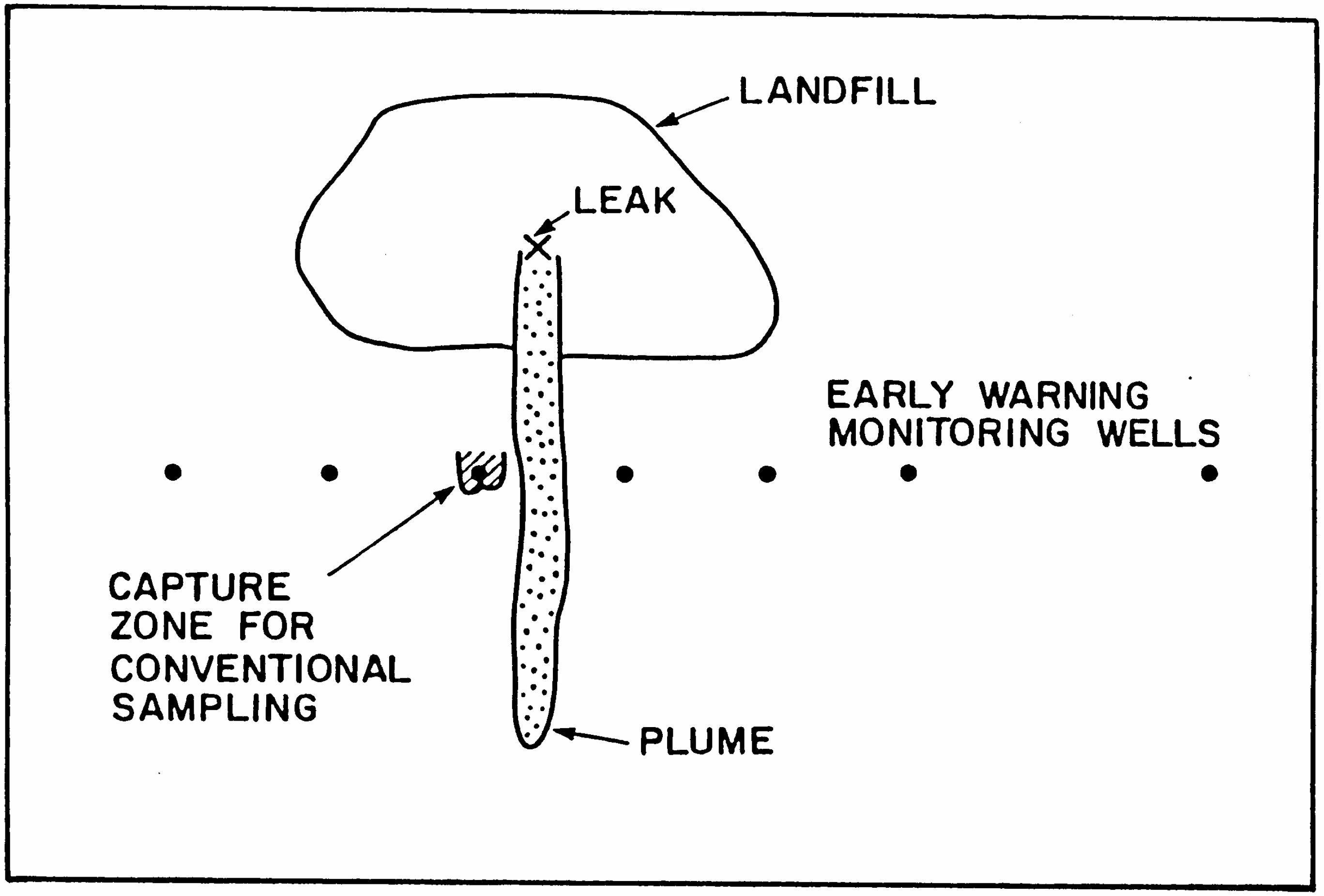

Figure 2. Pattern of Landfill Leakage – Groundwater Contamination – from Lined Landfills (after Cherry, 1990)

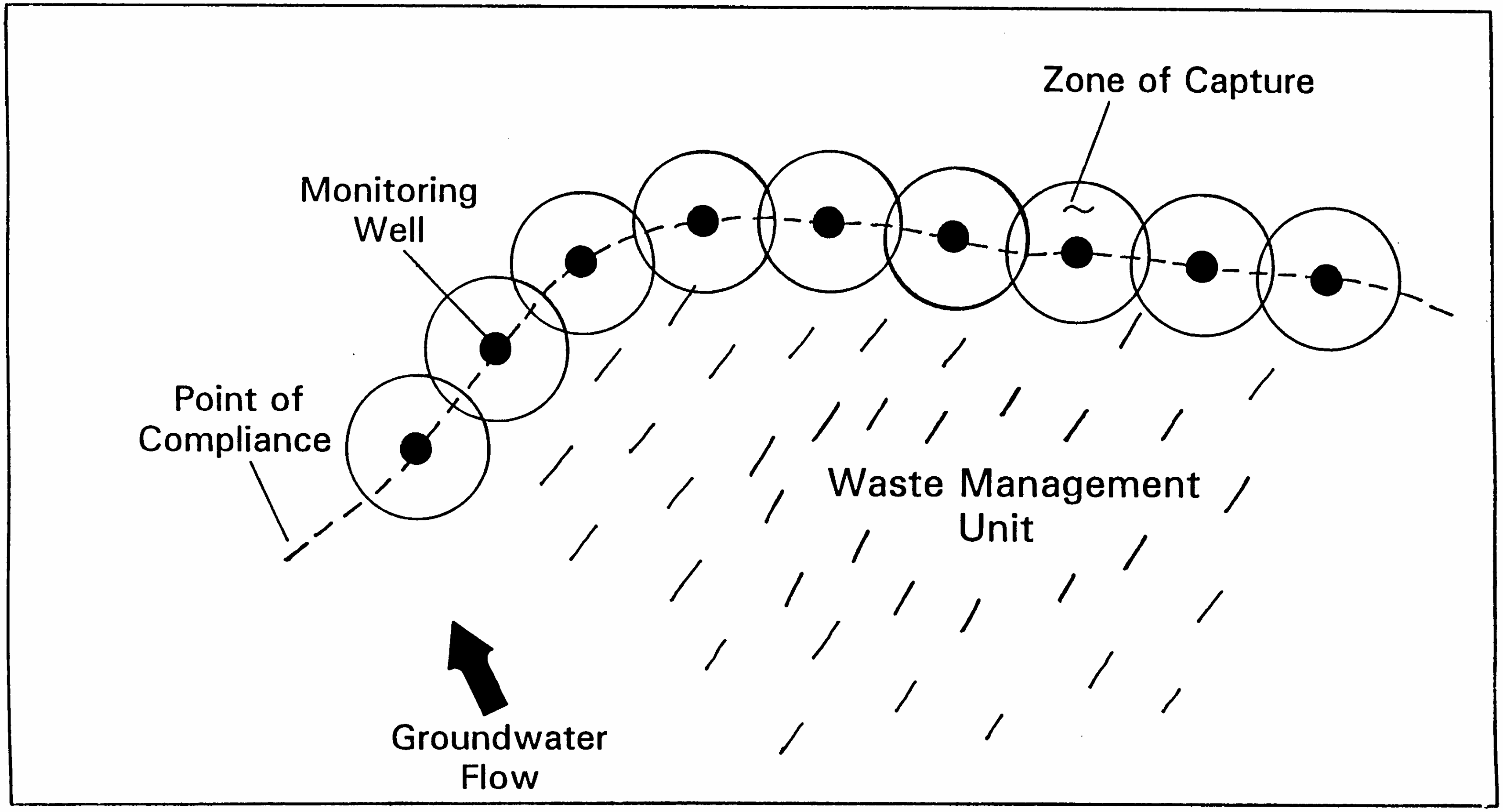

Figure 3. Zones of Capture of Standard Monitoring Wells Must Overlap to Detect Leakage from Lined Landfills (after Parsons and Davis, 1992)

vertical groundwater monitoring wells would have to be spaced no more than a few feet apart along the entire down-gradient edge of the landfill, creating a "picket fence" of wells.

Lee and Jones (1992a) discussed the fact that in addition to initial leakage from holes and other point-sources, FML's and compacted soil-clay liners deteriorate in performance over time, ultimately becoming essentially ineffective as barriers to leachate migration. Once massive and widespread failure of the liner system has occurred, the typical groundwater quality monitoring program of the type being designed today may be expected to be able to detect landfill pollution of groundwater. However by that time, the groundwaters would have been extensively polluted by the leachate that had been leaking.

Vertical Migration and Hydrogeological Considerations

According to Cherry (1991) leachate from municipal landfills can contain sufficient amounts of salt to cause them to be somewhat more dense than the area groundwaters. This would cause a finger-plume of leachate to sink along its horizontal trajectory until it becomes sufficiently diluted so that its density matches that of the area groundwater. Obviously, the hydrogeology of the area beneath and down-gradient from the landfill must be defined with a high degree of certainty if a potentially meaningful groundwater monitoring program is to be developed to detect landfill leakage.

The ability to define the shape and movement of a contaminant finger-plume from a lined landfill depends on the hydrogeological characteristics of the aquifer strata. In homogeneous, isotropic "sand" systems, the vertical and horizontal spread of point source discharges-leaks from a given point can be estimated with some degree of reliability. However, the hydrogeology of many locations in which landfills are sited is sufficiently complex so that predictions of the spread of a leachate plume are fairly unreliable. The presence of fractured bedrock, fissures, cavernous calcareous strata, and non-isotropic lenticular aquifers (such as former river beds) make the reliable prediction of flow paths from point-source leaks from lined landfills more difficult or even impossible and make the monitoring of groundwater for incipient leachate-pollution highly unreliable and virtually impossible. Haitjema (1991) stated,

> *"An extreme example of Equation (1) (aquifer heterogeneity) is flow through fractured rock. The design of monitoring well systems in such an environment is a nightmare and usually not more than a blind gamble."*
>
> * * *
>
> *"Monitoring wells in the regional aquifer are unreliable detectors of local leaks in a landfill."*

Even the fact that a monitoring well intercepts a fissure/crack does not mean that the leachate in that fissure system is reliably sampled during groundwater monitoring. The amount of water extracted during sampling is typically quite small; the result is that the zone of capture about the monitoring well, even in a fracture, is often very limited. Thus, leachate-contaminated groundwater can be present in a fracture without its being detected by the monitoring programs typically used.

Therefore, in addition to misconceptions about the nature of the spread of leachate from lined landfills, incomplete or unreliable assessment of the geological features of the subsurface system, and complex hydrogeology can further reduce the probability that the typical groundwater monitoring well array will intercept any plume of leachate-contaminated groundwater at the point of compliance for the MSW landfill monitoring program.

Volume of Leakage

There are some who try to argue that leaks from imperfections, perforations, holes, tears, and cracks in lined MSW landfills will be relatively inconsequential to groundwater quality on the basis of the assumption that the volume of groundwater that will be polluted will be "small." A review of the technical information available pertaining to the ability of lined landfills to prevent leachate migration shows that even new, well-designed and well-constructed composite-lined MSW landfills can leak beginning shortly after construction at a rate that can pollute large amounts of groundwater (Lee and Jones, 1992a). In their investigation of top-liner leakage in double-lined systems (including composite-lined systems), Bonaparte and Gross (1990) reported that even with good quality assurance in construction such liners leak shortly after being place into service; the rate of leakage they reported to be expected was 200 liters/hectare/day (20 gallons/acre/day). Further, the US EPA (1989) stated,

> *"EPA realizes that even with a good construction quality assurance plan, flexible membrane liners (FMLs) will allow some liquid transmission either through water vapor permeation of an intact FML, or through small pinholes or tears in a slightly flawed FML. Leakage rates resulting from these mechanisms can range from less than 1 to 300 gallons per acre per day (gal/acre/day)."*

As discussed by Jones-Lee and Lee (1993), because of the characteristically very high concentrations of a variety of contaminants in municipal landfill leachate, even "small" amounts of leachate (a few gal/acre/day) can pollute large amounts of groundwater with "hazardous" and "non-hazardous" but otherwise deleterious chemicals to a sufficient degree to render the groundwater unusable for domestic water supply purposes. Further, as discussed above, an aquifer contaminated with municipal landfill leachate cannot be "cleaned up" so that the waters in the aquifer would ever again be considered safe for domestic water supply use (Lee and Jones, 1991a; 1992a; Jones-Lee and Lee, 1993).

Monitoring Goal: Protecting Groundwater Quality

The US EPA Subtitle D regulations, as well as the MSW landfilling regulations of California and other states, indicate the intent to prevent the pollution of groundwater by landfill leachate. Landfill applicants have been known to cite groundwater monitoring programs as the last and ultimate defense against groundwater pollution by the facility. However, by their very nature, even if able to detect incipient leachate-pollution, groundwater monitoring programs do not detect leakage until the groundwater is already polluted. As noted above, once a groundwater and associated aquifer are polluted by landfill leachate, they are unsuitable for use as domestic water supplies; the groundwater cannot be considered safe even after conventional treatment to meet drinking water standards.

That fundamental flaw notwithstanding, while the groundwater monitoring performance standards of Subtitle D - to reliably assess the quality of groundwater passing the point of compliance - would appear to ensure a high degree of reliability in the groundwater monitoring system, the manner in which Subtitle D is implemented will allow significant groundwater pollution before action is required. US EPA (1991) stated with regard to the design of the groundwater monitoring program,

> *"The design must ensure that the concentration values listed in Table 1 of this section will not be exceeded in the uppermost aquifer at the relevant point of compliance, as specified by the Director of an approved State under paragraph (d) of this section,"*

While the Subtitle D allows a single composite liner to be equivalent in performance to meeting Table 1 requirements, it is obvious that this is inappropriate because of the eventual failure of the minimum Subtitle D liners to prevent leachate from entering the groundwater system underlying the landfill.

Table 1 includes only two dozen chemicals. While the chemicals named in that Table 1 are deleterious to beneficial uses of groundwater, they are not necessarily the most reliable indicators of incipient pollution of groundwater by MSW landfill leachate. As discussed by Lee and Jones (1983), more appropriate indicator parameters include the common bulk constituents of leachate such as sodium, chloride, sulfate, iron, manganese, and hydrogen sulfide. Further, all groundwater monitoring near landfills should include measurement of dissolved oxygen in the field. Because of the high oxygen demand of MSW landfill leachate, changes in dissolved oxygen concentration in an aquifer near a landfill can be a very sensitive indicator of leachate-pollution.

The values presented in Subtitle D's Table 1 are basically drinking water standards. Thus Subtitle D requires that drinking water standards be exceeded in a groundwater before action must be taken. There is a myriad non-conventional pollutants in MSW landfill leachate that may be hazardous to public health and numerous conventional pollutants for which there are no drinking water standards, or that are not included on Table 1, that are not being considered in making these evaluations of groundwater "pollution" by landfill leachate.

Another issue of concern regarding current approach for implementing regulatory provisions for guarding groundwater quality is the requirement to demonstrate a statistically significant increase in concentration of certain parameters across the landfill (upgradient vs. downgradient) With that demonstration, certain actions must be taken to investigate the extent of pollution; remediation must be initiated to clean up the aquifer to the extent possible. This presents a number of significant problems. First, some groundwater monitoring programs cannot incorporate reliable "upgradient" groundwater monitoring. This is of particular concern in landfills in head-areas of canyons or where there is a groundwater recharge divide. The construction of landfills in such areas alters the characteristics of the groundwater and therefore renders the "upgradient" - "downgradient" statistical evaluation of the groundwater characteristics unreliable for monitoring for evidence of groundwater pollution. Second, the groundwater monitoring program may not be sufficiently rigorous to enable the demonstration of statistical significance of the concentration differences across a landfill that may, in fact, indicate groundwater pollution.

A fundamental problem with regulations for and design of groundwater monitoring systems for lined MSW landfills is that they focus on component design and construction; inadequate attention is provided to the ability of the monitoring system - the numbers, types, and placement of wells, frequency of sampling, etc. - to meet the monitoring needs, i.e., to detect incipient groundwater pollution. Books on the topic of groundwater monitoring - such as that edited by Nielsen (1991) entitled, Practical Handbook of Ground-Water Monitoring, provide a wealth of information on the details of monitoring system components, but precious little on the issues of establishing a reliable groundwater monitoring system for the purpose at hand. In that book, Sara (1991) presented the chapter on "Ground-Water Monitoring System Design." He discussed many important considerations for establishing a general groundwater monitoring program for relatively simple hydrogeological settings with readily defined flow paths; focus was on broad leakage from unlined landfills. However, he did not discuss the additional groundwater monitoring challenges associated with lined landfills, and provided no guidance on how to develop a monitoring program to detect incipient leakage from such a unit that occurs, as discussed above, as narrow finger-plumes from point sources rather than as wide contaminant plumes. This is a significant omission since many waste management units in existence, as well as those that will be developed in the future, are lined. A critical analysis of the possible flow paths for lined MSW landfills shows that conventional vertical groundwater monitoring wells have little probability of reliably intercepting all plausible flow paths, which as discussed by Sara (1991) is a necessary component of a reliable groundwater monitoring system.

While the details of the monitoring well construction, etc. are important, in order to be a reliable monitoring program it must be appropriately developed to meet the objectives and purpose for the monitoring program. For many situations, such as definition of chemical characteristics of aquifers, or determination of the areal extent and degree of pollution of groundwater at Superfund sites or sites of chemical spills, use of conventional groundwater monitoring wells and well-arrays may be appropriate for intercepting all reasonable identified flow paths in meeting the groundwater sampling needs. For detection of incipient leakage from lined MSW landfills, however, the issue of paramount importance is the ability to intercept each potential flow path for narrow finger-plumes of leachate-contaminated groundwater that could emanate from any and all point sources in a liner system in complex hydrogeological systems. Parsons and Davis (1992) provided a decision matrix for developing a groundwater monitoring system that, if properly implemented, could meet the regulatory requirement for detection of incipient groundwater pollution at the point of compliance.

Some suggest that the monitoring of MSW landfill gases with conventional soil gas probes or other, dedicated gas leak detection systems such as the LASP system of Teledyne Geotech (1993), can be used to indicate liner leakage. In principle, detection of methane in the soil around a landfill or under the liner would be a clear indication that the liner system is not functioning as intended. However, in practice, some regulatory agencies tend to dismiss evidence of pollution of groundwater by MSW landfill gas-associated contaminants as irrelevant because it is not from liquid "leachate," even though MSW landfill gases including CO_2, methane, and chlorinated VOC's, can readily render a groundwater unusable for domestic purposes. While CO_2 is not typically considered a groundwater "pollutant," it can cause the dissolution of calcium carbonate in calcareous strata and lead to increased hardness and other scale-forming constituents that shorten the life of hot water heaters, dishwashers, other appliances, plumbing, and clothing, and increase energy consumption. This condition promotes the use of home water softeners which can increase the discharge sodium and chloride that can adversely affect water quality. Water utilities and homeowners throughout the country spend large amounts of money removing hardness from water because of its deleterious effects. The real issue is groundwater use-impairment, independent of the mode of pollutant transport - by leachate or gas. Furthermore, MSW landfills with efficient gas collection/removal systems may not show evidence of liner failure to prevent gas migration to the vadose zone.

In summary, it is prudent public health and groundwater quality protection strategy to consider any transport of MSW landfill leachate or gas to the substratum to be a significant threat to groundwater quality and cause for initiation of corrective action, independent of whether a drinking water standard is exceeded in the groundwater. Once leachate or gas breaches the landfill liner system, it is only a matter of time before groundwater pollution occurs. It is inappropriate, and not in keeping with the requirements for groundwater quality protection to wait until groundwater is polluted and groundwater monitoring (or downgradient production wells) detects the pollution, before action is taken to stop the pollution. Because of the virtual impossibility of monitoring incipient groundwater pollution as required in Subtitle D with conventional monitoring approaches, groundwater monitoring-based leakage detection systems cannot be relied upon to protect groundwater quality since by their very nature they require the prior pollution of groundwater.

Vadose Zone Monitoring

Vadose zone monitoring offers the potential for detecting incipient leakage of landfill liners. Unlike the US EPA Subtitle D requirement, California Chapter 15 regulations require that vadose zone monitoring be incorporated into MSW, as well as other, landfill designs if possible. WRCB (1991) states that a detection monitoring program, should incorporate a

> *"... sufficient number of monitoring points established at appropriate locations and depths to yield soil-pore liquid samples or soil-pore liquid measurements that provide the best assurance of the earliest possible detection of a release from the waste management unit;"*

However, the vadose zone monitoring systems that have been installed at landfills to meet this requirement, are typically inadequate to provide significantly reliable detection of incipient unsaturated transport of leachate.

Ballestero *et al.* (1991) described vadose zone monitoring methodologies and principles of unsaturated flow. As discussed by Lee (1991) some of the vadose zone monitoring approaches that have been allowed by regulatory agencies reflect a lack of understanding of the principles of unsaturated flow. For example, regulatory agencies have allowed landfill applicants to construct vertical boreholes as "vadose zone monitoring systems." Since vadose zone transport of fluid is typically to and through the smallest pores, a large pore, such as a borehole, would be avoided by the liquid moving through the vadose zone; such a system would thus not reliably sample unsaturated flow.

Significant problems have also been encountered with the use of pan lysimeters for unsaturated flow monitoring. Regulatory agencies have approved pan lysimeter systems consisting of few-foot area pans filled with gravel, placed under the landfill's clay liner, and connected to the surface with a tube through which fluid collected in the pan could be extracted. The coarse media in the pans are large pores that, as noted above, would be avoided by the unsaturated flow; the unsaturated flow path of leachate would be around such the pan, not into it. Further, even if the pans were filled with appropriate media to allow collection in the unsaturated flow path, the areal extent of the pans is small compared with the area through which unsaturated flow could occur. Such a system would, therefore, have a low probability of detecting incipient liner leakage.

Keller (1992a) reviewed key technical issues of the inappropriateness and unreliability of french drains (perforated pipe imbedded in gravel) as a vadose zone monitoring device for landfills. In concept, leachate leakage is supposed to flow through the unsaturated zone into the gravel and into the pipe, and be drained by gravity; leachate would be detected when the pipe produces liquid. As Keller discussed, however, because of the gravel medium, in order for such a system to collect leakage, the soil above the drain would have to be saturated. This would not be expected to occur with incipient unsaturated leachate leakage from a lined landfill. Even relatively large leakage rates would be undetectable even with relatively close spacing of the drain pipes.

Bumb *et al.* (1988) described parameters of importance in developing a vadose zone liner leak detection system using suction lysimeters. They estimated the necessary spacing of soil pore moisture sampling probes in a homogeneous medium under landfills and surface impoundments for effective vadose zone monitoring for "early warning systems" for liner leakage. The number and spacing required for suction lysimeters depends on the degree of saturation, the depth of sampling under the leak, the size of the hole (high-permeability area) in the liner, the rate of leakage, the hydraulic conductivity of the soil, the volume of fluid that must be collected and the duration of the collection period, the suction applied to the lysimeter, and the depth to the watertable. To illustrate their findings, they computed that in a particular loamy sand with a saturated hydraulic conductivity of 10^{-6} cm/sec, the maximum spacing of ceramic lysimeters would be 15.5 ft at a depth of 30 ft beneath the liner in order to collect 10 mL of liquid in one week, emanating from a 1-ft^2 area; for silty clays, the maximum lysimeter spacing was estimated to be 7 ft at a depth of 2 ft.

The authors were involved in a large-scale study of unsaturated transport of contaminants associated with wastewater spreading operations (Lee, 1991). In those studies it was found that porous vacuum cup lysimeters spaced a few feet apart in an undisturbed natural soil system yielded liquid that varied significantly in amount and chemical character. This is attributed to the pattern of unsaturated flow even beneath an even source of liquid.

Bumb *et al.* (1988) noted that heterogeneities in the stratum beneath a lined landfill or other facility being monitored, such as fractures, pockets of high and low permeability, or different soil types, can result in the passage of leachate as "fingers," and that monitoring networks need to make proper account of such conditions. Glass *et al*. (1988) also discussed the "fingering" phenomenon of liquid moving through unsaturated soil and noted that finger structures were associated with the textural changes in the soil, macropores in the soil, and other flow-concentrating features in the soil profile such as clay lenses and rocks. They reported that the instability of the wetting front in the vadose zone causes the formation of "fingers" of liquid that transport liquid more rapidly through the zone than expected based on "average" conditions. Implications of this characteristic of liquid movement through unsaturated areas for monitoring and predicting the fate of contaminants in the unsaturated zone are clear.

Glass *et al.* (1988) noted that monitoring programs commonly consist of collection of samples at a few locations. Depending on whether the monitoring intercepted a "finger" or not, it might indicate a higher or lower movement than "average." In landfill monitoring for groundwater quality protection, the key is the detection of incipient (first) leakage, so the interception of a finger would be fortuitous, but not predictable in establishing the monitoring program. The failure to intercept a "finger," the more probable situation, would result in failure to detect incipient leakage. Glass *et al.* concluded,

> *"The combination of instability, macropores and heterogeneities in the properties of the porous media leads to a much more complex water flow field than with any of them acting alone and poses a severe challenge for the modeling and monitoring of toxics within the vadose zone."*

Biggar and Nielsen (1976) had described the need to properly consider the flow paths of unsaturated transport of moisture, on a site-specific basis, nearly two decades ago. A statistical evaluation must be done in order to establish a reliable vadose zone monitoring network that has a determinable probability of detecting incipient leakage from any point in a landfill liner. For that analysis, the zone of capture of vadose zone monitoring devices must be matched to the potential flow paths through the vadose zone and the reliability with which detection of contaminant transport in the vadose zone is desired. If high reliability is desired, the sampling devices must be closely spaced; the zones of capture must overlap.

Keller (1991) described a vadose zone monitoring system that can be incorporated into the design of a lined landfill and may offer the potential to provide better early detection of liner leaks than currently used approaches. That system involves installation of a grid of small-diameter pipes in a sand layer beneath the landfill liner. Samples can be collected at various locations in the grid using the SEAMIST borehole membrane sampling system. Such a vadose zone monitoring system could be particularly effective for gas phase sampling for VOC's, but would have limited applicability for leachate monitoring unless the grid of pipes was very closely spaced.

While vadose zone monitoring offers the potential to provide early warning of liner leaks, in practice it is likely to be somewhat less effective in detecting liner leaks than the full-landfill-area pan lysimeter liner leak detection system. One of the major problems of vadose zone monitoring is that it is not possible to determine mass transport of liquid and contaminants through the region where sampling takes place based on the liquid collected. Lee (1991) reviewed some of the problems with trying to use vacuum cup lysimeters to quantitatively assess the chemical characteristics of the liquid in the vadose zone. In the operation of vacuum cup lysimeters, typically substantially greater vacuum is drawn on the lysimeter than the soil moisture tension. That can significantly change the moisture content in the vicinity of the lysimeter which, in turn, can set off a series of chemical reactions that alter the composition of the moisture sampled by the lysimeter. In addition, sorption and precipitation reactions can occur within the lysimeter probe that can also alter the composition of the fluid sampled.

The regulatory issue as typically framed today is not whether liner leaks occur but whether the leaks are of sufficient magnitude and composition to impair the use of groundwaters. Without knowledge of the amounts of contaminants being transported in the vadose zone, there will likely be considerable controversy over interpretation of the data collected in vadose zone monitoring. It will not be possible to reliably determine whether the leak detected in the vadose zone represents a leak of sufficient magnitude to cause an impairment of use of the groundwaters hydraulically connected to the landfill. With the full-landfill-area pan lysimeter approach, a rate of leachate collection in the pan can be determined which could enable more reliable interpretation of the significance of leachate leakage for groundwater pollution.

Those regulatory considerations notwithstanding, as discussed elsewhere, the magnitude of the allowable leakage rate (US EPA Action Liner Leakage Rate, ALR) should be based on a critical, in-depth, site-specific evaluation of the amount of leachate leakage through the liner that could impair the beneficial uses of the groundwaters. It is highly inappropriate to establish ALR's based on achievable performance of liner materials (e.g., plastic sheeting) chosen because of their low cost; the liner performance should be judged by the adequacy of groundwater quality protection they provide. The purpose of the liners is not to save the landfill applicant money in their construction, but to provide for protection of groundwater quality from pollution by landfill leachate for as long as the wastes represent a threat. Because of the high concentrations of even known hazardous and otherwise deleterious constituents in municipal solid waste landfill leachate, very small amounts of leakage can readily pollute large amounts of groundwater, rendering it unusable for domestic water supply purposes. Further, the presence of large amounts of non-conventional, unidentified organic contaminants in municipal landfill leachate that are not measured as individual compounds in groundwater monitoring programs, would also be expected to threaten the quality of groundwater that is or could be used for domestic purposes. Therefore, it is prudent public health policy to assume that any leachate-contamination of groundwater identified by any monitored parameter, independent of whether a drinking water standard exists for the parameter or the concentration of the monitored parameter exceeds a drinking water standard, should be considered to be excessive leakage that requires corrective action.

An alternative approach to collection of vadose zone liquid for monitoring for landfill liner leakage is to monitor for changes in moisture or salt content in the vadose zone. An increase in the moisture content could be used to signal a leak in the liner. Daniel *et al.* (1992) reported on the short-term performance of four vadose zone probes for such leak detection. The probes used were gypsum blocks, fiberglass resistance cells, heat dissipation sensors, and electrical resistivity probes. All of those probes performed satisfactorily in detecting changes in moisture content or salt content of the vadose zone moisture during the several-month period of study. However, for such systems to provide reliable "early detection," they must be able to function beneath lined landfill in perpetuity. In addition to concern about the basic structural materials of the probe, consideration must be given to the durability and life-time of the electrical contacts and connecting wires. There is little likelihood that non-retrievable moisture or salt detection devices of the type tested by Daniel *et al.* could function reliably for as long as the wastes represent a threat.

High Watertable Liner Leak Detection Systems

Landfills located in canyons, wetlands, and certain other areas can intercept springs where the watertable is at the surface of the ground. As an "engineered alternative" to the required physical separation between the bottom of the wastes and the high watertable (e.g., in California, 5 ft of separation), landfill applicants have been allowed to construct drainage layers which typically consist of a foot or two of sand below the landfill liner. The groundwater that normally would be discharged from the spring would, in concept, be carried in the drainage layer below the landfill and thereby achieve an "engineered" separation between the high watertable and the wastes. There are significant questions about the ability of sand layer drains and other groundwater drainage or diversion systems to function effectively ad infinitum to prevent groundwater from entering the wastes and producing additional leachate; such systems are known to be subject to clogging, structural integrity failure, etc.

Some landfill applicants proposing to place landfills in areas with high watertables with such "engineered alternative" separation have made claims that the groundwater drainage system will also serve as a "leak detection system." Such systems have a low probability of detecting incipient liner leakage. In order to be effective, monitoring parameters for leachate leakage must not be diluted to concentrations below reliable detection limits. Much greater dilution will occur in an underdrain groundwater diversion system than in the aquifer.

Further, since a high watertable is typically not uniform across the bottom of a landfill, there will be areas where groundwater is discharged at the surface, and other areas where the surface waters would enter the aquifer. In order for the underdrain system to reliably transport leachate that enters it, the upward flow of groundwater toward the landfill must be everywhere sufficient to prevent the leachate from passing through the underdrain into the underlying groundwater system. While landfill applicants and their consultants claim that no leachate-contaminated groundwater would pass into the aquifer because the drainage layer media is more permeable, it is obvious that such claims are without technical merit. In areas where there is not sufficient upward flow of groundwater, leachate-contaminated groundwater derived from upgradient areas of leakage through the liner would pass into the aquifer and not necessarily be detected by sampling of the underdrain water. The construction of the landfill often changes the groundwater hydrology, usually in unpredictable ways. At some sites, the upward flow of groundwater will be typically less after the landfill is constructed due to diminished groundwater recharge in the area. Because of this, more of the leachate-contaminated groundwater will enter the aquifer than predicted based on the pre-landfill conditions. In those areas where there is no upward flow of groundwater into the drain, leachate that passes through the liner will pass through the groundwater drain into the underlying aquifer system.

Overall, it can be concluded that groundwater drains constructed to compensate for high watertables will not be reliable for detecting incipient liner leakage that could lead to groundwater pollution.

Reliability of Groundwater Data

It has been the authors' experience that data generated from many groundwater monitoring programs are often unreliable and the quality of the data in reports is often "qualified" because of improper sample collection, handling, and processing; the inappropriate use of "standard" analytical methods; and the alteration of the chemical composition of the water being sampled by improper design and construction of monitoring wells. Because of these common problems, the chemical composition data generated in conventional groundwater monitoring programs are often highly erratic and unreliable, especially for some of the most important pollution-related parameters, such as heavy metals and volatile organic compounds (VOC's). It is rare that the chemical composition of groundwater would be as erratic as commonly reported based on groundwater monitoring.

A common indicator of improper monitoring well design, construction and/or sampling is the presence of significant amounts of particulate matter (suspended solids) in groundwater samples. Any time there are measurable amounts of particulate matter in a groundwater sample, the groundwater has not been reliably sampled. Some state regulatory agencies allow groundwater samples to be filtered when they contain notable suspended solids, prior to analysis for heavy metals and other constituents. That approach is well-known to be inappropriate. Aquifer particulates present in groundwater samples can readily sorb what had been dissolved contaminants derived from landfill leachate that are being transported in the aquifer. The filtration of such samples prior to analysis removes heavy metals and certain other contaminants that had been dissolved in the groundwater, and thus causes the underestimation of the concentrations of those contaminants in the groundwater. In order to eliminate the confusion about whether the metals measured were derived from the aquifer water or from the solids incorporated into a sample, the US EPA does not allow filtration of groundwater samples. If a landfill owner/operator does not construct and sample its monitoring wells properly, and obtains samples that contain aquifer solids, the owner/operator should not be permitted to filter the sample but rather be required to err on the side of groundwater quality and assume that the solids-associated contaminants were derived from the landfill leakage.

Another significant problem with the typical groundwater sampling program is the common failure to maintain the dissolved oxygen and other gas characteristics of the samples as they had been in the aquifer. As discussed by Lee and Jones (1983), the introduction of dissolved oxygen into a sample from an anoxic (oxygen-free) groundwater causes the oxidation of ferrous iron in the water and its precipitation as ferric iron. The ferric form of iron is a very efficient scavenger of many dissolved contaminants, causing them to become particulate. An analysis for dissolved constituents in such a sample thus underestimates the amount of dissolved contaminants in leachate-contaminated groundwater. It is very difficult to avoid the introduction of dissolved oxygen into water samples, and the loss of VOC's (many of which are highly volatile), during sampling. When the dissolved gas composition of a sample is affected during sampling or sample handling in the field or the laboratory, erratic results not representative of the groundwater character will be obtained.

Another component of groundwater monitoring that is commonly neglected is the reliability of determination of heavy metals and certain other important monitoring parameters at low but significant concentrations. Typical groundwater sampling and laboratory handling of samples conducted according to US EPA or other standardized procedures, allows contamination of the samples unless the sampling and analysis are conducted with "clean" techniques. Very few laboratories and sampling crews use such techniques. This consideration also contributes to the unreliability of much of the data generated on heavy metals and certain other constituents in groundwaters.

The frequency of the sampling of monitoring wells can significantly affect the appearance of the data and the reliability of their interpretation. MSW landfills in arid climates, where there is no precipitation for substantial periods of time, could be expected to go for appreciable periods each year without generating leachate. During the wet periods, however, moisture will pass down through the wastes, generating leachate. This means that the concentrations of contaminants in the groundwater sampled by a monitoring well may give the appearance of being highly erratic since at sometimes groundwater upgradient of the monitoring well will have had leachate added to it, while at other times, it will not. Far more frequent sampling and greater attention to proper data interpretation are needed especially in arid areas to track the pollution of groundwater by landfill leachate and gas; with quarterly sampling, the data will likely appear to be highly erratic.

Finally, what appear in a data set as "erratic" data tend to be casually dismissed and disregarded with cursory explanation. The appearance of "erratic" data should trigger investigation into the cause of the problem, action to rectify the problem, and collection of another, reliable set of samples.

Recommendations

Siting

Because of the inevitable failure of landfill containment systems of the type used today, the perpetual threat of chemicals and components in MSW to groundwater quality, and the important and irreplaceable nature of groundwater resources, the best approach for groundwater quality protection would be to not site municipal solid waste or certain industrial solid waste landfills in areas where groundwater hydraulically connected to the area is, or could be, used for domestic supply under plausible worst-case water-need scenarios. About the only groundwaters that should be considered "unusable" for exemption from this type of protection are highly saline waters that do not have an economic value for their mineral content. Waters with somewhat elevated levels of dissolved solids (not of landfill origin) compared to what is typically used for domestic water supply purposes can be treated or blended to produce waters that can be used for domestic purposes.

Waste Treatment

In order to provide reliable groundwater quality protection, alternative MSW management approaches that properly treat wastes prior to disposal should be adopted. Lee and Jones (1990) and Lee and Jones-Lee (1993a) discussed the fermentation/leaching "wet-cell" approach incorporating a reverse-gradient liner system as offering the potential for providing needed pre-burial treatment. Short of providing for the removal of leachable components of MSW prior to burial, landfilling approaches offer only temporary storage of wastes and carry the burden of perpetual and vigorous maintenance.

Liner Leakage Monitoring

A groundwater monitoring program cannot be relied upon to ensure groundwater quality protection since by the time it reveals a problem, groundwater would have already been polluted. If the regulatory agencies/decision-makers opt for a "dry tomb" landfilling approach, two composite "liners" should be required. The lower composite "liner" should be incorporated to function not as a conventional containment liner, but rather as part of a full-landfill-area pan lysimeter liner leakage monitoring system.

The pan lysimeter monitoring system should be developed to detect leakage of the upper composite liner that is sufficient to potentially lead to groundwater pollution. A full-landfill-area pan lysimeter monitoring system could be a sand layer coupled with a composite of an HDPE flexible membrane liner and two feet of compacted soil with a maximum permeability of $1x10^{-7}$ cm/sec. Thus, the minimum Subtitle D requirement for a single composite liner should be coupled with a requirement for a full-landfill-area pan lysimeter covering the complete area of the bottom of the landfill. Any penetration of the upper composite liner by leachate as detected in the pan lysimeter must be considered to represent a failure of the liner system that requires immediate steps to stop leachate passage through the upper composite liner or to exhume the waste. Requiring anything less would be erring on the side of cheaper-than-real garbage disposal costs at the expense of the groundwater resources, and financial and public health interests of future generations.

The concept of a full-landfill-area pan lysimeter liner leakage monitoring system is not significantly different from the unsaturated monitoring required now in California's Chapter 15 and in the landfilling regulations of some other states; in California, monitoring in the vadose zone under the liner is required where feasible, as an early warning system for leachate leakage through the liner. The unsaturated monitoring systems that have been developed are largely ineffective, however, because they sample a very limited area under the liner compared with the areas through which leakage could occur. By having the pan lysimeter under the entire landfill area, there would be a higher probability of early detection of significant leakage through the composite liner.

This approach is basically the same as that being used in New York, New Jersey, Pennsylvania, and being proposed for Michigan, and other states of a double-composite liner system with a leak detection system between the two liners. In those states, however, no reliable provisions are made to fund corrective action for the inevitable leakage through the upper composite liner, for as long as the wastes represent a threat. The full-landfill-area pan lysimeter monitoring system beneath a single composite liner, coupled with adequate post-closure care maintenance and funding should enable more reliable construction of "dry tomb" landfills, that would provide a greater likelihood of detecting liner leakage before widespread groundwater pollution has occurred. This approach would also require, however, perpetual and vigorous care, and that the owner/operator of the landfill take the necessary steps to prevent further leakage through the upper composite liner once leachate leakage is detected in the lysimeter system.

Those requirements are not fundamentally different from what is required upon detection of incipient leakage. While it may be possible under some geologic conditions to construct groundwater monitoring systems to detect incipient pollution more reliably than can be accomplished with the vertical monitoring wells, it will still be inferior to the full-landfill-area pan lysimeter system for detection of liner leakage.

Cover Monitoring

As discussed by Lee and Jones (1992a) and Lee and Jones-Lee (1993b), the underlying presumption of the "dry tomb" landfilling approach is that if the buried wastes can be kept dry, leachate-generation can be prevented. The key to keeping buried wastes dry in perpetuity is maintaining an impermeable cover on the buried wastes. The essential impossibility of that task is obvious, given the deficiencies in present approaches and the mechanisms of cover deterioration, the inadequacies in post-closure funding requirements, and the inability to inspect the low-permeability functional layer of a cover and detect incipient leakage through it (see Lee and Jones, 1992a). However, recently some new liner leak detection systems have been developed which if incorporated into landfill covers, offer the potential to detect when the low-permeability layer of a landfill cover has the potential to transport significant amounts of moisture through it. As an example, Robertson (1990) has developed what appears to be a testable liner system (RBL) that consists of a permeable zone sandwiched between two layers of geomembrane. The permeable zone is formed with a layer of geonet or coarse texturing on the inner face of one of the membranes. The geomembranes are sealed along the outer edges of the sandwich to form a cell one-half to one acre in area. Drainage tubes are connected to the permeable zone and a partial vacuum is applied to the permeable space through the drainage tubes.

Rather than using a composite (FML and compacted soil) in the cover, an RBL could be used as the low-permeability layer of the cover. When it is no longer possible to develop a vacuum in the RBL system, i.e., one of the FML's in the sandwich is leaking, it should be possible to remove the topsoil and drainage layer above the cell that is leaking and repair the leak. According to Rohrs (1993) the cost of that system is about 20% greater than the cost of the two FML's which, depending on the thickness used, would cost between \$1 and \$2/ft^2. Therefore, the costs are not significantly different from those for Subtitle D covers. While the Subtitle D-type cover that is currently being developed cannot be tested for failures in the low-permeability layer, the incorporation of a cover leak detection system, such as that described by Robertson, could significantly improve the ability to keep wastes in a "dry tomb" landfill dry. Unlike MSW management alternatives that remove leachable components prior to burial of residues (see discussion above), however, incorporation of such a system in the cover still requires *ad infinitum* cover maintenance and perpetual funding for the periodic repair/replacement of the cover system.

Groundwater Monitoring

With any landfilling of wastes, the area groundwater should be monitored, not for the detection of failure of the containment system, but rather as a design redundancy for the detection of a failure in the full-landfill-area pan lysimeter liner leakage monitoring system, or the reverse-gradient liner system of a fermentation/leaching wet cell. As discussed above, conventional groundwater monitoring well arrays are highly inadequate for early detection of liner leakage, before widespread pollution has occurred.

Progress is being made in the development and application of alternatives to the conventional "monitoring well" approach to monitoring groundwater quality in conjunction with waste management units. One particularly promising approach is horizontal monitoring wells across the down-groundwater-gradient face of the waste management unit. The ability to develop horizontal wells that can be sampled over a considerable length (hundreds of feet) has progressed rapidly in the past few years through application of drilling techniques developed in the oil industry to hazardous waste site investigation and remediation programs. At a workshop organized by the senior author devoted to "Groundwater Monitoring at 'Dry Tomb' Landfills: Problems and Suggested Alternative Approaches," at the National Ground Water Association Outdoor Action Conference last year, Losonsky (1992) discussed the use of horizontal drilling for the construction of groundwater quality monitoring wells associated with waste management units. Keller (1992b) described the use of the SEAMIST borehole membrane sampling systems for sampling from any location in horizontal wells. These technologies appear to hold considerable promise for greatly improving the reliability of groundwater quality sampling to detect groundwater pollution from lined landfills.

In proposing any groundwater quality monitoring program, a landfill applicant, whether public or private, should be required to consider plausible worst-case flow paths of leachate-contaminated groundwater from any location in the landfill liner through the down-gradient monitoring well array and demonstrate the realistic probability that the monitoring program would detect groundwater pollution at the point of compliance. The relationship of the plausible worst-case flow paths and the zones of capture of the monitoring wells should be well-documented for the specific landfill and aquifer-geologic system of concern. In addition to considering the lateral spread-dispersion of the groundwater contamination finger-plume described above, the vertical position and spread of the plume must also be calculated and considered in establishing the depths of sampling of the monitoring wells. It is suggested that the groundwater monitoring program be designed on a site-specific basis, with the demonstration of at least a 95% probability that the system will detect incipient groundwater pollution at the point of compliance.

In California, the point of compliance is the down-groundwater-gradient boundary of the waste management unit. The US EPA allows the point of compliance to be a maximum distance of 150 m from the waste management unit provided that that location is within the landfill owner's property. In those areas where the point of compliance is beyond the boundary of the waste management unit, the plane of the point of compliance should be sufficiently within the property boundary of the landfill such that when the monitoring wells detect leachate, the source can be stopped and the groundwater remediated before any leachate migrates beyond the property line and trespasses into groundwater beneath adjacent property-owners' lands. Under no circumstance should landfills be allowed to *contaminate* groundwaters under adjacent property owners' lands at any time. The contamination of groundwater beneath another's property should carry severe penalties for the owner/operator of the landfill.

In addition, the landfill applicant should be required to develop a trust fund of sufficient magnitude that once groundwater pollution is detected, sufficient monies will be available to prevent further migration of contaminants, remediate the groundwaters that became contaminated prior to detection, clean up the aquifer to the maximum extent possible, and, if the groundwater pollution cannot be stopped, exhume the wastes and properly treat them. That trust fund must be maintained for as long as the wastes represent a threat to groundwater quality, which for "dry tomb" landfills would normally be effectively forever.

The pre-permitting, critical evaluation of the reliability of groundwater quality monitoring programs proposed for new landfills should have a pronounced impact on the siting of new landfills. As regulatory agencies and the public become aware of the inaccuracies in the claims and assumptions made about the ability of groundwater quality monitoring programs of the type accepted today to detect leakage before widespread groundwater pollution has occurred, the authors believe that greater care will be exercised in siting, constructing, operating, maintaining, and funding closure and post-closure care for MSW landfills in a manner that recognizes that the containment systems will eventually fail, and that recognizes the devastating impact that MSW leachate-contamination of groundwater has on the usability of the groundwater and associated aquifer. This should result in significantly greater protection of groundwaters that are or could be used in the future for domestic water supply purposes.

Conclusions

The purpose of enacting Subtitle D was to protect groundwater quality from adverse impact by MSW landfill-derived hazardous and otherwise deleterious chemicals. Lee and Jones (1992d) characterized the Subtitle D "dry tomb" landfilling approach implemented by the US EPA, as a flawed technology for managing municipal solid wastes because it does not provide a high degree of protection of groundwater quality for as long as the wastes represent a threat. One of the most significant deficiencies in the approach is the reliance on groundwater monitoring as the basis for detecting when the liner systems have failed to prevent leachate leakage.

California regulations governing landfilling of wastes (WRCB, 1991) now link the magnitude of the contingency funding required for addressing landfill liner leaks to the quality of the liner leak detection and groundwater monitoring systems used. For example, the contingency funding that would be required for a landfill with a higher-quality system such as a full-landfill-area pan lysimeter liner leak detection system, would be expected to be much smaller than that required for a facility using only vertical monitoring wells spaced hundreds of feet apart. The general guidance for establishing a relationship between the magnitude of the contingency funding and the expected efficacy of the leak detection system has not been delineated. However, that provision is a significant step forward for protection of groundwater quality from impact by lined MSW landfills, provided that it is properly implemented so that adequate funds are available for as long as the wastes are a threat (forever), to stop further leakage through the liner and clean up the groundwater pollution to the maximum extent possible. As discussed elsewhere, this may require waste exhumation and treatment.

The prevention of groundwater pollution by MSW landfill-derived contaminants is essential for the protection of public health and groundwater resources. Conventional groundwater monitoring programs are unreliable for detecting incipient leakage of lined landfills because of inappropriate consideration for the nature of leakage of lined MSW landfills and for the manner of migration of leachate-contaminated groundwater, and the requirement of groundwater pollution before detection. Further, the minimum groundwater monitoring parameter requirements of Subtitle D are insufficient to detect incipient groundwater pollution.

The best approaches for the protection of groundwater quality from MSW landfill-derived contaminants is the pre-treatment of wastes to remove leachable components, or the siting of "dry tomb" landfills only in geologically stable areas in which it is well-documented that there are no hydraulic connections between the landfill area and waters that are or could be used for domestic purposes (Lee and Jones, 1991b). If regulatory agencies continue to permit "dry tomb" landfills in areas that are or could be hydraulically connected to groundwaters that are or could be used for domestic water supply, the following monitoring requirements should be added:

- a groundwater quality monitoring program with a demonstrated ability to detect incipient groundwater pollution from any point source in the lined landfill, at the point of compliance,
- a liner leak detection system that has a high probability of detecting incipient liner leakage, such as may be provided by a full-landfill-area pan lysimeter system,
- a testable leak detection system in the landfill cover,
- the availability of sufficient post-closure care funding to conduct appropriate monitoring, maintenance, remediation, and restoration for as long as the wastes remain buried, and a contingency for waste exhumation and treatment. This funding must be available for as long as the wastes remain buried.

Without such provisions, lined MSW landfills will do no more than postpone groundwater pollution and pass the costs of that pollution - public health impacts, groundwater resource loss, groundwater and aquifer remediation, and proper waste management - on to future generations.

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