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ACTION LEAKAGE RATES FOR LEAK DETECTION SYSTEMS

[Supplemental Background Document for
the Final Double Liners and Leak Detection Systems Rule for
Hazardous Waste Landfills, Waste Piles, and Surface Impoundments]

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ABSTRACT

This document supplements the background document [Ref. 4] for the May 29, 1987 proposed double liners and leak detection systems rule. This supplement explains the application of the formulas in the original background document to calculate an action leakage rate (called rapid and extremely large leak in the proposal), presents the results of action leakage rate calculations for facilities meeting the minimum design specifications in the final rule, and provides results from a more sophisticated 3-dimensional model. The action leakage rates, based on the minimum specifications in the final rule and a safety factor of two, are 100 gallons per acre per day (gpad) for landfills and waste piles, and 1,000 gpad for surface impoundments. The output from the 3-D model helps to visualize the shape of the flow for various design specifications and shows the relative impact of a number of factors on flow capacity.

This supplemental background document also presents additional data on flow rates actually achieved at a number of double-lined facilities. These numbers support the proposed and final rules by showing that facilities with good construction quality assurance (CQA) perform significantly better than those without. Further, only about 70% of the well designed facilities with good CQA meet 20 gpad which was proposed as the upper bound for a base action leakage rate, and sources of liquids other than top liner leakage can themselves result in flow rates from the leak detection system greater than 20 gpad, indicating that the proposed 20 gpad is too low for a practical action leakage rate.

Finally, this supplemental document also references a number of technical guidances the Agency has issued since the three proposals[1] that contain useful information relative to all of the design, performance, monitoring, and response action standards in the final rule.

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[1] Proposed in the Federal Register on:
May 29, 1987--Liners and Leak Detection Systems [52 FR 20218].
March 28, 1986 and April 17, 1987--Double Liners and Leachate Collection and Removal Systems [51 FR 10706 and 52 FR 12566].

CONTENTS

1. INTRODUCTION.....1

2. ACTUAL FLOW RATES MEASURED IN THE FIELD.....1

   2.1 Data From Commenters.....1
   2.2 Data From Operating Units.....1
   2.3 Evaluation of Available Information.....2
   Landfills with Geomembrane Top Liners.....2
   Surface Impoundments with Geomembrane Top Liners..4
   Landfills with Composite Liners.....5
   Surface Impoundments with Composite Top Liners...7
   2.4 Theoretical Analysis of Top Liner Performance.....7
   Available Information.....7
   Results of analysis.....7
   Frequency and Size of Geomembrane Defects....7
   Analysis Results.....8
   2.5 Summary.....9

3. ACTION LEAKAGE RATE.....10

   3.1 Determining an Action Leakage Rate.....10
   Results Using a 3-D Model.....12
   3.2 Alternative Action Leakage Rates.....13
   3.3 Action Leakage Rate Significance.....14

4. ADDITIONAL GUIDANCES AND REFERENCES.....15

5. CLOGGING.....15

6. CONCLUSIONS.....17

7. REFERENCES.....18

APPENDICES

A. EPA LINER GUIDANCES.....20
B. FLOW RATE RESULTS USING A 3-D COMPUTERIZED MODEL.....23
C. BACKGROUND INFORMATION ON THE 3-D VARIABLY SATURATED FLOW ANALYSIS MODEL.....52

1. INTRODUCTION

The purpose of this document is to supplement the original background documents supporting the 1986 and 1987 proposals for double liners and leachate collection and removal systems, and liners and leak detection system rules[2] for hazardous waste landfills, surface impoundments, and waste piles. A lot of information has been generated since the 1986 and 1987 proposals that further support this rulemaking. In particular, data on actual flow rates at double-lined landfills and surface impoundments and on top liner performance has been collected and evaluated, flow models have been applied to calculate action leakage rates, and a number of technical guidances have been published. This document discusses each of these.

2. ACTUAL FLOW RATES MEASURED IN THE FIELD

EPA acknowledged in the May 1987 preamble and background document that it had limited data on the performance capability of top liners in terms of flow rates and stated that the Agency is seeking additional data. Since the proposal, EPA has gathered information from a number of facilities, including some data submitted by commenters. This data is summarized here.

2.1 Data From Commenters

In response to EPA's request for more data, some commenters (facility operators) submitted actual flow data. One commenter claimed to achieve, after removal of construction water, a leakage rate of 2-3 gpad at six landfills and 0, 0, 18, and 75 gpad at four (non-regulated) surface impoundments. Commenters made a number of claims regarding other sources of liquids in leak detection systems: consolidation water (from clay in composite top liners) can be 10-50 gpad; construction water can be 10-50 gpad; vapor transmission through a top liner geomembrane can be 4 gpad; and ground water through a geomembrane in the bottom liner can be 20 gpad.

2.2 Data From Operating Units

Information on top liner performance can be obtained from an analysis of leachate detection, collection, and removal systems (LDCRS) flow rates. The results of field monitoring of LDCRS flows at double-lined landfills and surface impoundments have been presented by EPA [1987], Gross et al. [1990], and Bonaparte and Gross [1990]. The reference by Bonaparte and Gross includes the data from all the other references cited above, as well as a

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significant body of otherwise unpublished information. The findings from Bonaparte and Gross are presented in Section 2.3.

2.3 Evaluation of Available Information

Bonaparte and Gross [1990] presented LDCRS flow rate data for 55 individually-monitored double-lined landfill cells and 14 individually-monitored double-lined surface impoundments. The units are located in different climatic regions across the United States; however, most of the units are located in relatively moist climatic regions with average annual rainfalls ranging from 35 to 43 in (900 to 1,100 mm). For each unit, they presented information on the design and operation of the unit, as well as the rate of flow from the LDCRS. Then they evaluated the probable sources of the flow from each unit. Potential sources of flow are illustrated in Figure 1 and include: (i) leakage through the top liner; (ii) water from precipitation that percolates into the LDCRS during construction ("construction water"); (iii) water squeezed out of the clay component of a composite top liner as a result of clay consolidation ("consolidation water"); and (iv) ground water that infiltrates the bottom liner and enters the LDCRS ("infiltration water").

Landfills with Geomembrane Top Liners

In their paper, Bonaparte and Gross evaluated flow rate data from 23 landfill cells that were constructed with geomembrane top liners (instead of composite top liners). A geomembrane top liner represents the minimum technology requirement for top liners at hazardous waste management units regulated under 40 CFR Parts 264 and 265. The authors determined that for 16 of the 23 landfills cells, there could be no consolidation water, and, based on design and operating considerations, construction water and infiltratin water were unlikely sources of LDCRS flow. As a result, the measured LDCRS flow could only be attributed to top liner leakage. Eleven of the 16 landfill cells had been constructed using construction quality assurance (CQA) procedures in substantial conformance with EPA [1986] guidance. The other five cells were constructed using less stringent CQA procedures or no CQA at all.

Table 1 presents a summary of the data for the 16 landfill cells constructed with geomembrane top liners. In Table 1, the LDCRS flow rates are reported in units of gallons per acre of lined area per day (gpad).

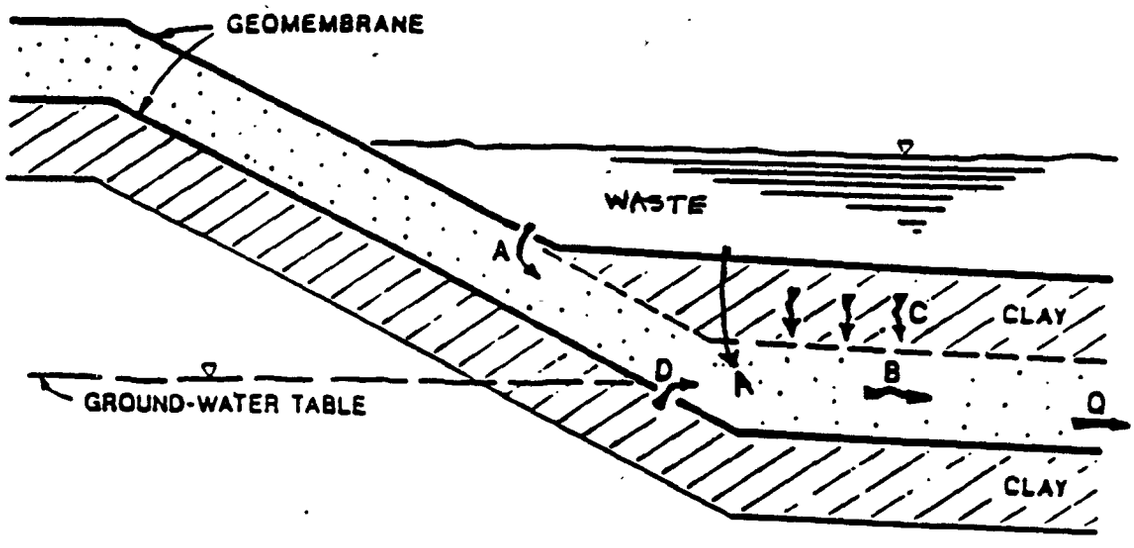

Figure 1. Sources of Flow in Leak Detection, Collection, and Removal Systems (LDCRSs).

Table 1. Comparison of average LDCRS flow rates at 16 landfill cell with geomembrane top liners (from Bonaparte and Gross [1990]).

Leakage Detection Layer Flow Rate	No. of Cells	
	CQA	No CQA
Flow rate less than 5 gpad	4	-
Flow rate in range of 5 to 20 gpad	4	1
Flow rate in range of 20 to 50 gpad	3	-
Flow rate greater than 50 gpad	-	4

From Table 1, it can be seen that of the eleven landfill cells that were constructed using a CQA program, four cells had average flow rates less than 5 gpad (50 liters per hectare per day (lphd)), and a total of eight cells had average flow rates less than 20 gpad (200 lphd). The data in Table 1 show that a base leakage rate of 20 gpad (200 lphd), which is the top of the range for the base action leakage rate in the proposal, is too low (i.e., not "practicable") since only 73 percent (eight out of eleven) of the cells that had properly constructed geomembrane top liners using rigorous CQA procedures achieved a LDCRS flow rate of less than 20 gpad (200 lphd).

Table 1 also provides evidence of the benefit of a rigorous CQA program. All eleven units constructed using CQA procedures had LDCRS flow rates of less than 50 gpad (500 lphd), and eight of the eleven facilities had flow rates of less than 20 gpad (200 lphd). In contrast, four of the five units that were constructed with less rigorous CQA procedures or with no CQA at all had LDCRS flow rates in excess of 50 gpad (500 lphd), and two units had LDCRS flow rates in excess of 100 gpad (1,000 lphd). At these two units LDCRS flow rates were on the order of 300 gpad (1,000 lphd). In summary, the LDCRS flow rates from waste management units with rigourous CQA programs are significantly lower than the flow rates from units without rigorous programs.

Based on these data, it appears that flow rates from LDCRSs of landfills that are properly constructed using rigorous CQA programs should be well less than 100 gpad (1,000 lphd). On the other hand, if a unit is constructed using less rigorous CQA procedures, LDCRS flow rates greater than 100 gpad (1,000 lphd) may occur.

Surface Impoundments with Geomembrane Top Liners

Conclusions similar to those given above for landfills can also be drawn for surface impoundments. Bonaparte and Gross [1990] presented data on LDCRS flow rates from eight double-lined surface impoundments having geomembrane top liners. The authors determined that for six of these surface impoundments, top liner leakage was the likely source of any LDCRS flow. Five of the six surface impoundments were constructed with rigorous CQA programs, including either ponding tests or leak location surveys; it is

not known if CQA was performed during the construction of the sixth surface impoundment. The authors reported that four of the six surface impoundments exhibited no LDCRS flow in the time period between the start of operation and the time the flow data was collected. The fifth surface impoundment exhibited no flow except during a short period between when a geomembrane defect developed and when it was repaired. The sixth surface impoundment exhibited a flow of about 0.2 gpad (2 lphd), except during a short period when the flow increased to about 40 gpad (400 lphd) due to a geomembrane defect. Thus, all six of the monitored surface impoundments with geomembrane top liners had LDCRS flow rates below 5 gpad (50 lphd) except during a short period between when a geomembrane defect developed and when it was repaired. This represents an extremely high level of performance; in fact it represents a higher level of top liner performance than was observed at landfills having geomembrane top liners. This high level of performance was obtained by using ponding tests and/or leak location surveys as part of the CQA program. These CQA techniques are typically better adapted to use at surface impoundments than landfills because surface impoundments are frequently smaller than landfill cells resulting in easier implementation of ponding tests or surveying techniques. In addition, geomembrane top liner defects that may develop after construction are generally easier to find and repair in a surface impoundment than in a landfill. The top liner in a surface impoundment is typically uncovered (or covered with only a thin veneer of soil), whereas the top liner in a landfill cell is covered with a drainage layer (leachate collection and removal system or LCRS) and then with a thick layer of waste which makes access to the liner difficult.

Based on the available data, it appears that flow rates from the LDCRSs of surface impoundments that are properly constructed using rigorous CQA programs (those that use leak location surveys or ponding tests) should be well less than 100 gpad (1,000 lphd). It should be anticipated, however, that if a unit is constructed using less rigorous CQA procedures, a flow rate greater than 100 gpad (1,000 lphd) could occur. It is interesting to note that leak location surveys and ponding tests represent two techniques that are frequently implemented as part of a response action plan at surface impoundments experiencing excessive flow from the LDCRS. The results described herein suggest that these techniques will be effective in reducing the LDCRS flow rate to below 100 gpad (1,000 lphd) at surface impoundments for which response actions are required.

Landfills with Composite Top Liners

The evaluations discussed above were for double-lined units having geomembrane top liners. It is also useful to consider units having composite top liners to assess the contribution of consolidation water from the clay component of the top liner toward potentially exceeding an action leakage rate. Although the action leakage rate in the final rule, as in the proposal, is based on total flow in the LDCRS, regardless of source, the response actions should consider sources other than leaks. For

this reason, it is relevant to compare LDCRS flow rate data from units with composite top liners.

Bonaparte and Gross [1990] evaluated LDCRS flow rate data from 32 landfill units with a composite top liner. Because the top liner is a composite liner, the primary source of the flow can be attributed to construction water plus consolidation water if an analysis of the time required for leakage to flow through the top liner (i.e., leakage breakthrough time) was greater than the time since the end of construction of the landfill. For 18 of these units, the authors attributed the flow primarily to construction plus consolidation water from the clay component of the composite top liner. Data on these 18 units are provided in Table 2.

Thirteen of the waste management units used to generate the data in Table 2 were constructed using CQA programs in substantial accordance with EPA [1986] guidance; four were constructed without CQA programs; and it is not known if CQA was performed during construction of the remaining unit.

Table 2. Average LDCRS flow rates at 18 landfill cells with composite top liners (from Bonaparte and Gross [1990]).

Leak Detection Layer Flow Rate	No. of Cells
< 5 gpad	5
5 to 20 gpad	8
> 20 to 50 gpad	3
> 50 to 100 gpad	2
> 100 gpad	0

From Table 2, it can be seen that only five of 18 (28 percent) of the landfill cells constructed with composite top liners have LDCRS flow rates of less than 5 gpad (50 lphd), and 13 of 18 cells (72 percent) have LDCRS flow rates of less than 20 gpad (200 gpad). This data is similar to that for geomembrane only top liners, indicating that construction water is rather insignificant at these units (perhaps because overburden pressures have yet to squeeze out the consolidation water). This data also indicates that perhaps a significant source of the liquids at the geomembrane only units is construction water. At any rate, this data further supports the conclusion that an action leakage rate of 20 gpad (200 lphd) is inappropriate since it would mean most waste management units with composite top liners will also have LDCRS flow rates that exceed the action leakage rate under normal operating conditions.

All 18 units with composite top liners exhibited average LDCRS flows below 100 gpad (1,000 lphd). Thus, it appears that properly constructed waste management units with composite top

liners are unlikely to exhibit LDCRS flows that exceed 100 gpad (1,000 lphd).

Surface Impoundments with Composite Top Liners

There is insufficient data to present observations on the performance of this category of facilities. However, it is anticipated that the performance of these facilities would be the same as the performance of landfills with composite top liners.

2.4. Theoretical Analysis of Top Liner Performance

A theoretical analysis of top liner performance was also performed. This analysis further supports the conclusion from the above data that 20 gpad is not a practical action leakage rate.

Available Information

In recent years, various investigators have developed analytical techniques for estimating leakage rates through liners. These investigations include: Bonaparte et al. [1989]; Brown et al. [1987]; EPA [1987]; Giroud and Bonaparte [1989a,b]; Giroud et al. [1991]; and Jayawickrama et al. [1987]. The reference presented by Bonaparte et al. [1989] presents equations to estimate leakage rates through both geomembrane liners and composite liners; these equations are used in the analysis below to estimate leakage rates through top liners.

To estimate the anticipated leakage rate through a top liner at a waste management unit, a frequency of defect and size of defect in the geomembrane component of the top liner must be assumed. Available information on the frequency and size of defects in properly-installed geomembrane liners had been reported by EPA [1987], Giroud and Bonaparte [1989a], Giroud and Fluent [1987], and Laine [1991]. This information is also used below to estimate leakage rates through top liners.

Results of Analysis

Frequency and Size of Geomembrane Defects. Giroud and Bonaparte [1989a] presented limited case study data, including CQA records, records of foresnic investigations, and LDCRS flow rate data, from which they drew "tentative" conclusions regarding the frequency and size of defects in geomembrane liners installed using rigorous CQA procedures. From their data, they recommended that for the purpose of estimating leakage rates through geomembranes, a geomembrane defect (hole) frequency of one to two per acre (two to five per hectare) be considered along with a defect size of 0.005 in^2 (3.2 mm^2). Recently Laine [1991] presented data from two leak location surveys in which geomembrane seam defects were identified at a frequency of two to five per acre (five to twelve per hectare). Thus, the frequency of defects found by Laine is twice as high as the frequency recommended by Giroud and Bonaparte for estimating leakage rates. However, the size of the defect found by Laine was typically very

small, i.e., pinhole sized with areas on the order of 0.001 in^2 (0.6 mm^2) or less. The defect size is about five times smaller than the defect size recommended by Giroud and Bonaparte for estimating leakage rates. Since the calculated leakage rate for a given installed area of geomembrane is proportional to the product of the size of the defect and the frequency of defects, the findings of both of the above-described investigations lead to comparable top liner leakage rates when used.

For the analysis of top liner leakage rates presented below, a defect frequency of one per acre (two per hectare) and a defect size of 0.005 in^2 (3.2 mm^2) is assumed.

Analysis Results. The results of calculations using the equations from Bonaparte et al. [1989] for steady-state leakage through geomembrane holes are presented below. For the calculations, it was assumed that the top liner consists of a geomembrane alone, and the hydraulic conductivity of the material overlying the geomembrane is 1×10^{-2} cm/s (1×10^{-4} m/s) which is appropriate for a landfill with a granular leachate collection and removal system (LCRS). The calculated top liner leakage rates, given the above-described conditions, are presented in Table 3.

Table 3. Calculated leakage rates through a geomembrane top liner.

Liquid head on top liner (ft)	Steady-State leakage rate (gpad)
0.1	10
1.0	60
10.0	220

Calculated top liner leakage rates would be much lower than those given in Table 3 if the top liner was a composite liner rather than a geomembrane alone. Conversely, the calculated top liner leakage rate would be somewhat higher if the material above the top liner had a higher permeability, or if the liner was exposed (as might be the case for a surface impoundment).

The calculation results presented above must be interpreted separately with respect to landfills and surface impoundments. For landfills, the design maximum liquid head in the LCRS is 1 ft (0.3 m). However, the average liquid head under normal operating conditions should be only on the order of 0.1 ft (0.03 m); in many instances, the average head may be only on the order of 0.1 ft (0.03 m), or even less. In this case the calculated results support a conclusion that under normal operating conditions (i.e., when there is an average hydraulic head in the LCRS of 0.1 ft (0.03 m), or less), the leakage rate through a properly designed geomembrane top liner, constructed using proper procedures and rigorous CQA, will frequently be less than 20 gpad

(200 1 phd). During periods of maximum leachate flow (e.g, after major storm events), top liner leakage rates in landfills with geomembrane top liners could temporarily exceed 20 gpad (200 lphd) and approach 60 gpad (600 lphd), since the liquid head in the LCRS during this period could easily exceed 0.1 ft (0.03m).

The calculation results suggest that for surface impoundments constructed with geomembrane top liners (where the liquid head may be on the order of 10 ft (3 m)), top liner leakage rates could easily exceed 20 gpad (200 lphd) and approach 200 gpad (2,000 lphd) even if there is only one small geomembrane defect per acre (two defects per hectare) of liner. Thus, to keep top liner leakage rates below 20 gpad, or even 200 gpad, in surface impoundments with geomembrane top liners, geomembrane defects need to be virtually eliminated. In most cases, this will only be accomplished using ponding tests, leak location surveys, or other "extraordinary" CQA procedures. As shown by the monitoring data presented in Section 2.3 of this report, when these CQA procedures are used, top liner leakage can be largely eliminated, at least for some period of time.

2.5 Summary

As stated in the proposal, and restated by some of the commenters, the existing empirical data base at the time of the proposal regarding actual flow rates was quite limited. EPA has, however, accumulated empirical data since the proposal on the performance of different liner designs. This data help give meaning to different flow rates in terms of the ability of owner/operators and technology to achieve and in terms of leaks versus other sources of liquids. This additional leakage rate data are consistent with the data submitted by the commenters.

The actual flow rate data presented above are summarized in Table 4, for all 40 units.

Table 4. Actual Flow Rates at Double-Lined Individually-Monitored Landfill and Surface Impoundment Units.

LDS FLOW RATE (GPAD)	NO. of UNITS	% of UNITS
< 5	15	38
5-20	13	32
>20-50	6	15
>50	6	15

NOTES TO TABLE: These are units where other sources, except construction water, were determined not to be a factor. Thirty-one of the 40 units were constructed with rigorous CQA, 7 were not, and 2 are unknown. Of the six at >50 gpad, at least four had no rigorous CQA.

This data shows that only 70% of the 40 units meet 20 gpad; and only 85% of the 40 units, but at least 95% of the units with rigorous construction quality assurance (CQA), meet 50 gpad. This indicates that 20 gpad and even 50 gpad are not practicable action leakage rates for the general situation.

This data in conjunction with the previous EPA data show that over the past 10 years, and especially in more recent years, facility owners and operators have been building and operating liner systems that work better and better to minimize flow through the top liner. The major contributions to this improvement have been better installation practices and better CQA.

3. ACTION LEAKAGE RATE

In the final rule, as in the May 29, 1987 proposal, the owner or operator of units subject to the leak detection system requirements must propose and the Regional Administrator (or State Director in authorized States) must approve an action leakage rate. "Action leakage rate" is defined in the final rule as "the maximum design flow rate that the leak detection system (LDS) can remove without the fluid head on the bottom liner exceeding 1 foot. The action leakage rate must include an adequate safety margin to allow for uncertainties in the design (e.g., slope, hydraulic conductivity, thickness of drainage material), construction, operation, and location of the LDS, waste and leachate characteristics, likelihood and amounts of other sources of liquids in the LDS, and proposed response actions (e.g., the action leakage rate must consider decreases in the flow capacity of the system over time resulting from siltation and clogging, rib layover and creep of synthetic components of the system, overburden pressures, etc.)." In short, the "action leakage rate" is the maximum design flow rate, with a safety factor, that the leak detection system can remove without the head on the bottom liner exceeding one foot (called rapid and extremely large leak in the May 29, 1987 proposal). The objective is to minimize the head or pressure on the bottom liner and thereby decrease the potential for migration of hazardous constituents out of the unit should a leak in the bottom liner, as well as the top liner, occur. The proposal background document [Ref. 4] presented a number of mathematical models for making such a determination. All of these models are based on Darcy's Law for non-turbulent flow through saturated media.

3.1 Determining an Action Leakage Rate

The proposal background document gives the following formula for flow originating through a hole in the liner, the most likely leak scenario for a geomembrane liner (pages 2.6-12 and 2.10-10, Ref. 4):

$$Q = k \cdot h \cdot \tan \alpha \cdot B_{avg} \qquad \text{[Equation 1]}$$

where Q = flow rate in the leak detection system (drainage layer),
h = head on the bottom liner,
k = hydraulic conductivity of the drainage medium,
α = slope of the leak detection system,

B_{avg} = average width of the flow in the leak detection system, perpendicular to the flow.

Assumming that the gradient of flow through the hole, at the hole, is sin α and depth of flow at the hole for concentrated flow = the thickness of the drainage layer:

$$B_{avg} = D/\sin \alpha$$

where D = leak detection system thickness.

Then, with D = 1 ft and sin α = 0.01, B_{avg} = 100 ft
0.02, B_{avg} = 50 ft
0.03, B_{avg} = 33 ft.

Using these values for B_{avg} and Equation 1 with $h \approx D = 1$ ft ($h \approx D$ for small values of α), Q in gpad =

k (cm/sec)	sin α	B_{avg} (ft)		
		33	50	100
1	.01	----	----	21,000
	.02	----	21,000	----
	.03	21,000	----	----
.1	.01	----	----	2,100
	.02	----	2,100	----
	.03	2,100	----	----
.01	.01	----	----	210
	.02	----	210	----
	.03	210	----	----

Thus, using the minimum specifications in today's rule: 1% slope, 12 in thick drainage layer, and 1 X 10^{-1} cm/sec hydraulic conductivity for surface impoundments and 1 X 10^{-2} cm/sec hydraulic conductivity for landfills and waste piles, and assuming that the head is 1 ft and the average width of flow (B_{avg}) is as given above, the results show maximum flow rates of 2,100 gpad for surface impoundments and 210 gpad for landfills and waste piles. Using a safety factor of two, as suggested in the example given in the proposed rule preamble, yields about 1,000 gpad for surface impoundments and 100 gpad for landfills and waste piles as the Agency recommended action leakage rates, for units that are designed to the minimum specifications in today's rule. As listed in the rule and above, the safety factor helps account for uncertainties in the design, construction, operation, and location of the drainage layer and potential decreases in flow over time as a result of overburden compressive forces and clogging caused by fines and biological and chemical actions in any leachate that seeps through. Of course, all of the above mechanisms that could result in potential decreases in flow over time should also be considered when selecting the design, especially the hydraulic conductivity of the drainage layer, and in construction. Because this calculation used the

minimum technical requirements and other design assumptions to maximize potential head on the bottom liner, and uses a safety factor, EPA believes that the units meeting the minimum technical requirements would not require action leakage rates below 100 gpad for landfills and waste piles and 1,000 gpad for surface impoundments.

Assuming the wetted area in the drainage layer beneath a small hole leak has approximately the shape of a cone from side view and a parabola from top view, the width of the parabola (B) is:

$$B = \frac{2\sqrt{Q/K}}{\sin\alpha}\sqrt{1+\frac{2x\sin\alpha}{\sqrt{Q/K}}}$$

where x = plan distance downslope from hole (i.e., B is a function of the distance x from the hole; most of B is at the hole with only slight increases downslope).

Assuming x = 0 (i.e., looking at B under the hole, $B = \frac{2\sqrt{Q/K}}{\sin\alpha}$) and substituting this value for B into Equation 1 modified for a triangular cross-section of flow (i.e., $Q = 1/2\ k \cdot h \cdot \tan\alpha \cdot B$) and solving for Q yields:

$$Q = k \cdot h^2 \qquad \text{[Equation 2]}$$

where h = head on the bottom liner and h < thickness of drainage layer.

This equation becomes the following if the condition is changed from "h < thickness of the drainage layer (D)" to "h ≥ D" (which is important for geonet calculations):

$$Q = k \cdot D\ (2h - D) \qquad \text{[Equation 3]}.$$

Solving Equation 3 using the minimum design specifications in the final rule, Q =

for .1 cm/sec: 2100 gpad
.01 cm/sec: 210 gpad
geonet: 6800 gpad.

These numbers are the same as the results given above for Equation 1.

Results Using a 3-D Model

Tables 1-4 and Figures 1-10 in Appendix B were developed from a 3-D model to show the relative effects of various design parameters and assumptions on flow capacity, and to show the shapes of the flow in the drainage layer for various designs and assumptions, including hole size and head. Appendix C gives background information on the 3-D model. The tables show that slope, length of run, and hole size have some effect on flow rate (e.g., 4% increase in flow rate when slope is increased from 1% to 2% [Tables 1, 3-5]; 1% increase in flow rate at 1% slope when

increasing length of run from 20 ft to 80 ft [Table 1; Figure 4 shows that length of run has negligible effect for slopes at or greater than the 1% minimum]; 43% increase when hole size is increased from .25 ft^2 to 1.0 ft^2 but a much less significant increase for holes > 3 ft^2 [Table 2; Figure 5 graphically shows the effect of leak size on flow rates]). However, the effect of these three variables is relatively insignificant compared to hydraulic conductivity, head, and drainage layer thickness (e.g., ten times increase (900%) when increased from .01 cm/sec to .1 cm/sec hydraulic conductivity [Tables 1, 3-5]; 382% increase when increased from no head to 2 ft head above the top liner, e.g., in a 2 ft deep surface impoundment [Table 3]; and 210% increase when geonet thickness is doubled from 5 mm to 10 mm [Table 5]).

Figures 2a-2d (side view) and 3a-b (top view) show the shape of the saturated zone for various designs, assuming no head above the top liner. These show only small portions of the bottom liner are actually exposed to the 1 ft head (as assumed in the simpler models discussed above). Figures 6-8b, however, show that as the head increases, so does the area of the bottom liner exposed to the greater heads. The graph for 8 ft head for surface impoundments is almost rectangular and therefore is not shown. Table 5 and Figure 10 show the results for geonets, which because of their high hydraulic conductivities have high flow rates.

Table 4 shows flow rates of 204 gpad and 2,040 gpad respectively for the landfill and surface impoundment specifications (i.e., 1% slope and hydraulic conductivity of 10^{-1} cm/sec for surface impoundments and 10^{-1} cm/sec for landfills, but with 1 ft of head above the top liner, 180 ft length of run, and a 1 ft^2 hole size). Comparing the results of the 3-D model to those of Equations 1 and 3, using the 1% slope and 10^{-1} cm/sec hydraulic conductivity for surface impoundments, shows that if the hole size is somewhat less than .25 ft^2, the flow rate with a 2 ft head would be about 2100 gpad [Table 3]. For 0 ft head above the top liner, the hole would be somewhat larger than 30 ft^2, or close to uniform flow [Figure 5].

3.2 Alternative Action Leakage Rates

While EPA recommends the above action leakage rates (100 and 1,000 gpad) for units that are built to the minimum design specifications, the Agency recognizes that a number of site-specific factors affect the maximum flow capacity of a leak detection system, and owners and operators may want to propose alternative action leakage rates. For example, the leak detection system design may be different than the minimums specified in the final rule. As indicated above, the hydraulic conductivity is a factor that significantly affects the flow capacity of the system. Since they are directly proportional, a ten times increase in hydraulic conductivity (i.e., from 10^{-2} to 10^{-1} cm/sec) increases the flow capacity ten times. Therefore, EPA believes that leak detection systems with greater hydraulic conductivities would have higher action leakage rates. In addition, owners or operators may have information to justify a

different width of flow in the above calculation. Or the owners or operators may justify a higher action leakage rate by using a different formula or model. While the Agency recommends the use of the above model for defining the maximum flow capacity of the leak detection system and action leakage rate, EPA recognizes that there may be alternative models available now or in the future that may more accurately predict system flow capacity to justify higher action leakage rates. Therefore owners or operators may propose to use an alternative model that they believe more accurately predicts the maximum flow capacity of the leak detection system. Or, owners or operators may want to do a field flow (pump) test on the leak detection system to show actual flow capacity, which may justify a higher action leakage rate. Finally, owners or operators may have flow rate data on similarly designed units to use to justify a different level. As more and more units are built, the Agency as well as owners or operators will develop a better data base that may be used to justify other action leakage rates.

3.3 Action Leakage Rate Significance

Action leakage rates must not exceed the maximum flow rate capacity of the leak detection system in order to assure that a response action is triggered for significant leaks. That is, if the action leakage rate were greater than the flow capacity of the system, the trigger level or action leakage rate would never be reached and response actions implemented, no matter how large or massive the failure. Further, an action leakage rate that is based on a maximum of 1 ft head assures that significant pressures on the bottom liner will not be experienced, thereby decreasing the potential for migration of hazardous constituents into the bottom liner. Finally, EPA believes that flow rates in excess of the minimum action leakage rates often indicate a major localized or general failure of the top liner. Flow rates of 1,000 gpad or greater represent significant flow rates and potentially significant hole sizes that may be readily identified and repaired. Flow rates between 100 gpad and 1,000 gpad are large enough that the sources other than a leak will probably not account for all the flow (i.e., there is probably a leak situation that should be looked into). For these reasons, it is necessary to maintain leak detection flow rates below the action leakage rate and for the owner or operator to take response actions for leaks greater than the action leakage rate.

The appropriate response action must be based on site-specific circumstances, including the magnitude of the actual flow rate (which is related to leak size), the ease of determining the source of leak and repairing it (e.g., often in a surface impoundment a hole can be observed from the surface, or a bulge in the top liner from underlying pressures may be observed from the surface indicating the possible leak location), and status of the unit (e.g., for a disposal unit about to close, it may be best to close the unit and get a sound cover on top rather than seek to find and repair a leak, especially for relatively low flow rates).

4. ADDITIONAL GUIDANCES AND REFERENCES

A number of technical guidance manuals have been published by EPA that discuss all the design features of the final rule. Some of these are listed in Appendix A. These cover: foundations and dikes; flexible membrane liners or geomembranes; soil/clay liners; composite liners; hydraulic conductivity and other properties of granular drainage layers, geonets, and clay/soil liners; leachate collection, and removal systems and leak detection systems designs; sumps and pumps; clogging; construction quality assurance and test fills; Darcy's Law and calculation of flow quantities, flow capacities, and time of travel or breakthrough times; response action plans; and covers.

5. CLOGGING

EPA sponsored studies [Bass et al., 1983; Bass, 1986; Ghassemi et al., 1986; Koerner et al., 1991] indicate that clogging of drainage layers of waste management units may potentially occur under some conditions. The results of the studies indicate that drainage layer clogging is caused primarily by sedimentation or biological growth. The results of the studies also suggest that the potential for clogging can be minimized by proper design and construction of the drainage layer. The potential for clogging of LDCRSs is generally lower than that for overlying leachate collection and removal systems (LCRSs) due to the relatively low volumes of flow in LDCRSs. Clogging of LDCRSs, however, could hinder the detection of leakage and the rapid removal of liquid from the LDCRS.

With this in mind, EPA is supporting the use of relatively permeable LDCRS materials in waste management units to minimize their potential for clogging. Fundamentally, a drainage material with large particles and, hence, large pore spaces, would have less potential for clogging than a material with smaller particles and, hence, smaller pore spaces. That is to say that materials such as coarse sands and fine gravels with a minimum hydraulic conductivity of 1 cm/s (1×10^{-2} m/s) would be less likely to clog than materials such as fine sand or silty sand with a minimum hydraulic conductivity of 1×10^{-2} cm/s (1×10^{-4} m/s).

Landfill Clogging[1]

Following is a summary of a research study looking at clogging.

Tested: * 2x10-2 cm/sec Ottawa sand (subrounded uniform size, 0.42mm--no. 40 sieve--avg particle size);
* 5x10-3 to 4.7x10-1 cm/sec filter fabrics (7 different geotextiles, including polypropylene (PP), polyethylene (PE), and polyester (PET)).

[Note: geotextiles use less space, are easier to transport, easier to place, and less expensive].

Tested using municipal waste leachate of different strengths.

Conclusions

* Flow rates always decreased (from 10-100%) over time: usually a sharp initial decrease followed by a continued linear, slightly linear, or sharply exponential decrease. In some cases flow decreased to levels that were not measurable by the experimental design.

* Sand (over geotextiles) clogged considerably more than those with geotextiles alone (23% flow retained for sand/geotextiles vs 34-45% flow retained with geotextiles alone).

* Type of polymer (PP, PE, & PET) appears to have no significance. Biological degradation of polymeric-based geotextiles did not occur.

* Stronger leachates (i.e., with higher BOD, COD, & TS) have greater clogging impacts. Particulate clogging appeared to be synergistic with the biological clogging.

* Both anaerobic and aerobic conditions promote clogging.

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[1] Koerner, Robert and George Koerner, Landfill Leachate Clogging of Geotextile (and Soil) Filters, EPA 600/2-91/025, August 1991 (NTIS # PB91-213660).

6. CONCLUSIONS

Facilities with good CQA perform significantly better than those without.

Facilities with good CQA appear to consistently achieve 50 gpad or less, taking into account other sources of liquids such as construction water and consolidation water. Whereas only about 70% of the facilities with good CQA achieve 20 gpad, which was the top of the range in the May 29, 1987 proposed rule. These results coupled with the magnitude of other sources of liquids indicates a practical action leakage rate is ≥ 100 gpad.

Calculations and models used to determine the action leakage rate show:

* Flow rates of 100 gpad for landfills and waste piles and 1,000 gpad for surface impoundments appear to be reasonable action leakage rates for the minimum specifications for slope and hydraulic conductivity in the final rule;
* Hydraulic conductivity is a significant factor (in all the models) since the flow rate is directly proportional to hydraulic conductivity: a change from 10^{-2} to 10^{-1} cm/sec increases the flow rate 10 times;
* Slope is relatively insignificant;
* Length of run is not a factor for slopes ≥ 1%;
* With no head above the top liner, the shape of flow is basically conical below the hole and rapidly tapers off, but with heads above the top liner more of the bottom liner is exposed to the higher heads;
* The size of leak is a factor that also influences whether the action leakage rate or flow capacity of the leak detection system will be exceeded. In the formula in the proposal background document, the size of leak is not considered since it is assumed that the hole is large enough to provide the maximum flow rate (Q) calculated. The 3-D model however confirms that the size of leak is indeed a limiting factor;
* Models that assume uniform leakage (which is an unrealistic assumption because the top liner is a geomembrane, not clay or other porous media) give higher flow capacities than models assuming one or more leaks through the top liner.

Clogging by fines or biological and chemical actions needs to be considered in the design (e.g., by the use of gradation or fabric filters and higher permeability drainage materials) and in the safety factor.

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APPENDIX A

EPA LINER GUIDANCES

DESIGN & CONSTRUCTION OF LINER SYSTEMS

A1. Guide to Technical Resources for the Design of Land Disposal Facilities, EPA-625-6-88-018, December 1988, 63p.

A2. Seminars--Requirements for Hazardous Waste Landfill Design, Construction and Closure, CERI-88-33, June 1988, 441p.

A3. Seminar Publication: Requirements for Hazardous Waste Landfill Design, Construction, and Closure, EPA-625-4-89-022, CERI, August 1989, 127p.

A4. Lining of Waste Containment and Other Impoundment Facilities, EPA-600-2-88-052, RREL, Sept. 1988, 1026p.

A5. Technical Guidance Document: Construction Quality Assurance for Hazardous Waste Land Disposal Facilities, EPA-530-SW-86-031, Oct. 1986, 99p.

CLAY/SOIL LINERS

A6. Design, Construction, and Evaluation of Clay Liners for Waste Management Facilities, EPA-530-SW-86-007F, Nov. 1988.

FML SEAMS

A7. Technical Guidance Document: The Fabrication of Polyethylene FML Field Seams, EPA-530-SW-89-069, Sept. 1989, 42p.

A8. MEMO: "Use of Construction Quality Assurance (CQA) Programs and Control of Stress Cracking in Flexible Membrane Liner Seams", Sylvia Lowrance to HWMDDs, Regions I-X, July 13, 1989, 14p.

A9. Field Inspector's Manual: Stress Cracking of Flexible Membrane Liner Seams, EPA, December 1988.

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A10. Design and Construction of Covers for Solid Waste Landfills, EPA-600-2-79-165, MERL, August 1979, 274p.

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A22. Draft Background Document on Double Liner Rule, EMCON Associates for EPA, September 1987.

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Liner-Waste Compatibility

A24. Liner Materials Exposed to Hazardous and Toxic Wastes, H. Haxo, Jr. et al, Matrecon, Inc. for EPA, September 1984, 271 pgs.

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APPENDIX B

FLOW RATE RESULTS USING A 3-D COMPUTERIZED MODEL

Leakage from Top Liner and Flux Through Drainage Layer for Double Lined Landfills and Surface Impoundments: Computer Simulations

For

Liner and Leak Detection Rule

January 1992

Technical Assessment Branch

Characterization and Assessment Division

Office of Solid Waste

Washington, D. C. 20460

CONTENTS

		Page
1.	Contents	i
2.	Acknowledgements	ii
3.	Introduction	1
4.	Modeling Approach	1
5.	Model Input Data	2
6.	Model Output	2
7.	Modeling Assumptions	2
8.	Simulation Scenarios	3
9.	Simulation Results	3
10.	List of Tables	4
11.	Tables 1 through 5	5
12.	List of Figures	11
13.	Figures 1 through 10	12

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LEAKAGE FROM TOP LINER AND FLUX THROUGH DRAINAGE LAYER OF DOUBLE LINED LANDFILLS AND SURFACE IMPOUNDMENTS: COMPUTER SIMULATIONS

INTRODUCTION

The Hazardous and Solid Waste Amendments of 1984 (HSWA) made many changes in Resource Conservation and Recovery Act (RCRA) sections covering regulations of hazardous waste. The minimum technology requirements of HSWA require EPA to revise regulations for liners and leak detection systems at hazardous waste management units. The Agency's minimum technology requirements for landfills, surface impoundments, and waste piles require a double liner system. The HSWA require an "approved leak detection system" to be utilized at these new units. The basis for the leak detection system is the leachate collection and removal system (LCRS) between the top and bottom liners as required in the regulations. The ultimate goal of the liner and leak detection system is to prevent the release of hazardous constituents from the unit.

The objective of the analyses described here is to simulate the leakage from the top liner of the double liner system and the movement of water through the underlying drainage layer to a drain. The results of computer simulations are for use in the development of action leakage rates (ALR). The action leakage rate is a leakage rate that requires implementation of a response action to prevent hazardous constituent migration out of the unit.

MODELING APPROACH

A three-dimensional finite element model, VAM3D, developed to simulate water flow and solute transport in variably saturated porous media was used to simulate flow from a punctured synthetic upper liner to a drainage layer. The model was used to perform the

three-dimensional simulations for the point source leak for both landfill and surface impoundment cases. A series of simulations were performed to investigate the effects of various input parameters on the hydraulic head distribution and drain discharge rates.

MODEL INPUT DATA

The following are the main input data for performing the simulation using a finite-element three-dimensional model:

Thickness, length, width and slope of the drainage layer; location and area of the leak; hydraulic conductivity of the drainage layer; location of the discharge drain; and hydraulic heads at the leak and drain locations.

MODEL OUTPUT

The model calculates the distribution of hydraulic head in the drainage layer and the flow rates through the leak in the liner and the discharge to the drain.

MODELING ASSUMPTIONS

A model represents an idealization of a natural system. Certain assumptions are necessary in making these representations. The following are main assumptions underlying the analyses reported here:

- Uniform properties throughout the drainage layer;
- Leak occurs through punctured hole of very small area compared to the area of the landfill;
- Thickness of the drainage layer is uniformly one foot;
- The bottom, sides and upstream boundaries of modeled region are impermeable;
- Steady state flow conditions prevail, and the flow in the unsaturated zone is negligible;

- o Flow in the saturated zone occurs approximately parallel to the slope of the bottom of the drainage layer;
- o The water level in the drain is maintained at a constant level near the bottom of the drainage layer;
- o For the landfill case, the hydraulic head at the leak is maintained at the top of the drainage layer for most of the cases studied; and
- o For the surface impoundment case, the hydraulic head at the leak is maintained at the impounded water level.

SIMULATION SCENARIOS

A number of scenarios for representing the various waste management units were selected for simulation:

1. Landfill and surface impoundment scenarios with a leak in the top liner; head in the drainage layer was kept at the top liner and other parameter were varied to determine effects on flow rates and head distribution. The water thickness above the top liner was more than zero for surface impoundments:

   a. Distance of leak point from the drain;
   b. Slope of the liner system;
   c. Size of the leak; and
   d. Hydraulic conductivity of the drainage layer.

2. Geonet scenario with similar parameter variations as for the above scenarios.

SIMULATION RESULTS

A summary of results is presented here in a series of Figures and Tables. The results are discussed in the Preamble to the liner/leak detection rule for the development of ARL.

LIST OF TABLES

Table		Page
1.	Flow Rates from Drainage Layer for Various Landfill Scenarios (gal/day)	5
2.	Effects of Liner Leak Size on Drain Discharge	6
3.	Drainage Layer Flow Rates for Surface Impoundments	7
4.	Drainage Layer Flow Rates for Landfills and Surface Impoundments	8
5.	Flow Rates Through a Geonet	9

Table 1. Flow Rates From Drainage Layer for Various Landfill Scenarios (gal/day)

Leak 20 feet from drain				
		Hydraulic Conductivity (K) in cm/sec		
Case	Slope	1	0.1	0.01
(A)	0%	7394.2	739.42	73.94
(B)	1%	8164.9	816.49	81.65
(C)	2%	8485.8	848.58	84.86
(D)	3%	8805.4	880.54	88.05

Leak 80 feet from drain			
	Hydraulic Conductivity (cm/sec)		
Case/ Slope	1	0.1	0.01
(E) 0%	6075.7	607.57	60.75
(F) 1%	8048.5	804.85	80.48
(G) 2%	8564.0	856.40	85.64
(H) 3%	8829.9	882.99	88.30

Landfill Area = 1 acre
Length Parallel to Flow = 100 ft.
Leak Area = 1 sq. ft.
Thickness of Drainage Layer = 1 ft.
Head Above Top Liner = 0

Table 2.
Effects of Liner Leak Size on Drain Discharge

Leak Area (sq. ft.)	Flow Rate (GPD)
0.123	479
0.175	532
0.25	564
1.0	805
3.0	1337
4.0	1480
12.5	1700
20	1840
25	1950
30	1955

Area of Landfill = 1 acre

Hydraulic Conductivity = 0.1 cm/sec

Slope = 1 percent

Distance of leak from drain = 80 feet

Head above top liner = 0

Table 3

Drain Flow Rates for Surface Impoundments

Hydraulic Head above Top Liner (ft.)	Slope (%)	Flow Rate (gpd) Hydraulic Conductivity (cm/sec.) 1	0.1	0.01
0	1	5640	564	56
1	1	15,400	1540	154
2	1	27,190	2719	272
0	2	5740	574	57
1	2	16,050	1605	161
2	2	28,750	2875	288

Area of waste management unit = 1 acre
Thickness of drainage layer = 1 ft
Distance from the leak = 80 ft
Leak area = 0.25 sq ft

Table 4.

Drainage Layer Flow Rates For Landfills and Surface Impoundments

Hydraulic Head above Top Liner (ft)	Slope (%)	Flow Rate (gpd) Hydraulic Conductivity (cm/sec) 1	0.1	0.01
1	1	20,400	2040	204
1	2	21,900	2190	219
0.5	1	13,900	1390	139
0.5	2	14,300	1430	143

Thickness of Drainage Layer = 1 ft
Total area of waste management unit = 1 acre
Length of unit along flow direction = 200 ft
Distance of Leak from drain = 180 ft
Leak size = 1 sq ft

Table 5. Flow Rates Through a Geonet

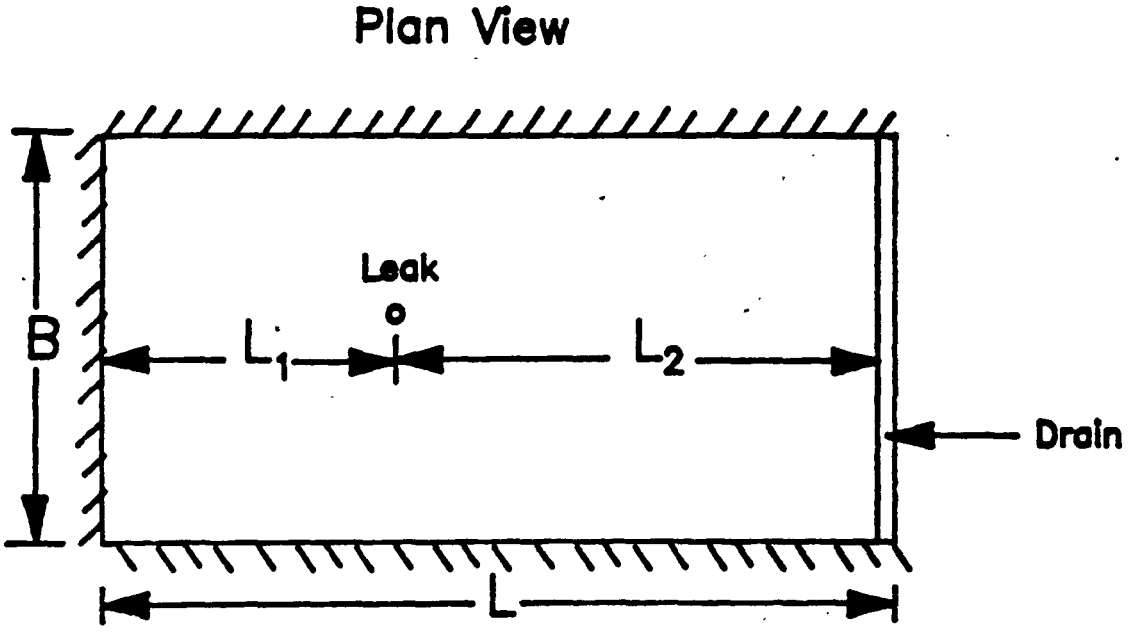
Thickness of Geonet (mm)	Hydraulic Head above Geonet (ft.)	Slope (%)	Flow Rate (gpd) Hydraulic Conductivity (cm/sec.) 1	0.1	0.01
5	1	0	81	8.1	0.8
5	1	1	524	52.4	5.2
5	1	2	751	75.1	7.5
5	1	3	977	97.7	9.8
5	2	0	160	16.0	1.6
5	2	1	813	81.3	8.1
5	2	2	1040	104.0	10.4
5	2	3	1264	126.4	12.6
10	1	0	164	16.4	1.6
10	1	1	1625	162.5	16.3
10	1	2	2090	209.0	20.9
10	1	3	2552	255.2	25.5

Leak Area = 0.25 sq. ft.

LIST OF FIGURES

Figure		Page
1.	Model Scenarios for Landfills and Surface Impoundments	11
2–a	Water–Table Profiles in Drainage Layer Due to a Leak in Top Liner (Cases A and E of Table 1 – No Slope)	12
2–b	Water–Table Profiles in Drainage Layer Due to a Leak in Top Liner (Cases F and B of Table 1 – 1% Slope)	13
2–c	Water–Table Profiles in Drainage Layer Due to a Leak in Top Liner (Cases C and G of Table 1 – 2% Slope)	14
2–d	Water–Table Profiles in Drainage Layer Due to a Leak in Top Liner (Cases D and H of Table 1 – 3% Slope)	15
3–a	Water–Table Contours for Case F (Table 1)	16
3–b	Water–Table Contours for Large Leak Area	17
4.	Landfill Drainage Layer Flux Vs Drainage Layer Slope for Different Leak Positions	18
5.	Drain Discharge for Different Leak Sizes	19
6.	Hydraulic Head Distribution in the Drainage Layer Due to a Hydraulic Head of 2 ft. Above Top Liner Leak Point	20
7.	Comparison of Water–Table Profiles for Various Surface Impoundment Scenarios	21
8–a	Water Table Profiles in the Drainage Layer Due to a Leak in Top Liner Under a Surface Impoundment (Case : 1% Slope)	22
8–b	Water Table Profiles in the Drainage Layer Due to a Leak in Top Liner Under a Surface Impoundment (Case : 2% Slope)	23
9	Thin Synthetic Drain Layer (GEONET) Scenario	24
10.	Drain Flux Vs Slope for the Thin Synthetic Layer	25

Figure 1.
Model Scenarios for
Landfills or Surface Impoundments



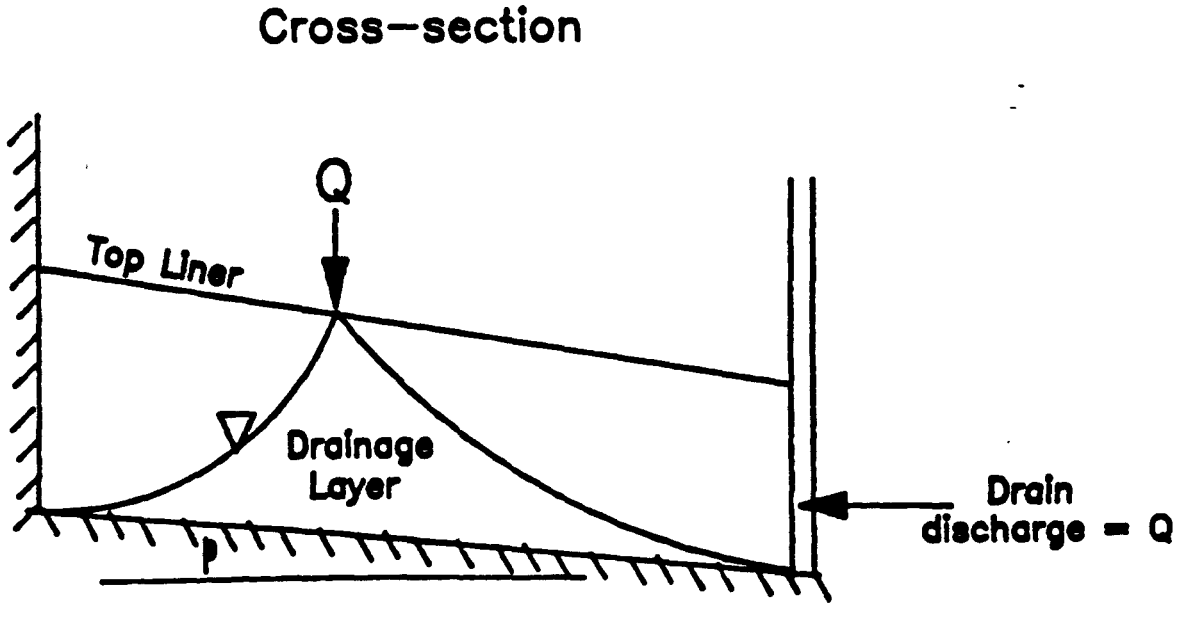
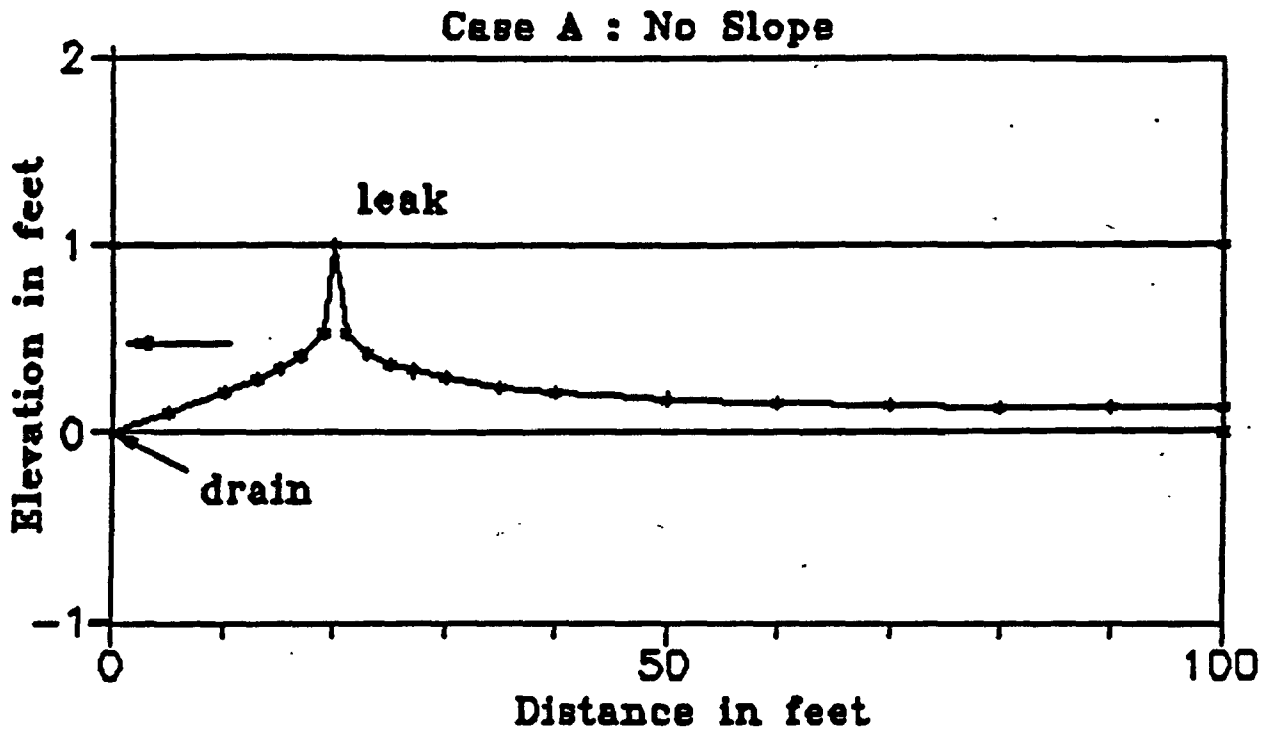


Figure 2-a. Water-Table Profiles in Drainage Layer Due to a Leak in Top Liner (Cases A and E of Table 1 – No Slope)



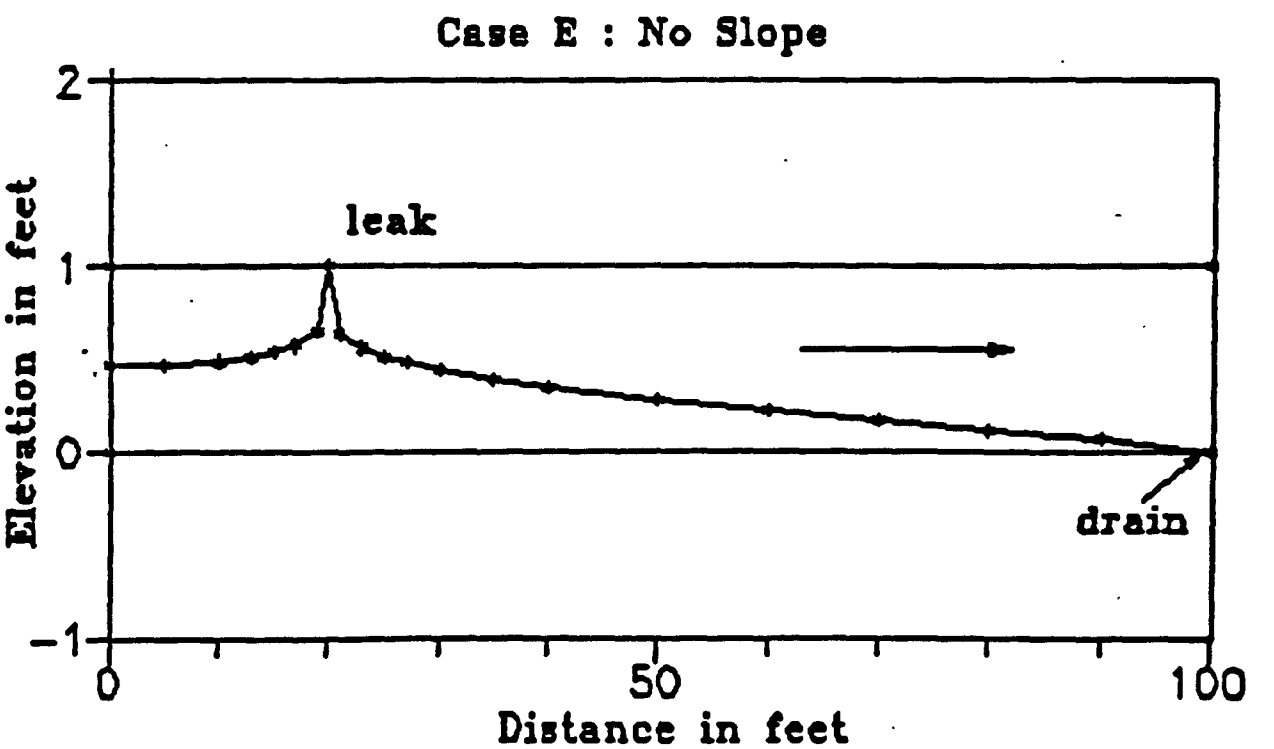
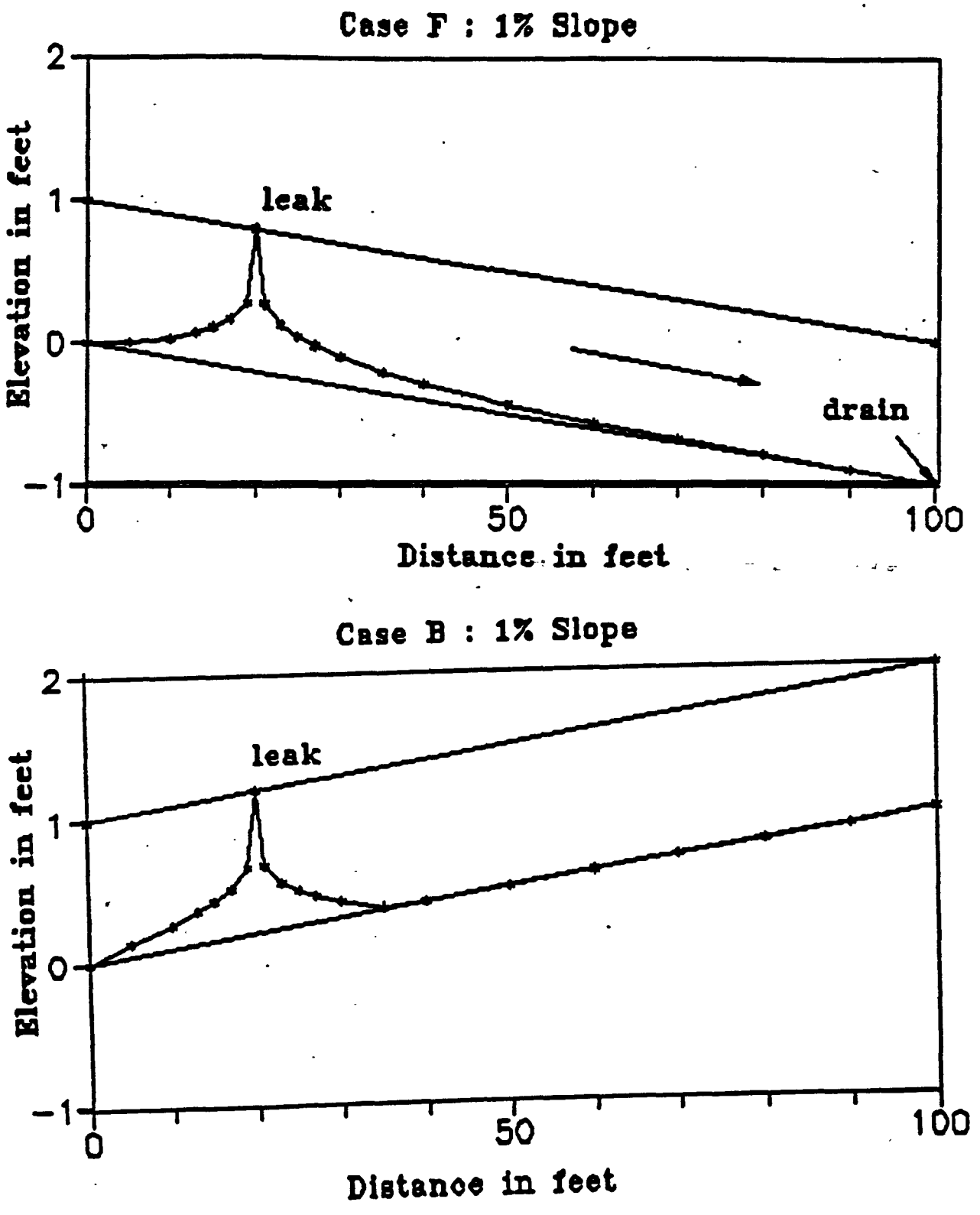
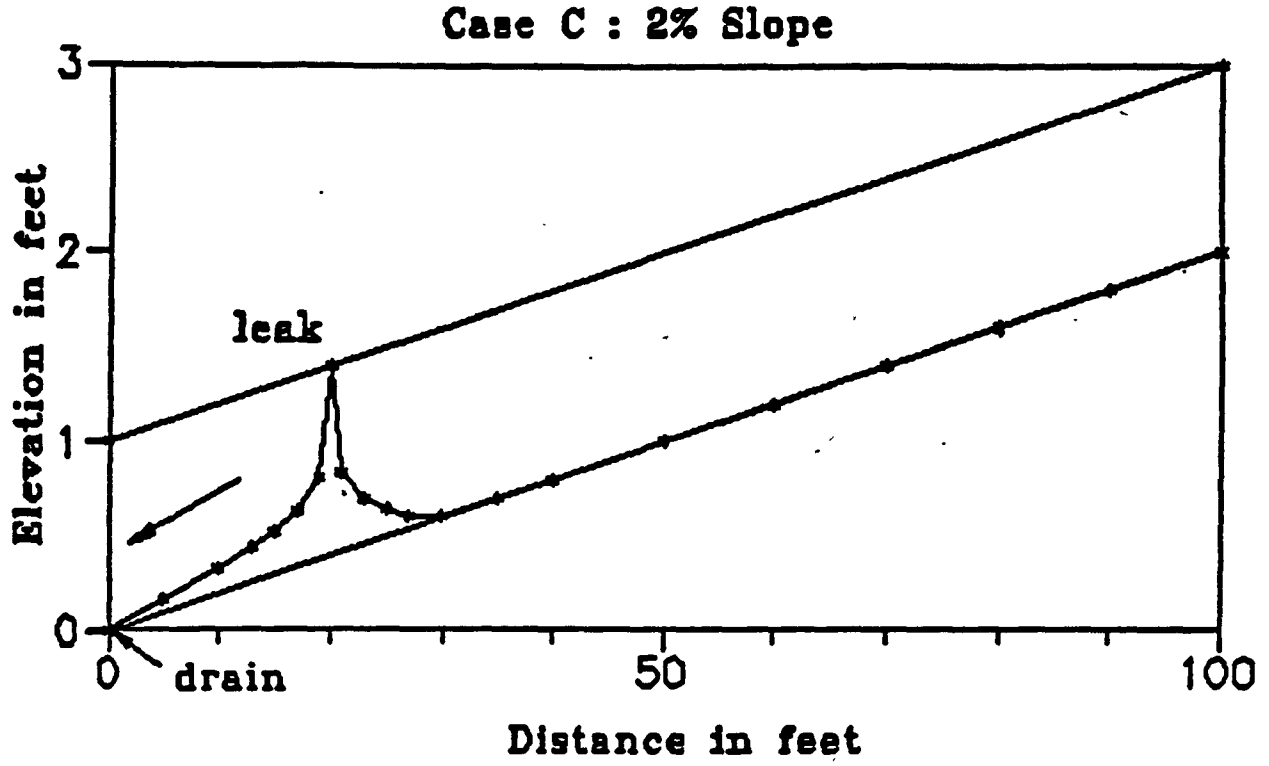


Figure 2-b. Water-Table Profiles in Drainage Layer Due to a Leak in Top Liner (Cases F and B of Table 1 – 1% Slope)



Note : Profiles do not change with changes in K, Q changes proportionately.

Figure 2–c. Water–Table Profiles in Drainage Layer Due to a Leak in Top Liner (Cases C and G of Table 1 – 2% Slope)



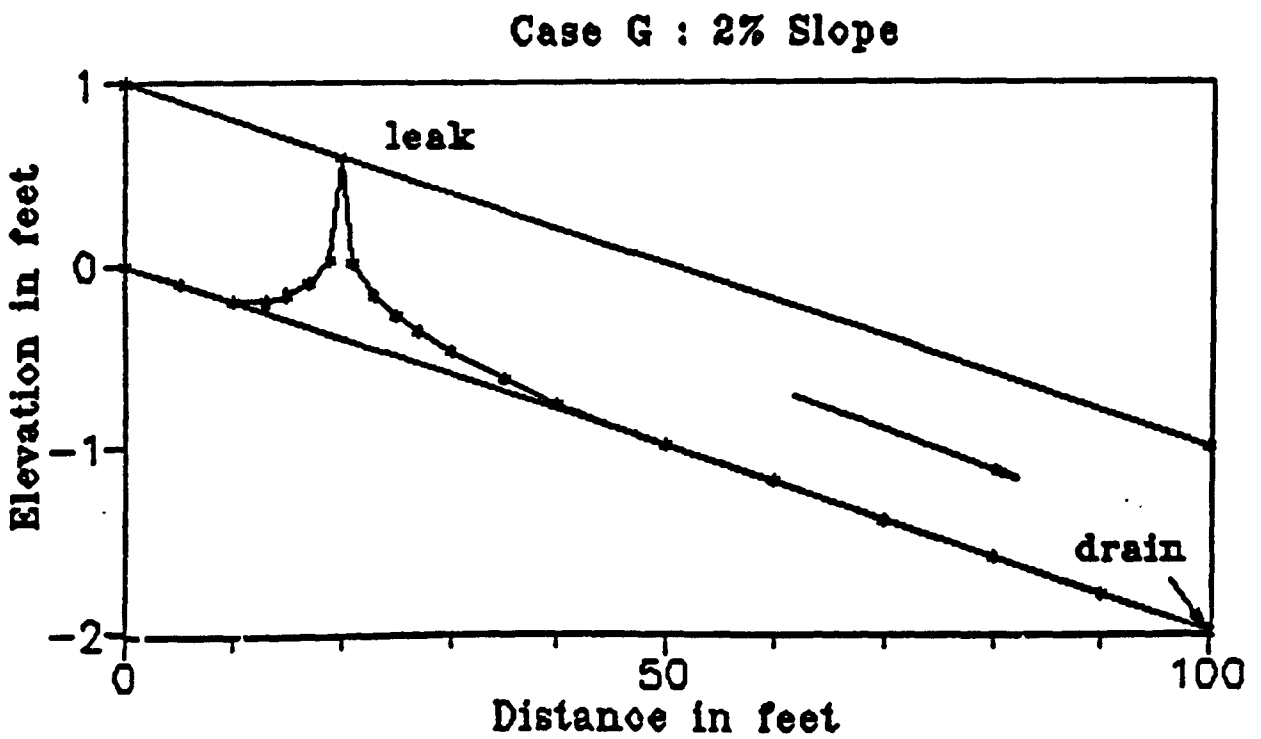
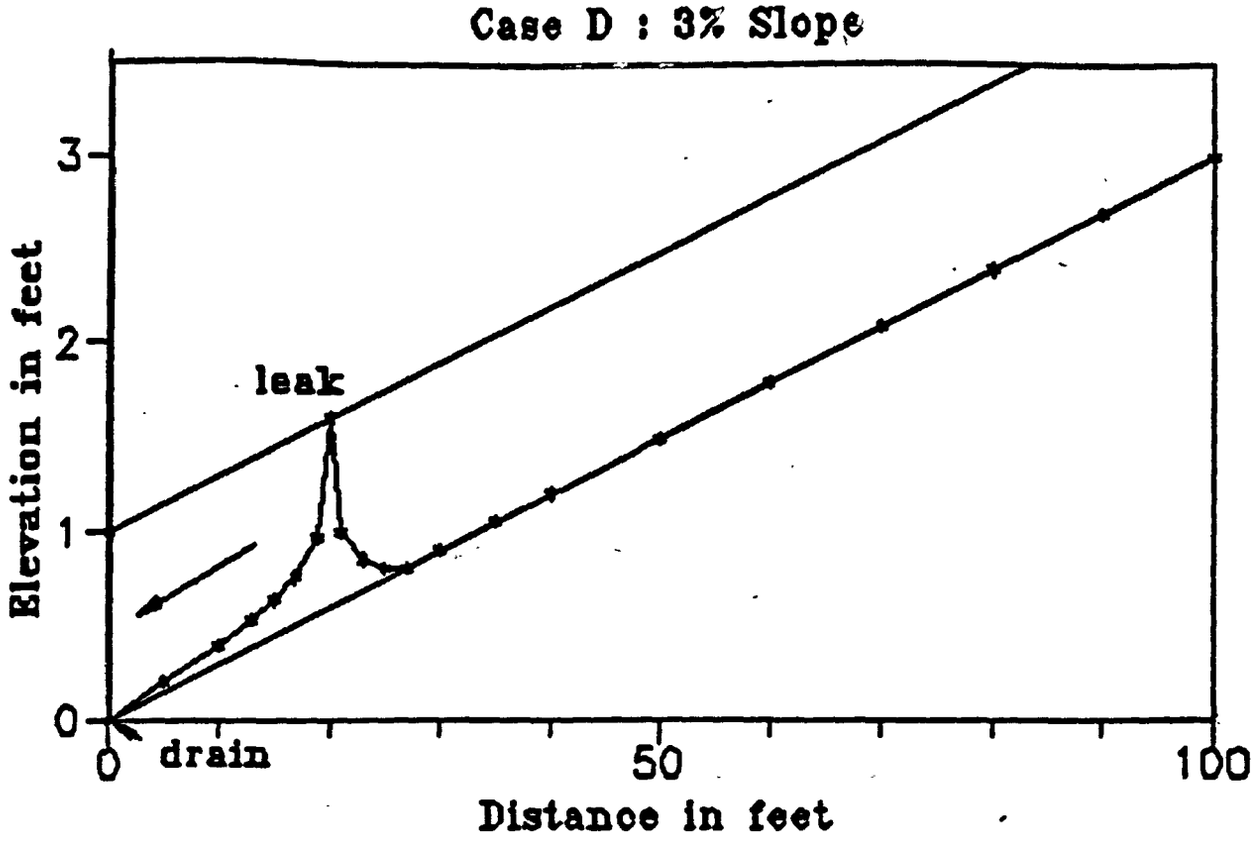
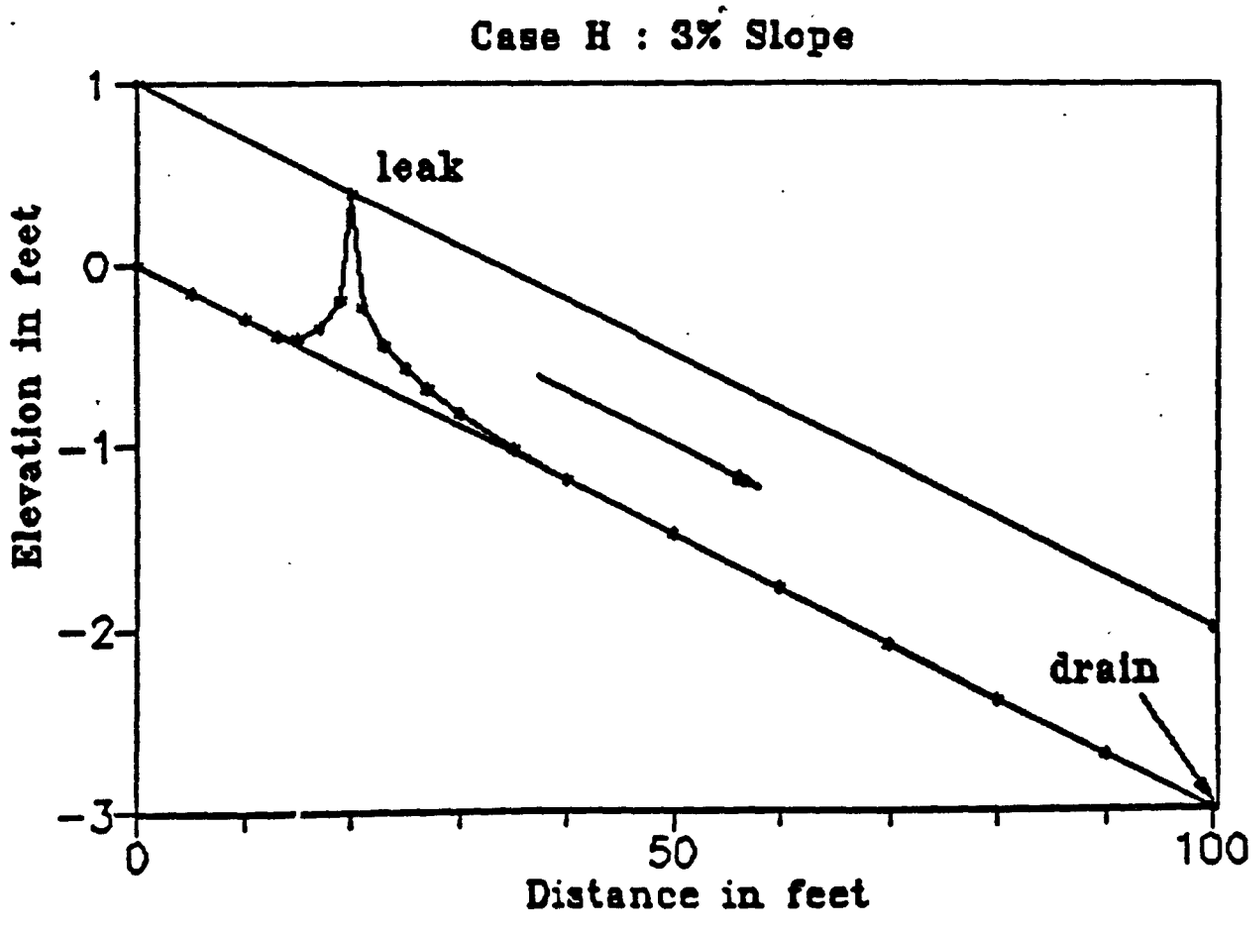


Figure 2–d. Water–Table Profiles in Drainage Layer Due to a Leak in Top Liner (Cases D and H of Table 1 – 3% Slope)





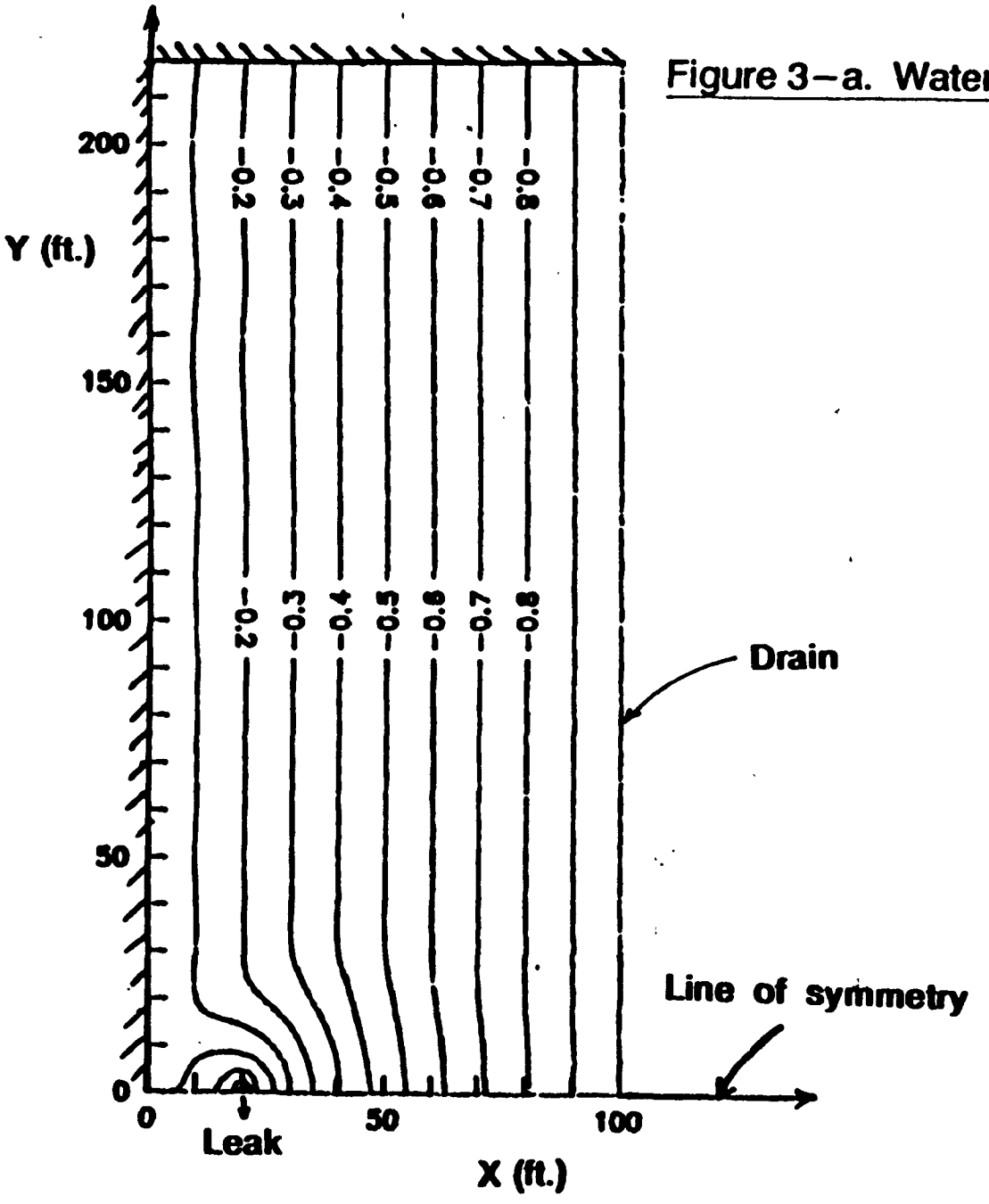


Figure 3–a. Water Table Contours for Case F (Table 1)

Leak area = 1 sq. ft.
Slope = 1%
Distance of leak from drain = 80 ft.
Contour interval = 0.1 ft.

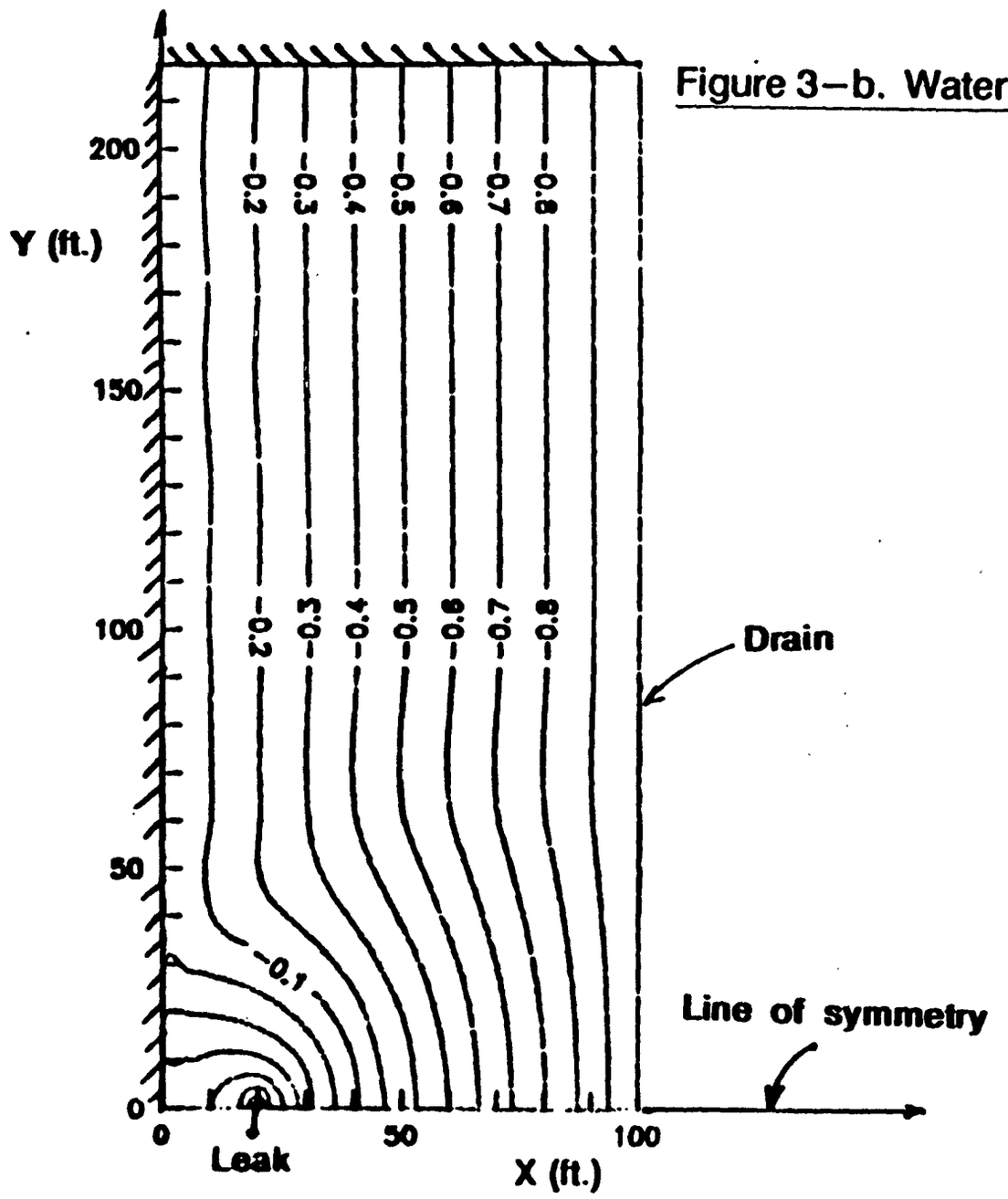


Figure 3–b. Water Table Contours for Large Leak Area

Leak area = 3 sq. ft.
Slope = 1%
Distance of leak from drain = 80 ft.
Contour interval = 0.1 ft.

Figure 4. Landfill Drainage Layer Flux Vs Drainage Layer Slope for Different Leak Positions

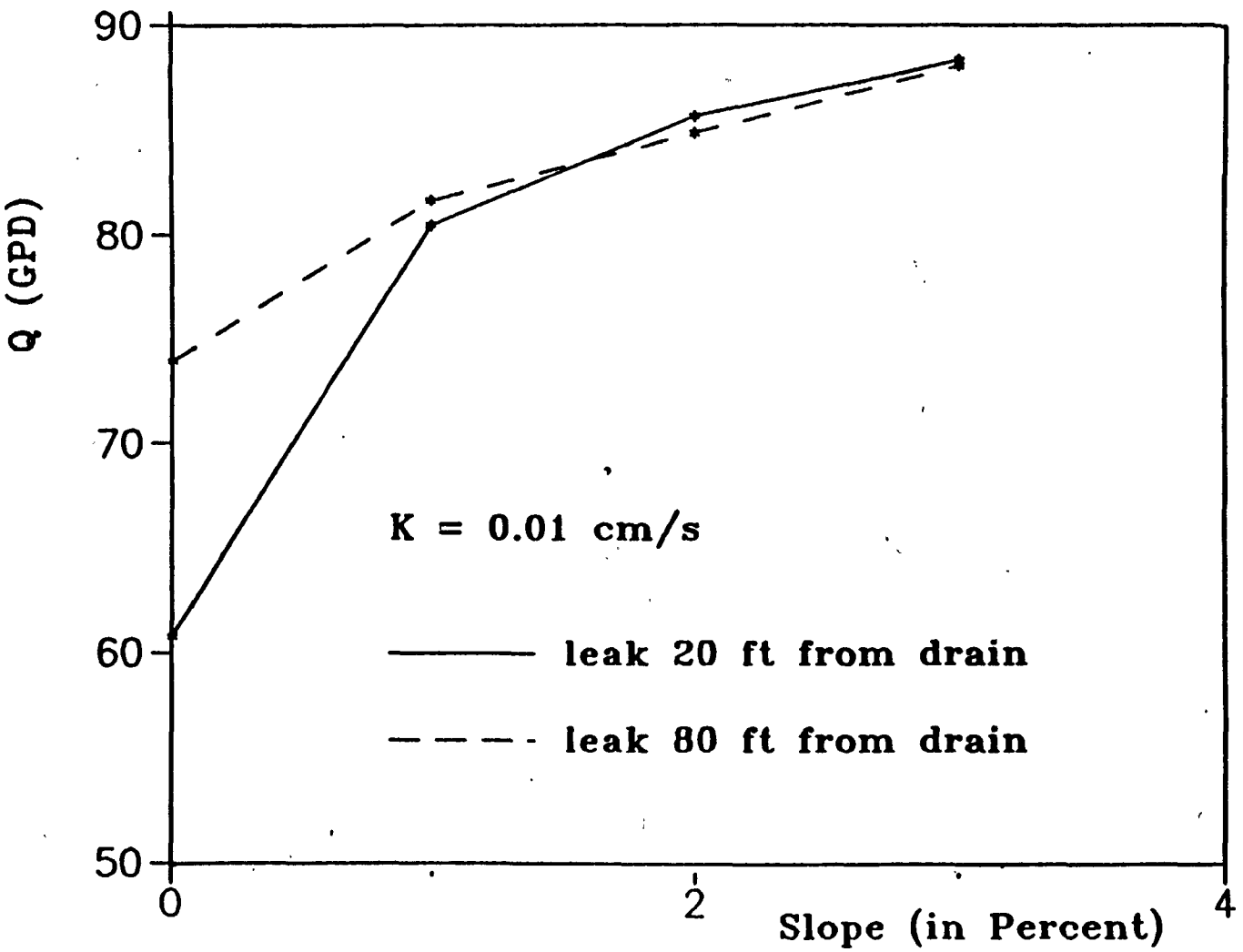


Figure 5
Drain Discharge for Different Leak Sizes

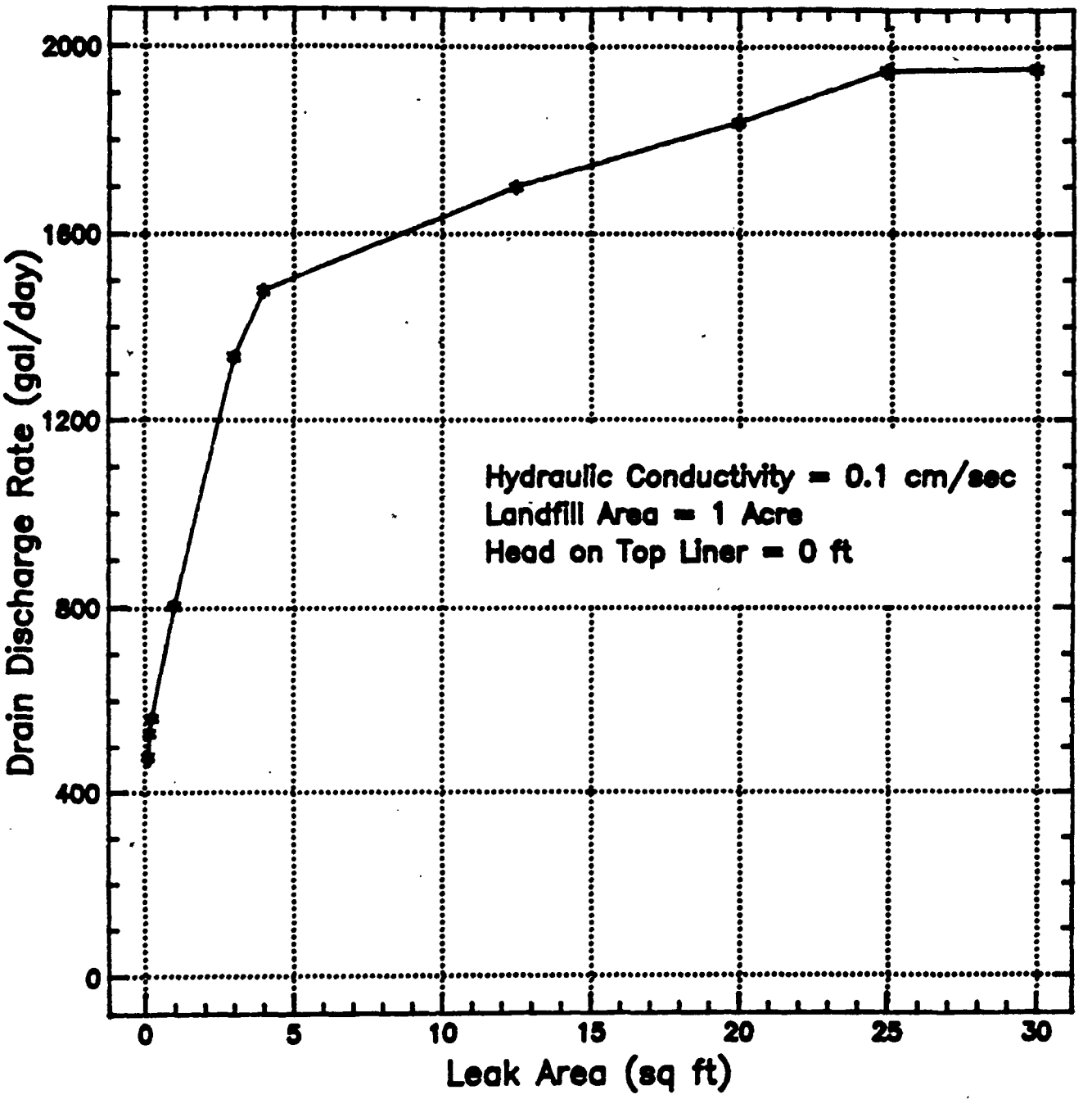
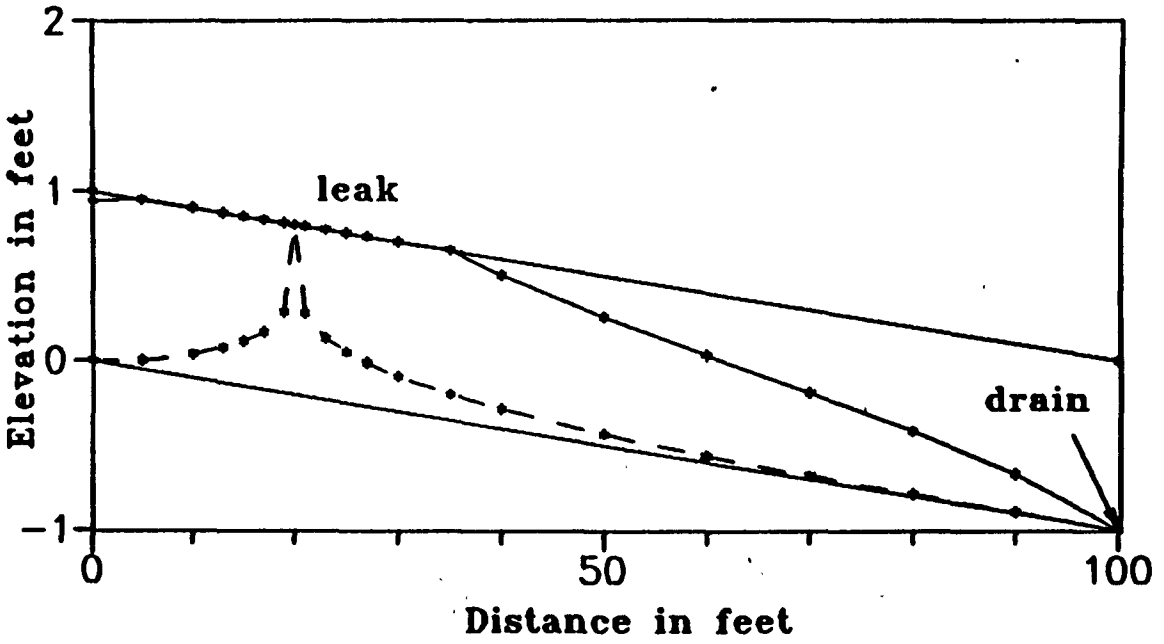


Figure 6. Hydraulic Head Distribution in the Drainage Layer Due to a Hydraulic Head of 2 ft. Above Top Liner Leak Point



for K = 0.1 cm/s

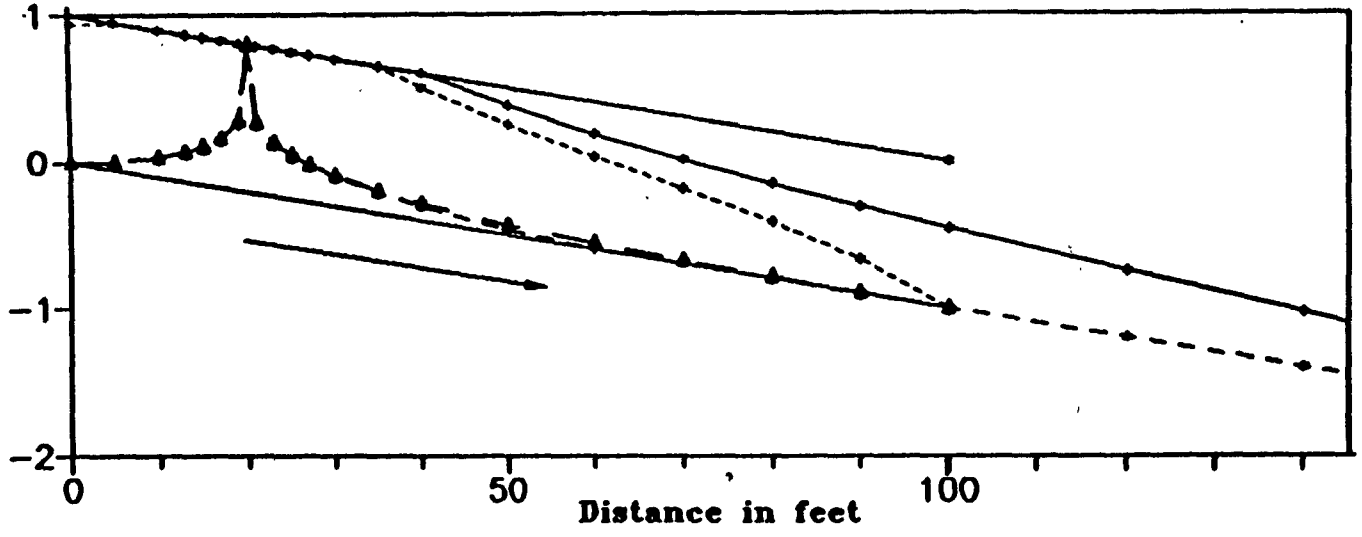
Q(2') = 3552 GPD

Q(0') = 80 GPD

——— Surface Impoundment = 2 feet

– – – Head at Leak = 0 feet

Figure 7. Comparison of Water–Table Profiles for Various Surface Impoundment Scenarios



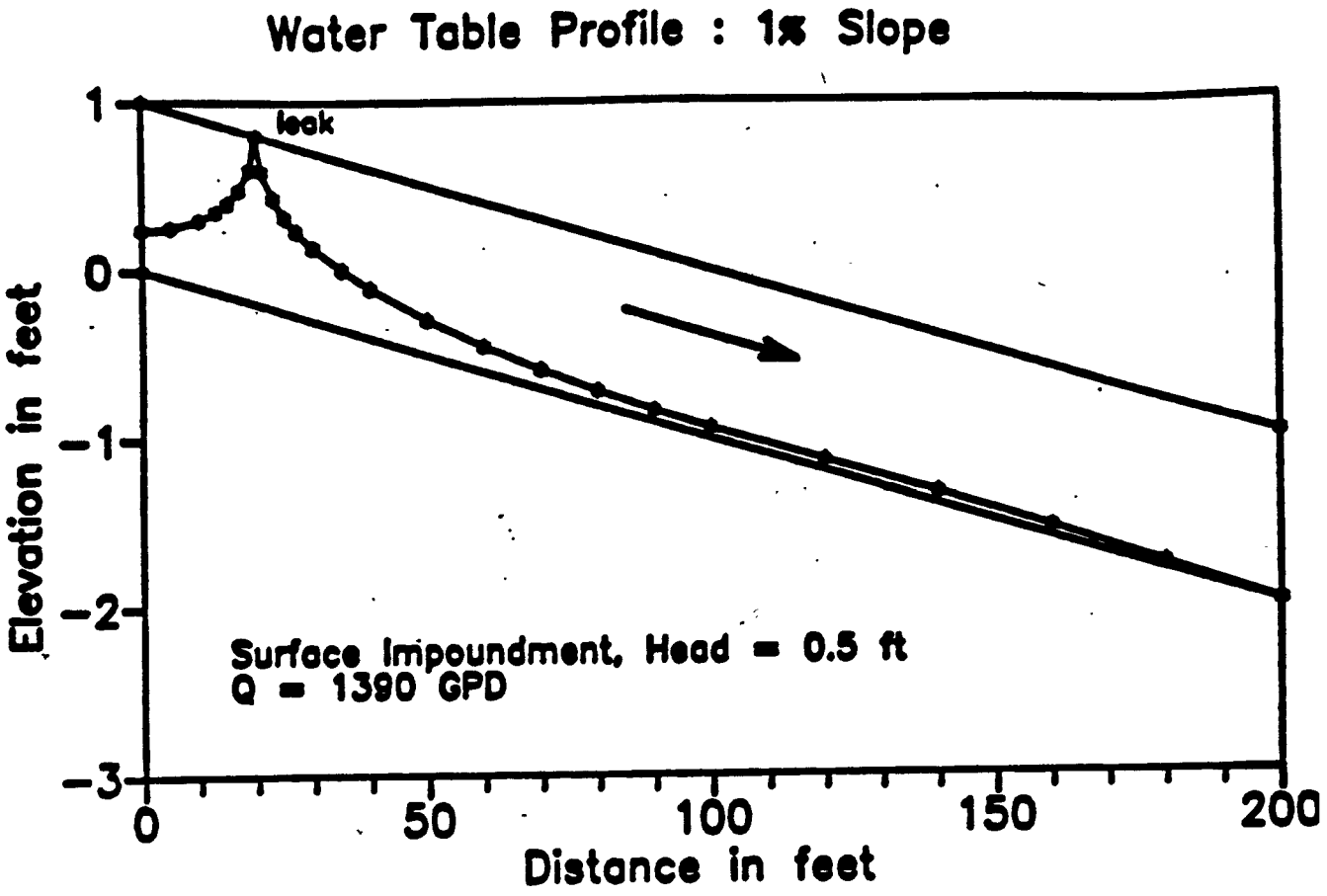
----- Surface Impoundment, Head = 2 ft, Case F [Q = 3552 GPD]

——— Surface Impoundment, Head = 2 ft on Length = 200 ft [Q = 3396 GPD]

— — · Length of Domain = 200 ft (Head at Leak = 0) [Q = 797 GPD]

-▲-▲-· Base Case (F) (Head at Leak = 0) [Q = 805 GPD]

Figure 8-a. Water Table Profiles in the Drainage Layer Due to a Leak in Top Liner Under a Surface Impoundment (Case : 1% Slope



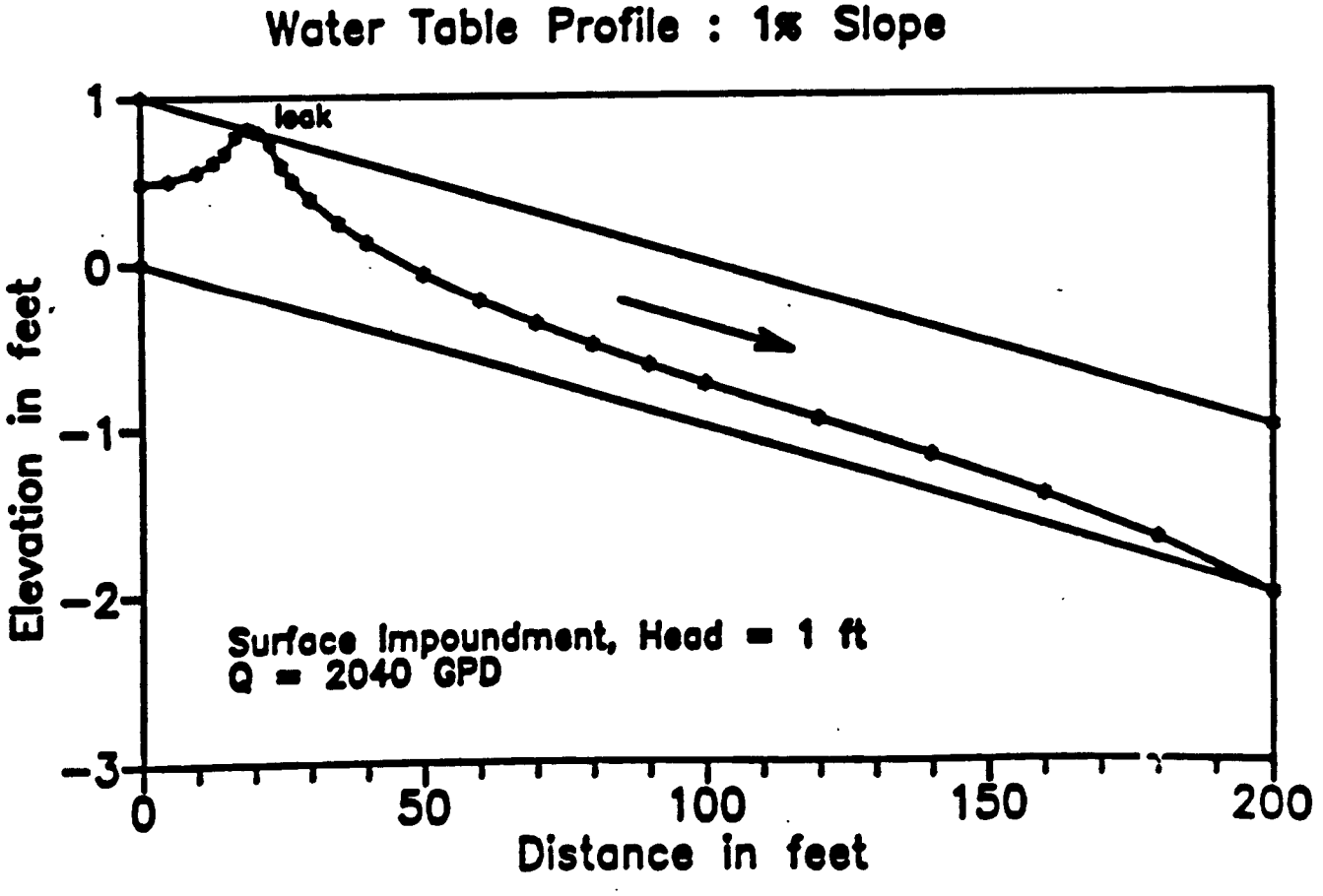
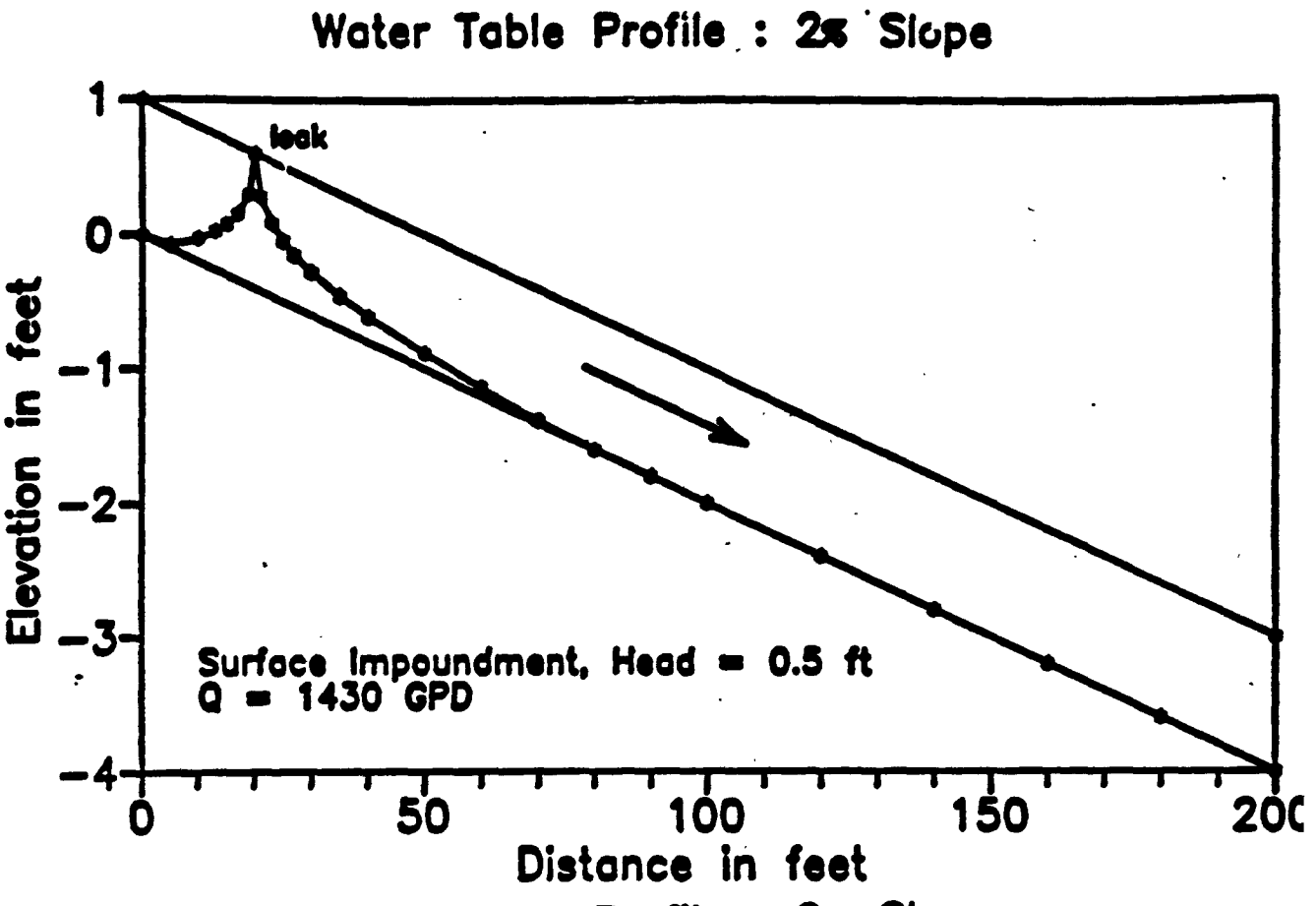


Figure 8–b. Water Table Profiles in the Drainage Layer Due to a Leak in Top Liner Under a Surface Impoundment (Case : 2% Slope)



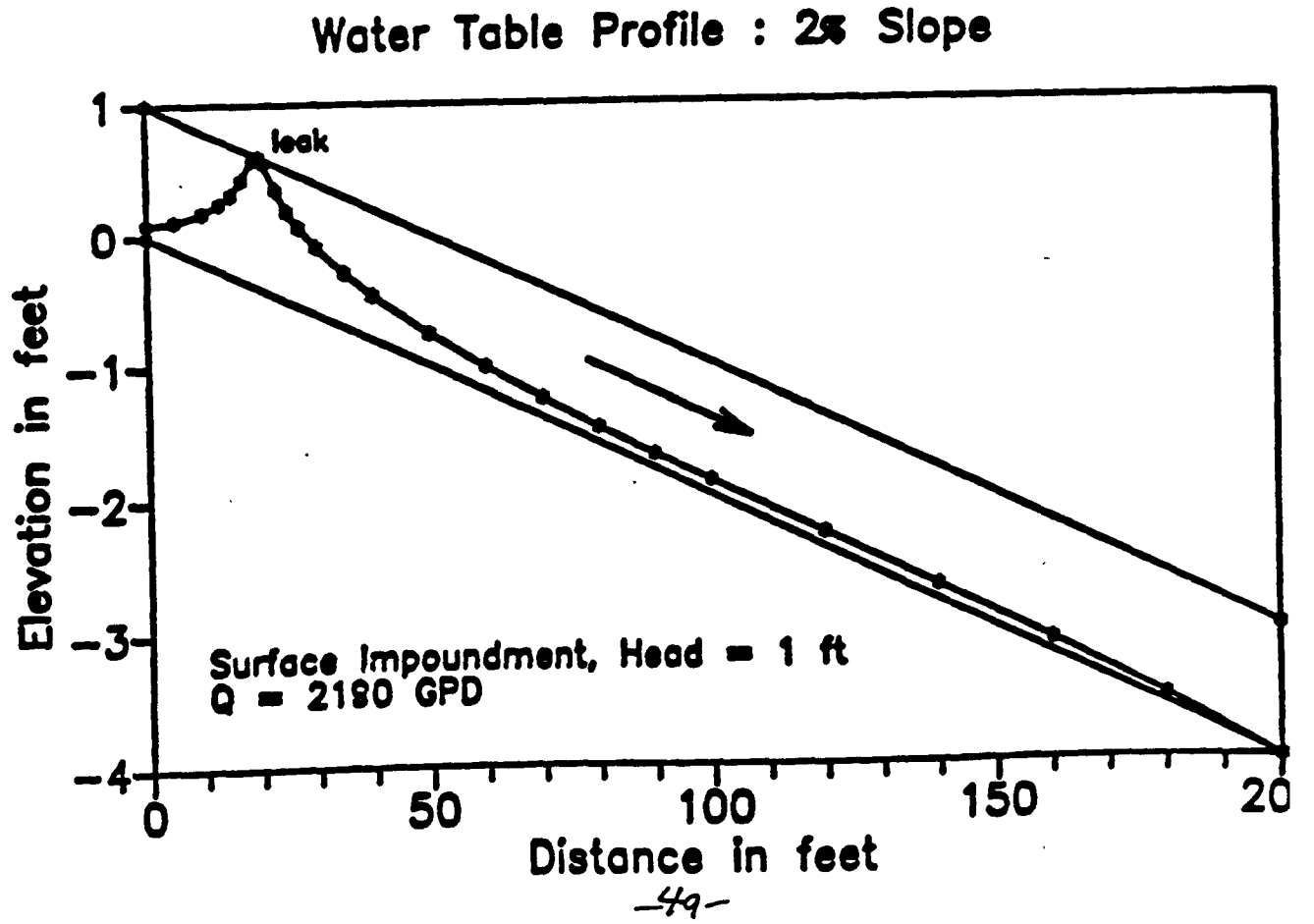


Figure 9.
Thin Synthetic Drain Layer (GEONET) Scenario

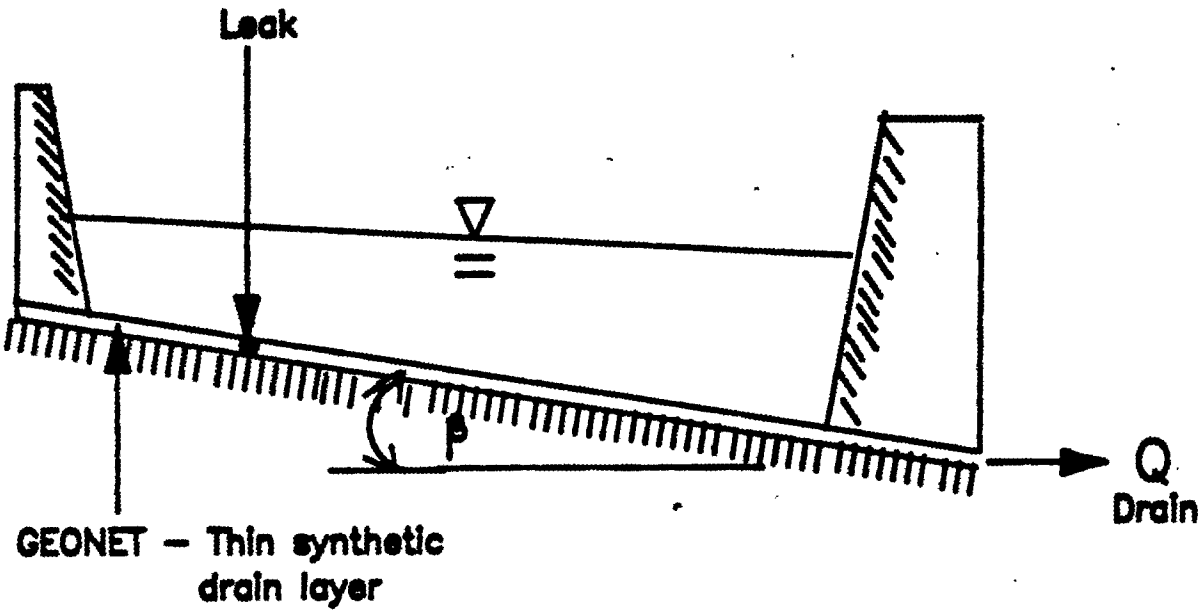
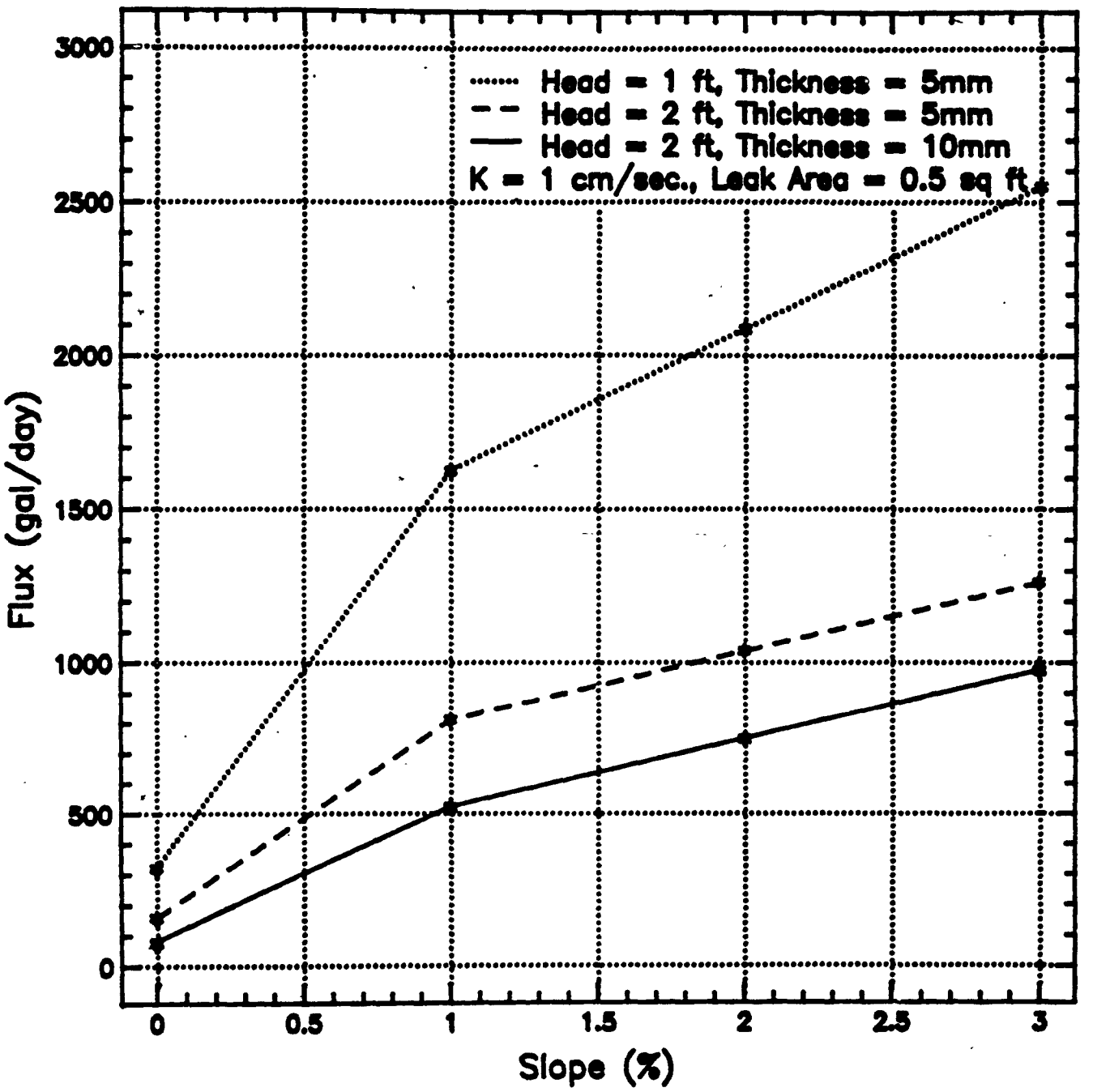


Figure 10

Drain Flux vs Slope for the Scenario of Thin Synthetic Layer



APPENDIX C

BACKGROUND INFORMATION ON THE 3-D VARIABLY SATURATED FLOW ANALYSIS MODEL

See also:

VAM2D--Variably Saturated Analysis Model in Two Dimensions, Version 5.2, Documentastion and User's Guide, NUREG/CR-5352, Rev 1, HydroGeoLogic, Inc. for U.S. Nuclear Regulatory Commission, October 1991.

Validation and Testing of the VAM2D Computer Code, NUREG/CR-5795, HydroGeoLogic, Inc. for U.S. Nuclear Regulatory Commission, October 1991.

DRAFT

VAM3D–CG – Variably Saturated Analysis Model in Three Dimensions

Version 2.3

HydroGeoLogic, Inc.
1165 Herndon Parkway
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Prepared for
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ABSTRACT

This report documents a three-dimensional finite element model, VAM3D-CG, developed for simulating saturated-unsaturated groundwater flow and solute transport with variable water table position and highly non-linear soil moisture conditions. The flow equation is approximated using the Galerkin finite element method. VAM3D-CG has the capacity to accommodate spatially variable hydraulic properties such as hydraulic conductivity, storativity, and effective porosity, with high degrees of variability.

Nonlinearities due to unsaturated soil properties, atmospheric boundary conditions (e.g., infiltration, evaporation, and seepage faces), and water uptake by plant roots are treated using the Picard iteration technique or linearized using the Newton-Raphson scheme. The transport equation may be approximated using an upstream-weighted finite element method to alleviate the problem of numerical oscillations. An orthogonal curvilinear coordinate system may be used to discretize the domain, and elements can be designed along subsurface formations.

Transport mechanisms considered include: advection, hydro-dynamic dispersion, adsorption, and first-order decay. Complex boundary conditions, such as no-flow, constant head, constant flux, constant gradient, and time-dependent head or flux, are easily incorporated into the model. VAM3D-CG employs a Preconditioned Conjugate Gradient (PCG) matrix solution scheme which allows several thousand nodal unknowns to be solved extremely cost-effectively in transient or steady-state mode. The code can easily be adapted for one-, two-, or three-dimensional applications, including axisymmetric configurations.

Several test problems are presented to verify the code and demonstrate its utility. These problems range from simple one-dimensional to complex three-dimensional problems.

INTRODUCTION

BACKGROUND AND PURPOSE OF THE CODE

VAM3DCG is a three-dimensional, finite element code developed to simulate moisture movement and solute transport in variably saturated porous media. The code is capable of simulating a wide range of conditions commonly encountered in the field. Simulations can be performed efficiently for fully three-dimensional, two-dimensional or axisymmetric problems. Both flow and transport simulations can be handled concurrently or sequentially. Material heterogeneities and anisotropy are handled by taking advantage of the finite element approach. Efficient matrix computational and solution schemes are employed in conjunction with simple rectangular prism elements to analyze problems involving highly nonlinear soil moisture characteristics. Many types of boundary conditions can be accommodated: 1) water table conditions, 2) atmospheric conditions associated with seepage faces, evaporation and nonponding infiltration, 3) water uptake by plant roots, 4) vertical recharge of the water table, and 5) pumping and injection wells.

The model formulation used in VAM3DCG is a descendant of the formulation used in the FLAMINCO and VAM3D code presented by Huyakorn, et al. (1986, 1987). HydroGeoLogic, Inc. has recently enhanced certain portions of the published algorithms and their coding to achieve greater flexibility, wider capability, and more robust numerical performances when dealing with some difficult cases. Where possible, the new VAM3DCG code has been rigorously checked against available analytical or semi-analytical solutions and similar numerical codes including UNSAT2, FEMWATER/FEMWASTE, SATURN,

FLAMINCO and VAM3D. A variety of field simulation problems described in the works of Huyakorn et al. (1984, 1985, 1987), Enfield et al. (1983), and Carsel et al. (1985) have been used to validate VAM3DCG and demonstrate is utility. Additional simulation problems are described in this report.

OVERVIEW OF CODE CAPABILITIES AND SALIENT FEATURES

Multidimensional modeling of water flow and waste migration in variably saturated subsurface systems can be a formidable task unless one is equipped with a proper code that accommodates various field conditions. Recognizing this point, VAM3DCG was developed to have not only essential modeling capabilities but also salient features that facilitate practical use. An overview of these aspects of the code is presented below.

1. VAM3DCG can perform transient analyses or single step steady-state analyses of both variably saturated water flow and solute transport problems. If the flow and transport problems are associated, a dual simulation can be made by solving the problems concurrently or sequentially in a single computer run.

2. The finite element formulation and nonlinear solution procedures in VAM3DCG are based on the state-of-the-art technology designed to accommodate a wide range of field conditions including highly nonlinear moisture characteristics, material heterogeneity and anisotropy, and rapidly fluctuating transient flow boundary conditions.

3. VAM3DCG uses highly efficient matrix computational and matrix solution techniques. The code is directly interfaced with newly developed ORTHOMIN and Preconditioned Conjugate Gradient matrix solvers designed to handle problems with large

number of nodal unknowns (on the order of several thousand or more) efficiently. This feature makes the code attractive to use on a minicomputer or a personal computer PC 386.

4. An orthogonal curvilinear mesh can be used with this version of VAM3D-CG, which makes the code attractive for undulating layered systems, and is better capable of handling irregular boundaries, geometry, and material properties.

5. The flow simulator of VAM3DCG can handle various boundary conditions and physical processes including infiltration, evaporation, plant root uptake, well pumping and recharging, and varying water table conditions. Temporal variations of head and flux boundary conditions can be handled conveniently using either continuous piecewise linear representations or discontinuous (stepped) representations. The VAM3DCG code may also be used as a modeling tool to supplement field investigation or other research study of complex flow and transport behavior in variably saturated media.

6. The transport simulator of VAM3DCG is designed to handle both conservative and nonconservative solutes. Its formulation is designed to have an upstream weighting capability as an option to circumvent numerical oscillations. Both pulse and step releases of contaminants from each source can be simulated.

APPLICABILITY OF THE CODE

The VAM3DCG code has many practical applications. Typical examples include the following:

- Investigation of moisture movement and evapotranspiration in the unsaturated zone including plant water uptake in the root zone.

- Watershed studies - used to predict the response of unconfined watersheds to different schemes of drainage or to infiltration and evaporation. The code computes spatial and temporal variations in the pressure head, water saturation, and flow rate across specified flow boundaries.

- Assessment of well performance and pumping test analy- sis - used to analyze flow in the vicinity of pumped wells, to predict well performance, and to prepare type curves for evaluation of pumping test data.

- Mine dewatering investigations - used to predict the change in elevations of water table or phreatic surface in response to mine dewatering operations. These pre- dictions can be obtained by performing areal or cross- sectional analyses of unconfined flow problems.

- Contaminant migration assessment - used to predict leakage rates and flow fields in unconfined aquifers underlying sewage ponds, surface impoundments, and landfills. VAM3DCG can simulate contaminant transport in variably or fully saturated porous media.

CODE USER REQUIREMENTS

In order to apply the VAM3DCG code effectively, the user will need:

- a thorough understanding of hydrogeological principles

- a basic understanding of finite element techniques

- an awareness of the code's capabilities and limitations

- familiarity with the editor, operating system, and file handling concepts of the computer system used.

It is also recommended that the user run some of the test problems provided to gain confidence and understanding in using the code.

COMPUTER EQUIPMENT REQUIREMENTS

VAM3DCG is written in ANSI Standard FORTRAN 77 and can be compiled on any standard micro, mini, or mainframe system. The source code was developed and tested on PRIME minicomputers and on PC386 micros using the FORTRAN 77 compiler developed by the University of Salford, United Kingdom. With minor conversion (e.g., changing OPEN FILE statements), the source code can be made to compile and run on any machine equipped with at least 2 megabytes of core memory, and a FORTRAN 77 compiler.

EXAMPLE VERIFICATION AND APPLICATION PROBLEMS

GENERAL

Three sets of test problems were used for verification of numerical schemes and demonstration of major capabilities of the VAM3DCG code. Specific purposes of the example problems presented in this chapter are described below.

- Simulation of water flow under variably saturated (or saturated-unsaturated) conditions
- Simulation of single component transport
- Coupled simulation of flow and transport problems with various types of boundary conditions
- Verification of the VAM3DCG code against analytical solutions and other finite element variably saturated flow and transport codes (UNSAT2, FEMWATER and FEMWASTE)
- Demonstration of computational efficiency of the Preconditioned Conjugate Gradient and ORTHOMIN algorithms implemented into the VAM3DCG code
- Application of VAM3DCG to sample field problems.

The first problem set comprises four transient and steady-state flow problems with different features of boundary conditions, dimensionality, and varying degree of nonlinearity. These problems are as follows:

- Transient one-dimensional horizontal flow in a soil slab
- Transient vertical infiltration in a soil column
- Transient two-dimensional flow in a rectangular soil slab
- Steady three-dimensional flow in an unconfined aquifer with a pumping well.

The second problem set comprises four transient transport problems. Three of these problems are associated with three of the seven flow problems just mentioned. The transport problems considered are listed as follows:

- One-dimensional horizontal transport in a soil slab
- Three-dimensional transport in uniform groundwater flow
- Two-dimensional transport in a rectangular soil slab
- Three-dimensional transport in an unconfined aquifer with a pumping well.

The third problem set comprises two associated flow and transport problems concerning the simulation of moisture movement and contaminant migration in the unsaturated zone surrounding a saltstone monolith in the z-area at the Savannah River Site, South Carolina.

PROBLEM DEFINITION AND SIMULATION PROCEDURE

TYPES OF PROBLEMS

The VAM3DCG code can be used in several types of investigations of water flow and moisture movement in subsurface systems. For demonstrative purposes, four typical examples are described. The first example (Figure 5.1) has application to the conceptual design and risk assessment for a low-level radioactive waste disposal site. It involves variably saturated flow around gravel and wick layers surrounding a low-level radioactive waste container placed in the unsaturated zone above a water table (Frind et al., 1977). For this study, VAM3DCG can be used to predict the flow pattern resulting from vertical recharge at the soil surface. The velocity field determined from flow simulations can be used as input to subsequent contaminant transport simulations. For the investigation or risk analysis of the potential for migration of radionuclides, VAM3DCG can be used to perform single-component transport simulations.

The second example (Figure 5.2) applies to drainage or mine dewatering problems involving analyses of seepage into a drain or mine pit. For this example, VAM3DCG can be used to perform saturated-unsaturated flow simulations taking into account groundwater recharge and drainage boundary conditions.

The third example applies to a landfill above an unconfined groundwater system intercepting a river (Figure 5.3). To evaluate the environmental impact of a land disposal unit (landfill or surface impoundment), it is essential to predict water flow and contaminant

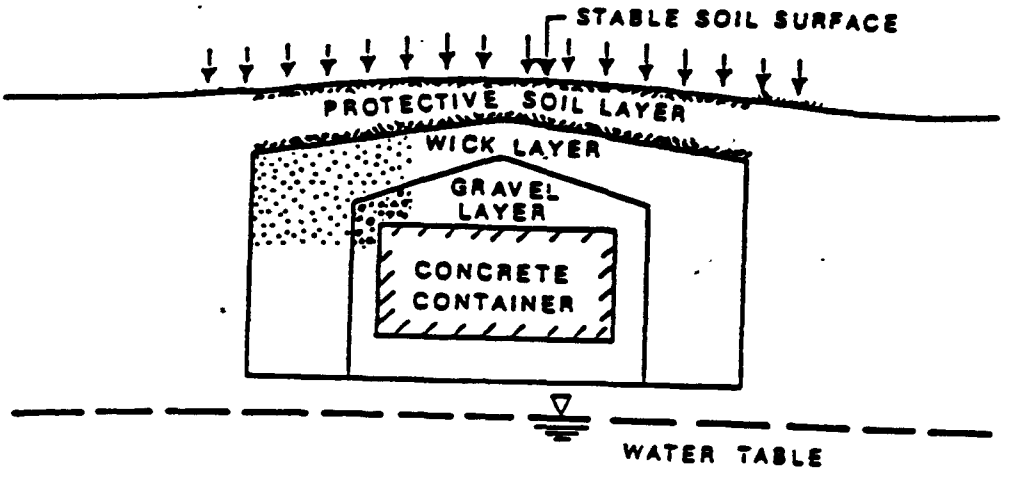

Figure 5.1. Basic geologic environment for a low-level waste container (Frind et al., 1977).

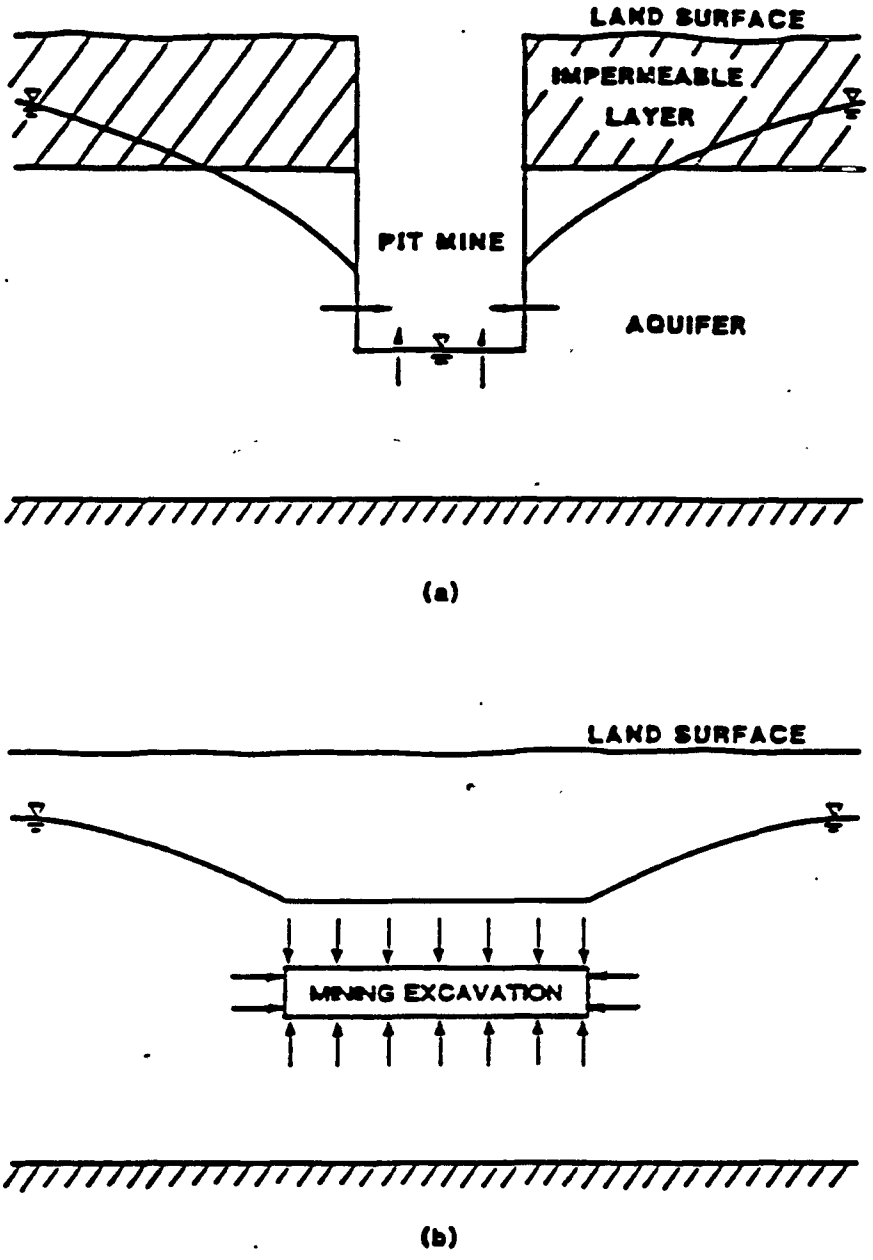

Figure 5.2. Groundwater seepage due to mine dewatering or underground drainage operations.

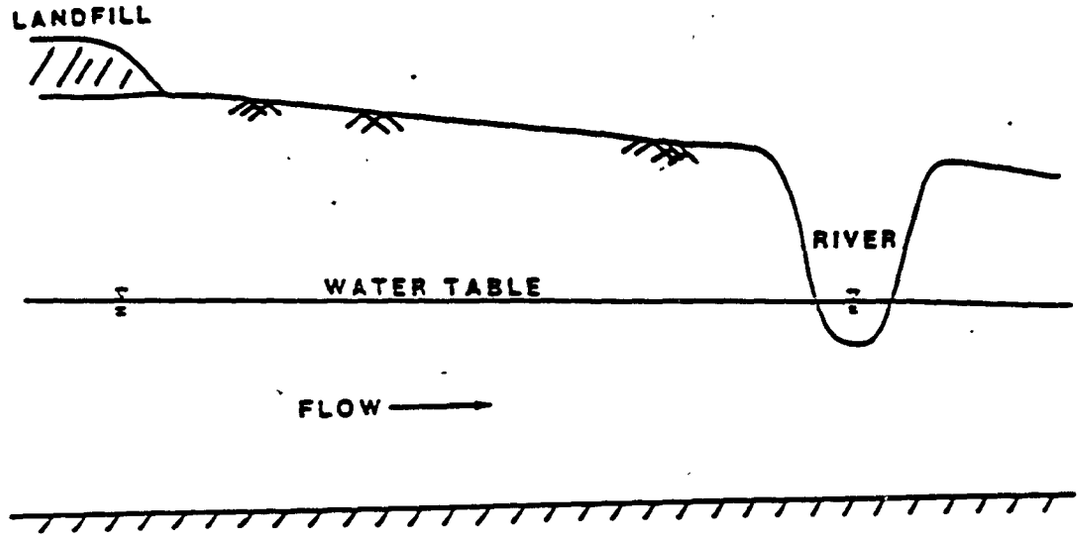

Figure 5.3. Groundwater contamination caused by a landfill.

migration in both unsaturated and saturated zones between the landfill and the river. VAM3DCG can be used to perform both the flow and transport simulations.

The fourth example concerns soil and groundwater contamination problems due to application of pesticides. In the situation depicted in Figure 5.4), VAM3DCG may be used to provide coupled transient simulations of moisture movement, groundwater flow and pesticide migration through the root zone, the vadose zone and the saturated zone of unconfined aquifer system. If chemical transformation and chained reactions of pesticides are important, the code may also be used to study these effects on the fate and transport.

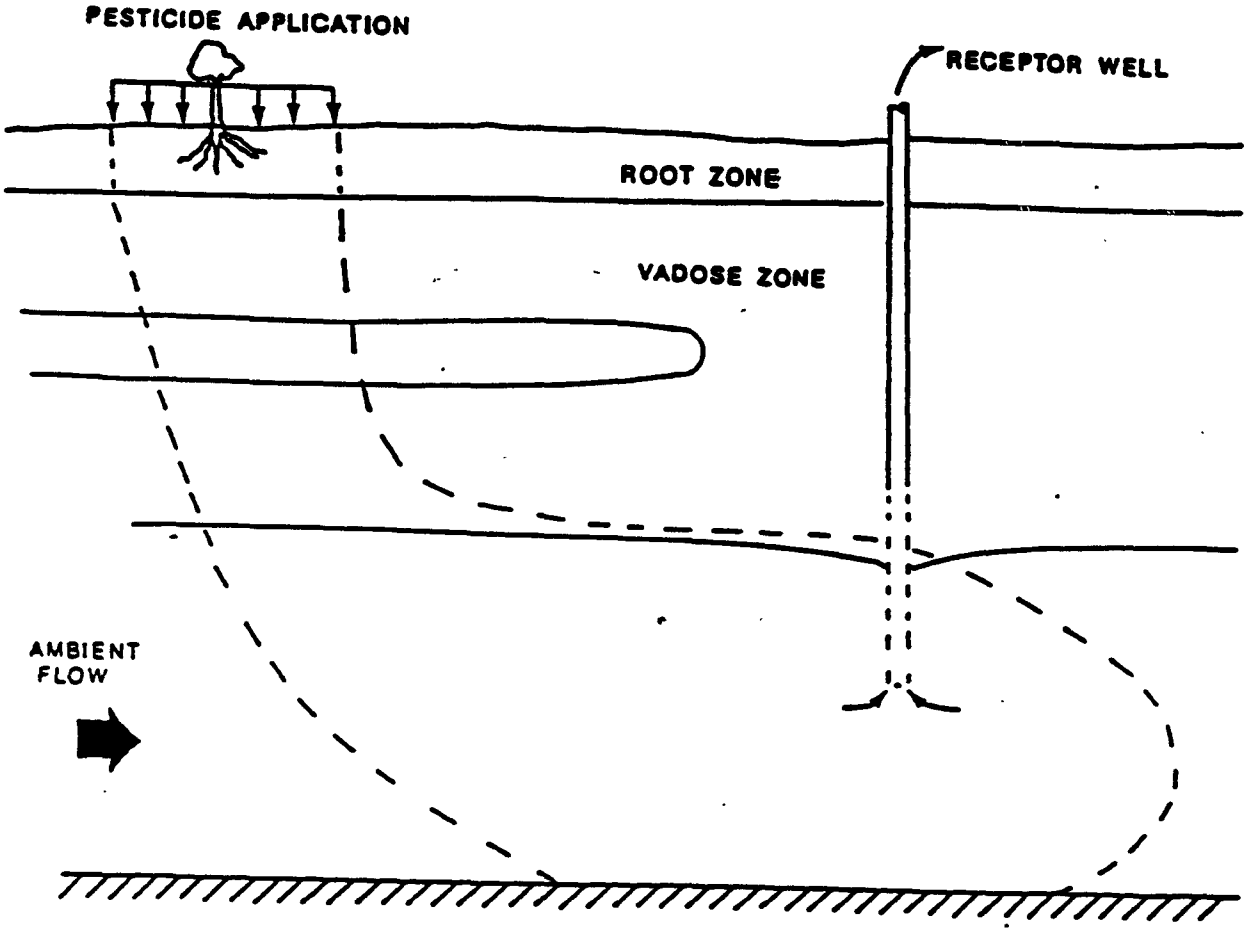

Figure 5.4. Soil and groundwater contamination caused by application of pesticides.

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