1 of 5

**FRESH KILLS LEACHATE TREATMENT AND MINIMIZATION STUDY
VOL. II: MODELING, MONITORING AND EVALUATION**

Final Report

Prepared for

**THE NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY**

Two Rockefeller Plaza
Albany, New York 12223

Project Managers

Barry Liebowitz

John Morelli

and

**NEW YORK CITY
DEPARTMENT OF SANITATION**

Bureau of Waste Management and Facilities Development

Landfill Engineering Unit

44 Beaver Street, 12th Floor

New York, New York 10004

Project Manager

Suedabeh Bayat

Prepared by

THE CITY COLLEGE OF NEW YORK

Department of Civil Engineering

138th Street and Convent Avenue

New York, New York 10031

Principal Investigators

John Fillos, Professor

Reza Khanbilvardi

1106-ERER-ER-89

Energy Authority
Report 93-13, Vol. II

September 1993

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

This report was prepared by the Research Foundation of the City University of New York at the City College of New York, Department of Civil Engineering in the course of performing work contracted for and sponsored by the New York State Energy Research and Development Authority and the New York City Department of Sanitation (hereafter the "Sponsors"). The opinions expressed in this report do not necessarily reflect those of the Sponsors or the State of New York, and reference to any specific product, service, process, or method does not constitute an implied or expressed recommendation or endorsement of it. Further, the Sponsors and the State of New York make no warranties or representations, expressed or implied, as to the fitness for particular purpose or merchantability of any product, apparatus, or service, or the usefulness, completeness, or accuracy of any processes, methods, or other information contained, described, disclosed, or referred to in this report. The Sponsors, the State of New York, and the contractor make no representation that the use of any product, apparatus, process, method, or other information will not infringe privately owned rights and will assume no liability for any loss, injury, or damage resulting from, or occurring in connection with, the use of information contained, described, disclosed, or referred to in this report.

First Printing: September 1993

ABSTRACT

The modeling study and field-scale analysis for leachate flow was done as a part of the New York City Department of Sanitation's comprehensive leachate management plan for Fresh Kills landfill. An estimate of leachate flow rate was first made by applying the hydrologic evaluation of landfill performance (HELP) model. The HELP model is based on a quasi two-dimensional and quasi steady state approach for hydrologically routing leachate movement across, into, through, and out of landfills. This model was developed by Schroeder et al. (1984) from the U.S. Army Corps of Engineers, Waterways Experiment Station for the Office of Research and Development of the U.S. Environmental Protection Agency.

The HELP model results showed that a total leachate flow of 0.6 mgd and 0.408 mgd occurred for the field conditions in 1983 for Sections 1/9 and 6/7 respectively of Fresh Kills landfill. The results were compared with previous estimates Wehran made in 1983. Wehran's estimates were made by applying Darcy's law using the field monitoring data, and by applying the Environmental Protection Agency (EPA) water-balance model. A total flow of 0.577 mgd and 0.416 mgd was estimated by applying Darcy's law using field-monitoring data for Sections 1/9 and 6/7, respectively. The leachate flow estimates were 0.897 mgd for Section 1/9 and 0.431 mgd for Section 6/7 using the EPA water-balance model.

The current field data collected by the New York City Department of Sanitation (NYCDOS) and the City College of New York (CCNY) was used to apply the HELP model to estimate current leachate flow rates. An estimate of total leachate flow of 0.6419 mgd and 0.653 mgd was obtained for an average rainfall condition for Sections 1/9 and 6/7, respectively. Using the HELP model, the leachate flow rates were found to be higher in 1990 than in 1983.

The HELP model simplified the leachate flow estimate by considering quasi steady state and the quasi two-dimensional flow process. The EPA water-balance model does not consider the complexities of moisture routing, moisture accumulating and moisture retention inside the landfill. Therefore, a model was needed to predict the leachate in a more physically based concept.

In this study, a two-dimensional, unsteady state flow investigation for landfill leachate (FILL) model was developed. The moisture content in the unsaturated zone is calculated by solving the two-dimensional unsaturated moisture-flow equation using finite-difference techniques. The moisture-flow in the unsaturated zone helps build up the saturated leachate mound at the bottom of a landfill. The unsteady variation of leachate mound-head has also been considered in the saturated zone of the landfill to compute the time-varying leachate flow rates both laterally and vertically.

The contribution of precipitation to the landfill leachate has been

investigated by computing evapotranspiration and surface runoff. The model was also used to simulate the leachate flow rates using the recent field data collected by The City College of New York (CCNY) and The New York City Department of Sanitation (NYCDOs) in 1989 to 1990. For an average rainfall, total leachate flow rates are estimated at 0.5252 mgd and 0.4746 mgd for Sections 1/9 and 6/7 respectively. The two-dimensional unsteady state FILL model indicates a lower value of leachate flow from the leachate mound in Section 6/7 compared to the values obtained by quasi two-dimensional (HELP), water balance (EPA), and steady state (Darcy's flow) models. The leachate flow estimates using the FILL model and other prevalent approaches are useful to establish the basis for control measures compared to the off-site leachate migration.

The field-scale analysis for leachate flow was done using the field data collected from the wells and piezometers, installed in and around landfill Sections 1/9 and 6/7. The leachate-monitoring program included collecting the leachate mound-level data for a six-month period. The monitoring points consisted of discretely screened piezometers and wells set at various depths down to the bottom of the landfill. The position of the iso-leachate mound-head lines, derived from the field data, represented and delineated the shape of the leachate mound inside the landfill. The field data of the leachate mound-head were used to analyze the hydraulic properties of the refuse and leachate flow rates through Sections 1/9 and 6/7. Piezometers and wells installed near the existing

leachate collection line in Section 1/9 helped establish the gradients to make a refined estimate of the hydraulic conductivity.

The hydraulic conductivity for the refuse in Section 1/9 was computed at 4.98 ft./day (0.00176 cm/sec). The previous value, determined from in-situ permeability tests conducted by Wehran (1983), was 10.2 ft./day (0.0036 cm/sec). The present hydraulic conductivity value of 4.98 ft./day, derived from the existing field conditions based on the measured flow rate from the existing collection system, is believed to be more representative of conditions in the landfill in Section 1/9. From the leachate mound-head contours and flow-gradients, the flow from different sections of the mound was identified. Finally, the leachate flow rates were computed using Darcy's law. A total flow of 0.529 mgd and 0.473 mgd was obtained for Sections 1/9 and 6/7 respectively. The estimates from the field monitoring data are lower than the estimates using the HELP model.

The FILL model was also adjusted to reflect the specific problems of final-cover hydraulics that helped estimate the leakage rate through the barrier and the efficiency of the final cover. The efficiency of the final cover is significantly affected by the hydraulic conductivity of the barrier.

ACKNOWLEDGEMENTS

The following individuals contributed to the research effort, preparation and review of this report.

Authors

Reza M. Khanbilvardi	Associate Professor, Department of Civil Engineering, The City College of New York, New York, New York.
John Fillos	Professor, Department of Civil Engineering, The City College of New York, New York, New York.
Shabbir Ahmed	Graduate Research Assistant, Department of Civil Engineering, The City College of New York, New York, New York.

Project Managers

Suedabeh Bayat	New York City Department of Sanitation.
Sami Stephan	New York City Department of Sanitation.
Phillip Gleason	New York City Department of Sanitation.
Barry Liebowitz	New York State Energy Research and Development Authority.

Technical Review Committee

Luis A. Carrio	Chief-Process Control Section, New York City, Department of Environmental Protection.
Lehn Franke	Professor, The City College of New York, New York, New York.
George P. Korfiatis	Director, Center for Environmental Studies, Stevens Institute of Technology, Hoboken, New Jersey.
John Jeris	Professor, Manhattan College, Riverdale, New York.
Jerald Palevsky	Professor, The City College of New York, New York, New York.

Daniel C. Walsh

New York State Department of
Environmental Conservation, New York, New
York.

Funding for the project was provided by the New York City
Department of Sanitation, The New York State Energy Research and
Development Authority and The City College of New York.

TABLE OF CONTENTS

Section	Page
SUMMARY	8-1
1 INTRODUCTION AND BACKGROUND	1-1
1.1 INTRODUCTION	1-1
1.2 FRESH KILLS LANDFILL	1-2
1.2.1 Hydrogeology of the Fresh Kills Site	1-5
1.3 OBJECTIVE	1-9
1.4 LITERATURE REVIEW	1-14
1.5 RATIONALE FOR A NEW MODEL	1-18
1.6 PREVIOUS ESTIMATES OF LEACHATE FLOW AT SECTIONS 1/9 AND 6/7	1-23
1.7 RAINFALL DATA ANALYSIS	1-27
2 HELP MODEL	2-1
2.1 INTRODUCTION	2-1
2.2 EVAPOTRANSPIRATION	2-2
2.3 RUNOFF	2-6
2.4 SNOWMELT	2-7
2.5 SUBSURFACE MOISTURE ROUTING	2-9
2.5.1 Vertical drainage	2-11
2.5.2 Lateral drainage	2-17
2.6 DATA REQUIRED FOR THE MODEL	2-21
2.7 LIMITATIONS	2-22
2.8 SENSITIVITY TEST	2-23
2.8.1 Model Run for the Base-case (Hypothetical Scheme)	2-24
2.8.2 Model results	2-26
2.9 FIELD APPLICATION	2-45
2.10 RESULTS AND DISCUSSION	2-64
2.10.1 Results in Section 1/9 for the Data in 1983	2-81
2.10.2 Results in Section 6/7 for the Data in 1983	2-84
2.10.3 Results in Section 1/9 for the New Data in 1989	2-85
2.10.4 Results in Section 6/7 for the New Data in 1989	2-87
2.10.5 Discussion	2-89

3	FILL MODEL	3-1
3.1	CONCEPTUALIZATION OF LEACHATE FLOW PROCESS	3-1
3.2	GOVERNING EQUATION IN THE UNSATURATED ZONE	3-3
3.3	HYDRAULIC CONDUCTIVITY AND DIFFUSIVITY FUNCTIONS	3-7
3.4	BOUNDARY AND INITIAL CONDITIONS	3-9
3.5	RUNOFF	3-11
3.6	SNOWMELT	3-15
3.7	GOVERNING EQUATION IN THE SATURATED ZONE	3-16
3.8	FINITE-DIFFERENCE FORMULATION OF THE GOVERNING EQUATIONS	3-20
	3.8.1 Unsaturated Moisture Flow Equation	3-21
	3.8.2 Boundary Conditions	3-24
	3.8.3 Runoff Equation	3-28
	3.8.4 Saturated Leachate Flow Equation	3-30
	3.8.5 Numerical Solution	3-32
3.9	FIELD APPLICATION	3-35
3.10	MODEL RESULTS	3-42
	3.10.1 Analysis of Results in Section 6/7 for the Data in 1983	3-70
	3.10.2 Analysis of Results in Section 1/9 for the Data in 1989	3-89
	3.10.3 Analysis of Results in Section 6/7 for the Data in 1989	3-91
	3.10.4 Discussion	3-92
4	LEACHATE MONITORING	4-1
4.1	INTRODUCTION	4-1
4.2	PROCEDURES	4-1
4.3	WELLS AND PIEZOMETERS	4-2
4.4	LEACHATE MOUND-HEAD CONTOURS	4-2
4.5	DETERMINATION OF HYDRAULIC CONDUCTIVITY	4-8
4.6	LEACHATE FLOW RATES	4-10
5	COMPARISON OF RESULTS	5-1
6	SIDE SLOPE MODELING	6-1
6.1	INTRODUCTION	6-1
6.2	GOALS	6-4
6.3	MODEL COMPONENTS	6-5
6.4	NUMERICAL SCHEME	6-8
6.5	MODEL APPLICATION	6-10
7	CONCLUSIONS AND RECOMMENDATIONS	7-1
	REFERENCES	R-1

APPENDIX	A	.....	A-1
APPENDIX	B	.....	B-1
APPENDIX	C	.....	C-1
APPENDIX	D	.....	D-1
APPENDIX	E	.....	E-1

LIST OF FIGURES

Figure	Page
1-1 Vicinity Plan for Fresh Kills Landfill	1-3
1-2 Fresh Kills Landfill	1-4
1-3 Typical Geologic Cross-section Through Fresh Kills Landfill	1-6
1-4a An Average Vertical Section of 1/9, October, 1989	1-10
1-4b An Average Vertical Section of 6/7, October, 1989	1-11
1-5 Side-Slope Criteria for Landfilling	1-12
1-6 Configuration of Leachate Flow in a One-dimensional Flow Model	1-20
1-7 Configuration of Leachate Flow in a Two-dimensional Flow Model	1-21
2-1 Configuration of HELP Model	2-10
2-2 Configuration of Vertical Flow Submodel	2-12
2-3 Configuration of Lateral Flow Submodel	2-19
2-4 A Hypothetical Landfill Section	2-25
2-5a Results of Sensitivity Analysis for a 10 percent Increase in the Values of the Soil Data	2-27
2-5b Results of Sensitivity Analysis for a 10 percent Decrease in the Values of the Soil Data	2-28
2-5c Results of Sensitivity Analysis for a 20 percent Increase in the Values of the Soil Data	2-29
2-5d Results of Sensitivity Analysis for a 20 percent Decrease in the Values of the Soil Data	2-30
2-5e Results of Sensitivity Analysis for a 50 percent Increase in the Values of the Soil Data	2-31
2-5f Results of Sensitivity Analysis for a 50 percent Decrease in the Values of the Soil Data	2-32
2-6a Results of Sensitivity Analysis for a 10 percent Increase in the Values of the Climatologic Data	2-33

2-6b	Results of Sensitivity Analysis for a 10 percent Decrease in the Values of the Climatologic Data	2-34
2-6c	Results of Sensitivity Analysis for a 20 percent Increase in the Values of the Climatologic Data	2-35
2-6d	Results of Sensitivity Analysis for a 20 percent Decrease in the Values of the Climatologic Data	2-36
2-6e	Results of Sensitivity Analysis for a 50 percent Increase in the Values of the Climatologic Data	2-37
2-6f	Results of Sensitivity Analysis for a 50 percent Decrease in the Values of the Climatologic Data	2-38
2-7a	Average Landfill Section for 1/9 in 1983	2-46
2-7b	Average Landfill Section for 6/7 in 1983	2-47
2-8a	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1983 for the Average Rainfall Year	2-51
2-8b	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1983 for the Peak Rainfall Year	2-52
2-9a	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1983 for the Average Rainfall Year	2-53
2-9b	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1983 for the Peak Rainfall Year	2-54
2-10a	Variation of Average Daily Lateral Flow in Section 1/9 using the Field Data in 1983	2-55
2-10b	Variation of Average Daily Vertical Flow in Section 1/9 using the Field Data in 1983	2-56
2-10c	Variation of Daily Total Flow in Section 1/9 using the Field Data in 1983	2-57
2-11a	Variation of Average Daily Lateral Flow in Section 6/7 using the Field Data in 1983	2-58
2-11b	Variation of Average Daily Vertical Flow in Section 6/7 using the Field Data in 1983	2-59

2-11c	Variation of Daily Total Flow in Section 6/7 using the Field Data in 1983	2-60
2-12a	Average Landfill Section of 1/9 for the Data in 1989	2-62
2-12b	Average Landfill Section of 6/7 for the Data in 1989	2-63
2-13a	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1989 for the Average Rainfall Year	2-65
2-13b	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1989 for the Peak Rainfall Year	2-66
2-14a	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1989 for the Average Rainfall Year	2-67
2-14b	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1989 for the Peak Rainfall Year	2-68
2-15a	Variation of Average Daily Lateral Flow in Section 1/9 using the Field Data in 1989	2-69
2-15b	Variation of Average Daily Vertical Flow in Section 1/9 using the Field Data in 1989	2-70
2-15c	Variation of Daily Total Flow in Section 1/9 for the Field Data in 1989	2-71
2-16a	Variation of Average Daily lateral Flow in Section 6/7 using the Field Data in 1989	2-72
2-16b	Variation of Average Daily Vertical Flow in Section 6/7 using the Field Data in 1989	2-73
2-16c	Variation of Daily Total Flow in Section 6/7 using the Field Data in 1989	2-74
2-17	Variation of Leachate Mound Head in Section 1/9 for the Field Data in 1989	2-75
2-18	Variation of Leachate Mound Head in Section 6/7 for the Field Data in 1989	2-76

3-1	Configuration of Leachate Flow Process in a Landfill	3-2
3-2	Definition Diagram for Total Potential	3-5
3-3	Runoff along an Inclined Surface	3-13
3-4	Saturated Flow at the Bottom of a landfill	3-18
3-5	Schematic Representation of a Landfill Section	3-22
3-6	Boundary Nodes along the Upper Surface of a Landfill	3-25
3-7	Finite-difference Scheme for the Kinematic Wave Equation	3-29
3-8	Finite-difference Scheme for the Saturated Leachate Flow Equation	3-31
3-9	Fresh Kills Section 6/7	3-39
3-10	An Average Vertical Section of 6/7 for the Field Data in 1983	3-40
3-11	Fresh Kills Section 1/9	3-41
3-12a	Schematic Representation of the Vertical Section for Section 1/9 for the Field Data in 1989	3-43
3-12b	Schematic Representation of the Vertical Section for Section 6/7 for the Field Data in 1989	3-44
3-13a	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1983 for the Average Rainfall Year	3-45
3-13b	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1983 for the Peak Rainfall Year	3-46
3-14	Variation of Lateral Flow (cu. ft./ft of width) in Section 6/7 using the Field Data in 1983	3-47
3-15	Variation of Vertical Flow (cu. ft./unit area, sq. ft.) in Section 6/7 using the Field Data in 1983	3-48
3-16a	Variation of Average Daily Lateral Flow in Section 6/7 using the Field Data in 1983 for the Average Rainfall Year	3-49

3-16b	Variation of Average Daily Lateral Flow in Section 6/7 using the Field Data in 1983 for the Peak Rainfall Year	3-50
3-17	Variation of Average Daily Vertical Flow in Section 6/7 using the Field Data in 1983	3-51
3-18a	Variation of Daily Total Flow in Section 6/7 using the Field Data in 1983 for the Average Rainfall Year	3-53
3-18b	Variation of Daily Total Flow in Section 6/7 using the Field Data in 1983 for the Peak Rainfall Year	3-54
3-19a	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1989 for the Average Rainfall Year	3-58
3-19b	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1989 for the Peak Rainfall Year	3-59
3-20a	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1989 for the Average Rainfall Year	3-60
3-20b	Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1989 for the Peak Rainfall Year	3-61
3-21	Variation of Lateral Flow (cu. ft./ft.of width) in Section 1/9 using the Field Data in 1989	3-62
3-22	Variation of Lateral Flow (cu. ft./ft.of width) in Section 6/7 using the Field Data in 1989	3-63
3-23	Variation of Average Daily Lateral Flow in Section 1/9 using the Field Data in 1989	3-64
3-24	Variation of Average Daily Lateral Flow in Section 6/7 using the Field Data in 1989	3-65
3-25	Variation of Vertical Flow (cu. ft./unit area, Sq. ft.) in Section 1/9 using the Field Data in 1989	3-66
3-26	Variation of Vertical Flow (cu. ft./unit area, Sq. ft.) in Section 6/7 using the Field Data in 1989	3-67

3-27	Variation of Average Daily Vertical Flow in Section 1/9 using the Field Data in 1989	3-68
3-28	Variation of Average Daily Vertical Flow in Section 6/7 using the Field Data in 1989	3-69
3-29	Variation of Daily Total Flow in Section 1/9 using the Field Data in 1989	3-71
3-30	Variation of Daily Total Flow in Section 6/7 using the Field Data in 1989	3-72
4-1a	Location of Piezometers and Wells in Section 1/9 ...	4-3
4-1b	Location of Piezometers and wells in Section 6/7 ...	4-4
4-2a	Leachate Mound-Head Contours in Section 1/9 for the Data Collected in October, 1989	4-6
4-2b	Leachate Mound-Head Contours in Section 6/7 for the Data Collected in October, 1989	4-7
4-3	Mound Subsections in Section 1/9 Contributing to the Leachate Flow	4-9
4-4	Mound Subsections in Section 6/7 Contributing to the Leachate Flow	4-12
6-1	Landfill Final-Cover Hydraulics	6-3
6-2	A Typical Finite-difference Grid for Final Cover ...	6-11

LIST OF TABLES

Table	Page
1-1 Comparison of the HELP and FILL models	1-22
1-2 Leachate Flow Rates by Water Balance Method and Darcy's Law for the Data in 1983	1-25
1-3 Annual Average and Peak Precipitation Values for All Months from 1949 to 1955	1-29
1-4 Average Monthly Values of Precipitation for All Months from 1949 to 1955	1-30
1-5 Monthly Values of Precipitation for the Average Precipitation Year 1954	1-31
1-6 Monthly Values of Precipitation for the Peak Precipitation Year 1951	1-32
1-7 Peak Monthly Values of Precipitation	1-33
1-8 Annual Values of Precipitation	1-34
2-1a Results of Sensitivity Analysis for Soil Data in 1974	2-39
2-1b Results of Sensitivity Analysis for Soil Data in 1975	2-40
2-2a Results of Sensitivity Analysis for Climatologic Data in 1974	2-41
2-2b Results of Sensitivity Analysis for Climatologic Data in 1975	2-42
2-3a Data Required for HELP model in Section 1/9	2-48
2-3b Data Required for HELP model in Section 6/7	2-49
2-4 Leachate Flow Rates Computed by the HELP Model for 1983 Data	2-61
2-5a Annual Values of Precipitation, Runoff, Evapotranspiration and Leachate Production in Section 1/9 for the 1983 Data	2-77
2-5b Annual Values of Precipitation, Runoff, Evapotranspiration and Leachate Production in Section 1/9 for the 1989 Data	2-77

2-6a	Annual Values of Precipitation, Runoff, Evapotranspiration and Leachate Production in Section 6/7 for the 1983 Data	2-78
2-6b	Annual Values of Precipitation, Runoff, Evapotranspiration and Leachate Production in Section 6/7 for the 1989 Data	2-78
2-7	HELP Model Results for the New Data Collected by CCNY-NYCDOS in 1989	2-79
2-8a	Peak Flow rates for the Data in 1983	2-80
2-8b	Peak Flow Rates for the Data in 1989	2-80
3-1a	Data Required for the FILL Model in Section 1/9	3-37
3-1b	Data Required for the FILL Model in Section 6/7	3-38
3-2	Leachate Flow Rates in Section 6/7 for the Data in 1983	3-55
3-3	Average Daily Values of Precipitation, Runoff, Evapotranspiration, and Leachate Production for the Model Run in Section 6/7 with the Data in 1983	3-56
3-4	Peak and Minimum Flow rates in 1983 in Section 6/7..	3-57
3-5	Leachate Flow Components Computed by the FILL Model using Data Collected by CCNY-NYCDOS in 1989	3-73
3-6	Average Values of Precipitation, Runoff, Evapotranspiration, and Leachate Production for the Model Run with 1989 Data	3-74
3-7	Peak and Minimum Flow for the Data Collected by CCNY-NYCDOS in 1989	3-75
3-8a	Leachate Mound-Head in Section 1/9 at the Start of the Average Rainfall Year	3-76
3-8b	Leachate Mound-Head in Section 1/9 at the Middle of the Average Rainfall Year	3-77
3-8c	Leachate Mound-Head in Section 1/9 at the End of the Average Rainfall Year	3-78
3-8d	Leachate Mound-Head in Section 1/9 at the Start of the Peak Rainfall Year	3-79
3-8e	Leachate Mound-Head in Section 1/9 at the Middle of the Peak Rainfall Year	3-80

3-8f	Leachate Mound-Head in Section 1/9 at the End of the Peak Rainfall Year	3-81
3-9a	Leachate Mound-Head in Section 6/7 at the Start of the Average Rainfall Year	3-82
3-9b	Leachate Mound-Head in Section 6/7 at the Middle of the Average Rainfall Year	3-83
3-9c	Leachate Mound-Head in Section 6/7 at the End of the Average Rainfall Year	3-84
3-9d	Leachate Mound-Head in Section 6/7 at the Start of the Peak Rainfall Year	3-85
3-9e	Leachate Mound-Head in Section 6/7 at the Middle of the Peak Rainfall Year	3-86
3-9f	Leachate Mound-Head in Section 6/7 at the End of the Peak Rainfall Year	3-87
4-1	Leachate Flow Rates Calculated from Field data	4-13
5-1	Leachate Flow Rates by Darcy's Law, Water-Balance Method and HELP for 1983 Data	5-3
5-2	Leachate Flow Rates by HELP and FILL Model in Section 6/7 for 1983 Data	5-6
5-3	Leachate Flow Rates by HELP and FILL Model in Section 1/9 for the Data in 1989	5-8
5-4	Leachate Flow Rates by HELP and FILL Model in Section 6/7 for the Data in 1989	5-8
5-5	Comparison of Average Leachate Flow Rates Computed by HELP, FILL, and Leachate Monitoring Data	5-11
6-1	Efficiency of Landfill Cover for Different Hydraulic Conductivity and Side Slope	6-13
6-2	Annual Values of Precipitation, Runoff, and Evapotranspiration	6-14

SUMMARY

The New York City Department of Sanitation is developing a comprehensive landfill leachate management plan for the Fresh Kills landfill, located on the western shore of Staten Island, New York. The 3000-acre facility, owned and operated by the City of New York, has been developed into four distinct mounds that correspond to areas designated as Sections 1/9, 2/8, 3/4 and 6/7.

In developing a comprehensive leachate management plan, the estimating leachate flow rates is important in designing appropriate treatment alternatives to reduce the offsite migration that pollutes both surface water and groundwater resources. Estimating the leachate flow rates from Sections 1/9 and 6/7 was given priority using an available model, hydrologic evaluation of landfill performance (HELP), and a new model, flow investigation for landfill leachate (FILL). The field-scale analysis for leachate flow included data collection of the leachate mound-level from piezometers and monitoring wells installed on-site, for six months period. From the leachate mound-head contours and flow-gradients, Leachate flow rates were computed using Darcy's Law.

An important input parameter the models use to estimate leachate flow rates is precipitation, and obtaining average and worst

rainfall data was planned. Rainfall data for Staten Island were taken from the New York City Department of Environmental Protection's (NYCDEP) data bank. From the NYCDEP rainfall data for 1949 to 1955, an average rainfall year (1954), and a peak rainfall year (1951), were selected.

To estimate leachate flow rates, the existing methodologies and available data were studied. The existing methodologies for estimating leachate flow include direct application of Darcy's Law after identifying the leachate mound from the field-monitoring data, application of the water-balance method, and the HELP model. Previous studies in 1983 for estimating leachate flow in Sections 1/9 and 6/7 used the direct application of Darcy's law and the water-balance method for field conditions. Using Darcy's Law, 0.577 mgd and 0.416 mgd were estimated for Sections 1/9 and 6/7 respectively. Applying the water-balance method, a leachate flow of 0.897 mgd and 0.431 mgd for Sections 1/9 and 6/7 respectively, is estimated. The HELP model was also applied for field conditions in 1983. The total leachate flow for Sections 1/9 and 6/7 was 0.600 mgd and 0.408 mgd respectively. The HELP model results are close to the results obtained by Darcy's Law using field data. In applying Darcy's Law, information from field data such as lateral and vertical hydraulic gradients, saturated thickness, and hydraulic conductivity value from in-situ recovery test data were used to estimate leachate flow rates. The overestimate of leachate flow rates by the water balance method is mostly due to ignoring

the leachate accretion, retention, and accumulation inside the landfill.

To study the present field condition in Sections 1/9 and 6/7, leachate mound-head data were collected from the piezometers and wells in those sections. From the boring data collected by NYCDOS, the refuse thickness in Section 1/9 and 6/7 was obtained. The HELP model was applied for these field conditions to estimate the variation of leachate flow rates during average and peak rainfall years. In Section 1/9, the total leachate flow was estimated at 0.6419 mgd when the lateral leachate flow was 0.5101 mgd. The total leachate flow in Section 6/7 was 0.653 mgd and 0.6576 mgd for the average and peak rainfall years, respectively.

The vertical leachate flow for Section 1/9 was estimated at 0.0473 mgd. In Section 1/9 the total leachate flow rate has been increased by 6.98 percent for the average rainfall year due to the change in the field's condition from 1983 to 1989. The total leachate flow rate in Section 6/7 increased by 60 percent (0.408 mgd to 0.653 mgd) in the average rainfall year due to changes in the field from 1983 to 1989. Using the data collected in 1989, the total leachate for Sections 1/9 and 6/7 was estimated by the HELP model at 1.2949 mgd and 1.2995 mgd for the average and peak rainfall years, respectively. The corresponding estimates using the HELP model were 1.008 mgd and 1.057 mgd for the average and peak rainfall years respectively using data collected in 1983 by Wehran

Engineering Company.

The leachate flow estimates described so far were based on simplified solution techniques such as the water-balance method and a quasi two-dimensional and quasi steady state approach such as the HELP model. As a result of simplifying the current approaches to estimate leachate flow rates, a two-dimensional unsteady state leachate flow model named FILL has been developed at The City University of New York to estimate leachate flow from a landfill. In addition to the two-dimensional unsteady state flow considerations in a landfill, FILL modelled the surface runoff by considering the effect of surface roughness and landfill side slope. In the HELP model, the surface runoff is computed using the Soil Conservation Service (SCS) curve number method that does not consider the effect of the aforementioned parameters. It is useful to compare the FILL model and the HELP model results with the existing information about leachate flow rates obtained by the EPA water-balance model and the 1983 field investigation. On the other hand, the FILL model was applied to illustrate its effectiveness in providing information on flow components, such as runoff, evapotranspiration, infiltration, and leachate flow rates in lateral and vertical directions. To compare the FILL model results with previous studies, application was made to Section 6/7 for the field data in 1983. The FILL model results show significant runoff from the landfill surface. In this model, runoff is computed based on hourly rainfall. The annual value of runoff

computed by the FILL model differs from the value computed by the HELP model. The total annual runoff of 23.76 inches is computed by the FILL model for an annual precipitation of 43.6 inches. However, the HELP model computes only 0.525 inches of annual runoff which seems to be unrealistic as there is less permeable daily soil cover on the waste and high slope along the landfill sides.

The evapotranspiration submodel computes the daily values of evaporation and transpiration using the modified Penman method in both the FILL and the HELP models. The evapotranspiration depends on runoff, infiltration, and moisture content of the soil. The high values of runoff make less water available for soil evapotranspiration when simulating the FILL model results.

The variation of the daily lateral flow by the HELP and the FILL models shows that a high lateral flow is computed by the HELP model at the onset of the simulation. However, the FILL model shows lower values of the lateral flow rates for most of the computational period. The average daily lateral flow computed by the FILL model is 0.325 mgd; the value computed by the HELP model is 0.365 mgd. The vertical flow values are observed to vary only insignificantly with time in both the FILL and HELP models. The results show that an average amount of 0.044 mgd and 0.043 mgd are computed by the FILL and the HELP models respectively. The insignificant variation of the vertical flow is due to the lower

value of the barrier hydraulic conductivity of 10^{-7} cm/sec in the landfill. It is observed that estimating the total leachate flow rate by the FILL model in Section 6/7 is 0.369 mgd and is less than the values computed by the HELP model and those computed previously by applying Darcy's Law and the EPA water-balance model.

The FILL model simulation was carried out for Sections 1/9 and 6/7 to estimate the variation of leachate flow rates for the present field condition. The lateral flow was estimated at 0.4207 mgd and 0.4256 mgd for Sections 1/9 and 6/7 respectively in the average rainfall year. The total leachate flow rates for the average rainfall condition in Sections 1/9 and 6/7 are 0.5252 mgd and 0.4746 mgd, respectively. The results computed by the HELP and FILL models differ significantly for the leachate flow computed for the present field conditions in both Sections 1/9 and 6/7. The total leachate flow is less by 0.117 mgd than that computed by the FILL model for Section 1/9 in the average rainfall year. Similar variations are also observed in the leachate flow rates for Section 6/7. Refinements in the leachate flow rates were achieved by comparing the model results with the leachate flow estimates from the current leachate mound head data collected by CCNY-NYCDOS.

To evaluate the existing field condition and to compute realistic leachate flow rate in Sections 1/9 and 6/7, leachate mound elevation data were collected from the piezometers and wells installed in those sections. The field investigation and recorded

data determined the existing hydraulic gradients at the site. In response to the hydraulic gradients, leachate flow rates occurred horizontally and vertically inside the landfill.

From the monitoring data, contours of leachate mound head were drawn for Sections 1/9 and 6/7. The leachate mounds were identified from the iso-elevation lines of leachate head within the landfill. In the field, the configuration of the leachate mound level variation was not uniform or linear. Because the leachate accretion process was periodic, the spatial variations of the mound established from the piezometer and monitoring well data are difficult to explain. However, the well-developed leachate mounding observed inside the landfill, indicated that a reasonable volume of leachate input from the vadose zone prevailed for a long time.

Comparing the results, it is observed that for Section 1/9 the leachate flow rate computed at 0.577 mgd in 1983 is greater than the 0.529 mgd computed in 1990 due to the difference in the hydraulic conductivity values used in Section 1/9. The hydraulic conductivity value of 10.2 ft./day as obtained by the in-situ permeability test in 1983 has been refined in this study. A more reliable estimate at 4.98 ft./day as the hydraulic conductivity value was obtained by applying Darcy's Law and using the field data of the leachate flow rates in the collection system as well as the flow-gradient established through the leachate mound levels that

came from the piezometers and monitoring wells.

Since there is no collection system installed in or around any part of Section 6/7, no refined estimate of the hydraulic conductivity value for this section was made. The hydraulic conductivity value of 56.67 ft/day, established by the in-situ permeability test and used to compute leachate flow rates in 1983, has been used to estimate leachate flow rates in 1990. The leachate flow rate has been increased from the 1983 value of 0.431 mgd to 0.473 mgd in 1990, an increase that indicates the unsteady characteristics due to change in the leachate mound retention, accumulation, and variation of leachate accretion.

Both the lateral and vertical flow components vary in Section 1/9 for the results obtained by the HELP, FILL, and leachate monitoring. The average lateral flow computed by the HELP, FILL, and monitoring data is 0.5101 mgd, 0.4207 mgd, and 0.439 mgd, respectively, for Section 1/9. The vertical leachate flow computed by HELP, FILL, and monitoring data is 0.1318 mgd, 0.1045 mgd, and 0.09 mgd, respectively, for Section 1/9. The leachate flow rates computed by the FILL model and leachate monitoring data vary significantly from those computed by the HELP model for Section 6/7. The lateral flow for Section 6/7 computed by the HELP model, FILL model and leachate monitoring data is 0.6057 mgd, 0.4256 mgd, and 0.426 mgd, respectively. The vertical leachate flow computed by the HELP, FILL model, and leachate monitoring data for Section

6/7 is 0.0473 mgd, 0.049 mgd, and 0.047 mgd respectively. The average leachate flow rates computed by the FILL model and leachate field-monitoring data are similar to each other.

The simulations for the seepage-drainage problem evaluated the efficiency of the landfill final-cover system by adjusting the FILL model to represent the specific problems of the landfill final-cover hydraulics. In the physical system of the landfill final-cover, a sloping topsoil layer with high hydraulic conductivity is constructed above the low hydraulic conductivity barrier layer to increase lateral drainage which helps limit vertical seepage through the barrier layer. The effects of the hydraulic conductivity of the barrier layer on the leakage rate was investigated. The decrease in the hydraulic conductivity of the barrier layer increases the efficiency of the landfill cover. The results show that the decrease in the hydraulic conductivity of the barrier layer from 10^{-6} cm/sec to 10^{-7} cm/sec produces an increase in the efficiency from 87.48 percent to 98.9 percent for a 33 percent side slope.

1 - INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

One of the major goals of this study is to predict leachate flow from Fresh Kills landfill in New York City. Leachate is formed from the precipitation that infiltrates through a solid waste landfill. The water extracts dissolved and/or suspended solids from the landfilled wastes. The resulting contaminated water is called leachate; it has the potential to pollute ground water and surface water.

To estimate the leachate flow the amount of runoff and evapotranspiration of precipitation needs to be accurately predicted. The total precipitation minus the runoff and total evapotranspiration (evaporation and transpiration of soil moisture) equals the amount of leachate that is added to the leachate mound already present in the landfill. Some of the infiltrated water, however, is retained by the soil matrix in the unsaturated zone. The leachate accretion results from moisture variation in the unsaturated zone, which contributes to the saturated leachate mound. Mathematical models are widely used to estimate the aforementioned flow components (runoff, evapotranspiration, infiltration, and leachate accretion) in landfills. Equations for

the flow components and boundary conditions develop the mathematical models that use numerical or analytical techniques to simulate the variation of leachate flow in a landfill.

1.2 FRESH KILLS LANDFILL

The Fresh Kills landfill is located on the western shore of Staten Island. The 3,000-acre facility, owned and operated by the City of New York, has been receiving household wastes for disposal since 1947. The landfill currently handles about 17,000 tons of refuse a day, six days a week.

The Fresh Kills landfill is located in an area bounded by tidal streams, as shown in Figure 1-1. The areas surrounding the landfill are mainly tidal wetlands that are bounded on the south by the Arthur Kill road and on the west by the Arthur Kill. According to the 1985 operations plan, the landfill has been developed into four distinct mounds, which correspond to the areas designated as Sections 1/9, 2/8, 3/4 and 6/7 as shown in Figure 1-2. The current study will focus on estimating leachate flow rates from Sections 1/9 and 6/7, 405 acres and 376 acres respectively, both of which are presently in operation.

Figure 1-1. Vicinity Plan for Fresh Kills Landfill.

Figure 1-4 ... Fresh Kills Landfill.

1.2.1 Hydrogeology of the Fresh Kills Site

Previous hydrogeologic investigation at the Fresh Kills landfill was done by drilling exploratory borings and installing monitoring wells (Wehran, 1983). This field study included the investigation of subsurface geology, groundwater occurrence, and leachate flow occurrence rates for site conditions in 1983. In general, the site geology is defined by several formations that include the Staten Island serpentinite; stockton/lockatong formation; residual clay; cretaceous sequence; cretaceous sand (lower and upper); cretaceous clay; cretaceous sediments; glacial deposits; glacial till; glaciolacustrine clay; glacial sand deposit; recent soil deposits (sand, silt and clay); and artificial fill materials.

As shown in Figure 1-3, the bedrock is overlain by cretaceous sands and clays. The cretaceous sands and clays in turn are overlain by glaciolacustrine clay, recent silt and sand. The youngest geologic materials consist of solid wastes and daily soil cover.

Groundwater occurs primarily within the bedding, joint, and fault planes that provide the pathways for groundwater flow in the bedrock. Because residual clay-deposits on top of the weathered rock are impermeable, they impede the flow of water vertically into the bedrock. Above the residual clay deposits, there are several unconsolidated cretaceous sequences. At least four water-bearing

PERCENTAGE OF RECHARGE (LEACHATE)
 REACHING EACH AQUIFER - APPROXIMATIONS
 BASED UPON AVAILABLE DATA AND
 CONSERVATIVE ASSUMPTIONS.

[10]

Figure 1-3. Typical Geologic Cross-section Through Fresh Kills Landfill.

zones were identified. These zones, from the deepest one, as shown in Figure 1-3 are:

- A confined lower water-bearing zone within the sparsely fractured bedrock;
- A confined cretaceous sand aquifer at lower zone;
- A confined cretaceous sand aquifer at upper zone; and
- An unconfined to semi-confined zone contained in the fill materials, the recent and glacial sand, the glacial sand, the glacial till, and the cretaceous sand.

Permeability of the geologic materials was previously determined using laboratory testing of "undisturbed" soil samples; in situ recovery testing; and laboratory grain-size distribution correlations. Laboratory permeability tests were performed on ten "undisturbed" soil samples (Wehran, 1983). The tests were performed only on coarse-grained materials. The permeability values ranged from 8.6×10^{-4} cm/sec for glacial till to 4.2×10^{-4} cm/sec for cretaceous sand. The results of these measurements are available in reports Wehran prepared in 1983. According to the available data, groundwater flow occurs stratigraphically from higher recharge areas to lower discharge areas. There is also the potential for downward movement of leachate (contaminated groundwater) from the upper zone to the underlying zones, but at very slow rates of migration. However, since the lateral permeability of the upper zone is significantly greater (10^4 times) than the permeability of the materials that form its base, lateral

flow to the adjacent tidal streams represents the major component of flow (Wehran, 1983).

The fill material in Section 1/9 is directly underlain by a variety of materials including recent silt, clay, and sand, glaciolacustrine clay, glacial till, and cretaceous clay. The recent silt and clay has an estimated average permeability of 1.0×10^{-6} cm/sec and is believed to be relatively impermeable in this Section. The fill material in Section 6/7 is underlain entirely by glaciolacustrine clay and/or glacial till, materials that are relatively impermeable and which restrict vertical movement of the leachate.

The hydrogeologic investigations were performed by the Landfill Engineering Division of NYCDOS during the installation of monitoring wells and piezometers in Sections 1/9 and 6/7. Field work for soil borings, testing and well installation added data on the refuse thickness in Sections 1/9 and 6/7. The refuse depth in Section 1/9 ranged from 10 to 120 feet in compacted thickness during the 1989-90 field study. This refuse is directly underlain by a variety of materials including recent silt, glaciolacustrine clay, glacial till, and cretaceous clay. The fill material in Section 6/7 is underlain entirely by glaciolacustrine clay and/or glacial till. The underlying materials are relatively impermeable and restrict vertical movement of the leachate. The refuse height in Section 6/7 ranged from 15 to 70 feet in 1989-90. From the

current refuse mound data, the average vertical sections for 1/9 and 6/7 are shown in Figures 1-4a and 1-4b.

1.3 OBJECTIVE

The objective of the study is to develop tools to estimate leachate flow from Fresh Kills Landfill. The first step involves estimating the average leachate flow rates and the associated peak flow rates from Sections 1/9 and 6/7. The average and peak flow rates will be estimated using mathematical models in an unsteady state flow condition. The Hydrologic Evaluation of Landfill Performance (HELP) model, developed by Schroeder, et al. (1984), can generate time-varying leachate flow rates considering an unsteady state solution for vertical flow and a series of steady state solutions for lateral flow. The HELP model is based on unsteady one-dimensional moisture-routing in the vertical direction. In the lateral direction, the flow rate is computed by solving the governing equations for a steady state condition. Two-dimensional mathematical models consider moisture-movement laterally and vertically in unsteady state flow conditions that represent time-varying field conditions and properties of the medium, such as changes in unsaturated hydraulic conductivity and diffusivity due to the variation of moisture content with time.

The side-slope criteria for landfilling is shown in Figure 1-5. The

Figure 1-4a. An Average Vertical Section of 1/9, October, 1989.

Figure 1-4b. An Average Vertical Section of 6/7, October, 1989.

Figure 1-5. Side-Slope Criteria for Landfilling.

surface runoff occurs on the landfill surface along the side slope which reduces the amount of net infiltration into the landfill. The techniques used to compute runoff in the other leachate flow models do not consider the effect of slope. A more accurate and realistic approach to compute runoff is incorporated in the two-dimensional leachate flow model using a kinematic wave equation to model the effect of slope.

In summary, the objectives of the present study are:

To apply the HELP model to Fresh Kills landfill Sections 1/9 and 6/7 to compute the average leachate flow rates;

To develop a two-dimensional unsteady state leachate flow model capable of simulating leachate flow rates in space and time. The model will also be able to predict the unsteady variation of leachate mound head inside the landfill. The model will be applied to Fresh Kills landfill sections 1/9 and 6/7 to simulate the variation of leachate flow rates;

To develop a surface runoff submodel that is incorporated into the main two-dimensional leachate flow model by considering the effect of side slope on the total runoff that occurs from a landfill;

To collect data on the variation of leachate head from the

monitoring wells and piezometers installed in Fresh Kills landfill Sections 1/9 and 6/7. (From these data, leachate mound head contours will be drawn to determine the gradients of flow that will be used to compute the lateral flow rate in Sections 1/9 and 6/7); and

The new model will also be used to determine the thickness of the cover soil and hydraulic conductivity of the barrier layer on the side slopes that give minimum percolation.

1.4 LITERATURE REVIEW

The water-balance method is a simple procedure used to estimate leachate flow from a landfill. This method was used in the Environmental Protection Agency (EPA) model developed by Fenn et. al. (1975). Using this method, the amount of water percolating through the solid waste is obtained by subtracting surface runoff, change in soil moisture and evapotranspiration from the total precipitation. In this method moisture movement through the refuse is not considered. The EPA model was used in a number of studies to estimate leachate generation rates for landfills in Cincinnati, Ohio; Orlando, Florida; and Los Angeles, California. Later models developed by Dass, et. al. (1977), Perrier and Gibson (1980), and Gee (1981) are also based on water-balance techniques.

Recent mathematical models (such as the HELP model and a numerical model developed by Korfiatis, 1984) consider moisture flow through the landfill in both steady and unsteady state flow conditions, and estimate leachate flow vertically and laterally in a landfill. Schroeder et. al. (1984) developed the Hydrologic Evaluation of Landfill Performance (HELP) model, which is based on a quasi two-dimensional, and quasi steady state approach for estimating leachate flow from waste disposal sites. This model is quasi two-dimensional, because it does not compute the vertical and lateral components of flow in each layer of the landfill profile simultaneously. The layers in which the hydraulic conductivity is large enough so that the flow occurs only downward and is not significantly restricted are called vertical percolation layers. According to HELP, in these layers, lateral flow components are assumed to be zero.

Layers in which hydraulic conductivity is high, but the flow is restricted in the downward direction by an impervious layer, are considered lateral drainage layers. The model is called quasi steady state because the vertical flow component is computed using an unsteady moisture routing equation and the lateral flow component is obtained from the steady state solution of the Boussinesq equation.

In the HELP model, the surface runoff at the upper boundary of the landfill is computed using a soil conservation service (SCS) curve-

number method, which does not consider the effect of surface roughness and slope along the side of the landfill.

The modified Penman method developed by Ritchie (1972) and used in the Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980) is used to compute the potential evapotranspiration in the HELP model. Despite the quasi two-dimensional and quasi steady state treatment of moisture movement, the HELP model is a deterministic computer-based model that uses climatologic and soil data to compute the leachate flow rates in a landfill.

Peyton and Schroeder (1988) applied the HELP model to 17 landfill sites in California, Kentucky, and Wisconsin. The leachate data were collected from the landfill sites and the model was verified by comparing the model results with the measured values of leachate flow. By calibrating the hydraulic conductivity in the model, good agreement between the predictions by the HELP model and field measurements was obtained for lateral drainage.

Application of flow models to simulate and estimate unsteady, unsaturated flows in solid waste landfills is still at an early stage. The governing equations used to characterize the leachate accretion on the leachate mound in the unsaturated zone, and leachate flow in the saturated zone are nonlinear second-order partial differential equations that require numerical solution

techniques to solve for the dependent variables that describe the landfill leachate flow processes.

A time-varying, one-dimensional leachate flow model was developed by Korfiatis (1984) using finite-difference numerical technique. Demetracopoulos, et. al. (1986) described the implicit finite-difference scheme for the one-dimensional unsteady state moisture flow equation which is solved to obtain the leachate accretion on the leachate mound. The implicit finite-difference expression for the moisture flow equation was solved by the successive application of the Gaussian elimination method, Korfiatis et. al. (1984) performed an experimental investigation with a small solid waste column, which was used to calibrate and verify the unsteady one-dimensional leachate flow model. The measured and predicted results were reasonably close to each other (Korfiatis et al., 1984).

The mass conservation principle and Darcy's Law is used to define the movement of saturated leachate within the leachate mound at the bottom of the landfill. Demetracopoulos et. al. (1984), Korfiatis et. al. (1986), and Demetracopoulos (1988) described the formulation and solution techniques to estimate leachate-mound head-height under steady state, quasi steady state, and unsteady state flow conditions.

1.5 RATIONALE FOR A NEW MODEL

While a simple model with many limitations can be developed to predict and evaluate the leachate flow process, a more complex model incorporating various aspects of the leachate flow process should give more realistic results. The Environmental Protection Agency (EPA) model developed by Fenn et. al. (1975) is based on the water-balance method in which the actual process of moisture movement through the refuse is not considered. The model using the water balance method does not include the computation for leachate mound head that is generated due to the leachate accumulation at the bottom of the landfill.

The HELP model developed by Schroeder et. al. (1984) is a quasi two-dimensional model to compute leachate flow in a quasi steady state flow condition. The vertical moisture flow is computed in an unsteady state condition while the lateral flow is obtained by solving the Boussinesq equation in a steady state condition. However, in the field, leachate mounding and leachate flow is strictly unsteady due to leachate accretion, and changes in the boundary condition.

The unsteady one-dimensional leachate flow model described by Korfiatis (1984) assumes that the flow is vertical, occurs in a column of solid waste, and does not depend on changes in the moisture content in other parts of the landfill as shown in Figure

1-6. However, in reality, moisture transport in one column depends on the moisture content in the other columns of the landfill. These effects can be taken into account by considering two-dimensional flow as shown in Figure 1-7.

The HELP model accounts for runoff, at the upper boundary (land surface) using the SCS curve number method, which does not consider the effect of slope along the side of the landfill. This limitation prohibits the user from applying the model along the landfill side slopes to get more realistic results for runoff and net infiltration into the refuse of a landfill.

As a result of shortcomings in the HELP model, a two-dimensional unsteady state flow investigation for landfill leachate (FILL) model has been developed to estimate leachate flow from a landfill. The two models are compared in Table 1-1. In the HELP model, moisture flows only vertically from layer to layer; in the new model, moisture content is computed at every grid point in a vertical plane. The kinematic wave equation (Bras, 1990) is used to compute runoff by considering the effect of slope and roughness of the landfill surface. The modified Penman method developed by Ritchie (1972) and used in the Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980) and HELP (Schroeder et. al., 1984), has been used to compute the potential evapotranspiration.

Legend:

Precipitation
 Evapotranspiration
 Runoff
 Solid Waste Column

P
 E
 R

Infiltration
 Vertical Flow
 Average Head

i
 v
 h

Figure 1-6. Configuration of Leachate Flow in a One-dimensional Flow Model.

Legend:

Precipitation

Evapotranspiration

Runoff

Infiltration

Moisture Flow

Figure 1-7. Configuration of Leachate Flow in a Two-dimensional Flow Model.

TABLE 1-1

COMPARISON OF THE HELP AND FILL MODELS

Components	HELP model	FILL model
1. Runoff	An average depth of runoff is computed using the SCS curve number method.	Runoff is computed along the landfill surface by taking the effects of slope and roughness of the surface into account. The results are obtained by solving the kinematic wave equation (Bras, 1990).
2. Infiltration	Assumed constant over the landfill and computed as follows: $I = P - E - R$ *	Variable over the landfill. It is obtained by solving Philip's (1969) equation which is dependent on moisture content, hydraulic conductivity, and depth of runoff flow.
3. Moisture flow	Moisture flow (vertical drainage) is assumed to occur only vertically from layer to layer and is defined by percolation minus retention in the soil.	Moisture flow is considered to occur both laterally and vertically. Moisture content is obtained by solving the 2-D unsaturated moisture flow equation.
4. Saturated zone	Flow is computed by solving the equation derived from Darcy's Law and the continuity equation in a steady state condition.	Flow is computed by solving the equation derived from Darcy's Law and the continuity equation in an unsteady state flow condition.

* I - Infiltration, P - Precipitation,
E - Surface Evapotranspiration, and R - Runoff.

Infiltration is a function of moisture content, hydraulic conductivity, and depth of water at the soil surface. The infiltration equation developed by Philip (1969), which considers the effect of the aforementioned parameters, is used in the present model. The solution of the two-dimensional unsteady state moisture flow equation gives the leachate accretion onto the leachate mound in the saturated zone. In the FILL model, the leachate mound head is obtained by solving the partial differential equation from the mass conservation principle in the saturated zone.

1.6 PREVIOUS ESTIMATES OF LEACHATE FLOW AT SECTIONS 1/9 AND 6/7

Estimates of leachate flow for the Fresh Kills landfill were made by applying Darcy's Law and the water-balance method (Wehran, 1983).

1. Water Balance Method. In the water-balance method, water entering and leaving the landfill is balanced. What percolates out of the landfill is the net effect of precipitation, evapotranspiration, surface runoff, and changes in soil moisture. These processes are related in the following water-balance equation; the dimensions are given in parenthesis.

$$\text{PERC} = P - R/O - ST - ET$$

where,

PERC = percolation of leachate (L),

P = precipitation (L),

R/O = runoff (L),

ST = change in soil moisture storage (L), and

ET = actual evapotranspiration (L).

The evapotranspiration values were obtained using the mean monthly tabulated values established by Thornthwaite (Thornthwaite and Mather, 1955). Tabulated values of monthly runoff coefficients were used to estimate the surface runoff. From Thornthwaite's soil-moisture retention tables, the values of soil moisture were assumed for landfill cover soil and for non-landfilled areas. The landfill surface was classified into five different conditions, based on field conditions at the different mounds. The conditions are described as follows (Wehran, 1983):

Vegetated landfill conditions, slope > percent;

Vegetated landfill conditions, slope < percent;

Landfill operational conditions and poorly vegetated areas;

Non-landfill conditions, generalized; and

Direct recharge to marsh and open water surfaces.

Using the water-balance method, a total of 897,000 gpd and 431,000 gpd of leachate flow is estimated for Sections 1/9 and 6/7 respectively as shown in Table 1-2. The estimates of leachate flow

TABLE 1-2

LEACHATE FLOW RATES BY WATER BALANCE METHOD
AND DARCY'S LAW FOR THE DATA IN 1983.

Section	Leachate flow (gpd)			
	Water balance method	Darcy's Law		
		Lateral flow	Vertical flow	Total flow
1/9	897,000	521,000	56,000	577,000
6/7	431,000	410,000	6,000	416,000

with a sample calculation for Sections 1/9 and 6/7 by the water-balance method are summarized in detail in Appendix A.

2. Darcy's Law Method. The configuration of the leachate mounds was determined by field measurements that were then used to draw hydraulic head contours for each Section. From these contours, the average lateral gradients for lateral flow in Sections 1/9 and 6/7 were estimated as 0.0147 (ft/ft) and 0.00522 (ft/ft) respectively (Wehran, 1983). The thickness of the saturated leachate mound was obtained by measuring the difference between the leachate mound level contours and the original ground levels beneath the mound. In-situ recovery tests in observation wells were performed to compute the hydraulic conductivity of the saturated zone. For Sections 1/9 and 6/7 the computed values were 0.0036 cm/sec (10.2 ft/day) and 0.02 cm/sec (56.67 ft/day) respectively. These data were used to estimate the lateral and vertical flow of leachate in the Fresh Kills landfill.

For lateral flow:

$$Q_L = Kbiw$$

where,

Q_L = lateral flow (L^3/T),

K = hydraulic conductivity (L/T),

b = saturated thickness (L),

w = width or perimeter of the leachate mound (L), and
i = hydraulic gradient (L/L).

For vertical flow:

$$Q_v = K_c i A$$

where,

Q_v = vertical flow (L^3/T),

K_c = hydraulic conductivity of the underlying clay (L/T),

i = hydraulic gradient (L/L), and

A = area of the landfill surface (L^2).

Total flow, $Q = Q_L + Q_v$

Using the above equations, a total flow of 577,000 gpd for Section 1/9 and 416,000 gpd for Section 6/7 were obtained as shown in Table 1-2. All the related parameters and calculations are shown in Appendix A.

1.7 RAINFALL DATA ANALYSIS

Rainfall data for Staten Island were obtained from New York City Department of Environmental Protection and analyzed to obtain the peak and average rainfall year. Data from these years were used to

run the HELP and FILL models to determine the variation of leachate flow for worst and average conditions in the landfill.

The average annual rainfall was obtained; and the annual rainfall for the year closest to the average annual value was selected as the average rainfall year. The year that gave the maximum annual precipitation was selected as the peak precipitation year.

The data for Staten Island from 1949 to 1955 were used in this study. Hourly values of precipitation are available for Staten Island. To analyze these data a computer program was written to collect the following information:

- The monthly average rainfall;

- The annual average rainfall;

- The peak rainfall year;

- The year having annual rainfall value closest to the average annual value;

- Monthly and annual rainfall values of the peak rainfall year;

- Peak monthly values;

- The daily values of the peak and average rainfall year; and

- The hourly values of the peak and average rainfall year.

Data from the Staten Island station, closest to the Fresh Kills landfill, were collected for seven years (1949 to 1955); the results appear in Tables 1-3 to 1-8.

TABLE 1-3
ANNUAL AVERAGE AND PEAK PRECIPITATION VALUES
FOR ALL MONTHS FROM 1949 TO 1955

Average annual precipitation	43.6 inches
Peak precipitation year	1951
Total precipitation in 1951	51.3 inches
Year closest to the average precipitation	1954
Total precipitation in 1954	43.6 inches

TABLE 1-4

**AVERAGE MONTHLY VALUES OF PRECIPITATION
FOR ALL MONTHS FROM 1949 TO 1955.**

Month	Av. Precipitation, in inches
January	3.2
February	3.1
March	4.9
April	3.6
May	4.1
June	2.3
July	2.9
August	6.2
September	2.8
October	3.1
November	3.9
December	3.5

TABLE 1-5

MONTHLY VALUES OF PRECIPITATION FOR THE
AVERAGE PRECIPITATION YEAR 1954.

Month	Precipitation (inches)
January	1.8
February	2.0
March	3.4
April	3.1
May	4.1
June	1.4
July	2.1
August	6.8
September	6.8
October	2.8
November	5.3
December	3.9

TABLE 1-6

**MONTHLY VALUES OF PRECIPITATION FOR THE
PEAK PRECIPITATION YEAR 1951**

Month	Precipitation (inches)
January	4.1
February	3.7
March	6.0
April	2.5
May	5.7
June	3.0
July	5.8
August	2.9
September	0.7
October	5.1
November	6.9
December	4.9

TABLE 1-7
PEAK MONTHLY VALUES OF PRECIPITATION

Month	Precipitation (inches)	Corresponding Year
January	6.3	1949
February	4.3	1950
March	8.6	1953
April	5.8	1953
May	6.3	1952
June	4.2	1952
July	6.0	1950
August	12.6	1955
September	6.8	1954
October	5.9	1955
November	6.9	1951
December	4.9	1951

TABLE 1-8
ANNUAL VALUES OF PRECIPITATION

Year	Precipitation (Inches)
1949	37.1
1950	41.7
1951	51.3
1952	47.1
1953	44.3
1954	43.6
1955	40.3

These data were used as input to the HELP and FILL models for Sections 1/9 and 6/7 of Fresh Kills landfill for 1954, the year closest to the average, and for 1951, the year that had the highest annual precipitation.

2 - HELP MODEL

2.1 INTRODUCTION

The overall computational scheme in the HELP model includes estimating evapotranspiration, runoff on the landfill surface and leachate flow on a barrier layer inside a landfill. The HELP model program computes daily evapotranspiration using the modified Penman method (Ritchie, 1972) and daily surface runoff by the Soil Conservation Service (SCS) curve number method. Daily infiltration is computed using the water-balance on the landfill surface, and is assumed to equal the difference between the sum of rainfall plus snowmelt, and the sum of runoff plus surface evaporation.

The moisture entering the landfill through the top soil cover moves downward through the refuse segments that are used to estimate an average leachate head on the barrier layer. The lateral flow is computed by substituting the value of leachate head into the expression obtained by the steady state solution of the Boussinesq equation. The net vertical flow from the mound is the percolation rate through the barrier layer at the bottom of the landfill, which is computed using Darcy's Law.

2.2 EVAPOTRANSPIRATION

The modified Penman method is used to compute potential evapotranspiration as developed by Ritchie (1972) and used in CREAMS (Knisel, 1980). The expression for the potential evapotranspiration is (Schroeder et al., 1984):

$$E_a = 1.28 A_i R_i / ((A_i + G) 25.4) \quad (2-1)$$

where,

E_a = potential evapotranspiration on day i (inches),

A_i = slope of saturation vapor pressure curve on day i ,

R_i = net solar radiation on day i (langleys), and

G = psychrometric constant which is assumed to remain constant at 0.68.

Evapotranspiration of available surface water occurs first. After available surface water is depleted, water from the soil column through evaporation and plant transpiration occurs. Evaporation from surface moisture is given by (Schroeder et al., 1984):

$$ESS_i = \begin{cases} E_a & \text{for } E_a \leq SNO_{i-1} + P_i \\ SNO_{i-1} + P_i & \text{for } E_a > SNO_{i-1} + P_i \end{cases} \quad (2-2)$$

where,

ESS_i = surface water evaporation on day i (inches),

SNO_{i-1} = amount of snow water at the end of day $i-1$, and

P_i = actual precipitation on day i (inches).

In the presence of actively transpiring plants, the potential soil evaporation is computed as follows (Schroeder et al., 1984):

$$ES_{O_i} = E_{O_i} e^{-0.4LAI} \quad (2-3)$$

where,

ES_{O_i} = potential soil evaporation on day i (inches),

LAI = leaf area index on day i , and E_{O_i} as defined previously.

During the nongrowing or dormant period, the dead or dormant vegetative cover reduces the potential soil evaporation. Then the potential soil evaporation for winter cover is expressed as (Schroeder et al., 1984):

$$ES_{O_i} = E_{O_i} e^{-0.4WCF} \quad (2-4a)$$

where,

WCF = winter cover factor.

Soil evaporation occurs in two stages. In stage one, soil

evaporation is equal to the potential soil evaporation ES_{0i} . In stage two, evaporation is controlled by the rate at which water can be transmitted through the soil.

An upper limit is set to control the stage-one soil evaporation. The upper limit to the stage-one evaporation is expressed as (Knisel, 1980):

$$U = [9(a_e - 3)^{0.42}]/25.4 \quad (2-4b)$$

where,

U = upper limit for stage-one evaporation (inches) and

a_e = soil transmissivity parameter for evaporation (mm/ $\sqrt{\text{day}}$).

The total of soil evaporation less infiltration is:

$$ES1T_i = \sum_{k=m}^i ES_k - IN_k \quad (2-4c)$$

where,

ES_k = soil evaporation on day k (inches),

m = last day when $ES1T_i$ equalled zero, and

IN_k = Precipitation - Runoff - ESS_k

When $ES1T_i$ is greater than U , stage-one evaporation stops and stage-two evaporation starts. Stage-two evaporation is controlled by soil transmissivity. Stage two evaporation from the soil is

estimated as (Knisel, 1980):

$$ES2_i = a_i [t_i^{1/2} - (t_i - 1)^{1/2}] / 25.4 \quad (2-4d)$$

where,

$ES2_i$ = stage-two soil evaporation for day i (inches), and

t_i = days since stage-one evaporation ended.

The potential plant transpiration is computed as (Schroeder et al., 1984):

$$EP_{O_i} = E_{O_i} LAI_i / 3.0 \quad (2-5)$$

where,

EP_{O_i} = potential plant transpiration on day i (inches).

The actual plant transpiration demand is expressed as (Schroeder et al., 1984):

$$EPD_i = \begin{cases} EP_{O_i} & \text{for } EP_{O_i} + ESS_i + ES_i \leq E_{O_i} \\ E_{O_i} - ESS_i - ES_i & \text{for } EP_{O_i} + ESS_i + ES_i > E_{O_i} \end{cases} \quad (2-6)$$

where,

ES_i = actual soil evaporation on day i (inches).

Using the relationship developed by Shanholtz and Lillard (1970), the actual plant transpiration is computed as:

$$EP_i = EPD_i [1.2 - (4EPD_i) + (SM_i - WP)/(FC - WP)] \quad (2-7)$$

where,

SM_i = soil moisture on day i (inches),

WP = wilting point (VOL/VOL), and

FC = field capacity (VOL/VOL).

The total evapotranspiration (ET) is equal to the sum of the evaporation from the soil (ES) and the plant transpiration (EP):

$$ET_i = \begin{cases} ES_i + EP_i & \text{when } (ES_i + EP_i) \leq (E_{oi} - ESS_i) \\ E_{oi} - ESS_i & \text{when } (ES_i + EP_i) > (E_{oi} - ESS_i) \end{cases} \quad (2-8)$$

2.3 RUNOFF

The Soil Conservation Service (USDA, Soil Conservation Service, 1972) curve number method is used to compute runoff in the HELP model. In this method, slope of the landfill surface is not considered. The SCS equation for runoff can be expressed as

(Schroeder, et. al., 1984)

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad (2-9)$$

Where,

Q = runoff (inches),

P = precipitation (inches),

S = retention parameter (inches).

The retention parameter S is expressed as a function of curve number (CN) as (Schroeder et. al., 1984):

$$S = 1000/CN - 10 \quad (2-10)$$

Daily values of runoff are computed from the daily precipitation by using equation (2-9) and (2-10).

2.4 SNOWMELT

The precipitation in the form of snow does not contribute to runoff and infiltration when the temperature remains below 32°F. The HELP model program assumes that the daily minimum temperature exceeds 32°F when the daily mean temperature (average of the daily maximum and minimum temperature) exceeds 41°F (Schroeder et al., 1988). In

this condition, snowmelt is assumed to occur during the entire day and it is computed by the degree-day method (USDA, Soil Conservation Service, 1972) as:

$$M_i = K (T_i - 32) \quad (2-11)$$

where,

M_i = amount of snowmelt on day i (inches),

K = a constant that varies with watershed and climatic conditions, the value of which is considered as 0.1, and

T_i = mean temperature on day i ($^{\circ}\text{F}$).

Snowmelt is assumed to occur only when the daily mean temperature is between 23°F and 41°F . The snowmelt is computed by interpolating between zero snowmelt at 23°F and the snowmelt computed by the degree-day method for $T_i = 41^{\circ}\text{F}$. The equations are as follows (Schroeder et al., 1988):

$$M_i = 0 \quad \text{for } T_i < 23^{\circ}\text{F} \text{ or } \text{SNO}_{i-1} = 0 \quad (2-12a)$$

$$M_i = 0.101[(T_i - 23)/18]^2(T_i - 32)/2 \quad (2-12b)$$

for $23 < T_i < 41$

and for $\text{SNO}_{i-1} \geq 0.1[(T_i - 23)/18]^2(T_i - 23)/2$

$$M_i = 0.1(T_i - 32) \quad (2-12c)$$

for $T_i \geq 41$ and $SNO_{i-1} \geq 0.1 (T_i - 32)$

$$M_i = SNO_{i-1} \quad (2-12d)$$

for $23 \leq T_i \leq 41$ and

$$SNO_{i-1} < 0.1 [(T_i - 23)/18]^2 (T_i - 23)/2$$

$$\text{or } T_i > 41 \text{ and } SNO_{i-1} < 0.1(T_i - 32)$$

where,

SNO_{i-1} = amount of snow water at the end of day $i-1$ (inches).

The amount of snowmelt on any day is added to the precipitation to be used in equation (2-9) to compute runoff.

2.5 SUBSURFACE MOISTURE ROUTING

The subsurface moisture routing is modelled by considering flow from one subprofile to the other. The overall configuration of the subprofiles in the HELP model is shown in Figure 2-1. The sequence and soil characteristics of the layers are specified in the model.

Using the information about soil characteristics and boundary condition (as the precipitation less surface evaporation and runoff) the moisture routing is done from top layer to the bottom

Source: Schroeder et al., 1984. HELP Model.
Vol. II. U.S. Army Engineer Water Ways
Experiment Station.

Figure 2-1. Configuration of HELP Model.

layer. The routing procedure helps estimate the vertical drainage, leachate head, and percolation through the barrier layer. Lateral drainage is computed from the steady state solution of the Boussinesq equation.

2.5.1 Vertical Drainage

The boundary condition for the vertical flow submodel is considered as the input estimated by subtracting surface evaporation and runoff from precipitation. The configuration of the vertical flow submodel is shown in Figure 2-2. The rate of vertical drainage is modelled by considering Darcy's Law in the unsaturated flow condition. Darcy's Law is expressed as:

$$q = K \frac{dh}{dl} \quad (2-13)$$

where,

- q = discharge per unit time per unit area perpendicular to the direction of flow (L/T),
- K = hydraulic conductivity (L/T),
- h = hydraulic head (L), and
- l = length along the direction of the flow (L).

Equation (2-13) is solved in the HELP model for the unsaturated

Source: Schroeder et al., 1984. HELP Model.
 Vol. II. U.S. Army Engineer Water Ways
 Experiment Station.

Figure 2-2. Configuration of Vertical Flow Submodel.

zone assuming hydraulic conductivity K for unsaturated condition, which is a function of soil moisture. Free drainage is assumed for the vertical moisture movement when the gradient is set equal to unity. Under these conditions the vertical drainage rate is equal to the hydraulic conductivity K in the unsaturated condition.

There are many empirical relations for the unsaturated hydraulic conductivity as a function of saturated hydraulic conductivity and soil moisture content. These empirical relations depend on the soil matrix which needs to be determined by experimental investigation of the unsaturated medium. In the HELP model the unsaturated hydraulic conductivity is expressed as a function of saturated hydraulic conductivity, soil moisture, residual soil moisture content, and saturated soil water content as (Schroeder et al., 1988):

$$K_u = K_s \left(\frac{SM - RS}{UL - RS} \right)^{3 + \frac{2}{\lambda}} \quad (2-14)$$

where,

K_u = unsaturated hydraulic conductivity (L/T),

K_s = saturated hydraulic conductivity (L/T),

SM = soil moisture content (VOL/VOL),

RS = residual soil moisture content (VOL/VOL),

UL = total porosity or the soil moisture content at saturation (VOL/VOL), and

λ = pore size distribution index.

Default values are available in the HELP model program for the above soil characteristics. Based on equations (2-14) the drainage rate from a segment j at time step i , $DR_i(j + 1)$ is written as (Schroeder et al., 1988):

$$DR_i(j+1) = K_s(j).DT. \left[\frac{SM_i(j) - RS(j)}{UL(j) - RS(j)} \right]^{3+2/\lambda_j} \quad (2-15)$$

where,

$K_s(j)$ = saturated hydraulic conductivity of segment j ,

DT = time interval,

$SM_i(j)$ = soil moisture of segment j ,

$RS(j)$ = residual soil moisture of segment j , and

$UL(j)$ = porosity of segment j

Considering midpoint routing, the continuity equation is written as (Schroeder et al., 1984):

$$\Delta S = (I_1 + I_2)/2 - (O_1 + O_2)/2 \quad (2-16)$$

where,

ΔS = change in storage during the time interval,

I_1 = inflow to storage at the beginning of the time interval,

I_i = inflow to storage at the end of the time interval,
 O_i = outflow from storage at the beginning of the time interval,
 and
 O_i = outflow from storage at the end of the time interval.

According to equation (2-16), the midpoint routing expression for the soil moisture content is written as (Schroeder et al., 1988):

$$\begin{aligned}
 SM_i(j) = SM_{i-1}(j) + 1/2 [DR_i(j) + DR_{i-1}(j)] \\
 - DR_i(j+1) - DR_{i-1}(j+1) - ET_i(j) \\
 - ET_{i-1}(j)]
 \end{aligned}
 \tag{2-17}$$

where,

i = time step and

j = segment number.

From equations (2-15) and (2-17) the nonlinear equation for $DR_i(j+1)$ is obtained as (Schroeder et al., 1988):

$$\begin{aligned}
 DR_i(j+1) + 2[UL(j) - RS(j)] \left[\frac{DR_i(j+1)}{K_s(j)DT} \right]^{\frac{1}{3+2/\lambda_j}} = 2[SM_{i-1}(j) - RS(j)] \\
 + DR_{i-1}(j) + DR_i(j) \\
 - DR_{i-1}(j+1) - ET_{i-1}(j) \\
 - ET_i(j)
 \end{aligned}
 \tag{2-18}$$

The routing proceeds from the top segment to the last segment at the bottom of the landfill.

After the computation of moisture content at each segment, the total head (TH) is computed as (Schroeder, et. al., 1988):

$$TH = TS(m) \frac{SM(m) - FC(m)}{UL(m) - FC(m)} + \sum_{j=m+1}^n TS_j \quad (2-19)$$

where,

TS(m) = thickness of the segment in inches,

n = number of the segment directly above the barrier soil layer,

m = the lowest segment that is not saturated.

The percolation through the barrier layer is written as (Schroeder et al., 1988):

$$q_p = K_c \left(\frac{TH + TC}{TC} \right) \cdot LF \quad (2-20)$$

where,

q_p = the rate of percolation through the barrier,

K_c = the saturated hydraulic conductivity of the barrier,

TH = total head above the barrier layer,

TC = thickness of the barrier, and

LF = leakage fraction which is equal to 1.0 for no synthetic liner.

2.5.2 Lateral Drainage

The lateral flow submodel is based on the linearized steady state solution of the Boussinesq equation. With the steady state assumption, the Boussinesq equation can be expressed as (Schroeder, et. al, 1988):

$$K \cos^2 \alpha \frac{d}{dx} \left(y \frac{dh}{dx} \right) + R - K_c \left(1 + \frac{y}{T} \right) = 0 \quad (2-21)$$

where,

x = horizontal distance from drain,

y = saturated thickness in the lateral drainage layer,

α = inclination angle of the lateral drainage plane,

h = elevation of leachate mound surface,

R = vertical drainage rate into saturated portion of lateral drainage layer,

K = effective saturated hydraulic conductivity in lateral drainage layer,

K_c = effective saturated hydraulic conductivity in barrier soil layer, and

T = thickness of barrier soil layer

The configuration of lateral flow submodel is illustrated in Figure 2-3.

Assuming a steady flow and by considering an average saturated thickness y , it can be written as (Schroeder, et. al, 1988):

$$Q_{LAT} = R - K_c \left(1 + \frac{\bar{y}}{T} \right) \quad (2-22)$$

where,

Q_{LAT} = flow rate to the drain per unit of the contributing surface area.

Substituting equation (2-22) into equation (2-21), the governing equation can be written as (Schroeder, et. al., 1988):

$$K \cos^2 \alpha \frac{d}{dx} \left(y \frac{dh}{dx} \right) + Q_{LAT} = 0 \quad (2-23)$$

In equation (2-23), h is transformed in terms of y and, the non-dimensional form of equation (2-23) with h in terms of y can be written as (Schroeder, et. al., 1988):

$$y^* \frac{d^2 y^*}{dx^{*2}} + \left(\frac{dy^*}{dx^*} \right)^2 + (\tan \alpha) \frac{dy^*}{dx^*} + \frac{Q_{LAT}^*}{\cos \alpha} = 0 \quad (2-24)$$

Source: Schroeder, 1986. HELP: Hydrologic Evaluation of Landfill Performance Model.

Figure 2-3. Configuration of Lateral Flow Submodel.

where,

L = one-half the horizontal distance between parallel drains,

$$x^* = x/L,$$

$$y^* = y/L, \text{ and}$$

$$Q_{LAT}^* = \frac{Q_{LAT}}{L}$$

Equation (2-24) was solved by numerical technique using different values of Q_{LAT} and α . The results were summarized to establish the relationship among Q_{LAT} , y , α , K and L as (Schroeder, et. al., 1988):

$$\begin{aligned} \bar{y} &= \frac{Q_0^*}{2 \sin \alpha \cos \alpha} \quad \text{for} \quad \bar{y}^* \leq 0.4 \sin^2 \alpha \\ &= 2 \frac{\pi}{4} \frac{\sqrt{Q_0^*}}{\cos \alpha} \cdot \frac{2\sqrt{0.4}}{\pi} \left[\left(\frac{Q_0^*}{0.4 \sin^2 \alpha} \right)^{\frac{1}{2 \ln[2(0.4)^{1/2}/\pi]}} \right] \quad (2-25) \\ &\quad \text{for} \quad \bar{y}^* \geq 0.4 \sin \alpha \end{aligned}$$

where,

y^* = mean value of y .

The above equation is used to compute lateral flow (Q_{LAT}) in the lateral drainage layer.

2.6 DATA REQUIRED FOR THE MODEL

The data required for running the HELP model are as follows:

Climatologic data:

- Daily precipitation;
- Mean monthly temperature;
- Mean monthly solar radiation;
- Leaf area index;
- Winter cover factor;
- Evaporative zone depth; and
- SCS curve number.

Soil Data:

- Porosity;
- Field capacity;
- Wilting point;
- Hydraulic conductivity; and
- Evaporation coefficient.

The following information is also required to run the HELP model:

- Thickness of layers (layers are cap, solid wastes and barrier soil layer or virgin ground);
- Whether the layer is compacted or not;
- Fraction of daily potential percolation through leaks in the

membrane (if membrane is present);

Area of the landfill surface;

Slope at the base of the lateral drainage layer, i.e., at the top of the barrier layer as shown in Figure 2-2;

Maximum drainage distance along the slope to the collector; and

Fraction of daily potential runoff from the surface that could infiltrate if the site is open (with no final cap).

2.7 LIMITATIONS

The limitations inherent in the application of the HELP model are:

Lateral flow is essentially assumed to be a steady state. Only vertical flow is assumed to be unsteady while the lateral flow is obtained by solving the Boussinesq equation in a steady state condition. However, in the field leachate mound development and leachate flow is strictly unsteady due to changes in the boundary conditions and leachate accretion;

In the HELP model, the runoff at the upper boundary is computed using SCS curve number method which does not take the effect of slope along the side of the landfill into account. This limitation prohibits the users from applying the model along the landfill side slopes to get more accurate results for runoff as well as net infiltration into the refuse of a landfill;

Infiltration into a landfill is computed as precipitation less surface evaporation and runoff. However, the infiltration process depends on the moisture content of the soil surface, hydraulic conductivity, porosity and capillary rise. When computing infiltration, the effect of the aforementioned factors is not considered. Also, infiltration is considered constant over the landfill;

Moisture flow in the unsaturated zone occurs primarily by diffusion at lower moisture contents (Korfiatis, et. al., 1984). But in the HELP model the diffusion process for moisture transport in the unsaturated zone is not considered; and

Lateral flow in the saturated zone is computed by considering a steady state solution of the Boussinesq equation. However, in the field, head variations and flow gradients in the leachate mound are strictly unsteady.

2.8 SENSITIVITY TEST

Simulations of a real field situation can only be achieved by using accurate data required by the model. Some field data can not be determined easily in active landfills (for example, hydraulic conductivity, porosity, wilting point, and field capacity). Variations in the value of leachate flow parameters have unequal

effects on the model results. Some of the parameters have greater effects than others. By identifying the more sensitive parameters, better predictions of the flow components in a landfill system can be obtained when field values are substituted. This can be investigated using sensitivity analysis and independently varying the model's parameters. The model results are compared to identify the parameters causing the most deviation. The HELP model has default values for soil and climatologic data. The soil data includes hydraulic conductivity, field capacity, wilting point, and evaporation coefficient. The climatologic data includes temperature, solar radiation, curve number, winter-cover factor, leaf-area index and evaporative zone depth.

2.8.1 Model Run for the Base-case (Hypothetical Scheme)

The base-case was a hypothetical landfill section consisting of an 80 ft. waste layer with 10 inches vegetative cover layer and one-foot barrier layer at the top and bottom, as shown in Figure 2-4. Sensitivity analysis included climatologic and soil data. Default values of climatologic data exist for New York City for five years from 1974 to 1978 in the HELP model. The model was run to obtain results for 1974 and 1975. Output of these two years was investigated to observe the sensitivity of parameters such as hydraulic conductivity, porosity, field capacity, wilting point, evaporation coefficient, temperature, solar radiation, curve

Figure 2-4. A Hypothetical Landfill Section.

number, winter-cover factor, leaf area index, and evaporative zone depth.

The model run was made to observe the effect on the model results for 10 percent, 20 percent, and 50 percent change in the values of the aforementioned input data. Monthly leachate flow variation (in 1974) for the change in the soil and climatologic data are shown in Figures 2-5a to 2-5f and 2-6a to 2-6f respectively. Annual leachate flow values have also been compared for the change in the parameters. Comparisons for 1974 and 1975 appear in Tables 2-1 and 2-2 respectively.

2.8.2 Model Results

Sensitivity analysis assumed the effect on model results for a 10 percent, 20 percent, and 50 percent increase or decrease of the values of the different parameters. Figures 2-5a to 2-5f and 2-6a to 2-6f show the variation of model results with respect to time due to change in the values of the parameters. Figures 2-5a to 2-5f indicates that the results due to a 10 percent, 20 percent and 50 percent change in the values of wilting point, field capacity, and evaporation coefficient do not differ significantly throughout the computational period in 1974.

During the earlier period of computation, close model results are

Figure 2-5a. Results of Sensitivity Analysis for a 10 percent Increase in the Values of the Soil Data.

Figure 2-5b. Results of Sensitivity Analysis for a 10 percent Decrease in the Values of the Soil Data.

Figure 2-5c. Results of Sensitivity Analysis for a 20 percent Increase in the Values of the Soil Data.

Figure 2-5d. Results of Sensitivity Analysis for a 20 percent Decrease in the Values of the Soil Data.

Figure 2-5e. Results of Sensitivity Analysis for a 50 percent Increase in the Values of the Soil Data.

2 of 5

Figure 2-5f. Results of Sensitivity Analysis for a 50 percent Decrease in the Values of the Soil Data.

Figure 2-6a. Results of Sensitivity Analysis for a 10 percent Increase in the Values of the Climatologic Data.

Figure 2-6b. Results of Sensitivity Analysis for a 10 percent Decrease in the Values of the Climatologic Data.

Figure 2-6c. Results of Sensitivity Analysis for a 20 percent Increase in the Values of the Climatologic Data.

Figure 2-6d. Results of Sensitivity Analysis for a 20 percent Decrease in the Values of the Climatologic Data.

Figure 2-6e. Results of Sensitivity Analysis for a 50 percent Increase in the Values of the Climatologic Data.

Figure 2-6f. Results of Sensitivity Analysis for a 50 percent Decrease in the Values of the Climatologic Data.

TABLE 2-1a

RESULTS OF SENSITIVITY ANALYSIS
FOR SOIL DATA IN 1974

Results due to	Annual leachate	Hydraulic conduct.	Porosity	Field cap.	Wilting point	Evaporation coefficient
initial default values	inches	1.4023	1.4023	1.4023	1.4023	1.4023
	cu.ft.	22945	22945	22945	22945	22945
10% increase	inches	1.5495	1.3744	1.4041	1.4046	1.403
	cu.ft.	25354	22488	22975	22983	22957
	%change	10.5	-2.0	0.13	0.16	0.05
10% decrease	inches	1.2569	1.4303	1.397	1.3964	1.4033
	cu.ft.	20566	23403	22858	22849	22961
	%change	-10.37	2.0	-0.38	-0.42	0.07
20% increase	inches	1.7017	1.3534	1.3425	1.4129	1.4036
	cu.ft.	27844	22144	21967	23119	22967
	%change	21.35	-3.49	-4.26	0.76	0.09
20% decrease	inches	1.111	1.3203	1.3889	1.3901	1.412
	cu.ft.	18180	21604	22726	22746	23104
	%change	-20.77	-5.85	-0.96	-0.87	0.69
50% increase	inches	2.16	1.3119	*	1.4271	1.4063
	cu.ft.	35343	21466		23351	23011
	%change	54.0	-6.45		1.77	0.29
50% decrease	inches	0.6883	*	1.4169	1.3649	1.4225
	cu.ft.	11262		23185	22334	23324
	%change	-50.92		1.04	-2.67	1.65

* HELP model did not run.

TABLE 2-1b
RESULTS OF SENSITIVITY ANALYSIS
FOR SOIL DATA IN 1975

Results due to	Annual leachate	Hydraulic conduct.	Porosity	Field cap.	Wilting point	Evaporation coefficient
initial default values	inches	1.6355	1.6355	1.6355	1.6355	1.6355
	cu.ft.	26760	26760	26760	26760	26760
10% increase	inches	1.8203	1.5961	1.6355	1.6405	1.634
	cu.ft.	29785	26116	26761	26943	26737
	%change	11.3	-2.41	0.0	0.31	-0.09
10% decrease	inches	1.4519	1.6741	1.6261	1.63	1.6364
	cu.ft.	23757	27392	26607	26671	26775
	%change	-11.22	2.36	-0.57	-0.34	0.06
20% increase	inches	2.0084	1.5593	1.5265	1.649	1.6389
	cu.ft.	32862	25515	24977	26981	26808
	%change	22.8	-4.66	-6.66	0.83	0.21
20% decrease	inches	1.273	1.3872	1.6174	1.6252	1.6549
	cu.ft.	20829	22698	26464	26593	27078
	%change	-22.16	-15.18	-1.11	-0.63	1.19
50% increase	inches	2.5809	1.4737	*	1.7075	1.645
	cu.ft.	42230	24114		27939	26916
	%change	57.8	-9.89		4.4	0.58
50% decrease	inches	0.756	*	1.6292	1.6021	1.6885
	cu.ft.	12371		26658	26215	27629
	%change	-53.78		-0.39	-2.04	3.24

* HELP model did not run.

TABLE 2-2a

RESULTS OF SENSITIVITY ANALYSIS
FOR CLIMATOLOGIC DATA IN 1974

Results due to	Annual leachate	Leaf area index	Winter cover factor	Tempera.	Solar radiat.	Evapo. zone depth	curve number
initial default values	inches	1.1139	1.1139	1.1139	1.1139	1.1139	1.1139
	cu.ft.	18226	18226	18226	18226	18226	18226
10% increase	inches	1.1079	1.1138	1.0802	1.0763	1.1139	1.1138
	cu.ft.	18128	18225	17676	17611	18226	18225
	%change	-0.54	-0.009	-3.0	-3.38	0.0	-0.009
10% decrease	inches	1.1186	1.1085	0.8272	1.1438	1.3691	1.1139
	cu.ft.	18303	18137	13534	18715	22402	18227
	%change	0.42	-0.48	-25.74	2.68	22.91	0.0
20% increase	inches	1.0902	1.1178	1.0685	1.0816	1.1139	1.1136
	cu.ft.	17839	18290	17484	17597	18226	18222
	%change	-2.13	0.35	-4.07	-2.9	0.0	-0.03
20% decrease	inches	1.1322	1.1050	0.8256	1.2045	1.3931	1.1139
	cu.ft.	18526	18080	13510	19709	22795	18226
	%change	1.64	-0.8	-25.88	8.13	25.07	0.0
50% increase	inches	1.0783	1.1261	1.0426	0.7412	1.1139	1.0889
	cu.ft.	17643	18426	17059	12127	18226	17816
	%change	-3.2	1.1	-6.4	-33.46	0.0	-2.24
50% decrease	inches	1.1937	1.1044	0.6231	1.3392	1.4459	1.1139
	cu.ft.	19532	18170	10196	21913	23659	18226
	%change	7.16	-0.85	-44.06	20.23	29.81	0.0

TABLE 2-2b

RESULTS OF SENSITIVITY ANALYSIS
FOR CLIMATOLOGIC DATA IN 1975

Results due to	Annual leachate	Leaf area index	Winter cover factor	Tempera.	Solar radiat.	Evapo. zone depth	Curve number
Initial default values	inches	1.4359	1.4359	1.4359	1.4359	1.4359	1.4359
	cu.ft.	23494	23494	23494	23494	23494	23494
10% increase	inches	1.428	1.438	1.4174	1.4192	1.4359	1.4358
	cu.ft.	23366	23529	23192	23221	23494	23493
	%change	-0.55	0.15	-1.29	-1.16	0.0	-0.007
10% decrease	inches	1.4431	1.4335	1.4457	1.4609	1.5583	1.4359
	cu.ft.	23613	23455	23655	23903	25498	23495
	%change	0.5	-0.17	0.68	1.74	8.52	0.0
20% increase	inches	1.4234	1.4406	1.4149	1.4021	1.4359	1.4355
	cu.ft.	23291	23572	23152	22942	23494	23480
	%change	-0.87	0.33	-1.46	-2.35	0.0	-0.03
20% decrease	inches	1.4591	1.4324	1.4492	1.4824	1.5875	1.4360
	cu.ft.	23875	23438	23713	24256	25976	23496
	%change	1.62	-0.24	0.93	3.24	10.56	0.007
50% increase	inches	1.4141	1.4475	1.3885	1.3004	1.4359	1.3967
	cu.ft.	23138	23685	22720	21278	23494	22854
	%change	-1.52	0.81	-3.30	-9.44	0.0	-2.73
50% decrease	inches	1.5036	1.4339	1.2651	1.5809	1.68	1.4359
	cu.ft.	24603	23462	20700	25868	27489	23495
	%change	4.71	-0.14	-11.9	10.1	17.0	0.0

observed due to changes in the value of the porosity. Higher deviation of the model results in the case of porosity can be seen in Figure 2-5d in the later half of the computation, from June to December, 1974. Similar deviation of model results are observed due to a 20 percent increase in the value of the field capacity as shown in Figure 2-5c. However, in almost all the other computational time steps, the results deviate far less due to the change in the values of the parameters. In all cases from Figures 2-5a to 2-5f, the variation in the model results due to change in the value of the hydraulic conductivity has the greatest significance.

Figures 2-6a to 2-6f show that the variation in the values of the curve number, winter-cover factor, and leaf-area index does not change the model results significantly. The results due to the increase of the values of these parameters deviate much less compared to the results obtained using default values, except for the deviation observed due to a 50 percent increase in solar radiation at the time steps between September and November as shown in Figure 2-6e. For decrease in the values, temperature is the most sensitive parameter due to the higher amount of deviation in the results as shown in Figures 2-6b, 2-6d, and 2-6f. Model results also vary significantly due to a 50 percent decrease in the values of evaporative zone depth and solar radiation at the time steps from July as shown in Figure 2-6f. However, in most of the computational period the deviation in results due to change in all

the parameters except temperature is insignificant.

Wilting point, evaporation coefficient, and field capacity are less sensitive parameters as shown in Tables 2-1a and 2-1b. For a 50 percent increase in the value of the evaporation coefficient, an increase of only 0.29 percent occurs in the model results as shown in Table 2-1a. Similar insignificant changes in the model results are observed due to variation in the field capacity and wilting point. Porosity shows a moderate variation in the results due to changes in it. Higher amount of variation in the results is observed due to decrease in its value as shown in Table 2-1. Hydraulic conductivity is the most sensitive parameter as shown by the results in Tables 2-1a and 2-1b. Results increase by 54 percent due to a 50 percent increase in its value as shown in Table 2-1a.

Sensitivity analysis for climatologic data, based on the results of annual leachate variation shows that the curve number, winter-cover factor, and leaf-area index are less sensitive parameters. No change in the results is observed due to decrease in the value of the curve number. Negligible change in the results occurs due to an increase in the value of the curve number. The highest change of 2.24 percent occurs due to a 50 percent increase in its value as shown in Table 2-2a. Evaporative zone depth is a moderately sensitive parameter indicating no change in the results due to an increase in its value. Decrease in the value of temperature causes

significant variation in the model results as shown in Tables 2-2a and 2-2b. Change in the values of solar radiation also causes significant change in the model results. A 50 percent increase in its value caused a 33.46 percent decrease in the model results in 1974 as shown in Table 2-2a.

2.9 FIELD APPLICATION

The HELP model was applied to Section 1/9 and 6/7 to estimate the leachate flow for the average and peak rainfall years. The model was applied to Sections 1/9 and 6/7 for the unsaturated and saturated thickness determined by Wehran in 1983. The vertical sections indicating the unsaturated and saturated zones are shown in Figures 2-7a and 2-7b for Sections 1/9 and 6/7 respectively. A saturated waste thickness of 22.5 ft. and six ft. was considered for Sections 1/9 and 6/7 respectively as determined by the previous study made by Wehran (1983).

The model run was made using the default values of temperature and solar radiation. Default values of soil data were used to define porosity, field capacity, and wilting point. The values of hydraulic conductivity for Sections 1/9 and 6/7 were 0.0036 cm/sec (10.2 ft./day) and 0.02 cm/sec (56.67 ft./day) respectively. The values of different parameters used by the HELP model for Sections 1/9 and 6/7 are summarized in Tables 2-3a and 2-3b respectively.

Figure 2-7a. Average Landfill Section for 1/9 in 1983.

Figure 2-7b. Average Landfill Section for 6/7 in 1983.

TABLE 2-3a

DATA REQUIRED FOR HELP MODEL
IN SECTION 1/9

Total area	405 acres
SCS runoff curve number	56.74
For waste layer:	
Thickness in 1983	35.67 ft.
Thickness in 1989	72.0 ft.
Porosity	0.457 vol/vol
Field capacity	0.0835 vol/vol
Wilting point	0.0327 vol/vol
Saturated hydraulic conductivity:	
Wehran (1983)	0.0036 cm/sec (10.2 ft./day)
CCNY-NYCDOS (1989)	0.00176 cm/sec (4.98 ft./day)
For bottom clay layer:	
Thickness	16.25 ft.
Porosity	0.43 vol/vol
Field capacity	0.3667 vol/vol
Wilting point	0.2804 vol/vol
Saturated hydraulic conductivity	0.0000001 cm/sec (0.000283 ft./day)

TABLE 2-3b
DATA REQUIRED FOR HELP MODEL
IN SECTION 6/7

Total area	376 acres
SCS runoff curve number	38.62
For waste layer:	
Thickness in 1983	21 ft.
Thickness in 1989	51 ft.
Porosity	0.417 vol/vol
Field capacity	0.0457 vol/vol
Wilting point	0.02 vol/vol
Saturated hydraulic conductivity	0.02 cm/sec (56.67 ft./day)
For bottom clay layer:	
Thickness	18.46 ft.
Porosity	0.430 vol/vol
Field capacity	0.3667 vol/vol
Wilting point	0.2804 vol/vol
Saturated hydraulic conductivity	0.0000001 cm/sec (0.000283 ft./day)

Monthly values of precipitation, runoff, evapotranspiration and net infiltration for the peak and average rainfall years are shown in Figures 2-8a and 2-8b and 2-9a and 2-9b for Sections 1/9 and 6/7 respectively. The lateral, vertical and total flow of leachate in the average and peak rainfall years is shown in Figures 2-10a to 2-10c and 2-11a to 2-11c for Sections 1/9 and 6/7 respectively. The average daily lateral and vertical flow of leachate for Section 1/9 and 6/7 is shown in Table 2-4.

The HELP model was also run with recent data collected from the field by CCNY-NYCDOS, to estimate flow components for the present field condition. Hydraulic conductivity for Section 1/9 from field data (1989) reveals a significantly lower value of 4.98 ft./day than that used by Wehran (1983) of 10.2 ft./day. The new value of hydraulic conductivity (4.98 ft./day) was used in the present application of HELP model in Section 1/9 for the new data. The detailed computation of the new value of hydraulic conductivity from the mound level data and leachate flow rates from the collection line are described in Section 4. In Section 6/7 the previous value of hydraulic conductivity of 56.67 ft./day determined by Wehran (1983) was used for the application of the HELP model. Since 1983, the average head increased from 22.5 ft. to 34.42 ft., and from six ft. to 9.67 ft. in Sections 1/9 and 6/7 respectively. The present overall vertical configuration of Sections 1/9 and 6/7 for the application of the HELP model is shown in Figures 2-12a and 2-12b.

Figure 2-8a. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1983 for the Average Rainfall Year.

Figure 2-8b. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1983 for the Peak Rainfall Year.

Figure 2-9a. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7, using the Field Data in 1983 for the Average Rainfall Year.

Figure 2-9b. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1983 for the Peak Rainfall Year.

Figure 2-10a. Variation of Average Daily Lateral Flow in Section 1/9 using the Field Data in 1983.

Figure 2-10b. Variation of Average Daily Vertical Flow in Section 1/9 using the Field Data in 1983.

Figure 2-10c. Variation of Daily Total Flow in Section 1/9 using the Field Data in 1983.

Figure 2-11a. Variation of Average Daily Lateral Flow in Section 6/7 using the Field Data in 1983.

Figure 2-11b. Variation of Average Daily Vertical Flow in Section 6/7 using the Field Data in 1983.

Figure 2-11c. Variation of Daily Total Flow in Section 6/7 using the Field Data in 1983.

TABLE 2-4
LEACHATE FLOW RATES COMPUTED BY THE HELP MODEL
FOR 1983 DATA

Section	Leachate flow (mgd)					
	Average rainfall year			Peak rainfall year		
	Lateral flow	Vertical flow	Total flow	Lateral flow	Vertical flow	Total flow
1/9	0.5	0.1	0.6	0.506	0.101	0.607
6/7	0.365	0.043	0.408	0.406	0.044	0.45

Figure 2-12a. Average Landfill Section of 1/9 for the Data in 1989.

Figure 2-12b. Average Landfill Section of 6/7 for the Data in 1989.

Monthly values of precipitation, runoff, evapotranspiration, and net infiltration for the average and peak rainfall years are shown in Figures 2-13a and 2-13b and 2-14a and 2-14b for Sections 1/9 and 6/7 respectively for the recent data.

Monthly variation of lateral, vertical, and total flow for Sections 1/9 and 6/7 are shown in Figures 2-15a to 2-15c and 2-16a to 2-16c respectively. The variation of leachate mound head for the average and peak rainfall years in Sections 1/9 and 6/7 is shown in Figures 2-17 and 2-18 respectively. The total annual precipitation, runoff, evapotranspiration, and leachate production is shown in Tables 2-5a and 2-5b for Section 1/9 and 2-6a and 2-6b for Section 6/7 for the data Wehran collected in 1983 and CCNY-NYCDOS in 1989. The average daily lateral, vertical and total flow for both the Sections 1/9 and 6/7 is shown in Table 2-7 for the model run with the recent data. The peak flow rates indicated by the model output are shown in Tables 2-8a and 2-8b for the data in 1983 and 1989.

2.10 RESULTS AND DISCUSSION

The HELP model was applied to Fresh Kills Section 1/9 and 6/7 for the data collected in 1983 by Wehran and for the data collected in 1989 by CCNY-NYCDOS. Variations of the model results for 1983 and 1989 for Sections 1/9 and 6/7 are analyzed as follows:

Figure 2-13a. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1989 for the Average Rainfall Year.

Figure 2-13b. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1989 for the Peak Rainfall Year.

Figure 2-14a. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1989 for the Average Rainfall Year.

Figure 2-14b. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1989 for the Peak Rainfall Year.

Figure 2-15a. Variation of Average Daily Lateral Flow in Section 1/9 using the Field Data in 1989.

Figure 2-15b. Variation of Average Daily Vertical Flow in Section 1/9 using the Field Data in 1989.

□ Average rainfall
 + Peak rainfall
 Figure 2-15c. Variation of Daily Total Flow in Section 1/9 for the Field Data in 1989.

Figure 2-16a. Variation of Average Daily Lateral Flow in Section 6/7 using the Field Data in 1989.

Figure 2-16b. Variation of Average Daily Vertical Flow in Section 6/7 using the Field Data in 1989.

Figure 2-16c. Variation of Daily Total Flow in Section 6/7 using the Field Data in 1989.

Figure 2-17. Variation of Leachate Mound Head in Section 1/9 for the Field Data in 1989.

Figure 2-18. Variation of Leachate Mound Head in Section 6/7 for the Field Data in 1989.

TABLE 2-5a

ANNUAL VALUES OF PRECIPITATION, RUNOFF,
EVAPOTRANSPIRATION AND LEACHATE PRODUCTION
IN SECTION 1/9 FOR THE 1983 DATA

Flow parameter	Average rainfall year		Peak rainfall year	
	Inches	Million Gallons	Inches	Million Gallons
Precipitation	46.58	512.2	51.34	564.57
Runoff	0.042	0.462	0.0	0.0
Evapotranspiration	31.161	342.67	29.095	319.95
Leachate production	15.377	169.10	22.245	244.62

TABLE 2-5b

ANNUAL VALUES OF PRECIPITATION, RUNOFF,
EVAPOTRANSPIRATION AND LEACHATE PRODUCTION
IN SECTION 1/9 FOR THE 1989 DATA

Flow parameter	Average rainfall year		Peak rainfall year	
	Inches	Million Gallons	Inches	Million Gallons
Precipitation	46.58	512.2	51.34	564.57
Runoff	0.077	0.847	0.0	0.0
Evapotranspiration	31.723	348.85	30.419	334.51
Leachate production	14.78	162.53	20.921	230.06

TABLE 2-6a

**ANNUAL VALUES OF PRECIPITATION, RUNOFF,
EVAPOTRANSPIRATION AND LEACHATE PRODUCTION
IN SECTION 6/7 FOR THE 1983 DATA**

Flow parameter	Average rainfall year		Peak rainfall year	
	Inches	Million Gallons	Inches	Million Gallons
Precipitation	46.58	475.50	51.34	524.09
Runoff	0.525	5.36	1.323	13.50
Evapotranspiration	28.368	289.59	27.083	276.47
Leachate production	17.687	180.55	22.934	234.12

TABLE 2-6b

**ANNUAL VALUES OF PRECIPITATION, RUNOFF,
EVAPOTRANSPIRATION AND LEACHATE PRODUCTION
IN SECTION 6/7 FOR THE 1989 DATA**

Flow parameter	Average rainfall year		Peak rainfall year	
	Inches	Million Gallons	Inches	Million Gallons
Precipitation	46.58	475.50	51.34	524.09
Runoff	0.542	5.53	1.387	14.16
Evapotranspiration	28.239	288.27	27.387	279.59
Leachate production	17.8	181.70	22.566	230.36

TABLE 2-7

**HELP MODEL RESULTS FOR THE NEW DATA
COLLECTED BY CCNY-NYCDOS IN 1989**

Section	Leachate Flow (mgd)					
	Lateral Flow		Vertical Flow		Total Flow	
	Average rain	Peak rain	Average rain	Peak rain	Average rain	Peak rain
1/9	0.5101	0.5101	0.1318	0.1318	0.6419	0.6419
6/7	0.6057	0.6103	0.0473	0.0473	0.653	0.6576

TABLE 2-8a

PEAK FLOW RATES FOR THE DATA IN 1983

Section	Leachate Flow (mgd)					
	Lateral Flow		Vertical Flow		Total Flow	
	Average rain	Peak rain	Average rain	Peak rain	Average rain	Peak rain
1/9	0.576	0.576	0.1056	0.1056	0.6816	0.6816
6/7	0.514	0.5143	0.046	0.046	0.56	0.56

TABLE 2-8b

PEAK FLOW RATES FOR THE DATA IN 1989

Section	Leachate Flow (mgd)					
	Lateral Flow		Vertical Flow		Total Flow	
	Average rain	Peak rain	Average rain	Peak rain	Average rain	Peak rain
1/9	0.574	0.574	0.1381	0.1381	0.7121	0.7121
6/7	0.984	0.984	0.053	0.053	1.037	1.037

2.10.1 Results in Section 1/9 for the Data in 1983

The HELP model results in Section 1/9 indicate that the evapotranspiration contributes significantly to the total loss from the precipitation and soil moisture. Figure 2-8a shows that the highest value, 5.91 inches of evapotranspiration, occurred in August during the average rainfall year. Higher values of evapotranspiration occur from July to September due to higher ambient temperatures (68.2 to 76.4°F) then. Similar variations are also observed for the peak rainfall year as shown in Figure 2-8b. A total of 31.16 inches of evapotranspiration occurs in the average rainfall year, which is about 66.6 percent of total precipitation in that year as shown in Table 2-5a. For the peak rainfall year, 29.1 inches of evapotranspiration occur which is about 56 percent of the total precipitation in the peak precipitation year as shown in Table 2-5a.

The runoff computed by the HELP model using the default values of curve number in the present landfill section is small compared to the total rainfall. In Section 1/9, a total annual surface runoff of 0.042 inches occurs during the average rainfall year, which is only 0.09 percent of the total rainfall in that year as shown in Table 2-5a. No runoff occurs during the peak rainfall year. The runoff in the HELP model is computed using the SCS curve number method. In this method, surface slope is not considered when computing surface runoff. This limitation in the formulation can

not produce high runoff values for increase in slope along the landfill side.

The net infiltration is the precipitation less evapotranspiration and surface runoff. In the average rainfall year, a total of 15.38 inches of net infiltration occur in Section 1/9 which is about 33 percent of total precipitation in that year as shown in Table 2-5a. In the peak rainfall year about 43.33 percent of precipitation enters into the landfill as net infiltration. The HELP model estimates the total infiltration as the precipitation less runoff and surface evaporation. The infiltration-water is the input at the upper boundary which leads to the vertical drainage of moisture, as leachate accumulating on the leachate-head ultimately leads to lateral and vertical flow of leachate in the landfill.

Figure 2-10a shows that the highest lateral flow of 0.564 mgd occurs in the first month and gradually decreases throughout the remainder of the year, in the average rainfall-year. Leachate mound-head decreases as well. For the average rainfall-year an average lateral flow of 0.5 mgd occurs in Section 1/9 as shown in Table 2-4. Variation of lateral flow in the peak-rainfall year is similar to the variation in the average rainfall-year. For the peak-rainfall year, average lateral flow of 0.506 mgd is observed in Section 1/9 as shown in Table 2-4. Using the HELP model an increase of precipitation by 11.2 percent from the average-rainfall year comparable to the peak-rainfall year would increase lateral

flow about 1.2 percent. The vertical flow for average and peak-rainfall year are 0.10 mgd and 0.101 mgd respectively as shown in Table 2-4. It shows that an insignificant increase of only 1 percent occurs for vertical flow due to a 10.22 percent increase in the precipitation from the average rainfall-year to the peak rainfall-year. The total flow of 0.60 mgd and 0.607 mgd occur in the average and peak rainfall-year respectively. This shows an increase in the total flow of 1.17 percent for the increase in the precipitation from the average rainfall-year to the peak rainfall-year. The remaining leachate should be stored inside the landfill for creating the leachate mound.

Leachate production is the total precipitation less runoff and evapotranspiration. The leachate production of 169.10 million gallons (per year) and 244.62 million gallons (per year) occur during the average and peak rainfall-year respectively as shown in Table 2-5a. From this value the daily production rate is 0.463 million gallons and 0.670 million gallons for the average and peak rainfall-years respectively. Comparing these production rates with the total flow rates in Table 2-4 (0.600 mgd for the average and 0.607 mgd for the peak rainfall year) the average production rate (mean of average and peak rainfall-year is 0.567 mgd) is slightly lower than the average leachate flow rate (mean of flow rates of peak and average rainfall-year which is 0.604 mgd).

2.10.2 Results in Section 6/7 for the Data in 1983

The monthly pattern of runoff, evapotranspiration, and net infiltration for Section 6/7 is similar to that for Section 1/9. Again, evapotranspiration is significantly higher than runoff. The annual runoff of 0.525 inches and 1.323 inches respectively occurs during the average and peak rainfall-year in Section 6/7 as shown in Table 2-6a. The runoff values for Section 6/7 are only about 1.13 percent and 2.58 percent of annual precipitation for the average and peak rainfall-years respectively.

The net infiltration into the landfill system in Section 6/7 is estimated at 17.687 inches and 22.934 inches in the average and peak rainfall-year respectively as shown in Table 2-6a. This corresponds to 37.97 percent and 44.67 percent of the annual precipitation in the average and peak rainfall-years respectively. The highest net infiltration occurs during November, in both the average and peak rainfall-years, and is 3.724 inches and 4.994 inches respectively when rainfall was 5.25 inches and 7.03 inches as shown in Figure 2-9.

The variation of lateral flow for the average and peak rainfall year is shown in Figure 2-11a. Figure 2-11a shows that the daily lateral flow decreases with time. This happens due to a very high hydraulic conductivity value of 56.67 ft/day which allows more

leachate to flow at the beginning and causes a sharp drop of leachate mound head to cause the decrease in the flow rates with time. Similar variations are also observed for the lateral flow in peak rainfall-years and vertical flow in both the average and peak rainfall-years. The average lateral flow for the average and peak rainfall-years is 0.365 mgd and 0.406 mgd respectively as shown in Table 2-4. The vertical flow for the average and peak rainfall years is 0.043 mgd and 0.044 mgd respectively as shown in Table 2-4. The total flow for the average and peak rainfall-year is 0.408 mgd and 0.45 mgd respectively as shown in Table 2-4. Lateral flow increases by 11.23 percent for an increase of 10.22 percent of precipitation from the average to the peak rainfall year. The vertical flow component does not change significantly for the increase in the precipitation. An increase of only 2.33 percent occurs due to 10.22 percent increase of precipitation from the average to the peak rainfall year. The total flow increases by 10.3 percent for the 10.22 percent increase in precipitation.

2.10.3 Results in Section 1/9 for the New Data in 1989

The HELP model was used to estimate the flow components for Section 1/9 with the new data collected by CCNY-NYCDOS. The total waste thickness increased on the average, from 35.67 ft. to 72 ft. from 1983 to 1989 as shown in Figures 2-7a and 2-12a. Also, the saturated-thickness increased from 22.5 ft. to 34.42 ft. during the

same period. In addition, the hydraulic conductivity was estimated at 4.98 ft./day and using this value the flow components for Section 1/9 were computed. The runoff value is insignificant for the new data in the average rainfall-year. Total annual surface runoff of 0.077 inches occurs during the average rainfall-year as shown in Table 2-5b. For the new data, no runoff is obtained from the upper surface of the landfill by applying the HELP model in Section 1/9 during the peak rainfall-year which is not realistic with respect to the actual field situation.

The low values of runoff are due to the unrealistic curve number chosen by the HELP model from the default values during the model run. The evapotranspiration is significantly higher than the surface runoff. The evapotranspiration was estimated to be 31.72 inches and 30.42 inches which is 68.1 percent and 59.25 percent of the total precipitation during the average and peak rainfall-year respectively as shown in Table 2-5b. High values of evapotranspiration contribute significantly to the total loss of moisture from the surface and from inside the landfill. The net infiltration is 14.78 inches and 20.92 inches respectively for the average and peak rainfall-year as shown in Table 2-5b. Precipitation contributes about 31.73 percent and 40.75 percent to the net infiltration.

Variations of the lateral flow are almost proportional for the average and peak rainfall-year. The results differ in February

when lateral flows are 0.5389 mgd and 0.5581 mgd for the average and peak rainfall-year respectively as shown in Figure 2-15a. The vertical flow does not vary for the average and peak rainfall condition as shown in Figure 2-15b. The increase in rainfall from the average to the peak rainfall year is 10.22 percent and the vertical flow component is insensitive to this increase. A peak vertical flow of 0.1366 mgd occurs for February for both the average and peak rainfall-year as shown in Figure 2-15b. The average lateral flow of 0.5101 mgd and vertical flow of 0.1318 mgd occurs for both the average and peak rainfall years as shown in Table 2-7. The total flow of 0.6419 mgd occurs in both the average and peak rainfall-year for Section 1/9 as shown in Table 2-7. The average lateral, vertical, and total flow are the same for both the average and peak rainfall years.

2.10.4 Results in Section 6/7 for the New Data in 1989

The model results for evapotranspiration, runoff, and net infiltration in Section 6/7 are shown in Figures 2-14a and 2-14b for the average and peak rainfall years. The total evapotranspiration of 28.239 inches and 27.387 inches occurs during the average and peak rainfall year respectively as shown in Table 2-6b. The surface runoff is insignificant compared to the value of the evapotranspiration. The annual surface runoff of only 0.542 inches and 1.387 inches occurs during the average and peak

rainfall-years respectively as shown in Table 2-6b. The surface runoff is only 1.16 percent and 2.7 percent of the total precipitation during the average and peak rainfall years respectively. The net infiltration into landfill Section 6/7 is estimated at 17.8 inches and 22.566 inches respectively for the average and peak rainfall years as shown in Table 2-6b. This net infiltration leads to a leachate outflow rate of 0.498 mgd and 0.631 mgd for the average and peak rainfall years respectively as shown in Table 2-6b.

The variation of lateral, vertical, and total flow for the average and peak rainfall year in Section 6/7 is shown in Figures 2-16a, 2-16b, and 2-16c respectively. The pattern of the variation of the lateral flow for both the average and peak rainfall year is similar. The lateral flow for the peak rainfall year is higher than for the average rainfall year; however, the difference is insignificant. The average lateral flow for the average and peak rainfall year is 0.6057 mgd and 0.6103 mgd respectively as shown in Table 2-7. This indicates an increase of only 0.76 percent in the lateral flow for an increase of 10.22 percent in the precipitation from the average to the peak rainfall year. The variation of lateral flow does not depend only on the variation of precipitation. The lateral flow depends on the variation of evapotranspiration, runoff, moisture drainage rate, leachate mound head, and hydraulic conductivity of the medium. The vertical flow is almost the same for the average and peak rainfall year. The

vertical flow varies from 0.0517 mgd to 0.0436 mgd for both the average and peak rainfall year as shown in Figure 2-16b. The average vertical flow of 0.0473 mgd occurs during the average and peak rainfall years. The total flow of 0.653 mgd and 0.6576 mgd occurs during the average and peak rainfall years respectively. An increase of 0.7 percent in the total flow occurs due to the increase of precipitation from the average to peak rainfall year by 10.22 percent.

2.10.5 Discussion

To effectively apply the HELP model to Fresh Kills' landfill Section 1/9 and 6/7, the most sensitive data to realistically estimate leachate flow rates were identified by a sensitivity analysis of parameters used in the model.

Hydraulic conductivity is the most sensitive parameter. For a 50% decrease in its value, the model result (percolation) decreased by 50.92 percent which is significant. A significant increase in the percolation of 54 percent occur due to 50 percent increase in the value of the hydraulic conductivity as shown in Table 2-1a. Similar variations are also observed for the 10 percent and 20 percent change in the value of the hydraulic conductivity. The evaporation coefficient is the least sensitive parameter. For a 50% increase in its values, an increase of only 0.58 occurs in the

annual leachate values as shown in Table 2-1b.

Similar insignificant changes in the results are observed for field capacity and wilting point due to their large variation. The variation in the leachate flow due to the change in the porosity is also insignificant. For a 20 percent decrease in the value of porosity, a 5.85 percent decrease in the leachate flow occurs as shown in Table 2-1a. Also for a 50 percent increase in the value of porosity, the results decrease by 6.45 percent as shown in Table 2-1a.

The effect of porosity on the model results is moderate. However, in some cases, a significant effect is observed. For a 20 percent decrease in its value, a 15.18 percent decrease in the model results occur as shown in Table 2-1b. Also, a 9.89 percent decrease in the model results occur due to a 50 percent increase in the porosity value. Therefore, the default values available for field capacity, wilting point and evaporation coefficient can be successfully used for the leachate prediction by the HELP model in a landfill. The default values were derived by experiments conducted by the U. S. Army Corps of Engineers (Schroeder et al., 1984). But, the reasonably accurate estimate of hydraulic conductivity must be done because of the strong effect on the model results due to its change. Porosity is a moderately sensitive parameter. The overall effect due to the change in it is insignificant. The significance for this default value of the

porosity can be used to predict the leachate flow in a landfill.

Climatological data are needed for the model run. These data include leaf-area index, winter-cover factor, temperature, solar radiation, evaporative zone depth and curve number. It is difficult to estimate leaf-area index, winter-cover factor, evaporative zone depth and curve number for an active landfill. However, an estimate was made by Schroeder, et. al. (1984) for all of these parameters and provision is made for the model to use these parameters from the default values. The sensitivity analysis for all the climatologic data (except precipitation) was done to observe the effect on the model results due to their variation.

The overall effect of the leaf-area index, winter-cover factor, evaporative zone depth, and curve number is insignificant on the model results. Curve number is the least sensitive parameter. For a 50 percent decrease in the value of curve number, no change in the model results is observed as shown in Table 2-2a. Winter-cover factor changes the model results by 0.85 percent for a 50 percent decrease in its value and is shown in Table 2-2a. The model result decreases by 1.52 percent due to a 50 percent increase in the leaf-area index as shown in Table 2-2b. No change in the model results is observed due to increase in the evaporative zone depth. Temperature and solar radiation have an effect on the model results. It is observed that for a 50% decrease, the model result decreases by 44.06 percent as shown in Table 2-2a. Table 2-2a also

shows that for a 50 percent increase in the value of solar radiation, the model results decrease by 33.46 percent which is significant. Therefore, the default values available for leaf-area index, winter-cover factor, evaporative zone depth, and curve number can be used to predict leachate generation in the landfills. Due to the sensitivity of temperature and solar radiation, it is necessary to measure these data in the field more accurately to get a accurate estimate of the leachate flow in the field.

The HELP model was applied to investigate the leachate production rate and leachate flow rate in the Fresh Kills' landfill Section 1/9 and 6/7. The model was applied to both Sections for the data Wehran collected in 1983 to investigate the leachate flow process. The model was also applied to determine the flow components based on the current data collected by CCNY-NYCDOS for this study. The study was done to investigate the variation of leachate flow for the field data collected by Wehran (1983) and CCNY-NYCDOS. The predictions were made for the average and peak rainfall years. The average and peak rainfall years were obtained by analyzing rainfall data from the New York City Department of Environmental Protection from 1949 to 1955. The flow components predicted by the HELP model are evapotranspiration, runoff, lateral flow and vertical flow. In the HELP model results, evapotranspiration is the dominant parameter that contributes the maximum to the total losses of moisture from the surface and from infiltration water for the average and peak rainfall years. The surface runoff is

insignificant as predicted by the model with the default value of the curve number.

The net infiltration into the landfill is the dominant factor leading to the leachate accretion, which ultimately causes the lateral and vertical flow at the bottom of the landfill. The net infiltration into the landfill is considered as the total leachate produced in the landfill. For the model results with the 1983 data, the average leachate production rate for the average rainfall-year in Section 1/9 and Section 6/7 is 0.463 mgd as shown in Table 2-5a and 0.495 mgd as shown in Table 2-6a, respectively.

The corresponding results for the data in 1989 are 0.445 mgd as shown in Table 2-5b and 0.498 mgd as shown in Table 2-6b. For the peak rainfall-year, the production rate in Section 1/9 and 6/7 for the data in 1983 is 0.670 mgd as shown in Table 2-5a and 0.641 mgd as shown in Table 2-6a respectively. The corresponding values for the 1989 data are 0.63 mgd as shown in Table 2-5b and 0.631 mgd as shown in Table 2-6b. The total flow of 0.60 mgd and 0.607 mgd occurs in the average and peak rainfall years respectively for Section 1/9 using 1983 data in the HELP model as shown in Table 2-4. For Section 6/7, the corresponding values are 0.408 mgd and 0.450 mgd as shown in Table 2-4.

The results in Table 2-7 for the data in 1989 shows that the total flow increases for both the average and peak rainfall years. The

average leachate flow of 0.6419 mgd is the same for both the average and peak rainfall-years in Section 1/9. In Section 6/7, the leachate flow in the average and peak rainfall-years is 0.653 mgd and 0.6576 mgd respectively. The model results for leachate flow rates for the data in 1983 and 1989 as shown in Tables 2-4 and 2-7, reveal that the leachate flow rate has increased. In Section 1/9 the leachate flow rate has increased by 6.98 percent for the average rainfall year due to the change in the field condition from 1983 to 1989. A large increase in the leachate flow rate is seen in Section 6/7. The leachate flow rate in Section 6/7 increased 60.0 percent (0.408 mgd to 0.653 mgd as shown in Tables 2-4 and 2-7) in the average rainfall-year due to a change in the field data from 1983 to 1989. The total leachate flow for Section 1/9 and 6/7 is 1.2949 mgd and 1.2995 mgd for the average and peak rainfall-years respectively with field data collected in 1989. The total leachate flow for Sections 1/9 and 6/7 was 1.008 mgd and 1.057 mgd for the average and peak rainfall-years respectively using the data Wehran collected in 1983. An overall increase of 28.46 percent and 22.94 percent occurs in the average and peak rainfall-years respectively due to the change in the field data from 1983 to 1989.

The peak daily flows for the data in 1983 and 1989 are shown in Tables 2-8a and 2-8b respectively. For the field data in 1983 the peak daily values indicated by HELP model are 0.6816 mgd and 0.56 mgd respectively for Sections 1/9 and 6/7 as shown in Table 2-8a. The values are higher than the average daily flow by 13.6 percent

and 37.25 percent for Sections 1/9 and 6/7 respectively in the average rainfall-year. For the field data in 1989 the total peak daily flows for Sections 1/9 and 6/7 are 0.7121 mgd and 1.037 mgd respectively as shown in Table 2-8b. Comparing results in Tables 2-8a, 2-8b and 2-7 for the field data in 1989, the peak daily values are higher than the average daily values by 10.94 percent and 58.8 percent respectively for Sections 1/9 and 6/7 in the average rainfall-year. Similar variations are observed in the peak rainfall-year. The total peak daily flows for Sections 1/9 and 6/7 due to the field data in 1983 and 1989 are 1.2416 mgd and 1.75 mgd respectively. The peak daily flow of 1.75 mgd is higher than 1.2416 mgd by 40.95 percent, which appears to be an over estimation of peak daily flow compared to the previous estimates of leachate flow.

3 - FILL MODEL

3.1 CONCEPTUALIZATION OF LEACHATE FLOW PROCESS

The input to the upper boundary of the solid waste landfill is the precipitation less runoff and evapotranspiration. Runoff occurs at the top of the landfill which is dependent on the slope, roughness, hydraulic conductivity, and moisture content. The portion of the precipitation remaining after runoff is the infiltration which depends on the depth of flow on the surface and also on the hydraulic conductivity and moisture content of the top soil. The moisture flow in the landfill basically occurs in three phases - flow through the cover, flow through the wastes, and flow through the bottom liner or virgin ground beneath the wastes as shown in Figure 3-1. The fraction of infiltration that enters into the unsaturated zone in the landfill changes the moisture content and thus leads to a build-up of leachate to form a saturated leachate mound. Then the lateral and vertical flows can be estimated when the hydraulic gradient of the leachate mound-head in the saturated zone is known.

The movement of moisture inside the landfill can be estimated by using a simple one-dimensional or quasi two-dimensional model. In this case, it is assumed that the flow in one area of the landfill

Figure 3-1. Configuration of Leachate Flow Process in a Landfill.

is not dependent on the changes in the moisture content in other parts of the landfill. However, moisture flow in one column depends on changes in the moisture content in the other columns of the landfill. These effects can be taken into account by considering a two-dimensional flow condition. Since the leachate flow varies in both space and time, an unsteady state two-dimensional flow with time-varying boundary conditions can be considered to predict the time history of leachate flow inside the landfill for the real field simulation. The present FILL model is based on a two-dimensional unsteady state approach.

3.2 GOVERNING EQUATION IN THE UNSATURATED ZONE

The unsteady moisture flow in the unsaturated zone can be formulated by using Darcy's Law and the equation of continuity. Darcy's Law was formulated for flow through a saturated porous media where hydraulic conductivity is a function of the pore properties of the medium and the properties of the fluid. Buckingham (1907) established that Darcy's Law might apply to the liquid flow in the unsaturated media in a modified form in which the hydraulic conductivity K , instead of being a constant, is regarded as a function of the volumetric moisture content. The extension of Darcy's Law was verified later by several investigators (Gardner, 1958; Childs and Collis-George, 1959; Brooks and Corey, 1964; Brutsaert, 1967; Klute, 1972; Mualem, 1976;

and Clapp and Hornberger, 1978) and it is now a generally accepted theory for unsaturated liquid flow. According to Darcy's Law, the specific discharge in the unsaturated zone is:

$$q = -K(\theta) \nabla \phi \quad (3-1)$$

where,

q = volume flow rate per unit cross-sectional area normal to the direction of flow (L/T),

ϕ = total potential (L),

$K(\theta)$ = unsaturated hydraulic conductivity (L/T),

$\theta = V_w/V$ = volumetric moisture content (vol/vol),

V_w = volume of water in the soil mass (L³), and

V = total volume of the soil mass (L³).

The total potential head ϕ is illustrated in Figure 3-2 which shows the negative suction head developed in the unsaturated zone. Figure 3-2 shows that the total potential head is:

$$\phi = -z - \Delta \quad (3-2)$$

For unsaturated soil Δ is the suction head and considering $\Delta = \psi$ the total potential head ϕ is:

$$\phi = -\psi - z \quad (3-3)$$

Source: Bear, 1979. Hydraulics of Groundwater.
McGraw-Hill Book Company. p. 196.

Figure 3-2. Definition Diagram for Total Potential.

The continuity equation can be written as (Willis and Yeh, 1987):

$$-\nabla \cdot \rho \mathbf{q} = \frac{\partial(\rho \theta)}{\partial t} \quad (3-4)$$

where,

ρ = density of water.

Assuming incompressible flow:

$$-\nabla \cdot \mathbf{q} = \frac{\partial \theta}{\partial t} \quad (3-5)$$

From equations (3-1), (3-3), (3-4), and (3-5):

$$-\nabla \cdot K(\theta) \nabla \psi - \frac{\partial K(\theta)}{\partial z} = \frac{\partial \theta}{\partial t} \quad (3-6)$$

Equation (3-6) can be written as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[-K(\theta) \frac{\partial \psi}{\partial x} \right] + \frac{\partial}{\partial y} \left[-K(\theta) \frac{\partial \psi}{\partial y} \right] + \frac{\partial}{\partial z} \left[-K(\theta) \frac{\partial \psi}{\partial z} \right] - \frac{\partial K(\theta)}{\partial z} \quad (3-7)$$

Considering two-dimensional flow domain, equation (3-7) can be written as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[-K(\theta) \frac{\partial \psi}{\partial x} \right] + \frac{\partial}{\partial z} \left[-K(\theta) \frac{\partial \psi}{\partial z} \right] - \frac{\partial K(\theta)}{\partial z} \quad (3-8)$$

Assuming ψ as the single-valued function of θ , equation (3-8) can be written as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[-K(\theta) \frac{\partial \psi}{\partial \theta} \frac{\partial \theta}{\partial x} \right] + \frac{\partial}{\partial z} \left[-K(\theta) \frac{\partial \psi}{\partial \theta} \frac{\partial \theta}{\partial z} \right] - \frac{\partial K(\theta)}{\partial z} \quad (3-9)$$

The soil moisture diffusivity $D(\theta)$ can be written as:

$$D(\theta) = -K(\theta) \frac{\partial \psi}{\partial \theta} \quad (3-10)$$

Therefore, the two-dimensional unsaturated moisture flow equation can be written as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[D(\theta) \frac{\partial \theta}{\partial x} \right] + \frac{\partial}{\partial z} \left[D(\theta) \frac{\partial \theta}{\partial z} \right] - \frac{\partial K(\theta)}{\partial z} \quad (3-11)$$

This equation is solved to obtain the moisture content in the unsaturated zone of a landfill. Solution of moisture content generates the time history of leachate input rate on the saturated leachate mound.

3.3 HYDRAULIC CONDUCTIVITY AND DIFFUSIVITY FUNCTIONS

The values of the unsaturated hydraulic conductivity vary with the moisture content in the soil. In the unsaturated media, the hydraulic conductivity is expressed in a modified form as a function of the volumetric moisture content (Clapp and Hornberger, 1978). The unsaturated hydraulic conductivity as a function of

moisture content θ can be expressed as (Campbell, 1974):

$$K(\theta) = K_s \left(\frac{\theta}{\theta_s} \right)^{2b+3} \quad (3-12)$$

where,

$K(\theta)$ = unsaturated hydraulic conductivity as a function of moisture content (L/T),

θ_s = saturation moisture content (vol/vol),

K_s = saturated hydraulic conductivity (L/T),

b = slope of moisture characteristic curve plotted on log-log paper and is known as Campbell's parameter.

From equation (3-10), it is clear that to determine the diffusivity coefficient, the value of the suction head has to be differentiated with respect to moisture content θ . The suction head ψ as a function of moisture content θ can be expressed as (Bristow and Williams, 1987):

$$\psi(\theta) = \psi_e \left(\frac{\theta}{\theta_s} \right)^{-b} \quad (3-13)$$

where,

$\psi(\theta)$ = suction head as a function of moisture content θ ,

ψ_e = air entry suction head.

Reasonable estimates for ψ_e can be obtained from the moisture characteristic curves. In practice moisture content at air entry $\theta_e = 0.9\theta_s$, and in general, θ_e varies between $0.8\theta_s$ and θ_s (Rogowski, 1971).

From equations (3-10), (3-12), and (3-13), the diffusivity relationship in the unsaturated zone can be expressed as:

$$D(\theta) = bK(\theta) \left(\frac{\psi_e}{\theta_s} \right) \left(\frac{\theta_s}{\theta} \right)^{b+1} \quad (3-14)$$

The above relationships for unsaturated diffusivity and hydraulic conductivity are used in the unsaturated moisture flow equation to compute the moisture content and hence the moisture flow rate in the unsaturated zone.

3.4 BOUNDARY AND INITIAL CONDITIONS

Boundary conditions define the dependent variable at the boundaries of the domain. In the FILL model, two types of upper boundary

conditions are considered, the unsaturated condition and the saturated condition. For the unsaturated-flow condition, the moisture flux is composed of precipitation less evapotranspiration and runoff. This condition at the upper boundary occurs when net precipitation intensity is less than the saturated hydraulic conductivity (Demetracopoulos et al., 1986). Therefore, the input at the boundary for the unsaturated flow condition can be written as:

$$\text{INPUT} = P - ET - R \quad (3-15)$$

where,

P = precipitation (L),

ET = evapotranspiration (L), and

R = rainfall (L).

The modified Penman method developed by Ritchie (1972) and used in HELP (Schroeder, et. al., 1984) is used to compute the potential evapotranspiration. The necessary expressions for the computation of evapotranspiration are described on pages 2-2 to 2-5. The saturated boundary condition exists for the upper surface of the landfill when the net precipitation intensity is greater than or equal to the saturated hydraulic conductivity (Demetracopoulos et al., 1986). In this situation, the upper boundary condition is expressed as:

$$\theta = \theta_s \quad (3-16)$$

where,

θ_s = moisture content at saturation.

At the lower boundary, a free-drainage condition is considered, which is expressed as (Korfiatis et al., 1984):

$$\frac{\partial \theta}{\partial z} = 0 \quad (3-17)$$

The initial condition is defined as the known values of moisture content in the landfill section. Therefore, at time $t=0$, the initial water contents are:

$$\theta(x, z, 0) = g(x, z) \quad (3-18)$$

where $g(x, z)$ is the known volumetric water content at all points in the x - z plane.

3.5 RUNOFF

Conservation of mass requires that the change in water level (h) with time, equals the sum of the negative of the change of flow rate with distance and difference of rainfall and infiltration. This can be expressed as [(Brass, 1990; Chow et al., 1988; and

Hillel, 1980), Figure 3-3):

$$\frac{\partial H}{\partial t} + \alpha \frac{\partial H^m}{\partial s} = \bar{q} \quad (3-19)$$

where,

$$\bar{q} = p - f$$

H = depth of runoff (L),

$$\alpha = 1.49S^{1/2}/n$$

s = slope,

n = roughness coefficient,

p = rainfall rate (L/T),

f = infiltration rate (L/T), and

$$m = 1.67.$$

When capillary forces are dominant, the infiltration equation can be expressed as (Haverkamp et al., 1987):

$$I(t) = S_0(t)^{\frac{1}{2}} \quad (3-20)$$

From which:

$$\text{Infiltration rate, } f = \frac{dI}{dt} = \frac{S_0}{2} (t)^{-\frac{1}{2}} \quad (3-21)$$

where,

I(t) = cumulative infiltration per unit surface,

Figure 3-3. Runoff along an Inclined Surface.

S_0 = sorptivity, reflecting the capacity of soil to absorb water by simple capillary forces, and
 t = time.

Adjustment in the value of S_0 for changing boundary condition has been made by the expression developed by Philip (1969):

$$S_0 = \left\{ 2K_s (\theta_s - \theta_i) (H - h_f) \right\}^{\frac{1}{2}} \quad (3-22)$$

where,

K_s = hydraulic conductivity at saturation (L/T),

θ_s = moisture content at saturation (vol/vol),

θ_i = initial moisture content (vol/vol),

H = depth of water at the soil surface (L), and

h_f = the pressure value defining wetting front, which is constant in space and time (L).

Yu-Si (1987) defined h_f as the capillary head $-h_c$ at the wetting front in the expression for sorptivity S_0 . Thus, equation (3-22) can be written as:

$$S_0 = \left\{ 2K_s (\theta_s - \theta_i) (H + h_c) \right\}^{\frac{1}{2}} \quad (3-23)$$

This equation for sorptivity is used to compute the rate of infiltration along the upper boundary of the landfill. Value of sorptivity from equation (3-23) is used in equation (3-21) at different time steps to compute the infiltration rate. The infiltration rate is subtracted from the rainfall rate (as shown in equation 3-19), which is called the rainfall excess and this is the source term for the kinematic wave equation (3-19). In the kinematic wave equation (3-19), the right hand side, i.e. rainfall excess, is known and the value of the depth of runoff is computed at different positions on the landfill surface considering the slope and surface roughness. The equation is solved by using the stable numerical scheme explained on pages 3-28 to 3-30.

3.6 SNOWMELT

If the mean daily temperature is below 32°F, the precipitation is stored on the surface as snow. When the temperature exceeds 32°F, snow continues to melt and contributes to the infiltration and/or runoff. The amount of snowmelt is added to the rainfall for use in equation (3-19). The amount of snowmelt for no rain is computed as (Viessman et al., 1977):

$$M = K' (1-F) (0.004 I_d) (1-A) + E (0.0084 V) \{ 0.22 (T_s - 32) + (0.78 (T_d - 32)) \} + 0.029 F (T - 32) \quad (3-24)$$

where,

M = melt, inches/day,

K' = melting coefficient, $0.9 < K' < 1.1$

F = forest cover factor,

I_s = solar radiation, langley's/day,

A = albedo (reflection coefficient),

E = exposure coefficient $0.3 < K < 1.0$,

V = wind velocity (mph),

T_a = air temperature °F, and

T_d = dew point temperature °F.

If there is rain on snow, the equation for snowmelt is (Wanielista, 1990):

$$M = 0.09 + (0.029 + 0.084 EV + 0.007P)(T_a - 32) \quad (3-25)$$

where,

V = wind velocity (mph),

P = rainfall (inches per day), and

T_a = air temperature, °F.

3.7 GOVERNING EQUATION IN THE SATURATED ZONE

The leachate head at the bottom of the landfill develops due to the leachate input from the unsaturated zone to the mound. The

hydraulics of the leachate mound at the bottom of the landfill has been studied by Korfiatis et al. (1984), Schroeder et al. (1984) and Demetracopoulos (1988). The submodel to compute the leachate head can be formulated by performing a liquid balance on a control volume in the saturated zone as shown in Figure 3-4. According to Darcy's Law, the lateral drainage in the saturated zone for an inclined bottom can be written as (Bear, 1972):

$$q_d = -K_s h \frac{\partial z}{\partial x} \quad (3-26)$$

where,

K_s = saturated hydraulic conductivity (L/T),

h = saturated thickness of the landfill section (L), and

z = elevation of water table from a reference datum (L).

Figure 3-4 shows that:

$$z = h + b$$

$$\text{or, } z = h + x \tan \gamma$$

From which:

$$\frac{\partial z}{\partial x} = \frac{\partial h}{\partial x} + \tan \gamma$$

Therefore, the lateral drainage can be written as:

Figure 3-4. Saturated Flow at the Bottom of a Landfill.

$$q_d = -K_s h \left[\frac{\partial h}{\partial x} + \tan \gamma \right] \quad (3-27)$$

Assuming a fully saturated bottom liner, the leakage rate can be expressed as (Korfiatis and Demetracopoulos, 1986):

$$q_l = K_c \left(\frac{h + d}{d} \right) \quad (3-28)$$

where,

K_c = saturated hydraulic conductivity of the clay liner (L/T),

and

d = thickness of clay at the bottom of the landfill (L).

The mass conservation principle states that the sum of all flow rates into the control volume must equal the rate of volume change in the control volume. This yields (Korfiatis and Demetracopoulos, 1986):

$$-\frac{\partial q_d}{\partial x} + N_l - K_c \left(\frac{h + d}{d} \right) = n_e \frac{\partial h}{\partial t} \quad (3-29)$$

where,

N_l = leachate accretion onto the drainage layer (L/T),

n_e = effective porosity of the solid waste material,

The leachate accretion is expressed as (Korfiatis et al., 1984):

$$N_l = K(\theta) - D(\theta) \frac{\partial \theta}{\partial z} \quad (3-30)$$

Substituting equation (3-27) into equation (3-29):

$$\frac{\partial}{\partial x} \left[K_s h \left(\frac{\partial h}{\partial x} + \tan \gamma \right) \right] + N_1 - K_c \left(\frac{h + d}{d} \right) = n_e \frac{\partial h}{\partial t} \quad (3-31)$$

Equation (3-31) is solved to obtain the leachate head at the bottom of the landfill which is used to compute lateral and vertical flow of leachate from the landfill to the perimeter or collection system.

3.8 FINITE-DIFFERENCE FORMULATION OF THE GOVERNING EQUATIONS

The governing partial differential equations incorporated into the two-dimensional leachate flow model, represents runoff at the upper boundary, moisture flow in the unsaturated zone along with the boundary conditions, and movement of leachate at the bottom of the landfill. All these equations are discretized using the finite-difference technique to obtain a system of algebraic equations for simultaneous solution of the dependent variables by numerical methods. Application of the finite-difference techniques is described for each of the governing partial differential equations in the following sections.

3.8.1 Unsaturated Moisture-Flow Equation

In the finite difference method, the unsaturated moisture-flow equation (3-11) is discretized in x-z-t space. The horizontal and vertical lines in x- and z-directions are divided into segments of lengths of Δx and Δz respectively. These constitute rectangular nodal areas in the vertical plane having a nodal point at the centroid of the rectangles as shown in Figure 3-5. The time is divided into intervals of duration Δt . An implicit finite-difference scheme was employed by Demetracopoulos et al. (1986) to discretize the one-dimensional unsaturated moisture flow equation. In the present model, the same concept of the finite-difference scheme is used to discretize the two-dimensional unsaturated moisture flow equation (3-11). According to Figure 3-5, discretization of equation (3-11) for the (i,j)th grid point yields:

$$\begin{aligned} \frac{\theta_{1,j}^{k+1} - \theta_{1,j}^k}{\Delta t} = & \frac{1}{(\Delta x)^2} \left[D_{1+\frac{1}{2},j} \left(\theta_{1+1,j} - \theta_{1,j} \right) - D_{1-\frac{1}{2},j} \left(\theta_{1,j} - \theta_{1-1,j} \right) \right] \\ & + \frac{1}{(\Delta z)^2} \left[D_{1,j+\frac{1}{2}} \left(\theta_{1,j+1} - \theta_{1,j} \right) - D_{1,j-\frac{1}{2}} \left(\theta_{1,j} - \theta_{1,j-1} \right) \right] \\ & - \frac{1}{\Delta z} \left(K_{1,j+\frac{1}{2}} - K_{1,j-\frac{1}{2}} \right) \end{aligned} \quad (3-32)$$

Figure 3-5. Schematic Representation of a Landfill Section.

where,

k = initial time level, and

$k+1$ = forward time level.

The diffusivity $D(\theta)$, and hydraulic conductivity $K(\theta)$ in the right-hand side of equation (3-32) are functions of the moisture content θ . By evaluating $D(\theta)$ and $K(\theta)$ at the forward time level and defining moisture content θ also at the forward-time level, the implicit finite-difference equation is obtained as follows:

$$\begin{aligned} \frac{\theta_{1,j}^{k+1} - \theta_{1,j}^k}{\Delta t} = & \frac{1}{(\Delta x)^2} \left[D_{1+\frac{1}{2},j}^{k+1} \left(\theta_{1+1,j}^{k+1} - \theta_{1,j}^{k+1} \right) - D_{1-\frac{1}{2},j}^{k+1} \left(\theta_{1,j}^{k+1} - \theta_{1-1,j}^{k+1} \right) \right] \\ & + \frac{1}{(\Delta z)^2} \left[D_{1,j+\frac{1}{2}}^{k+1} \left(\theta_{1,j+1}^{k+1} - \theta_{1,j}^{k+1} \right) - D_{1,j-\frac{1}{2}}^{k+1} \left(\theta_{1,j}^{k+1} - \theta_{1,j-1}^{k+1} \right) \right] \\ & - \frac{1}{\Delta z} \left(K_{1,j+\frac{1}{2}}^{k+1} - K_{1,j-\frac{1}{2}}^{k+1} \right) \end{aligned} \quad (3-33)$$

This system of algebraic equations can be solved by the successive application of the Gauss-Seidel iteration method. In the successive application of the iteration method, the coefficients are first computed using the moisture values of the previous time step, the system is solved for one iteration and the new moisture

values are used to update the coefficients. This iteration procedure is continued until two consecutive sets of moisture values agree within a prescribed tolerance criterion.

3.8.2 Boundary Conditions

The upper boundary of the landfill includes negligible slope at the top and steep slope along the sides. The upper boundary condition for the boundaries at the top and at the side slope for unsaturated moisture flow condition can be described by mathematical expression and then a finite-difference technique can be applied to get a system of algebraic equations to compute moisture values at the surface.

The upper boundary conditions are defined by considering the flow of moisture from the boundary node (i,j) to the adjacent nodes $(i+1,j)$ and $(i,j+1)$ in both the horizontal and vertical directions respectively as shown in Figure 3-6.

Equation (3-5) can be written as:

$$-\frac{\partial q}{\partial x} - \frac{\partial q}{\partial z} = \frac{\partial \theta}{\partial t} \quad (3-34)$$

Moisture flow in x-direction (q_x) can be written as:

$$q_x = -D(\theta) \frac{\partial \theta}{\partial x} \quad (3-35)$$

Figure 3-6. Boundary Nodes along the Upper Surface of a Landfill.

where,

$$D(\theta) = -K(\theta) \frac{\partial \psi}{\partial \theta}$$

ψ = suction head,

$D(\theta)$ = diffusivity (L^2/T)

Equation (3-34) can be written for the boundary node (1,j) as:

$$-\frac{q_{1+1,j} - q_{1,j}}{\Delta x} - \frac{q_{1,j+1} - q_{1,j}}{\Delta z} = \frac{\theta_{1,j}^{k+1} - \theta_{1,j}^k}{\Delta t} \quad (3-36)$$

where,

$q_{1,j}$ = rainfall rate - evapotranspiration rate

- runoff rate

From equation (3-35) the finite-difference expression $q_{1+1,j}$ can be written as:

$$q_{1+1,j} = -D_{1+\frac{1}{2},j} \left(\frac{\theta_{1+1,j} - \theta_{1,j}}{\Delta x} \right) \quad (3-37)$$

From equation (3-1):

$$q_z = K_z(\theta) - D(\theta) \frac{\partial \theta}{\partial z} \quad (3-38a)$$

From which:

$$q_{1,j+1} = -D_{1,j+\frac{1}{2}} \left(\frac{\theta_{1,j+1} - \theta_{1,j}}{\Delta z} \right) + K_{1,j+\frac{1}{2}} \quad (3-38b)$$

Substituting (3-37) and (3-38b) in (3-36), the implicit finite-difference expression is obtained as:

$$\begin{aligned}
 -\frac{\theta_{1,j}^{k+1} - \theta_{1,j}^k}{\Delta t} = & -\frac{1}{\Delta z} \left[-D_{1,j+\frac{1}{2}}^{k+1} \left(\frac{\theta_{1,j+1}^{k+1} - \theta_{1,j}^{k+1}}{\Delta z} \right) + K_{1,j+\frac{1}{2}}^{k+1} \right] + \frac{q_{1,j}^{k+1}}{\Delta z} \\
 & -\frac{1}{\Delta x} \left[-D_{1+\frac{1}{2},j}^{k+1} \left(\frac{\theta_{1+1,j}^{k+1} - \theta_{1,j}^{k+1}}{\Delta x} \right) \right] + \frac{q_{1,j}^{k+1}}{\Delta x}
 \end{aligned} \tag{3-39}$$

The implicit expression (3-39) is solved to obtain the moisture content along the upper boundary which depends on precipitation less evapotranspiration and runoff. For the lower boundary, the moisture flux is considered zero (Korfiatis et al., 1984):

$$\frac{\partial \theta}{\partial z} = 0 \tag{3-40a}$$

Using the forward difference technique, equation (3-40a) can be written as:

$$\frac{\theta_{1,j+1}^{k+1} - \theta_{1,j}^{k+1}}{\Delta z} = 0 \tag{3-40b}$$

This expression (3-40b) is solved for the moisture content at the lower boundary nodes.

3.8.3 Runoff Equation

The overland flow equation or the kinematic wave equation (3-19) is transformed into a system of algebraic expressions using an explicit finite-difference scheme. The finite-difference scheme is explained for two-dimensional grid in x-t plane as shown in Figure 3-7.

The finite-difference analogy to equation (3-19) can be expressed as (Bras, 1990):

$$\frac{\Delta H}{\Delta t} + \alpha \frac{\Delta H^m}{\Delta x} = \bar{q} \quad (3-41)$$

Different finite-difference expressions yield different numerical schemes associated with their own stability and convergence criteria. Bras (1990) developed the implicit scheme associated with its own stability criteria. This implicit expression with respect to Figure 3-7 is:

$$\frac{H_1^{k+1} - H_1^k}{\Delta t} + \frac{\alpha}{\Delta x} \left[\left(H_{1+1}^{k+1} \right)^m - \left(H_1^{k+1} \right)^m \right] = \bar{q} \quad (3-42)$$

The unknown variable h_{i+1}^{j+1} is then obtained as follows:

$$H_{1+1}^{k+1} = \left[\frac{\bar{q} \Delta x}{\alpha} - \frac{H_1^{k+1} \Delta x}{\alpha \Delta t} + \left(H_1^{k+1} \right)^m + \frac{H_1^k \Delta x}{\alpha \Delta t} \right]^{1/m} \quad (3-43)$$

This implicit expression (3-43) is consistent but it is stable for

Figure 3-7. Finite-difference Scheme for the Kinematic Wave Equation.

a certain condition. Bras (1990) established the stability criterion for the convergence as:

$$\alpha \frac{\Delta t}{\Delta x} m h^{m-1} \geq 1 \quad (3-44)$$

The solution procedure at each segment consists of solving for the depth of flow (h) at time t and then advancing the solution to forward time level t + Δt considering the values of h at the previous time level t as the initial condition.

3.8.4 Saturated Leachate Flow Equation

Finite-difference expression for the saturated flow equation (3-31) can be obtained by discretizing it in the finite-difference grid as shown in Figure 3-8. The transformed finite-difference equation can be written as:

$$\begin{aligned} \frac{1}{(\Delta x)^2} \left[T_{i+1/2} (h_{i+1} - h_i) - T_{i-1/2} (h_i - h_{i-1}) \right] - K_{s1} \tan \gamma_i \left(\frac{h_{i+1} - h_{i-1}}{2\Delta x} \right) + N_{11} \\ - K_{c1} \left(\frac{h_i + d_i}{d_i} \right) = n_{e1} \left(\frac{h_i^{k+1} - h_i^k}{\Delta t} \right) \end{aligned} \quad (3-45)$$

This system of finite-difference equations can be solved simultaneously for each grid point by evaluating all the dependent variables at the forward time level, k+1. Therefore, the implicit expression for the equation (3-45) can be written as:

Figure 3-8. Finite-difference Scheme for the Saturated Leachate Flow Equation.

1.0

1.1

1.25

1.4

1.6

4.5

5.0

5.6

6.3

7.1

8.0

9.0

10

11.2

12.5

14

16

18

20

22.5

25

28

32

36

40

45

50

56

6.3

7.1

8.0

9.0

10

11.2

12.5

14

16

18

20

22.5

25

28

32

36

40

45

50

56

6.3

7.1

8.0

9.0

10

11.2

12.5

14

16

18

20

22.5

25

28

32

36

40

45

50

56

6.3

2.8

3.2

3.6

4.0

4.5

5.0

5.6

6.3

7.1

8.0

9.0

10

11.2

12.5

14

16

18

20

22.5

25

28

32

36

40

45

50

56

6.3

7.1

8.0

9.0

10

3 of 5

$$\begin{aligned}
& \frac{1}{(\Delta x)^2} \left[T_{i+\frac{1}{2}}^{k+1} \left(h_{i+1}^{k+1} - h_i^{k+1} \right) - T_{i-\frac{1}{2}}^{k+1} \left(h_i^{k+1} - h_{i-1}^{k+1} \right) \right] - K_{s1} \tan \gamma_1 \left(\frac{h_{i+1}^{k+1} - h_{i-1}^{k+1}}{2\Delta x} \right) \\
& + N_{li} - K_{cl} \left(\frac{h_i^{k+1} + d_i}{d_i} \right) = n_{el} \left(\frac{h_i^{k+1} - h_i^k}{\Delta t} \right)
\end{aligned} \tag{3-46}$$

The leachate accretion N_u is computed by substituting moisture values in equation (3-30) which helps build up leachate mound head. The values of leachate mound head h at each grid point are the only unknowns in equation (3-46) and are solved simultaneously at each time step.

3.8.5 Numerical Solution

The system of finite-difference equations derived from the partial differential equations (3-11) and (3-31) can be solved by a process of successive application of the Gauss-Seidel iteration method. To solve the system of algebraic equations for moisture content in the unsaturated zone, the relaxation scheme (Thomas, 1973) of the Gauss-Seidel iteration method is used. The values of the moisture content θ are assumed and the improved values are then calculated with the known initial and boundary conditions. A residual flow is caused by the discrepancy between the exact solution and approximate values of the moisture content. This is gradually diminished by the process of relaxation and more accurate values of moisture content are obtained.

From equation (3-33) the residual value can be expressed as:

$$\begin{aligned}
 \text{RES}_{1,j} = & -\frac{1}{\Delta t} \left(\theta_{1,j}^{k+1} - \theta_{1,j}^k \right) + \frac{1}{(\Delta x)^2} \left[D_{1+\frac{1}{2},j}^{k+1} \left(\theta_{1+1,j}^{k+1} - \theta_{1,j}^{k+1} \right) \right. \\
 & - D_{1-\frac{1}{2},j}^{k+1} \left(\theta_{1,j}^{k+1} - \theta_{1-1,j}^{k+1} \right) \left. \right] + \frac{1}{(\Delta z)^2} \left[D_{1,j+\frac{1}{2}}^{k+1} \left(\theta_{1,j+1}^{k+1} \right. \right. \\
 & \left. \left. - \theta_{1,j}^{k+1} \right) - D_{1,j-\frac{1}{2}}^{k+1} \left(\theta_{1,j}^{k+1} - \theta_{1,j-1}^{k+1} \right) \right] - \frac{1}{\Delta z} \left(K_{1,j+\frac{1}{2}}^{k+1} - K_{1,j-\frac{1}{2}}^{k+1} \right) \quad (3-47)
 \end{aligned}$$

Adding $\Delta \theta_{1,j}^{k+1}$ to $\theta_{1,j}^{k+1}$ in equation (3.33):

$$\begin{aligned}
 \frac{\theta_{1,j}^{k+1} + \Delta \theta_{1,j}^{k+1} - \theta_{1,j}^k}{\Delta t} = & \frac{1}{(\Delta x)^2} \left[D_{1+\frac{1}{2},j}^{k+1} \left(\theta_{1+1,j}^{k+1} - \theta_{1,j}^{k+1} - \Delta \theta_{1,j}^{k+1} \right) \right. \\
 & - D_{1-\frac{1}{2},j}^{k+1} \left(\theta_{1,j}^{k+1} + \Delta \theta_{1,j}^{k+1} - \theta_{1-1,j}^{k+1} \right) \left. \right] \\
 & + \frac{1}{(\Delta z)^2} \left[D_{1,j+\frac{1}{2}}^{k+1} \left(\theta_{1,j+1}^{k+1} - \theta_{1,j}^{k+1} - \Delta \theta_{1,j}^{k+1} \right) \right. \\
 & - D_{1,j-\frac{1}{2}}^{k+1} \left(\theta_{1,j}^{k+1} + \Delta \theta_{1,j}^{k+1} - \theta_{1,j-1}^{k+1} \right) \left. \right] \\
 & - \frac{1}{\Delta z} \left(K_{1,j+\frac{1}{2}}^{k+1} - K_{1,j-\frac{1}{2}}^{k+1} \right) \quad (3-48)
 \end{aligned}$$

From which:

$$\Delta\theta_{1,j}^{k+1} = \frac{\text{RES}_{1,j}}{\frac{1}{\Delta t} + \frac{1}{(\Delta x)^2} \left(D_{1+\frac{1}{2},j}^{k+1} + D_{1-\frac{1}{2},j}^{k+1} \right) + \frac{1}{(\Delta z)^2} \left(D_{1,j+\frac{1}{2}}^{k+1} + D_{1,j-\frac{1}{2}}^{k+1} \right)} \quad (3-49)$$

The coefficient of residual is termed relaxation coefficient. Therefore,

$$\text{RELAX}_{1,j} = \frac{1.0}{\frac{1}{\Delta t} + \frac{1}{(\Delta x)^2} \left(D_{1+\frac{1}{2},j}^{k+1} + D_{1-\frac{1}{2},j}^{k+1} \right) + \frac{1}{(\Delta z)^2} \left(D_{1,j+\frac{1}{2}}^{k+1} + D_{1,j-\frac{1}{2}}^{k+1} \right)} \quad (3-50)$$

Thus, the moisture content at point (1,j) for the new time step $t = k + 1$, is:

$$\theta_{1,j}(\text{new}) = \theta_{1,j}(\text{old}) + \Delta\theta_{1,j}(\text{new}) \quad (3-51)$$

which is:

$$\theta_{1,j}(\text{new}) = \theta_{1,j}(\text{old}) + \text{RELAX}_{1,j} * \text{RES}_{1,j} \quad (3-52)$$

The coefficients are first computed using the moisture values of the previous time step to get the new moisture values which are again used to update the coefficients. Successive application of this iteration technique is continued until two consecutive sets of values agree within a prescribed tolerance criterion. The same technique is applied to solve the implicit finite-difference

expression (3-46) to compute the leachate mound head at the bottom of a landfill.

3.9 FIELD APPLICATION

The FILL model was applied to Section 1/9 and 6/7 of Fresh Kills landfill to estimate the leachate flow rates in these sections. The characteristics of the landfill matrix (porosity, field capacity, wilting point, and hydraulic conductivity) and local climatological data were used to estimate the leachate flow rates in Sections 1/9 and 6/7. The climatological data (temperature and solar radiation) were used to compute evapotranspiration and snowmelt. These data were obtained from the HELP model (Schroeder et al., 1988). Values of leaf-area index and winter-cover factor were also obtained from the default values of the HELP model. Soil data (porosity, field capacity, and wilting point) were also obtained from the default values of the HELP model. Hydraulic conductivity for solid waste in Section 6/7 of Fresh Kills landfill was 0.02 cm/sec using the recovery test conducted by Wehran (1983). This value of hydraulic conductivity is used in the model to compute moisture content and leachate flow in Section 6/7. A six-inch daily cover is placed on top the solid wastes with an average hydraulic conductivity value of 10^{-4} cm/sec. The landfill upper boundary has the daily cover with the aforementioned hydraulic conductivity. Due to the lack of data for the initial soil water

content, the model was run by considering the field capacity the initial condition.

The FILL model was applied to Section 1/9 for the data collected by CCNY-DOS in 1989. However, for Section 6/7, the model was applied for data collected by Wehran (1983) and data collected by CCNY-DOS in 1989. The hydraulic conductivity for Section 1/9 was estimated using leachate mound-head data and flow rates in the existing collection pipe along the perimeter of the landfill Section 1/9. The hydraulic conductivity value of 0.00176 cm/sec (4.98 ft./day) was estimated for Section 1/9 and was used in the application of the FILL model. The information to run the model for Section 1/9 and 6/7 is summarized in Tables 3-1a and 3-1b.

Using the data Wehran collected in 1983, the new model was applied to Section 6/7 as shown in Figure 3-9. An average vertical Section for the area in landfill Section 6/7 was obtained from the exploratory boring data collected by Wehran (1983). This vertical section was schematized into the network of nodal areas shown in Figure 3-10. There are a total of 77 grid points into which the information about hydraulic conductivity, initial moisture content, and the lengths of intervals in x (horizontal) and z (vertical) directions are given.

Similarly with the new data collected by CCNY-NYCDOS, new average vertical sections for Sections 1/9 as shown in Figure 3-11 and 6/7

TABLE 3-1a

DATA REQUIRED FOR THE FILL MODEL
IN SECTION 1/9

Area	405 acres
Waste thickness:	
Wehran (1983)	35.67
CCNY-NYCDOS (1989)	72.0 ft.
Hydraulic conductivity:	
Daily cover	0.0001 cm/sec. (0.2835 ft./day)
Waste inside the landfill	
Wehran (1983)	0.0036 cm/sec (10.2 ft./day)
CCNY-NYCDOS (1989)	0.00176 cm/sec (4.98 ft./day)
Bottom clay	0.0000001 cm/sec. (0.00028 ft./day)
Porosity:	
Waste	0.457 vol/vol
Bottom clay	0.43 vol/vol
Field capacity:	
Waste	0.0835 vol/vol
Bottom clay	0.3667 vol/vol
Wilting point:	
Waste	0.0327 vol/vol
Bottom clay	0.2804 vol/vol
Campbell's parameter	4.0

TABLE 3-1b

DATA REQUIRED FOR THE FILL MODEL
IN SECTION 6/7

Area	376 acres.
Waste thickness:	
Wehran (1983)	21ft.
CCNY-NYCDOS (1989)	51 ft.
Hydraulic conductivity:	
Daily cover	0.0001 cm/sec. (0.2835 ft./day)
Waste inside the landfill	0.02 cm/sec. (56.67 ft./day)
Bottom clay	0.0000001 cm/sec. (0.000283 ft./day)
Porosity:	
Waste	0.417 vol/vol
Bottom clay	0.2804 vol/vol
Field capacity:	
Waste	0.0454 vol/vol
Bottom clay	0.2804 vol/vol
Wilting point:	
Waste	0.02 vol/vol
Bottom clay	0.2804 vol/vol

Figure 3-9. Fresh Kills Section 6/7.

Figure 3-10. An Average Vertical Section of 6/7
for the Field Data in 1983.

Figure 3-11. Fresh Kills Section 1/9.

were obtained as illustrated in Figures 3-12a and 3-12b respectively. In this case, for the vertical section in Figure 3-12a of Section 1/9, a total of 128 grid points are drawn to schematize the vertical section. For the recent data, the vertical section for Section 6/7 was drawn with a total of 64 grid points as shown in Figure 3-12b.

3.10 MODEL RESULTS

The model results were obtained for Section 6/7 by running the model for the data Wehran collected in 1983. The model was applied for the average and peak rainfall years to Section 6/7 for the data in 1983. The monthly variation of precipitation, runoff, evapotranspiration, and net infiltration for the average and peak rainfall-years is shown in Figures 3-13a and 3-13b. The variation of total monthly volume of lateral flow in cu. ft./ft. of width of the landfill is shown in Figure 3-14. The variation of total monthly volume of vertical flow in cu.ft./(unit area, sq. ft.) is shown in Figure 3-15.

The variation of average daily lateral flow (in mgd) for the average and peak rainfall years is shown in Figures 3-16a and 3-16b. The variation of average daily vertical flow for the average and peak rainfall years is shown in Figure 3-17. The total leachate flow is the sum of the lateral and vertical flows in the

Figure 3-12a. Schematic Representation of the Vertical Section for Section 1/9 for the Field Data in 1989.

Figure 3-12b. Schematic Representation of the Vertical Section for Section 6/7 for the Field Data in 1989.

Figure 3-13a. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1983 for the Average Rainfall Year.

Figure 3-13b. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1983 for the Peak Rainfall Year.

Figure 3-14. Variation of Lateral Flow (cu. ft./ft of width) in Section 6/7 using the Field Data in 1983.

Figure 3-15. Variation of Vertical Flow (cu. ft./unit area, sq. ft.) in Section 6/7 using the Field Data in 1983.

Figure 3-16a. Variation of Average Daily Lateral Flow in Section 6/7 using the Field Data in 1983 for the Average Rainfall Year.

Figure 3-16b. Variation of Average Daily Lateral Flow in Section 6/7 using the Field Data in 1983 for the Peak Rainfall Year.

Figure 3-17. Variation of Average Daily Vertical Flow in Section 6/7 using the Field Data in 1983.

landfill. The variation of total daily flow with time, as obtained by the FILL model in Section 6/7 for the data in 1983 is shown in Figures 3-18a and 3-18b. The leachate flow rates for the lateral, vertical and total flow in Section 6/7 for the data in 1983 are shown in Table 3-2.

The daily values of precipitation, runoff, evapotranspiration, and leachate production rates for Section 6/7 are shown in Table 3-3. The model results for the peak and minimum flows in Section 6/7 for the data in 1983 are shown in Table 3-4.

The model was applied to Sections 1/9 and 6/7 with recent data collected by CCNY-NYCDOS in 1989. The monthly variation of precipitation, runoff, evapotranspiration, and net infiltration for Sections 1/9 and 6/7 is shown in Figures 3-19a and 3-19b for Section 1/9 and 3-20a and 3-20b for Section 6/7. The monthly values of lateral flow in cu. ft./ft. of the width of the landfill for Sections 1/9 and 6/7 are shown in Figures 3-21 and 3-22 respectively. The variations of the daily values of lateral flow (in million gallons) with time are shown in Figures 3-23 and 3-24 for Sections 1/9 and 6/7 respectively. The variation of vertical flow in cu. ft./(unit area, sq. ft.) for Sections 1/9 and 6/7 are shown in Figures 3-25 and 3-26 respectively.

The variation of daily vertical flow in million gallons is shown in Figure 3-27 and 3-28 in Sections 1/9 and 6/7 respectively. The

Figure 3-18a. Variation of Daily Total Flow in Section 6/7 using the Field Data in 1983 for the Average Rainfall Year.

Figure 3-18b. Variation of Daily Total Flow in Section 6/7 using the Field Data in 1983 for the Peak Rainfall Year.

TABLE 3-2
LEACHATE FLOW RATES IN SECTION 6/7
FOR THE DATA IN 1983

Rainfall year	Lateral flow (mgd)	Vertical flow (mgd)	Total flow (mgd)
Average rainfall year	0.325	0.044	0.369
Peak rainfall year	0.385	0.049	0.434

TABLE 3-3

**AVERAGE DAILY VALUES OF PRECIPITATION,
RUNOFF, EVAPOTRANSPIRATION, AND LEACHATE
PRODUCTION FOR THE MODEL RUN IN SECTION
6/7 WITH THE DATA IN 1983**

Rainfall year	Precipi- tation (mgd)	Runoff (mgd)	Evapotrans- piration (mgd)	Leachate Production (mgd)
Average rainfall	1.22	0.665	0.421	0.271
Peak rainfall	1.436	0.813	0.420	0.363

TABLE 3-4
PEAK AND MINIMUM FLOW RATES
IN 1983 IN SECTION 6/7

Rainfall year	Peak Flow (mgd)	Minimum Flow (mgd)
Average rainfall	0.419	0.285
Peak rainfall	0.668	0.334

Figure 3-19a. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1989 for the Average Rainfall Year.

Figure 3-19b. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 1/9 using the Field Data in 1989 for the Peak Rainfall Year.

Figure 3-20a. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1989 for the Average Rainfall Year.

Figure 3-20b. Variation of Precipitation, Runoff, Evapotranspiration, and Net Infiltration in Section 6/7 using the Field Data in 1989 for the Peak Rainfall Year.

Figure 3-21. Variation of Lateral Flow (cu. ft./ft of width) in Section 1/9 using the Field Data in 1989.

Figure 3-22. Variation of Lateral Flow (cu. ft./ft of width) in Section 6/7 using the Field Data in 1989.

Figure 3-23. Variation of Average Daily Lateral Flow in Section 1/9 using the Field Data in 1989.

Figure 3-24. Variation of Average Daily Lateral Flow in Section 6/7 using the Field Data in 1989.

Figure 3-25. Variation of Vertical Flow (cu. ft./unit area, sq. ft.) in Section 1/9 using the Field Data in 1989.

Figure 3-26. Variation of Vertical Flow (cu. ft./unit area, sq. ft.) in Section 6/7 using the Field Data in 1989.

Figure 3-27. Variation of Average Daily Vertical Flow in Section 1/9 using the Field Data in 1989.

Figure 3-28. Variation of Average Daily Vertical Flow in Section 6/7 using the Field Data in 1989.

total flow is the sum of the lateral and the vertical flows in mgd and the variation of total flow with time for Section 1/9 and 6/7 is shown in Figures 3-29 and 3-30 respectively. The average daily lateral, vertical, and total flow for Sections 1/9 and 6/7 is shown in Table 3-5. The daily values of precipitation, runoff, evapotranspiration, and leachate production in million gallons for Sections 1/9 and 6/7 are shown in Table 3-6. The peak and minimum flow rates for Sections 1/9 and 6/7 due to the recent data are shown in Table 3-7. Tables 3-8a to 3-8f and 3-9a to 3-9f show the variation of leachate mound inside the landfill for Sections 1/9 and 6/7 respectively.

3.10.1 Analysis of Results in Section 6/7 for the Data in 1983

In the FILL model results, the surface runoff is higher than the evapotranspiration as shown in Figures 3-13a and 3-13b for most of the computational period. Based on the hourly values, the runoff submodel runs for 24 hours a day when the temperature is above freezing (32°F) and when there is rainfall and/or snowmelt at the landfill surface. Figure 3-13a shows that the maximum runoff value of 4.53 inches occurs during August for the average rainfall-year. The precipitation in this period was 6.83 inches. For the peak rainfall-year, a total monthly maximum value of 4.54 inches of runoff occurs during November as shown in Figure 3-13b. The precipitation in that month was 6.97 inches. The total annual runoff of 23.76 inches and 29.24 inches occurs during the average

Figure 3-29. Variation of Daily Total Flow in Section 1/9 using the Field Data in 1989.

Figure 3-30. Variation of Daily Total Flow in Section 6/7 using the Field Data in 1989.

TABLE 3-5

**LEACHATE FLOW COMPONENTS COMPUTED BY
THE FILL MODEL USING DATA COLLECTED
BY CCNY-NYCDOS IN 1989**

Section	Lateral Flow (mgd)		Vertical Flow (mgd)		Total Flow (mgd)	
	Average rainfall	Peak rainfall	Average rainfall	Peak rainfall	Average rainfall	Peak rainfall
1/9	0.4207	0.4327	0.1045	0.1053	0.5252	0.5380
6/7	0.4256	0.4359	0.049	0.049	0.4746	0.4849

TABLE 3-6

**AVERAGE DAILY VALUES OF PRECIPITATION,
RUNOFF, EVAPOTRANSPIRATION, AND LEACHATE
PRODUCTION FOR THE MODEL RUN WITH 1989 DATA**

Flow parameter	Flow components in mgd			
	Section 1/9		Section 6/7	
	Average rainfall	Peak rainfall	Average rainfall	Peak rainfall
Precipitation	1.314	1.55	1.220	1.436
Runoff	0.71	0.881	0.643	0.802
Evapotranspiration	0.455	0.451	0.422	0.418
Leachate Production	0.293	0.377	0.283	0.371

TABLE 3-7

**PEAK AND MINIMUM FLOW FOR THE DATA
COLLECTED BY CCNY-NYCDOS IN 1989**

	Leachate flow rates (mgd)			
	Section 1/9		Section 6/7	
	Peak flow	Minimum flow	Peak flow	Minimum flow
Rainfall year				
Average rainfall	0.443	0.391	0.622	0.266
Peak rainfall	0.447	0.411	0.622	0.302

TABLE 3-8a

LEACHATE MOUND-HEAD IN SECTION 1/9
AT THE START OF THE AVERAGE RAINFALL YEAR

Barrier	*Column no.	Depth of mound (ft)
1	1	4.01
1	2	7.77
1	3	11.10
1	4	15.55
1	5	20.00
1	6	23.63
1	7	26.81
1	8	30.63
1	9	32.28
1	10	33.84
1	11	32.30
1	12	31.49
1	13	29.98
1	14	26.36
1	15	23.60
1	16	20.55
1	17	18.08
1	18	15.01
1	19	11.52
1	20	7.14
1	21	3.79

* Refer to Figure 3-12a for column no.

TABLE 3-8b

LEACHATE MOUND-HEAD IN SECTION 1/9
AT THE MIDDLE OF THE AVERAGE RAINFALL YEAR

Barrier	*Column no.	Depth of mound (ft)
1	1	8.60
1	2	12.50
1	3	15.73
1	4	18.53
1	5	21.05
1	6	23.22
1	7	25.09
1	8	26.48
1	9	27.41
1	10	27.99
1	11	28.27
1	12	28.22
1	13	27.64
1	14	26.04
1	15	24.13
1	16	21.97
1	17	19.54
1	18	16.77
1	19	13.56
1	20	9.39
1	21	0.00

* Refer to Figure 3-12a for column no.

TABLE 3-8c

LEACHATE MOUND-HEAD IN SECTION 1/9
AT THE END OF THE AVERAGE RAINFALL YEAR

Barrier	*Column no.	Depth of mound (ft)
1	1	8.66
1	2	13.05
1	3	16.11
1	4	18.57
1	5	20.66
1	6	22.42
1	7	23.91
1	8	24.98
1	9	25.70
1	10	26.16
1	11	26.39
1	12	26.38
1	13	25.97
1	14	24.73
1	15	23.20
1	16	21.43
1	17	19.37
1	18	16.97
1	19	14.10
1	20	10.16
1	21	0.00

* Refer to Figure 3-12a for column no.

TABLE 3-8d

LEACHATE MOUND-HEAD IN SECTION 1/9
AT THE START OF THE PEAK RAINFALL YEAR

Barrier	*Column no.	Depth of mound (ft)
1	1	4.01
1	2	7.77
1	3	11.10
1	4	15.55
1	5	20.00
1	6	23.63
1	7	26.81
1	8	30.63
1	9	32.28
1	10	33.84
1	11	32.30
1	12	31.49
1	13	29.98
1	14	26.36
1	15	23.60
1	16	20.55
1	17	18.08
1	18	15.01
1	19	11.52
1	20	7.14
1	21	3.79

* Refer to Figure 3-12a for column no.

TABLE 3-8e

LEACHATE MOUND-HEAD IN SECTION 1/9
AT THE MIDDLE OF THE PEAK RAINFALL YEAR

Barrier	*Column no.	Depth of mound (ft)
1	1	8.66
1	2	12.72
1	3	15.97
1	4	18.78
1	5	21.30
1	6	23.47
1	7	25.34
1	8	26.73
1	9	27.67
1	10	28.25
1	11	28.52
1	12	26.48
1	13	27.89
1	14	26.29
1	15	24.38
1	16	22.22
1	17	19.78
1	18	17.01
1	19	13.79
1	20	9.59
1	21	0.00

* Refer to Figure 3-12a for column no.

TABLE 3-8f

**LEACHATE MOUND-HEAD IN SECTION 1/9
AT THE END OF THE PEAK RAINFALL YEAR**

Barrier	*Column no.	Depth of mound (ft)
1	1	8.66
1	2	13.84
1	3	17.17
1	4	19.79
1	5	21.96
1	6	23.77
1	7	25.31
1	8	26.41
1	9	27.14
1	10	27.60
1	11	27.83
1	12	27.81
1	13	27.38
1	14	26.14
1	15	24.59
1	16	22.79
1	17	20.68
1	18	18.23
1	19	15.26
1	20	11.14
1	21	0.00

*** Refer to Figure 3-12a for column no.**

TABLE 3-9a

**LEACHATE MOUND-HEAD IN SECTION 6/7
AT THE START OF THE AVERAGE RAINFALL YEAR**

Barrier	*Column no.	Depth of mound (ft)
1	1	0.75
1	2	2.44
1	3	4.63
1	4	5.57
1	5	7.17
1	6	8.95
1	7	9.48
1	8	9.79
1	9	7.89
1	10	6.34
1	11	4.73
1	12	3.17
1	13	1.68
1	14	0.54

* Refer to Figure 3-12b for column no.

TABLE 3-9b

**LEACHATE MOUND-HEAD IN SECTION 6/7
AT THE MIDDLE OF THE AVERAGE RAINFALL YEAR**

Barrier	*Column no.	Depth of mound (ft)
1	1	0.76
1	2	3.06
1	3	4.23
1	4	5.10
1	5	5.77
1	6	6.09
1	7	6.16
1	8	6.14
1	9	6.04
1	10	5.72
1	11	5.13
1	12	4.39
1	13	3.27
1	14	0.00

* Refer to Figure 3-12b for column no.

TABLE 3-9c

**LEACHATE MOUND-HEAD IN SECTION 6/7
AT THE END OF THE AVERAGE RAINFALL YEAR**

Barrier	*Column no.	Depth of mound (ft)
1	1	0.53
1	2	2.47
1	3	3.42
1	4	4.13
1	5	4.67
1	6	4.91
1	7	4.96
1	8	4.95
1	9	4.88
1	10	4.65
1	11	4.19
1	12	3.62
1	13	2.74
1	14	0.00

* Refer to Figure 3-12b for column no.

TABLE 3-9d

LEACHATE MOUND-HEAD IN SECTION 6/7
AT THE START OF THE PEAK RAINFALL YEAR

Barrier	*Column no.	Depth of mound (ft)
1	1	0.75
1	2	2.44
1	3	4.63
1	4	5.57
1	5	7.17
1	6	8.95
1	7	9.48
1	8	9.79
1	9	7.89
1	10	6.34
1	11	4.73
1	12	3.17
1	13	1.68
1	14	0.54

* Refer to Figure 3-12b for column no.

TABLE 3-9e

**LEACHATE MOUND-HEAD IN SECTION 6/7
AT THE MIDDLE OF THE PEAK RAINFALL YEAR**

Barrier	*Column no.	Depth of mound (ft)
1	1	0.77
1	2	3.08
1	3	4.25
1	4	5.13
1	5	5.79
1	6	6.11
1	7	6.19
1	8	6.16
1	9	6.06
1	10	5.75
1	11	5.15
1	12	4.41
1	13	3.29
1	14	0.00

* Refer to Figure 3-12b for column no.

TABLE 3-9f

LEACHATE MOUND-HEAD ON SECTION 6/7
AT THE END OF THE PEAK RAINFALL YEAR.

Barrier	*Column no.	Depth of mound (ft)
1	1	0.35
1	2	2.97
1	3	4.00
1	4	4.75
1	5	5.32
1	6	5.58
1	7	5.64
1	8	5.62
1	9	5.55
1	10	5.31
1	11	4.81
1	12	4.16
1	13	3.16
1	14	0.00

* Refer to Figure 3-12b for column no.

and peak rainfall-years which are about 54.5 percent and 56.69 percent respectively of the annual precipitation values.

The evapotranspiration submodel computes the daily values of evaporation and transpiration using the Modified Penman method (Ritchie, 1972). In this case, evapotranspiration depends on runoff, infiltration and moisture content of the soil. The high values of runoff make less amount of water available for soil evaporation. The net effect is the low values of evapotranspiration in the prediction of the FILL model results. It is observed in Figures 3-13a and 3-13b that the maximum evapotranspiration occurs during July and August. The total annual evapotranspiration of 15.07 inches and 15.0 inches occur in the case of the FILL model during the average and peak rainfall years respectively.

The net infiltration is the precipitation less evapotranspiration and runoff. The total annual net infiltration of 9.72 inches and 12.98 inches which are 22.29 percent and 25.28 percent of the total annual rainfall occur during the average and peak rainfall-years respectively.

The outflows from the saturated zone are the vertical flow through the clay at the bottom of the landfill and the lateral flow towards the perimeter or the collection system. The variation of average daily lateral, vertical, and total flow in different months is

plotted and shown in Figures 3-16a, 3-16b, 3-17, 3-18a and 3-18b. For the average rainfall-year, the lateral flow computed by the FILL model is 0.325 mgd as shown in Table 3-2. For the peak rainfall year, the lateral flow of 0.385 mgd is obtained by the FILL model as shown in Table 3-2. The highest lateral flow of 0.382 mgd and 0.589 mgd occurs during December for the average and peak rainfall years as shown in Figures 3-16a and 3-16b respectively.

The vertical component of leachate flow is small compared to the lateral flow. For the average rainfall-year, 0.044 mgd percolates through the clay at the bottom of the landfill as shown in Table 3-2. In the peak rainfall year, the vertical flow is 0.049 mgd as shown in Table 3-2, which indicates an increase of 11.36 percent due to a 17.75 percent increase in the precipitation. The total flow of 0.369 mgd and 0.434 mgd as shown in Table 3-2 occurs during the average and peak rainfall-years, indicating an increase of 17.62 percent due to 17.75 percent increase in the precipitation. The increase in total flow due to increase in rainfall from the average rainfall-year to peak rainfall-year is consistent.

3.10.2 Analysis of Results In Section 1/9 For The Data In 1989

The variation of precipitation, runoff and evapotranspiration as shown in Figures 3-19a and 3-19b indicates that the surface runoff is high which occurs because the side slope allows more water to

flow on the landfill surface as surface runoff. The maximum runoff value of 5.22 inches occurs during September due to 6.78 inches of rainfall in the average rainfall-year as shown in Figure 3-19a. The minimum runoff value of 0.18 inches occurs due to 1.75 inches of rainfall in January during the average rainfall-year as shown in Figure 3-19a. The total annual runoff of 23.56 inches and 29.25 inches occurs during the average and peak rainfall-years respectively.

The evapotranspiration is also an important parameter which contributes to the total losses from precipitation and from soil moisture in a landfill. The highest amount of evapotranspiration occurs during July in both the average and peak rainfall-years as shown in Figures 3-19a and 3-19b. The evapotranspiration mainly depends on the temperature of the model area. The higher temperature values cause the maximum monthly evapotranspiration of 3.06 inches during July in average and peak rainfall-years.

The variation of net infiltration with time is also shown in Figure 3-19a and 3-19b for the average and peak rainfall-years. The total net infiltration of 9.72 inches and 14.96 inches occurs during the average and peak rainfall-years respectively. The net infiltration is 22.29 percent and 29.14 percent of the total precipitation during the average and peak rainfall-years respectively.

The leachate flow rates computed by the FILL model indicates that

the lateral flow rate varies from 0.4429 mgd to 0.3943 mgd as shown in Figure 3-23 for the average rainfall-year. The vertical flow varies from 0.1027 mgd to 0.1059 mgd during the average rainfall-year as shown in Figure 3-27. In the peak rainfall-year the daily lateral flow varies from 0.4436 mgd to 0.413 mgd as shown in Figure 3-23. The vertical flow varies from 0.1039 mgd to 0.1059 mgd, during the peak rainfall-year as shown in Figure 3-27. The total leachate flow increases from 0.5252 mgd to 0.5380 mgd in the average to peak rainfall-year as shown in Table 3-5. Table 3-6 shows that the average leachate production rate is 0.293 mgd and 0.377 mgd during average and peak rainfall-years respectively. The leachate production rate is less than the leachate flow rate which indicates that the decrease in the storage of leachate mound occurs due to higher leachate flow rates rather than the leachate production rates.

3.10.3 Analysis of Results in Section 6/7 for the Data in 1989

The model results for Section 6/7 with the recent data collected by CCNY-NYCDOS indicates that the total annual runoff of 23.0 inches and 28.68 inches occurs during the average and peak rainfall years respectively. The monthly runoff value varies from 0.18 inches to 5.16 inches which occur respectively due to 1.75 inches and 6.78 inches of monthly rainfall in average rainfall-year as shown in Figure 3-20a. For the peak rainfall-year, the monthly runoff value varies from 0.16 inches to 4.63 inches due to the monthly rainfall

value of 0.73 inches and 6.97 inches respectively as shown in Figure 3-20b. The net infiltration is 10.15 inches and 13.28 inches which are 23.28 percent and 25.87 percent of the total precipitation during the average and peak rainfall years respectively. The variation of monthly lateral flow shown in Figure 3-24 indicates that the lateral flow decreases from January to December for average and peak rainfall years. An average lateral flow of 0.4256 mgd and 0.4359 mgd occurs during the average and peak rainfall years respectively as shown in Table 3-5. The average vertical flow of 0.049 mgd remains the same for average and peak rainfall-years. The total flow increases from 0.4746 mgd to 0.4849 mgd for the average to peak rainfall-year. The increase in total flow is due to the increase in precipitation from the average to the peak rainfall-year.

3.10.4 Discussion

The new model results obtained for Section 6/7 using the data in 1983 shows that the average leachate production rates of 0.271 mgd and 0.363 mgd occur during the average and peak rainfall-years respectively as shown in Table 3-3. The leachate production rate occurs due to the net infiltration into the landfill which is considered as the precipitation less evapotranspiration and surface runoff at the upper boundary of the landfill. Table 3-3 shows that an average value of 0.665 mgd of runoff and 0.421 mgd of

evapotranspiration occurs during the average rainfall year in Section 6/7 for the data in 1983. The corresponding values are 0.813 mgd and 0.420 mgd for the peak rainfall year. The runoff is computed by considering hourly rainfall values. The runoff submodel is run for one-hour time intervals 24 hours a day. The runoff submodel is executed when the temperature is above 32°F and when there is precipitation and/or snowmelt on the landfill surface.

In the FILL model, solution of the unsteady saturated flow equation (3-31) generates the time-history of leachate mound-head. From the values of the computed leachate mound-head, the gradient of flow is obtained to compute the variation of lateral and vertical flow with time. The initial condition for the leachate mound-head was defined from the field data collected by Wehran (1983). The initial condition was given as the saturated thickness of six ft. obtained by Wehran (1983) as shown in Table 3-1b. The leachate mound head varies due to the time-varying leachate accretion onto the saturated leachate mound. The variation of leachate mound-head and gradient with respect to time generates a time history of lateral, vertical, and total flow at the bottom of the landfill.

The total flow of 0.369 mgd and 0.434 mgd occur during the average and peak rainfall-years respectively as shown in Table 3-2. The increase in the total flow of 17.62 percent occurs due to a 17.75 percent increase in the rainfall from the average to peak rainfall

year. The variation in result is consistent with the variation in the precipitation which is an input parameter for the model. Comparing the results in Tables 3-2 and 3-3, the total leachate flow rates are higher than the total leachate production rates for both average and peak rainfall-years. The model also estimates the peak and minimum leachate flow during the average and peak rainfall-year. In the average rainfall-year, a peak value of 0.419 mgd and a minimum value of 0.285 mgd occur in the landfill Section 6/7 as described in Table 3-4. The peak and minimum values of leachate flow are 0.668 mgd and 0.334 mgd respectively during the peak rainfall-year in Section 6/7 as described in Table 3-4.

The FILL model results using recent data as shown in Table 3-6 indicates that the runoff occurs at the rate of 0.710 mgd in Section 1/9 during the average rainfall year. Surface runoff is higher than the actual evapotranspiration at the upper boundary. The average daily evapotranspiration in the average rainfall year is 0.455 mgd.

The average leachate production rates in Section 1/9 for the average and peak rainfall years are 0.293 mgd and 0.377 mgd respectively as shown in Table 3-6. The average leachate production rates in Section 6/7 are 0.283 mgd and 0.371 mgd for the average and peak rainfall years respectively as shown in Table 3-6. Comparing the results in Tables 3-5 and 3-6, the leachate flow rates are higher than the leachate production rates in Sections 1/9

and 6/7 for the average and peak rainfall years. For the average rainfall year, the total leachate flow rates in Sections 1/9 and 6/7 are 0.5252 mgd and 0.4746 mgd respectively as shown in Table 3-5. The total leachate flow rates in Sections 1/9 and 6/7 are 0.5422 mgd and 0.4849 mgd respectively for the peak rainfall year as shown in Table 3-5. The peak and minimum values of leachate flow rates as shown in Table 3-7, indicates that leachate flow rates vary from 0.391 mgd to 0.443 mgd in the average rainfall year for Section 1/9. The peak and minimum leachate flow rates in Section 1/9 for the peak rainfall year are 0.447 mgd and 0.411 mgd respectively. For Section 6/7, the leachate flow rate varies from a minimum of 0.266 mgd to a peak of 0.622 mgd during the average rainfall-year. The leachate flow rates vary from a minimum of 0.302 mgd to a peak 0.622 mgd in the peak rainfall-year in Section 6/7. These results for the peak and minimum flow rates represent the unsteady variation of leachate flow rates in a landfill.

For Fresh Kills landfill Section 6/7, the leachate mound head increases from six ft. in 1983 to 9.67 ft. in 1989 as shown in Figure 2-12b. Due to the variation of leachate mound-head and waste thickness in Section 6/7, the total leachate flow rate increases from 0.369 mgd in 1983 to 0.4746 mgd in 1989 for the average rainfall condition as shown in Tables 3-2 and 3-5. Similarly, for the peak rainfall condition the leachate flow rate increases from 0.434 mgd to 0.4849 mgd for the change in field conditions from 1983 to 1989 as shown in Tables 3-2 and 3-5.

4 - LEACHATE MONITORING

4.1 INTRODUCTION

The data on leachate mound gradients around Fresh Kills landfill Sections 1/9 and 6/7 were obtained by measuring leachate heads in piezometers and wells. These data support the analysis of hydraulic properties and flow rates in both sections. Piezometers and wells installed near the collection line in Section 1/9 help establish the gradients to make a refined estimate of the hydraulic conductivity of Section 1/9. From the leachate mound-head contours and the flow gradients, different sections of the mound that contribute to the flow were identified. Finally, the leachate flow rates were computed using Darcy's Law.

4.2 PROCEDURES

The field equipment used to obtain leachate mound head readings at all monitoring wells and piezometers included : stainless steel water level measuring tape (100 ft.); chalk; and a field notebook. The procedures used to measure leachate mound levels were:

Leachate mound heads were measured from the top of the inner

riser pipe of all wells and piezometers using the wetted tape method;

Leachate heads were recorded to the nearest 0.01 feet; and

All measurements in a section were taken in one day.

4.3 WELLS AND PIEZOMETERS

There were 10 wells in each of the Sections 1/9 and 6/7 that were installed along the perimeter of the landfill. There were fifteen piezometers (including cluster piezometers) in Section 1/9 and nine piezometers (including cluster piezometers) in Section 6/7. The wells were located above wetlands and screened in the refuse. The piezometers were paired with the wells about 200 to 500 feet upgradient. These wells and piezometers met all the leachate mound head data requirements to estimate leachate flow in both sections. The location of the piezometers and wells in Sections 1/9 and 6/7 is shown in Figures 4-1a and 4-1b. The leachate mound-head data collected from the wells and piezometers and the installation details are given in Appendix B.

4.4 LEACHATE MOUND-HEAD CONTOURS

Leachate mound-heads in Sections 1/9 and 6/7 were represented by contours drawn from head data collected from the piezometers and

Figure 4-1a. Location of Piezometers and Wells in Section 1/9.

Figure 4-1b. Location of Piezometers and Wells in Section 6/7.

wells. The leachate mound-head data were collected from October 1989 to April 1990, when a total of five sets of data were collected. The leachate mound-head contours for Sections 1/9 and 6/7 using the first data set are shown in Figures 4-2a and 4-2b respectively.

The leachate mound-head contours for Section 1/9 are drawn with a contour interval of five ft. The maximum iso-leachate mound-head line is 35.0 ft. In Section 1/9, the leachate mound-head with the highest mound elevation of 35.0 ft. covers a large part of the landfill area. Another mound covering a small portion of Section 1/9 is in the landfill area surrounded by Fresh Kill and West Shore Expressway as shown in Figure 4-2a. These mounds contribute to the leachate flow from Section 1/9 in the lateral and vertical directions.

The head-contour interval for Section 6/7 is one ft. In this section, a single mound is observed as shown in Figure 4-2b. The maximum head in the leachate mound in this section is 10.0 ft. The highest leachate mound-head in Section 6/7 (≈ 35 ft) is considerably less than the highest leachate mound-head in Section 1/9 (≈ 10 ft). This could be due to less waste thickness in Section 6/7 compared to Section 1/9.

The contours of leachate mound-heads provide a means of obtaining a refined estimate of the hydraulic conductivity in Section 1/9 and

Figure 4-2a. Leachate Mound-Head Contours in Section 1/9 for the Data Collected in October, 1989.

Figure 4-2b. Leachate Mound-Head Contours in Section 6/7 for the Data Collected in October, 1989.

an estimate of flow gradients that are used to compute the leachate flow rates in Sections 1/9 and 6/7.

4.5 DETERMINATION OF HYDRAULIC CONDUCTIVITY

The collection system for Section 1/9 is along West Shore Expressway in Veterans Ave. Two pump stations are incorporated with the collection line as shown in Figure 4-2a. Pump station A collects leachate from line A which is 1485 ft. long. This station pumps leachate at the rate of 44,300 gpd (Source: NYCDOS). Pump station B collects leachate at the rate of 84,000 gpd (Source: NYCDOS) from lines B and C, which are respectively 1950 ft. and 900 ft. long respectively. The total length of the collection lines is 4335 ft.

The head contours in Section 1/9 show the variation in gradients in the landfill. Based on the differences in gradients, the leachate mound is divided into subsections. Mound subsections 1, 2, 4, 5, and 6 are contributing flow to the collection line as shown in Figure 4-3. The average gradients for these subsections were computed from the contours and are listed in Appendix C. The average gradients for mound subsections 1, 2, 4, 5, and 6 are 0.0218, 0.0219, 0.1191, 0.0581, and 0.0297 respectively. With these values of flow gradients and the total flow rate in the collection line, Darcy's Law was used to compute the hydraulic

Figure 4-3. Mound Subsections in Section 1/9 Contributing to the Leachate Flow.

conductivity of the refuse in landfill Section 1/9. The detailed calculation is given in Appendix D. The hydraulic conductivity computed from the gradients of flow and the collection rate in landfill Section 1/9 is 4.98 ft/day (0.00176 cm/sec). The previous value determined from in-situ permeability tests (Wehran, 1983) is 10.2 ft/day (3.6×10^{-1} cm/sec). The recent hydraulic conductivity estimate of 4.98 ft/day is based on observed flow rates in the collection system. For this reason the recent hydraulic conductivity estimate of 4.98 ft/day is probably more representative of existing conditions in landfill Section 1/9.

4.6 LEACHATE FLOW RATES

The leachate flow rates were computed from the monitoring well and piezometer head data which were contoured to define the shape of the mound inside the landfill. Based on the leachate mound-head contours, the gradients of flow lines were used in Darcy's Law to compute lateral flows. The steps in the computation of leachate flow rates are:

Leachate mound heads were obtained by subtracting the depth of the leachate level in wells and piezometers from the elevation of the top of the PVC pipe;

Head contours were drawn for Sections 1/9 and 6/7 from the

leachate mound-head data from the piezometers and monitoring wells;

The contoured leachate mounds were divided into subsections, depending on the mound geometry and variations of leachate head as shown in Figures 4-3 and 4-4;

The average gradients, depths, and widths of flow for each of the mound subsections was obtained; and

Darcy's Law was used to compute lateral flows by substituting these values of gradients, depth of flow, and width. In addition, an average depth of leachate was computed for Sections 1/9 and 6/7, which was used to compute the vertical flow through the clay layer at the bottom of the landfill.

The detailed computations for lateral and vertical flow for Sections 1/9 and 6/7 are shown in Appendix E. The calculated lateral flow, vertical flow and total flow for the two sections are listed in Table 4-1.

Figure 4-4. Mound Subsections in Section 6/7 Contributing to the Leachate Flow.

TABLE 4-1

LEACHATE FLOW RATES CALCULATED FROM FIELD DATA

Section	Lateral Flow (mgd)	Vertical Flow (mgd)	Total Flow (mgd)
1/9	0.439	0.090	0.529
6/7	0.426	0.047	0.473

5 - COMPARISON OF RESULTS

One of the main objectives of the present study was to estimate the leachate flow rates in Sections 1/9 and 6/7 of Fresh Kills landfill. In order to achieve that objective, the existing methodologies and available data were studied. Available data for leachate flow estimate of Sections 1/9 and 6/7 include previous field investigation for leachate mound and in-situ permeability tests. The existing methodologies for leachate flow estimate include direct application of Darcy's law after identifying leachate mound in the field, application of water balance method and application of models that predict the leachate flow by representing the leachate flow process inside the landfill.

Estimating leachate by the direct application of Darcy's law and water-balance method are based on simple approaches. Direct application of Darcy's Law gives a value of leachate flow rate that does not represent the changes due to the time-varying boundary conditions and unsteady behavior of leachate flow rates. The water-balance method does not consider the movement of leachate inside the landfill. Therefore, the process of leachate retention, accumulation, and accretion is ignored in the computation made by the water-balance method. Previous studies for estimating leachate flow in Sections 1/9 and 6/7 were made by directly applying of

Darcy's Law and water-balance method. By Darcy's Law, an estimate of 0.577 mgd and 0.416 mgd were made for Sections 1/9 and 6/7 respectively as shown in Table 5-1. Application of the water-balance method shows an estimate of leachate flow of 0.897 mgd and 0.431 mgd for Sections 1/9 and 6/7 respectively as shown in Table 5-1. Since the water-balance method does not consider the direction of leachate flow inside the landfill, the results obtained using this method do not indicate the lateral and vertical flow component of the landfill leachate flow.

To use Darcy's Law, the lateral and vertical hydraulic gradients were obtained by plotting the potentiometric contours of the leachate mound-head. Lateral hydraulic gradients for Sections 1/9 and 6/7 were 0.0167 ft/ft and 0.00522 ft/ft respectively (Wehran, 1983). Using hydraulic gradient, saturated thickness, and the value of the hydraulic conductivity, the lateral flow for Section 1/9 and 6/7 was computed at 0.521 mgd and 0.410 mgd respectively as shown in Table 5-1. Similarly, the vertical flow through the bottom clay was also computed for Sections 1/9 and 6/7. The vertical flow of 0.056 mgd and 0.006 mgd was obtained for Sections 1/9 and 6/7 respectively as shown in Table 5-1. It appears that the total flow in Section 6/7 computed using Darcy's Law and the water-balance method is similar. The total flow computed by the water-balance method in Section 1/9 differs significantly from the values obtained by applying Darcy's Law. The total flow in Section 1/9 increases by about 55.5 percent in the water-balance method

TABLE 5-1

**LEACHATE FLOW RATES BY DARCY'S LAW, WATER-BALANCE METHOD
AND HELP FOR 1983 DATA**

Section	Leachate Flow (mgd)						
	Darcy's Law			Water Balance Method	HELP (average rainfall)		
	Lateral Flow	Vertical Flow	Total Flow	Total Flow	Lateral Flow	Vertical Flow	Total Flow
1/9	0.521	0.056	0.577	0.897	0.50	0.10	0.60
6/7	0.410	0.006	0.416	0.431	0.365	0.043	0.408

with respect to the flow computed by Darcy's Law. In the water-balance method, no information about the saturated thickness and hydraulic conductivity was used. But in the case of the application of Darcy's Law, information about lateral and vertical hydraulic gradients, saturated thickness, and hydraulic conductivity value from in-situ recovery test data was used that indicates that landfill leachate flow conditions were better represented than the water-balance method. Therefore, the results obtained by applying Darcy's Law using the subsurface information of the landfill must be more credible than the results obtained using the water-balance method.

The HELP model was applied to compute the leachate flow in Sections 1/9 and 6/7 of Fresh Kills landfill for the data in 1983. The lateral flow computed for Sections 1/9 and 6/7 indicates close agreement with the values computed by Darcy's Law as shown in Table 5-1. In Table 5-1 the vertical flow value computed by the HELP model in Section 1/9 differs by about 78 percent compared to the value computed by Darcy's Law. A significant variation is also observed in the case of the vertical flow values for Section 6/7. The total flow of leachate computed by Darcy's Law (0.416 mgd), water balance method (0.431 mgd), and HELP model (0.408 mgd) are very close to each other in the case of the results for Section 6/7. The total flow for Section 1/9 computed by Darcy's Law, water-balance method and the HELP model are 0.577 mgd, 0.897 mgd, and 0.60 mgd respectively. The value of the total flow computed by

the HELP model for Section 1/9 differs by 5.2 percent compared to the value computed by Darcy's Law. Darcy's Law was applied for a certain field condition without any simulation for the variation of the moisture flow due to the changing boundary conditions (boundary conditions depend on rainfall, temperature, evapotranspiration, runoff, and net infiltration). However, the HELP model considers the complex process of one-dimensional (vertical direction only) moisture routing in the unsaturated zone by considering the input as the precipitation less runoff and surface water evaporation. Also, the lateral flow due to the leachate head is computed by considering steady state solution of the Boussinesq equation. These analyses of flow components lead to represent the field behavior more accurately than previous studies made by the application of Darcy's Law and water-balance method.

The FILL model was applied to Section 6/7 to estimate the leachate flow rates for the data in 1983. The leachate flow rates for Section 6/7 that were computed for the data in 1983 by the HELP and FILL model are shown in Table 5-2. For the average rainfall-year, the lateral flow computed by the HELP and FILL model are 0.365 mgd and 0.325 mgd respectively as shown in Table 5-2. A difference of about 0.040 mgd is observed in the results between the HELP and FILL model. For the peak rainfall-year, the lateral flow of 0.406 mgd and 0.385 mgd respectively was obtained by the HELP and FILL model as shown in Table 5-2. The lateral leachate flow computed by the HELP is higher by 0.021 mgd than the value computed by the FILL

TABLE 5-2

**LEACHATE FLOW RATES BY HELP AND FILL MODEL
IN SECTION 6/7 FOR 1983 DATA**

Rainfall year	Leachate flow (mgd)					
	HELP Model			FILL Model		
	Lateral Flow	Vertical Flow	Total Flow	Lateral Flow	Vertical Flow	Total Flow
Average rainfall year	0.365	0.043	0.408	0.325	0.044	0.369
Peak rainfall year	0.406	0.044	0.450	0.385	0.049	0.434

model in the peak rainfall-year. The average vertical flow values of 0.043 mgd and 0.044 mgd are computed by the HELP and FILL model respectively for the average rainfall-year as shown in Table 5-2.

To study the present field condition in Sections 1/9 and 6/7, leachate mound elevation data were collected from the piezometers and wells installed in those sections. From the boring data, the present refuse thickness at different locations in Section 1/9 and 6/7 was obtained. The HELP and FILL models were applied for the present field condition to estimate the variation of leachate flow rates during the average and peak rainfall years. The leachate flow rates computed by the HELP and FILL model for the present field condition at Sections 1/9 and 6/7 are summarized in Tables 5-3 and 5-4 respectively. The results computed by the HELP and FILL models differ significantly for the leachate flow computed for the present field conditions in Sections 1/9 and 6/7. The total leachate flow computed by the FILL model is less by 0.117 mgd than that computed by the HELP model. Variations are also observed for the lateral and vertical leachate flow rates in both the average and peak rainfall-years. The HELP model results show the same leachate flow rates in the average and peak rainfall-years. However, leachate flow rates vary in the case of the results computed by the FILL model for the average and peak rainfall years. The leachate flow rates computed by the HELP and FILL model for Section 6/7 also show significant differences as shown in Table 5-4. The total flow computed by the HELP model is higher by 0.178

TABLE 5-3

LEACHATE FLOW RATES BY HELP AND FILL MODEL
IN SECTION 1/9 FOR THE DATA IN 1989

Rainfall year	Leachate Flow (mgd)					
	HELP Model			FILL Model		
	Lateral Flow	Vertical Flow	Total Flow	Lateral Flow	Vertical Flow	Total Flow
Average rainfall year	0.5101	0.1318	0.6419	0.4207	0.1045	0.5252
Peak rainfall year	0.5101	0.1318	0.6419	0.4327	0.1053	0.5380

TABLE 5-4

LEACHATE FLOW RATES BY HELP AND FILL MODEL
IN SECTION 6/7 FOR THE DATA IN 1989

Rainfall year	Leachate Flow (mgd)					
	HELP Model			FILL Model		
	Lateral Flow	Vertical Flow	Total Flow	Lateral Flow	Vertical Flow	Total Flow
Average rainfall year	0.6057	0.0473	0.653	0.4256	0.049	0.4746
Peak rainfall year	0.6103	0.0473	0.6576	0.4359	0.049	0.4849

mgd than that computed by the FILL model. The lateral leachate flow component differs significantly. However, the vertical flow component computed by the HELP and FILL model does not differ significantly as shown in Table 5-4. The vertical flow computed by the HELP model is 0.0473 mgd; that computed by the FILL model is 0.049 mgd.

The difference in results between the HELP and FILL model is due to the use of different approaches for computing runoff, leachate accretion in the unsaturated zone, and flow components (lateral and vertical flow) in the saturated zone of the landfill. As the FILL model considers the effect of the slope of the landfill surface, it gives a better estimate of surface runoff. Also, the model considers the two-dimensional variation of moisture movement in the unsteady state flow condition. All these considerations give a better representation of the field condition than the HELP model which is based on one-dimensional moisture routing. The variation of leachate mound head is strictly unsteady due to the changes in the leachate accretion on the saturated leachate mound. The FILL model considers the unsteady state condition for the computation of leachate mound head to generate lateral flow of leachate from the landfill. But the HELP model considers a steady state solution for lateral flow. Therefore, the results obtained by the FILL model are more realistic than those obtained by the HELP model.

From the monitoring data, contours of leachate mound head were

drawn for Sections 1/9 and 6/7. The leachate mounds were identified from the iso-elevation lines of leachate head inside the landfill. From the variation of leachate heads inside the landfill, the hydraulic gradients for different flow sections were obtained as explained in Section 4. Application of Darcy's Law for the leachate mound obtained from the leachate monitoring data gives the estimate of leachate flow rates for the existing field condition. A summary of the average flow rates computed by the HELP and FILL models and the leachate flow rates computed for the existing field condition from the leachate monitoring data appears in Table 5-5. Estimates differ for both the lateral and vertical flow components obtained by the HELP, FILL, and leachate monitoring for Section 1/9. The average lateral flow computed by the HELP, FILL, and leachate monitoring data are 0.5101 mgd, 0.4207 mgd, and 0.459 mgd respectively for Section 1/9. The vertical flow component of leachate computed by the HELP, FILL, and monitoring data are 0.1318 mgd, 0.1045 mgd, and 0.09 mgd respectively for Section 1/9. The leachate flow rates computed by the FILL model and monitoring data vary significantly compared to those computed by the HELP model for Section 6/7. The lateral flow for Section 6/7 computed by the HELP, FILL, and monitoring data is 0.6057 mgd, 0.4256 mgd, and 0.426 mgd respectively. The vertical flow computed by the HELP, FILL, and leachate monitoring data for Section 6/7 is 0.0473 mgd, 0.049 mgd, and 0.047 mgd respectively. The total flow computed by the FILL model and leachate monitoring data for Section 6/7 is 0.4746 mgd and 0.473 mgd respectively. The average leachate

TABLE 5-5

**COMPARISON OF AVERAGE LEACHATE FLOW RATES COMPUTED BY
HELP, FILL, AND LEACHATE MONITORING DATA**

Sec.	Leachate Flow (mgd)								
	Lateral Flow			Vertical Flow			Total Flow		
	HELP Model	FILL Model	Field Data	HELP Model	FILL Model	Field Data	HELP Model	FILL Model	Field Data
1/9	0.5101	0.4207	0.439	0.1318	0.1045	0.09	0.6419	0.5252	0.529
6/7	0.6057	0.4256	0.426	0.0473	0.049	0.047	0.653	0.4746	0.473

flow rates computed by the FILL model and leachate monitoring data in the field are similar to each other. However, the total leachate flow estimate by the HELP model is significantly higher than the estimate by the FILL model and leachate monitoring data in Section 6/7. The total leachate flow estimate by the HELP model is 0.653 mgd for Section 6/7 which is higher by 0.180 mgd than the estimate from the leachate monitoring data.

6 - SIDE SLOPE MODELING

6.1 INTRODUCTION

The infiltration fraction of rainfall is the only contributor to leachate generation. The final cover at the top of the landfill is used to control the infiltration fraction of rainfall that tends to percolate through the barrier and ultimately reach the mound carrying dissolved or suspended materials from the waste. The final cover for the landfill includes a clay cap plus an intermediate drainage layer and a top layer of soil for vegetation. According to 6 NYCRR part 360-2.13 (q), and 360-2.15 (a), a low permeability (10^{-7} cm/sec) barrier soil cover having a minimum compacted thickness of 18 inches along with the barrier protection layer of soil not less than 24 inches thick, must be used. The top layer of soil overlying the barrier layer protects the soil barrier layer from dissociation cracking, frost action, root penetration, and erosion along the top and side slope of the landfill. The final cover for a landfill can also be conceptualized by considering the clay as the barrier layer plus an intermediate drainage layer and a top layer of soil for vegetation. In this study, a collection system for the infiltration fraction of precipitation is investigated by considering different thicknesses and hydraulic conductivities of the top drainage layer and barrier soil layer. The collection system is considered along the

perimeter at the end of the different stages of side slopes in the landfill. The landfill final-cover hydraulics are shown in Figure 6-1.

The input at the boundary of the closed landfill or at the top of the final cover is precipitation less runoff and evapotranspiration. Not all the infiltration water passes through the cover. Some infiltration water is lost through evapotranspiration. The input at the top of the final cover determines the variation in moisture content inside the landfill and recharge rate on the mound. Therefore, to estimate the net infiltration from the precipitation, it is important to determine runoff and evapotranspiration accurately. Along the landfill side slope, the inclination of the landfill surface affects surface runoff. The kinematic wave equation (Chow et al., 1988) is used to compute runoff considering the effect of slope and surface roughness. The quantity of precipitation less evapotranspiration and surface runoff or net infiltration is given as input at the boundary, and using this boundary condition, moisture flow rates onto the drainage layer are obtained by solving the unsaturated moisture flow equation in two dimensions (Demetracopoulos et, al., 1986). The moisture flow rate to the drainage layer is used as the source term in the Boussinesq equation (Demetracopoulos, 1988) to compute flow rate into the proposed collection system from the drainage layer in an unsteady state condition as shown in Figure 6-1.

Figure 6-1. Landfill Final-Cover Hydraulics.

The modeling to represent the final-cover hydraulics will help determine the quantity of infiltration water intercepted by the collection system before percolating through the waste to become part of leachate flow. Different scenarios, depending on different values of thickness and hydraulic conductivity of the cover soil and barrier layer, would be investigated. The values of hydraulic conductivity and the thickness of the layered final cover will be determined, to ensure maximum interception of infiltration fraction of precipitation by the proposed collection system and minimum percolation (based on 94.4 percent efficiency of barrier layer, specified in part 360, six NYCRR, Solid Waste Management Facilities) through the soil barrier into the waste inside the landfill.

6.2 GOALS

The final cover at the top of the landfill controls the infiltration fraction of rainfall before it becomes part of leachate flow. The landfill final cover along with the barrier soil layer (hydraulic conductivity 10^{-7} cm/sec) ensures generating the minimum quantity of leachate. In this study, the efficiency of a new collection system to intercept the infiltration fraction of rainfall along the perimeter at the end of the landfill side slope is investigated.

6.3 MODEL COMPONENTS

The model represents the present physical system to estimate leakage rate through the clay layer at the top of the landfill. The flow field for the infiltration that enters the soil cover system at the top of the landfill is illustrated in Figure 6-1. At the upper boundary, direct surface runoff occurs due to the side slope. Surface water evaporation and transpiration are also incorporated into the computational scheme. The input at the upper boundary is precipitation less surface runoff and evapotranspiration. The physical system shown in Figure 6-1 shows that an unsaturated moisture flow condition exists above the saturated water mound that is developed due to moisture accretion on the bottom clay layer. The unsaturated moisture flow and the saturated head variations occur in the top soil layer above the barrier. This physical process has been described mathematically along with the boundary conditions in Section 3. It is assumed that the flow through the bottom clay layer is not necessarily saturated. A variably saturated flow in the bottom clay layer is considered. The two-dimensional variably saturated flow equation governing the present physical process is written as (Bear, 1979):

$$C(\psi) \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x} \left[K(\psi) \frac{\partial \psi}{\partial x} \right] + \frac{\partial}{\partial z} \left[K(\psi) \left(\frac{\partial \psi}{\partial z} + 1 \right) \right] \quad (6-1)$$

where,

ψ = pressure head,

$C(\psi)$ = soil water capacity as a function of pressure head, and

$K(\psi)$ = unsaturated hydraulic conductivity as a function of pressure head.

The seepage in the barrier layer is obtained by solving equation (6-1). The upper boundary condition is defined by the ponding depth (h) above the barrier layer. The ponding depth is computed by solving the Boussinesq equation as described in Section 3. At the lower boundary it is assumed that the water movement is governed by the gravitational forces. The capillary fringe effects are unimportant because the groundwater table is located far enough away from the barrier.

Therefore, the lower boundary condition becomes:

$$q = -K(\psi) \quad (6-2)$$

To complete the solution of equation (6-1), the material properties relating K and C must be specified along with the boundary and initial conditions. There are several unsaturated hydraulic conductivity formula suggested by various authors. Gardner (1958) suggested the hydraulic conductivity formulae as a

4 of 5

function of pressure head expressed as:

$$K(\psi) = K_s \left(\frac{a}{b + |\psi|^c} \right) \quad (6-3)$$

where a, b, and c are constants.

The analytical expression for $K(\psi)$ appeared in Haverkamp et. al. (1977) can be written as:

$$K(\psi) = K_s \left(\frac{A}{A + |\psi|^c} \right) \quad (6-4)$$

A and c are constants with the value of 1.175×10^6 and 4.74 respectively for $K_s = 30$ cm/hr. In the present model, the value of c was changed to obtain stable results for the present soil conditions of the barrier layer. The values of c considered for the hydraulic conductivities of 10^{-6} cm/sec, and 10^{-7} cm/sec are 5.0 and 5.53 respectively.

The relationship for soil water capacity that was used by Wright and Miller (1982), has been used in the present model formulation and can be expressed as:

$$C(\psi) = - \left(\theta_s - \theta_o \right) \left(\frac{B}{\psi} \right) \left(\frac{\psi_e}{\psi} \right)^B \quad (6-5)$$

where,

θ_s = porosity,

θ_o = field capacity,

B = empirical coefficient which varies from 1.0 for glass beads to 0.46 for a clay soil (Wright and Miller, 1982),

ψ = pressure head, and

ψ_e = air entry pressure head.

In the present model run, the value of the coefficient B was 1.0 for the barrier layer (Wright and Miller, 1982).

6.4 NUMERICAL SCHEME

The numerical finite-difference technique used to solve equation (6-1) is the implicit scheme defined by Richtmeyer (1957) and was used primarily by Rubin and Steinhardt (1963). Liakopoulos (1965), and Freeze (1969). The solution for ψ at any grid point is obtained for the current time level $t = k+1$ for $i=1,2,\dots, n$ along x-axis and $j= 1,2,\dots,n$ along z-axis. The solution for ψ in the finite-difference grid point (i,j) is $\psi_{i,j}^{k+1}$. With this notation, the system of finite-difference equations for equation (6-1) is:

$$C(\psi_v) \left(\frac{\psi_{i,j}^{k+1} - \psi_{i,j}^k}{\Delta t} \right) = \frac{1}{\Delta x} \left\{ \frac{K(\psi_I)}{2\Delta x} \left(\psi_{i+1,j}^k + \psi_{i+1,j}^{k+1} - \psi_{i,j}^k - \psi_{i,j}^{k+1} \right) \right. \\ \left. - \frac{K(\psi_{II})}{2\Delta x} \left(\psi_{i,j}^k + \psi_{i,j}^{k+1} - \psi_{i-1,j}^k - \psi_{i-1,j}^{k+1} \right) \right\}$$

$$\begin{aligned}
& + \frac{1}{\Delta z} \left\{ K(\psi_{III}) \left[1 + \frac{1}{2\Delta z} \left(\psi_{1,j+1}^k + \psi_{1,j+1}^{k+1} \right. \right. \right. \\
& \quad \left. \left. - \psi_{1,j}^k - \psi_{1,j}^{k+1} \right) \right] - K(\psi_{IV}) \left[1 + \frac{1}{2\Delta z} \left(\psi_{1,j}^k \right. \right. \\
& \quad \left. \left. + \psi_{1,j}^{k+1} - \psi_{1,j-1}^k - \psi_{1,j-1}^{k+1} \right) \right] \right\} \quad (6-6)
\end{aligned}$$

The values of ψ_I , ψ_{II} , ψ_{III} , ψ_{IV} , and ψ_V at a particular time step are determined by the extrapolation from previous time steps as described by Rubin and Steinhardt (1963). These are expressed as:

$$\psi_I = \frac{3}{4} \left(\psi_{1+1,j}^k + \psi_{1,j}^k \right) - \frac{1}{4} \left(\psi_{1+1,j}^{k-1} + \psi_{1,j}^{k-1} \right) \quad (6-7a)$$

$$\psi_{II} = \frac{3}{4} \left(\psi_{1,j}^k + \psi_{1-1,j}^k \right) - \frac{1}{4} \left(\psi_{1,j}^{k-1} + \psi_{1-1,j}^{k-1} \right) \quad (6-7b)$$

$$\psi_{III} = \frac{3}{4} \left(\psi_{1,j+1}^k + \psi_{1,j}^k \right) - \frac{1}{4} \left(\psi_{1,j+1}^{k-1} + \psi_{1,j}^{k-1} \right) \quad (6-7c)$$

$$\psi_{IV} = \frac{3}{4} \left(\psi_{1,j}^k + \psi_{1,j-1}^k \right) - \frac{1}{4} \left(\psi_{1,j}^{k-1} + \psi_{1,j-1}^{k-1} \right) \quad (6-7d)$$

$$\psi_V = \frac{1}{2} \left(\psi_{1,j}^k + \psi_{1,j}^{k-1} \right) \quad (6-7e)$$

The extrapolated values for ψ (ψ_I , ψ_{II} , ψ_{III} , ψ_{IV} , and ψ_V) given above in equations (6-7a) to (6-7e) are used to determine the K and C

values for a particular node at a particular time step. This numerical scheme was also used to describe and solve for the unsaturated moisture flow equation (θ -based) in the top soil.

6.5 MODEL APPLICATION

The present numerical model was used to investigate the efficiency of the landfill cover system along the side slope. The leakage through the barrier layer of the landfill cover was simulated by applying the model, developed for the variably saturated flow condition. A 25-ft. horizontal length of the side slope was considered. A typical finite-difference grid employed to run the model for the landfill side slope is shown in Figure 6-2. The hydraulic conductivity of the top soil was 10^{-4} cm/sec. The leakage rate through the barrier layer was investigated for the hydraulic conductivity of 10^{-6} cm/sec and 10^{-7} cm/sec. Then, the efficiency of the barrier layer was determined as:

$$\text{Efficiency (\%)} = 100 - \frac{Q_L \cdot 100}{P} \quad (6-8)$$

where,

Q_L = total annual leakage through the barrier (L), and

P = total annual precipitation (L).

Figure 6-2. A Typical Finite-difference Grid for Landfill Final Cover.

The model runs were done by NYCDOS using the rainfall data of the average rainfall year collected from NYCDEP to determine the efficiency of landfill cover system for 33 percent and 4 percent side slopes. The total rainfall of the average rainfall year was 43.6 inches. The efficiencies for different side slopes and the hydraulic conductivity of the barrier layer are given in Table 6-1. The efficiency of the cover system varies for the change in the hydraulic conductivity of the barrier layer.

The upper boundary condition for the unsaturated moisture flow equation in the top soil depends on the surface runoff and evapotranspiration. The surface runoff and evapotranspiration computed for the two side slopes are in Table 6-2.

The efficiency of the landfill cover is significantly affected by the hydraulic conductivity of the barrier layer. This has been demonstrated by the model results. The hydraulic conductivity of the barrier layer was changed from 10^{-6} cm/sec to 10^{-7} cm/sec. The efficiency increases from 87.48 percent to 98.9 percent due to the decrease in the hydraulic conductivity value of the barrier layer from 10^{-6} cm/sec to 10^{-7} cm/sec as shown in Table 6-1.

TABLE 6-1

**EFFICIENCY OF LANDFILL COVER FOR DIFFERENT
HYDRAULIC CONDUCTIVITY AND SIDE SLOPE**

Hydraulic conduct. of top soil (cm/sec)	Thickness (inches)		Hydraul. conduct. of the barrier (cm/sec)	Side slope (%)	Efficiency (%)
	Top soil	Barrier			
10-4	30	18	10-7	33	98.90
				4	98.49
			10-6	33	87.48
				4	85.79

TABLE 6-2

**ANNUAL VALUES OF PRECIPITATION, RUNOFF,
AND EVAPOTRANSPIRATION**

Precipitation (inches)	Side slope (%)	Runoff (inches)	Evapotranspiration (inches)
43.6	33	14.49	16.81
	4	9.82	16.00

7 - CONCLUSIONS AND RECOMMENDATIONS

The leachate flow estimates for Fresh Kills landfill Sections 1/9 and 6/7 were made using existing models and a new model (FILL). The previous estimates were compared by applying the models for the field conditions at that time. The simulations indicated that the leachate flow rates were overestimated by the EPA water-balance model which is based on a simple procedure of hydrologic water balance on top the landfill surface. For Section 1/9, total flow of 0.897 mgd was estimated using the EPA water-balance model, whereas an estimate of 0.60 mgd was estimated by applying the HELP model that considers accumulation, retention, and movement of leachate inside the landfill using quasi two-dimensional and a quasi steady state approach. An estimate of 0.431 mgd was made using the EPA water-balance model for Section 6/7. The estimate of total leachate flow for Section 6/7 was 0.408 mgd using the HELP model and 0.369 mgd using the FILL model that is based on a two-dimensional and unsteady state flow approach.

The sensitivity analysis for different input parameters of the HELP model indicated that hydraulic conductivity is the most sensitive parameter for the leachate flow estimate in a landfill. The available data from the previously conducted in-situ recovery test were collected. The hydraulic conductivity values were also

determined from the recently collected field data from the piezometers, monitoring wells, and the collection system. The hydraulic conductivity value for the refuse within Section 1/9 was computed at 4.98 ft/day (0.00176 cm/sec). The previous value, determined from an in-situ permeability test was 10.2 ft/day (0.0036 cm/sec). The present hydraulic conductivity value of 4.98 ft/day, derived from the existing field conditions and based on the measured flow rate from the existing collection system, is believed to be more representative of the existing conditions in the landfill in Section 1/9.

This new value was used in conjunction with present field conditions to simulate the leachate flow rates using the HELP and the FILL model. Also, the new value of hydraulic conductivity was used in conjunction with the monitored leachate head to calculate leachate flow rates using Darcy's Law. Since there is no collection system installed in or around any part of Section 6/7, no refined estimate of the hydraulic conductivity value for this section was made. The hydraulic conductivity value of 56.67 ft/day, was established by the in-situ permeability test and used to compute leachate flow rates in 1983 and in 1990.

Due to the gradual increase in the refuse mound height in Sections 1/9 and 6/7 since 1983, it has been felt that the current variation of leachate mound and the leachate flow rates inside the landfill should be investigated to establish an appropriate leachate

management plan. The field investigation to determine leachate flow rates was accomplished by collecting data from wells and piezometers installed in and around Sections 1/9 and 6/7. The present field conditions such as, leachate mound-heads, refuse thickness, and hydraulic conductivity value was used to run the HELP and the FILL models. The complete leachate monitoring data were also used to estimate the leachate flow rates by applying Darcy's law. The following models were applied to estimate leachate flow rates.

HELP model. The HELP model is a deterministic model that considers the leachate flow process from one layer to another in a landfill profile by considering a quasi two-dimensional and quasi steady state approach. The one-dimensional unsaturated leachate flow is considered only in the vertical direction in an unsteady state flow condition. The lateral flow is computed by an analytical solution of the Boussinesq equation in a steady state flow condition. The surface runoff estimated by the SCS curve number method shows a low value (0.077 inches in Section 1/9) for the default values of curve number used in the model run. The leachate flow rates increase in both Sections for the field conditions from 1983 to 1989. A total leachate flow of 0.6419 mgd and 0.4746 mgd was estimated for Sections 1/9 and 6/7 respectively for the average rainfall-year. The combined leachate flow from Sections 1/9 and 6/7 is 1.2949 mgd and 1.2995 mgd estimated for the average and peak rainfall-years respectively. An overall increase in leachate flow rate is 28.46

percent and 22.94 percent in the average and peak rainfall-years respectively due to the change in the field condition from 1983 to 1989.

FILL model. The FILL model was formulated by considering a two-dimensional unsteady state leachate accretion that contributes to the saturated zone to help build up the leachate mound in a two-dimensional domain of a landfill. In this model, the leachate flow field is represented in a vertical section. The evapotranspiration is considered to occur from the landfill surface at the upper boundary. The kinematic wave equation that considers the effect of landfill side slope and surface roughness is solved to compute the surface runoff. The amount of precipitation less infiltration is the source term for computing the depth of runoff by solving the kinematic wave equation. The infiltration, among other factors, is a function of the hydraulic conductivity of the soil cover and its effect is also considered in the solution for the depth of surface runoff.

An interesting conclusion is obtained by the FILL model results for surface runoff. A significant amount of surface runoff occurs from the landfill surface because of the side slope and less permeable daily soil cover on the operating landfill in Sections 1/9 and 6/7. The total annual runoff of 23.56 inches and 29.25 inches occurs during the average and peak rainfall-years respectively. Comparing the solution by the kinematic wave

equation in the FILL model with the SCS curve number technique in the HELP model, shows the importance of considering the effect of side slope, hydraulic conductivity, and surface roughness to compute surface runoff.

The two-dimensional unsteady state leachate flow model (FILL), indicates a lower value of leachate flow from the leachate mound compared to the values estimated by the HELP model. The total leachate flow for Section 1/9 was estimated at 0.5252 mgd and 0.5422 mgd in the average and peak rainfall-years respectively. The corresponding values estimated for Section 6/7 were 0.4746 mgd and 0.4849 mgd in the average and peak rainfall-years respectively.

Leachate monitoring. The field investigation to determine leachate flow rates collected data from wells and piezometers installed in and around Section 1/9 and 6/7. The contours drawn from the field data were used to obtain a refined estimate of the hydraulic conductivity in Section 1/9 and also to estimate the flow gradients that were used in Darcy's Law to compute the leachate flow rates in Sections 1/9 and 6/7. The total leachate flow was estimated at 0.529 mgd and 0.473 mgd for Sections 1/9 and 6/7 respectively. It should be noted that the leachate flow rate has been decreased from the 1983 value of 0.577 mgd to 0.529 mgd in 1990 for Section 1/9. The decrease in the leachate flow rate is due to a lower value of the hydraulic conductivity, obtained from the field data in Section 1/9. For Section 6/7, the leachate flow rate has

increased by 0.042 mgd in 1990 compared to the 1983 value. This leachate flow rate increase indicates the unsteady characteristics from change in the leachate mound retention, accumulation, and variation of leachate accretion. The temporal variation of these flow processes has not been explained by applying Darcy's Law. However, the application of Darcy's law for the leachate mound, as obtained from more complete field leachate monitoring data should provide a better estimate of leachate flow rate for the existing field conditions.

All the methodologies used to estimate the leachate flow rates have been evaluated and compared with the actual field condition. It was valuable to compare the FILL and HELP model results with the existing information of leachate flow rates obtained by the field investigation from 1989 to 1990. Although comparable results were predicted by the FILL model, yet it is required to fully validate the model for different field conditions. The model is yet to expand so that it includes the moisture movement in the multi-layered soil-cover system on the landfill and through the intermediate barrier layers in a landfill. A large amount of data for the two-dimensional finite-difference grid needs to be stored to run the model. The large amount of data restrict the use in some cases where the domain discretization requires a finer mesh network. The optimization of the array dimensions and user-friendly interaction of the model need to be developed. The major uncertainties in making more accurate simulations are in the

material properties such as the coefficients related to the soil moisture diffusivity $D(\theta)$, soil water capacity $C(\psi)$, and hydraulic conductivity $K(\theta)$. These uncertainties can only be resolved by experimental studies in landfill refuse materials. The experimental studies can also help establish direct analysis and validation of the model results.

REFERENCES

Bear, Jacob, 1979. *Hydraulics of Groundwater*. McGraw-Hill Inc., New York. p. 196.

Bear, Jacob, 1972. *Dynamics of Fluids in Porous Media*. American Elsevier Publishing Company Inc. New York. pp. 368-369.

Bras, Rafael L., 1990. *Hydrology : An Introduction to Hydrologic Science*. Addison-Wesley Publishing Company, Inc., California. pp. 485-488.

Brutsaert, W., 1967. "Some Methods of Calculating Unsaturated Permeability." *Trans. ASCE*, 10, pp. 400-404.

Brooks, R. H. and A. T. Corey, 1964. "Hydraulic Properties of Porous Media." *Hydrology Paper No. 3*. Colorado State University.

Buckingham, E., 1907. "Studies of the Movement of Soil Moisture." *U.S. Dept. Agr. Bureau Soils Bull.*, No. 38.

Bristow Keith L. and John Williams, 1987. Sensitivity of Simulated infiltration to Changes in Soil Hydraulic Properties. In : *Infiltration Development and Application*. Editor : Yu-Si Fok.

University of Hawaii at Manoa. pp. 555-564.

Campbell, G. S., 1974. "A Simple Method For Determining Unsaturated Conductivity from Moisture Retention Data." Soil Science 117(6) : pp. 311-314.

Childs, E. C. and N. Collis-George, 1959. "The Permeability of Porous Materials." Proc. Roy. Soc., A201, pp 392-405.

Chow, Ven Te, David R. Maidment, and Larry W. Mays, 1988. Applied Hydrology. McGraw-Hill Inc., New York. pp. 281-302.

Clapp, R. B. and G. M. Hornberger, 1978. "Empirical Equations for Some Soil Hydraulic Properties." Water Res. Res., 14(4). pp. 601-604.

Dass, P., G. R. Tamke, and C. M. Stoffel, 1977. "Leachate Production at Sanitary Landfill Sites." Journal of the Environmental Engineering Division. ASCE, Vol. 103, No. EE6. pp. 981-988.

Demetracopoulos, Alexander C., George P. Korfiatis, Efsthios L. Bourodimos, and Edward G. Nawy, 1984. "Modeling for Design of Landfill Bottom Liners." Journal of Environmental Engineering. Vol. 110, No. 6. pp 1084-1098.

Demetracopoulos, Alexander C., George P. Korfiatis, Efstathios L. Bourodimos, and Edward G. Nawy, 1986. "Unsaturated Flow Through Solid Waste Landfills : Model and Sensitivity Analysis." Water Resources Bulletin. American Water Resources Association. Vol. 22(4). pp. 601-609.

Demetracopoulos, Alexander C., 1988. "Overview of Landfill Bottom Liner Hydraulics." Water Resources Bulletin. American Water Resources Association. pp. 49-56.

Fenn Dennis G., Keith J. Henley, and Truett V. Degere, 1975. "Use of the Water Balance for Predicting Leachate Generation from Solid Waste Disposal Sites." Report SW-168. U. S. Environmental Protection Agency. pp. 8-11.

Freeze, R. A., 1969. "The Mechanism of Natural Groundwater Recharge and Discharge: 1. One-dimensional, Vertical, Unsteady, Unsaturated Flow Above a Recharging or Discharging Groundwater Flow System." Water Resources Research, Vol. 5, pp. 153-171.

Gardner, W. R., 1958. "Some Steady State Solutions of the Unsaturated Moisture Flow Equation with Application to Evapotranspiration from a Water Table." Soil Sci., Vol. 85, pp. 228-232.

Gee, J. R., 1981. "Prediction of Leachate Accumulation in Sanitary

Landfills." Proceedings, 4th Annual Conferences of Applied Research and Practice on Municipal and Industrial Waste. University of Wisconsin at Madison.

Haverkamp, R., et al., 1977. "A comparison of Numerical Simulation Models for One-dimensional Infiltration." Proc., Soil Science Society of America, Vol. 41, pp. 285-294.

Haverkamp, R., L. Rendon, and G. Vachaud, 1987. "Infiltration Equations and Their Applicability for Predictive Use." In : Infiltration Development and Application. Editor : Yu- Si Fok . University of Hawaii at Manoa. pp. 142-152.

Hillel Daniel, 1980. Application of Soil Physics. Academic Press Inc. pp 40-43.

Klute, A., 1972. "The Determination of the Hydraulic Conductivity and Diffusivity of Unsaturated Soils." Soil Sci., 113(4). pp. 264-276.

Korfiatis, G. P., 1984 . Modeling the Moisture Transport Through Solid Waste Landfills. Ph.D. Dissertation, Rutgers University, Piscataway. NJ. 259 pp.

Korfiatis, George P., Alexander C. Demetracopoulos, Efstathios L. Bourodimos, and Edward G. Nawy, 1984. "Moisture Transport in a

Solid Waste Column." Journal of Environmental Engineering, Vol. 110, No. 4. pp. 780-796.

Korfiatis, George P. and Alexander C. Demetracopoulos, 1986. "Flow Characteristics of Landfill Leachate Collection Systems and Liners." Journal of Environmental Engineering, Vol. 112, No. 3. pp 538-550.

Knisel, W. J., Jr., Editor, 1980. CREAMS : A Field Scale Model for Chemical Runoff and Erosion from Agricultural Management System. Vol. I, II, III, Draft copy, US Department of Agriculture, Report 24. 643 pp.

Liakopoulos, A. C., 1965. "Variation of the Permeability Tensor Ellipsoid in Homogeneous Anisotropic Soils." Water Resources Research, 1, pp. 135-141.

Muallem, Y., 1976. "A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media." Water Resources Research, 12(3). pp. 513-522.

Parsons Brinckerhoff and NYCDOS, 1985. Appendix A - Water Quality Technical Report, Fresh Kills Landfill. Report submitted by Parsons Brinckerhoff. December.

Perrier, E. R. and A. C. Gibson, 1980. Hydrogeologic Simulation on

Solid Waste Disposal Sites. EPA - WS - 868, US EPA, Cincinnati, Ohio.

Peyton, Lee and Paul R. Schroeder, 1988. "Field Verification of HELP Model for Landfills." Journal of Environmental Engineering, ASCE. Vol. 114. No. 2. pp. 247-269.

Philip, J. R., 1969. "Theory of Infiltration." In : Advances in Hydrosience, V. T. Chow (ed), Academic Press, Inc. New York. pp. 215-296.

Richtmeyer, R. D., 1957. Difference Methods for Initial Value Problems. Interscience Publishers, New York. pp. 101-104.

Ritchie, J. T., 1972. "A Model for Predicting Evaporation from Row Crop with Incomplete Cover." Water Resources Research, 8(5). pp. 1204-1213.

Rogowski, A. S., 1971. "Watershed Physics : Model of the Soil Moisture Characteristic." Water Resources Research, 7(6). pp. 1575-1582.

Rubin, J. and R. Steinhardt, 1963. "Soil Water Relations During Rain Infiltration, 1, Theory." Proc. of the Soil Science Society of America, 27, pp. 246-251.

Schroeder, Paul R., 1986. HELP: Hydrologic Evaluation of Landfill Performance Model. U. S. Army Corps of Engineers, Vicksburg, Mississippi.

Schroeder, P. R., A. C. Gibson, and M. D. Smolen, 1984. The Hydrologic Evaluation of Landfill Performance (HELP) Model. Volume II, Documentation for Version 1. U. S. Army Engineers Water Ways Experiment Station, Vicksburg, Mississippi. Produced by National Technical Information Service, U. S. Department of Commerce, Springfield, VA 22161. pp. 14-20.

Schroeder, P. R., B. M. McEnroe, R. L. Peyton, and J. W. Sjostrom, 1988. The Hydrologic Evaluation of Landfill Performance (HELP) Model, Vol. IV. Documentation for Version 2. U. S. Army Engineers Waterways Experiment Station, Vicksburg, Mississippi 39181-0631.

Shanholtz, V. O., and J. B. Lillard, 1970. "A Soil Water Model for Two Contrasting Tillage Practices." Bulletin 38, Virginia Water Resources Research Center, VPISU, Blacksburg, VA. pp. 217.

Thomas, R. J., 1973. Groundwater Models. Produced by Food and Agricultural Organization of the United Nations, Rome.

Thornthwaite, C. W., and J. R. Mather, 1955. The Water Balance. Centerton, N. J. (Drexel Institute of Technology. Laboratory of Climatology. Publications in Climatology, Vol. 8, No. 1).

Thornthwaite, C. W., and J. R. Mather, 1957. Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance. Centerton, N.J. p. 185-311. (Drexel Institute of Technology. Laboratory of Technology. Publications in Climatology, Vol. 10. No. 3).

USDA, Soil Conservation Service, 1972. National Engineering Handbook, Section 4, Hydrology. U.S. Government Printing Office. Washington, D. C.

Viessman, Warren J. R., John W. Knapp, Gary L. Lewis, and Terence E. Harbaugh, 1977. Introduction to Hydrology. Harper & Row Publishers, New York. pp. 372-374.

Wanielista, Martin, 1990. Hydrology and Water Quality Control. John Wiley & Sons, Inc., New York. pp. 57-58.

Wehran Engineering Co., 1983. Hydrologic Investigation, Fresh Kills Landfill Solid Waste Disposal Operation Plan. Vol. 1 (p. 4-22, p. 4-31 to 4-35). Vol. II (Appendix B), Hydrogeologic Report. Prepared for : Parsons Brinckerhoff-Cosulich Consultants, One Penn Plaza, NY. P. 4-31 to 4-35.

Willis, Robert and W-G Yeh Williams, 1987. Groundwater Systems Planning and Management. Prentice-Hall, Inc. Englewood Cliffs, NJ. 416 pp.

Wright, S. J., and C. J. Miller, 1982. "Estimates of Seepage through Clay Covers on Hazardous Waste Landfills." Hazardous Waste Management for the 80's. T. L. Sweeney et al., eds. Ann Arbor Science Publishers, Ann Arbor, Mich., pp. 343-356.

Yu-Si, F., 1987. "Evolution of Algebraic Equations." In : Infiltration Development and Application. Editor : Yu-Si Fok. University of Hawaii at Manoa. pp. 38-48.

6 NYCRR Part 360, Solid Waste Management Facilities, Effective December 31, 1988. New York State Department of Environmental Conservation. Albany, NY.

APPENDIX A

LEACHATE FLOW RATES BY WATER-BALANCE METHOD AND DARCY'S LAW

A.1 COMPUTATION OF LEACHATE FLOW FOR SECTION 1/9 AND 6/7 BY WATER-BALANCE METHOD

The water-balance method has been applied in Fresh Kills Landfill for five landfill conditions as follows:

- (i) Vegetated landfilled conditions, slope > 1 percent.
 - Potential evapotranspiration is maximum.
 - Runoff coefficients 20 percent except 60 percent in January.
 - Soil moisture storage three inches.
- (ii) Vegetated landfill conditions, slope < 1 percent.
 - Potential evapotranspiration is maximum.
 - Runoff coefficient 10 percent except 40 percent in January.
 - Soil moisture storage three inches.
- (iii) Landfilled operational conditions and poorly vegetated areas.
 - Evaporation only.
 - Runoff coefficients 20 percent except 60 percent in January.

- Soil moisture storage three inches.

(iv) Non-landfilled conditions generalized

- Potential evapotranspiration is maximum.
- Runoff coefficients 20 percent except 60 percent in January.
- Soil moisture storage 10 inches.

(v) Direct recharge to marsh and open water

- Potential evapotranspiration is maximum.
- No runoff.
- Available moisture is unlimited.

**Calculation of Percolation Rate and Leachate Generation Using
Water-Balance Method:**

For different site conditions, monthly values of percolation are computed. Values of percolation from January to December are then summed up to get the yearly percolation rate.

For site conditions, having slopes > 1 percent, calculations of percolation for January are:

(From Thornthwaite's Tables) Potential Evapotranspiration,

$$PE = 0.0$$

Adjusted Potential Evapotranspiration, AdjPE = 0.0

Coefficient of runoff, = 0.60

Precipitation, P = 3.31 inches.

$$\begin{aligned} \text{Runoff} &= 0.6 \times 3.31 \\ &= 1.99 \text{ inches} \end{aligned}$$

$$\begin{aligned} \text{Infiltration} &= P - R/O \\ &= 3.31 - 1.99 = 1.32 \text{ inches.} \end{aligned}$$

$$\begin{aligned} \text{Change in storage } ST &= \text{Storage in January} - \text{Storage in December} \\ &= 3.00 - 3.00 = 0.0 \text{ inches.} \end{aligned}$$

$$\begin{aligned} \text{PERC} &= P - R/O - ST - \text{Adj PE} \\ &= 3.31 - 1.99 - 0.0 - 0.00 \\ &= 1.32 \text{ inches.} \end{aligned}$$

Therefore, for January:

$$\text{PERC} = 1.32 \text{ inches.}$$

Similarly, For February:

	PERC = 2.66 inches.
March:	PERC = 2.95 inches.
April:	PERC = 1.37 inches.
May :	PERC = 0.0 inches.
June :	PERC = 0.0 inches.
July :	PERC = 0.0 inches.
August:	PERC = 0.0 inches.

September:	PERC = 0.0 inches.
October:	PERC = 0.0 inches.
November:	PERC = 0.44 inches.
December:	PERC = 2.95 inches.

Adding all the values of percolation from January to December the yearly value of percolation for site conditions, having slopes > 1 percent is 11.7 (inches/year).

In this way, for site conditions, slopes < 1 percent,

Percolation = 14.99 inches/year;

For operational site conditions and poorly vegetated areas

Percolation = 20.21 inches/year; and

For off-site generalized conditions,

Percolation = 9.55 inches/year.

The leachate generation rates computed by using the water-balance method for sections 1/9 and 6/7 are summarized in Tables A-1 and A-2.

TABLE A-1

LEACHATE GENERATION RATE USING WATER-BALANCE METHOD
FOR SECTION 1/9

Segment Number	Mound No. *	Slope Condition	Percolation Rate (in/yr)	Area (acres)	Generation rate (gpd)	Total (gpd)
45	1	>1%	11.70	60	52,000	275,000
	1	operational	20.21	148	223,000	
53	1	>1%	11.70	31	27,000	156,000
	1	operational	20.21	86	129,000	
	2	>1%	11.70	6	5,000	59,000
	2	operational	20.21	36	54,000	
54south	2	operational	20.21	29	44,000	44,000
55	2	>1%	11.70	30	26,000	39,000
	2	<1%	14.99	2	2,000	
	2	operational	20.21	7	11,000	
56	1	operational	20.21	76	114,000	139,000
	1	>1%	11.70	29	25,000	
	2	operational	20.21	12	18,000	185,000
	2	<1%	14.99	6	7,000	
	2	>1%	11.70	84	73,000	
	2	Nonsolid waste area	9.55	107	73,000	
	2	Offsite groundwater			14,000	

* Mound numbers 1 and 2 belong to Section 1/9.

TABLE A-2
LEACHATE GENERATION RATE USING WATER-BALANCE METHOD
FOR SECTION 6/7

Segment Number	Mound No. *	Slope Condition	Percolation Rate(in/yr)	Area (acres)	Generation rate (gpd)	Total (gpd)
55	5	>1%	11.70	27	23,000	38,000
	5	<1%	14.99	13	15,000	
56	5	<1%	14.99	8	9,000	22,000
	5	>1%	11.70	15	13,000	
57	5	<1%	14.99	34	38,000	69,000
	5	>1%	11.70	35	31,000	
58	5	<1%	14.99	14	16,000	54,000
	5	>1%	11.70	44	38,000	
60	5	>1%	11.70	137	119,000	39,000
	5	<1%	14.99	19	21,000	
	5	operational	20.21	46	69,000	139,000
		Runoff recharge			39,000	

* Mound number 5 belongs to Section 6/7.

Leachate generation rate for Section 1/9 and 6/7 by water balance method :

$$\begin{aligned}
 & (897,000 + 431,000) \text{ gpd} \\
 & = 1,328,000 \text{ gpd} \\
 & = 1.328 \text{ mgd}
 \end{aligned}$$

Source : Hydrogeologic Investigation
Volume - II, Appendix B
Wehran Eng.
October, 1983

**A.2 COMPUTATION OF LEACHATE FLOW FOR SECTION 1/9 AND 6/7 USING
DARCY'S LAW**

Section 1/9

Lateral Flow:

According to Darcy's Law,

$$Q_L = K b i w$$

Where,

Q_L = Lateral Flow

K = hydraulic conductivity

$$= 3.6 \times 10^{-3} \text{ cm/sec}$$

b = Saturated thickness

$$= 22.5 \text{ ft.}$$

Width w = 20,650 ft.

Gradient i = $25/1700 = 0.0147$

Therefore,

$$\begin{aligned} Q_L &= 3.6 \times 10^{-3} (\text{cm/sec}) \times (1 \text{ ft.} / 30.5 \text{ cm}) \times 24 \times 3600 (\text{sec/day}) \\ &\quad \times 0.0147 \times 22.5 \text{ ft.} \times 20650 \text{ ft.} \times 7.48 (\text{gallon} / 1 \text{ ft.}^3) \\ &= 521,000 \text{ cpd.} \end{aligned}$$

Vertical Flow:

$$Q_v = K i A$$

where,

Q_v = Vertical Flow

K = Hydraulic conductivity

$$= 1 \times 10^{-7} \text{ cm/sec}$$

i = Gradient

$$= 15/10 = 1.5$$

A = Area = 405 acres

Therefore,

$$\begin{aligned} Q_v &= 1 \times 10^{-7} (\text{cm/sec}) \times (1 \text{ ft.} / 30.5 \text{ cm}) \times 24 \times 3600 (\text{sec/day}) \\ &\quad \times 1.5 \times 405 \text{ acres} \times 43560 (\text{ft.}^2/\text{acre}) \times 7.48 (\text{gallon}/\text{ft.}^3) \\ &= 56,000 \text{ gpd.} \end{aligned}$$

Total Flow = $Q_L + Q_v$

$$= (521,000 + 56,000) \text{ gpd}$$

$$= 577,000 \text{ gpd.}$$

Section 6/7

Lateral Flow

$$Q_L = k b i w$$

Here, hydraulic conductivity $K = 2 \times 10^{-2} \text{ cm/sec.}$

$$\text{gradient } i = 10/1150 = 0.00522$$

saturated thickness $b = 6 \text{ ft.}$

$$\text{width } w = 31,000 \text{ ft.}$$

Therefore,

$$\begin{aligned} Q_L &= 2 \times 10^{-2} \times (1 \text{ ft.} / 30.5 \text{ cm}) \times 24 \times 3600 \times (\text{sec/day}) \times 6 \text{ ft.} \times 0.00522 \\ &\quad \times 31,000 \text{ ft.} \times 7.48 \times (\text{gallon}/\text{ft.}^3) \end{aligned}$$

$$= 410,000 \text{ gpd.}$$

Vertical Flow:

$$Q_v = K \ i \ A$$

Here, hydraulic conductivity $K = 1 \times 10^{-7} \text{ cm/sec}$

$$\text{Gradient } i = 0.17$$

$$\text{Area } A = 376 \text{ acres}$$

Therefore,

$$\begin{aligned} Q_v &= 10^{-7} \times (110 \text{ ft.} / 10.5 \text{ cm}) \times 24 \times 3600 \times (\text{sec/day}) \times 0.17 \times 376 \\ &\quad \times 43560 \text{ ft.}^2 \times 1.48 (\text{gallon/ft.}^3) \\ &= 5,900 \text{ gpd} \\ &= 6,000 \text{ gpd} \end{aligned}$$

$$\begin{aligned} \text{Total Flow} &= (410,000 + 6,000) \text{ gpd} \\ &= 416,000 \text{ gpd.} \end{aligned}$$

Total Flow in Sections 1/9 and 6/7 is:

$$\begin{aligned} Q &= (577000 + 416000) \text{ gpd} \\ &= 993000 \text{ gpd} \\ &= 1.0 \text{ million gallons per day} \end{aligned}$$

Note: The necessary data used for computation are available in:

Volume 1
Hydrogeologic Report
Wehran Eng.

P. 4-31 to 4-35

APPENDIX B
PIEZOMETER AND MONITORING WELL DATA

B-1

STRATA RIM ELEV. PVC pipe 38.65'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill, U</u>																															
			LOCATION : <u>Staten Island, New York</u>																															
			SECTION : <u>1/9</u> NO : <u>W-2</u>																															
			COORDINATES - N1 <u>-34,123</u> E1 <u>-41,260</u>																															
			DATE OF INSTALLATION : <u>4/13/89</u>																															
			RES. ENG. : <u>MIRZA BAIG (FRH)</u>																															
			TYPE : <u>4" PVC monitoring well</u>																															
			INTAKE AREA (PVC pipe) :																															
			depth to bottom, ft = <u>30'</u>																															
			depth to top, ft = <u>20</u>																															
			length, ft = <u>10</u>																															
			diameter, in = <u>4</u> ft = <u>0.33</u>																															
			STANDPIPE/RISER (PVC pipe) :																															
			elevation of rim, ft = <u>38.65</u>																															
			diameter, in = <u>4</u> ft = <u>0.33</u>																															
			<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>10/16/89</td> <td>10:45 AM</td> <td>27.34</td> <td>11.31</td> </tr> <tr> <td>01/30/90</td> <td>1:50 AM</td> <td>29.30</td> <td>9.35</td> </tr> <tr> <td>02/12/90</td> <td>10:10 AM</td> <td>28.15</td> <td>10.50</td> </tr> <tr> <td>03/15/90</td> <td>9:37 AM</td> <td>28.23</td> <td>10.42</td> </tr> <tr> <td>04/13/90</td> <td>8:19 AM</td> <td>28.50</td> <td>10.15</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/16/89	10:45 AM	27.34	11.31	01/30/90	1:50 AM	29.30	9.35	02/12/90	10:10 AM	28.15	10.50	03/15/90	9:37 AM	28.23	10.42	04/13/90	8:19 AM	28.50	10.15				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																															
DATE	CLOCK																																	
10/16/89	10:45 AM	27.34	11.31																															
01/30/90	1:50 AM	29.30	9.35																															
02/12/90	10:10 AM	28.15	10.50																															
03/15/90	9:37 AM	28.23	10.42																															
04/13/90	8:19 AM	28.50	10.15																															
			REMARKS :																															

Sand

Gravel

Bentonite

Grout

STRATA RIM ELEV. PVC pipe 34.00'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																																	
			LOCATION : <u>Staten Island, New York</u>																																	
			SECTION : <u>1/9</u> NO : <u>W-3</u>																																	
			COORDINATES - N: <u>-32,112</u> E: <u>-41,890</u>																																	
			DATE OF INSTALLATION : <u>4/10/89</u>																																	
			RES. ENG. : <u>MIRZA BAIG</u>																																	
			TYPE : <u>4" PVC monitoring well</u>																																	
			INTAKE AREA (PVC pipe) :																																	
			depth to bottom , ft= <u>22</u>																																	
			depth to top, ft= <u>12</u>																																	
			length, ft= <u>10</u>																																	
			diameter, in= <u>4</u> ft= <u>0.33</u>																																	
			STANDPIPE/RISER (PVC pipe) :																																	
			elevation of rim, ft= <u>34.00</u>																																	
			diameter, in= <u>4</u> ft= <u>0.33</u>																																	
			<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th>DEPTH (ft) RIM TO WATER</th> <th>ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> <th></th> <th></th> </tr> </thead> <tr> <td>10/16/89</td> <td>10:20 AM</td> <td>10.47</td> <td>23.53</td> </tr> <tr> <td>01/30/90</td> <td>2:05 PM</td> <td>10.73</td> <td>23.27</td> </tr> <tr> <td>02/12/90</td> <td>10:20 AM</td> <td>10.35</td> <td>23.65</td> </tr> <tr> <td>03/15/90</td> <td>9:36 AM</td> <td>10.70</td> <td>23.30</td> </tr> <tr> <td>04/13/90</td> <td>8:26 AM</td> <td>10.55</td> <td>23.45</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK			10/16/89	10:20 AM	10.47	23.53	01/30/90	2:05 PM	10.73	23.27	02/12/90	10:20 AM	10.35	23.65	03/15/90	9:36 AM	10.70	23.30	04/13/90	8:26 AM	10.55	23.45				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																																	
DATE	CLOCK																																			
10/16/89	10:20 AM	10.47	23.53																																	
01/30/90	2:05 PM	10.73	23.27																																	
02/12/90	10:20 AM	10.35	23.65																																	
03/15/90	9:36 AM	10.70	23.30																																	
04/13/90	8:26 AM	10.55	23.45																																	
			REMARKS :																																	
<div style="display: flex; justify-content: space-between; margin-top: 10px;"> <div> <div style="display: flex; align-items: center; margin-bottom: 5px;"> <div style="width: 20px; height: 10px; border: 1px solid black; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px);"></div> Sand </div> <div style="display: flex; align-items: center; margin-bottom: 5px;"> <div style="width: 20px; height: 10px; border: 1px solid black; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 4px 4px;"></div> Gravel </div> </div> <div> <div style="display: flex; align-items: center; margin-bottom: 5px;"> <div style="width: 20px; height: 10px; border: 1px solid black; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px);"></div> Bentonite </div> <div style="display: flex; align-items: center; margin-bottom: 5px;"> <div style="width: 20px; height: 10px; border: 1px solid black; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px);"></div> Grout </div> </div> </div>																																				

STRATA RIM ELEV. PVC pipe 19.70'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																															
			LOCATION : <u>Statens Island, New York</u>																															
			SECTION : <u>1/9</u> NO : <u>W-4</u>																															
			COORDINATES - N: <u>31,829</u> E: <u>42,691</u>																															
			DATE OF INSTALLATION : <u>4/20/89</u>																															
			RES. ENG. : <u>Ralph Capone</u>																															
			TYPE : <u>4" PVC monitoring well</u>																															
			INTAKE AREA (PVC pipe) :																															
			depth to bottom , ft= <u>9.7</u>																															
			depth to top, ft= <u>4.7</u>																															
			length, ft= <u>5</u>																															
			diameter, in= <u>4</u> ft= <u>0.33</u>																															
			STANDPIPE/RISER (PVC pipe) :																															
			elevation of rim, ft= <u>19.70</u>																															
			diameter, in= <u>4</u> ft= <u>0.33</u>																															
Sand Bentonite Gravel Grout		0																																
		5																																
		10																																
		15																																
		20																																
		25																																
		30																																
			<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>10/16/89</td> <td>12:32 PM</td> <td>8.7</td> <td>11.0</td> </tr> <tr> <td>01/30/90</td> <td>11:00 AM</td> <td>7.36</td> <td>12.34</td> </tr> <tr> <td>02/12/90</td> <td>8:10 AM</td> <td>7.65</td> <td>12.05</td> </tr> <tr> <td>03/15/90</td> <td>9:50 AM</td> <td>7.83</td> <td>11.87</td> </tr> <tr> <td>04/14/90</td> <td>8:34 AM</td> <td>7.8</td> <td>11.9</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/16/89	12:32 PM	8.7	11.0	01/30/90	11:00 AM	7.36	12.34	02/12/90	8:10 AM	7.65	12.05	03/15/90	9:50 AM	7.83	11.87	04/14/90	8:34 AM	7.8	11.9				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																															
DATE	CLOCK																																	
10/16/89	12:32 PM	8.7	11.0																															
01/30/90	11:00 AM	7.36	12.34																															
02/12/90	8:10 AM	7.65	12.05																															
03/15/90	9:50 AM	7.83	11.87																															
04/14/90	8:34 AM	7.8	11.9																															
			REMARKS :																															

B-5

STRATA RIM ELEV. PVC pipe 33.70'	INSTALLATION DETAILS	DEPTH (ft)
FILL		0
		10
		20
		30
		40
		50

	Sand		Bentonite
	Gravel		Grout

PROJECT : Fresh Kills Landfill
 LOCATION : Staten Island, New York
 SECTION : 1/9 NO : N-7
 COORDINATES - N: -36,189 E: -46,239
 DATE OF INSTALLATION : 5/8/89
 RES. ENG. : Ralph Capone
 TYPE : 4" PVC Monitoring Well
 INTAKE AREA (PVC pipe) :

depth to bottom , ft= 35

depth to top, ft= 25

length, ft= 10

diameter, in= 4 ft= 0.33

STANDPIPE/RISER (PVC pipe) :

elevation of rim, ft= 33.70

diameter, in= 4 ft= 0.33

READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)
DATE	CLOCK		
10/16/89	2:30 PM	25.2	8.5
1/30/90	10:50 AM	25.95	7.75
2/12/90	7:32 AM	25.95	7.75
3/15/90	7:00 AM	26.4	7.30
4/13/90	6:47 AM	26.2	7.50

REMARKS :

STRATA RIM ELEV. PVC pipe 19.40'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>			
			LOCATION : <u>Staten Island, New York</u>			
			SECTION : <u>Y9</u> NO : <u>W-8</u>			
			COORDINATES - N: <u>-34,564</u> E: <u>-46,618</u>			
			DATE OF INSTALLATION : <u>04/21/89</u>			
			RES. ENG. : <u>Ralph Borne</u>			
			TYPE : <u>4" PVC monitoring well</u>			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= <u>18</u>			
			depth to top, ft= <u>8</u>			
			length, ft= <u>10</u>			
			diameter, in= <u>4</u> ft= <u>0.33</u>			
			STANDPIPE/RISER (PVC pipe) :			
			elevation of rim, ft= <u>19.40</u>			
			diameter, in= <u>4</u> ft= <u>0.33</u>			
			READING TIME		DEPTH (ft)	ELEVATION
			DATE	CLOCK	RIM TO WATER	OF WATER (ft)
			10/16/89	4:30 PM	9.63	9.77
			1/30/90	12:10 PM	10.08	9.32
			2/12/90	9:12 AM	10.12	9.28
			3/15/90	7:25 AM	10.3	9.10
			4/13/90	7:07 AM	10.35	9.05
			REMARKS :			

Sand

Bentonite

Gravel

Grout

Dark grey
silty clay
with patchy
decomposed
vegetation

STRATA RIM ELEV. PVC pipe 39.72'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>French Kills Landfill</u> LOCATION : <u>Slate Island, New York</u> SECTION : <u>1/9</u> NO : <u>W-9</u> COORDINATES - N: <u>-33,291</u> E: <u>-46,119</u> DATE OF INSTALLATION : <u>04/27/88</u> RES. ENG. : <u>Ralph Capone</u> TYPE : <u>4" PVC monitoring well</u> INTAKE AREA (PVC pipe) : depth to bottom , ft= <u>29.5</u> depth to top, ft= <u>14.5</u> length, ft= <u>10.0</u> diameter, in= <u>4</u> ft= <u>0.33</u> STANDPIPE/RISER (PVC pipe) : elevation of rim, ft= <u>39.72</u> diameter, in= <u>4</u> ft= <u>0.33</u>																															
		0	<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> <tr> <td>10/16/89</td> <td>3:45 PM</td> <td>17.38</td> <td>22.34</td> </tr> <tr> <td>1/30/90</td> <td>12:40 PM</td> <td>21.04</td> <td>18.68</td> </tr> <tr> <td>2/12/90</td> <td>8:49 AM</td> <td>20.55</td> <td>19.17</td> </tr> <tr> <td>3/15/90</td> <td>7:44 AM</td> <td>20.85</td> <td>18.87</td> </tr> <tr> <td>4/13/90</td> <td>7:17 AM</td> <td>20.75</td> <td>18.97</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/16/89	3:45 PM	17.38	22.34	1/30/90	12:40 PM	21.04	18.68	2/12/90	8:49 AM	20.55	19.17	3/15/90	7:44 AM	20.85	18.87	4/13/90	7:17 AM	20.75	18.97				
		READING TIME			DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																												
		DATE					CLOCK																											
		10/16/89			3:45 PM	17.38	22.34																											
		1/30/90			12:40 PM	21.04	18.68																											
		2/12/90			8:49 AM	20.55	19.17																											
		3/15/90			7:44 AM	20.85	18.87																											
		4/13/90			7:17 AM	20.75	18.97																											
		10																																
20																																		
30																																		
40																																		
50																																		
60																																		
70																																		
LEGEND Sand Bentonite Gravel Grout			REMARKS :																															

STRATA RIM ELEV.	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>French Kills Landfill</u>				
PVC pipe 30.45'		0	LOCATION : <u>Staten Island, New York</u>				
		5	SECTION : <u>1/9</u> NO : <u>W-10</u>				
		10	COORDINATES - N: <u>-31,813</u> E: <u>-45,293</u>				
		15	DATE OF INSTALLATION : <u>04/21/89</u>				
		20	RES. ENG. : <u>Ralph Capone</u>				
		20.65	TYPE : <u>4" PVC Monitoring well</u>				
		25	INTAKE AREA (PVC pipe) :				
			depth to bottom , ft= <u>20</u>				
			depth to top, ft= <u>10</u>				
			length, ft= <u>10</u>				
	diameter, in= <u>4</u> ft= <u>0.33</u>						
	STANDPIPE/RISER (PVC pipe) :						
	elevation of rim, ft= <u>30.45</u>						
	diameter, in= <u>4</u> ft= <u>0.33</u>						
No sample taken			READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	
			DATE	CLOCK			
				10/16/89	4:45 PM	9.3	21.15
				1/30/90	11:25 AM	9.5	20.95
				2/12/90	8:25 AM	9.35	21.10
				3/15/90	7:55 AM	9.94	20.51
				4/13/90	7:38 AM	8.74	21.71
		REMARKS :					

Sand

Bentonite

Gravel

Grout

STRATA RIM ELEV. PVC pipe 31.53	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>			
			LOCATION : <u>Statens Island, New York</u>			
			SECTION : <u>1/9</u>		NO : <u>W-11</u>	
			COORDINATES - N: <u>-31,046</u> E: <u>-43,327</u>			
			DATE OF INSTALLATION : <u>5/15/89</u>			
			RES. ENG. : <u>Ralph Capone</u>			
			TYPE : <u>4" PVC monitoring well</u>			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= <u>29.5</u>			
			depth to top, ft= <u>19.5</u>			
			length, ft= <u>10</u>			
			diameter, in= <u>4</u> ft= <u>0.33</u>			
			STANDPIPE/RISER (PVC pipe) :			
			elevation of rim, ft= <u>31.53</u>			
			diameter, in= <u>4</u> ft= <u>0.33</u>			
<div style="display: flex; flex-direction: column; align-items: center;"> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); border: 1px solid black; margin-bottom: 5px;"></div> <div style="width: 100%; height: 100%; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 10px 10px; border: 1px solid black; margin-bottom: 5px;"></div> </div>						

STRATA RIM ELEV. PVC pipe 36.59'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u> LOCATION : <u>Statens Island, New York</u> SECTION : <u>V9</u> NO : <u>P-1</u> COORDINATES - N: <u>-31,503</u> E: <u>-42,151</u> DATE OF INSTALLATION : <u>4/18/89</u> RES. ENG. : <u>Aly Mohammed</u> TYPE : <u>2" PVC Piezometer</u> INTAKE AREA (PVC pipe) : depth to bottom , ft= <u>35</u> depth to top, ft= <u>25</u> length, ft= <u>10</u> diameter, in= <u>2</u> ft= <u>0.17</u> STANDPIPE/RISER (PVC pipe) : elevation of rim, ft= <u>36.53</u> diameter, in= <u>2</u> ft= <u>0.17</u>	
Silt & clay				

STRATA RIM ELEV. PVC pipe	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>French Kills Landfill</u>																															
44.84'			LOCATION : <u>Statens Island, New York</u>																															
			SECTION : <u>V9</u> NO : <u>P-2</u>																															
			COORDINATES - N: <u>-33,257</u> E: <u>-42,500</u>																															
			DATE OF INSTALLATION : <u>4/17/89</u>																															
			RES. ENG. : <u>Ralph Capone</u>																															
			TYPE : <u>2" PVC piezometer</u>																															
			INTAKE AREA (PVC pipe) :																															
			depth to bottom , ft= <u>40</u>																															
			depth to top, ft= <u>30</u>																															
			length, ft= <u>10</u>																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
			STANDPIPE/RISER (PVC pipe) :																															
			elevation of rim, ft= <u>44.84</u>																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
			<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>10/16/89</td> <td>1:40 PM</td> <td>36.0</td> <td>8.84</td> </tr> <tr> <td>1/30/90</td> <td>10:01 AM</td> <td>35.98</td> <td>8.86</td> </tr> <tr> <td>2/12/90</td> <td>7:05 AM</td> <td>35.27</td> <td>9.57</td> </tr> <tr> <td>3/15/90</td> <td>6:30 AM</td> <td>32.95</td> <td>11.89</td> </tr> <tr> <td>4/13/90</td> <td>6:30 AM</td> <td>34.60</td> <td>10.24</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/16/89	1:40 PM	36.0	8.84	1/30/90	10:01 AM	35.98	8.86	2/12/90	7:05 AM	35.27	9.57	3/15/90	6:30 AM	32.95	11.89	4/13/90	6:30 AM	34.60	10.24				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																															
DATE	CLOCK																																	
10/16/89	1:40 PM	36.0	8.84																															
1/30/90	10:01 AM	35.98	8.86																															
2/12/90	7:05 AM	35.27	9.57																															
3/15/90	6:30 AM	32.95	11.89																															
4/13/90	6:30 AM	34.60	10.24																															
			REMARKS :																															
<div style="display: flex; justify-content: space-between;"> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); display: inline-block;"></div> Sand </div> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); display: inline-block;"></div> Bentonite </div> </div> <div style="display: flex; justify-content: space-between; margin-top: 5px;"> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 4px 4px; display: inline-block;"></div> Gravel </div> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(90deg, transparent, transparent 2px, black 2px, black 4px); display: inline-block;"></div> Grout </div> </div>																																		

FILL

Red brown
clay sand
silt with
some gravel

STRATA RIM ELEV. PVC pipe 20.65'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																															
			LOCATION : <u>Staten Island, New York</u>																															
			SECTION : <u>1/9</u> NO : <u>P-3</u>																															
			COORDINATES - N: <u>-33,739</u> E: <u>-42,589</u>																															
			DATE OF INSTALLATION : <u>4/11/89</u>																															
			RES. ENG. : <u>MIRZA BANIG</u>																															
			TYPE : <u>2" PVC piezometer</u>																															
			INTAKE AREA (PVC pipe) :																															
			depth to bottom , ft= <u>25</u>																															
			depth to top, ft= <u>15</u>																															
			length, ft= <u>10</u>																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
			STANDPIPE/RISER (PVC pipe) :																															
			elevation of rim, ft= <u>20.65</u>																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
			<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>10/16/89</td> <td>1:50 PM</td> <td>11.07</td> <td>9.58</td> </tr> <tr> <td>11/30/90</td> <td>10:07 AM</td> <td>10'55</td> <td>10'10</td> </tr> <tr> <td>2/12/90</td> <td>7:17 AM</td> <td>10'55</td> <td>10'10</td> </tr> <tr> <td>3/15/90</td> <td>6:46 AM</td> <td>10'17</td> <td>10'98</td> </tr> <tr> <td>4/13/90</td> <td>6:32 AM</td> <td>10'20</td> <td>10'95</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/16/89	1:50 PM	11.07	9.58	11/30/90	10:07 AM	10'55	10'10	2/12/90	7:17 AM	10'55	10'10	3/15/90	6:46 AM	10'17	10'98	4/13/90	6:32 AM	10'20	10'95				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																															
DATE	CLOCK																																	
10/16/89	1:50 PM	11.07	9.58																															
11/30/90	10:07 AM	10'55	10'10																															
2/12/90	7:17 AM	10'55	10'10																															
3/15/90	6:46 AM	10'17	10'98																															
4/13/90	6:32 AM	10'20	10'95																															
			REMARKS :																															
<div style="display: flex; justify-content: space-between;"> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); display: inline-block;"></div> Sand </div> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 4px 4px; display: inline-block;"></div> Bentonite </div> </div> <div style="display: flex; justify-content: space-between; margin-top: 5px;"> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); display: inline-block;"></div> Gravel </div> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(90deg, transparent, transparent 2px, black 2px, black 4px); display: inline-block;"></div> Grout </div> </div>																																		

STRATA RIM ELEV. PVC pipe 64.70'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																															
			LOCATION : <u>Statens Island, New York</u>																															
			SECTION : <u>1/9</u> NO : <u>P-5</u>																															
			COORDINATES - N: <u>-35,618</u> E: <u>-45,371</u>																															
			DATE OF INSTALLATION : <u>5/8/89</u>																															
			RES. ENG. : <u>Ralph Capone</u>																															
			TYPE : <u>2" PVC piezometer</u>																															
			INTAKE AREA (PVC pipe) :																															
			depth to bottom , ft= <u>48.5</u>																															
			depth to top, ft= <u>32.5</u>																															
			length, ft= <u>10</u>																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
			STANDPIPE/RISER (PVC pipe) :																															
			elevation of rim, ft= <u>64.70</u>																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
			<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tr> <td>10/16/89</td> <td>3:05 PM</td> <td>41.85</td> <td>22.85</td> </tr> <tr> <td>1/30/90</td> <td>10:40 AM</td> <td>43.73</td> <td>20.97</td> </tr> <tr> <td>2/12/90</td> <td>8:00 AM</td> <td>42.75</td> <td>21.95</td> </tr> <tr> <td>3/15/90</td> <td>7:18 AM</td> <td>43.75</td> <td>20.95</td> </tr> <tr> <td>4/13/90</td> <td>7:01 AM</td> <td>42.2</td> <td>22.50</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/16/89	3:05 PM	41.85	22.85	1/30/90	10:40 AM	43.73	20.97	2/12/90	8:00 AM	42.75	21.95	3/15/90	7:18 AM	43.75	20.95	4/13/90	7:01 AM	42.2	22.50				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																															
DATE	CLOCK																																	
10/16/89	3:05 PM	41.85	22.85																															
1/30/90	10:40 AM	43.73	20.97																															
2/12/90	8:00 AM	42.75	21.95																															
3/15/90	7:18 AM	43.75	20.95																															
4/13/90	7:01 AM	42.2	22.50																															
			REMARKS :																															
<div style="display: flex; justify-content: space-between;"> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px); display: inline-block;"></div> Sand </div> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 4px 4px; display: inline-block;"></div> Bentonite </div> </div> <div style="display: flex; justify-content: space-between; margin-top: 5px;"> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px); display: inline-block;"></div> Gravel </div> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(90deg, transparent, transparent 2px, black 2px, black 4px); display: inline-block;"></div> Grout </div> </div>																																		

B-15

B-16

STRATA RIM ELEV. PVC pipe 52.72'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>			
			LOCATION : <u>Statens Island, New York</u>			
			SECTION : <u>1/9</u> NO : <u>P-8</u>			
			COORDINATES - N: <u>-35,976</u> E: <u>-45,298</u>			
			DATE OF INSTALLATION : <u>5/4/89</u>			
			RES. ENG. : <u>Ralph Capone</u>			
			TYPE : <u>2" PVC piezometer</u>			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= <u>49.6</u>			
			depth to top, ft= <u>39.6</u>			
			length, ft= <u>10</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
			STANDPIPE/RISER (PVC pipe) :			
			elevation of rim, ft= <u>52.72</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
			READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)
			DATE	CLOCK		
		0	10/16/89	2:15 PM	39.74	12.98
		10	1/30/90	10 18 AM	40.98	11.74
		20	2/12/90	7 24 AM	40.73	11.99
		30	3/15/90	6 55 AM	41.06	11.66
		40	4/13/90	6:41 AM	41.36	11.36
		50				
		60				
		70				
			REMARKS :			

Sand

Bentonite

Gravel

Grout

STRATA RIM ELEV. PVC pipe 55.92'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u> LOCATION : <u>Statu Island, New York</u> SECTION : <u>1/9</u> NO : <u>P-9</u> COORDINATES - N: <u>-39,682</u> E: <u>-46,139</u> DATE OF INSTALLATION : <u>4/25/89</u> RES. ENG. : <u>Aly Mohammed</u> TYPE : <u>2" PVC piezometer</u> INTAKE AREA (PVC pipe) : depth to bottom , ft= <u>35</u> depth to top, ft= <u>25</u> length, ft= <u>10</u> diameter, in= <u>2</u> ft= <u>0.17</u> STANDPIPE/RISER (PVC pipe) : elevation of rim, ft= <u>55.92</u> diameter, in= <u>2</u> ft= <u>0.17</u>																																
FILL 		0	<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> <tr> <td>10/16/89</td> <td>4:20 PM</td> <td>31.2</td> <td>24.72</td> </tr> <tr> <td>1/30/90</td> <td>12:17 PM</td> <td>31.78</td> <td>24.14</td> </tr> <tr> <td>2/12/90</td> <td>9:13 AM</td> <td>31.75</td> <td>24.17</td> </tr> <tr> <td>3/15/90</td> <td>7:30 AM</td> <td>32.10</td> <td>23.82</td> </tr> <tr> <td>4/13/90</td> <td>7:10 AM</td> <td>32.05</td> <td>23.87</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </table>			READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/16/89	4:20 PM	31.2	24.72	1/30/90	12:17 PM	31.78	24.14	2/12/90	9:13 AM	31.75	24.17	3/15/90	7:30 AM	32.10	23.82	4/13/90	7:10 AM	32.05	23.87				
		READING TIME				DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																												
		DATE						CLOCK																											
		10/16/89				4:20 PM	31.2	24.72																											
		1/30/90				12:17 PM	31.78	24.14																											
		2/12/90				9:13 AM	31.75	24.17																											
		3/15/90				7:30 AM	32.10	23.82																											
		4/13/90				7:10 AM	32.05	23.87																											
		10																																	
20																																			
30																																			
40																																			
50																																			
60																																			
70																																			

Sand

Bentonite

Gravel

Grout

STRATA RIM ELEV.	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>			
PVC pipe 58.70'			LOCATION : <u>Statens Island, New York</u>			
			SECTION : <u>1/9</u> NO : <u>P-10</u>			
			COORDINATES - N: <u>-33,589</u> E: <u>-45,678</u>			
			DATE OF INSTALLATION : <u>5/4/89</u>			
			RES. ENG. : <u>Ralph Capone</u>			
			TYPE : <u>2" PVC piezometer</u>			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= <u>34.5</u>			
			depth to top, ft= <u>24.5</u>			
			length, ft= <u>10</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
			STANDPIPE/RISER (PVC pipe) :			
			elevation of rim, ft= <u>58.70</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
			READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)
			DATE	CLOCK		
		0				
		10				
		20				
		30				
		40				
		50	10/16/89	3:55 PM	21.05	37.65
			1/30/90	12:55 PM	23.09	34.80
			2/12/90	8:54 AM	23.14	35.56
			3/15/90	7:46 AM	23.06	35.64
			4/13/90	7:21 AM	22.55	36.15
		70	REMARKS :			
<div style="display: flex; justify-content: space-between; align-items: center;"> <div style="text-align: center;"> Sand </div> <div style="text-align: center;"> Bentonite </div> </div> <div style="display: flex; justify-content: space-between; align-items: center; margin-top: 5px;"> <div style="text-align: center;"> Gravel </div> <div style="text-align: center;"> Grout </div> </div>						

STRATA RIM ELEV. PVC pipe 71.33'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>			
			LOCATION : <u>Staten Island, New York</u>			
			SECTION : <u>1/9</u> NO : <u>P-11</u>			
			COORDINATES - N: <u>-32,168</u> E: <u>-45,010</u>			
			DATE OF INSTALLATION : <u>5/12/89</u>			
			RES. ENG. : <u>Ralph Capone</u>			
			TYPE : <u>2" PVC piezometer</u>			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= <u>49</u>			
			depth to top, ft= <u>32</u>			
			length, ft= <u>15</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
			STANDPIPE/RISER (PVC pipe) :			
			elevation of rim, ft= <u>71.33</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
FILL	[Diagram of piezometer installation showing fill, grout, and riser]	0				
		10				
		20				
		30				
		40				
		50				
			READING TIME	DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	
			DATE	CLOCK		
			10/16/89	5:00 PM	32.95	38.38
			11/30/90	11:35 AM	34.7	36.63
			2/12/90	8:30 AM	34.44	36.89
			3/19/90	8:20 AM	34.57	36.76
			4/13/90	7:52 AM		
			REMARKS :			
			On 4/13/90, Active landfill Piezometer is lost.			

Sand

Bentonite

Gravel

Grout

STRATA RIM ELEV. PVC pipe 62.60'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>			
			LOCATION : <u>Staten</u>			
			SECTION : <u>1/9</u> NO : <u>C-1A</u>			
			COORDINATES - N: <u>-31,381</u> E: <u>-91,676</u>			
			DATE OF INSTALLATION : <u>3/31/89</u>			
			RES. ENG. : <u>Ralph Capone</u>			
			TYPE : <u>2" PVC piezometer</u>			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= <u>50.5</u>			
			depth to top, ft= <u>45.5</u>			
			length, ft= <u>10</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
			STANDPIPE/RISER (PVC pipe) :			
			elevation of rim, ft= <u>62.60'</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
Sand Bentonite Gravel Grout	Sand Bentonite Gravel Grout	0	READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)
		10	DATE	CLOCK		
		20	10/16/89	11:40 AM	12.05	50.55
		30	1/30/90	1.12 PM	9.78	52.82
		40	2/12/90	9:59 AM	8.70	53.90
		50	3/15/90	9:26 AM	10.0	52.60
		60	4/13/90	8:04 AM	9.65	52.95
		70				
		REMARKS : <u>Reached bottom at 18.25 ft from the rim (pvc)</u>				

STRATA RIM ELEV. PVC pipe 62.82'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																																								
			LOCATION : <u>Staten Island</u>																																								
			SECTION : <u>1/9</u> NO : <u>C-1B</u>																																								
			COORDINATES - N: <u>-31,388</u> E: <u>-41,685</u>																																								
			DATE OF INSTALLATION : <u>3/30/89</u>																																								
			RES. ENG. : <u>Brad Staub</u>																																								
			TYPE : <u>2" PVC piezometer</u>																																								
			INTAKE AREA (PVC pipe) :																																								
			depth to bottom , ft= <u>61</u>																																								
			depth to top, ft= <u>56</u>																																								
			length, ft= <u>5</u>																																								
			diameter, in= <u>2</u> ft= <u>0.17</u>																																								
			STANDPIPE/RISER (PVC pipe) :																																								
			elevation of rim, ft= <u>62.82</u>																																								
			diameter, in= <u>2</u> ft= <u>0.17</u>																																								
		0	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>10/16/89</td> <td>11:40 AM</td> <td></td> <td></td> </tr> <tr> <td>1/30/90</td> <td>1:12 PM</td> <td></td> <td></td> </tr> <tr> <td>2/12/90</td> <td>9:53 AM</td> <td></td> <td></td> </tr> <tr> <td>3/15/90</td> <td>9:27 AM</td> <td></td> <td></td> </tr> <tr> <td>4/13/90</td> <td>8:05 AM</td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> </tbody> </table>			READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/16/89	11:40 AM			1/30/90	1:12 PM			2/12/90	9:53 AM			3/15/90	9:27 AM			4/13/90	8:05 AM														
	READING TIME					DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																																				
	DATE	CLOCK																																									
	10/16/89	11:40 AM																																									
	1/30/90	1:12 PM																																									
	2/12/90	9:53 AM																																									
	3/15/90	9:27 AM																																									
	4/13/90	8:05 AM																																									
	10																																										
	20																																										
	30																																										
	40																																										
	50																																										
	60																																										
	70																																										
			REMARKS : <u>No leachate mound observed</u> <u>- Reached bottom at 17.8 ft from</u> <u>the top of the rim (PVC).</u>																																								

Sand Bentonite
 Gravel Grout

STRATA RIM ELEV. PVC pipe	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																															
			LOCATION : <u>Staten Island, New York</u>																															
			SECTION : <u>1/9</u> NO : <u>C-2</u>																															
			COORDINATES - N: _____ E: _____																															
			DATE OF INSTALLATION : <u>6/19/89</u>																															
			RES. ENG. : <u>Ralph Capone</u>																															
			TYPE : <u>2" PVC piezometer</u>																															
			INTAKE AREA (PVC pipe) :																															
			depth to bottom , ft= <u>80'</u>																															
			depth to top, ft= <u>60'</u>																															
			length, ft= <u>20</u>																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
			STANDPIPE/RISER (PVC pipe) :																															
			elevation of rim, ft= _____																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
		0	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>1/30/90</td> <td>11:55 AM</td> <td>62.7</td> <td>35.53</td> </tr> <tr> <td>2/12/90</td> <td>8:40 AM</td> <td>60.55</td> <td>37.68</td> </tr> <tr> <td>3/15/90</td> <td>8:25 AM</td> <td>60.55</td> <td>37.88</td> </tr> <tr> <td>4/13/90</td> <td>7:48 AM</td> <td>60.1</td> <td>38.13</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	1/30/90	11:55 AM	62.7	35.53	2/12/90	8:40 AM	60.55	37.68	3/15/90	8:25 AM	60.55	37.88	4/13/90	7:48 AM	60.1	38.13								
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																															
DATE	CLOCK																																	
1/30/90	11:55 AM	62.7	35.53																															
2/12/90	8:40 AM	60.55	37.68																															
3/15/90	8:25 AM	60.55	37.88																															
4/13/90	7:48 AM	60.1	38.13																															
20																																		
60																																		
70																																		
80																																		
90																																		
100																																		
120'																																		
120'																																		
		REMARKS : <u>PVC - 25' from G.L.</u>																																

STRATA RIM ELEV. PVC pipe 74.03'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																															
			LOCATION : <u>Statue Island, New York</u>																															
			SECTION : <u>1/9</u> NO : <u>C-3A</u>																															
			COORDINATES - N: <u>-39.151</u> E: <u>-45.933</u>																															
			DATE OF INSTALLATION : <u>4/27/89</u>																															
			RES. ENG. : <u>Ralph Capone</u>																															
			TYPE : <u>2" PVC piezometer</u>																															
			INTAKE AREA (PVC pipe) :																															
			depth to bottom , ft= <u>49.5</u>																															
			depth to top, ft= <u>44.5</u>																															
			length, ft= <u>10</u>																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
			STANDPIPE/RISER (PVC pipe) :																															
			elevation of rim, ft= <u>74.03</u>																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
			<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>10/16/89</td> <td>5:25 PM</td> <td>40.5</td> <td>33.53</td> </tr> <tr> <td>1/30/90</td> <td>12:35 PM</td> <td>41.1</td> <td>32.93</td> </tr> <tr> <td>2/12/90</td> <td>9:30 AM</td> <td>41.03</td> <td>33.0</td> </tr> <tr> <td>3/15/90</td> <td>7:37 AM</td> <td>40.8</td> <td>33.23</td> </tr> <tr> <td>4/13/90</td> <td>7:28 AM</td> <td>40.53</td> <td>33.50</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/16/89	5:25 PM	40.5	33.53	1/30/90	12:35 PM	41.1	32.93	2/12/90	9:30 AM	41.03	33.0	3/15/90	7:37 AM	40.8	33.23	4/13/90	7:28 AM	40.53	33.50				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																															
DATE	CLOCK																																	
10/16/89	5:25 PM	40.5	33.53																															
1/30/90	12:35 PM	41.1	32.93																															
2/12/90	9:30 AM	41.03	33.0																															
3/15/90	7:37 AM	40.8	33.23																															
4/13/90	7:28 AM	40.53	33.50																															
			REMARKS :																															
<div style="display: flex; justify-content: space-between;"> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px);"></div> Sand </div> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px);"></div> Bentonite </div> </div> <div style="display: flex; justify-content: space-between; margin-top: 5px;"> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 4px 4px;"></div> Gravel </div> <div> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(90deg, transparent, transparent 2px, black 2px, black 4px);"></div> Grout </div> </div>																																		

STRATA RIM ELEV.	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																															
PVC pipe <u>72.65'</u>			LOCATION : <u>Statu Island, New York</u>																															
			SECTION : <u>1/9</u> NO : <u>C-3B</u>																															
			COORDINATES - N: <u>-34,140</u> E: <u>-45,935</u>																															
			DATE OF INSTALLATION : <u>4/26/89</u>																															
			RES. ENG. : <u>Ralph Capone</u>																															
			TYPE : <u>2" PVC piezometer</u>																															
			INTAKE AREA (PVC pipe) :																															
			depth to bottom , ft= <u>65</u>																															
			depth to top, ft= <u>60</u>																															
			length, ft= <u>5'</u>																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
			STANDPIPE/RISER (PVC pipe) :																															
			elevation of rim, ft= <u>72.65'</u>																															
			diameter, in= <u>2</u> ft= <u>0.17</u>																															
			<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>10/16/89</td> <td>3:25 PM</td> <td>39.7</td> <td>32.95</td> </tr> <tr> <td>1/30/90</td> <td>12:30 PM</td> <td>40'2</td> <td>32'45</td> </tr> <tr> <td>2/12/90</td> <td>9:30 AM</td> <td>40'15</td> <td>32'50</td> </tr> <tr> <td>3/15/90</td> <td>7:33 AM</td> <td>40'0</td> <td>32'65</td> </tr> <tr> <td>4/13/90</td> <td>7:30 AM</td> <td>39'70</td> <td>32'95</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/16/89	3:25 PM	39.7	32.95	1/30/90	12:30 PM	40'2	32'45	2/12/90	9:30 AM	40'15	32'50	3/15/90	7:33 AM	40'0	32'65	4/13/90	7:30 AM	39'70	32'95				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																															
DATE	CLOCK																																	
10/16/89	3:25 PM	39.7	32.95																															
1/30/90	12:30 PM	40'2	32'45																															
2/12/90	9:30 AM	40'15	32'50																															
3/15/90	7:33 AM	40'0	32'65																															
4/13/90	7:30 AM	39'70	32'95																															
			REMARKS :																															

Sand

Bentonite

Gravel

Grout

STRATA	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : Fresh Kills Landfill			
RIM ELEV. PVC pipe 31.23'			LOCATION : Staten Island, New York			
			SECTION : 6/7 NO : W-1			
			COORDINATES - N: -25,916 E: -35,954			
			DATE OF INSTALLATION : 05/22/89			
			RES. ENG. : Ralph Capone			
			TYPE : 4" PVC monitoring well			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= 32.5			
			depth to top, ft= 17.5			
			length, ft= 15'			
			diameter, in= 4 ft= 0.33			
			STANDPIPE/RISER (PVC pipe) :			
			elevation of rim, ft= 31.23			
			diameter, in= 4 ft= 0.33			
			READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)
			DATE	CLOCK		
			10/24/89	11:00 AM	27'55"	3'68"
			11/30/90	3:25 PM	27'44"	3'79"
			2/12/90	11:11 AM	27'44"	3'79"
			3/15/90	10:20 AM	27'58"	3'65"
			4/13/90	10:50 AM	27'55"	3'68"
REMARKS :						

Sand
 Bentonite
 Gravel
 Grout

STRATA RIM ELEV.	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>			
PVC pipe 27.13'			LOCATION : <u>Statue Island, New York</u>			
			SECTION : <u>6/7</u> NO : <u>W-2</u>			
			COORDINATES - N: <u>-28,118</u> E: <u>-35,787</u>			
			DATE OF INSTALLATION : <u>05/22/89</u>			
			RES. ENG. : <u>Ralph Capone</u>			
			TYPE : <u>4" PVC monitoring well</u>			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= <u>29.5'</u>			
			depth to top, ft= <u>14.5</u>			
			length, ft= <u>15</u>			
			diameter, in= <u>4</u> ft= <u>0.33</u>			
			STANDPIPE/RISER (PVC pipe) :			
			elevation of rim, ft= <u>29.13</u>			
			diameter, in= <u>4</u> ft= <u>0.33</u>			
			READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)
			DATE	CLOCK		
		0				
		10				
		20				
		30				
		40				
		50	10/24/89	10:25	19.96	9.17
			11/30/90	8:06 AM	22.45	6.68
			2/12/90	11:27 AM	22.43	6.70
			2/15/90	10:25 AM	22.70	6.43
		60	4/13/90	8:56 AM	22.69	6.44
			REMARKS :			

Sand

Bentonite

Gravel

Grout

STRATA RIM ELEV.	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																																	
PVC pipe 13.30'			LOCATION : <u>Statue Island, New York</u>																																	
			SECTION : <u>6/7</u> NO : <u>14-2</u>																																	
			COORDINATES - N: <u>-29,905</u> E: <u>-35,822</u>																																	
			DATE OF INSTALLATION : <u>03/20/89</u>																																	
			RES. ENG. : <u>Ralph Capone</u>																																	
			TYPE : <u>4" monitoring well</u>																																	
			INTAKE AREA (PVC pipe) :																																	
			depth to bottom , ft= <u>14.2</u>																																	
			depth to top, ft= <u>4.2</u>																																	
			length, ft= <u>10</u>																																	
			diameter, in= <u>4</u> ft= <u>0.33</u>																																	
			STANDPIPE/RISER (PVC pipe) :																																	
			elevation of rim, ft= <u>13.30'</u>																																	
			diameter, in= <u>4</u> ft= <u>0.33</u>																																	
			<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>10/24/89</td> <td></td> <td></td> <td></td> </tr> <tr> <td>11/30/90</td> <td>4:05 PM</td> <td>5'30"</td> <td>8'0"</td> </tr> <tr> <td>2/12/90</td> <td>11:40 AM</td> <td>5'25"</td> <td>8'05"</td> </tr> <tr> <td>3/15/90</td> <td>11:05 AM</td> <td>5'33"</td> <td>7'97"</td> </tr> <tr> <td>4/13/90</td> <td>9:02 AM</td> <td>5'35"</td> <td>7'95"</td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> </tbody> </table>				READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/24/89				11/30/90	4:05 PM	5'30"	8'0"	2/12/90	11:40 AM	5'25"	8'05"	3/15/90	11:05 AM	5'33"	7'97"	4/13/90	9:02 AM	5'35"	7'95"				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																																	
DATE	CLOCK																																			
10/24/89																																				
11/30/90	4:05 PM	5'30"	8'0"																																	
2/12/90	11:40 AM	5'25"	8'05"																																	
3/15/90	11:05 AM	5'33"	7'97"																																	
4/13/90	9:02 AM	5'35"	7'95"																																	
			REMARKS : <u>Well could not able to be located on 10/24/90</u> <u>pvc = 125' from ground level</u>																																	
			<div style="display: flex; justify-content: space-between;"> Sand Bentonite </div> <div style="display: flex; justify-content: space-between;"> Gravel Grout </div>																																	

STRATA RIM ELEV. PVC pipe 20.30'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>			
			LOCATION : <u>Staton Island, New York</u>			
			SECTION : <u>6/7</u> NO : <u>W-4</u>			
			COORDINATES - N: <u>-31,246</u> E: <u>-36,180</u>			
			DATE OF INSTALLATION : <u>03/16/89</u>			
			RES. ENG. : <u>Ralph Capone</u>			
			TYPE : <u>4" Monitoring well</u>			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= <u>19 1/2</u>			
			depth to top, ft= <u>9 1/2</u>			
			length, ft= <u>10</u>			
			diameter, in= <u>4</u> ft= <u>0.33</u>			
			STANDPIPE/RISER (PVC pipe)			
			elevation of rim, ft= <u>20.30'</u>			
			diameter, in= <u>4</u> ft= <u>0.33</u>			
			READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)
			DATE	CLOCK		
		0	10/25/89	12:00	13.93	6.37
		5	11/30/90	9:24 AM	14.25	6.05
		10	2/12/90	12:33 PM	14.28	6.02
		15	3/15/90	11:15 AM	14.85	5.45
		20	4/13/90	9:43 AM	14.4	5.90
		25				
		30				
			REMARKS :			

Sand

Gravel

Bentonite

Grout

STRATA RIM ELEV. PVC pipe 20.74'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>	
			LOCATION : <u>Staten Island, New York</u>	
			SECTION : <u>6/7</u> NO : <u>W-5</u>	
			COORDINATES - N1 <u>-31,955</u> E1 <u>-36,795</u>	
			DATE OF INSTALLATION : <u>3/16/89</u>	
			RES. ENG. : <u>Brad Staub</u>	
			TYPE : <u>4" Monitoring well</u>	
			INTAKE AREA (PVC pipe) :	
			depth to bottom , ft= <u>24</u>	
			depth to top, ft= <u>14</u>	
			length, ft= <u>10</u>	
			diameter, in= <u>4</u> ft= <u>0.33</u>	
			STANDPIPE/RISER (PVC pipe) :	
			elevation of rim, ft= <u>20.74'</u>	
			diameter, in= <u>4</u> ft= <u>0.33</u>	
FILL	0	5	READING TIME	
			DATE	CLOCK
			10/24/89	2:50 PM
			11/30/90	9:15 AM
			12/12/90	12:34 PM
10	15	DEPTH (ft)		
		RIM TO	ELEVATION	
		WATER	OF WATER	
		(ft)	(ft)	
		16.43	4.31	
20	25	17.12	3.62	
		16.85	4.09	
		17.0	3.74	
		16.36	3.88	
REMARKS :				

Sand

Bentonite

Gravel

Grout

STRATA RIM ELEV. PVC pipe 17.27	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Rock Kills Landfill</u> LOCATION : <u>Statens Island, New York</u> SECTION : <u>6/7</u> NO : <u>W-7</u> COORDINATES - N: <u>-30.147</u> E: <u>-38.564</u> DATE OF INSTALLATION : <u>5/15/89</u> RES. ENG. : <u>Ann Marie Giarratana</u> TYPE : <u>4" monitoring well</u> INTAKE AREA (PVC pipe) : depth to bottom , ft= <u>20</u> depth to top, ft= <u>10</u> length, ft= <u>10</u> diameter, in= <u>4</u> ft= <u>0.33</u> STANDPIPE/RISER (PVC pipe) : elevation of rim, ft= <u>17.27</u> diameter, in= <u>4</u> ft= <u>0.33</u>
FILL Grout		0 10 20	<table border="1" style="width:100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>10/24/89</td> <td>3:35 PM</td> <td>14.70</td> <td>2.57</td> </tr> <tr> <td>11/30/90</td> <td>8:50 AM</td> <td>15.97</td> <td>1.30</td> </tr> <tr> <td>2/12/90</td> <td>11:57 AM</td> <td>15.80</td> <td>1.47</td> </tr> <tr> <td>3/15/90</td> <td>11:35 AM</td> <td>16.2</td> <td>1.07</td> </tr> <tr> <td>4/13/90</td> <td>9:16 AM</td> <td>15.9</td> <td>1.37</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>			READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/24/89	3:35 PM	14.70	2.57	11/30/90	8:50 AM	15.97	1.30	2/12/90	11:57 AM	15.80	1.47	3/15/90	11:35 AM	16.2	1.07	4/13/90	9:16 AM	15.9	1.37				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																																
DATE	CLOCK																																		
10/24/89	3:35 PM	14.70	2.57																																
11/30/90	8:50 AM	15.97	1.30																																
2/12/90	11:57 AM	15.80	1.47																																
3/15/90	11:35 AM	16.2	1.07																																
4/13/90	9:16 AM	15.9	1.37																																
<div style="display: flex; justify-content: space-between;"> <div> Sand </div> <div> Bentonite </div> </div> <div style="display: flex; justify-content: space-between;"> <div> Gravel </div> <div> Grout </div> </div>			REMARKS : <u>Oil in the well</u>																																

STRATA RIM ELEV. PVC pipe 11.61'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																															
			LOCATION : <u>Staten Island, New York</u>																															
			SECTION : <u>6/7</u> NO : <u>W-8</u>																															
			COORDINATES - N: <u>-27.814</u> E: <u>-37.513</u>																															
			DATE OF INSTALLATION : <u>5/31/89</u>																															
			RES. ENG. : <u>Ralph Capone</u>																															
			TYPE : <u>4" PVC monitoring well</u>																															
			INTAKE AREA (PVC pipe) :																															
			depth to bottom , ft= <u>18</u>																															
			depth to top, ft= <u>8</u>																															
			length, ft= <u>10</u>																															
			diameter, in= <u>4</u> ft= <u>0.33</u>																															
			STANDPIPE/RISER (PVC pipe) :																															
			elevation of rim, ft= <u>11.61</u>																															
			diameter, in= <u>4</u> ft= <u>0.33</u>																															
			<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>10/24/89</td> <td>12:45 PM</td> <td>7.12</td> <td>4.49</td> </tr> <tr> <td>11/30/90</td> <td>7:35 AM</td> <td>7.15</td> <td>4.46</td> </tr> <tr> <td>2/12/90</td> <td>10:47 AM</td> <td>7.54</td> <td>4.07</td> </tr> <tr> <td>3/15/90</td> <td>10:45 AM</td> <td>7.98</td> <td>3.63</td> </tr> <tr> <td>4/13/90</td> <td>10:20 AM</td> <td>7.75</td> <td>3.86</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/24/89	12:45 PM	7.12	4.49	11/30/90	7:35 AM	7.15	4.46	2/12/90	10:47 AM	7.54	4.07	3/15/90	10:45 AM	7.98	3.63	4/13/90	10:20 AM	7.75	3.86				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																															
DATE	CLOCK																																	
10/24/89	12:45 PM	7.12	4.49																															
11/30/90	7:35 AM	7.15	4.46																															
2/12/90	10:47 AM	7.54	4.07																															
3/15/90	10:45 AM	7.98	3.63																															
4/13/90	10:20 AM	7.75	3.86																															
			REMARKS :																															

<div style="display: flex; justify-content: space-between; align-items: center;"> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px);"></div> Sand </div> <div style="display: flex; justify-content: space-between; align-items: center; margin-top: 5px;"> <div style="border: 1px solid black; width: 20px; height: 10px; background: radial-gradient(circle, black 1px, transparent 1px); background-size: 4px 4px;"></div> Gravel </div>	<div style="display: flex; justify-content: space-between; align-items: center;"> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(-45deg, transparent, transparent 2px, black 2px, black 4px);"></div> Bentonite </div> <div style="display: flex; justify-content: space-between; align-items: center; margin-top: 5px;"> <div style="border: 1px solid black; width: 20px; height: 10px; background: repeating-linear-gradient(45deg, transparent, transparent 2px, black 2px, black 4px);"></div> Grout </div>
---	---

B-34

STRATA RIM ELEV. PVC pipe 10.16'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																															
			LOCATION : <u>Staten Island, New York</u>																															
			SECTION : <u>6/7</u> NO : <u>W-10</u>																															
			COORDINATES - N: <u>-25,239</u> E: <u>-36,370</u>																															
			DATE OF INSTALLATION : <u>5/23/89</u>																															
			RES. ENG. : <u>Aly Mohammad</u>																															
			TYPE : <u>4" monitoring well</u>																															
			INTAKE AREA (PVC pipe) :																															
			depth to bottom , ft= <u>15</u>																															
			depth to top, ft= <u>7</u>																															
			length, ft= <u>8</u>																															
			diameter, in= <u>4</u> ft= <u>0.33</u>																															
			STANDPIPE/RISER (PVC pipe) :																															
			elevation of rim, ft= <u>10.16</u>																															
			diameter, in= <u>4</u> ft= <u>0.33</u>																															
<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p><u>FILL</u></p> <p><u>Grey Sandy Silt some clay</u></p> </div> <div style="width: 45%; text-align: right;"> <p>20.87</p> </div> </div>		0	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td>10/24/89</td> <td>12:15 PM</td> <td>8.25</td> <td>1.91</td> </tr> <tr> <td>11/30/90</td> <td>7:00 AM</td> <td>9'0</td> <td>1'61</td> </tr> <tr> <td>2/12/90</td> <td>10:35 AM</td> <td>9'05</td> <td>1'11</td> </tr> <tr> <td>3/15/90</td> <td>10:10 AM</td> <td>9'55</td> <td>0'61</td> </tr> <tr> <td>4/13/90</td> <td>10:35 AM</td> <td>9'15</td> <td>1'01</td> </tr> <tr> <td> </td> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	10/24/89	12:15 PM	8.25	1.91	11/30/90	7:00 AM	9'0	1'61	2/12/90	10:35 AM	9'05	1'11	3/15/90	10:10 AM	9'55	0'61	4/13/90	10:35 AM	9'15	1'01				
		READING TIME			DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																												
		DATE					CLOCK																											
		10/24/89			12:15 PM	8.25	1.91																											
		11/30/90			7:00 AM	9'0	1'61																											
		2/12/90			10:35 AM	9'05	1'11																											
		3/15/90			10:10 AM	9'55	0'61																											
		4/13/90			10:35 AM	9'15	1'01																											
5																																		
10																																		
15																																		
20																																		
25																																		

Sand

Gravel

Bentonite

Grout

B-36

B-37

STRATA RIM R.L. PV. PVC pipe 30.65'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>			
			LOCATION : <u>Staten Island, New York</u>			
			SECTION : <u>6/7</u> NO : <u>P-3</u>			
			COORDINATES - N: <u>-29,920</u> E: <u>-36,149</u>			
			DATE OF INSTALLATION : <u>3/23/89</u>			
			RES. ENG. : <u>Ralph Capone</u>			
			TYPE : <u>2" Piezometer</u>			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= <u>29</u>			
			depth to top, ft= <u>14</u>			
			length, ft= <u>10</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
			STANDPIPE/RISER (PVC pipe) :			
			elevation of rim, ft= <u>30.65</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
			READING TIME		DEPTH (ft)	ELEVATION
			DATE	CLOCK	RIM TO WATER	OF WATER (ft)
			10/24/89			
			11/30/90	9:10 PM	14'25"	16'40"
			2/12/90	11:44 AM	15'22"	15'43"
			3/15/90	11:10 AM	15'9"	14'75"
			4/13/90	9:05 AM	15'95"	15'20"
			REMARKS : <u>Piezometer located on 11/30/90</u>			

Sand

Gravel

Bentonite

Grout

STRATA RIM ELEV. PVC pipe	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																															
<u>21.67'</u>		<u>0</u>	LOCATION : <u>Staten Island, New York</u>																															
			SECTION : <u>6/7</u> NO : <u>P-5</u>
FILL		<u>5</u>	COORDINATES - N: <u>-30,136</u> E: <u>-38,002</u>																															
		<u>10</u>	DATE OF INSTALLATION : <u>5/23/89</u>																															
		<u>15</u>	RES. ENG. : <u>AGY Mohammad</u>																															
		<u>20</u>	TYPE : <u>2" PVC piezometer</u>
<u>25</u>	INTAKE AREA (PVC pipe) :																															
			depth to bottom , ft= <u>19.5</u>																															
			depth to top, ft= <u>9.5</u>																															
			length, ft= <u>10</u>
diameter, in= <u>2</u> ft= <u>0.17</u>																															
		STANDPIPE/RISER (PVC pipe) :																																
		elevation of rim, ft= <u>21.67</u>																																
		diameter, in= <u>2</u> ft= <u>0.17</u>																																
			<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr> <td><u>10/24/89</u></td> <td><u>3:45</u></td> <td><u>16.88</u></td> <td><u>4.79</u></td> </tr> <tr> <td><u>1/30/90</u></td> <td><u>8:50 AM</u></td> <td><u>20.1</u></td> <td><u>1.57</u></td> </tr> <tr> <td><u>2/12/90</u></td> <td><u>11:50 AM</u></td> <td><u>17.9</u></td> <td><u>3.77</u></td> </tr> <tr> <td><u>3/15/90</u></td> <td><u>11:30 AM</u></td> <td><u>18.3</u></td> <td><u>3.37</u></td> </tr> <tr> <td><u>4/13/90</u></td> <td><u>9:11 AM</u></td> <td><u>18.15</u></td> <td><u>3.52</u></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> </tr> </tbody> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK	<u>10/24/89</u>	<u>3:45</u>	<u>16.88</u>	<u>4.79</u>	<u>1/30/90</u>	<u>8:50 AM</u>	<u>20.1</u>	<u>1.57</u>	<u>2/12/90</u>	<u>11:50 AM</u>	<u>17.9</u>	<u>3.77</u>	<u>3/15/90</u>	<u>11:30 AM</u>	<u>18.3</u>	<u>3.37</u>	<u>4/13/90</u>	<u>9:11 AM</u>	<u>18.15</u>	<u>3.52</u>				
READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																															
DATE	CLOCK																																	
<u>10/24/89</u>	<u>3:45</u>	<u>16.88</u>	<u>4.79</u>																															
<u>1/30/90</u>	<u>8:50 AM</u>	<u>20.1</u>	<u>1.57</u>																															
<u>2/12/90</u>	<u>11:50 AM</u>	<u>17.9</u>	<u>3.77</u>																															
<u>3/15/90</u>	<u>11:30 AM</u>	<u>18.3</u>	<u>3.37</u>																															
<u>4/13/90</u>	<u>9:11 AM</u>	<u>18.15</u>	<u>3.52</u>																															
			REMARKS :

Sand
 Bentonite
 Gravel
 Grout

B-40

STRATA RIM ELEV. PVC pipe 48.50'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>			
			LOCATION : <u>Staten Island, N.Y.</u>			
			SECTION : <u>6/7</u> NO : <u>P-7</u>			
			COORDINATES - N: <u>-26,615</u> E: <u>-37,666</u>			
			DATE OF INSTALLATION : <u>6/7/89</u>			
			RES. ENG. : <u>Ralph Capone</u>			
			TYPE : <u>2" PVC piezometer</u>			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= <u>44.5</u>			
			depth to top, ft= _____			
			length, ft= <u>15'</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
			STANDPIPE/RISER (PVC pipe) :			
			elevation of rim, ft= <u>48.50</u>			
			diameter, in= <u>2</u> ft= <u>0.17</u>			
			READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)
			DATE	CLOCK		
		0	10/24/89	12:35 PM		
		10	11/30/90	7:20 AM		
		20	2/12/90	11:00 AM	10.82	37.68
		30	3/15/90	10:45 AM	No water	
		40	4/13/90	10:37 AM	No water	
		50				
		60				
			REMARKS : <u>Tape was not able to be lowered below 12'.</u>			

Sand Bentonite	Gravel Grout
-------------------------	-----------------------

B-42

STRATA RIM ELEV. PVC pipe 32.31'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>			
			LOCATION : <u>Staten Island, New York</u>			
			SECTION : <u>6/7</u>		NO : <u>C-2</u>	
			COORDINATES - N1 <u>-29,193</u> E1 <u>-36,009</u>			
			DATE OF INSTALLATION : <u>6/5/89</u>			
			RES. ENG. : <u>A. M. Giarratana</u>			
			TYPE :			
			INTAKE AREA (PVC pipe) :			
			depth to bottom , ft= <u>34.5</u>			
			depth to top, ft= <u>14.5</u>			
			length, ft= <u>20</u>			
			diameter, in= _____ ft= _____			
			STANDPIPE/RISER (PVC pipe) :			
			elevation of rim, ft= <u>32.31</u>			
			diameter, in= _____ ft= _____			
			READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)
			DATE	CLOCK		
			10/24/89	4:40	23.12	9.19
			11/30/90	7:55 AM	23.98	8.53
			2/12/90	11:22 AM	24.0	8.31
			3/15/90	10:30 AM	23.2	9.11
			4/13/90	8:52 AM	24.4	7.91
			REMARKS :			

Sand	Bentonite
Gravel	Grout

STRATA RIM ELEV. PVC pipe 29.48'	INSTALLATION DETAILS	DEPTH (ft)	PROJECT : <u>Fresh Kills Landfill</u>																																											
			LOCATION : <u>Statens Island, New York</u>																																											
			SECTION : <u>6/7</u> NO : <u>C-3</u>																																											
			COORDINATES - N: <u>-30.851</u> E: <u>-96.586</u>																																											
			DATE OF INSTALLATION : <u>3/23/89</u>																																											
			RES. ENG. : <u>Brad Staub</u>																																											
			TYPE : <u>2" PVC piezometer</u>																																											
			INTAKE AREA (PVC pipe) :																																											
			depth to bottom , ft= <u>24.83</u>																																											
			depth to top, ft= <u>14.83</u>																																											
			length, ft= <u>10</u>																																											
			diameter, in= <u>2</u> ft= <u>0.17</u>																																											
			STANDPIPE/RISER (PVC pipe) :																																											
			elevation of rim, ft= <u>29.48</u>																																											
			diameter, in= <u>2</u> ft= <u>0.17</u>																																											
FILL	12'	0	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">READING TIME</th> <th rowspan="2">DEPTH (ft) RIM TO WATER</th> <th rowspan="2">ELEVATION OF WATER (ft)</th> </tr> <tr> <th>DATE</th> <th>CLOCK</th> </tr> </thead> <tbody> <tr><td> </td><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td><td> </td></tr> <tr><td> </td><td> </td><td> </td><td> </td></tr> </tbody> </table>		READING TIME		DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)	DATE	CLOCK																																				
		READING TIME			DEPTH (ft) RIM TO WATER	ELEVATION OF WATER (ft)																																								
		DATE					CLOCK																																							
5																																														
10																																														
15																																														
20																																														
25																																														
30																																														

Sand

Bentonite

Gravel

Grout

REMARKS : Piezometer was not able to be located

APPENDIX C

COMPUTATION OF FLOW GRADIENTS FOR DIFFERENT MOUND SUBSECTIONS

SECTION 1/9:

MOUND SUBSECTION 1 (FIGURE 6-3a, SECTION 1/9):

$$\text{Gradient at 1,1} = \frac{25 - 20}{393.7} = 0.0127$$

$$\text{Gradient at 1,2} = \frac{25 - 20}{307.1} = 0.0163$$

$$\text{Gradient at 1,3} = \frac{25 - 20}{188.98} = 0.0265$$

$$\text{Gradient at 2,1} = \frac{20 - 15}{181.1} = 0.0276$$

$$\text{Gradient at 3,1} = \frac{15 - 10}{173.25} = 0.0289$$

$$\text{Gradient at 3,2} = \frac{15 - 10}{181.1} = 0.0276$$

$$\text{Gradient at 3,3} = \frac{15 - 10}{196.85} = 0.0254$$

$$\text{Gradient at 4,1} = \frac{30 - 25}{512.69} = 9.62 * 10^{-3}$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(0.0127 + 0.0163 + \dots + 0.0254 + 9.62 * 10^{-3})}{8} \\ &= 0.0218 \end{aligned}$$

MOUND SUBSECTION 2 (FIGURE 4-3a, SECTION 1/9):

$$\text{Gradient at 1,1} = \frac{35 - 30}{507.87} = 9.85 * 10^{-3}$$

$$\text{Gradient at 1,2} = \frac{35 - 30}{590.55} = 8.47 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{30 - 25}{370.1} = 0.0135$$

$$\text{Gradient at 2,2} = \frac{30 - 25}{259.84} = 0.019$$

$$\text{Gradient at 2,3} = \frac{30 - 25}{188.98} = 0.0265$$

$$\text{Gradient at 3,1} = \frac{25 - 20}{370.1} = 0.0135$$

$$\text{Gradient at 3,2} = \frac{25 - 20}{283.46} = 0.0176$$

$$\text{Gradient at 4,1} = \frac{20 - 15}{188.98} = 0.0265$$

$$\text{Gradient at 4,2} = \frac{20 - 15}{153.54} = 0.0326$$

$$\text{Gradient at 4,3} = \frac{20 - 16}{149.61} = 0.033$$

$$\text{Gradient at 5,1} = \frac{15 - 10}{185.04} = 0.027$$

$$\text{Gradient at 5,2} = \frac{15 - 10}{145.67} = 0.034$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(9.85 * 10^{-3} + 8.47 * 10^{-3} + \dots + 0.027 + 0.034)}{12} \\ &= 0.0219 \end{aligned}$$

MOUND SUBSECTION 3 (FIGURE 4-3a, SECTION 1/9):

$$\text{Gradient at 1,1} = \frac{35 - 30}{322.83} = 0.0155$$

$$\text{Gradient at 1,2} = \frac{35 - 30}{251.97} = 0.0198$$

$$\text{Gradient at } 2,1 = \frac{30 - 25}{181.1} = 0.0276$$

$$\text{Gradient at } 2,2 = \frac{30 - 25}{137.8} = 0.0363$$

$$\text{Gradient at } 3,1 = \frac{25 - 20}{216.54} = 0.023$$

$$\text{Gradient at } 3,2 = \frac{25 - 20}{149.60} = 0.033$$

$$\text{Gradient at } 4,1 = \frac{20 - 15}{82.68} = 0.06$$

$$\text{Gradient at } 4,2 = \frac{20 - 15}{51.2} = 0.098$$

$$\text{Gradient at } 5,1 = \frac{15 - 10}{122.0} = 0.041$$

$$\text{Gradient at } 5,2 = \frac{15 - 10}{98.43} = 0.051$$

$$\text{Average Gradient} = \frac{(0.0155 + 0.0198 + \dots + 0.041 + 0.051)}{10}$$

$$= 0.041$$

MOUND SUBSECTION 4 (FIGURE 4-3a, SECTION 1/9):

$$\text{Gradient at 1,1} = \frac{35 - 30}{114.2} = 0.044$$

$$\text{Gradient at 2,1} = \frac{30 - 25}{94.5} = 0.053$$

$$\text{Gradient at 3,1} = \frac{25 - 20}{31.5} = 0.159$$

$$\text{Gradient at 4,1} = \frac{20 - 15}{31.5} = 0.159$$

$$\text{Gradient at 5,1} = \frac{15 - 10}{27.56} = 0.181$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(0.044 + 0.053 + 0.159 + 0.159 + 0.181)}{5} \\ &= 0.1191 \end{aligned}$$

MOUND SUBSECTION 5 (FIGURE 4-3a, SECTION 1/9):

$$\text{Gradient at 1,1} = \frac{35 - 30}{80.3} = 0.062$$

$$\text{Gradient at 1,2} = \frac{35 - 30}{118.11} = 0.042$$

$$\text{Gradient at 1,3} = \frac{35 - 30}{188.98} = 0.0265$$

$$\text{Gradient at 2,1} = \frac{30 - 25}{98.43} = 0.051$$

$$\text{Gradient at 2,2} = \frac{30 - 25}{118.11} = 0.042$$

$$\text{Gradient at 2,3} = \frac{30 - 25}{196.85} = 0.025$$

$$\text{Gradient at 3,1} = \frac{25 - 20}{74.8} = 0.067$$

$$\text{Gradient at 3,2} = \frac{25 - 20}{228.35} = 0.022$$

$$\text{Gradient at 3,3} = \frac{25 - 20}{342.35} = 0.015$$

$$\text{Gradient at 4,1} = \frac{20 - 15}{31.5} = 0.1587$$

$$\text{Gradient at 4,2} = \frac{20 - 15}{110.24} = 0.045$$

$$\text{Gradient at 4,3} = \frac{20 - 15}{137.8} = 0.036$$

$$\text{Gradient at 5,1} = \frac{15 - 10}{39.37} = 0.127$$

$$\text{Gradient at 5,2} = \frac{15 - 10}{43.31} = 0.115$$

$$\text{Gradient at 5,3} = \frac{15 - 10}{141.73} = 0.035$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(0.062 + 0.042 + \dots + 0.127 + 0.035)}{15} \\ &= 0.0581 \end{aligned}$$

MOUND SUBSECTION 6 (FIGURE 4-3a, SECTION 1/9):

$$\text{Gradient at 1,1} = \frac{35 - 30}{220.47} = 0.023$$

$$\text{Gradient at 1,2} = \frac{35 - 30}{299.2} = 0.017$$

$$\text{Gradient at 2,1} = \frac{30 - 25}{236.22} = 0.021$$

$$\text{Gradient at 2,2} = \frac{30 - 25}{322.85} = 0.015$$

$$\text{Gradient at 3,1} = \frac{25 - 20}{393.7} = 0.0127$$

$$\text{Gradient at 4,1} = \frac{20 - 15}{141.73} = 0.0353$$

$$\text{Gradient at 5,1} = \frac{15 - 10}{90.55} = 0.0552$$

$$\text{Gradient at 5,2} = \frac{15 - 10}{110.24} = 0.0454$$

$$\text{Gradient at 5,3} = \frac{15 - 10}{118.11} = 0.0423$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(0.023 + 0.017 + \dots + 0.0454 + 0.0423)}{9} \\ &= 0.0297 \end{aligned}$$

MOUND SUBSECTION 7 (FIGURE 4-3a, SECTION 1/9):

$$\text{Gradient at 1,1} = \frac{35 - 30}{452.76} = 0.011$$

$$\text{Gradient at 1,2} = \frac{35 - 30}{385.83} = 0.013$$

$$\text{Gradient at 2,1} = \frac{30 - 25}{315.96} = 0.0159$$

$$\text{Gradient at } 2,2 = \frac{30 - 25}{149.61} = 0.0334$$

$$\text{Gradient at } 2,3 = \frac{30 - 25}{125.98} = 0.0397$$

$$\text{Gradient at } 3,1 = \frac{25 - 20}{78.74} = 0.0635$$

$$\text{Gradient at } 3,2 = \frac{25 - 20}{86.61} = 0.0577$$

$$\text{Gradient at } 3,3 = \frac{25 - 20}{157.48} = 0.0318$$

$$\text{Gradient at } 4,1 = \frac{20 - 15}{78.74} = 0.0635$$

$$\text{Gradient at } 5,1 = \frac{15 - 10}{106.3} = 0.047$$

$$\text{Gradient at } 5,2 = \frac{15 - 10}{161.42} = 0.031$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(0.011 + 0.013 + \dots + 0.047 + 0.031)}{11} \\ &= 0.037 \end{aligned}$$

MOUND SUBSECTION 8 (FIGURE 4-3a, SECTION 1/9):

$$\text{Gradient at 1,1} = \frac{35 - 30}{173.2} = 0.0289$$

$$\text{Gradient at 2,1} = \frac{30 - 25}{157.48} = 0.0318$$

$$\text{Gradient at 3,1} = \frac{25 - 20}{149.61} = 0.0334$$

$$\text{Gradient at 4,1} = \frac{20 - 15}{94.5} = 0.0529$$

$$\text{Gradient at 5,1} = \frac{15 - 10}{110.24} = 0.0454$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(0.0289 + 0.0318 + 0.0334 + 0.0529 + 0.0454)}{5} \\ &= 0.0385 \end{aligned}$$

MOUND SUBSECTION 9 (FIGURE 4-3a, SECTION 1/9):

$$\text{Gradient at 1,1} = \frac{35 - 30}{425.2} = 0.0118$$

$$\text{Gradient at 1,2} = \frac{35 - 30}{531.50} = 9.61 \times 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{30 - 25}{370.1} = 0.0135$$

$$\text{Gradient at 2,2} = \frac{30 - 25}{913.39} = 5.47 * 10^{-3}$$

$$\text{Gradient at 3,1} = \frac{25 - 20}{196.85} = 0.0254$$

$$\text{Gradient at 4,1} = \frac{20 - 15}{165.35} = 0.0302$$

$$\text{Gradient at 4,2} = \frac{20 - 15}{212.6} = 0.0235$$

$$\text{Gradient at 5,1} = \frac{15 - 10}{157.48} = 0.0318$$

$$\text{Gradient at 5,2} = \frac{15 - 10}{188.98} = 0.0265$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(0.0118 + 9.41 * 10^{-3} + \dots + 0.0318 + 0.0265)}{9} \\ &= 0.0197 \end{aligned}$$

MOUND SUBSECTION 10 (FIGURE 4-3a, SECTION 1/9):

$$\text{Gradient at 1,1} = \frac{30 - 25}{984.25} = 5.08 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{25 - 20}{173.23} = 0.0289$$

$$\text{Gradient at 3,1} = \frac{20 - 15}{228.35} = 0.0219$$

$$\text{Gradient at 3,2} = \frac{20 - 15}{192.91} = 0.0259$$

$$\text{Gradient at 4,1} = \frac{15 - 10}{251.97} = 0.0198$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(5.08 * 10^{-3} + 0.0289 + 0.0219 + 0.0259 + 0.0198)}{5} \\ &= 0.02 \end{aligned}$$

MOUND SUBSECTION 11 (FIGURE 4-3a, SECTION 1/9):

$$\text{Gradient at 1,1} = \frac{20 - 15}{377.95} = 0.01323$$

$$\text{Gradient at 1,2} = \frac{20 - 15}{118.11} = 0.0423$$

$$\text{Gradient at 1,3} = \frac{20 - 15}{102.36} = 0.0488$$

$$\begin{aligned}\text{Average Gradient} &= \frac{(0.01323 + 0.0423 + 0.0488)}{3} \\ &= 0.0348\end{aligned}$$

MOUND SUBSECTION 12 (FIGURE 4-3a, SECTION 1/9)

$$\text{Gradient at 1,1} = \frac{20 - 15}{236.22} = 0.021$$

MOUND SUBSECTION 13 (FIGURE 4-3a, SECTION 1/9)

$$\text{Gradient at 1,1} = \frac{20 - 15}{169.30} = 0.0295$$

SECTION 6/7:

MOUND SUBSECTION 1 (FIGURE 4-3b, SECTION 6/7):

$$\text{Gradient at 1,1} = \frac{10 - 9}{231.25} = 4.32 \times 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{231.25} = 4.32 \times 10^{-3}$$

$$\text{Gradient at 3,1} = \frac{8 - 7}{212.5} = 4.71 * 10^{-3}$$

$$\text{Gradient at 4,1} = \frac{7 - 6}{237.5} = 4.21 * 10^{-3}$$

$$\text{Gradient at 5,1} = \frac{6 - 5}{237.5} = 4.12 * 10^{-3}$$

$$\text{Gradient at 6,1} = \frac{5 - 4}{206.25} = 4.85 * 10^{-3}$$

$$\text{Gradient at 7,1} = \frac{4 - 3}{243.75} = 4.10 * 10^{-3}$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(4.32 * 10^{-3} + 4.71 * 10^{-3} + \dots + 4.85 * 10^{-3} + 4.10 * 10^{-3})}{7} \\ &= 4.38 * 10^{-3} \end{aligned}$$

MOUND SUBSECTION 2 (FIGURE 4-3b, SECTION 6/7)

$$\text{Gradient at 1,1} = \frac{10 - 9}{237.5} = 4.21 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{237.5} = 4.21 * 10^{-3}$$

$$\text{Gradient at 3,1} = \frac{8 - 7}{243.75} = 4.1 * 10^{-3}$$

$$\text{Gradient at 4,1} = \frac{7 - 6}{262.50} = 3.81 * 10^{-3}$$

$$\text{Gradient at 5,1} = \frac{6 - 5}{212.5} = 4.71 * 10^{-3}$$

$$\text{Gradient at 6,1} = \frac{5 - 4}{225} = 4.44 * 10^{-3}$$

$$\text{Gradient at 7,1} = \frac{4 - 3}{262.50} = 3.81 * 10^{-3}$$

$$\text{Gradient at 7,2} = \frac{4 - 3}{150.0} = 6.67 * 10^{-3}$$

$$\text{Gradient at 7,3} = \frac{4 - 3}{75} = 0.0133$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(4.21 * 10^{-3} + 4.21 * 10^{-3} + \dots + 6.67 * 10^{-3} + 0.0133)}{9} \\ &= 5.48 * 10^{-3} \end{aligned}$$

MOUND SUBSECTION 3 (FIGURE 4-3b, SECTION 6/7)

$$\text{Gradient at 1,1} = \frac{10 - 9}{168.75} = 5.93 * 10^{-3}$$

$$\text{Gradient at 1,2} = \frac{10 - 9}{237.5} = 4.21 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{112.5} = 8.89 * 10^{-3}$$

$$\text{Gradient at 2,2} = \frac{9 - 8}{187.5} = 5.33 * 10^{-3}$$

$$\text{Gradient at 2,3} = \frac{9 - 8}{225.0} = 4.44 * 10^{-3}$$

$$\text{Gradient at 3,1} = \frac{8 - 7}{175.0} = 5.71 * 10^{-3}$$

$$\text{Gradient at 3,2} = \frac{8 - 7}{225} = 4.44 * 10^{-3}$$

$$\text{Gradient at 4,1} = \frac{7 - 6}{162.50} = 6.15 * 10^{-3}$$

$$\text{Gradient at 4,2} = \frac{7 - 6}{193.75} = 5.16 * 10^{-3}$$

$$\text{Gradient at 5,1} = \frac{6 - 5}{193.75} = 5.16 * 10^{-3}$$

$$\text{Gradient at 6,1} = \frac{5 - 4}{112.5} = 8.89 * 10^{-3}$$

$$\text{Gradient at 6,2} = \frac{5 - 4}{225} = 4.44 * 10^{-3}$$

$$\text{Gradient at 6,3} = \frac{5 - 4}{118.75} = 8.42 * 10^{-3}$$

$$\text{Gradient at 7,1} = \frac{4 - 3}{62.5} = 0.016$$

$$\text{Gradient at 7,2} = \frac{4 - 3}{87.5} = 0.0114$$

$$\text{Gradient at 7,3} = \frac{4 - 3}{43.75} = 0.0229$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(5.93 * 10^{-3} + 4.21 * 10^{-3} + \dots + 0.0114 + 0.0229)}{16} \\ &= 7.97 * 10^{-3} \end{aligned}$$

MOUND SUBSECTION 4 (FIGURE 4-3b, SECTION 6/7)

$$\text{Gradient at 1,1} = \frac{10 - 9}{218.75} = 4.57 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{168.75} = 5.93 * 10^{-3}$$

$$\text{Gradient at 3,1} = \frac{8 - 7}{125} = 8 * 10^{-3}$$

5 of 5

$$\text{Gradient at } 4,1 = \frac{7 - 6}{175} = 5.71 * 10^{-3}$$

$$\text{Gradient at } 4,2 = \frac{7 - 6}{300} = 3.33 * 10^{-3}$$

$$\text{Gradient at } 5,1 = \frac{6 - 5}{193.75} = 5.16 * 10^{-3}$$

$$\text{Gradient at } 5,2 = \frac{6 - 5}{237.5} = 4.21 * 10^{-3}$$

$$\text{Gradient at } 6,1 = \frac{5 - 4}{231.25} = 4.32 * 10^{-3}$$

$$\text{Gradient at } 6,2 = \frac{5 - 4}{112.5} = 8.89 * 10^{-3}$$

$$\text{Gradient at } 6,3 = \frac{5 - 4}{162.5} = 6.15 * 10^{-3}$$

$$\text{Gradient at } 7,1 = \frac{4 - 3}{87.5} = 0.0114$$

$$\text{Gradient at } 7,2 = \frac{4 - 3}{125} = 8 * 10^{-3}$$

$$\text{Gradient at } 7,3 = \frac{4 - 3}{187.5} = 5.33 * 10^{-3}$$

$$\begin{aligned}\text{Average Gradient} &= \frac{(4.57 \times 10^{-3} + 5.93 \times 10^{-3} + \dots + 8 \times 10^{-3} + 5.33 \times 10^{-3})}{13} \\ &= 6.23 \times 10^{-3}\end{aligned}$$

MOUND SUBSECTION 5 (FIGURE 4-3b, SECTION 6/7)

$$\text{Gradient at 1,1} = \frac{10 - 9}{181.25} = 5.52 \times 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{225} = 4.44 \times 10^{-3}$$

$$\text{Gradient at 3,1} = \frac{8 - 7}{150} = 6.67 \times 10^{-3}$$

$$\text{Gradient at 3,2} = \frac{8 - 7}{175} = 5.71 \times 10^{-3}$$

$$\text{Gradient at 4,1} = \frac{7 - 6}{150} = 6.67 \times 10^{-3}$$

$$\text{Gradient at 4,2} = \frac{7 - 6}{300} = 3.33 \times 10^{-3}$$

$$\text{Gradient at 5,1} = \frac{6 - 5}{200} = 5 \times 10^{-3}$$

$$\text{Gradient at 5,2} = \frac{6 - 5}{212.5} = 4.71 \times 10^{-3}$$

$$\text{Gradient at 6,1} = \frac{5 - 4}{125} = 8 * 10^{-3}$$

$$\text{Gradient at 6,2} = \frac{5 - 4}{175} = 5.71 * 10^{-3}$$

$$\text{Gradient at 7,1} = \frac{4 - 3}{193.75} = 5.16 * 10^{-3}$$

$$\text{Gradient at 7,2} = \frac{4 - 3}{200} = 5 * 10^{-3}$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(5.52*10^{-3} + 4.44*10^{-3} + \dots + 5.16*10^{-3} + 5*10^{-3})}{12} \\ &= 5.5 * 10^{-3} \end{aligned}$$

MOUND SUBSECTION 6 (FIGURE 4-3b, SECTION 6/7)

$$\text{Gradient at 1,1} = \frac{10 - 9}{125} = 8 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{125} = 8 * 10^{-3}$$

$$\text{Gradient at 3,1} = \frac{8 - 7}{100} = 0.01$$

$$\text{Gradient at 4,1} = \frac{7 - 6}{112.5} = 8.89 * 10^{-3}$$

$$\text{Gradient at 5,1} = \frac{6 - 5}{93.75} = 0.01$$

$$\text{Gradient at 6,1} = \frac{5 - 4}{112.5} = 8.89 * 10^{-3}$$

$$\text{Gradient at 7,1} = \frac{4 - 3}{100} = 0.01$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(8 * 10^{-3} + 8 * 10^{-3} + \dots + 8.89 * 10^{-3} + 0.01)}{7} \\ &= 9.21 * 10^{-3} \end{aligned}$$

MOUND SUBSECTION 7 (FIGURE 4-3b, SECTION 6/7)

$$\text{Gradient at 1,1} = \frac{10 - 9}{112.5} = 8.89 * 10^{-3}$$

$$\text{Gradient at 1,2} = \frac{10 - 9}{143.75} = 6.96 * 10^{-3}$$

$$\text{Gradient at 1,3} = \frac{10 - 9}{156.25} = 6.4 * 10^{-3}$$

$$\text{Gradient at 1,4} = \frac{10 - 9}{200} = 5 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{106.25} = 9.41 * 10^{-3}$$

$$\text{Gradient at 3,1} = \frac{8 - 7}{75} = 9.41 * 10^{-3}$$

$$\text{Gradient at 4,1} = \frac{7 - 6}{81.25} = 0.0123$$

$$\text{Gradient at 5,1} = \frac{6 - 5}{75} = 0.0133$$

$$\text{Gradient at 6,1} = \frac{5 - 4}{100} = 0.01$$

$$\text{Gradient at 7,1} = \frac{4 - 3}{112.5} = 8.89 * 10^{-3}$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(9.41 * 10^{-3} + 0.0133 + \dots + 6.4 * 10^{-3} + 5 * 10^{-3})}{9} \\ &= 9.45 * 10^{-3} \end{aligned}$$

MOUND SUBSECTION 8 (FIGURE 4-3b, SECTION 6/7)

$$\text{Gradient at 1,1} = \frac{10 - 9}{225} = 4.44 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{81.25} = 0.0123$$

$$\text{Gradient at 2,2} = \frac{9 - 8}{118.75} = 8.42 * 10^{-3}$$

$$\text{Gradient at } 3,1 = \frac{8 - 7}{112.5} = 8.89 * 10^{-3}$$

$$\text{Gradient at } 3,2 = \frac{8 - 7}{125} = 8 * 10^{-3}$$

$$\text{Gradient at } 4,1 = \frac{7 - 6}{106.25} = 9.41 * 10^{-3}$$

$$\text{Gradient at } 5,1 = \frac{6 - 5}{143.75} = 6.96 * 10^{-3}$$

$$\text{Gradient at } 5,2 = \frac{6 - 5}{225} = 4.44 * 10^{-3}$$

$$\text{Gradient at } 5,3 = \frac{6 - 5}{93.75} = 0.0107$$

$$\text{Gradient at } 6,1 = \frac{5 - 4}{131.25} = 7.62 * 10^{-3}$$

$$\text{Gradient at } 7,1 = \frac{4 - 3}{106.25} = 9.41 * 10^{-3}$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(4.44 * 10^{-3} + 0.0123 + \dots + 7.62 * 10^{-3} + 9.41 * 10^{-3})}{11} \\ &= 8.23 * 10^{-3} \end{aligned}$$

MOUND SUBSECTION 9 (FIGURE 4-3b, SECTION 6/7)

$$\text{Gradient at 1,1} = \frac{10 - 9}{293.75} = 3.4 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{181.25} = 5.52 * 10^{-3}$$

$$\text{Gradient at 2,2} = \frac{9 - 8}{325} = 3.08 * 10^{-3}$$

$$\text{Gradient at 3,1} = \frac{8 - 7}{112.5} = 8.89 * 10^{-3}$$

$$\text{Gradient at 3,2} = \frac{8 - 7}{225} = 4.44 * 10^{-3}$$

$$\text{Gradient at 4,1} = \frac{7 - 6}{175} = 5.71 * 10^{-3}$$

$$\text{Gradient at 4,2} = \frac{7 - 6}{275} = 3.64 * 10^{-3}$$

$$\text{Gradient at 5,1} = \frac{6 - 5}{331.25} = 3.02 * 10^{-3}$$

$$\text{Gradient at 6,1} = \frac{5 - 4}{300} = 3.33 * 10^{-3}$$

$$\text{Gradient at 6,2} = \frac{5 - 4}{350} = 2.86 * 10^{-3}$$

$$\text{Gradient at 7,1} = \frac{4 - 3}{68.75} = 0.015$$

$$\text{Gradient at 7,2} = \frac{4 - 3}{125} = 8 * 10^{-3}$$

$$\text{Gradient at 7,3} = \frac{4 - 3}{300} = 3.33 * 10^{-3}$$

$$\text{Gradient at 7,4} = \frac{4 - 3}{300} = 3.33 * 10^{-3}$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(3.4 * 10^{-3} + 5.52 * 10^{-3} + \dots + 3.33 * 10^{-3} + 3.33 * 10^{-3})}{14} \\ &= 5.22 * 10^{-3} \end{aligned}$$

MOUND SUBSECTION 10 (FIGURE 4-3b, SECTION 6/7)

$$\text{Gradient at 1,1} = \frac{10 - 9}{243.75} = 4.1 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{275} = 3.64 * 10^{-3}$$

$$\text{Gradient at 2,2} = \frac{9 - 8}{368.75} = 2.71 * 10^{-3}$$

$$\text{Gradient at } 3,1 = \frac{8 - 7}{262.5} = 3.81 * 10^{-3}$$

$$\text{Gradient at } 3,2 = \frac{8 - 7}{350.0} = 2.86 * 10^{-3}$$

$$\text{Gradient at } 4,1 = \frac{7 - 6}{437.5} = 2.29 * 10^{-3}$$

$$\text{Gradient at } 4,2 = \frac{7 - 6}{250.0} = 4 * 10^{-3}$$

$$\text{Gradient at } 4,3 = \frac{7 - 6}{200} = 5 * 10^{-3}$$

$$\text{Gradient at } 4,4 = \frac{7 - 6}{225} = 4.44 * 10^{-3}$$

$$\text{Gradient at } 5,1 = \frac{6 - 5}{450.0} = 2.22 * 10^{-3}$$

$$\text{Gradient at } 5,2 = \frac{6 - 5}{300} = 3.33 * 10^{-3}$$

$$\text{Gradient at } 5,3 = \frac{6 - 5}{318.75} = 3.14 * 10^{-3}$$

$$\text{Gradient at } 5,4 = \frac{6 - 5}{387.5} = 2.58 * 10^{-3}$$

$$\text{Gradient at } 6,1 = \frac{5 - 4}{337.5} = 2.96 * 10^{-3}$$

$$\text{Gradient at } 6,2 = \frac{5 - 4}{287.5} = 3.48 * 10^{-3}$$

$$\text{Gradient at } 6,3 = \frac{5 - 4}{312.4} = 3.2 * 10^{-3}$$

$$\text{Gradient at } 6,4 = \frac{5 - 4}{393.75} = 2.54 * 10^{-3}$$

$$\text{Gradient at } 7,1 = \frac{4 - 3}{287.5} = 3.48 * 10^{-3}$$

$$\text{Gradient at } 7,2 = \frac{4 - 3}{300} = 3.33 * 10^{-3}$$

$$\text{Gradient at } 7,3 = \frac{4 - 3}{387.5} = 2.58 * 10^{-3}$$

$$\text{Gradient at } 7,4 = \frac{4 - 3}{375} = 2.67 * 10^{-3}$$

$$\text{Average Gradient} = \frac{(4.1 * 10^{-3} + 3.64 * 10^{-3} + \dots + 2.58 * 10^{-3} + 2.67 * 10^{-3})}{21}$$

$$= 3.26 * 10^{-3}$$

MOUND SUBSECTION 11 (FIGURE 4-3b, SECTION 6/7)

$$\text{Gradient at 1,1} = \frac{10 - 9}{225} = 4.44 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{206.25} = 4.85 * 10^{-3}$$

$$\text{Gradient at 3,1} = \frac{8 - 7}{250} = 4 * 10^{-3}$$

$$\text{Gradient at 3,2} = \frac{8 - 7}{250} = 6 * 10^{-3}$$

$$\text{Gradient at 3,3} = \frac{8 - 7}{200} = 5 * 10^{-3}$$

$$\text{Gradient at 4,1} = \frac{7 - 6}{175} = 5.71 * 10^{-3}$$

$$\text{Gradient at 4,2} = \frac{7 - 6}{162.5} = 6.15 * 10^{-3}$$

$$\text{Gradient at 4,3} = \frac{7 - 6}{187.5} = 5.33 * 10^{-3}$$

$$\text{Gradient at 5,1} = \frac{6 - 5}{418.75} = 2.39 * 10^{-3}$$

$$\text{Gradient at } 5,2 = \frac{6 - 5}{368.75} = 2.71 * 10^{-3}$$

$$\text{Gradient at } 5,3 = \frac{6 - 5}{250} = 4 * 10^{-3}$$

$$\text{Gradient at } 6,1 = \frac{5 - 4}{381.25} = 2.62 * 10^{-3}$$

$$\text{Gradient at } 6,2 = \frac{5 - 4}{262.5} = 3.81 * 10^{-3}$$

$$\text{Gradient at } 6,3 = \frac{5 - 4}{168.75} = 5.93 * 10^{-3}$$

$$\text{Gradient at } 7,1 = \frac{4 - 3}{325} = 3.08 * 10^{-3}$$

$$\text{Gradient at } 7,2 = \frac{4 - 3}{187.5} = 5.33 * 10^{-3}$$

$$\text{Gradient at } 7,3 = \frac{4 - 3}{100} = 0.01$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(4.441 * 10^{-3} + 4.85 * 10^{-3} + \dots + 5.33 * 10^{-3} + 0.01)}{17} \\ &= 4.67 * 10^{-3} \end{aligned}$$

MOUND SUBSECTION 12 (FIGURE 4-3b, SECTION 6/7)

$$\text{Gradient at 1,1} = \frac{10 - 9}{187.5} = 5.33 * 10^{-3}$$

$$\text{Gradient at 2,1} = \frac{9 - 8}{200} = 5 * 10^{-3}$$

$$\text{Gradient at 3,1} = \frac{8 - 7}{162.5} = 6.15 * 10^{-3}$$

$$\text{Gradient at 4,1} = \frac{7 - 6}{175} = 5.71 * 10^{-3}$$

$$\text{Gradient at 5,1} = \frac{6 - 5}{187.5} = 5.33 * 10^{-3}$$

$$\text{Gradient at 6,1} = \frac{5 - 4}{125} = 8 * 10^{-3}$$

$$\text{Gradient at 7,1} = \frac{4 - 3}{50} = 0.02$$

$$\begin{aligned} \text{Average Gradient} &= \frac{(5.33 * 10^{-3} + 5 * 10^{-3} + \dots + 8 * 10^{-3} + 0.02)}{7} \\ &= 7.93 * 10^{-3} \end{aligned}$$

APPENDIX D

DETERMINATION OF HYDRAULIC CONDUCTIVITY FROM PUMPING DATA IN THE COLLECTION SYSTEM

The leachates entering the collection line are coming from the leachate mound subsections 1, 2, 4, 5, and 6. From line A, leachate is pumped by pump station A. From line B and C, leachate is pumped by pump station B.

Total length of collection line A = 1485.0 ft.

Pumping rate of station A = 44300 gpd (source : NYCDOS)

From which : gpd/ft. in line A = $44300/1485 = 29.83$

Total length of line B and C = 2850 ft.

Pumping rate of station B = 84,000 gpd (source : NYCDOS)

From which : gpd/ft. in line B and C = $84000/2850 = 29.47$

Mound Subsection 1:

Line A :

Length of collection pipe = 600 ft.

Total flow = $600 * 29.83 = 17898$ gpd = 2392.78 cu.ft/day

Average depth of flow = 22.38 ft. (Appendix E).

Gradient of flow = 0.0218 (Appendix C).

Applying Darcy's Law :

$$Q = K i A$$

$$\text{or, } 2392.78 = K * 0.0218 * 600 * 22.38$$

From which : $K = 8.17 \text{ ft./day.}$

Therefore, the hydraulic conductivity in mound subsection 1 is 8.17 ft./day.

Mound Subsection 2 :

Line A :

Length of collection pipe = 885 ft.

$$\begin{aligned} \text{Total flow} &= 885 * 29.83 = 26399.55 \text{ gpd} \\ &= 3529.35 \text{ cu. ft./day} \end{aligned}$$

Average depth of flow = 25.46 ft (Appendix E).

Gradient of flow = 0.0219 (Appendix C).

Applying Darcy's law :

$$Q = K i A$$

$$\text{or, } 3529.35 = K * 0.0219 * 885 * 25.46$$

From which : $K = 7.1 \text{ ft./day.}$

Therefore, the hydraulic conductivity in mound subsection 2 is 7.1 ft./day.

Mound Subsection 4 :

Line B :

Length of collection pipe = 325 ft.

Total flow = $325 * 29.47 = 9577.75$ gpd
= 1280.45 cu. ft./day

Average depth of flow = 26.45 ft. (Appendix E).

Gradient of flow = 0.1191 (Appendix C).

Applying Darcy's Law :

$$Q = K i A$$

$$\text{or, } 1280.45 = K * 0.1191 * 325 * 26.45$$

From which : $K = 1.25$ ft./day.

Therefore, the hydraulic conductivity in mound subsection 4 is 1.25 ft./day.

Mound Subsection 5 :

Line B:

Length of collection pipe = 1625 ft.

Total flow = $1625 * 29.47 = 47888.75$ gpd
= 6402.24 cu. ft./day

Average depth of flow = 23.68 ft. (Appendix E).

Gradient of flow = 0.0581 (Appendix C).

Applying Darcy's Law :

$$Q = K i A$$

$$\text{or, } 6402.24 = K * 0.0581 * 1625 * 23.68$$

From which : $K = 2.86 \text{ ft./day}$

Therefore, the hydraulic conductivity in mound subsection 5 is 2.86 ft./day .

Mound Subsection 6 :

Line C :

Length of collection pipe = 900 ft.

Total flow = $900 * 29.47 = 26523 \text{ gpd}$

$$= 3545.86 \text{ cu. ft./day}$$

Average depth of flow = 22.42 ft. (Appendix E).

Gradient of flow = 0.0297 (Appendix C).

Applying Darcy's Law :

$$Q = K i A$$

$$\text{or, } 3545.86 = K * 0.0297 * 900 * 22.42$$

From which : $K = 5.92 \text{ ft./day}$.

Therefore, the hydraulic conductivity in mound subsection 6 is 5.92 ft./day .

Average Hydraulic Conductivity (K_{av}) :

$$X = \sum_{i=1}^N K_i * (\text{Length of collection pipe})_i$$

N = Total number of subsections along the collection line.

Y = Total length of the collection pipe.

Therefore,

$$\begin{aligned} X &= 8.17*600 + 7.1*885 + 1.25*325 + 2.86*1625 + 5.92*900 \\ &= 21567.2 \end{aligned}$$

$$\begin{aligned} \text{and } Y &= 600 + 885 + 325 + 1625 + 900 \\ &= 4335 \end{aligned}$$

$$K_{av} = X/Y = 21567.2/4335 = 4.98 \text{ ft./day.}$$

Therefore, the hydraulic conductivity computed from the data of the leachate collection system in Section 1/9 is 4.98 ft./day.

APPENDIX E

DETERMINATION OF LEACHATE FLOW RATES FROM PIEZOMETER AND MONITORING WELL DATA

The average depth of flow is computed as:

$$D_{av} = \frac{\sum_{i=1}^n \left(\text{Depth between two contours} \right)_i \cdot \left(\text{Distance between two contours} \right)_i}{\sum_{i=1}^n \left(\text{Distance between two contours} \right)_i}$$

where,

n = number of stream tubes in the contour map.

Gradients of flow for each subsection have been computed as in Appendix C. Darcy's Law is applied to compute the flow.

SECTION 1/9

MOUND SUBSECTION 1:

Average depth of mound:

$$\begin{aligned} D_{av} &= (22.5 \cdot 296.59 + 17.5 \cdot 181.1 + 12.5 \cdot 183.75 + 27.5 \cdot 519.69) / 1181.11 \\ &= 22 \text{ ft.} \end{aligned}$$

In this subsection flow is known from the pumping rate data and is 17898 gpd.

$$Q_1 = 17898 \text{ gpd (Appendix D)}$$

MOUND SUBSECTION 2:

Average depth of mound:

$$\begin{aligned} D_{av} &= (32.5*549.21 + 27.5*272.97 + 22.5*326.78 + 17.5*164.04 \\ &\quad + 12.5*165.36) / 1478.36 \\ &= 25.46 \text{ ft.} \end{aligned}$$

In this subsection, flow is known from the data available from the collection system, which is:

$$Q_2 = 26399.55 \text{ gpd (Appendix D)}$$

MOUND SUBSECTION 3:

Average depth of mound:

$$D_{av} = (32.5*238.84 + 27.5*135.83 + 22.5*144.36 + 17.5*66.94$$

$$+ 12.5 \times 89.22) / 675.19$$

$$= 25.23 \text{ ft.}$$

Gradient of Flow $i = 0.041$ (Appendix C)

Width = 1063.0 ft.

Hydraulic conductivity $K = 4.98 \text{ ft./day}$

By Darcy's Law:

$$Q_1 = 4.98 \times 0.041 \times 25.23 \times 1063$$

$$= 5476.0 \text{ cu. ft./day}$$

$$= 40960.5 \text{ gpd}$$

MOUND SUBSECTION 4:

Average depth of mound:

$$D_{av} = (32.5 \times 114.2 + 27.5 \times 94.5 + 22.5 \times 31.5 + 17.5 \times 31.5$$

$$+ 12.5 \times 27.56) / 299.0$$

$$= 26.45 \text{ ft.}$$

In this subsection, flow is known from the data available from the collection system, which is:

$$Q_4 = 9577.75 \text{ gpd (Appendix D)}$$

MOUND SUBSECTION 5:

Average depth of mound:

$$\begin{aligned} D_v &= (32.5*129.13 + 27.5*137.80 + 22.50*215.22 + 17.5*93.18 \\ &\quad + 12.5*74.8)/650.13 \\ &= 23.68 \text{ ft.} \end{aligned}$$

In this subsection, flow is known from the data available from the collection system, which is:

$$Q_s = 47888.75 \text{ gpd (Appendix D)}$$

MOUND SUBSECTION 6:

Average depth of mound:

$$\begin{aligned} D_v &= (32.3*259.84 + 27.5*279.54 + 22.5*393.7 + 17.5*141.73 \\ &\quad + 12.5*106.3)/1181.11 \\ &= 22.42 \text{ ft.} \end{aligned}$$

In this subsection, flow is known from the data available from the collection system, which is:

$$Q_s = 26523.0 \text{ gpd (Appendix D)}$$

MOUND SUBSECTION 7:

Average depth of mound:

$$\begin{aligned} D_{av} &= (32.5*328.09 + 27.5*161.42 + 22.5*88.58 + 17.5*55.12 \\ &\quad + 12.5*41.34)/674.6 \\ &= 27.54 \text{ ft.} \end{aligned}$$

Gradient of Flow $i = 0.0378$ (Appendix C)

Width = 1653.0 ft.

Hydraulic conductivity $K = 4.98 \text{ ft./day}$

By Darcy's law:

$$\begin{aligned} Q_7 &= 4.98*0.0378*1653.0*27.54 \\ &= 8388.18 \text{ cu. ft./day} \\ &= 62743.6 \text{ gpd} \end{aligned}$$

MOUND SUBSECTION 8:

Average depth of mound:

$$\begin{aligned} D_{av} &= (32.5*149.61 + 27.5*133.86 + 22.5*125.98 + 17.5*53.15 \\ &\quad + 12.5*56.43)/519.03 \\ &= 25.07 \text{ ft.} \end{aligned}$$

Gradient of Flow $i = 0.0385$ (Appendix C)

Width = 2244 ft.

Hydraulic conductivity K = 4.98 ft./day

By Darcy's Law:

$$\begin{aligned}Q_1 &= 4.98 * 0.0385 * 2244 * 25.07 \\&= 10786.17 \text{ cu. ft./day} \\&= 80680.55 \text{ gpd}\end{aligned}$$

MOUND SUBSECTION 9:

Average depth of mound:

$$\begin{aligned}D_{av} &= (32.5 * 392.39 + 27.5 * 480.32 + 22.5 * 196.85 + 17.5 * 157.48 \\&\quad + 12.5 * 122.06) / 1349.1 \\&= 25.7 \text{ ft.}\end{aligned}$$

Gradient of Flow i = 0.0197 (Appendix C)

Width = 2440 ft.

Hydraulic conductivity K = 4.98 ft./day

By Darcy's Law:

$$\begin{aligned}Q_9 &= 4.98 * 0.0197 * 2440 * 25.7 \\&= 6152.0 \text{ cu. ft./day} \\&= 46017.2 \text{ gpd}\end{aligned}$$

MOUND SUBSECTION 10:

Average depth of mound:

$$\begin{aligned} D_v &= (27.5 * 984.25 + 22.5 * 173.23 + 17.5 * 210.63 \\ &\quad + 12.5 * 204.73) / 1572.84 \\ &= 23.66 \text{ ft.} \end{aligned}$$

Gradient of Flow $i = 0.02$ (Appendix C)

Width = 803.15 ft.

Hydraulic conductivity $K = 4.98$ ft./day

By Darcy's Law:

$$\begin{aligned} Q_{10} &= 4.98 * 0.02 * 803.15 * 23.66 \\ &= 1892.65 \text{ cu. ft./day} \\ &= 14157.04 \text{ gpd} \end{aligned}$$

MOUND SUBSECTION 11:

Average depth of mound:

$$D_v = 17.5 \text{ ft.}$$

Gradient of Flow $i = 0.0348$ (Appendix C)

Width = 2050.0 ft.

Hydraulic conductivity $K = 4.98$ ft./day

By Darcy's Law:

$$\begin{aligned} Q_{11} &= 4.98 * 0.0348 * 2050 * 17.5 \\ &= 6217.28 \text{ cu. ft./day} \\ &= 46505.3 \text{ gpd} \end{aligned}$$

MOUND SUBSECTION 12:

Average depth of mound:

$$D_m = 17.5 \text{ ft.}$$

Gradient of Flow $i = 0.021$ (Appendix C)

Width = 720.0 ft.

Hydraulic conductivity $K = 4.98 \text{ ft./day}$

By Darcy's law:

$$\begin{aligned} Q_{12} &= 4.98 * 0.021 * 720.0 * 17.5 \\ &= 1317.71 \text{ cu. ft./day} \\ &= 9856.46 \text{ gpd} \end{aligned}$$

MOUND SUBSECTION 13:

Average depth of mound:

$$D_m = 17.5 \text{ ft.}$$

Gradient of Flow $i = 0.0295$ (Appendix C)

Width = 500 ft.

Hydraulic conductivity $K = 4.98$ ft./day

By Darcy's Law:

$$\begin{aligned} Q_{13} &= 4.98 * 0.0295 * 500.0 * 17.5 \\ &= 1285.46 \text{ cu. ft./day} \\ &= 9615.26 \text{ gpd} \end{aligned}$$

Therefore, the lateral Leachate flow rate in Section 1/9 is:

$$\begin{aligned} Q_t &= Q_1 + Q_2 + Q_3 + \dots + Q_{13} \\ &= (17898 + 26399.55 + 40960.5 + 9577.75 + 47888.75 + 26523.0 \\ &\quad + 62743.6 + 80680.55 + 46017.2 + 14157.04 + 46509.3 \\ &\quad + 9856.46 + 9615.26) \text{ gpd} \\ &= 438822.86 \text{ gpd} \\ &= 0.439 \text{ mgd} \end{aligned}$$

For vertical flow:

An average depth for the whole section is:

$$\begin{aligned} h &= (22.38 + 25.46 + 25.23 + 26.45 + 23.68 + 22.42 + 27.54 \\ &\quad + 25.07 + 25.70 + 23.66 + 17.5 + 17.5 + 17.5) / 13 \\ &= 23.1 \text{ ft.} \end{aligned}$$

Hydraulic conductivity of the clay, $K_c = 10^{-7}$ cm/sec

$$= 0.000283 \text{ ft/day}$$

Area of landfill surface = 405 acres

Thickness of clay at the bottom $d = 16.25$ ft.

The vertical flow:

$$Q_v = K_c A \frac{(h + d)}{d}$$

$$= 0.000283 * (405 * 43560) * \frac{(23.1 + 16.25)}{16.25}$$

$$= 12089.8 \text{ cu. ft./day}$$

$$= 90432.0 \text{ gpd}$$

$$= 0.09 \text{ mgd}$$

Total leachate flow in Section 1/9 is:

$$Q_T = Q_L + Q_v$$

$$= (0.439 + 0.09) \text{ mgd}$$

$$= 0.529 \text{ mgd}$$

SECTION 6/7

MOUND SUBSECTION 1:

Average depth of mound:

$$D_{av} = (9.5 * 231.25 + 8.5 * 231.25 + 7.5 * 212.5 + 6.5 * 237.5 +$$

$$+ 5.5*237.5 + 4.5*206.25 + 3.5*243.75)/1600$$

$$= 6.49 \text{ ft.}$$

$$\text{Gradient of Flow } i = 4.38 * 10^{-3} \text{ (Appendix C)}$$

$$\text{Width} = 1787.5 \text{ ft.}$$

$$\text{Hydraulic conductivity } K = 56.67 \text{ ft./day}$$

By Darcy's Law:

$$Q_1 = K i A$$

$$= 56.67*4.38*10^{-3}* 1787.5*6.49$$

$$= 2879.51 \text{ cu. ft./day}$$

$$= 21538.71 \text{ gpd}$$

$$= 0.0215 \text{ mgd}$$

MOUND SUBSECTION 2:

Average depth of mound:

$$D_{av} = (9.5*237.5 + 8.5*237.5 + 7.5*243.75 + 6.5*262.5 +$$

$$+ 5.5*212.5 + 4.5*225 + 3.5*162.5)/1581.25$$

$$= 6.68 \text{ ft.}$$

$$\text{Gradient of Flow } i = 5.48*10^{-3} \text{ (Appendix C)}$$

$$\text{Width} = 1575.0 \text{ ft.}$$

$$\text{Hydraulic conductivity } K = 56.67 \text{ ft./day}$$

By Darcy's Law:

$$\begin{aligned}Q_2 &= K i A \\&= 56.67 * 5.48 * 10^{-3} * 1575 * 6.68 \\&= 3267.31 \text{ cu. ft./day} \\&= 24439.5 \text{ gpd}\end{aligned}$$

MOUND SUBSECTION 3:

Average depth of mound:

$$\begin{aligned}D_{av} &= (9.5 * 203.13 + 8.5 * 175 + 7.5 * 200 + 6.5 * 178.13 + \\&\quad + 5.5 * 193.75 + 4.5 * 152.1 + 3.5 * 64.58) / 1166.69 \\&= 6.90 \text{ ft.}\end{aligned}$$

Gradient of Flow $i = 7.97 * 10^{-3}$ (Appendix C)

Width = 2000.0 ft.

Hydraulic conductivity $K = 56.67 \text{ ft./day}$

By Darcy's Law:

$$\begin{aligned}Q_3 &= K i A \\&= 56.67 * 7.97 * 10^{-3} * 2000 * 6.90 \\&= 6232.91 \text{ cu. ft./day} \\&= 46622.14 \text{ gpd}\end{aligned}$$

MOUND SUBSECTION 4:

Average depth of mound:

$$D_v = (9.5*218.75 + 8.5*168.75 + 7.5*125 + 6.5*237.5 + 5.5*215.63 + 4.5*168.75 + 3.5*133.33)/1267.71$$

$$= 6.63 \text{ ft.}$$

Gradient of Flow = $6.23*10^{-3}$ (Appendix C)

Width = 1175.0 ft.

Hydraulic conductivity K = 56.67 ft./day

By Darcy's Law:

$$Q_d = K i A$$

$$= 56.67*6.23*10^{-3}*1175*6.63$$

$$= 2750.38 \text{ cu. ft./day}$$

$$= 20572.84 \text{ gpd}$$

MOUND SUBSECTION 5:

Average depth of mound:

$$D_v = (9.5*181.25 + 8.5*225 + 7.5*162.5 + 6.5*225 + 5.5*206.25 + 4.5*150.0 + 3.5*196.88)/1346.88$$

$$= 6.54 \text{ ft.}$$

Gradient of Flow = $5.5*10^{-3}$ (Appendix C)

Width = 987.5 ft.

Hydraulic conductivity K = 56.67 ft./day

By Darcy's Law:

$$\begin{aligned}Q_5 &= K i A \\&= 56.67 * 5.5 * 10.9 * 987.5 * 6.54 \\&= 2012.94 \text{ cu. ft./day} \\&= 15056.79 \text{ gpd}\end{aligned}$$

MOUND SUBSECTION 6:

Average depth of mound:

$$\begin{aligned}D_{av} &= (9.5 * 125 + 8.5 * 125 + 7.5 * 100 + 6.5 * 112.5 + 5.5 * 93.75 + \\&\quad + 4.5 * 112.5 + 3.5 * 100) / 768.75 \\&= 6.64 \text{ ft.}\end{aligned}$$

$$\text{Gradient of Flow} = 9.21 * 10^{-3} \text{ (Appendix C)}$$

$$\text{Width} = 2187.5 \text{ ft.}$$

$$\text{Hydraulic conductivity } K = 56.67 \text{ ft./day}$$

By Darcy's Law:

$$\begin{aligned}Q_6 &= K i A \\&= 56.67 * 9.21 * 10^{-3} * 2187.5 * 6.64 \\&= 7581.04 \text{ cu. ft./day} \\&= 56706.20 \text{ gpd}\end{aligned}$$

MOUND SUBSECTION 7:

Average depth of mound:

$$\begin{aligned} D_{av} &= (9.5*153.13 + 8.5*106.25 + 7.5*75 + 6.5*81.25 + 5.5*75 + \\ &\quad + 4.5*100.0 + 3.5*112.5)/703.13 \\ &= 6.69 \text{ ft.} \end{aligned}$$

Gradient of Flow $i = 9.45*10^{-3}$ (Appendix C)

Width = 2800 ft.

Hydraulic conductivity $K = 56.67 \text{ ft./day}$

By Darcy's Law:

$$\begin{aligned} Q_7 &= K i A \\ &= 56.67*9.45*10^{-3}*2800*6.69 \\ &= 10031.58 \text{ cu. ft./day} \\ &= 75036.19 \text{ gpd} \end{aligned}$$

MOUND SUBSECTION 8:

Average depth of mound:

$$\begin{aligned} D_{av} &= (9.5*225 + 8.5*99.98 + 7.5*118.75 + 6.5*106.25 + \\ &\quad + 5.5*154.17 + 4.5*131.25 + 3.5*106.25)/941.65 \\ &= 6.77 \text{ ft.} \end{aligned}$$

Gradient of Flow $i = 8.23*10^{-3}$ (Appendix C)

Width = 1737.5 ft.

Hydraulic conductivity K = 56.67 ft./day

By Darcy's Law:

$$\begin{aligned}Q_1 &= K i A \\&= 56.67 * 8.23 * 10^{-3} * 1737.5 * 6.77 \\&= 5486.14 \text{ cu. ft./day} \\&= 41036.3 \text{ gpd}\end{aligned}$$

MOUND SUBSECTION 9:

Average depth of mound:

$$\begin{aligned}D_{av} &= (9.5 * 293.73 + 8.5 * 253.13 + 7.5 * 168.75 + 6.5 * 225 + \\&\quad + 5.5 * 331.25 + 4.5 * 325 + 3.5 * 198.44) / 1795.3 \\&= 6.5 \text{ ft.}\end{aligned}$$

Gradient of Flow = $5.22 * 10^{-3}$ (Appendix C)

Width = 1975.0 ft.

Hydraulic conductivity K = 56.67 ft./day

By Darcy's law:

$$\begin{aligned}Q_9 &= K i A \\&= 56.67 * 5.22 * 10^{-3} * 1975 * 6.5 \\&= 3797.56 \text{ cu. ft./day}\end{aligned}$$

$$= 28405.72 \text{ gpd}$$

MOUND SUBSECTION 10:

Average depth of mound:

$$\begin{aligned} D_{av} &= (9.5*243.75 + 8.5*321.88 + 7.5*306.25 + 6.5*278.13 \\ &\quad + 5.5*364.06 + 4.5*332.81 + 3.5*337.5)/2184.38 \\ &= 6.33 \text{ ft.} \end{aligned}$$

Gradient of Flow $i = 3.26*10^{-3}$, (Appendix C)

Width = 3487.5 ft.

Hydraulic Conductivity $K = 56.67 \text{ ft./day}$

By Darcy's Law:

$$\begin{aligned} Q_{10} &= K i A \\ &= 56.67*3.26*10^{-3}*3487.5*6.33 \\ &= 4078.39 \text{ cu. ft./day} \\ &= 30506.36 \text{ gpd} \end{aligned}$$

MOUND SUBSECTION 11:

Average depth of mound:

$$D_w = (9.5*225 + 8.5*206.25 + 7.5*233.33 + 6.5*175 + 5.5*345.83 + 4.5*270.83 + 3.5*204.17)/1660.21$$

$$= 6.39 \text{ ft.}$$

Gradient of Flow $i = 4.67*10^{-3}$ (Appendix C)

Width = 1887.5 ft.

Hydraulic conductivity $K = 56.67 \text{ ft./day}$

By Darcy's Law:

$$Q_d = K i A$$

$$= 56.67*4.67*10^{-3}*1887.5*6.39$$

$$= 3191.96 \text{ cu. ft./day}$$

$$= 23875.89 \text{ gpd}$$

MOUND SUBSECTION 12:

Average depth of mound:

$$D_w = (9.5*187.5 + 8.5*200 + 7.5*162.5 + 6.5*175 + 5.5*187.5 + 4.5*125 + 3.5*50)/1087.5$$

$$= 6.99 \text{ ft.}$$

Gradient of Flow $i = 7.93*10^{-3}$ (Appendix C)

Width = 1787.5 ft.

Hydraulic conductivity $K = 56.67 \text{ ft./day}$

By Darcy's Law:

$$\begin{aligned}Q_{12} &= K \ i \ A \\&= 56.67 * 7.93 * 10^{-3} * 1787.5 * 6.99 \\&= 5615.0 \text{ cu. ft./day} \\&= 42000.0 \text{ gpd}\end{aligned}$$

Therefore, the lateral leachate flow rate in Section 6/7 is:

$$\begin{aligned}Q_1 &= Q_1 + Q_2 + Q_3 + \dots + Q_{12} \\&= 21538.71 + 24439.5 + 46622.14 + 20572.84 + 15056.79 + \\&\quad 56706.20 + 75036.19 + 41036.3 + 28405.72 + 30506.36 + \\&\quad 23875.89 + 42000.0 \\&= 425796.64 \text{ gpd} \\&= 0.426 \text{ mgd}\end{aligned}$$

For vertical flow:

An average depth for the whole section is:

$$\begin{aligned}h &= (6.49 + 6.68 + 6.90 + 6.63 + 6.54 + 6.64 + 6.69 + 6.77 + \\&\quad + 6.50 + 6.33 + 6.39 + 6.99) / 12 \\&= 6.63 \text{ ft.}\end{aligned}$$

$$\begin{aligned}\text{Hydraulic conductivity of the clay, } K_v &= 10^{-7} \text{ cm/sec} \\&= 0.000283 \text{ ft./day}\end{aligned}$$

Area of landfill surface A = 376 acres

Thickness of clay at the bottom d = 18.45 ft.

The vertical flow:

$$\begin{aligned} Q_v &= K_v A \frac{(h + d)}{d} \\ &= 0.000283 * (376 * 43560) * \frac{(6.63 + 18.45)}{18.45} \\ &= 6300.77 \text{ cu. ft/day} \\ &= 47129.73 \text{ gpd} \\ &= 0.047 \text{ mgd} \end{aligned}$$

Total leachate flow in Section 6/7 is:

$$\begin{aligned} Q_T &= Q_L + Q_v \\ &= (0.426 + 0.047) \text{ mgd} \\ &= 0.473 \text{ mgd} \end{aligned}$$

**DATE
FILMED**

12/22/93

END