

PNL-10872
UC- 2000

HANFORD PROTOTYPE-BARRIER STATUS
REPORT: FY 1995

G. W. Gee
A. L. Ward
B. G. Gilmore
M. W. Ligothe
S. O. Link

November 1995

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 183

Pacific Northwest National Laboratory
Richland, Washington 99352

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

at

MASTER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

EXECUTIVE SUMMARY

Testing and monitoring of the prototype surface-barrier, located at the 200 BP-1 Operable Unit in the 200 East Area of the Hanford Site, was initiated in October, 1994 and has continued for one year. During the year, the surface was revegetated and surveyed and root-observation tubes were installed to follow root growth and water penetration into the surface cover. Wind erosion was documented, water erosion measured, and detailed measurements of plant establishment and water balance collected on the prototype.

Wind erosion occurred only in the first three months, when the surfaces were nonvegetated. After vegetation was established, there was no measurable loss of soil from the surface from wind erosion. In March, 1995, the surface on the north half of the prototype barrier was irrigated with 70 mm of water in 8 hours, an amount in excess of a 1000-year storm event for the Hanford Site. In spite of the extreme water application, runoff was found to be only a small fraction of the applied water (less than 2 mm out of 70 mm applied). After March, water applications via irrigation and precipitation were adjusted to meet yearly target amounts of 480 mm/yr by accounting for the extreme March event and adding water in April and May to make up for lower-than-target applications earlier in the year.

Water infiltration, redistribution, and drainage on the surface and side-slopes of the barrier were documented for the 1000-year storm event and for other periods throughout the year. During the year, no drainage occurred from any of soil covered plots, for either irrigated or ambient (non-irrigated) treatments. In contrast, drainage was observed on all of the sideslope plots whether irrigated or not. Drainage from the side-slopes was attributed to coarse (rock and gravel) surfaces and lack of vegetation. The most drainage occurred from the clean-fill (gravel) surfaces. Sideslope water infiltration is an issue that will need to be addressed in design of above-grade surface barriers at the Hanford Site. Extended area of side-slopes could potentially induce excessive water infiltration at the edges of waste sites.

Water content and storage were documented with down-well-type neutron probes using vertical

and horizontal arrays of access tubes. The water storage data indicate that after one year, the water storage has been depleted throughout the entire 2-m soil profile to a common lower-limit (about 115 mm) for both irrigated and ambient treatments. Vegetation was able to extract water easily and efficiently at all depths. Data from the root observation tubes confirmed the presence of roots at all monitoring depths. Water storage changes observed in the 2-m-deep soil cover of the prototype barrier are similar to those observed previously in lysimeter tests using 1.5-m-deep soils. The storage data indicate that the 2-m-deep profile is not excessive for Hanford Site conditions and that water can be removed effectively from the entire soil volume even under elevated precipitation (e.g., irrigated) conditions.

Vegetation was established quickly on the soil-covered sections of the prototype barrier. The transplanted shrubs and seeded grasses were established successfully in November of 1994. Subsequently there was a prolific invasion of tumbleweed (*Salsola kali*), which grew rapidly and completely covered the plot by early summer 1995. There appeared to be no measurable difference between vegetative growth on the irrigated and nonirrigated (ambient) sections of the prototype for tumbleweed. However, for shrub seedlings, the shoot height of sagebrush (*Artemisia tridentata*) and rabbitbrush (*Chrysothamnus nauseosus*) were both greater on the irrigated than on the ambient plots. The sideslopes remained nearly vegetation free during the first year of testing. Lack of vegetation on the sideslopes is likely the result of a poor rooting environment (low water storage) in the coarse (rock and gravel) materials.

Monitoring of surface subsidence, water balance, wind and water erosion, and vegetation changes will continue for the next two years. Drainage from sideslopes and movement of materials on sideslopes will be carefully documented. Evaluations will be made regarding the sideslope issues, including excess drainage and subsidence near or at the edge of the prototype barrier.

ACKNOWLEDGMENTS

We wish to thank our support staff, Jason Ritter, Rod Davis, Ray Clayton, Gary Dennis, and Bill Perkins, who ably assisted in the testing and monitoring of the prototype during the year. We also acknowledge support from Melvin Campbell and Wally Walters, who supported this study in its early stages and have now retired from PNL. Melvin provided the engineering design, including the water and electrical supply, for the irrigation and snowmaking systems and conducted the initial tests of these systems. Wally conceived, designed, and built the slope-creep gauges for the sideslopes and initiated the first survey of the prototype. We thank them for their foresight and valuable technical assistance. We also wish to thank Dick Wing, who was the cognizant engineer (formerly with Westinghouse Hanford and IT Corp) who reviewed the initial testing and monitoring proposals and provided valuable insight for this work. We also thank Mark Buckmaster, of Bechtel Hanford, Inc. (BHI), cognizant engineer for the prototype barrier who has provided management oversight and support to this work. Funding for the testing and monitoring of the prototype has been provided by the U.S. Department of Energy's Environmental Restoration Program (EM-40) under contract DE-AC06-76RLO 1830.

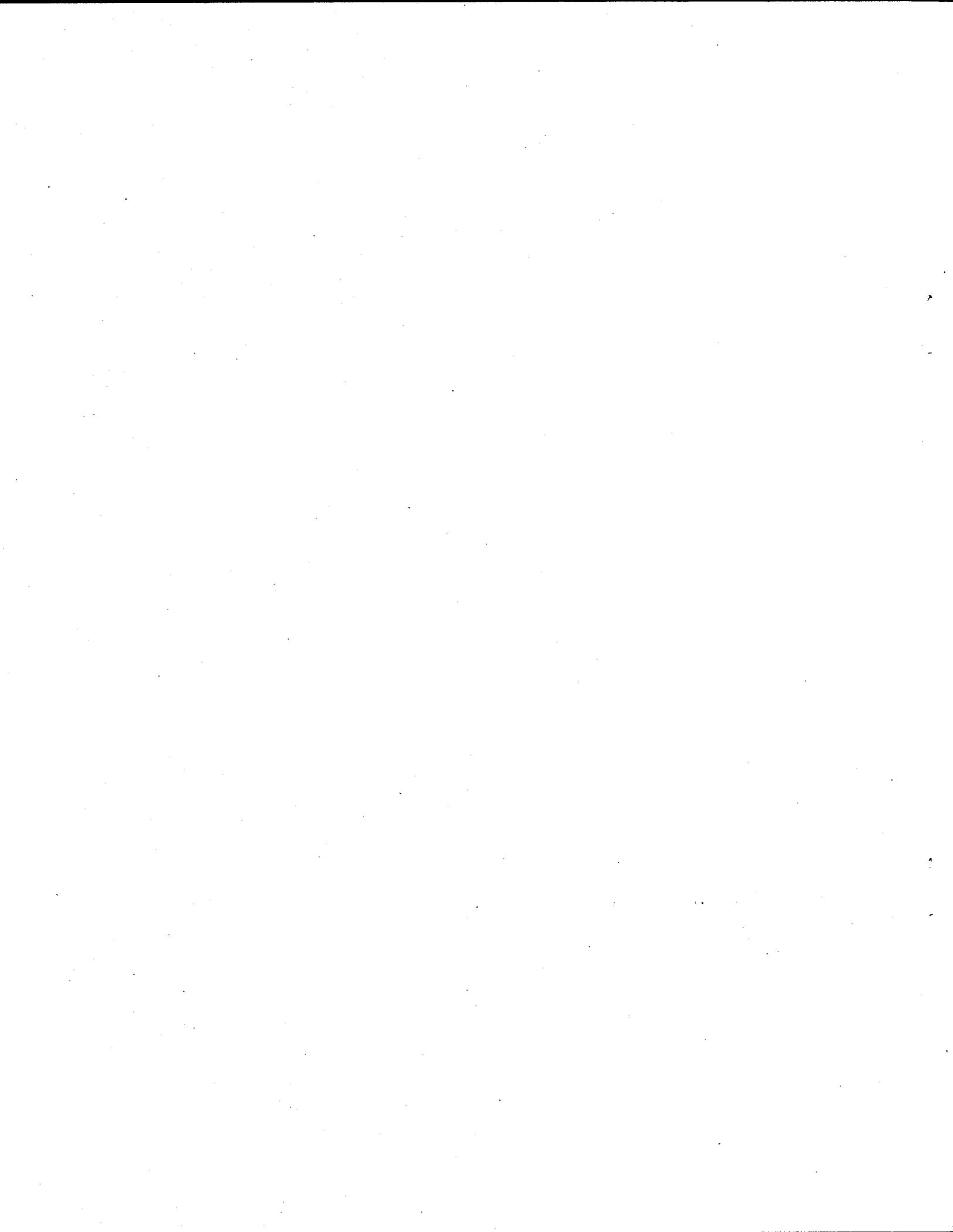
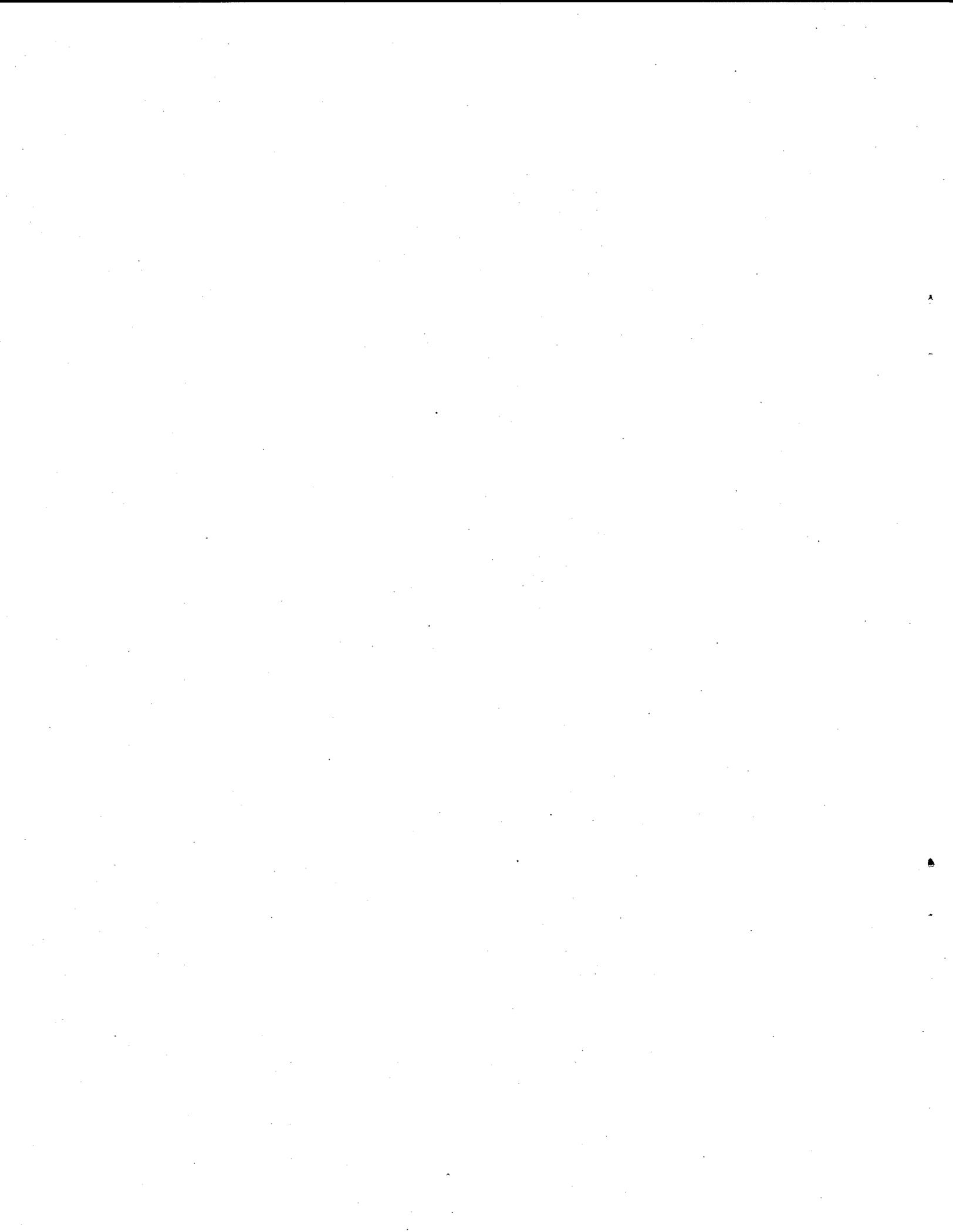


TABLE OF CONTENTS

EXECUTIVE SUMMARY	iii
ACKNOWLEDGMENTS	v
1.0 INTRODUCTION	1.1
2.0 WATER BALANCE EVALUATION	2.1
2.1 PRECIPITATION AND IRRIGATION	2.2
2.2 VERTICAL SOIL WATER CONTENT MEASUREMENTS	2.5
2.2.1 Vertical Neutron Probe Measurements	2.6
2.2.2 Capacitance Probe Measurements	2.8
2.2.3 Time Domain Reflectometry (TDR) Measurements	2.10
2.2.4 Electromagnetic Induction Measurements	2.13
2.3 HORIZONTAL SOIL WATER CONTENT MEASUREMENTS	2.14
2.3.1 Horizontal Silt-Loam Measurements	2.15
2.3.2 Below Asphalt Measurements	2.17
2.4 SOIL WATER POTENTIAL	2.19
2.5 DRAINAGE	2.21
2.6 SOIL WATER STORAGE	2.26
2.7 WATER BALANCE	2.27
2.8 SUMMARY	2.28
3.0 WATER EROSION MONITORING	3.1
3.1 CONTROLLED AREA TESTING	3.1
3.1.1 Objective	3.1
3.1.2 Methods	3.2
3.1.3 Results	3.2
3.2 TEMPORARY TEST PLOT	3.4

3.2.1	Objective	3.4
3.2.2	Methods	3.4
3.2.3	Results	3.5
3.3	SOIL SURFACE MONITORING	3.7
3.3.1	Objectives	3.7
3.3.2	Methods	3.7
3.4	EVALUATION	3.8
3.4.1	Results	3.8
3.5	CREEP AND SETTLEMENT GAUGES	3.9
3.6	SOIL PROPERTIES	3.13
3.6.1	Soil Water Content	3.13
3.6.2	Density	3.13
3.7	PLANTS	3.14
3.8	SUMMARY	3.14
4.0	WIND EROSION MONITORING TASK	4.1
4.1	SCOPE AND OBJECTIVES	4.1
4.2	WIND EROSION TESTING AND MONITORING ACTIVITIES	4.2
4.2.1	Prototype Barrier Surface Layer	4.2
4.2.2	Surface Layer Composition and Deflation/Inflation	4.3
4.2.3	Wind Stress Monitoring	4.5
4.2.4	Monitoring Saltation Stresses and Sand Drift Rate	4.9
4.3	CONCLUSIONS AND RECOMMENDATIONS	4.14
5.0	REVEGETATION AND BIOINTRUSION	5.1
5.1	REVEGETATION	5.1
5.2	BIOINTRUSION	5.2
5.2.1	Vegetative Composition	5.2
5.2.2	Plant Distribution	5.3
5.2.3	Plant Gas Exchange	5.4
5.2.4	Root and Soil Water Observations	5.8

5.2.5	Plant Size	5.9
5.3	ANIMAL OBSERVATIONS	5.14
5.4	CONCLUSIONS	5.14
6.0	FUTURE TESTING AND MONITORING PLANS	6.1
6.1	WATER BALANCE MONITORING AND TESTS	6.1
6.2	WATER EROSION AND SURFACE STABILITY MEASUREMENTS	6.2
6.3	WIND EROSION	6.2
6.4	BIOINTRUSION	6.3
7.0	REFERENCES	7.1
8.0	BARRIER PUBLICATIONS	8.1



FIGURES

1.1	Completed Prototype Barrier at the 200 BP-1 Operable Unit, 200 East Area Hanford Site, Washington, photo taken September 1995.	1.2
2.2	Schematic of the prototype surface barrier showing the layout of precipitation treatments and instrumentation	2.1
2.2	Long-term (1946-1994) average, and WY 1995 precipitation based on the HMS records (after Hoitink and Burk 1995	2.3
2.3	Precipitation data for the PSB during WY 1995. Ambient precipitation data were recorded by the HMS	2.5
2.4	Mean profiles of water content averaged by treatment at the PSB in FY 1995 on (a) 01/04, (b) 03/23; (c) 03/27, after the 1000-yr storm, and (d) 05/31, as measured by NP	2.7
2.5	Temporal changes in water mean content profiles (averaged by treatment) over the summer of FY 1995 on (a) 3X treatments and (b) 1X treatments, as measured by NP.	2.8
2.6	Comparison of $\theta(z)$ measured by CP and NP on two dates in FY 1995 on (a) 3X plots on 03/23, (b) 3X plots on 03/27, (c) ambient plots on 03/23, and (b) ambient on 03/27.	2.9
2.7	Temporal variation in $\theta(z)$ over a 4-hr period on 03/25/95. Measurements were taken on the 3X plot at (a) station 1 and (b) station 3 using segmented TDR probes	2.11
2.8	Comparison of $\theta(z)$ measured by TDR and NP (3X treatments) on (a) 03/23/95 and (b) 03/27/95, two days after the 1000-yr storm event	2.12
2.9	Comparison of $\theta(z)$ measured by TDR and NP on 09/09/95 on (a) 3X treatment, and (b) ambient treatments	2.12
2.10	Comparison of bulk electrical conductivity profile, measured by EM38, and θ measured by NP on 09/30/94.	2.14
2.11	Horizontal, silt loam water contents on (a) 12/29/94, and in 1995 on (b) 05/31, (c) 07/14, and (d) 10/12, on the 3X and ambient treatments	2.16
2.12	Temporal changes in horizontal NP counts in the vicinity of the edge of the asphalt pad at the northeastern corner of the PSB	2.17
2.13	Spatial distribution of averaged NP horizontal counts at 1.0 m below the asphalt pad on two dates in FY 1995	2.19

2.14	Spatially averaged profiles of matric potential for the 3X treatments at selected times during FY 1995	2.20
2.15	Schematic of dosing siphon vault and the associated sensors and components (not to scale)	2.22
2.16	Sideslope drainage records for the period 03/29/95 to 09/30/95 on (a) 4W, (b) 4E, (c) 1W, and (d) 1E	2.23
2.17	Silt loam drainage records for the period 03/29/95 to 09/30/95 on (a) 6W, (b) 6E, (c) 3W, and (d) 3E..	2.24
2.18	Soil water storage in FY 1995 on the 3X and ambient treatments. Storage was calculated from NP measurements of water content..	2.26
3.1	Runoff hydrograph, rainfall application and sediment concentration amounts for 1000-year water application tests	3.6
3.2	Topographic contours of barrier surface A) December 1994 B) August 1995	3.10
3.3	Prototype surface elevation differences in intervals of 5mm. Differences from December 1994 and August 1995	3.11
3.4	Three-dimensional elevation change map for prototype barrier. Changes from December 1994 to August 1995	3.12
3.5	Surface soilwater content December 1994 contours in August 1995	3.16
3.6	Surface soil density in December 1994 and August 1995	3.17
3.7	Prototype barrier soil density changes December 1994 to August 1995	3.18
3.8	Prototype barrier grass density contours for April 1995. Density is grass number per 9 m ²	3.19
4.1	Peak gust wind profiles measured over the elevated surface of the prototype barrier, 10/26/94	4.8
4.2	Daily total solar radiation, 9/15/94 through 8/31/95	4.8
4.3	Measured vertical profiles of soil and sand blowing across the surface of the prototype barrier, 8/29/94 - 11/1/94	4.12
4.4	Normalized vertical profile of soil and sand blowing across the surface of the prototype barrier, 8/29/94 - 11/1/94	4.12

4.5	Particle size distribution of material collected in dust traps, 8/29/94 - 11/1/94	4.13
5.1	Prototype barrier native and invasive alien forb density contours for April 1995. Density is plant number per 9 m ²	5.5
5.2	Prototype barrier dead <i>Chrysothamnus nauseosus</i> shrub density contours for April 1995. Density is plant number per 9 m ²	5.6
5.3	Prototype barrier dead <i>Artemisia tridentata</i> shrub density contours for April 1995. Density is plant number per 9 m ²	5.7
5.4	Stomatal conductance during the spring on <i>Artemisia tridentata</i> and <i>Chrysothamnus nauseosus</i> in ambient precipitation and irrigated treatments	5.10
5.5	Transpiration rates during the spring of <i>Artemisia tridentata</i> and <i>Chrysothamnus nauseosus</i> in ambient precipitation and irrigated treatments	5.11
5.6	Net photosynthetic rates during the spring on <i>Artemisia tridentata</i> and <i>Chrysothamnus nauseosus</i> in ambient precipitation and irrigated treatments	5.11
5.7	Root length density with depth in the ambient precipitation and irrigated treatments	5.12
5.8	Root length density for combined treatments (ambient and irrigated)	5.12
5.9	Shoot height of <i>Artemisia tridentata</i> , <i>Chrysothamnus nauseosus</i> , and <i>Salsola kali</i> in the ambient precipitation and irrigated treatments for late July	5.13

TABLES

2.1	Drainage (mm of water) by treatment at the PSB during FY 1995..	2.25
2.2	Water balance for silt loam 3X treatments at the PSB in FY 1995..	2.29
2.3	Water balance for silt loam 1X treatments at the PSB in FY 1995	2.30
3.1	Daily rainfall amounts at barrier controlled area test plot in mm.	3.3

1.0 INTRODUCTION

Surface barriers (or covers) have been proposed for use at the Hanford Site as a means to isolate certain waste sites that, for reasons of cost or worker safety or both, may not be exhumed. Surface barriers are intended to isolate the wastes from the accessible environment and to provide long-term protection to future populations that might use the Hanford Site. Currently, no "proven" long-term barrier system is available. For this reason, the Hanford Site Permanent Isolation Surface-Barrier Development Program (BDP) was organized to develop the technology needed to provide long-term surface barrier capability for the Hanford Site for the U.S. Department of Energy (DOE) (Wing 1994). Designs have been proposed to meet the most stringent needs for long-term waste disposal.

The objective of the current barrier design is to use natural materials to develop a protective barrier system that isolates wastes for at least 1000 years by limiting water, plant, animal, and human intrusion; and minimizing erosion. The design criteria for water drainage has been set at 0.5 mm/yr (Myers and Duranceau 1994). While other design criteria (i.e., wind, water, and biointrusion rates) are more qualitative, it is clear that waste isolation for an extended time is the prime objective of the design. Constructibility and performance are issues that can be tested and dealt with by evaluating prototype designs prior to extensive construction and deployment of covers for waste sites at Hanford.

The Barrier Development Plan (Wing 1994) has been the baseline planning document for the development of protective barrier systems on the Hanford Site. The plan identifies, describes, and logically relates the tasks required to resolve the technical concerns regarding protective barrier systems. The document was intended to provide information regarding technical developments, cost estimates, and scheduled completion dates of barrier and marker development tasks. The plan provides general direction for and integration of all Hanford Site barrier studies. This program through a series of sequential steps, has led to the construction of a prototype barrier over an operable unit (200-BP-1) at the Hanford Site. Details of the design, construction, and initial testing plan for the prototype barrier are available in published barrier documents (see Section 8.0). The prototype consists of a 2.5 ha surface barrier, that covers an existing waste site (B-57 Crib). Figure 1.1 is an areal view of the completed prototype barrier as seen in September 1995.

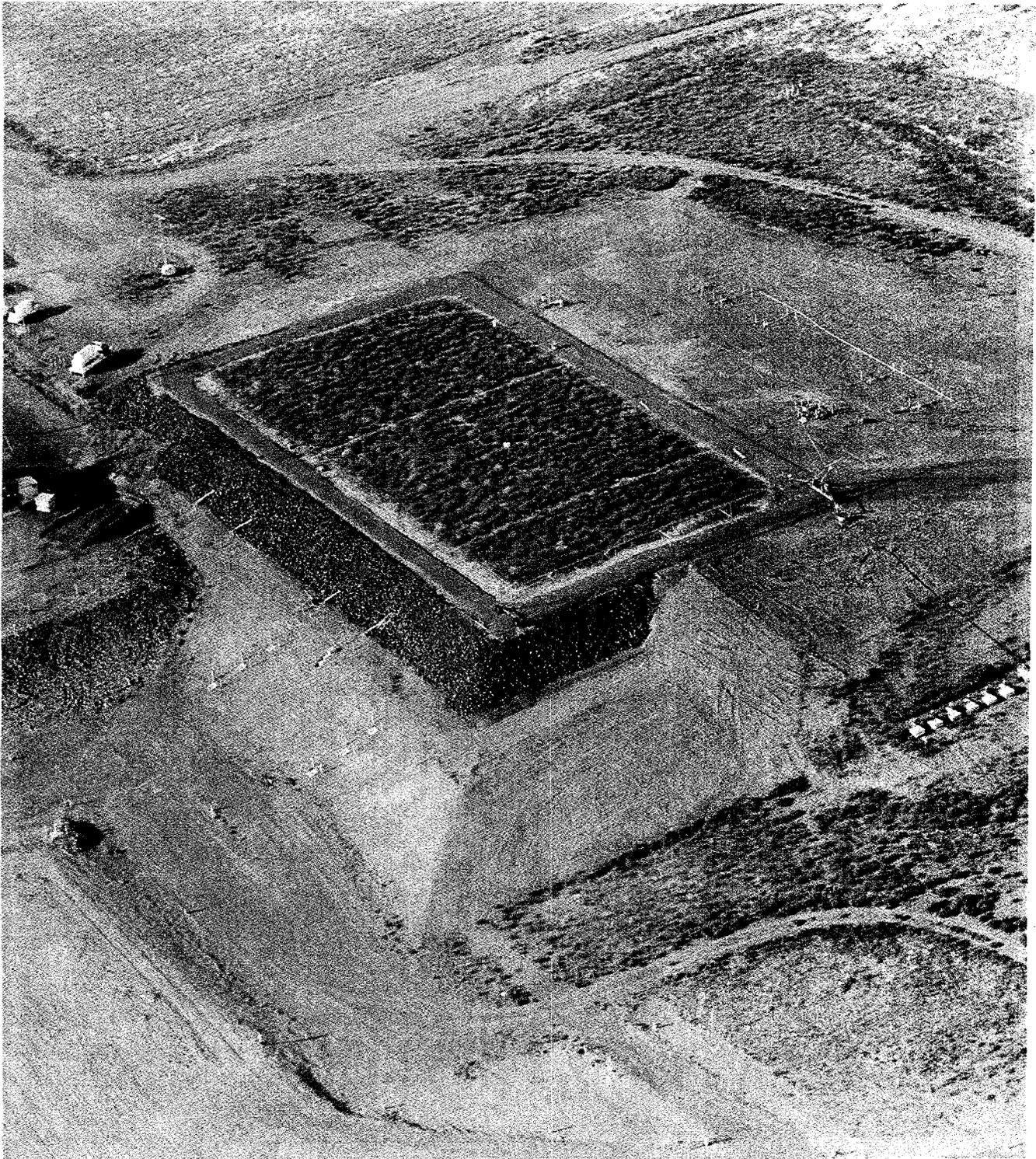


Figure 1.1. Completed prototype barrier at the 200 BP-1 Operable Unit, 200 East Area Hanford Site, Washington. Photo taken in September 1995.

The testing and monitoring of the prototype constitutes a significant commitment by DOE to evaluate the performance of surface barriers at the Hanford Site. The full-scale prototype protective barrier has allowed engineers and scientists to gain experience in barrier design, construction, and performance that could be gained in no other way (Wing and Gee 1994; Gee et al. 1994, Petersen et al. 1995). The essential elements of the testing and monitoring consist of testing the prototype under ambient (natural precipitation) and irrigated (elevated precipitation) conditions. The irrigation treatment includes application of an extreme (1000-year) event in March of each test year and the total application (including precipitation) of 480 mm/yr (3 times the annual average precipitation). Detailed water balance measurements (including precipitation, irrigation, water storage and drainage) are currently being monitored. Water erosion, wind erosion, and biointrusion parameters are also being documented on the prototype barrier.

It should be noted that several treatments and measurements described in the original test plan (Gee et al. 1993a) will not be accomplished. These include tracer tests, noninvasive geophysical measurements, and artificial snow applications. In addition, the detailed data base management task has been omitted. Individual tasks (water balance, wind, water erosion, and biointrusion) have assumed the responsibility for archiving task data that can be assembled from electronic and manual records and are on file with each manager of individual project tasks..

This document summarizes work completed in FY 1995 on the prototype barrier. Water balance, water erosion, wind erosion, revegetation, and biointrusion testing and monitoring activities are described in detail in Sections 2.0 through 5.0, with the status of each major activity summarized at the end each section. Planned activities for FY 1996 are summarized in Section 6.0. A current list of barrier publications is provided at the end of this document.

2.0 WATER BALANCE EVALUATION

The primary function of the Water Balance Task is to demonstrate the ability of the prototype surface barrier (PSB) to control infiltration of water to the underlying waste. Of particular importance is the generation of complete, multi-year, water-balance data sets that can be used to prove effectiveness of the barrier for extended times. These data, supported by hydraulic property and plant characterization data, are crucial for assessing long-term barrier performance. Such an assessment is important to the direction of future barrier development activities.

Testing and monitoring for the Water Balance Task is organized based on two precipitation treatments. Figure 2.1 shows a schematic of the PSB and includes the layout of the precipitation treatments and instrumentation.

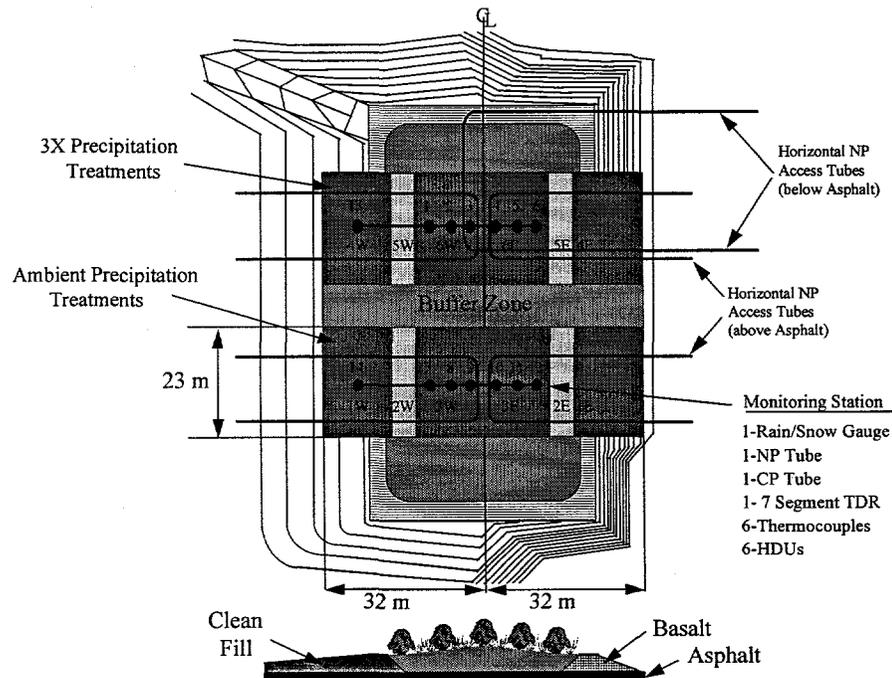


Figure 2.1 Schematic of the prototype surface barrier showing the layout of precipitation treatments and instrumentation (not to scale).

A detailed discussion of the treatments is provided by Gee et al. (1994). Briefly, the northern half of the barrier is irrigated at three times the average annual rainfall (3X) for Hanford. The southern half receives only ambient precipitation.

A total of 14 monitoring stations have been installed on the PSB, seven on the irrigated treatment areas and seven on the ambient precipitation treatment areas. On each precipitation treatment area, six stations are located on the silt loam surface and one on the clean-fill side slope. Each station is equipped with vertical access tubes for the neutron probe (NP) and capacitance probe (CP), a seven-segment, shorting-diode Time Domain Reflectometry (TDR) probe, heat dissipation units (HDUs), and thermocouples. Complete descriptions of these sensors, their principles of operation, and interpretation of their measurements are discussed by Gee et al. (1994). In the northeastern corner of the PSB, there are three sets of horizontal NP access tubes for monitoring water content changes under the asphalt layer. Both the 3X and ambient treatments are instrumented with horizontal NP access tubes for monitoring water content at the 2.0 m depth.

Data collection for the Water Balance Task commenced soon after construction was completed. On 08/08/94, a series of soil cores were taken from the PSB surface to determine the placed water contents and bulk densities. The depths of measurement ranged from 2.0 to 35 cm in the silt loam-admix. At the end of construction, the dry bulk density, ρ_b , was $1.38 \pm 0.121 \text{ g m}^{-3}$, while the volumetric water content, θ , was $0.107 \pm 0.019 \text{ m}^3 \text{ m}^{-3}$. In early September 1994, a total of 150 mm of water was applied to the surface to reduce wind erosion and to facilitate the installation of instruments and access tubes in the surface of the PSB. On 09/30/94, the first NP measurements of vertical profiles of water content were taken. An electromagnetic induction survey of bulk electrical conductivity for predicting water contents was also conducted on that date. This section summarizes the results of the Water Balance Task for Fiscal Year (FY) 1995.

2.1 PRECIPITATION AND IRRIGATION

For FY 1995, precipitation recorded at the Hanford Meteorological Station (HMS) on the 200 Area Plateau was assumed to be representative of precipitation at the PSB. These data were used for irrigation scheduling and water balance evaluation. The water year (WY) is defined at the period

11/01/94 to 10/31/95 during which irrigation water is applied. Figure 2.2 shows the long-term average (1946-1994) annual precipitation for the Hanford Site distributed over WY 1995, and the actual precipitation for 1995 recorded at the HMS. These records show that in all months, except November and August, precipitation exceeded the long term average. The summer months (June - September) produced a total of 47 mm, compared to the long-term average of 33.5 mm. In the winter of WY 1995, conditions favorable to snow production were limited and no artificial snow was applied to the prototype. However, the winter (November - February) precipitation was 1.5 times the long-term average. Overall, there was a total of 279.2 mm of precipitation, which is almost twice as much as the long-term average and normal (calculated for the period 1961-1990) levels of 167.9 and 159 mm, respectively (Hoitink and Burk 1995). The first year of monitoring was essentially wetter than normal.

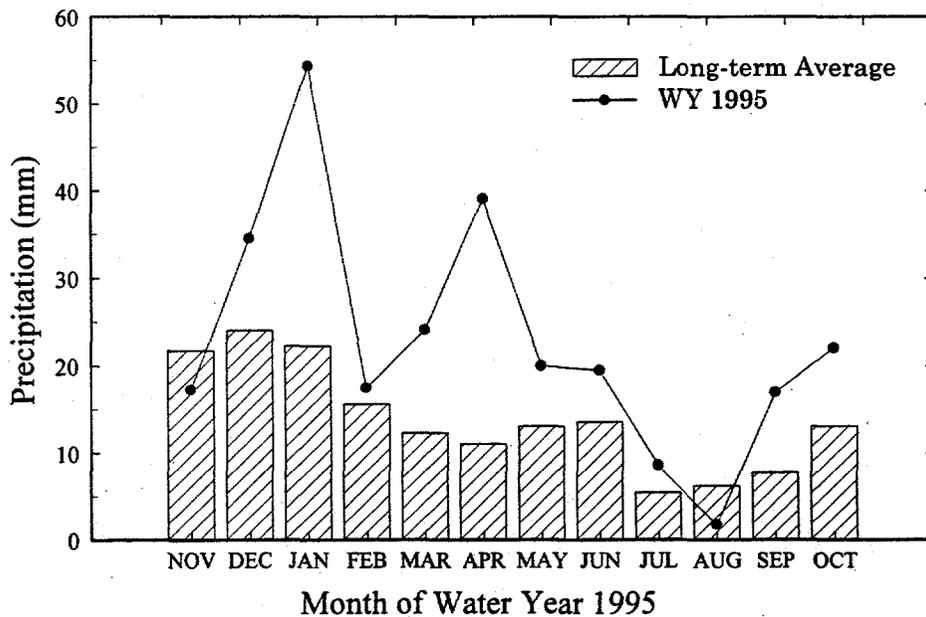


Figure 2.2 Long-term (1946-1994) average and WY 1995 precipitation based on the HMS records (after Hoitink and Burk 1995).

Precipitation was also monitored at the PSB using 14 precipitation meters and a tipping bucket gauge. During FY 1995, these data were collected on an hourly basis. When compared to HMS records, these data show that precipitation events can be highly localized. However, they have been used only in a qualitative sense while assessing the reliability and accuracy of the meters. It is expected that in FY 1996, precipitation records from the PSB will be used in irrigation scheduling and water balance evaluation.

Since soil water movement and storage is sensitive to changes in precipitation, such as those caused by changes in climate, the testing and monitoring plan called for extreme event testing in the form of elevated precipitation (Gee et al. 1993a). Based on the work of Petersen et al. (1993), it is not expected that future climate changes over the next 1000 years will cause precipitation to exceed three times the normal level. Thus, irrigation at three times the annual average would provide more than adequate stress on the PSB. To evaluate the effects of such a stress, an irrigation plan was developed to bring the total water applied on the irrigated treatments to at least 3X the long-term annual average precipitation.

Problems with the water supply and the operation of the irrigation system delayed the start of the irrigation until February 1995. Irrigation was generally applied biweekly during WY 1995. The amount of water applied in each irrigation event was usually calculated based on the precipitation since the last irrigation cycle and a 10.0-mm margin to allow for natural precipitation events.

Figure 2.3 shows cumulative plots of the 3X target application and the total water application (irrigation + precipitation) for WY 1995. The sharp increase at about 150 days after 11/01/95 represents the 1000-yr storm application of 71.0 mm. At the end of the first year of testing and monitoring, the total amount of irrigation water applied on the 3X treatments was 200.6 mm. This brought the total amount of water applied for the year to 479.7 mm. The year ended with the PSB receiving only 0.25 mm less than the planned 3X target. A similar irrigation schedule will be used during the WY 1996, which will commence on 11/01/95.

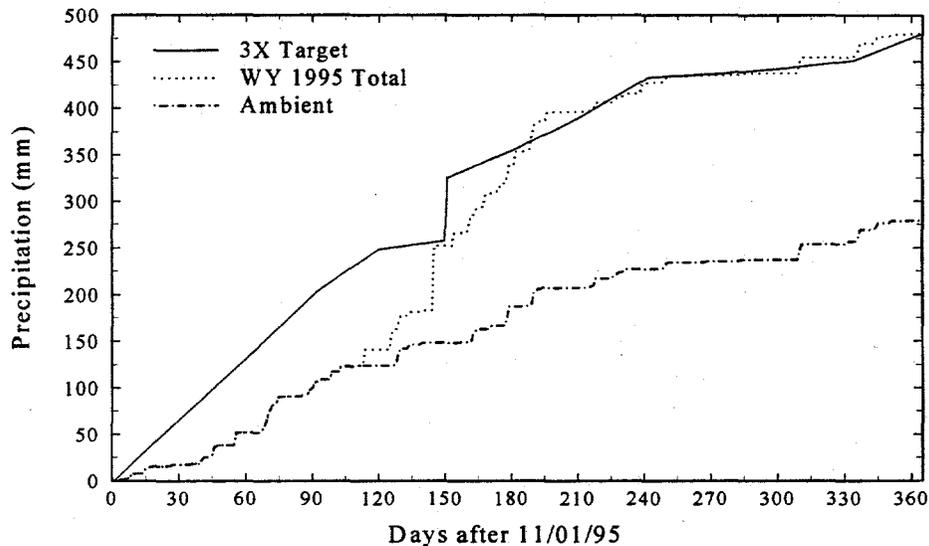


Figure 2.3 Precipitation data for the PSB during WY 1995. Ambient precipitation data were recorded by the HMS (Hoitink and Burk 1995).

2.2 VERTICAL MEASUREMENTS OF SOIL WATER CONTENT

Vertical profiles of water content, $\theta(z)$, are important for estimating water storage (S) and temporal changes in storage. These data are critical in evaluating the functionality of the PSB. It is expected that by the end of the testing and monitoring program, these data will be also be of use in helping to select a cost-effective and accurate technique for long-term monitoring of engineered barriers.

During FY 1995, a variety of invasive techniques, and one noninvasive method, were used to measure soil water content, θ , as a function of depth and time. The invasive techniques included neutron scattering using the probe NP; capacitance or frequency domain measurements using the CP; and TDR measurements using remote diode shorting probes. The noninvasive, electromagnetic induction (EMI) technique was used on one occasion. Given the long history of use of the NP at the

Hanford Site, this technique is used as a standard. The procedures for NP measurement of θ at the PSB, calibration, and the resulting calibration functions for converting NP count rates to θ were presented by Ward and Gee (1995). Use of NP-measured water content data to estimate soil water storage will be discussed in Section 2.6. In this report, all data are spatially averaged over the six monitoring stations on the silt loam surface to provide treatment averages. Results obtained from the various techniques are compared in the following sections.

2.2.1 Vertical Neutron Probe Measurements

Water contents were measured by NP in the vertical access tubes at least twice per month during FY 1995. Measurements were taken at 0.15-m intervals from the surface in each access tube. Figure 2.4 show examples of $\theta(z,t)$ averaged over the six silt loam access tubes on each of the 3X and ambient (1X) treatments. In early January 1995, both treatments showed almost identical distributions of $\theta(z)$. All of the profiles show a primary wetting front at a depth of 1.35 m, probably a remnant of the 150 mm of water applied just after construction was completed in September 1994. The profiles are also characterized by a discontinuity in $\theta(z)$ at 0.90 m. This is a reflection of the textural discontinuity at the silt loam-admix/silt loam interface, which occurs at 1.0 m. Twice-monthly measurements allowed close tracking of changes in $\theta(z)$ during FY 1995. The soil profile experienced significant drying during the summer months, as shown in Figure 2.5. All of the water loss is attributed to evapotranspiration (ET).

Between the period 08/22/95 and 10/12/95, a total of 39.4 mm of rain fell. That rainfall was responsible for the small increase in water content at the surface observed over the same period. Because of the high evaporative demand, this water did not penetrate very deeply in the profile and it is clear that the water content continued to decrease in the deeper part of the profile. Measurement of root length densities in April 1995 showed a maximum density at 1.35 m. By the end of FY 1995, the profile was significantly drier than it was during the early post construction period. This rapid removal of water exemplifies the expected response of a vegetated capillary barrier and confirms the findings of the Field Lysimeter Test Facility (FLTF) studies at a much larger scale. The FLTF consists of 24 lysimeters, 20 of which were constructed as capillary barriers and 4 to simulate surfaces that lack isolation barriers (gravel-covered coarse sand) . Over the period 1988 to 1993,

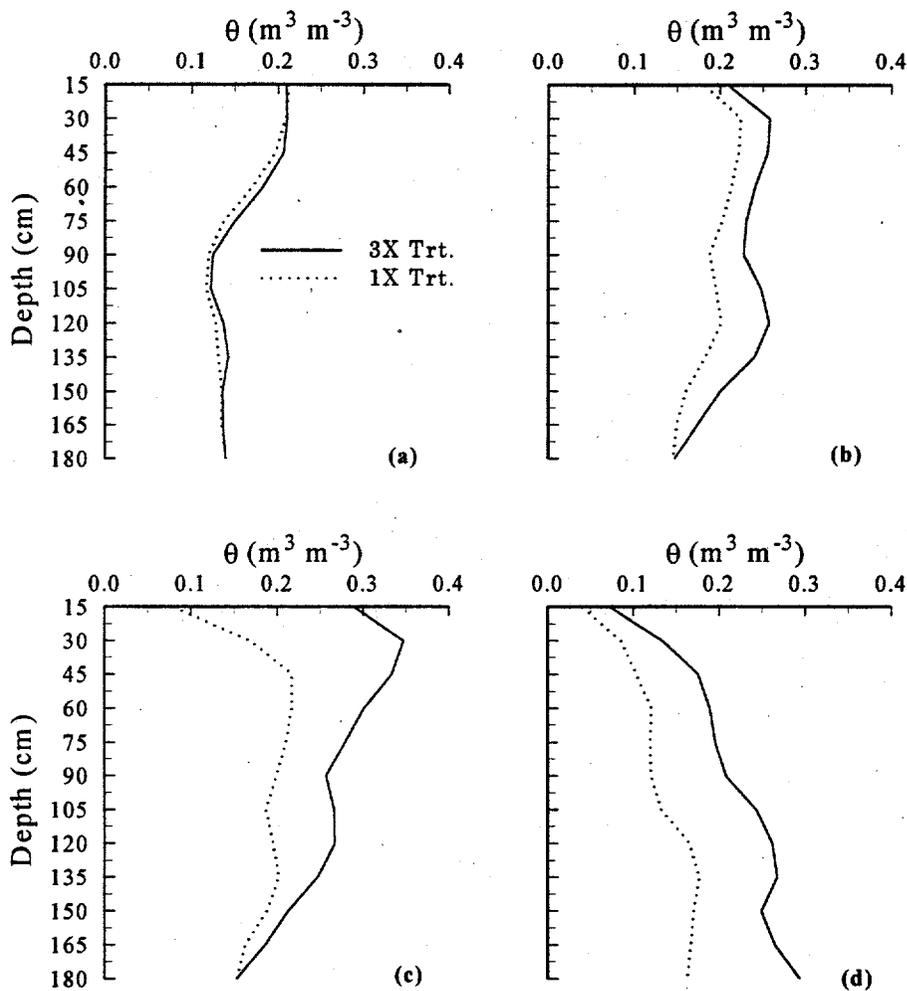


Figure 2.4 Mean profiles of water content averaged by treatment at the PSB in FY 1995 on (a) 01/04, (b) 03/23, (c) 03/27, after the 1000-yr storm, and (d) 05/31, as measured by NP.

these lysimeters were exposed to precipitation treatments ranging from ambient (non-irrigated) precipitation, averaging 169 mm yr^{-1} , to elevated precipitation of 480 mm yr^{-1} . Data from the FLTF showed that vegetation plus soil evaporation could return at least 480 mm of water per year to the atmosphere.

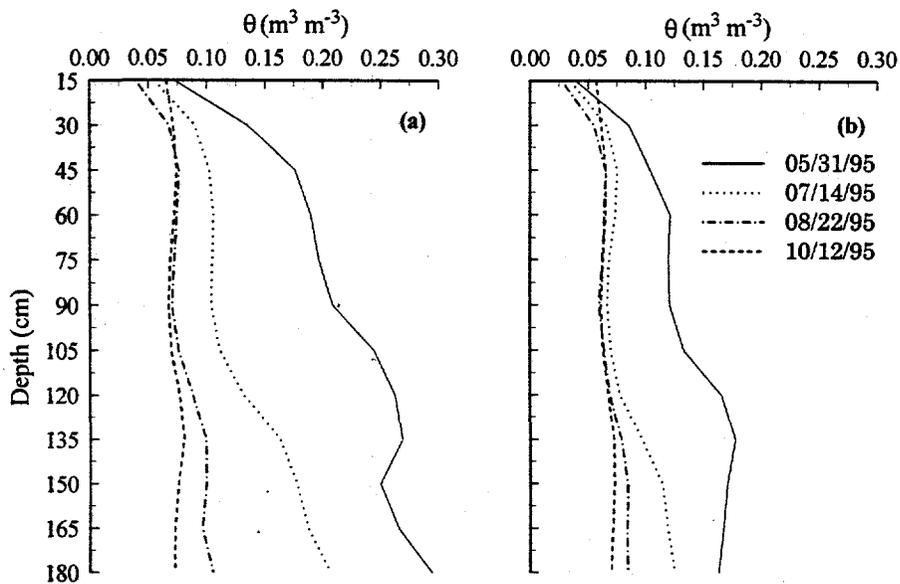


Figure 2.5 Temporal changes in water mean content profiles (averaged by treatment) over the summer of FY 1995 on (a) 3X treatments and (b) 1X treatments, as measured by NP.

2.2.2 Capacitance Probe Measurements

During FY 1995, the CP was also used to measure frequency shifts at the 14 locations on the PSB. These measurements were taken at 0.15-m increments and converted to $\theta(z)$ using a calibration function developed for the PSB. Figure 2.6 compares averaged $\theta(z)$ profiles measured with the CP and NP in preparation for the 1000-yr storm event in March 1995 and two days after the storm. Although the general trend in the profiles is somewhat similar, the CP underestimates $\theta(z)$ relative to the NP. This is inconsistent with published studies, most of which show that the CP generally overestimates θ relative to the NP. Our calibration data show the CP to be relatively insensitive to

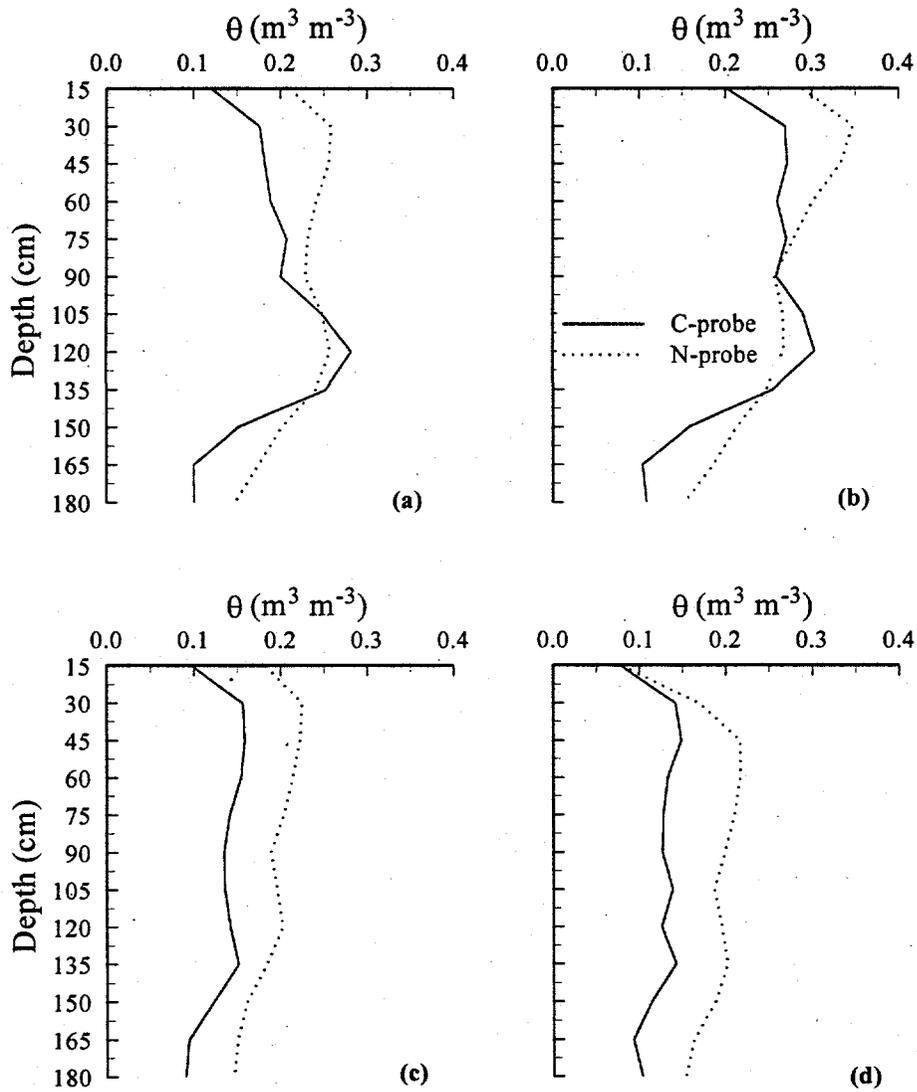


Figure 2.6 Comparison of $\theta(z)$ measured by CP and NP on two dates in FY 1995, (a) 3X plots on 03/23, (b) 3X plots on 03/27, (c) ambient plots on 03/23, and (d) ambient plots on 03/27.

changes in θ at the wetter end of the moisture range. It is believed that the utility of this technique can be improved by a more thorough calibration, one that reflects the variation in texture at the PSB. An attempt to cross-calibrate the CP using NP data from adjacent access tubes was initiated in late FY 1995. Until a more thorough calibration is completed, use of the CP data to estimate soil water storage cannot be recommended.

2.2.3 Time Domain Reflectometry Measurements

The TDR system is the only one allowing automated measurements and remote interrogation at the PSB. Measurement of $\theta(z)$ by TDR at the PSB uses segmented remote-diode shorting probes which permit monitoring of $\theta(z)$ profiles with a single, vertically installed probe at each monitoring station (see Figure 2.1). The system is controlled by a CR10 datalogger (Campbell Sci. Inc.) and interrogated remotely by radio telemetry. Measurements for FY 1995 commenced in March and were taken daily at 1.0-hr intervals.

At present, unexplained temporal variations in $\theta(z)$, especially at the two end segments, is a major concern with the Moisture Point TDR system. Figure 2.7 show examples of $\theta(z)$ measurements taken at 1-hr intervals over a 4-hr period. During this period, there was no activity that can explain the observed variations in $\theta(z)$. However, averaging $\theta(z)$ profiles over a 4-hr period generally reduces the standard deviation to acceptable limits. While the standard deviation on the intermediate segments is generally less than $0.01 \text{ m}^3 \text{ m}^{-3}$, it can be as high as $0.06 \text{ m}^3 \text{ m}^{-3}$, and $0.10 \text{ m}^3 \text{ m}^{-3}$ on the top and end segments, respectively.

The MP-917 system recorded $\theta(z)$ profiles within 15 min. of the cessation of irrigation during the 1000-yr storm event. None of the other techniques permitted monitoring of $\theta(z)$ during or immediately after the storm and therefore no comparisons can be made. However, comparison of TDR and NP $\theta(z)$ profiles from 03/27/95, 2 days after the storm, show similarity in the general trends (Figure 2.8), when the difference in spatial resolution is considered. It should be noted that with TDR, θ is averaged over the length of the segment and reported at the midpoint of the segment.

A striking feature is the fact that the TDR underestimates θ relative to the NP. This is

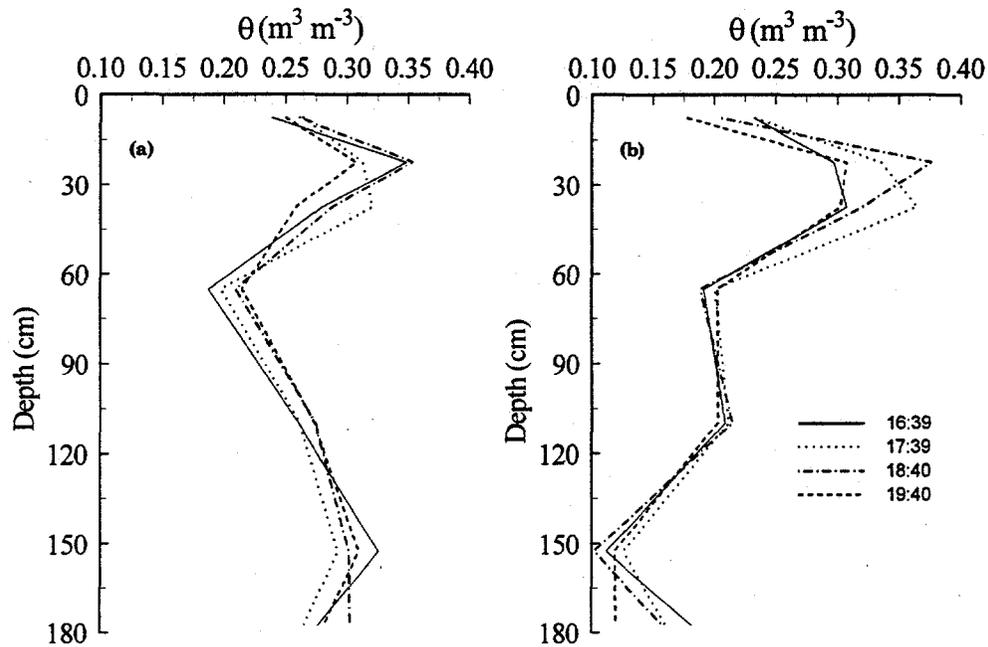


Figure 2.7 Temporal variation in $\theta(z)$ over a 4-hr period on 03/25/95. Measurements were taken on the 3X plot at (a) station 1 and (b) station 3 using segmented TDR probes.

inconsistent with published studies which suggest that the TDR generally overestimates water content relative to the NP. However, a comparison of TDR and NP data in early September 1995, after the soil profile had undergone significant drying, shows the opposite. While the trends in $\theta(z)$ are still similar, the TDR now overestimates θ (see Figure 2.9).

Since the TDR and NP have different principles of operation, different volumes of influence, and measure different forms of water in the soil, it can be argued that comparison should be done only on a qualitative level. However, the differences in $\theta(z)$ and the resulting effect on the estimation of water storage is a source of major concern that cannot be overlooked. It is believed that these differences can be resolved after conducting a thorough calibration of the MP-917 system.

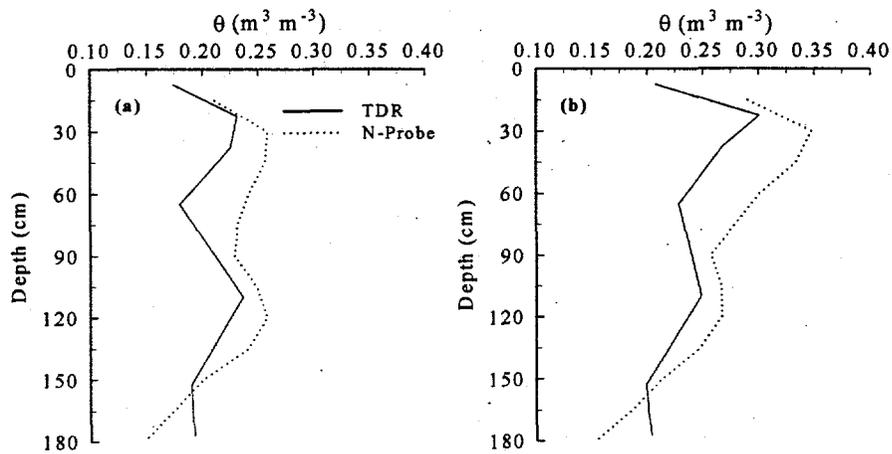


Figure 2.8 Comparison of $\theta(z)$ measured by TDR and NP (3X treatments) on (a) 03/23/95 and (b) 03/27/95, two days after the 1000-yr storm event.

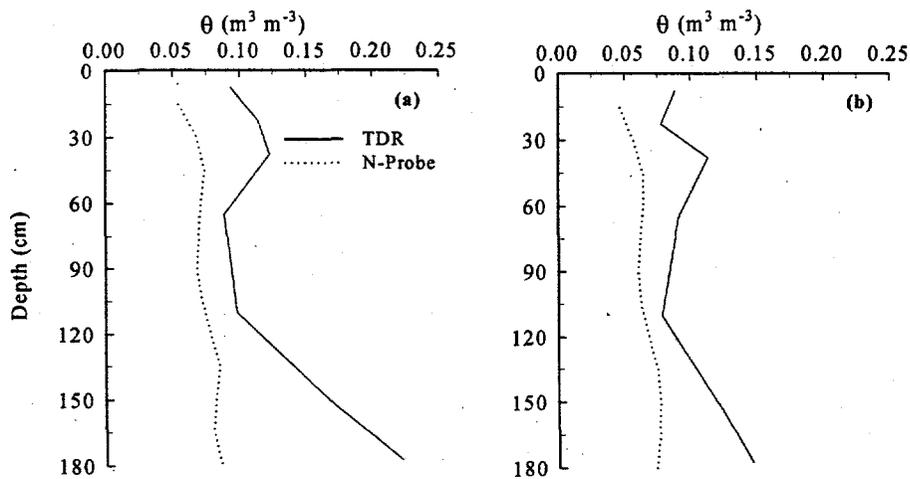


Figure 2.9 Comparison of $\theta(z)$ measured by TDR and NP on 09/09/95 on (a) 3X treatment, and (b) ambient treatments.

The results of a laboratory experiment suggests that the relationship between water content and the soil dielectric permittivity (κ) that is used by the MP-917 software is inappropriate for the Warden silt loam used to construct the surface layer of the PSB. The current model assumes a linear relationship between θ and $\sqrt{\kappa}$. The results of our laboratory study suggest a nonlinear relationship. Although these results explain the overestimation of θ in the lower ranges, they do not explain the discrepancy at higher values of θ and will require further study. Because of a lack of funding, there are no plans to conduct any further evaluation of the MP-917 TDR system in FY 1996.

2.2.4 Electromagnetic Induction Measurements

Under conditions of low solute concentration, it has been shown that EMI method can be used to determine the spatial variation of θ by measuring the bulk electrical conductivity, σ_a . An initial EMI survey was conducted at the PSB on September 30, 1994 using the EM38 and EM31 meters. The EM38 has a penetration depth of 0.75 m to 1.5 m, and the EM31 has a penetration depth ranging from 3.0 to 6.0 m. Despite the extensive network of buried cables, access tubes and sensors, it was possible to locate interference-free areas where reliable EMI measurements were possible. The EMI data were processed using an inverse method with Tikhonov regularization (Hendrickx 1994). During the EMI survey, the neutron probe was used also to measure θ across the two (ambient and 3X) treatments.

Figure 2.10 shows the distribution of σ_a , as a function of depth, derived from EM38 measurements. Since dry soil is a poor conductor, it is assumed that value of σ_a is a reflection of θ . There is some similarity in the general trends of NP-measured $\theta(z)$ and the $\sigma_a(z)$ distributions. The NP located the wetting front at between 0.3 and 0.45 m, while the EM38 located the wetting front, assumed to be the zone of highest σ_a , at between 0.4 and 0.6 m. The EM31, which has a greater depth of penetration located the maximum σ_a at 2.0 m, and showed a rapid decrease in σ_a after 2.0 m (Hendrickx 1994). The high σ_a is most likely due to the 2.0 m of silt loam at the surface with the underlying coarse layers being responsible for the later decrease.

The results of this survey suggest that with the proper monitoring procedures, appropriate calibration, and improved analytical techniques, the EMI method may offer a simple, rapid, low-cost

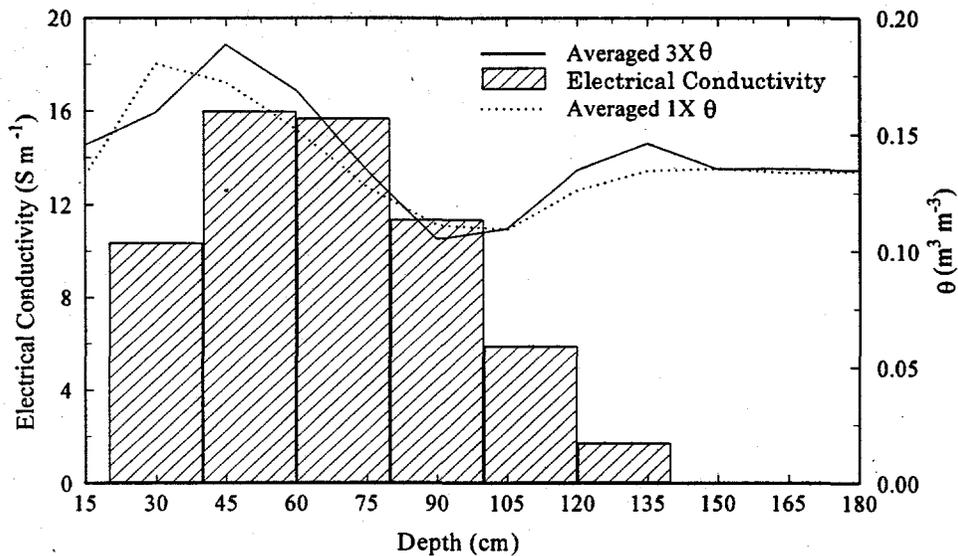


Figure 2.10 Comparison of bulk electrical conductivity profile, measured by EM38, and θ measured by NP on 09/30/94.

method for the large-scale monitoring of engineered barriers. However, because of funding limitations, there will be no further evaluation of the technique in FY 1996.

2.3 HORIZONTAL MEASUREMENTS OF SOIL WATER CONTENT

Horizontal NP measurements of water content, $\theta(x)$, are essential to the detection of any water that infiltrates beyond the depth of the vertical measurements, and permit the monitoring of horizontal variations in the depth of water penetration. Two horizontal neutron access tubes are installed at 2.0 m, near the interface between the soil layer and the sand filter, in each of the treatments (see Figure 2.1). To monitor the lateral movement of water back under the PSB from the

sideslopes (underflow), three horizontal access tubes were installed, starting at 1.0 m below the asphalt pad and at 1.0 intervals below each other, under the northeastern section of asphalt pad in the 3X treatment (see Figure 2.1).

During FY 1995, horizontal neutron probe measurements were taken at least once per month. The NP is usually inserted into a carrier in the access tube of interest and pulled to the maximum possible distance inside the tube (a function of NP cable length and radius of curvature on the access tube). For the silt loam tubes, this positions the probe 28 m from the edge of the asphalt pad, or 6.0 m from the center line of the barrier on the west side, and to within 4.0 m of the center line on the east side (see Figure 2.1). For the three below-asphalt access tubes, the maximum distance is 32 m from the edge of the asphalt pad, which is coincident with the center line of the barrier. All horizontal NP measurements are taken from the maximum insertion distance moving outward (towards the edge of the barrier) in 1.0-m increments. Data collected during FY 1995 are summarized below for four selected dates.

2.3.1 Horizontal Silt-loam Measurements

The first set of horizontal NP readings taken in taken in December 1994 showed a relatively uniform distribution of water contents over the ambient and 3X treatments (Figure 2.11a). These data were used to define the initial condition for horizontal measurements. The tubes are numbered 1 and 2, starting at the northern end of each treatment. Despite weekly irrigations, the silt loam-sand filter interface did not show a significant increase in θ until May 1995. Figure 2.11b shows the $\theta(x)$ distribution on 05/06/95, about 42 days after the application of the 1000-yr storm event. The dotted lines represent the treatment boundaries shown in Figure 2.1. It was around this time that the vertical NP measurements showed the wetting front had reached the maximum depth of measurement on the vertical access tubes (1.85 m). The greatest increases in θ were observed in the range $x = \pm 14-18$ m, which encompasses the transition zones (5W, 2W, 5E, 2E, Figure 2.1). As the plant cover became established and summer progressed, the rate of evapotranspiration increased. Thus, the soil profile experienced significant drying, as observed in July 1995 (Figure 2.11c). The last set of readings for WY 1995 were taken on 10/12/95. By this time, both the ambient and 3X treatments had been depleted to levels below the initial condition (Figure. 2.11a) as shown in Figure 2.11d.

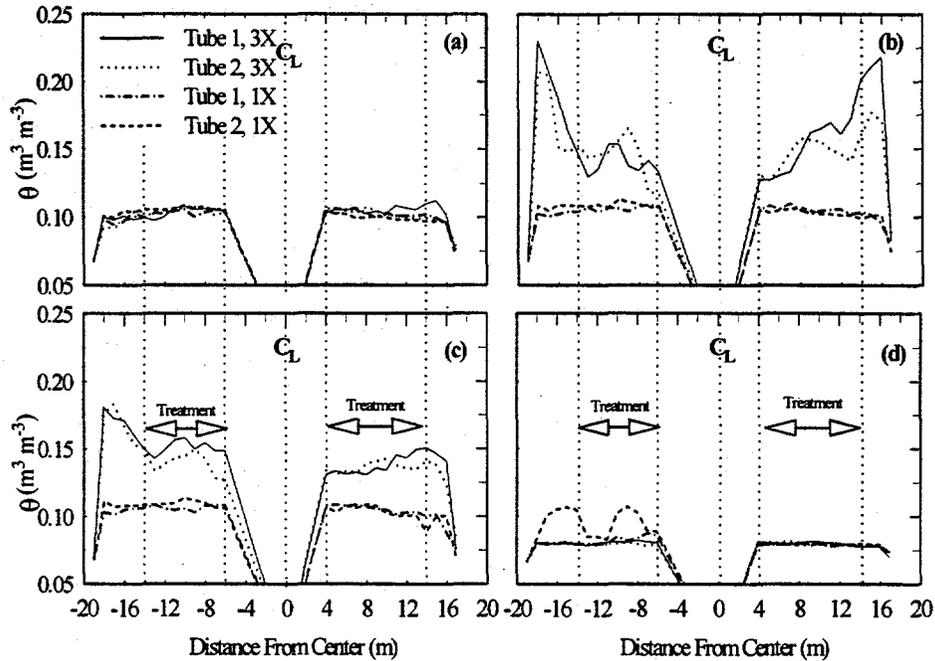


Figure 2.11 Horizontal, silt loam water contents on (a) 12/29/94, and in 1995 on (b) 05/31, (c) 07/14, and (d) 10/12, on the 3X and ambient treatments.

The observed decline in water content levels to less than the initial condition exemplifies the expected performance of a vegetated capillary barrier. Thus far, there are not enough data to define the complete annual cycling expected for water storage. However, these data, in combination with those obtained from the vertical measurements, may be used to establish a baseline performance for the prototype. Water contents in the top 2.0 m showed a steady decrease over the summer to reach a minimum by early October. This occurrence has important implications for water storage capacity, and will be discussed further in Section 2.6.

2.3.2 Below-Asphalt Measurements

The below-asphalt measurements were taken at least once per month in the access tubes under the asphalt pad. With the asphalt pad being the last line of defense for any water that escapes recycling, these measurements are important in monitoring the pad's functionality. Measurements on these tubes are also important for quantifying any underflow that occurs from around the sideslopes. Because of the difficulty in performing an *in situ* calibration of the NP for below-asphalt measurements, there is presently no reliable calibration relationship to convert NP counts to volumetric water content. However, the dynamics of water movement can be deduced from any changes in NP counts over time. An increase with time would indicate an increase in water content, while a decrease indicates a reduction in water content, provided these changes are greater than the normal deviation in the count rate of the instrument.

Figure 2.12 plots the temporal changes in NP counts in the vicinity of the edge of the asphalt pad, measured on the two upper access tubes (1.0 m depth) in the northeastern corner of the PSB. In

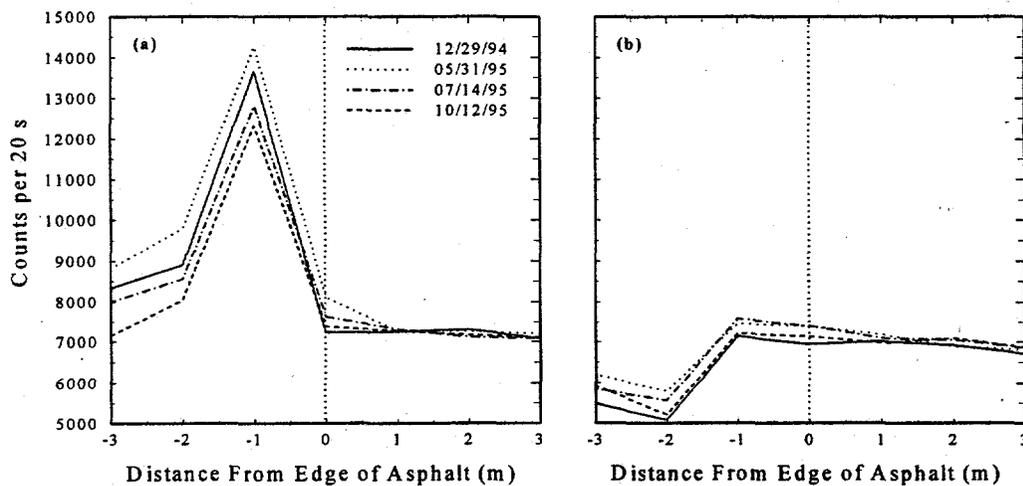


Figure 2.12 Temporal changes in horizontal NP counts in the vicinity of the edge of the asphalt pad at the northeastern corner of the PSB.

this plot, the spatial coordinate $x=0$ represents the edge of the asphalt pad. A negative coordinate represents locations to the east of the asphalt (away from the barrier) and a positive coordinate represent locations under the asphalt. As with the horizontal, silt loam NP measurements, readings taken on 12/29/94 are treated as the initial condition. The first tube is located at the northernmost edge of the barrier and was installed under an uncurbed section of the asphalt pad.

Figure 2.12a shows the temporal changes in this region. The most dramatic changes in water content occur at 1.0 m from the asphalt pad (away from the barrier). This zone has always been at a higher water content than the surrounding areas. This is not surprising since any water that reaches the asphalt is not drained to the dosing siphons, as in the curbed areas, but runs off the pad in this region. Between 12/29/94 and 05/31/94, this region showed an increase in water content. An increase was also observed up to 1.0 m under the asphalt pad. This increase is indicative of a lateral movement of water back under the barrier, i.e. underflow, and is most likely due to the water that was shed after the 1000-yr storm event.

Following this increase, water contents have decreased almost back to the initial levels at the edge ($x=0$), and under the asphalt. The same has occurred at the point 1.0 m away from the barrier.

Figure 2.12b shows a similar plot for the second tube, which is 24.3 m to the west of the first tube. This tube is located in a curbed area (under 4E treatment, Figure 2.1). Thus, the increase in water content around the edge of the pad is less dramatic.

Since conditions beyond the 1.0 m location (under the barrier) were quite similar, data from the two access tubes were averaged to produce a single curve. Figure 2.13 compares the averages obtained on 12/29/94 and 10/12/95. The average count per 20 s under the barrier was 6981 ± 90 on 12/29/95 and 6933 ± 100 on 10/12/95. The difference between the two dates is well within the variance in the difference in two NP counts. Thus, after 10 months, the average count under the barrier has not changed.

The under-asphalt lysimeter has recently been automated for water removal and measurements. The lysimeter is currently undergoing a series of leak tests.

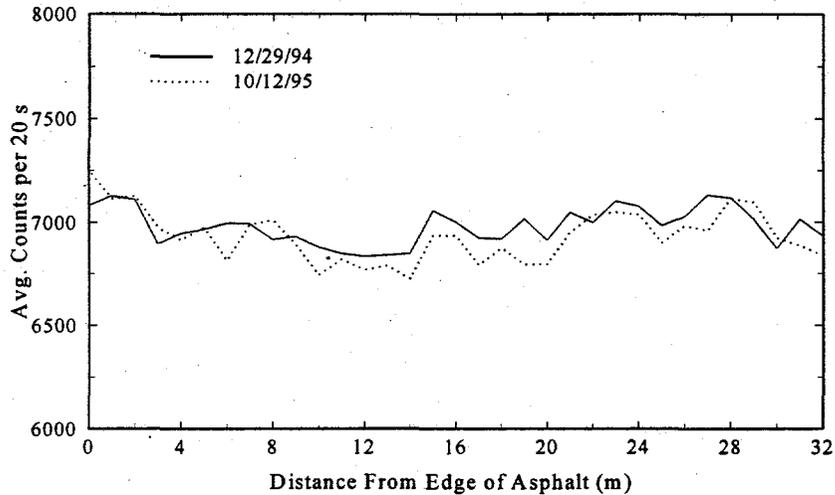


Figure 2.13 Spatial distribution of averaged NP horizontal counts at 1.0 m below the asphalt pad on two dates in FY 1995.

2.4 SOIL WATER POTENTIAL

Soil water potential is a measure of the energy status of water in soil and determines how much water is available for movement or plant uptake. The direction of flow is largely governed by the potential gradients. At the PSB, matric potential in the soil layer was monitored with heat dissipation units (HDUs). At the soil/sand interface, matric potential was monitored with fiberglass blocks (FGBs) installed adjacent to the horizontal NP access tubes.

Figure 2.14 shows profiles of matric potential, ψ , averaged over the 3X treatment at selected times during FY 1995. Two days after the 1000-yr storm (03/27/95), ψ reached a maximum of -3.0×10^{-5} MPa at 0.45 m. Over the next few months the observed trends in ψ demonstrate important features of a vegetated capillary barrier. In the months following the storm, water moved deeper into

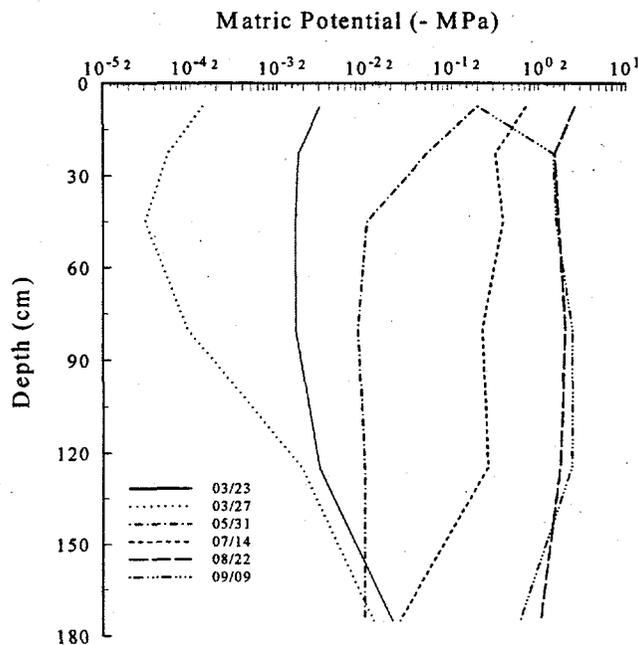


Figure 2.14 Spatially averaged profiles of matric potential for the 3X treatments at selected times during FY 1995.

the profile and ψ reached values as high as -0.02 MPa at 1.8 m by the end of May. Matric potential had already decreased to less than 3.0 MPa in the top 0.3 m of both the 3X and ambient treatments. For water to move in the liquid phase in an unsaturated soil, ψ must be greater than -0.075 MPa (0.20 m^3 m^{-3} in Warden silt loam). Thus, although the criterion for drainage was met, no drainage occurred. This demonstrates the effectiveness of the textural discontinuity at 2.0 m in preventing drainage while water in the fine soil layer is recycled to the atmosphere.

Another important feature reflected in the observed trends is that of evapotranspiration. Matric potential continued to decrease throughout the summer, which is expected since the rate of

evapotranspiration is also highest at this time. By early September, matric potentials were as low as -2.5 MPa in the top 1.0 m and around -0.6 MPa at 1.8 m in the 3X treatments. On the ambient treatment, for the same period, measurements exceeded the range of calibration in the top 1.0 m and were -7.8 MPa at the 1.8 m depth.

Measurements of ψ adjacent to the horizontal NP tubes at the 2.0-m depth also show a similar cycle, only lagged in time. On the northeast corner of the 3X treatment, ψ showed a rapid decrease in April following the application of the 1000-yr storm. The southeast corner of the 3X treatment showed a similar, but less pronounced, response. In both cases, ψ reached a maximum by the end of May and has been decreasing ever since. The decrease in potential at 2.0 m is confirmed by the NP (see Figure 2.5) and HDU (Figure 2.14) measurements, although the rate of decrease in the bottom 1.0 m appears to have slowed.

At ψ less than -0.075 MPa, movement is still possible in the form of either water films or vapor, or both. This is probably responsible for continued drying of the profile in the top 1.0 m. The higher potentials in the bottom 1.0 m suggest that evapotranspiration may be limited at the deeper depths, probably because of limited root development.

2.5 DRAINAGE

The PSB is equipped with a siphon-based monitoring system capable of measuring drainage with a resolution of between 0.02 and 0.06 mm of water, depending on the treatment size. Each siphon is equipped with a pressure transducer, calibrated to give the equivalent height of water (mm) drained from each treatment (see Figure 2.1). There is also a tipping bucket rain gage, through which all water entering the vault passes, and a thermocouple to measure water temperature (Figure 2.15).

In the early part of FY 1995, considerable effort was expended trying to correct leaks and other problems with the siphons. Problem-free drainage measurements started in March and data were recorded on an hourly basis throughout the year. Figure 2.16 shows the drainage recorded from the sideslopes over the period 03/27/95 to 09/30/95. Each peak represents a dose of the siphon and corresponds to the discharge of over 550 L of water (Ward and Gee 1995). During this period, the

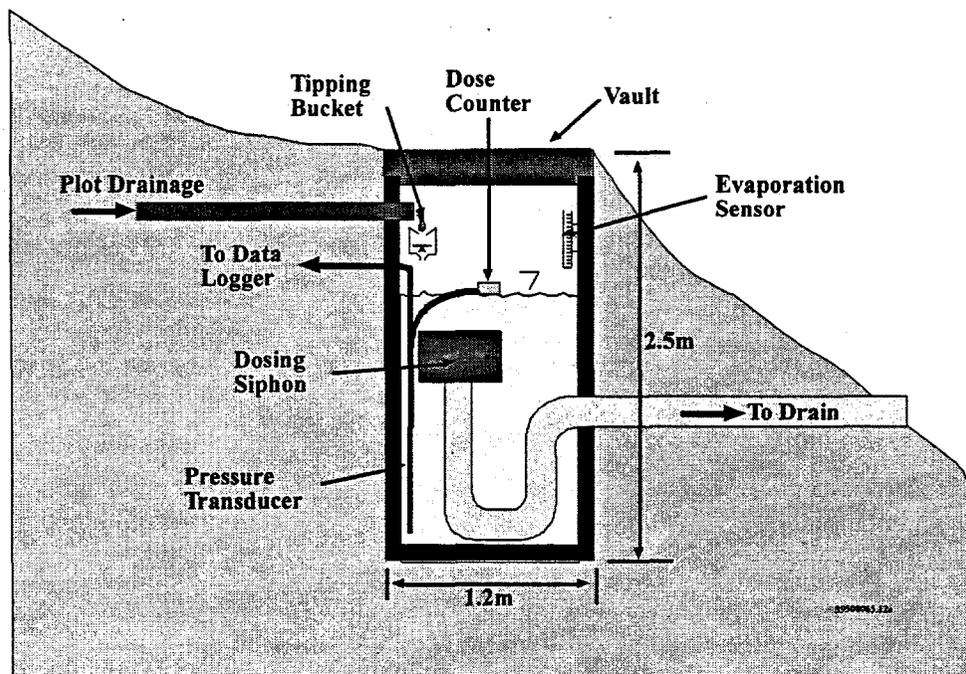


Figure 2.15 Schematic of a dosing siphon vault and the associated sensors and components (not to scale).

4W siphon (see Figure 2.1) recorded 12 doses, equivalent to the drainage of 12,117 L of water from the 4W treatment (Figure 2.16a). The 4W treatment is located on the 3X side of the clean fill sideslope. The vault collecting drainage from 1W treatment (ambient treatment) recorded 12 doses, or 6900 L of water (Figure 2.16c). In comparison, the basalt sideslope treatments recorded considerably less drainage. On the 3X treatment, 4E recorded only eight complete doses, while on the ambient treatment, only two complete doses were recorded.

Another interesting observation is the bimodal nature of the drainage hydrograph on 4E and 1E and the absence of drainage during the summer months (Figure 2.16d). Sieve analysis of the fractured basalt show that there is a considerable amount of fine textured material included with the larger basalt blocks. This material will have a higher storage capacity than washed basalt, and as such will act as a store until there is enough water for breakthrough and drainage. The open structure of the basalt sideslope would certainly permit advective air flow between the blocks, which could enhance evaporation from the block surfaces. This phenomenon would most likely be enhanced in the

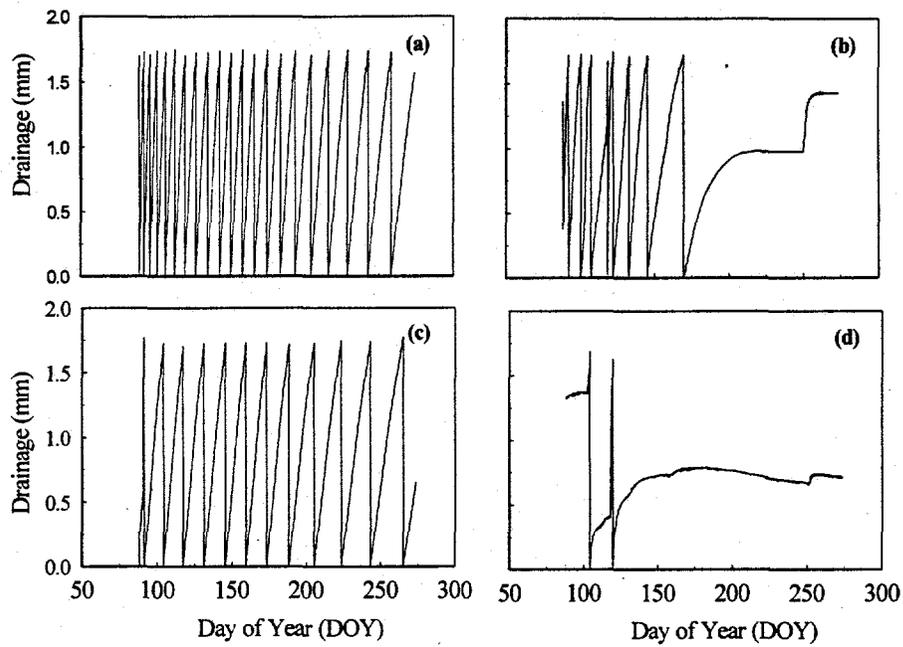


Figure 2.16 Sideslope drainage records for the period 03/29/95 to 09/30/95 on (a) 4W, (b) 4E, (c) 1W, and 1E.

summer months and could reduce the amount of water available for infiltration. This mechanism is worthy of further study to optimize sideslope design.

Figure 2.17 show drainage records for the silt loam treatments. To date, there has been no drainage from the irrigated or ambient precipitation silt loam treatments.

Table 2.1 shows the monthly drainage, by treatment, starting on 03/29/95. Throughout FY 1995, the treatments on the clean-fill slope have drained considerably more water than the corresponding treatments on the basalt sideslope. For example, the 4W treatment generated almost

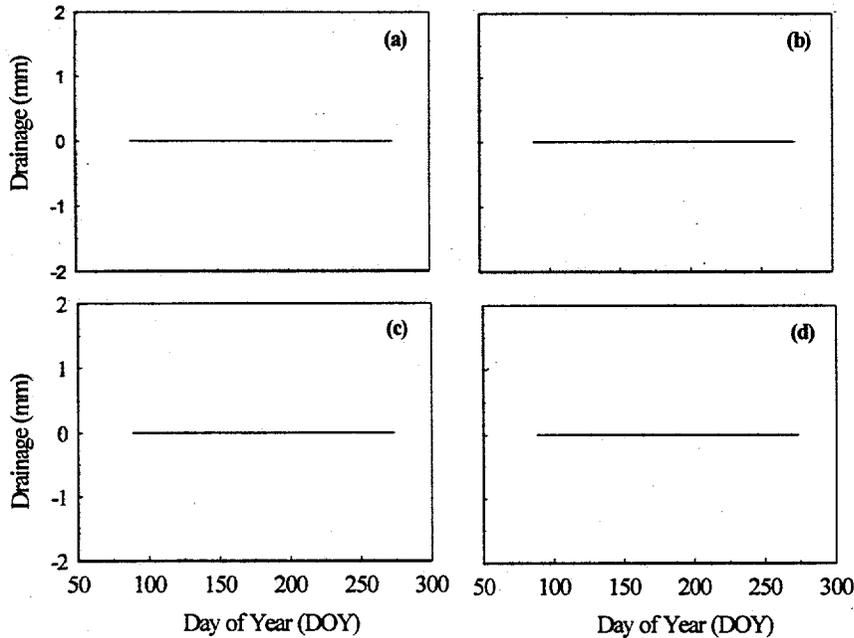


Figure 2.17 Silt loam drainage records for the period 03/29/95 to 09/30/95 on (a) 6W, (b) 6E, (c) 3W, and (d) 3E.

2.5 times the drainage generated by 4E. It is possible that the 4W and 4E treatments could have received drainage water from the irrigation system. However, there is no doubt that the 1W and 1E treatments both received identical amounts, coming only from natural precipitation. Even then the 1W treatment generated more than 5 times the drainage generated by 1E.

The transition zone on the NW side of the PSB (5W) also generated some 5.5 mm of drainage, while the corresponding 5E generated only 1.0 mm. Two factors may have been responsible for this difference. First, it may be related to the clean-fill sideslope's ability to act as a better watershed. Second, during the 1000-yr storm in March, the northwest corner of the 3X treatment was

Table 2.1. Drainage (mm of water) by treatment at the PSB during FY 1995.

Month	WEST SIPHONS						EAST SIPHONS					
	6	5	4	3	2	1	1	2	3	4	5	6
Mar	0	0.130	1.490	0	0	0.310	0.020	0	0	0.960	0	0
Apr	0	1.430	9.430	0	0	4.070	2.210	0	0	7.040	0	0
May	0	0.990	6.890	0	0	3.820	0.480	0	0	4.320	0.160	0
Jun	0	0.810	6.260	0	0	3.670	0.070	0	0	1.690	0.320	0
Jul	0	0.780	4.930	0	0.020	3.060	0	0	0	0.390	0.290	0
Aug	0	1.090	4.050	0	0.370	2.770	0	0	0	0	0.290	0
Sep	0	0.995	3.116	0	0.553	2.363	0.050	0	0	0.449	0.015	0
Total (mm)	0	6.225	36.166	0	0.943	20.063	2.840	0	0	14.849	1.065	0

ponded. Ponding did not occur on the northeast side. It appears that most of this water has drained via the 5W and 4W treatments, since no drainage has been recorded from the silt loam irrigated (6W) treatment.

Based on the results of numerical simulations, there has been some speculation regarding the amount of drainage generated by the various sideslope designs. These data represent the first of their kind documenting sideslope performance. It appears as if the clean-fill slope is a much better water shed. At present, the response of the sideslopes to irrigation has not been evaluated since there were no controlled tests in FY 1995. The response of the two sideslopes to irrigation will be thoroughly investigated in FY 1996. These data will prove to be invaluable to the final design of above-grade surface barriers.

2.6 SOIL WATER STORAGE

For FY 1995, soil water storage, S , was computed from NP measurements of water content profiles, $\theta(z)$. Storage at a given time was calculated as

$$S = \int_0^L \theta(z) dz \quad [1]$$

where L is maximum depth of measurement, i.e., 1.8 m. Figure 2.18 shows a plot of S versus day of year (DOY) for both treatments during FY 1995.

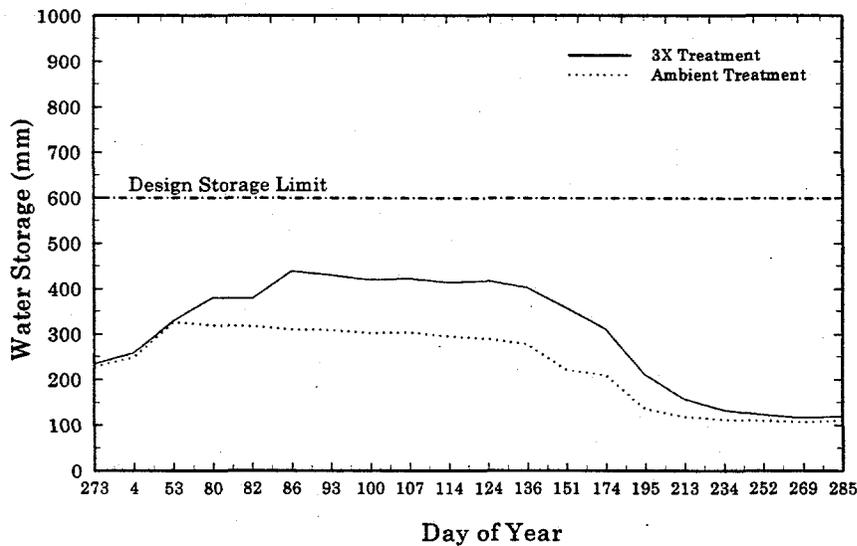


Figure 2.18 Soil water storage in FY 1995 on the 3X and ambient treatments. Storage was calculated from NP measurements of water content.

The first NP measurements were taken at the end of September 1994 and, as expected, treatment effects were negligible. The mean initial storage was 234 mm on the 3X and 223 mm on the ambient treatment. With both treatments exposed to only natural precipitation, S remained essentially

the same until 02/22/95, when irrigation started on the 3X plots. A sharp increase in S occurred on 03/27/95 following the 1000-yr storm. At no time did storage exceed the design limit of 600 mm.

Despite the differences in the amount of water received by the two treatments, the trend in S over time appears to be quite similar. Since DOY=86 (03/27/95), neither of the two treatments have gained any water. The rapid depletion in storage over the summer months is expected, given the high rate of evapotranspiration. By DOY=285 (10/12/95), water storage averaged 120 mm on the 3X treatment and 110 mm on the ambient treatment. These data show the effectiveness of plants in removing water from the soil during the late spring and summer months. These results are qualitatively similar to those previously observed in vegetated lysimeters at Hanford, as reported by Link et al. (1995a). Link et al. (1995a) noted that water was removed to essentially the same lower limit of storage for both irrigated and ambient (nonirrigated) surface barrier treatments. At these depleted levels of storage, the silt loam could accommodate winter precipitation before evapotranspiration resumes in the spring. The storage on the ambient treatment will likely remain at the depleted levels until late February 1996.

2.7 WATER BALANCE

A water for the PSB is an account of all quantities of water added to, removed from and stored in the upper 2.0 m of soil. In the simplest sense, the water balance may be written in terms of the change in soil water storage,

$$\Delta S = (P + I) - (R + D + ET) \quad [2]$$

where

ΔS = change in water storage

P = natural precipitation

I = irrigation/snow

R = surface runoff

D = drainage from the soil profile

ET = evapotranspiration

The change in storage, ΔS , between two times, t_1 and t_2 , was calculated as

$$\Delta S = \int_0^L \int_{t_1}^{t_2} \frac{\partial \theta}{\partial t} dz dt \quad [3]$$

The variety of instruments and measurement systems provided data that were sufficient to evaluate the water balance over FY 1995. All of the components, except ET, were measured during the year. Estimates of ET for the two treatments were obtained by difference. Water balance calculations for the two treatments are shown in Tables 2.2 and 2.3.

These calculations show a general decrease in storage, with the rate of decrease increasing in the summer months. Estimates of ET showed a general increase over the year reaching a maximum of about 6 mm on the 3X and 4.0 mm on the ambient treatment in late June and early July. These rates quite similar to the mean potential evapotranspiration for the same period as reported by Gee et al. (1989). In general, ET was higher on the irrigated treatments. The total amount of water loss by ET on the 3X treatments was about 1.5 times greater than on the ambient treatment. By the end of September, ET had decreased to similar rates on both treatments. In response to the 22 mm of precipitation between 09/26 and 10/12/95, ET again increased on both treatments.

These data reflect the importance of documenting the influence of plants on the water balance at the PSB. This task will require continued availability of high-quality input data, such as those collected during the past year. Based on these results, it is apparent that ET can return to the atmosphere in excess of the 480 mm yr⁻¹ that is received by the ambient treatments. Vegetation on the PSB was able to use all available water.

2.8 SUMMARY

After completing only the first year of testing and monitoring, the following observations can be made.

- Despite having an unusually wet year that produced more than twice the long-term annual average precipitation, and an application of 70 mm over 8 hours for the 1000-yr storm

Table 2.2. Water balance for the silt loam 3X treatments at the PSB in FY 1995

t_1	t_2	ΔS (mm)	P (mm)	I (mm)	R (mm)	D (mm)	ET (mm d ⁻¹)
09/30/94	01/01/94	25.41	75.44	0	0	0	0.64
01/04/94	02/22/95	69.89	71.88	16.96	0	0	0.53
03/21/95	03/23/95	-2.51	0	0	0	0	1.26
03/23/95	03/27/95	60.43	0.25	71.00	1.78	0	2.20
03/27/95	04/03/95	-8.20	0	13.18	0	0	3.06
04/03/95	04/10/95	-10.66	2.29	26.48	0	0	5.63
04/10/95	04/17/95	-2.55	12.7	13.38	0	0	3.36
04/17/95	04/24/95	-8.14	3.57	8.82	0	0	2.93
04/24/95	05/04/95	3.64	20.57	13.55	0	0	3.05
05/04/95	05/16/95	-14.54	19.81	22.68	0	0	4.75
05/16/95	05/31/95	-45.48	0.254	0	0	0	3.05
05/31/95	06/23/95	-46.18	19.56	0	0	0	2.86
06/23/95	07/14/95	-100.0	7.62	0	0	0	5.13
07/14/95	08/01/95	-52.47	1.02	0	0	0	2.97
08/01/95	08/22/95	-25.16	1.78	0	0	0	1.28
08/22/95	09/09/95	-10.60	17.02	0	0	0	1.53
09/09/95	09/26/95	-65.10	17.02	0	0	0	0.38
09/26/95	10/12/95	3.0	17.02	0	0	0	1.20
FY 1995 Totals		-113.99	298.45	204.00	1.78	0	614.66

Table 2.3. Water balance for the silt loam 1X treatments at the PSB in FY 1995

t ₁	t ₂	ΔS (mm)	P (mm)	I (mm)	R (mm)	D (mm)	ET (mm d ⁻¹)
09/30/94	01/04/95	21.23	75.44	0	0	0	0.68
01/04/95	02/22/95	76.88	78.74				0.04
02/22/95	03/21/95	-7.18	24.13	0	0	0	1.16
03/21/95	03/23/95	-1.45	0	0	0	0	0.73
03/23/95	03/27/95	-6.98	0	0	0	0	1.75
03/27/95	04/03/95	-7.32	0	0	0	0	1.05
04/03/95	04/10/95	-5.97	2.29	0	0	0	1.18
04/10/95	04/17/95	0.87	12.7	0	0	0	1.69
04/17/95	04/24/95	-8.02	3.56	0	0	0	1.65
04/24/95	05/04/95	-5.21	20.57	0	0	0	2.58
05/04/95	05/16/95	-12.27	19.81	0	0	0	2.67
05/16/95	05/31/95	-57.10	0.254	0	0	0	3.82
05/31/95	06/23/95	-10.91	19.56	0	0	0	1.32
06/23/95	07/14/95	-73.25	7.62	0	0	0	3.85
07/14/95	08/01/95	-18.38	1.02	0	0	0	1.08
08/01/95	08/22/95	-6.31	1.78	0	0	0	0.39
08/22/95	09/09/95	-2.52	17.02	0	0	0	1.09
09/09/95	09/26/95	-3.26	0	0	0	0	0.19
09/26/95	10/12/95	3.57	22.35	0	0	0	1.17
FY 1995 Totals		-117.84	298.45	0	0	0	416.29

event, the design storage capacity of the barrier was never exceeded. Measured storage showed no increases beyond late March.

- Soil water potential and horizontal NP measurements at the 2.0-m depth in the 3X treatments indicate conditions were such that drainage could have occurred after the 1000-yr storm. However, the fact that there was no drainage from the 3X treatments demonstrates the effectiveness of the hydraulic barrier in preventing drainage while the water is recycled to the atmosphere.
- No water has penetrated the asphalt pad, as demonstrated by the under-asphalt NP measurements. However, there is evidence of underflow on the northeastern corner of the asphalt pad.
- Plants obviously play a very important role in removing water from the soil during the late spring and summer. Our observations that plants will remove water to the same storage limit independent of irrigation treatment are qualitatively similar to those reported by Link et al. (1995a) for vegetated Hanford lysimeters.
- Observations of sideslope drainage show that the clean-fill slope rapidly drains most of the water intercepted. Drainage from the clean fill slope was between 3 and 5 times more than from the basalt slope. Clean fill drainage was also as much as 32% of natural precipitation. These observations are opposite to those anticipated by Gee et al. (1993b) based on FLTF data, and emphasize the importance of scale effects.
- Evaluation of the water balance using NP-measured water contents shows a peak rate of evapotranspiration of 6.0 mm d^{-1} in the June-July period, falling off to 2.0 mm d^{-1} in early September. Thus, plants will play a significant role in increasing the storage capacity of the silt loam for winter precipitation.

- For the long-term monitoring of engineered barriers, a variety of invasive and noninvasive techniques have been identified. Technologies such as TDR and EMI show considerable promise for quick, safe, low-cost measurements. However, these techniques will require further study before they can be adopted.

3.0 WATER EROSION MONITORING

The purpose of monitoring the barrier soil surface is to collect data and information on the erosional behavior of the soil under natural rainfall and snowmelt conditions (Gee et al. 1993a). The dominant erosional processes are rainsplash coupled with overland runoff in which rainsplash loosens soil particles and makes them available for transport by runoff. To reduce soil erosion, the prototype barrier uses both a pea-gravel admix and vegetation to reduce rainsplash erosion. The gravel admix was blended with the soil during construction, and vegetation was established by hydroseeding the surface after construction.

Another factor contributing to erosion is runoff volume. For a given rainfall event, as the slope length and surface area increases, the volume of runoff increases. The prototype provides an opportunity to monitor a representative length of barrier and surface area under local climatic conditions. The monitoring plan consists of two separate data collection efforts: 1) measurement of runoff and sediment yield from a 6-m-wide x 15-m-long flume installed on the soil surface (controlled area monitoring), and 2) observation and documentation of the effects of precipitation over the larger remaining surface area (barrier-surface monitoring).

3.1 CONTROLLED AREA TESTING

A permanent test plot for water erosion measurements was established on the south end of the prototype. The study plot was designed to measure runoff and sediment yield.

3.1.1 Objective

Because of the large area of the prototype barrier top surface, a program to monitor total runoff and sediment yield from the barrier surface was not recommended or implemented (Gee et al. 1993a). Construction of a controlled area (6.1-m-wide x 15.24-m-long) on the barrier surface for monitoring erosion and runoff was used to quantify the amount of soil loss and runoff. This controlled area of the barrier surface was used to provide baseline information under natural climatic

conditions. Monitoring of an extreme rainfall event was also done using a similar temporary test strip on the irrigated portion (north half) of the barrier. Soil properties were monitored and recorded throughout the year as part of the effort to document the changes to the barrier surface.

3.1.2 Methods

The construction and instrumentation of the test plot was described in Gee et al. (1994). Information from the dataloggers and sampling equipment was collected on a monthly basis and after every rainstorm event.

3.1.3 Results

There was no measurable runoff from the permanent test plot. This is not unexpected, given the conditions of the southern half of the barrier surface. These conditions--vegetation coverage of 85 to 95%, low (>5.0%) moisture content, and no significant rainfall--were found during testing of the McGee Ranch erosion test plots to indicate that little if any runoff would occur (Gilmore and Walters 1993). The previous testing on the large-scale test plots with gravel admix and untreated soils, both with vegetation and an antecedent moisture content of 1.6 and 5.6% respectively had runoff of approximately 1% for a 1-hour-long rainstorm with an intensity of 64 mm/hr. The rainstorms that occurred at the barrier location throughout the year accumulated less than 10 mm/day. Table 1 summarizes the rainstorms that occurred at the barrier from November 1994 through July 1995.

Table 3.1. Daily rainfall amounts at barrier-controlled area test plot (mm).

Day	1994		1995						
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
1		0.254		2.286					
2								0.508	0.254
3									
4								2.54	
5									
6								5.08	
7				7.366		0.254	1.524		0.508
8	1.778		3.048		1.524				0.762
9	2.54		8.128	0.254	7.874		3.048		0.762
10	2.286		4.572		3.81	1.016	0.762		
11	0.254		3.556	4.826			0.508		
12		5.588	0.254	0.254		8.382			
13			2.286			1.016	0.508		
14			5.08		2.794	0.762		1.27	
15	3.81	0.254						0.254	
16	1.016	7.366						0.508	
17		1.016	0.254					0.762	
18	0.254	0.762		0.508	0.254				
19						0.508		3.302	
20					1.016	2.032			
21									
22									
23					0.254				
24						0.254			
25			1.524						
26		11.68							0.508
27	0.762					7.112			
28			3.302			9.398			
29	0.508		1.27						
30			4.318						
31			0.762						

3.2 TEMPORARY TEST PLOT

In conjunction with the 1000-year storm test conducted in March, 1995, a water erosion plot was established on the irrigated (north) side of the prototype barrier.

3.2.1 Objective

A temporary test plot was constructed in the northwest quadrant of the barrier to quantify the amounts of overland runoff, infiltration, and sediment yield from the top surface during the application of a total rainfall amount equivalent to the projected 1000-year storm. Although this test did not simulate a natural rainfall event, it was thought it could provide some significant insight into the expected performance of the barrier by comparing to the results of previous erosion tests (Gilmore and Walters 1993).

3.2.2 Methods

A 3.05-m by 15.25-m (10-ft by 50-ft) test plot running the length of one side of the top surface from the crown to the sideslope was constructed in the northwest quadrant in the testing and monitoring area located on the barrier. The plot was constructed with plastic lawn edging around the perimeter of the plot. Using plastic lawn edging allowed for minimal disturbance of the surface and aided in the removal of the test plot after testing. The collection flume was made of 12-in. pvc with a slot cut into it and a reducer at one end to allow collection of the runoff samples in 1-L sample bottles. Sample collection of runoff and sediment yield data was done manually during the test from a pit dug at the south end of the collection flume. Rain gauges were placed every 3 m along the north side of the test plot and read after every series of passes of the rainfall applicator. One additional gauge was placed outside of, and at, the longitudinal center of the plot. This rain gauge was used to collect the total amount of rainfall for the test.

Rainfall was applied with the mobile irrigation sprinkler system used to apply the additional water amounts for the 3x precipitation area on the barrier. This applicator does not simulate the conditions of natural rainfall and is used only to apply specific volumes of water to the barrier surface. The differences between the sprinkler system and a natural rainfall include drop size, drop distribution, and total amount of energy imparted to the surface. The irrigation system also travels up and down the length the test area, with the sprinklers covering an area approximately 3-4 m wide. Each trip of the irrigation system was considered to be the full travel along the test area and the return to the starting position. Therefore, each trip included two passes of the sprinklers over the test plot with the return pass immediately following the first pass. The time between complete trips varied between 15 to 17 minutes. This means that there was a significant amount of time during the test when no rainfall was applied to the test plot. This uneven application of water allowed infiltration of greater amounts of water stored on the surface in localized ponds (depression storage) than would normally occur during a natural rainstorm.

3.2.3 Results

Figure 3.1 is a time series plot of the runoff hydrograph, rainfall application, and sediment concentration amounts for the test. This figure shows that the first three series of trips of the irrigation system over the test plot did not produce any runoff. Each additional trip of the irrigation system produced runoff with the amount for each pass staying relatively the same until the fifth hour of the test. After the fifth hour of testing the runoff amounts were increasing until problems with the power supply to the irrigation system caused a 35-minute delay between the 13th and 14th trips. When the water application was resumed, the runoff amounts again increased with each successive trip until the completion of the test. During the tenth trip of the test, a small amount of water was observed running along the side of the collection flume, forming a small gully and bypassing the collector. Sample collection was halted and the gully filled so all of the runoff could flow into the collector for sampling and measurement.

The total volume of runoff was estimated as 1.79 +/- 0.11 mm. This amount was determined by estimating the amount of runoff for each pass from the runoff hydrograph and summing the results. The amount of runoff for the tenth pass was estimated as an average of the ninth and eleventh passes.

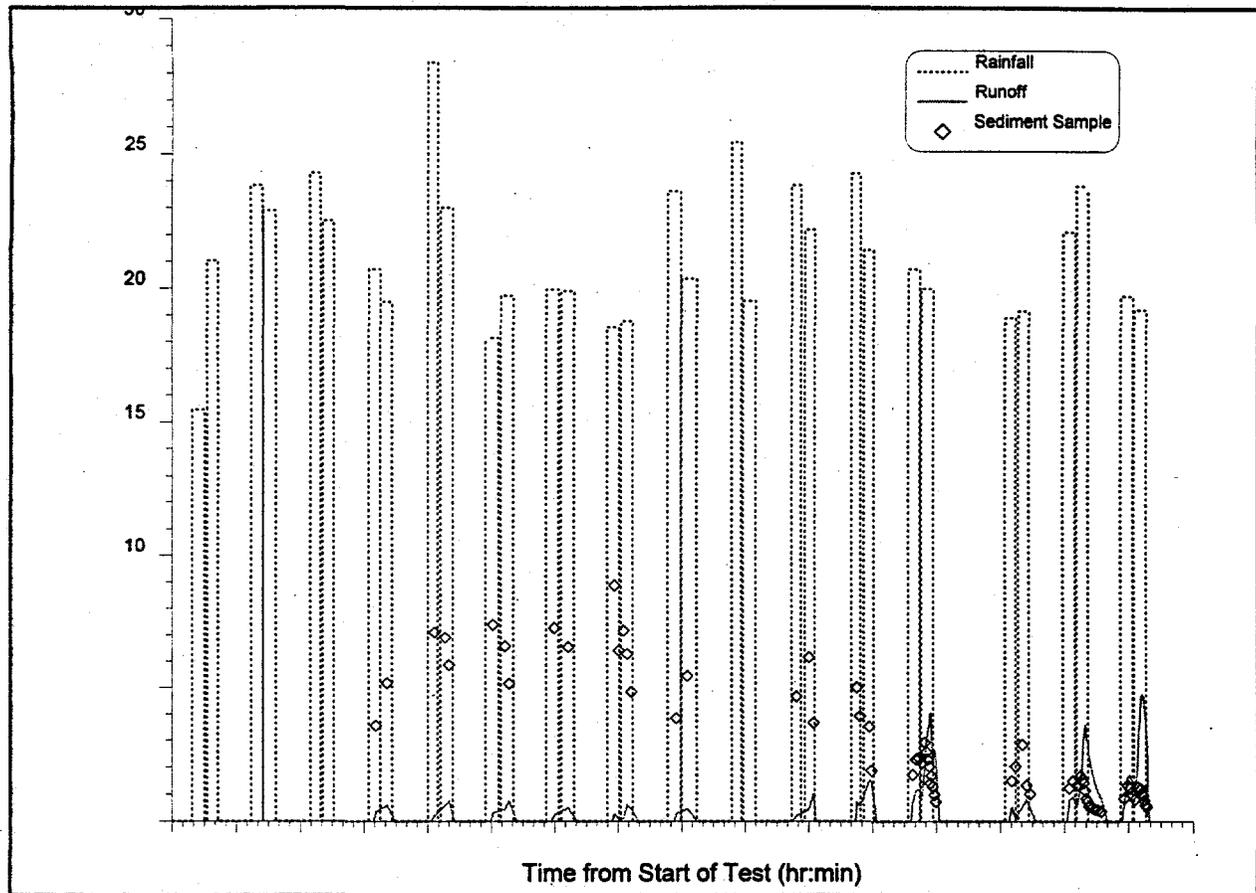


Figure 3.1. Runoff hydrograph, rainfall application, and sediment concentration amounts for 1000-year water application tests.

The rest of the water that was applied was assumed to infiltrate into the barrier. These runoff results agree within in 5% of the runoff estimated in the water balance task (Section 2).

Initial sediment concentrations collected during the test were approximately 7 g/L. This amount fell to approximately 1 g/L at the end of the test. This pattern of sediment yield, high initial concentrations falling to approximately 1 g/L, is consistent with the erosion test plot work done at

McGee ranch for surfaces with little or no vegetation. This pattern indicates that future sediment yield will be very low (<1 g/L) for the barrier surface as it ages.

3.3 SOIL SURFACE MONITORING

Surveying for topographic surface changes was initiated on the prototype barrier in 1994 and continued through FY 1995.

3.3.1 Objectives

Soil surface monitoring is being done to document seasonal or annual changes in the elevations and soil properties of the prototype barrier surface. Detailed measurements of surface elevations and soil properties are collected throughout the year. The individual measurements are compiled and used to generate topographic maps and isopleths of the various soil properties. This mapping identifies and documents the degree of nonuniformity of near-surface moisture (localized accumulations) together with the other soil properties and any changes in those values over the barrier life. Vegetation and biointrusion information (Task 02.6) is also used to identify any correlates with soil properties and erosional features.

3.3.2 Methods

The monitoring was conducted on a monthly and seasonal basis as needed. The 3-m x 3-m grid system (Gee et al. 1994) was established following construction and initial surface elevations, and soil property data were taken at that time. An additional surface elevation survey was conducted in late July 1995. Soil properties were collected in early May, with another collection date planned for late September. Vegetation surveys were obtained from biointrusion task activities (see Section 5.0).

Survey data were collected at the location of each stake of the grid system using of Electronic Distance Measuring (EDM) survey equipment. Vertical control was provided by the use of the four permanent survey monuments emplaced at the outside corners of the site location of the prototype barrier during the construction phase. The survey data were used to make the contour maps with the

aid of 3-D gridding software. The differences in elevation between the initial survey and the second survey were also plotted with the same software.

The soil property data were collected at the approximate center of each grid cell using a Troxler nuclear density gauge. The Troxler provides moisture content and wet and dry densities. This data an indicative of near- surface conditions (>20 cm) only, and do not provide information for the full soil column of the barrier. Alternate data collection techniques with the Troxler could be performed to provide soil property information for depths up to 1 m if necessary. The soil property data were used to generate maps with isopleths of equal values for the moisture contents and dry densities of the barrier surface.

The vegetation data were also used to generate a map with isopleths of equal values for plant density per grid cell.

3.4 ELEVATION

Elevation changes were measured on the prototype barrier using standard surveying EPM techniques as described previously. Elevations were monitored on the soil surfaces and on the rip-rap sideslope using the creep gage monitoring points..

3.4.1 Results

Figure 3.2 is topographic contour maps of the barrier surface for December 1994 and August 1995. The December map was generated with the elevation data of any plants on the barrier surface. The August map was generated with data collected after significant plant growth on the barrier surface. Both maps show the same general contours of the surface with no major changes in the slope of the surface. However, a small but overall gain in elevation is apparent over the full surface from December to August.

Figure 3.3 is a contour map of the elevation changes of the barrier surface between December 1994 and August 1995 and a surface map of the same elevation changes. There are five areas where

changes in this area are most likely the result of the excavation and backfill. The two northern corners, of the barrier surface show local gains in elevation of 5 cm and 7 cm in the northwest and northeast corners respectively. These are areas where accumulations of runoff have concentrated during the application of additional water by the irrigation system. This concentration of runoff deposited soil eroded and transported during the water application. The two other areas with significant changes are at the southeast corner and the area centered at 24-m north and 26-m east. The southeast corner shows a decrease in elevation of approximately 1 cm. This change appears to be related to an increase in density and the lowest moisture content of any area on the barrier surface. The area at 24-m north and 26-m east is located around the wind erosion monitoring equipment. This area shows a localized decrease in density that may account for the change in elevation. There are no other significant changes in moisture content or plant density to explain the increase in elevation.

3.5 CREEP AND SETTLEMENT GAUGES

Results of the creep gauge monitoring (Table 3.2) show that only gauge number 2 showed any significant movement. The other gauges experienced small changes in location and elevations. This movement is most likely the result of settling of the sideslope into a more stable and compact arrangement. The directions of gauge movement (bearing) indicate the changes are random and not in any preferred orientation. The movement of gauge number 2 may also be the result of settling as visual inspection of the area around the gauge did not indicate any mass movement of the sideslope. Additional monitoring of this area will be closely scrutinized.

The settlement gauges that were emplaced on the top of the asphalt pad were also surveyed. The results of the survey show that there have been no settlement changes within the survey measurement error (2-4 mm). Future surveying of these gauges will be consistent with the second survey and will identify any changes.

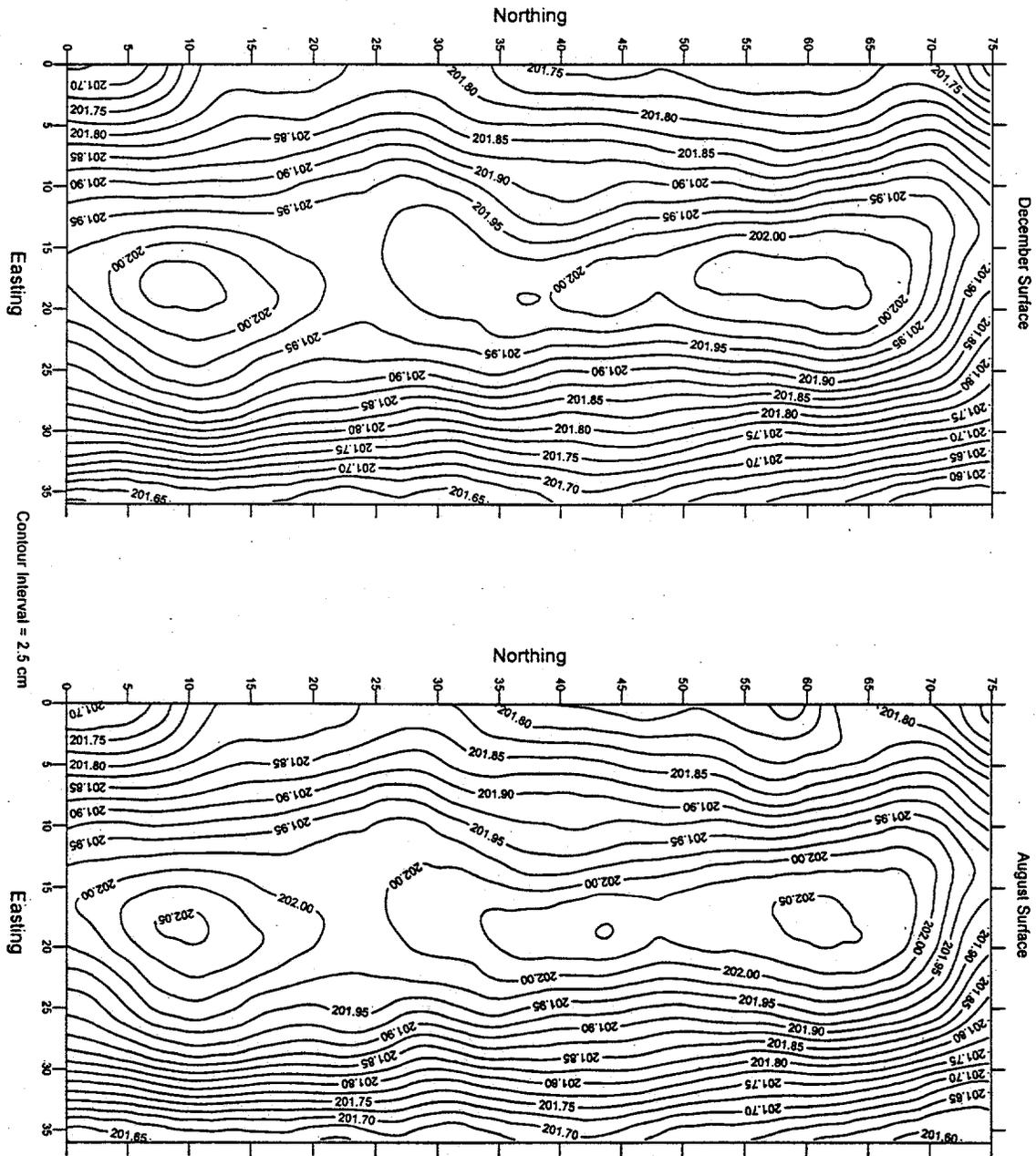


Figure 3.2. Topographic contours of barrier surface a) December 1994 and b) August 1995.

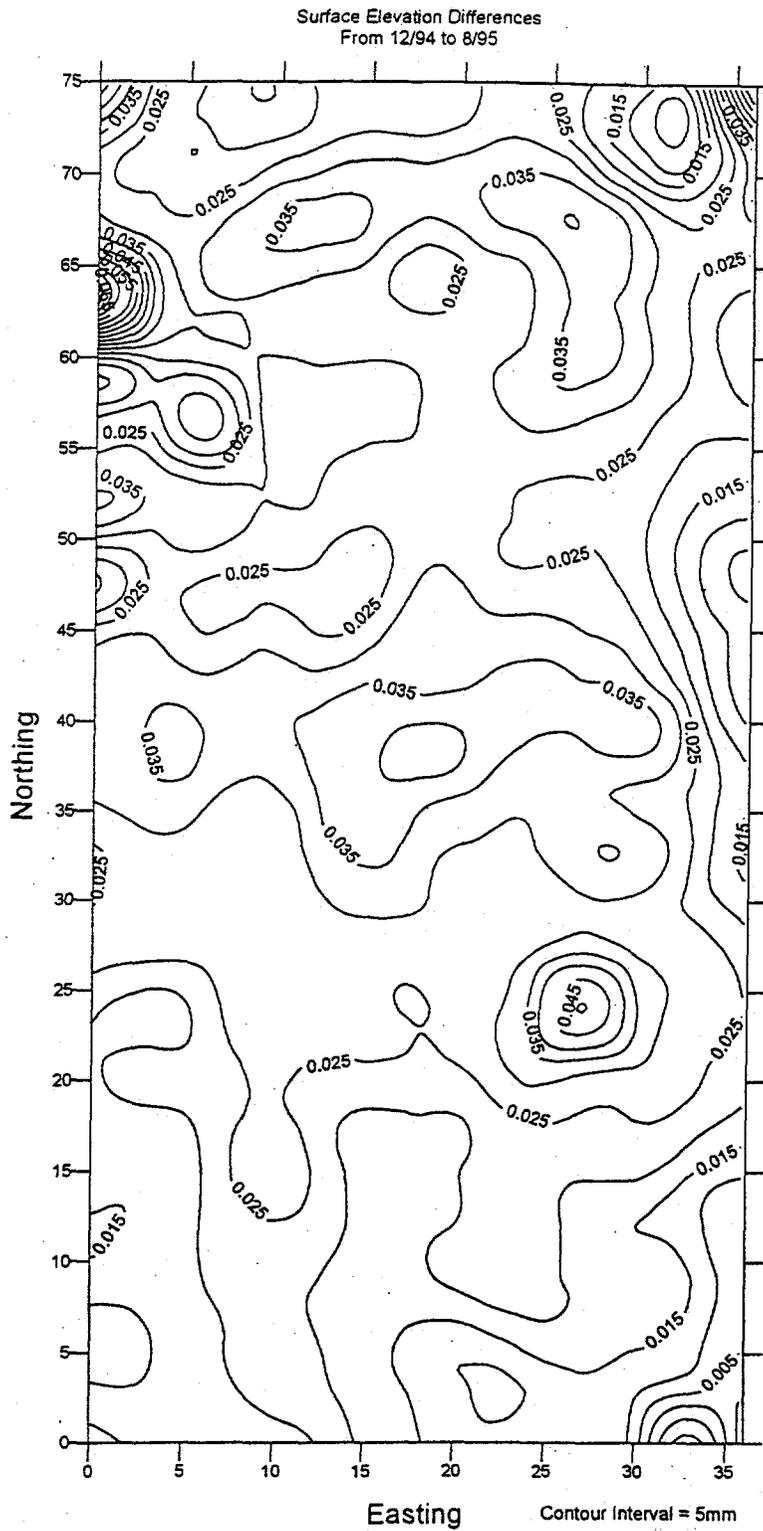
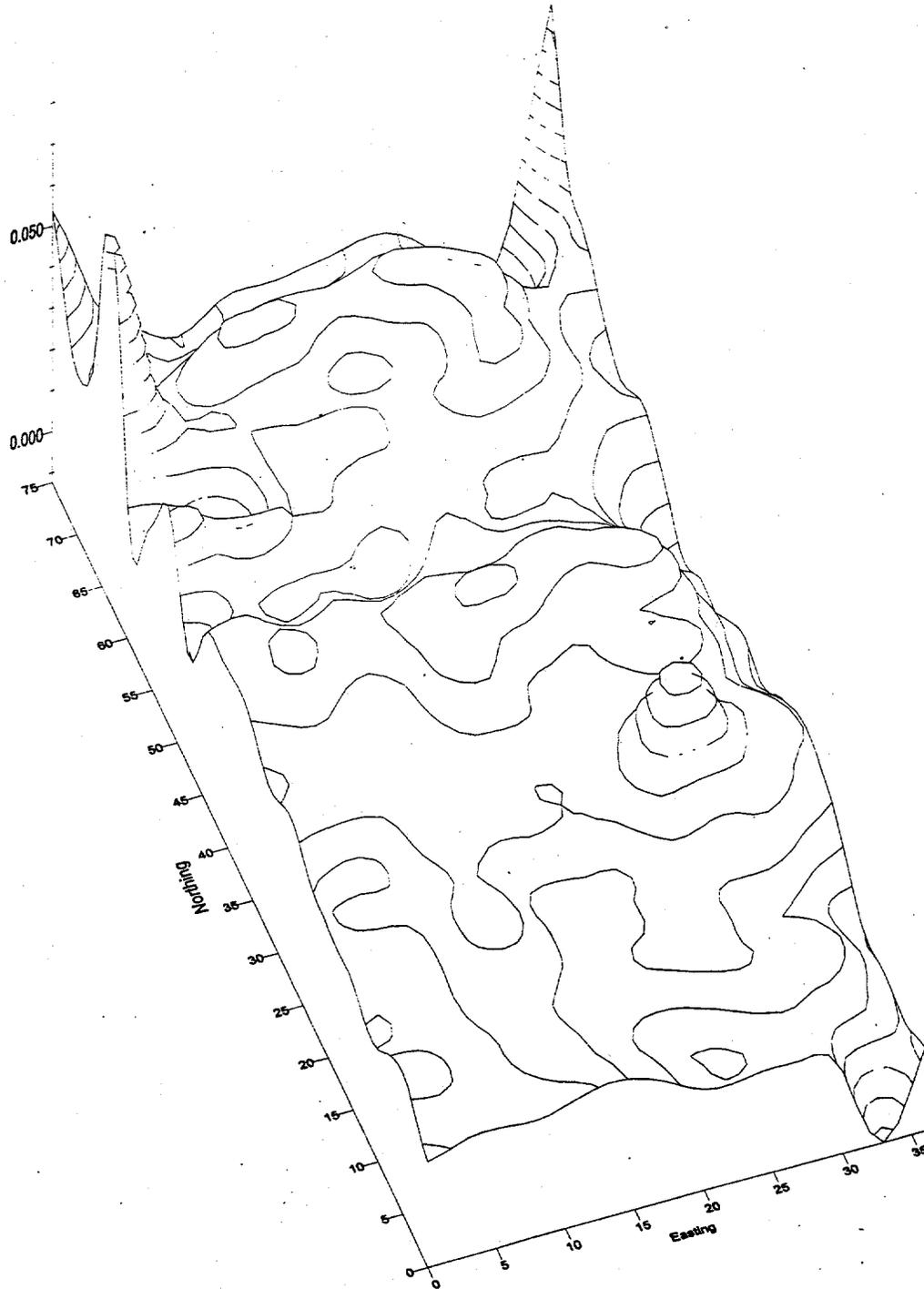


Figure 3.3. Prototype surface elevation differences in intervals of 5 mm. Differences from December 1994 and August 1995.

Elevation Changes from December 1994
to August 1995



Contour Interval = 5mm

Figure 3.4. Three-dimensional elevation change map for prototype barrier. Changes from December 1994 to August 1995.

3.6 SOIL PROPERTIES

Soil water, density, and plant cover were documented during the survey of the prototype surface.

3.6.1 Soil Water Content

Figure 3.5 is maps of the moisture contents in the winter and spring (December and May). As Figure 3.5 shows, the moisture content of the barrier surface in December was very uniform. The singular high moisture content located at 44-m north and 20-m east is the result of large amounts of water applied to the area during calibration of the water infiltration task equipment. The uniformity of the moisture content is the result of recent snowfalls with melting prior to taking the soil properties data. Figure 3.5 shows the effects of the application of additional water on the north half of the barrier. The south half of the barrier has not received any additional water application and the moisture contents reflect the differences between the two halves. Also, the northeast corner has the highest water contents on the barrier surface. This area of high moisture content is consistent with observations of water ponding in the area during the application of the additional water and the localized elevation increase from December to August. The southeast corner has the lowest water content on the barrier, consistent with the increase in density and decrease of elevation in this area.

3.6.2 Density

Figure 3.6 is maps of the dry densities in the winter and spring (December and May). The density of the barrier surface in December was fairly uniform, with an average value of 1857 kg/m^3 . Figure 3.6 shows that the south portion of the surface had a lower average density than the rest of the barrier. The change in densities from December to May is quite dramatic. The average density for the barrier surface in May was 1722 kg/m^3 , a decrease of 135 kg/m^3 . The north half of the barrier, the irrigated portion, shows the effects of the additional water application as a lower dry density and is consistent with the moisture contents shown in Figure 3.5. However, there is an unexpected area of lower densities across the width of the surface from 18-m north to 32-m north. These densities are approximately equal to the irrigated portion, but there is not an associated increase in moisture

contents or elevation changes that would explain these lower densities. The plant density map (Figure 3.8) does indicate that there is generally a greater amount of plants in this area than the rest of the surface. Figure 3.7 is a map of the density changes of the barrier surface from December to May. This map also shows the same strip of lower densities across the area of 18-m north to 32-m north as larger changes from initial conditions. The southeast portion of the barrier surface was the only area that had an increase of density between measurement periods. This is consistent with minimal change in elevation observed for this same area.

3.7 PLANTS

A qualitative assessment of plant density was made in August 1995 during the field survey of the prototype barrier. Figure 3.8 is a map of number of plants for each grid cell, or plant density. This map also shows that the southeast portion of the surface had a lower amount of plants per area, and a somewhat greater plant density in the strip 18-m north to 32-m north. The northwest portion of the barrier was observed on field inspection trips to have an extensive growth of grasses, as is also indicated on the map by the highest plant densities on the barrier surface. The analysis of the number of plants to moisture content did not indicate any correlations. This was somewhat unexpected but is probably the result of the hydroseeding of the surface and the higher-than-normal precipitation over the past year.

3.8 SUMMARY

The temporary erosion test plot indicated that the performance of the barrier was similar to the field erosion tests that were done as preliminary work prior to construction of the prototype. This result would support the conclusion that the surface will experience little erosion during extreme rainfall events. There was no settlement of the asphalt layer, as indicated by changes in elevation of settlement gauges attached directly to the asphalt layer underlying the prototype barrier. Nor was there any consistent movement (change of elevation) of the creep gauges on the rock sideslope, suggesting that the rock slope is stable and should not exhibit failure (slippage) under present or elevated precipitation conditions currently being tested on the prototype. However, there is only one year of

monitoring data and these observations will need to be validated with further monitoring over the life of the prototype.

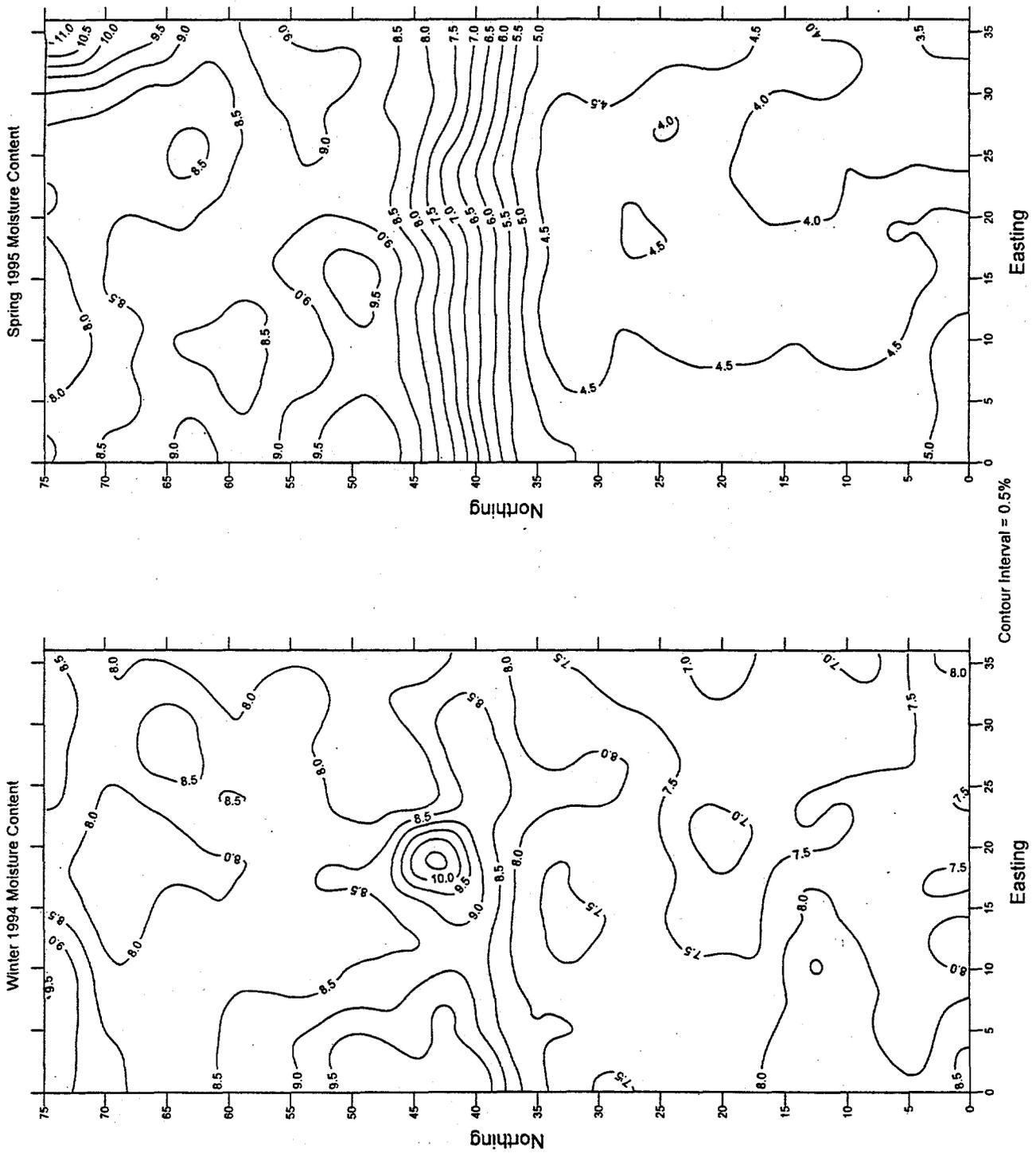


Figure 3.5. Surface soilwater content in December 1994, and Contours in August 1995

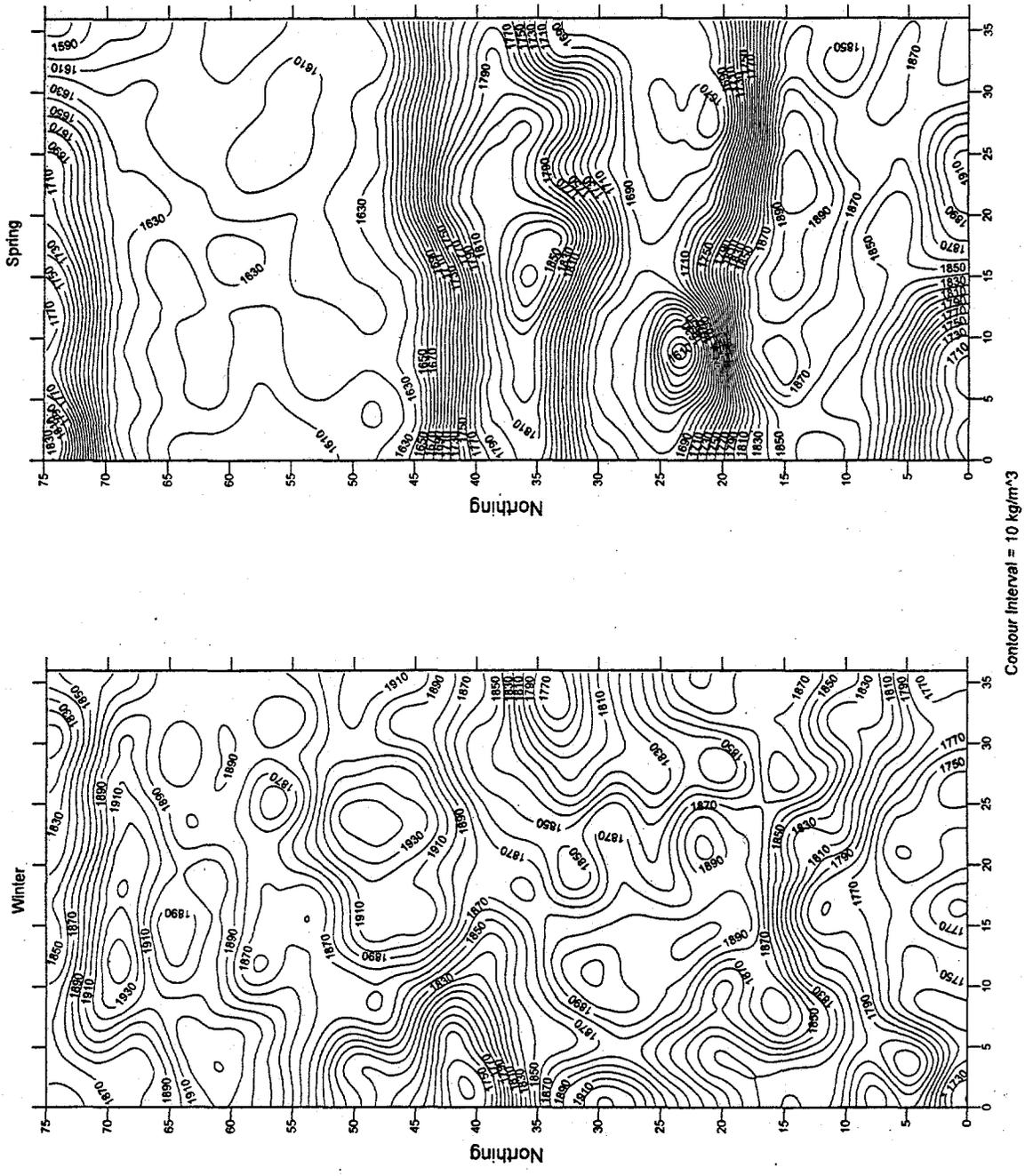


Figure 3.6. Surface soil density in December 1994 and August 1995

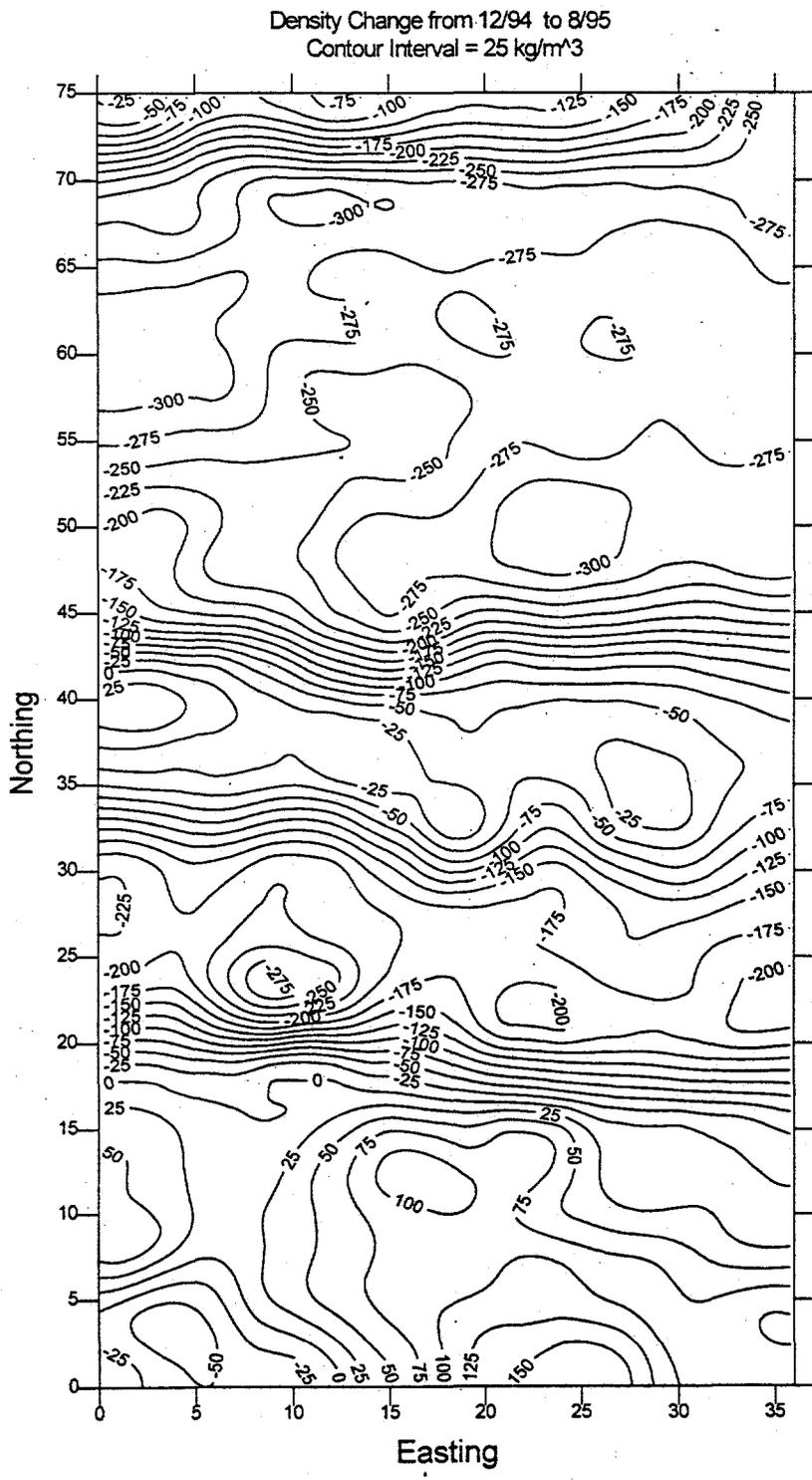


Figure 3.7. Prototype barrier soil density changes December 1994 to August 1995

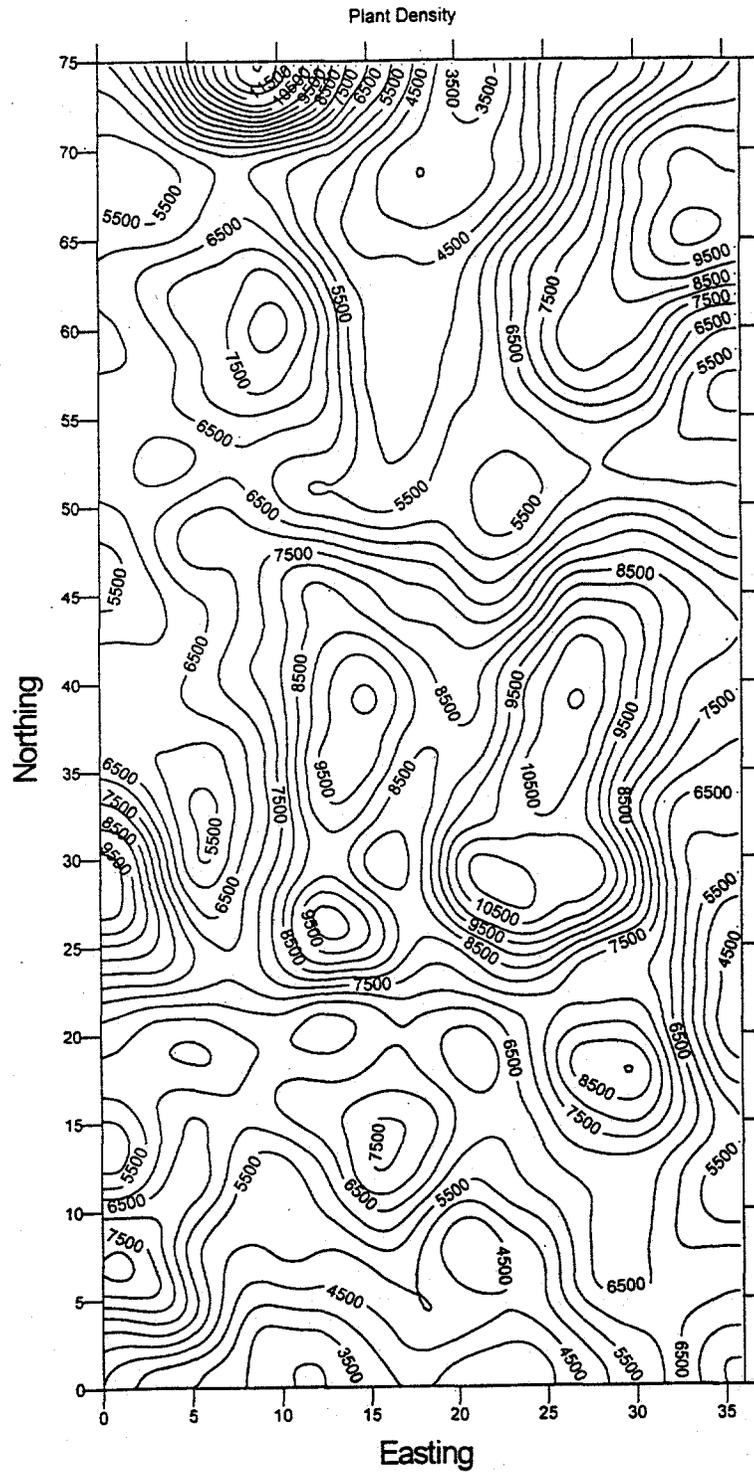


Figure 3.8. Prototype barrier plant density contours for August 1995. Density is plan number per 9 m².

4.0 WIND EROSION MONITORING TASK

The first of three planned years of monitoring work was performed in FY 1995 to study the influence of eolian stresses on the stability and function of the admixture surface of the prototype barrier. As a part of this effort, measurements are being performed to validate the selection of test parameters in past wind tunnel tests that provided design-basis information for the surface layer. The influence of erosion on the two types of sideslopes is also being monitored. Most wind erosion monitoring work is being performed over the south, nonirrigated half of the prototype barrier where erosive stresses are maximized and most closely represent the worst-case conditions needed for wind erosion monitoring. While normal erosion events are of interest, monitoring systems in use were designed and selected for continuous use to ensure data are obtained in the event of the occurrence of high-intensity wind storms (e.g., wind storms with >10-year return period).

4.1 SCOPE AND OBJECTIVES

The construction of a full-scale PSB at Hanford provides an opportunity to monitor actual conditions and effects of wind on the surface and to compare these results with assumptions made during wind tunnel tests. The results of wind tunnel tests of simulated surface layer admixtures, reported previously by Ligothke and Klopfer (1990) and Ligothke (1993), provided information with which the design basis of the surface layer of the prototype barrier was developed. The scope and objective of several wind erosion monitoring activities were listed and described briefly by Gee et al. (1993a), and, in modified form, include:

- Monitor the influence of eolian stresses on the surface layer under irrigated and natural conditions after disturbances caused by construction and then vegetation-establishment
- Measure actual rates of surface deflation or inflation
- Obtain micrometeorological information about erosive stresses that impact the barrier

- Obtain information about abrasive sand particle scouring (saltation).

In addition, two other testing and monitoring objectives have been proposed for the period after most other monitoring activities have ceased, presuming site restrictions and work priorities permit:

- Create a sand dune and monitor its impact on surface erosion, plant community viability, and soil reservoir water balance
- Remove established vegetation by fire or other means and study the erosive impacts under conditions simulating a post-wildfire draught.

4.2 WIND EROSION TESTING AND MONITORING ACTIVITIES

Four wind erosion testing and monitoring activities were performed on the surface of the prototype barrier that was constructed in 1994 over and to the north of the B57 waste crib at the 200-BP-1 operable unit at the 200 East Area of Hanford. Work performed was based on the test plan by Gee et al. (1993a). Changes to the scope of the wind erosion monitoring task occurred during the year as the growth of vegetation reduced the need for using saltation sensors and dust traps.

4.2.1 Prototype Barrier Surface Layer

During construction in 1994, the top 1-m fine-soil surface layer was amended to add of 15 wt% pea gravel. The gravel was added to act as an agent to resist erosion of the soil by wind during periods following construction, wildfires, droughts, or other periods of increased susceptibility of the surface to eolian stresses. The decision to use 15 wt% pea gravel was based in part on the results of wind tunnel tests (Ligotke and Klopfer 1990; Ligotke 1993) and in part as a compromise with needs of water storage in the surface layer which is decreases as gravel concentration increases. The constructability of an admixture on the scale of the prototype surface layer was evaluated. Issues resolved during the early stages of the testing and monitoring project included: 1) unforeseen practical difficulties were not encountered during construction, and 2) it was possible to maintain a relatively uniform admixture composition (also see Section 4.2.2).

The preparation and placement of the 1-m-thick pea gravel admixture did not pose unusual construction difficulties. A pug-mill operation was set up at the construction site to mix clean pea gravel with silt-loam from the same source used to construct the lower soil layer. The material was dumped on the surface and then shaped using a tracked caterpillar. The final surface was ripped to provide a surface density within specifications. The concentration of pea gravel near the surface was found to be fairly uniform (Section 4.2.2).

To allow comparison with previous studies, two gravel samples were obtained from the pile used when constructing the prototype barrier. The size distribution of gravel in the samples was measured using Method D422-63 (ASTM 1984). Average results, the mass percentage passing selected sieves, included: $97.4 \pm 0.2\%$ less than 0.80 cm, $69.4 \pm 0.9\%$ less than 0.63 cm, $14.6 \pm 1.8\%$ less than 0.475 cm, and $0.4 \pm 0.1\%$ less than 0.33 cm, and 0% less than 0.24 cm. Both samples indicated an average gravel particle size of 0.5 cm, with 90% of the mass of the samples consisting of gravel sized between 0.3 and 0.8 cm. The gravel was similar to the bulk pea gravel used previously in wind tunnel tests (Ligotke 1993).

4.2.2 Surface Layer Composition and Deflation/Inflation

Testing and monitoring was initiated to study the suitability of a 15 wt% pea gravel admixture in the top 1-m soil layer to provide resistance to wind erosion. Knowledge of the long-term condition of the surface as it ages under both deflationary and inflationary influences will assist this evaluation. During deflationary periods, the concentration of pea gravel at and near the surface is expected to increase and form an armor as soil particles are removed by wind. During inflationary periods, a layer of soil that is largely free of pea gravel is expected to form on the surface. Questions to be answered during the three-year study will reveal the ability of the surface to resist eolian stresses. What is the distribution of pea gravel at the surface, and does it change compared with its bulk distribution in the soil layer? When deflationary conditions prevail, are measured rates of erosion comparable to wind tunnel test results, does a pea gravel armor form and reduce rates of erosion, and do scoured areas form near upwind edges or in other areas? When inflationary conditions prevail, do sand deposits form, does the distribution of pea gravel change at the surface? What erosion or deposition occurs on the sideslopes, and how does orientation and slope influence sideslope erosion or deposition? Visual

surveys during the early stages of the project revealed that pea gravel did concentrate at the surface, however, wind conditions were such that no significant soil removal occurred and no obvious armor was formed.

Grab samples were obtained twice during the first year of the study and were analyzed to determine surface composition. In both cases, the samples were obtained from 24 locations evenly spaced within the rectangular surface of the barrier. The first set of samples was obtained on 8/24/94, immediately following construction (after the surface was ripped to decrease density and before redistribution of the surface by wind). The samples were scooped from the surface to a maximum depth of about 7 cm, and contained bulk masses between 1.5 and 2.0 kg. The second set of samples was obtained 4/11/95 after the surface had consolidated during the first winter and after vegetation was initially established by hydroseeding. These samples were obtained by coring the soil column to a depth of 10 cm. Each sample was collected as two sections, representing the soil column at 0 - 2 cm (surface) and 2 - 10 cm (bulk) depths. As the surface grid had been established by the second sample date, the grid locations of each sample were also recorded. Both sample sets provided six samples from each quadrant of the surface. Additional surface samples are scheduled to be obtained annually as surface conditions permit, or more often if the appearance of the surface changes significantly.

Sample analyses provided baseline information on pea gravel concentrations and distributions in the soil column. Also obtained from the samples was information on soil moisture and density (below). Pea gravel concentrations, wt%, were determined as the mass of pea gravel per the combined mass of dried soil and pea gravel. Based on the results of pea gravel size distribution (Section 4.2.1), the gravel was separated from the soil using a 0.33-cm sieve. The average bulk pea gravel concentration was $14.4 \pm 2.0\%$ (August 1994) and $14.1 \pm 1.5\%$ (April 1995). (Separating gravel larger than 1.3 cm from the second set of samples, the bulk pea gravel concentration was slightly smaller, at $13.2 \pm 1.4\%$.) These results indicated that the actual pea gravel concentration in the surface admixture, including a small quantity of gravel larger than 1.3 cm, was 95% of the target level for construction. Average pea gravel concentrations were similar for both north (irrigated) and south (nonirrigated) regions of the barrier surface. In August 1994, before irrigation had been applied, the bulk pea gravel concentration averaged $15.3 \pm 2.2\%$ in the north half and $13.5 \pm 1.2\%$ in the south

half. In April 1995, after irrigation and hydroseeding, the bulk pea gravel concentration averaged $13.9 \pm 1.4\%$ in the north half and $14.3 \pm 1.6\%$ in the south half.

The comparison of pea gravel concentrations in the top 2 cm of the soil column with bulk concentrations provided an indication that no significant soil loss had occurred by the April 1995 sample date. Although the average concentration of pea gravel in the top 2 cm of the soil column was found to exceed the bulk concentration by 5 to 7%, the uncertainty in the measurement (based on one standard deviation of the averages) was estimated to be roughly twice the difference. Neglecting uncertainty, the measurements indicated roughly a 33% increase in the concentration of pea gravel in the top 0.3 cm of the surface. That an increase actually occurred was evidenced by visual observations that the pea gravel did indeed concentrate on the surface early in the study period.

Incidental information was also generated on moisture content (soil and admixture) from the two sets of surface samples. Similarly, information was also generated on density (wet and dry, soil and admixture) from the April 1995 data set. These data were tabulated and made available as general information for the overall testing and monitoring project. Average soil moisture content of the August 1994 samples was $3.4 \pm 1.4\%$ (6 of 24 samples were dried). Average soil moisture content of the April 1995 samples was $17.1 \pm 0.3\%$ from the bulk samples and $8.9 \pm 0.7\%$ from the surface samples (all 48 samples were dried). Separated into north (irrigated) and south (non-irrigated) regions, the dry admixture densities were: $1.54 \pm 0.11 \text{ g/cm}^3$ (north, bulk), $1.43 \pm 0.10 \text{ g/cm}^3$ (south, bulk), $1.7 \pm 0.2 \text{ g/cm}^3$ (north, surface), and $1.9 \pm 0.3 \text{ g/cm}^3$ (south, surface). Again separated into north (irrigated) and south (non-irrigated) regions, the dry soil densities were: $1.32 \pm 0.09 \text{ g/cm}^3$ (north, bulk), $1.23 \pm 0.08 \text{ g/cm}^3$ (south, bulk), $1.5 \pm 0.2 \text{ g/cm}^3$ (north, surface), and $1.6 \pm 0.3 \text{ g/cm}^3$ (south, surface).

4.2.3 Wind Stress Monitoring

The first full year of monitoring wind boundary layers was completed on 9/6/95. The objective of this work is to provide information on the eolian stresses on the surface of the prototype barrier during wind storms. This information provide validation of the choices of wind shear stresses applied during the wind tunnel tests of the erosion-resistant layer of the barrier's fine soil reservoir. Measurements

are being made near the center of the top surface and near one edge; measurements are also being made over a typical nearby surface for comparison. The following testing and monitoring questions are being addressed. Are peak values of wind stress comparable, but less than, published values and those selected for wind tunnel tests? How much larger are wind stresses at the prototype top elevation than at ground level? Is the difference significant with respect to the ability of the barrier to resist deflation?

Three wind boundary layer stations are being used to monitor wind stresses. The data record from the two stations on the surface of the prototype barrier was initiated on 9/6/94, the data record from the third station located off the elevated surface of the barrier was initiated on June 4, 1995. Wind Station 01 is located south of the center of the top surface of the prototype barrier. Station 02 is located in the southeast quadrant, nearer to the steep riprap sideslope. Station 03 is located west-southwest of the prototype barrier. The configuration of each wind stations includes a wind direction sensor and four wind speed sensors, at elevations of 0.25, 0.50, 1.0, and 2.0 m above the surfaces. Air temperature is also measured at Stations 01 and 02, and solar radiation is measured at Station 01. A single solar-powered datalogger is used to record data from Stations 01 and 02, a second datalogger is used for Station 03. Anemometer calibrations were confirmed in a wind tunnel, the direction sensors were aligned to read 0 degree when directed true north (18 degree declination), and the connection of each sensor to the dataloggers was checked and validated. Not included in the present system is a near-surface moisture probe; before the use of such a probe was achieved, the wet weather and establishment of vegetation reduced the need for such measurements (Section 4.2.4).

Data from the wind stations are being recorded continuously, and success of the activity depends on obtaining data from most of the significant wind events that occur during the three-year monitoring period. All wind station measurements are recorded hourly and on 10-min intervals. A threshold wind speed of 7.5 m/s was selected to initiate the shorter interval acquisition rate during windy periods. In addition to recording average and peak-gust wind speed data, the hourly output includes the magnitude, direction, and time of peak gusts, and the 10-min output includes similar information (for each anemometer) on the shorter cycle. A procedure for converting data files to data records was developed. Currently, data are tracked using three types of files. One file is used to track summary information on daily averages. A second file is used to track hourly averages. The third file contains

the detailed boundary layer data generated during windy periods when the 10-min average wind speed exceeds the threshold value. A method for selecting wind speed records for surface shear stress calculations is being developed.

The first year of the study was generally characterized by normal or less-than-normal winds, and only one peak wind gust was recorded that exceeded 18 m/s (measured at the 2 m level). Such a wind gust would be expected to have a 1 or 2 year return period. (For comparison, the maximum 15-m peak gust reported by the Hanford Meteorological Station during the same period was a 24 m/s gust in May, yielding a return period of 1 to 1.5 year.) The peak wind gusts at the prototype barrier between September 1994 and August 1995 were recorded on 10/26/94. With the datalogger operating at the rapid acquisition rate, the boundary layer profiles of wind over the prototype surface were recorded. These are shown, as an example, in Figure 4.1. From the boundary layers, the friction velocity, u^* , was estimated to have been 0.9 to 1.0 m/s. The wind tunnel tests of the surface were performed at u^* values between 0.4 and 2.2 m/s (Ligotke 1993). The set of wind boundary layer information being generated during this study can be used to track mean and peak-gust wind speed information during selected or continuous intervals (also see Section 4.2.4). For evaluating the potential for sand drift and eolian erosion, the wind speed records can also be used with wind direction records to prepare wind and peak-gust roses.

In addition to wind speed and direction data, the wind stations are used to provide air temperature and solar radiation records. These data provide information useful to the evaluation of water balance by measurement and modeling. Daily and hourly air temperature records are available. Daily total and hourly average solar radiation records are available. As an example of the data set, daily total solar radiation levels are shown September 1994 through August 1995 in Figure 4.2; the daily levels ranged from 12 mW/m² on 2/7/95 to 883 mW/m² on 6/26/95.

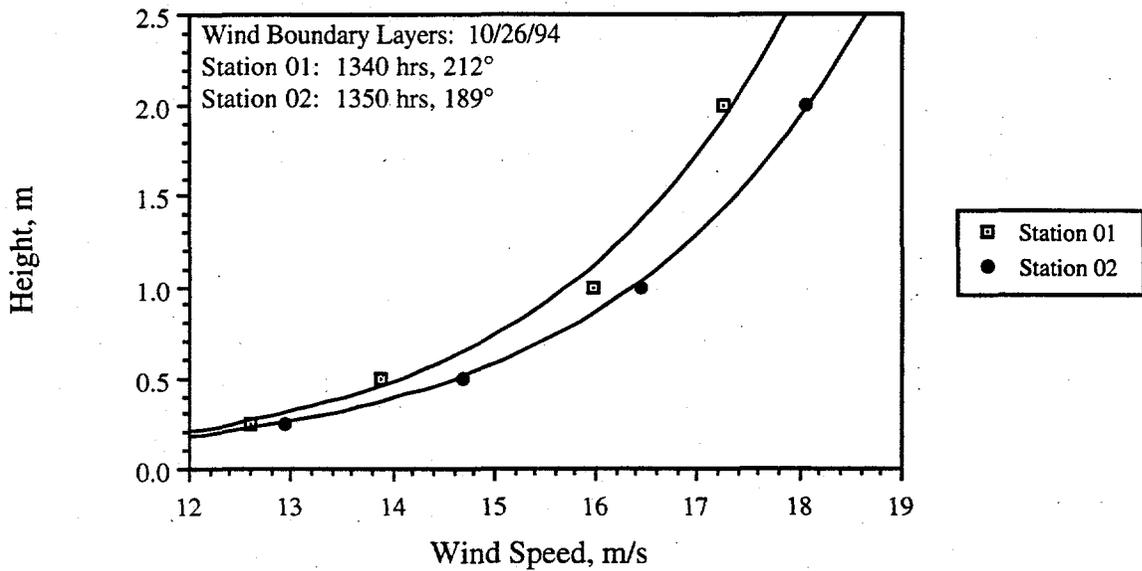


Figure 4.1 Peak gust wind profiles measured over the elevated surface of the prototype barrier, 10/26/94

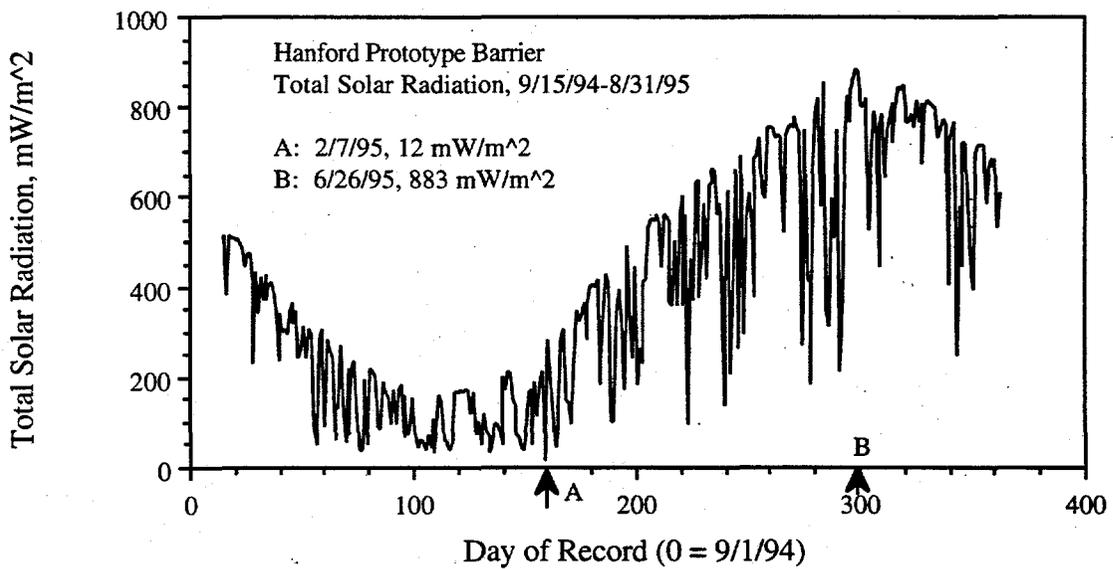


Figure 4.2 Daily total solar radiation, 9/15/94 through 8/31/95

4.2.4 Monitoring Saltation Stresses and Sand Drift Rate

The movement of wind-driven sand over the surface of the barrier is expected to be a significant natural mechanism by which eolian stresses are applied to the surface of the barrier. Measuring the stresses and drift rates of soil and sand over the surface of the barrier will provide an important indication of the magnitude of these stresses. A series of questions are being addressed by this study. Are peak values comparable to, but less than, the published values selected for wind tunnel tests? Are sand particle saltation stresses and sand drift potentials at the top surface of the monitored barrier greater or less than those at ground level? Is the difference significant with respect to the capacity of the barrier to resist deflation? The results of saltation measurements will be compared with wind boundary layer and surface shear stress information to identify stresses and evaluate the resistance of the surface to eolian erosion. Saltation stresses are anticipated to be greater on the surface of the monitored barrier than on the surrounding desert. This is because prevailing winds are likely to drive saltating sand along the graded sideslope and to the top of the barrier surface. Monitoring data will be used to quantify and evaluate the presence and influence of saltating sand grain shear stresses on the barrier surface. These stresses are expected to be equal to or less than the sand flux rates applied to physical models in a wind tunnel. Measured rates of sand transport will be correlated with meteorological and surface conditions and compared with published estimates.

By the end of August, 1994, two types of measurement devices had been deployed on the top surface of the barrier, located near the east edge of the southeast quadrant of the surface. Simple physical traps were co-located with piezoelectric saltation sensors. Both types of devices had been selected for this study because they provided the opportunity to collect the mass of material blowing across the surface of the barrier and the opportunity to characterize the kinetic energy of sand grains impacting the surface. The devices were tested comparatively in a wind tunnel in 1994 to gain insight into operational requirements and limitations. Both types of devices performed well in the field, especially during the initial several months after

establishment of dense vegetation, the usefulness of the devices decreased, and they were removed in September 1995. The systems have been retained, and will be used to augment the testing and monitoring effort should vegetation become significantly reduced, or, the systems may be used to augment arid-site surface barrier technology development studies at related sites. It is also possible that funding levels will permit limited seasonal use of the systems at the site to characterize the rate and energy levels of saltating sand that blows onto the barrier during wind storms. Given adequate conditions during the study, this data would allow the evaluation of long-term sand drift rates and erosion potential at the site.

The piezoelectric saltation sensors were connected to a datalogger that energized the sensors when the 10-min mean wind speed exceeded 7.5 m/s. The sensors, with cylindrical cross-sections to eliminate dependence on wind direction, provided a count record of sand grain impacts and a time record of the total kinetic energy of each erosion event. The sensors were arrayed in the same locations as the dust traps, and at elevations of 0.25 m (three sensors), 0.50, and 1.0 m above the surface of the barrier. As with the dust traps, the single station with multiple sensors was used to provide information on the vertical profile of sand grain impact intensities above the surface of the barrier. The sensors were Model H7 (Sensit Company, Portland, North Dakota). Data files were generated during the limited and not excessively windy period after construction and before the surface became stabilized by rainfall and hydroseeding. These data will be compared with the wind records and dust trap results.

The dust traps were arrayed at elevations of 0.125, 0.25, 0.50, and 1.0 m above the surface; one station contained three traps at 0.25, 0.50, and 1.0 m, one station contained a single trap at 0.125 m, and two stations contained single traps at 0.25 m. The station with multiple traps was used to measure the vertical distribution of soil and sand above the surface of the barrier. The traps were of the type described by Fryrear (1986), and each had an integral wind vane that served to orient the collection plane of the trap into the wind. The traps were positioned singly or grouped on poles and allowed to orient into the wind freely. Dust and sand blowing over the surface was collected in the traps through a 10 cm² opening. Material collected in the traps was removed frequently and transported from the field in tin sample containers. The cleaned traps were left in the field to continue the collection process. Collected material was transported to a laboratory and weighed to determine dry mass.

When sufficient material was obtained, sieves were used to separate the medium sand ($> 500 \mu\text{m}$), the fine sand ($100 - 500 \mu\text{m}$), and the very fine sand and silt ($< 100 \mu\text{m}$). Material collected in the middle range was that expected to consist of sand grains most susceptible to be transported in saltation. This sand is expected to cause the greatest enhancement of soil particle loss from a surface exposed to wind.

Monitoring data from the dust traps provided information on the rate, vertical distribution, quantity, and composition of material blowing over the surface of the barrier. The traps were sampled nine times between 8/29/94 and 11/1/94. At an elevation of 0.25 m, average quantities of material collected from the three traps ranged from 0.07 to 2.9 g. In eight of the nine samples, the vertical profile of suspended material over the surface appeared similar, regardless of the intensity of the dust storms, as shown in Figure 4.3. The single case which varied from the norm was collected on 10/1/94 and showed a roughly uniform concentration profile, however, the total mass collected during that period was very small and subject to the greatest relative uncertainty. Excluding that sample, the normalized shape of the vertical distribution of blowing soil and sand over the surface was very uniform, as shown in Figure 4.4. These results indicate the vertical distribution of material blowing across the surface was $62 \pm 4\%$ at 0.125 m, $24 \pm 4\%$ at 0.25 m, $10 \pm 2\%$ at 0.50 m, and $4 \pm 2\%$ at 1.0 m. Using this information, the total quantity of material blowing by the stations during the nine measurement periods was determined to have varied from 25 to 2500 g per meter of width. A comparative evaluation of these results with the wind speed and soil moisture data during these periods is planned. It is expected that the results will show a decrease in soil loss as the surface aged. Unfortunately, wind records indicate no unusual (>2 year return period) winds occurred during the measurement periods; had such a wind storm occurred, the value of these results would have been enhanced.

The composition of the material collected in dust traps was dominated by very fine sand and silt particles smaller than $106 \mu\text{m}$ (Figure 4.5). Because of their small sizes, such particles have the greatest tendency to remain suspended once they are removed from the surface by wind. In addition, as much as 20% of the particulate mass collected in the dust traps consisted of fine sand grains between 106 and $500 \mu\text{m}$ in size, with the greatest quantities found within 0.5 m of the surface. These sand grains are those most likely to be transported by wind in saltation, short-distance vertical

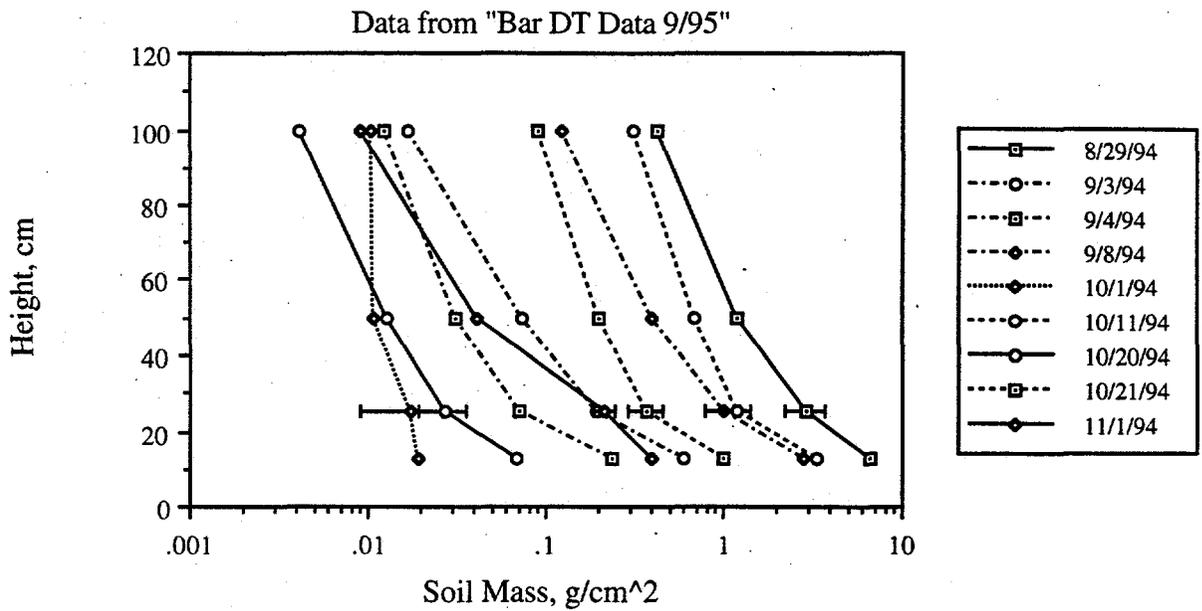


Figure 4.3 Measured vertical profiles of soil and sand blowing across the surface of the prototype barrier, 8/29/94 - 11/1/94.

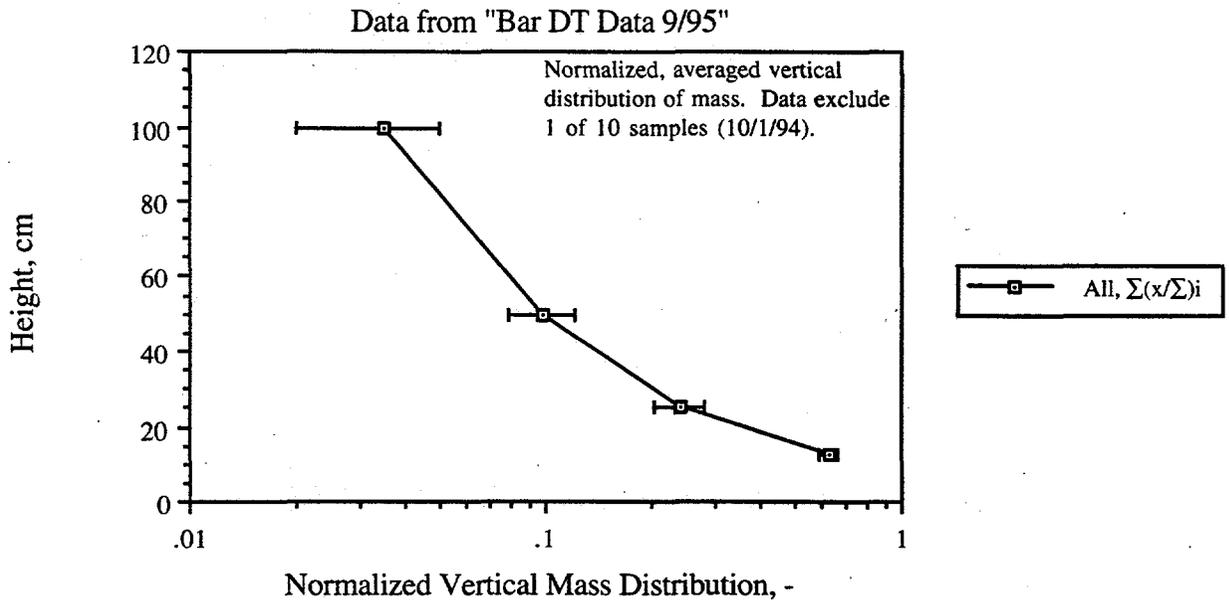


Figure 4.4 Normalized vertical profile of soil and sand blowing across the surface of the prototype barrier, 8/29/94 - 11/1/94.

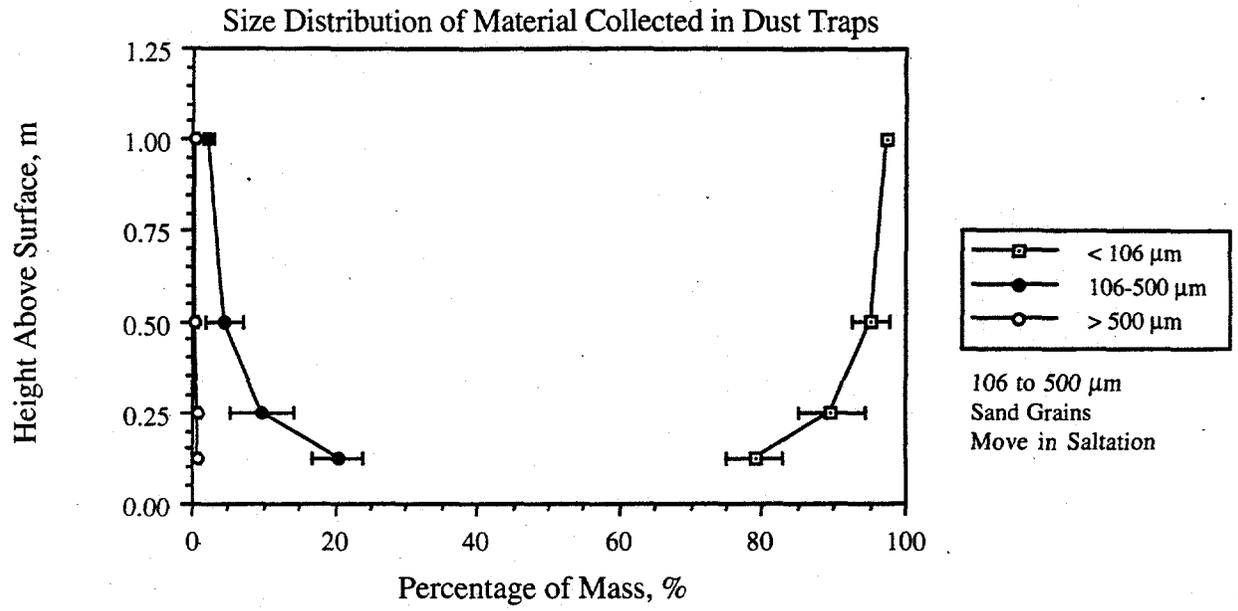


Figure 4.5 Particle size distribution of material collected in dust traps, 8/29/94 - 11/1/94.

hopping with low-angle terminal impacts that cause the much smaller silt-sized particles to be ejected from the surface. Because of this, grains in this size range have the greatest potential for causing or increasing the erosion of soil surfaces by wind. Only very small quantities, less than 1%, of sand grains $>500 \mu\text{m}$ were found in the traps. Such particles are generally transported by wind in creep, sliding and rolling along or near the surface. Taken in bulk, regardless of position, the size distribution of all material collected was $89 \pm 4\%$ less than $106 \mu\text{m}$, $10 \pm 4\%$ between 106 and $500 \mu\text{m}$, and $<1\%$ greater than $500 \mu\text{m}$.

4.3 CONCLUSIONS AND RECOMMENDATIONS

A testing and monitoring activity was performed to document, measure, and evaluate the influences of eolian stresses on the surface of a full-scale prototype surface barrier. In August through October 1994, soil loss by wind was sufficient to initiate the formation of a pea-gravel armor on the surface. After the surface was stabilized by rainfall and vegetation, no further significant loss of the fine soil was observed during the remainder of 1995. Wind boundary layer profiles and peak gusts were monitored throughout the first of three planned years of the project. Representative physical samples of soil and sand blowing over the surface of the barrier were obtained during the three months following construction, the time period most closely representing possible worst case surface conditions. After vegetation was established on the surface, the rate of soil loss was largely eliminated, consequently, the study was re-directed to focus on necessary wind measurements and the physical traps and sensors were removed from the site. Also decreased was the frequency of surface composition sampling to evaluate concentrations of the pea gravel armor. Use of these methods during the remaining years of the study will be opportunistic; the devices will only be used to evaluate the rate of sand drift on to the barrier or to monitor conditions in the case that vegetation is removed or lost.

5.0 REVEGETATION AND BIOINTRUSION

Plants and animals will significantly influence the hydrologic, water and wind erosion characteristics of the prototype barrier (Link et al. 1995b). Studies on the biological component of the prototype barrier in Fiscal Year 1995 included work on the revegetation of the surface and the subsequent monitoring of biotic characteristics.

5.1 REVEGETATION

The initial work concerning seed collection and germination of the shrubs, *Artemisia tridentata* and *Chrysothamnus nauseosus*, used in revegetation was described in Link (1995). The surface was revegetated with seedlings of the shrubs and seeded with native perennial grasses in November, 1994. On November 7 shrub planting was initiated and completed the next day. Twenty-seven hundred holes were drilled at a density of 1 hole m⁻² on the prototype surface. Two seedlings were placed in each hole. There were 1350 *C. nauseosus* and 4050 *A. tridentata* seedlings planted. The seedlings were approximately 20 cm tall.

Perennial grasses were established by hydroseeding the barrier surface and surrounding slopes. The hydroseeding mix included seeds, fertilizer, mulch and a tacking agent. The native perennial grass seed mixture included *Poa sandbergii* (34 kg ha⁻¹), *Agropyron dasystacium* (5.6 kg ha⁻¹), *Oryzopsis hymenoides* (22 kg ha⁻¹), *Poa ampla* (11 kg ha⁻¹), *Stipa comata* (5.6 kg ha⁻¹), *Pseudoroegneria spicata* (14 kg ha⁻¹), and *Sitanion hystrix* (3.4 kg ha⁻¹). Seed of *S. hystrix* was collected in June, 1994 on the Fitzner-Eberhardt Arid Lands Ecology Reserve (ALE). The other perennial grasses originated from sources in the semi-arid West. The fertilizer was applied as 67 kg ha⁻¹ of total nitrogen, 67 kg ha⁻¹ of available phosphoric acid (P₂O₅), and 67 kg ha⁻¹ of soluble potash (K₂O) in solution. The mulch was applied as 2,240 kg ha⁻¹ of Eco-Fibre 100% virgin wood fiber. A degradable glue was added to the mulch as a tackifier at 67 kg ha⁻¹. The hydroseeding was applied on November 10 with the above material in a slurry form. The material was mixed with water using power augers in a large tank on a truck, then dispersed under pressure from large hoses onto the ground.

Plant establishment on the surface was successful with very little loss of perennial shrubs. The status of the seedlings was assessed on December 2. *Artemisia tridentata* (sagebrush) seedlings all appeared to be viable with new vegetative growth on some individuals. *Chrysothamnus nauseosus* seedlings were hydrated, but most had lost green foliage. About 20% had some green foliage remaining. *Chrysothamnus nauseosus* (rabbitbrush) naturally is winter deciduous. Observations on December 21 indicated no change. Grasses had not germinated yet.

5.2 BIOINTRUSION

The biotic characteristics documented included the developing plant community (composition and distribution), gas exchange rates, rooting depth and dispersion, soil water content in relation to the plants, plant size, and animal observations.

5.2.1 Vegetative Composition

The vegetative composition of the surface besides the previously mentioned 2 shrubs and 7 perennial grasses used in revegetation included several invasive alien and native species. The invasive aliens included *Bromus tectorum*, *Chorispora tenella*, *Draba verna*, *Erodium cicutarium*, *Lactuca serriola*, *Poa bulbosa*, *Salsola kali*, *Sisymbrium altissimum*, and *Triticum aestivum*. Native species included *Achillaea millifolium*, *Ambrosia acanthicarpa*, *Amsinckia tessellata*, *Chenopodium leptophyllum*, *Descurainia pinnata*, and *Phacelia linearis*. This species list is subject to change as new species appear on the surface. It should be noted that all these species arrived on the surface, possibly from wind blown or animal (including humans) transport onto the surface. It is possible that some species were incorporated onto the surface by virtue of being in the transported soil seed bank, but we feel this to be a minor contribution because the soils for the surface were subsoils (at least 1 m below the surface) and are not likely to contain many seeds. Most seeds in the soil bank in the shrub-steppe are within 2 cm of the surface (Kemp 1989).

5.2.2 Plant Distribution

Plant distribution on the prototype barrier surface was quantified and used to relate vegetative characteristics to soil water characteristics. Perennial grasses were mapped by counting shoots within a 0.1 m² in each of 300 9-m² quadrats. These samples were physically located in the southwest corner of each quadrat. Forb species (natives and invasive aliens) were counted in each quadrat. The number of dead of each shrub species were counted in each quadrat. These observations were taken between April 7 and April 13, 1995. The effect of irrigation was tested using a mean t-test where quadrats are considered experimental units. The middle row of quadrats was deleted from analysis because it forms a border between the treatments. Each half then has 144 quadrats used in the analyses. Analyses were done using JMP version 2.0.2 software (Sall et al. 1991). Data are presented as means \pm one standard error.

Grasses exhibited significant spatial patterns across the surface (Figure 3.8). Grass numbers were highly variable ranging from <2000 up to 12000 shoots 9-m² quadrat. There was no effect of irrigation on grass numbers per 9-m² quadrat (ambient precipitation: 6745 \pm 263; irrigated: 6780 \pm 235). Surface soil water was measured with a Troxler probe in the center of each quadrat within two weeks of the period when the grasses were quantified (Figure 3.5). These data allowed us to test the hypothesis that surface soil water content will be negatively correlated with grass density across the surface. One would expect that areas with large numbers of grasses will be dryer than areas with few grasses. This hypothesis was tested in the ambient precipitation and irrigated portions of the surface. We tested the hypothesis by determining if the slope of the linear regression ($\theta = b_0 + b_1$ grass density) where θ is percentage volumetric soil water content, is different from zero. There was no relationship in either treatment (irrigated: $b_1 = 0$, $t = -1.32$, $p = 0.1883$; ambient precipitation: $b_1 = 0$, $t = -1.24$, $p = 0.216$). We suspect a negative correlation will develop between surface soil water content and vegetation later in the summer when most of the water will have been removed by transpiration. We have observed a negative correlation between soil water content and plant density in a native deep-rooted perennial community at McGee Ranch (Link et al. 1994). We conclude that the spatial pattern in grass numbers is, likely, a result of the hydroseeding technique used to apply the seeds. Seeds were sprayed from a hose onto the surface and it was not possible to distribute the seeds evenly.

Native and invasive alien forbs also exhibited significant variation across the surface (Figure 5.1). The number of native and invasive alien forbs ranged from 0 to 10 per 9-m² quadrat. There was no effect of irrigation on average forb numbers per 9-m² quadrat (ambient precipitation: 3.62 ± 0.22 ; irrigated: 4.15 ± 0.22). Invasive alien species were not common in the spring, but *Salsola kali* (tumbleweed) became the dominant species by July. *Salsola kali* became the dominant species because of its relatively large size and almost complete coverage of all surfaces by late July. This species is an early invader on disturbed soils in the West and will become only a minor component on the surface after the perennial species have become established (Allen 1988).

The number of dead *C. nauseosus* ranged from 0 to 3 per 9-m² quadrat (Figure 5.2). There was no effect of irrigation on the average number of dead *C. nauseosus* per 9-m² quadrat (ambient precipitation: 0.326 ± 0.049 ; irrigated: 0.375 ± 0.054). There was a total of 109 dead *C. nauseosus* on the surface that represents a survival percentage of 92% [(1350-109)/1350].

The number of dead *A. tridentata* ranged from 0 to 2 per 9-m² quadrat (Figure 5.3). Comparisons on the number of dead *A. tridentata* between ambient and irrigated plots were tested using the non-parametric Wilcoxin/Kruskal-Wallis Test ($p=0.05$) because of the large number of zero values. There were more dead *A. tridentata* per 9-m² quadrat in the irrigated treatment (0.09) than in the ambient precipitation treatment (0.014) [$\chi^2 = 4.6873$, $df = 1$, $p = 0.0304$]. There was a total of 18 dead *A. tridentata* on the surface that represents a survival percentage of 99.6% [(4050-18)/4050]. The greater number of dead *A. tridentata* in the irrigated plot suggests that the additional water created a stress in this species.

5.2.3 Plant Gas Exchange

Plant gas exchange data were collected to document the transpiration rates of the shrub species on the surface. Plant condition was assessed by measuring net photosynthetic rates. This was done with a Li-Cor 6200 gas exchange system. Observations were made twice in February and once in late March. Observations were made in the ambient precipitation treatment on all date while observations in the irrigated treatment were made only in March. Gas exchange data are collected by placing a

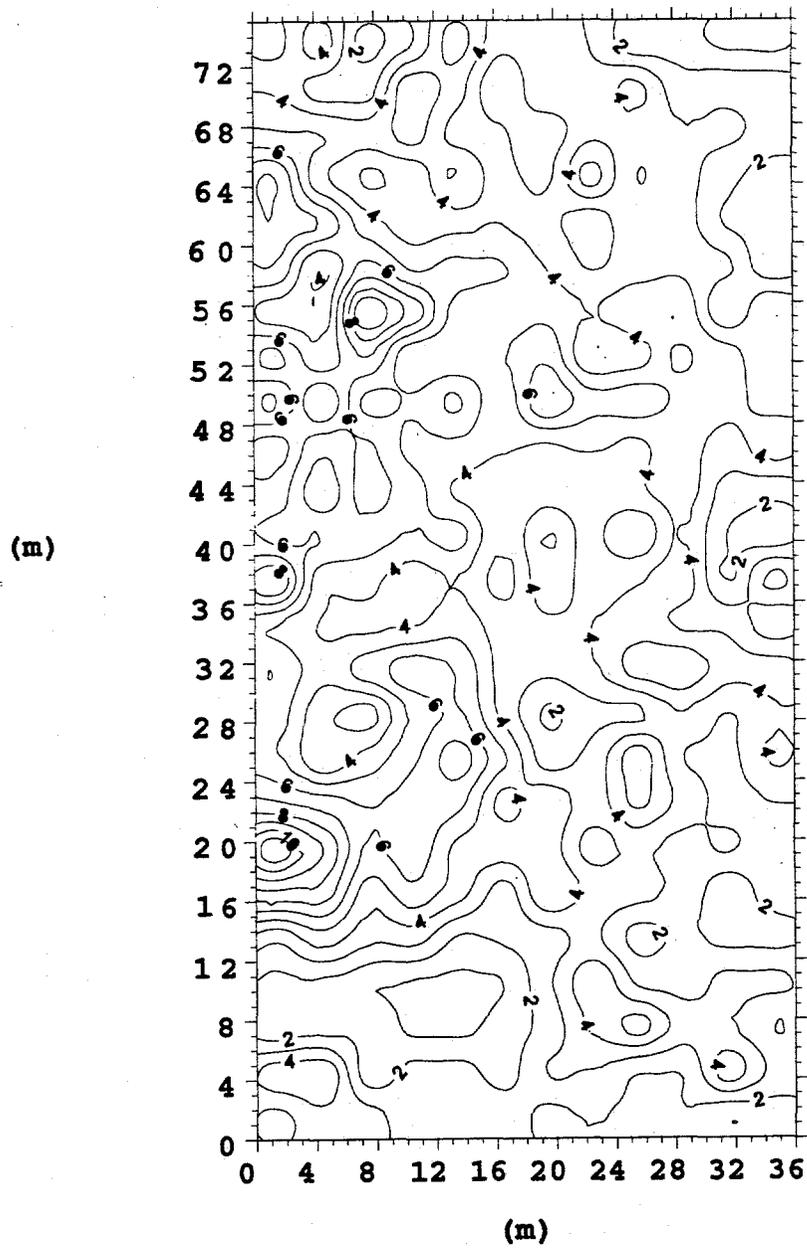


Figure 5.1 Prototype barrier native and invasive alien forb density contours for April 1995. Density is plant number per 9m².

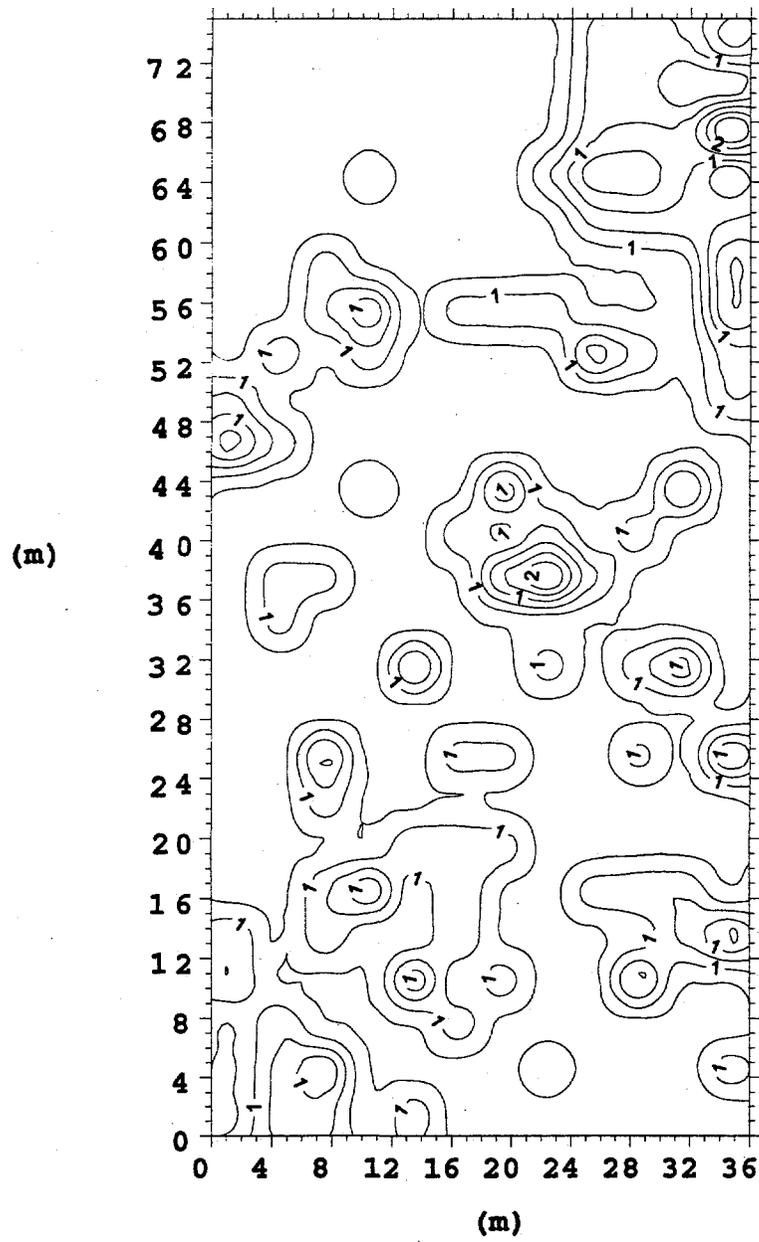


Figure 5.2 Prototype barrier dead *Chrysothamnus nauseosus* shrub density contours for April 1995. Density is plant number per 9 m².

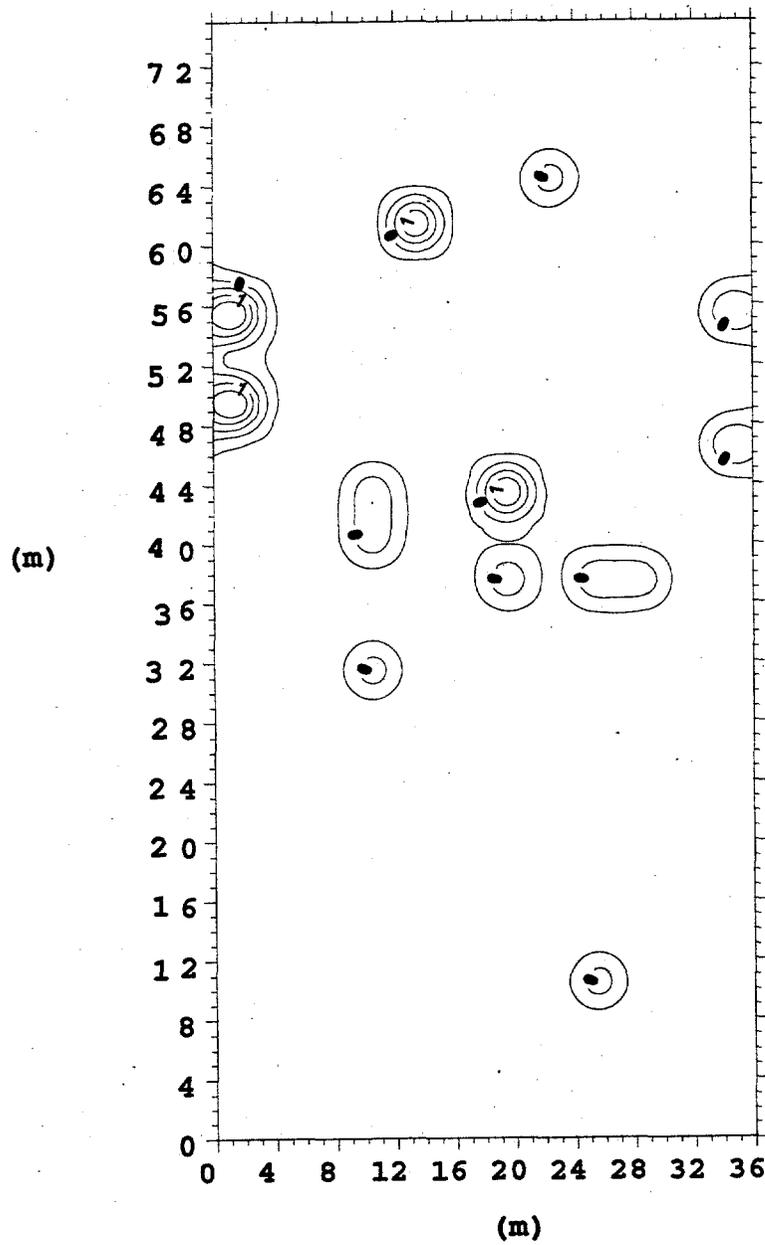


Figure 5.3 Prototype barrier dead *Artemisia tridentata* shrub density contours for April 1995. Density is plant number per 9 m².

chamber over stem tips (10 cm long) and allowing water vapor and CO₂ to change over a few minutes that yields rate information. Data were collected non-destructively and repeatedly on the same individuals over the observation period. To determine leaf area without clipping the plants we counted the number of leaves observed and then estimated the dimensions of an average leaf to compute a total stem tip leaf area. The first observations on *C. nauseosus* were on only green stems because the leaves had not elongated yet. These data are expressed on a stem area basis. All observations were taken at mid-day and in full sun.

Stomatal conductance increased from near 0.08 mol m⁻²s⁻¹ in February to approximately 0.13 mol m⁻²s⁻¹ in March (Figure 5.4). There were no differences between species or between treatments within species on any of the 3 days ($p > 0.05$). Transpiration rates increased from near 0.75 mol m⁻²s⁻¹ to 2.2 mol m⁻²s⁻¹ at the end of the observation period (Figure 5.5). There were no differences between species or between treatments within species on any of the 3 days ($p > 0.05$). The threefold increase in rates is much greater than the increase in stomatal conductance over the same period implying that the vapor pressure gradient is the stronger driver of water loss than is stomatal conductance.

Net photosynthetic rates increased from near 1 μmol m⁻²s⁻¹ to 7 μmol m⁻²s⁻¹ over the period for *C. nauseosus* and from 3 μmol m⁻²s⁻¹ to 7 μmol m⁻²s⁻¹ for *A. tridentata* (Figure 5.6). There were no differences between species or between treatments within species on any of the 3 days ($p > 0.05$). There is evidence for a reduction in net photosynthesis in the irrigated treatment compared with the ambient precipitation treatment for *A. tridentata* given that $p = 0.0519$. If this effect is true we would conclude that a reduction in net photosynthesis is associated with the irrigated treatment. It is possible that *A. tridentata* is experiencing physiological stress in association with too much water. This observation helps explain the significantly higher mortality rate for *A. tridentata* in the irrigated treatment discussed above.

5.2.4 Root and Soil Water Observations

Root observations are important to make because of their strong association with the water extraction function of plants. Rooting depth and root length density data are required by soil-plant-atmosphere models to predict soil water dynamics. Root observations were taken using a Circon

Agricultural Camera in clear minirhizotron tubes inclined at a 45 degree angle. Six root observation tubes (minirhizotrons) were placed in each of the irrigated and non-irrigated halves of the surface for a total of 12 observation tubes. Observations were taken from July 13 to July 21. The videos of each root tube were examined to compute root length density. This was done by counting each root that intersected with the tube surface and each intersecting branching root from a root already in contact with the tube. Counts were taken in an area the width of the viewing area (1.55 cm) and 10 cm long. The count data are then divided by the observation area to yield a root length density value (Upchurch and Ritchie 1983). Volumetric water content with depth was collected using a neutron probe in 6 holes in each half of the surface near the minirhizotrons.

Root length density increased with depth down to 150 cm and decreased below that (Figure 5.7). There was no difference between the ambient precipitation and irrigated treatments for root length density with depth ($p > 0.05$), so the data were combined (Figure 5.8). Roots were observed at the bottom (~ 180 cm deep) of some of the minirhizotrons. Soil water content was less in the ambient precipitation area than in the irrigated area and increased with depth (see Figure 2.5). Root length density patterns were similar to that of soil water contents with depth except for the higher water content and lower root length density at the greatest depths. The rooting pattern suggests that these plants are actively mining water. We suspect root length density will increase at the lowest depths as the surface layers dry through the summer.

5.2.5 Plant Size

The size of plants in water limited ecosystems is positively correlated with available water (Link et al. 1990). We measured shoot height as a measure of size to see if plants were taller in the irrigated treatment compared with the ambient precipitation treatment. Shrubs were significantly (*C. nauseosus*: $p = 0.033$; *A. tridentata*: $p = 0.008$) taller in the irrigated area than in the ambient precipitation area while the water treatment had no ($p = 0.197$) effect on the shoot height of *S. kali* (Figure 5.9).

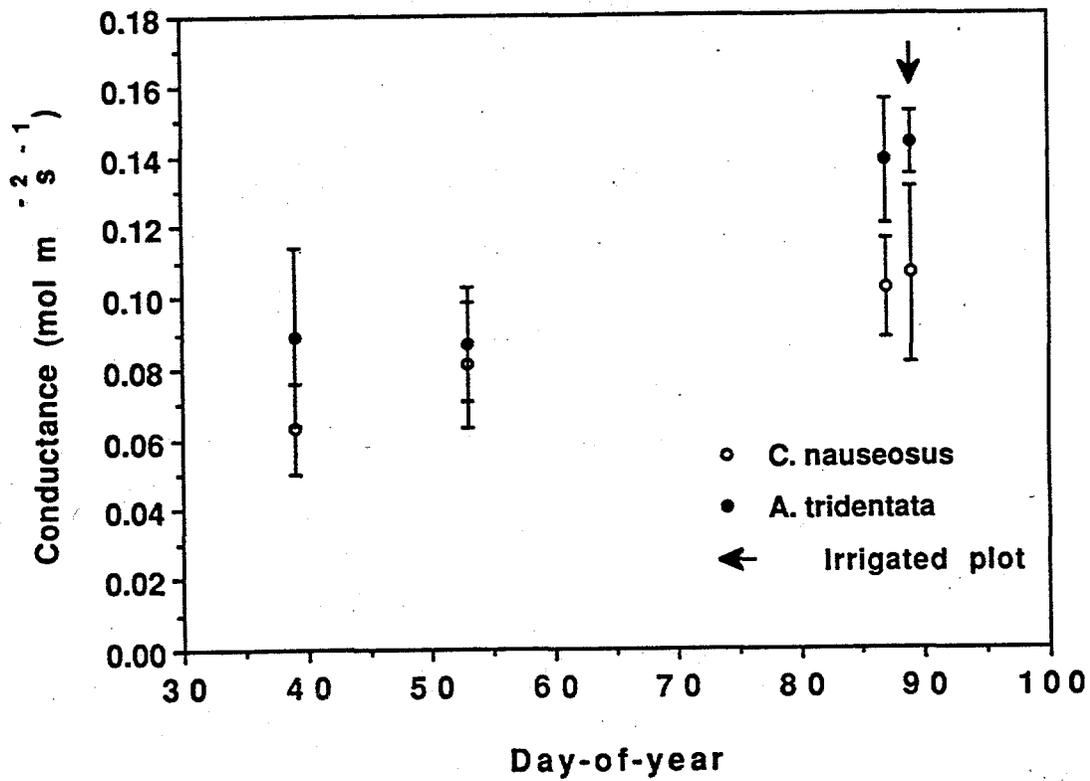


Figure 5.4 Stomatal conductance during the spring on *Artemisia tridentata* and *Chrysothamnus nauseosus* in ambient precipitation and irrigated treatments.

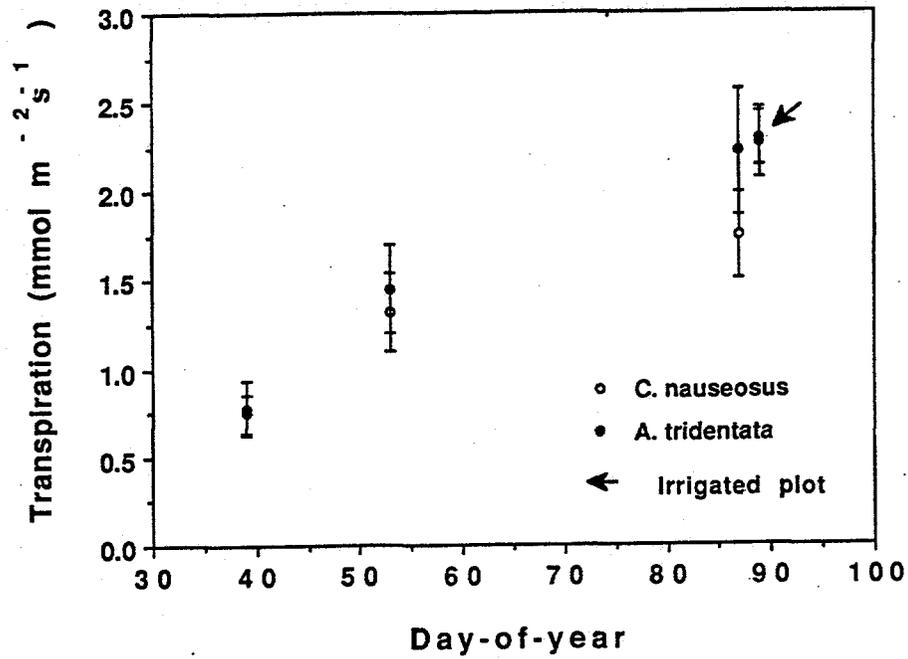


Figure 5.5 Transpiration rates during the spring on *Artemisia tridentata* and *Chrysothamnus nauseosus* in ambient precipitation and irrigated treatments.

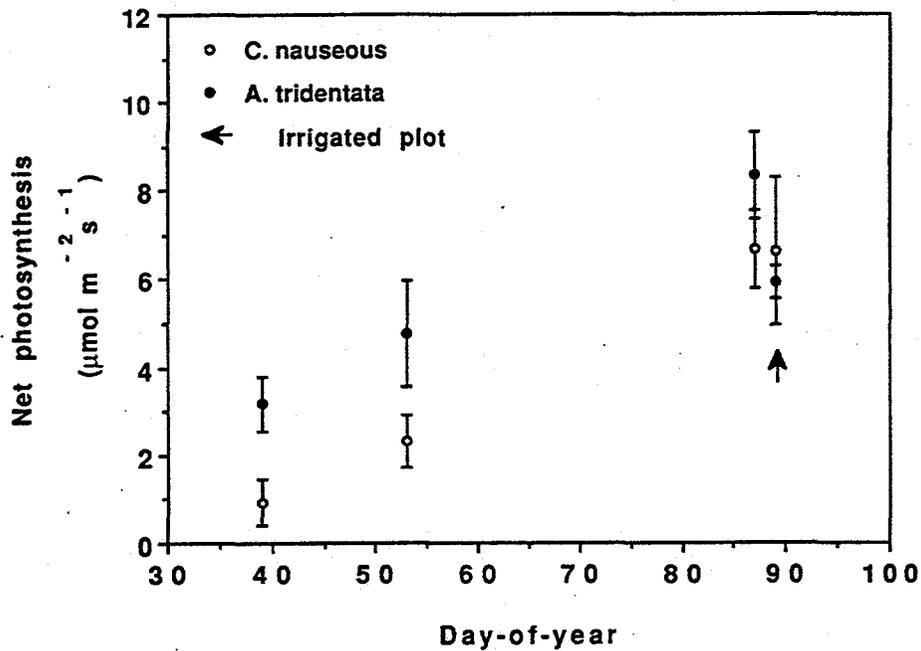


Figure 5.6 Net photosynthetic rates during the spring on *Artemisia tridentata* and *Chrysothamnus nauseosus* in ambient precipitation and irrigated treatments.

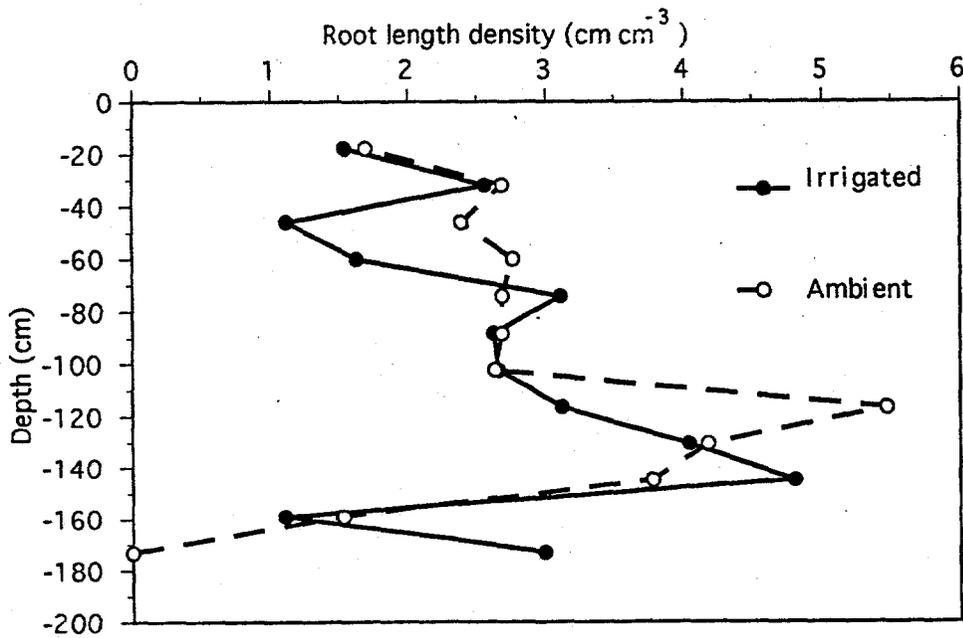


Figure 5.7 Root length density with depth in the ambient precipitation and irrigated treatments.

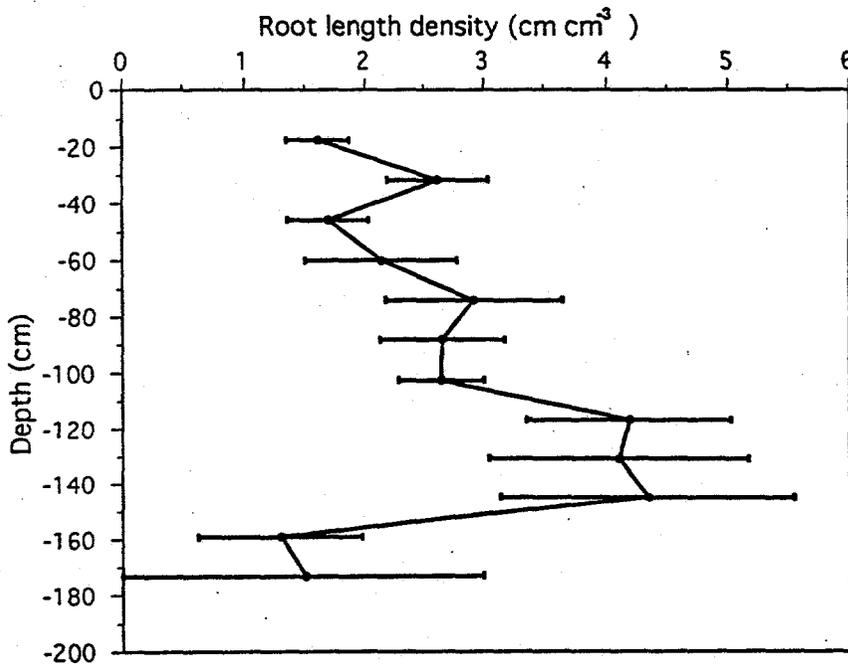


Figure 5.8 Root length density for combined treatments (ambient and irrigated).

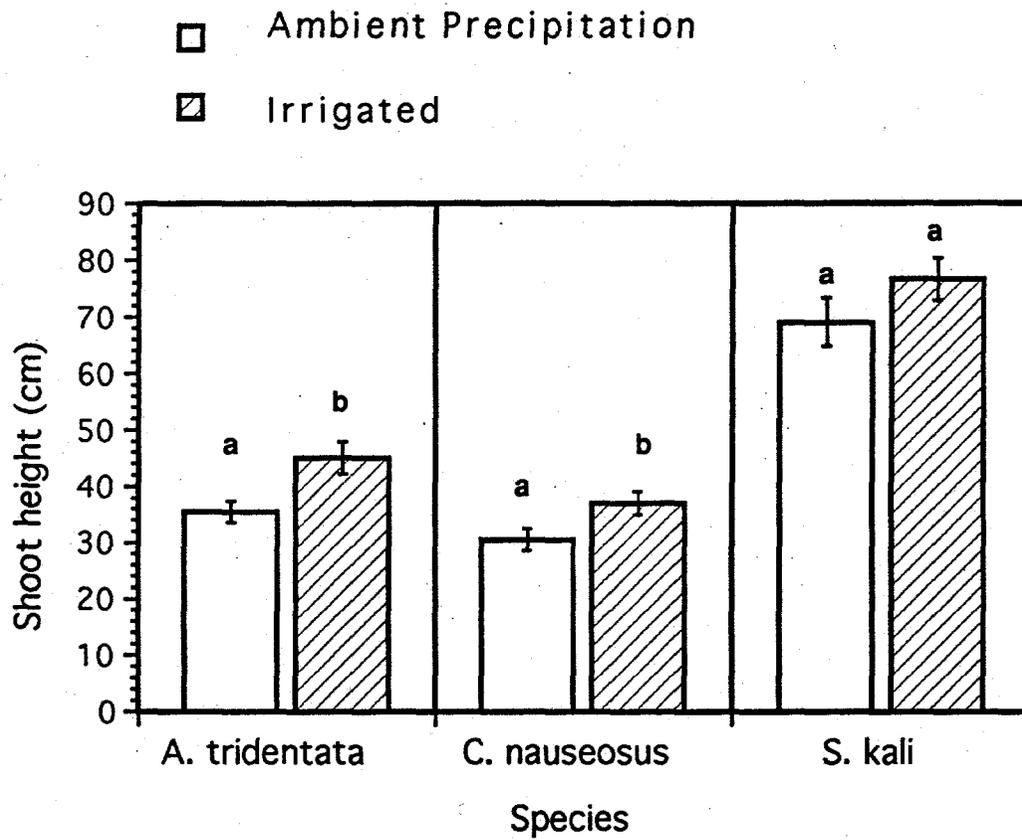


Figure 5.9 Shoot height of *Artemisia tridentata*, *Chrysothamnus nauseosus*, and *Salsola kali* in the ambient precipitation and irrigated treatments for late July.

5.3 ANIMAL OBSERVATIONS

Animals can influence the surface by turning over the soil that can, potentially, change erosional characteristics. In addition, animals can modify plant communities, again by turning over the soil and through the effects of urine and fecal deposition on the surface (Link et al. 1995b). Observations on animals on the surface were taken during the year. Birds were observed frequently on the surface consuming seeds. We did not observe any mammals or the evidence of mammals on the surface. Some of the most interesting insect observations were made while examining roots. We observed a colony of what appeared to be termites at a depth of about 80 cm along the root tube. We anticipate that animal activity will increase with time on the surface.

5.4 CONCLUSIONS

The establishment of a viable and highly diverse plant community on the surface has already had a significant effect on the function of the surface. The complete coverage by deep rooted perennial and annuals has completely dried out the soil cap even with high initial water application and irrigation. In addition, the plants have virtually eliminated evidence of wind and water erosion. Continued monitoring of the plant community and its ability to maximize evapotranspiration and minimize erosion is needed beyond the initial conditions to make sure that its abilities will continue under drier conditions.

6.0 FUTURE TESTING AND MONITORING PLANS

FY 1996 plans call for continued testing and monitoring of the prototype barrier in the following four areas: water balance, water erosion, wind erosion, and biointrusion. Specific concerns that will be addressed include: water infiltration and drainage from sideslopes under irrigated and ambient conditions; performance of the pan lysimeter under the asphalt layer on the prototype; water balance monitoring network performance; sideslope movement and stability, settlement of all areas on the prototype; vegetation succession and animal invasion of sideslopes and soil surfaces.

6.1 WATER BALANCE MONITORING AND TESTS

Activities will include continued testing of instrumentation to measure complete water balance on the soil surface and the side slope plots under irrigated and ambient conditions. Irrigation will be continued in FY 1996, but no artificial snow will be applied. Irrigation will continue as planned through winter but will not be applied under freezing conditions. During the last week of March 1996 there will be a water application (irrigation) of 70 mm of water during an 8 hour period. A total of 480 mm will be applied during the year via irrigation and precipitation, an amount equal to 3 times the annual average precipitation.

Water balance parameters, precipitation, water storage and drainage will all be monitored nearly continuously for the duration of the testing. Neutron probes will be used as the primary monitoring instrument to assess water accumulation in the soil and in the sideslope and under the sideslopes at the edge of the barrier. Drainage will continue to be monitored on a continuous basis to document water drainage from both soil and sideslope plots under irrigated and ambient conditions. Profiles of water contents at and below the edge of the barrier will be constructed to document the lateral flow of water from the sideslopes. The pan lysimeter underneath the asphalt will be monitored over the next year for drainage. Seepage rates will be correlated with water applications to the sideslope. An investigation will be conducted to determine the reason for more water draining from the clean-fill (gravel) sideslope than from the rock sideslopes.

6.2 WATER EROSION AND SURFACE STABILITY MEASUREMENTS

Surface stability (elevation changes) and sideslope creep will continue to be documented. Water erosion (runoff and sediment yield) will be documented throughout the year. The runoff plot, originally on the south (ambient) side of the barrier has been relocated on the north (irrigated) side. This plot will be maintained throughout the year and will be used to document snowmelt events and all responses to irrigation and elevated precipitation. This plot will be automated and will be used during the 1000-year-storm test in March to document surface response to intense storm events. If winter runoff (e.g., snowmelt) conditions warrant, the south plot will be retrofitted and used in a manual mode to document runoff under ambient (non-irrigated) conditions.

6.3 WIND EROSION

Wind erosion will be documented using established stations to monitor peak gust winds and wind boundary layers during wind storms. This data set will be used to determine the levels of eolian stresses on the top surface versus those occurring at normal ground level. Saltation sensors and dust traps, used to document soil losses during 1995 until vegetation became well established, will not be used on the surface of the barrier unless vegetation is removed or lost. Dust traps will be used periodically, as weather conditions permit, near the top of the graded sideslope to document sand transport rates from the surrounding area onto the surface of the barrier. It is necessary to compare sand movement to surface conditions and wind patterns in order to define the potential for soil removal by wind. Surface accumulations or armor formation will be documented by annual surface composition measurements. Data from the wind and dust trap stations will continue to be analyzed and documented.

6.4 BIOINTRUSION

Both animal and plant intrusion will be documented. Plant community dynamics will be documented. We anticipate over the next two years that there will be a reduction of early successional species, such as tumbleweed. Plant count and estimates of total biomass will be taken at least twice during the year. Plant phenology will be recorded and the key physiological responses of plant to irrigation and water stress will be documented. This effort will be scaled according to the available funding. Root tube scans to document root growth and density will be taken in the fall and spring. Animal invasion will be documented. Animal burrow density will be plotted and compared with typical animal populations typical of other waste sites at Hanford.

7.0 REFERENCES

- Allen, E. B. 1988. *Some trajectories of succession in Wyoming sagebrush grassland: implications for restoration*. Pages 89-112 in E. B. Allen, editor. *The reconstruction of disturbed arid lands*. ALAS Selected Symposium, Westview Press. Boulder, Colorado, USA.
- ASTM. 1984. *Standard method for particle-size analysis of soils*. D422-63, American Society for Testing and Materials, Philadelphia, Pennsylvania.
- Fryrear, D. W. 1986. A Field Dust Sampler. *J. Soil and Water Conservation* 41(2):117-120.
- Gee, G. W., M. L. Rockhold, J. L. Downs. 1989. *Status of FY 1988 soil-water balance studies on the Hanford site*. PNL-6750, Pacific Northwest Laboratory, Richland, Washington.
- Gee, G. W., L. L. Cadwell, H. D. Freeman, M. W. Ligothke, S. O. Link, R. A. Romine, and W. H. Walters, Jr. 1993a. *Testing and monitoring plan for the permanent isolation surface barrier prototype*. PNL-8391, Pacific Northwest Laboratory, Richland, Washington.
- Gee, G. W., D. G. Felmy, J. L. Downs, J. C. Ritter, M. D. Campbell, M. J. Fayer, R. R. Kirkham, and S. O. Link. 1993b. *Field Lysimeter test facility status report IV: FY 993*. PNL- 8911, Pacific Northwest Laboratory, Richland, Washington.
- Gee, G. W., H. D. Freeman, W. H. Walters, Jr., M. W. Ligothke, M. D. Campbell, A. L. Ward, S. O. Link, S. K. Smith, B. G. Glimore and R.A. Romine. 1994. *Hanford prototype surface barrier status report: FY 1994*. PNL-10275. Pacific Northwest Laboratory, Richland, Washington.
- Gilmore, B.G., and W.H. Walters. 1993. *Water Erosion Field Tests for Hanford Protective Barriers: FY 1992 Status Report*. PNL--8949, Pacific Northwest Laboratory, Richland, Washington.
- Hendrickx, J. M. H. 1994. *Electromagnetic induction for non-intrusive monitoring of surface barriers for radioactive wastes*. Letter report to Battelle Pacific Northwest Laboratories, December 1994.
- Hoitink, D. J., and K. W. Burk. 1995. *Climatological data summary 1994, with historical data*. PNL-10553, Pacific Northwest Laboratory, Richland, Washington.
- Kemp, P. R.. 1989. Seed banks and vegetation processes in deserts. *Ecology of soil seed banks* (M.A. Leck, V.T. Parker, and R.L. Simpson, eds.), pp. 367-384. Academic Press, Inc., San Diego, California.
- Ligothke, M.W., and D.C. Klopfer. 1990. *Soil erosion rates from mixed soil and gravel surfaces in a wind tunnel*. PNL-7435, Pacific Northwest Laboratory, Richland, Washington.
- Ligothke, M.W. 1993. *Soil erosion rates caused by wind and saltating sand stresses in a wind tunnel*. PNL-8478, Pacific Northwest Laboratory, Richland, Washington.

Link, S. O. 1995. Establishment of Vegetation on the Prototype Surface. In: *Hanford site protective barrier development program: Fiscal year 1994 highlights* K. L. Petersen, S. O. Link, G. W. Gee, eds. PNL-10605, Pacific Northwest Laboratory, Richland, Washington.

Link, S.O., G.W Gee, and J. L. Downs. 1990. The effect of water stress on phenological and ecophysiological characteristics of cheatgrass and Sandbergs's bluegrass. *J. Range Management* 43:506-513.

Link, S. O., W. J. Waugh, J. L. Downs, M. E. Thiede, J. C. Chatters, and G. W. Gee. 1994. Effects of coppice dune topography and vegetation on soil water dynamics in a cold-desert ecosystem. *J. Arid Environments*. 27: 265-278.

Link, S. O., L. L. Cadwell, M. R. Sackschewsky, D. S. Landeen, and K. L. Petersen. 1995a. *The role of plants and animals in isolation barriers: Hanford, Washington*. PNL-10788, Pacific Northwest Laboratory, Richland, Washington.

Link, S. O., N. R. Wing, and G. W. Gee. 1995b. The development of permanent isolation barriers for buried wastes in cool deserts: Hanford, Washington. *Journal of Arid Land Studies* 4: 215-224.

Myers, D. R., and D. A. Duranceau (eds.). 1994. *Prototype Hanford surface barrier: Design basis document*. BHI-00007, Bechtel Hanford, Inc., Richland, Washington.

Petersen, K. L., J. C. Chatters, and W. J. Waugh. 1993. *Long-term Climate Change Assessment Study Plan for the Hanford Site Permanent Isolation Barrier Development Program*. WHD-EP-0569 Rev. 1, Westinghouse Hanford Company, Richland, Washington.

Petersen, K. L., S. O. Link, and G. W. Gee. 1995. *Hanford Site long-term surface barrier development program: Fiscal year 1994 highlights*. PNL-10605, Pacific Northwest Laboratory, Richland, Washington.

Sall, J., Ng, K., and Hecht, M. 1991. *Statistical visualization for the Macintosh (JMP)*. SAS Institution, Inc., Cary, NC.

Upchurch, D. R. and J. T. Ritchie. 1983. Root observations using a video recording system in mini-rhizotrons. *Agronomy J.* 75:1009-1015.

Ward, A. L., and G. W. Gee. 1995. *Performance evaluation of the water balance monitoring systems at the prototype surface barrier*. Letter Report Milestone 02.04 to Bechtel Hanford Inc. June 16, 1995. Pacific Northwest Laboratory, Richland, Washington.

Wing, N. R. 1994. *Permanent isolation surface barrier development plan*. WHC-EP-0673, Westinghouse Hanford Company, Richland, Washington.

Wing, N.R., and G.W. Gee. 1994. Quest for the Perfect Cap. *Civil Engineering* 64(10):388-41.

8.0 BARRIER PUBLICATIONS

1. Phillips, S. J., M. R. Adams, T. W. Gilbert, C. C. Meinhardt, R. M. Mitchell, and W. J. Waugh. 1985. "Engineered Barrier Test Facility Status Report: 1984." RHO-WM-SR-3P, Rockwell Hanford Operations, Richland, Washington.
2. Phillips, S. J., T. W. Gilbert, and M. R. Adams. 1985. "Preliminary Engineering Specifications for a Test Demonstration Multilayer Protective Barrier Cover System." RHO-WM-EV-8 P, Rockwell Hanford Operations, Richland, Washington.
3. Fayer, M. J., W. Conbere, P. R. Heller, and G. W. Gee. 1985. "Model Assessment of Protective Barrier Designs." PNL-5604, Pacific Northwest Laboratory, Richland, Washington.
4. Myers, D. R. 1985. "Disposal Materials Study." RHO-WP-EV-12P, Rockwell Hanford Operations, Richland, Washington.
5. Adams, M. R., and M. F. Kaplan. 1986. "Marker Development for Hanford Waste Site Disposal." In Waste Management '86, (Vol. 1), pp. 425-431, ed. R. G. Post. University of Arizona, College of Engineering and Mines, Tucson, Arizona.
6. Phillips, S. J., and J. N. Hartley. 1986. "Protective Barrier Systems for Final Disposal of Hanford Waste Sites." In Waste Management '86, (Vol. 1), pp. 433-437, ed. R. G. Post. University of Arizona, College of Engineering and Mines, Tucson, Arizona.
7. Kaplan, M. F., and M. R. Adams. 1986. "Using the Past to Protect the Future: Marking Nuclear Waste Disposal Sites." Archeology 39(5):51-54.
8. Adams, M. R., and N. R. Wing. 1986. "Protective Barrier and Warning Marker System Development Plan." RHO-RE-OL-35P, Rockwell Hanford Operations, Richland, Washington.
9. Fayer, M. J. 1987. "Model Assessment of Protective Barrier Designs: Part II." PNL-6297, Pacific Northwest Laboratory, Richland, Washington.
10. Last, G. V., M. A. Glennon, M. A. Young, and G. W. Gee. 1987. "Protective Barrier Materials Analysis: Fine Soil Site Characterization." PNL-6314, Pacific Northwest Laboratory, Richland, Washington.
11. Gee, G. W. 1987. "Preliminary Analysis of the Performance of the Protective Barrier and Marker System." In Final Environmental Impact Statement, Disposal of Hanford Defense High-Level, Transuranic and Tank Wastes, Appendix M, DOE/EIS-0113, U.S. Department of Energy - Richland, Operations Office, Richland, Washington.

12. Kirkham, R. R., G. W. Gee, and J. L. Downs. 1987. "Field Lysimeter Test Facility for Protective Barriers: Experimental Plan." PNL-6351, Pacific Northwest Laboratory, Richland, Washington.
13. Waugh, W. J., and S. O. Link. 1988. "Barrier Erosion Control Test Plan: Gravel Mulch, Vegetation, and Soil Water Interactions." WHC-EP-0067, Westinghouse Hanford Company, Richland, Washington.
14. Wing, N. R., M. D. Campbell, J. L. Downs, G. W. Gee, R. R. Kirkham, and S. J. Phillips. 1988. "Protective Barrier Development: The Field Lysimeter Test Facility." In Proceedings of the International Topical Meeting on Nuclear and Hazardous Waste Management Spectrum '88, pp. 196-198. American Nuclear Society, Inc., La Grange Park, Illinois, WHC-SA-0203-FP, Westinghouse Hanford Company, Richland, Washington.
15. Phillips, S. J., M. S. Ruben, and R. R. Kirkham. 1988. "Engineered Surface Barriers for Waste Disposal Sites: Lysimeter Facility Design and Construction." In DOE Model Conference Proceedings, pp. 1229-1238. CONF-881054. Oct. 3-7, Martin Marietta, Oak Ridge, Tennessee.
16. Ligothe, M. W. 1988. "Soil Erosion Rates from Mixed Soil and Gravel Surfaces in a Wind Tunnel: A Preliminary Report." PNL-6677, Pacific Northwest Laboratory, Richland, Washington.
17. Waugh, W. J., and M. G. Foley. 1988. "Protective Barrier Climate-Change Impacts: Technical Workshop Findings and Recommendations." PNL-6615, Pacific Northwest Laboratory, Richland, Washington.
18. Ligothe, M. W. 1989. "Surface Stability Test Plan for Protective Barriers." PNL-6722, Pacific Northwest Laboratory, Richland, Washington.
19. Gee, G. W., R. R. Kirkham, J. L. Downs, and M. D. Campbell. 1989. "The Field Lysimeter Test Facility (FLTF) at the Hanford Site: Installation and Initial Tests." PNL-6810, Pacific Northwest Laboratory, Richland, Washington.
20. Gee, G. W., M. D. Campbell, H. D. Freeman, and J. F. Cline. 1989. "Assessment of Cover Systems at the Grand Junction, Colorado, Uranium Mill Tailings Pile: 1987 Field Measurements." PNL-6762, Pacific Northwest Laboratory, Richland, Washington.
21. Petersen, K. L. 1989. "The Long-Term Climate Change Assessment Task of the Hanford Site, Washington Protective Barrier Development Program." WHC-SA-0537-FP, Westinghouse Hanford Company, Richland, Washington.
22. Cadwell, L. L., L. E. Eberhardt, and M. A. Simmons. 1989. "Animal Intrusion Studies for Protective Barriers: Status Report for FY 1988." PNL-6869, Pacific Northwest Laboratory, Richland, Washington.

23. Freeman, H. D., G. W. Gee, and J. F. Relyea. 1989. "Field Study Plan for Alternate Barriers." PNL-6840, Pacific Northwest Laboratory, Richland, Washington.
24. Freeman, H. D., and G. W. Gee. 1989. "Hanford Protective Barriers Program Asphalt Barrier Studies - FY 1988." PNL-6874, Pacific Northwest Laboratory, Richland, Washington.
25. Waugh, W. J. 1989. "Gravel Admix, Vegetation and Soil Water Interactions in Protective Barriers: Experimental Design, Construction and Initial Conditions." PNL-6616, Pacific Northwest Laboratory, Richland, Washington.
26. Freeman, H. D., and G. W. Gee. 1989. "Hanford Protective Barriers Program: Status of Asphalt Barrier Study - FY 1989." PNL-7513, Pacific Northwest Laboratory, Richland, Washington.
27. Link, S. O., and W. J. Waugh. 1989. "Evapotranspiration Studies for Protective Barriers: Experimental Plans." PNL-6899, Pacific Northwest Laboratory, Richland, Washington.
28. Petersen, K. L. 1990. "The Long-Term Climate Change Assessment Task of the Protective Barrier Development Program for Low-Level Waste Site Remediation at the Hanford Site, Washington." In High Level Radioactive Waste Management. Vol 2, pp. 1235-1239. Proceeding of an International Topical Meeting. American Nuclear Society, La Grange Park, Illinois. (WHC-SA-0808-FP, Westinghouse Hanford Company, Richland, Washington).
29. Fayer, M. J. 1990. "Test Plan for Hydrologic Modeling of Protective Barriers." PNL-7152, Pacific Northwest Laboratory, Richland, Washington.
30. Wing, N. R., and G. W. Gee (eds.). 1990. "Hanford Site Protective Barrier Development Program: Fiscal Year 1989 Highlights." WHC-EP-0318, Westinghouse Hanford Company, Richland, Washington.
31. Campbell, M. D., G. W. Gee, M. J. Kanyid, and M. L. Rockhold. 1990. "Field Lysimeter Test Facility: Second Year (FY 1989) Test Results." PNL-7209, Pacific Northwest Laboratory, Richland, Washington.
32. Landeen, D. S., L. L. Cadwell, L. E. Eberhardt, R. E. Fitzner, and M. A. Simmons. 1990. "Animal Intrusion Field Test Plan." WHC-EP-0253, Westinghouse Hanford Company, Richland, Washington.
33. Link, S. O., M. E. Thiede, R. D. Evans, J. L. Downs, and W. J. Waugh. 1990. "Evapotranspiration Studies for Protective Barriers: FY 1988 Status Report." PNL-6985, Pacific Northwest Laboratory, Richland, Washington.
34. Relyea, J. F., M. R. Sackschewsky, and W. J. Waugh. 1989. "Small-Tube Lysimeter Facility Status Report for Fiscal Year 1989." WHC-EP-0297, Westinghouse Hanford Company, Richland, Washington.

35. Walters, W. H., K. A. Hoover, and L. L. Cadwell. 1990. "Project Test Plan for Runoff and Erosion on Fine-Soil Barrier Surfaces and Rock-Covered Side Slopes." PNL-6791, Pacific Northwest Laboratory, Richland, Washington.
36. Hoover, K. A., L. L. Cadwell, and W. H. Walters. 1990. "Hanford Protective Barriers Program: Water Erosion Studies - FY 1989." PNL-7214, Pacific Northwest Laboratory, Richland, Washington.
37. Landeen, D. S. 1990. "Animal Intrusion Status Report for Fiscal Year 1989." WHC-EP-0299, Westinghouse Hanford Company, Richland, Washington.
38. Ligothe, M. W., and D. C. Klopfer. 1990. "Soil Erosion Rates from Mixed Soil and Gravel Surfaces in a Wind Tunnel." PNL-7435, Pacific Northwest Laboratory, Richland, Washington.
39. Waugh, W. J., M. E. Thiede, C. J. Kemp, L. L. Cadwell, and S. O. Link. 1990. "Field Study of Gravel Admix, Vegetation, and Soil Water Interactions: Protective Barrier Program Status Report - FY 1989." PNL-7440, Pacific Northwest Laboratory, Richland, Washington.
40. Hunter, C. R., A. J. Busacca, and W. J. Waugh. 1990. "A Feasibility Study of Modeling Pedogenic Carbonates in Soils and Sediments at the U.S. Department of Energy's Hanford Site." PNL-7413, Pacific Northwest Laboratory, Richland, Washington.
41. Wing, N. R., and G. W. Gee. 1990. "Protective Barrier Development: Overview." In Proceedings of the Twenty-Eighth Hanford Symposium on Health and the Environment, Environmental Monitoring, Restoration, and Assessment: What Have We Learned?, pp. 147-151, ed. R. H. Gray, Pacific Northwest Laboratory, Richland, Washington. WHC-SA-0619 FP, Westinghouse Hanford Company, Richland, Washington.
42. Wing, N. R., and G. W. Gee. 1990. "Protective Barrier Development: Overview." In Proceedings of the International Topical Meeting on Nuclear and Hazardous Waste Management Spectrum '90, pp. 335-337. American Nuclear Society, Inc., La Grange Park, Illinois. WHC-EP-0380, Westinghouse Hanford Company, Richland, Washington.
43. Glantz, C. S., M. N. Schwartz, K. W. Burk, R. B. Kaspar, M. W. Ligothe, and D. J. Perrault. 1990. "Climatological Summary of Wind and Temperature Data for the Hanford Meteorology Monitoring Network." PNL-7471, Pacific Northwest Laboratory, Richland, Washington.
44. Campbell, M. D., and G. W. Gee. 1990. "Field Lysimeter Test Facility: Protective Barrier Test Results (FY 1990, The Third Year)." PNL-7558, Pacific Northwest Laboratory, Richland, Washington.
45. Sackschewsky, M. R., J. C. Chatters, S. O. Link, and C. A. Brandt. 1991. "Protective Barrier Program: Test Plan for Plant Community Dynamics." WHC-EP-0380. Westinghouse Hanford Company, Richland, Washington.

46. Nichols, W. E. 1991. "Comparative Simulations of a Two-Layer Landfill Barrier Using the Help Version 2.0 and UNSAT-H Version 2.0 Computer Codes." PNL-7583, Pacific Northwest Laboratory, Richland, Washington.
47. Landeen, D. S. 1991. "Animal Intrusion Status Report for Fiscal Year 1990." WHC-EP-0398. Westinghouse Hanford Company, Richland, Washington.
48. Campbell, M. D., G. W. Gee, R. R. Kirkham, S. J. Phillips, and N. R. Wing. 1991. "Water Balance Lysimetry at a Nuclear Waste Site." In Proceedings of the International Symposium on Lysimetry, pp. 125-134, ed. R. G. Allen, American Soc. Civil Engr., New York.
49. Kirkham, R. R., M. L. Rockhold, G. W. Gee, M. J. Fayer, M. D. Campbell, and L. J. Fritschen. 1991. "Lysimeters: Data acquisition and analysis." In Proceedings of the International Symposium on Lysimetry, pp. 362-370, ed. R. G. Allen, American Soc. Civil Engr., New York.
50. Phillips, S. J., J. F. Relyea, C. J. Kemp, N. R. Wing, M. D. Campbell, G. W. Gee, M. J. Graham, R. R. Kirkham, and M. S. Rubin. 1991. "Development of Hanford Site Lysimeter Facilities." In Proceedings of the International Symposium on Lysimetry, pp. 19-27, ed. R. G. Allen. American Soc. Civil Engr., New York.
51. Waugh, W. J., M. E. Thiede, L. L. Cadwell, G. W. Gee, H. D. Freeman, M. R. Sackschewsky, and J. F. Relyea. 1991. "Small Lysimeters for Documenting Arid Site Water Balance." In Proceedings of the International Symposium on Lysimetry, pp. 151-159, ed. R. G. Allen. American Soc. Civil Engr., New York.
52. Cadwell, L. L. (ed.). 1991. "Hanford Site Protective Barrier Development Program: Fiscal Year 1990 Highlights." PNL-7831, Pacific Northwest Laboratory, Richland, Washington.
53. Petersen, K. L. 1991. "Modern and Pleistocene Climatic Patterns in the West." WHC-EP-0523, Westinghouse Hanford Company, Richland, Washington.
54. Chatters, J. C., and H. A. Gard. 1991. "Archaeological Mounds as Analogs of Engineered Covers for Waste Disposal Sites Literature Review and Progress Report." PNL-7718, Pacific Northwest Laboratory, Richland, Washington.
55. Sackschewsky, M. R., C. J. Kemp, L. L. Cadwell, M. E. Thiede, and W. J. Waugh. 1991. "Status Report for the Small-Tube Lysimeter Facility Fiscal Year 1990." WHC-EP-0381, Westinghouse Hanford Company, Richland, Washington.
56. Fayer, M. J., M. L. Rockhold, and D. J. Holford. 1992. "Model Assessment of Protective Barriers: Part III Status of FY 1990 Work." PNL-7975, Pacific Northwest Laboratory, Richland, Washington.

57. Petersen, K. L. 1992. "A Warm and Wet Little Climate Optimum and a Cold and Dry Little Ice Age in the Southern Rocky Mountains, U.S.A." WHC-SA-1382-FP. Westinghouse Hanford Company, Richland, Washington.
58. Link, S. O., J. L. Downs, M. E. Thiede, D. J. Lettau, T. R. Twaddell, and R. A. Black. 1992. "Evapotranspiration Studies for Protective Barriers: FY 1990 Status Report." PNL-8032, Pacific Northwest Laboratory, Richland, Washington.
59. Link, S. O., M. E. Thiede, J. L. Downs, D. J. Lettau, and W. J. Waugh. 1992. "Evapotranspiration Studies for Protective Barriers: FY 1989 Status Report." PNL-8033, Pacific Northwest Laboratory, Richland, Washington.
60. Fayer, M. J., M. L. Rockhold, and M. D. Campbell. 1992. "Hydrologic Modeling of Protective Barriers: Comparison of Field Data and Simulation Results." Soil Sci. Soc. Am. J., 56:690-700.
61. Wing, N. R. 1992. "A Peer Review of the Hanford Site Permanent Isolation Surface Barrier Development Program." WHC-MR-0392. Westinghouse Hanford Company, Richland, Washington.
62. Gee, G. W., M. J. Fayer, M. L. Rockhold, and M. D. Campbell. 1992. "Variations in Recharge at the Hanford Site." Northwest Sci., 66:237-250.
63. Gee, G. W., M. D. Campbell, G. S. Campbell, and J. H. Campbell. 1992. "Rapid Measurement of Low Soil Water Potentials Using A Water Activity Meter." Soil Sci. Soc. Am. J., 56:1068-1070.
64. Ligothke, M. W. 1993. "Soil Erosion Rates Caused by Wind and Saltating Sand Stresses in a Wind Tunnel." PNL-8478, Pacific Northwest Laboratory, Richland, Washington.
65. Fayer, M. J. 1993. "Model Assessment of Protective Barriers: Part IV, Status of FY 1992 Work." PNL-8498, Pacific Northwest Laboratory, Richland, Washington.
66. Wing, N. R., and G. W. Gee. 1993. "The Development of Permanent Isolation Surface Barriers: Hanford Site, Richland, Washington, U.S.A." In Proceedings of Geoconfinement '93, pp. 357-362. June 8-11, 1993, Montpellier, France. WHC-SA-1799-FP, Westinghouse Hanford Company, Richland, Washington.
67. Petersen, K. L., J. C. Chatters, and W. J. Waugh. 1993. "Long-Term Climate Change Assessment Study Plan for the Hanford Site Permanent Isolation Barrier Development Program." WHC-EP-0569 Rev. 1, Westinghouse Hanford Company, Richland, Washington.
68. Wing, N. R. 1993. "The Results of Laboratory Test to Determine the Physical Properties of Various Barrier Construction Materials." WHC-SD-ER-DP-006, Westinghouse Hanford Company, Richland, Washington.

69. Gee, G. W., L. L. Cadwell, H. D. Freeman, M. W. Ligothke, S. O. Link, R. A. Romine, and W. H. Walters, Jr. 1993. "Testing and Monitoring Plan for the Permanent Isolation Surface Barrier Prototype." PNL-8391, Pacific Northwest Laboratory, Richland, Washington.
70. Cadwell, L. L., S. O. Link, and G. W. Gee. 1993. "Hanford Site Permanent Isolation Surface Barrier Development Program: Fiscal Year 1992 and 1993 Highlights." PNL-8741, Pacific Northwest Laboratory, Richland, Washington.
71. Link, S. O., R. N. Kickert, M. J. Fayer, and G. W. Gee. 1993. "A Comparison of Simulation Models for Predicting Soil Water Dynamics in Bare and Vegetated Lysimeters." PNL-8675, Pacific Northwest Laboratory, Richland, Washington.
72. Sackschewsky, M. R., C. J. Kemp, and L. L. Cadwell. 1993. "Status Report for the Small-Tube Lysimeter Facility Fiscal Year 1992." WHC-EP-0597, Westinghouse Hanford Company, Richland, Washington.
73. Petersen, K. L., and J. C. Chatters. 1993. "Long-Term Climate Change Assessment Task for the Hanford Site Permanent Isolation Barrier Development Program: Status through FY 1992." WHC-EP-0644, Westinghouse Hanford Company, Richland, Washington.
74. Chamness, M. 1993. "An Investigation of Bergmounds as Analogs to Erosion Control Factors on Protective Barriers." PNL-8841, Pacific Northwest Laboratory, Richland, Washington.
75. Bjornstad, B. N., and S. S. Teel. 1993. "Natural Analog Study of Engineered Protective Barriers at the Hanford Site." PNL-8840, Pacific Northwest Laboratory, Richland, Washington.
76. U.S. Department of Energy (DOE). 1993. "Treatability Test Plan for the 200-BP-1 Prototype Surface Barrier." DOE/RL-93-27, Department of Energy, Richland, Washington.
77. Gee, G. W., D. Felmy, J. C. Ritter, R. R. Kirkham, S. O. Link, J. L. Downs, and M. J. Fayer. 1993. "Field Lysimeter Test Facility: Status Report IV." PNL-8911, Pacific Northwest Laboratory, Richland, Washington.
78. Gaylord, D. R., L. D. Stetler, G. D. Smith, and R. W. Mars. 1993. "Summary of 1990 Eolian Characterization Studies, Hanford Site, Washington." PNL-8862, Pacific Northwest Laboratory, Richland, Washington.
79. Wing, N. R. 1993. "Permanent Isolation Surface Barrier: Functional Performance." WHC-EP-0650, Westinghouse Hanford Company, Richland, Washington.
80. Gilmore, B. G., and W. H. Walters. 1993. "Water Erosion Field Tests for Hanford Protective Barriers: FY 1992 Status Report." PNL-8949, Pacific Northwest Laboratory, Richland, Washington.

81. Kirkham, R. R. 1993. "Comparison of Surface Energy Fluxes with Satellite-Derived Surface Energy Flux Estimates from a Shrub-Steppe." PNL-9003, Pacific Northwest Laboratory, Richland, Washington.
82. U.S. Department of Energy (DOE) 1993. "Report on Value Engineering Study of Permanent Isolation Surface Barrier and Warning Marker System Development Plan at the Hanford Site." DOE/RL/12074--8, Department of Energy, Richland, Washington.
83. Wing, N. R. 1994. "Permanent Isolation Surface Barrier Development Plan." WHC-EP-0673, Westinghouse Hanford Company, Richland, Washington.
84. Waugh, W. J., J. C. Chatters, G. V. Last, B. N. Bjornstad, S. O. Link, and C. R. Hunter. 1994. "Barrier Analogs: Long-Term Performance Issues, Preliminary Studies, and Recommendations." PNL-9004, Pacific Northwest Laboratory, Richland, Washington.
85. Link, S. O., L. L. Cadwell, C. A. Brandt, J. L. Downs, R. E. Rossi, and G. W. Gee. 1994. "Biointrusion Test Plan for the Permanent Isolation Surface Barrier Prototype." PNL-9411, Pacific Northwest Laboratory, Richland, Washington.
86. Kirkham, R. R., and G. W. Gee. 1994. "Experimental Plan and Construction Guidance for Hanford Protective Barrier Test at Hill AFB, Utah." PNL-9412, Pacific Northwest Laboratory, Richland, Washington.
87. Freeman, H. D., and R. A. Romine. 1994. "Hanford Permanent Isolation Barrier Program: Asphalt Technology Test Plan." PNL-9336, Pacific Northwest Laboratory, Richland, Washington.
88. Link, S. O., W. J. Waugh, J. L. Downs, M. E. Thiede, J. C. Chatters, and G. W. Gee. 1994. "Effects of Coppice Dune Topography and Vegetation on Soil Water Dynamics in a Cold-Desert Ecosystem." J. Arid Environ. 27: 265-278.
89. Waugh, W. J., M. E. Thiede, D. J. Bates, L. L. Cadwell, G. W. Gee, and C. J. Kemp. 1994. "Plant Cover and Water Balance in Gravel Admixtures at an Arid Waste-Burial Site." J. Environ. Qual. 23:676-685.
90. Landeen, D. S. 1994. "The Influence of Small Mammal Burrowing Activity on Water Storage at the Hanford Site." WHC-EP-0730, Westinghouse Hanford Company, Richland, Washington.
91. USDOE. 1994. "Constructability Report for the 200-BP-1 Prototype Surface Barrier." DOE/RL-94-76, U.S. Department of Energy, Richland Operations Office, Richland, Washington.
92. Myers, D. R., and D. A. Duranceau (eds.). 1994. "Prototype Hanford Surface Barrier: Design Basis Document." BHI-00007, Bechtel Hanford, Inc., Richland, Washington.

93. Wing, N. R., and G. W. Gee. 1994. "Quest for the Perfect Cap." *Civil Engineering* 64(10):38-41.
94. Gee, G. W., and N. R. Wing (eds.). 1994. In-Situ Remediation: Scientific Basis for Current and Future Technologies, Parts 1-2. Thirty-Third Hanford Symposium on Health and the Environment. November 7-11, 1994, Pasco, Washington. Battelle Press, Columbus, Ohio.
95. Wing, N. R., and G. W. Gee. 1994. "The Development of Surface Barriers at the Hanford Site." In G. W. Gee and N. R. Wing (eds.) pp. 427-440. In-Situ Remediation: Scientific Basis for Current and Future Technologies, Parts 1-2. Thirty-Third Hanford Symposium on Health and the Environment. November 7-11, 1994, Pasco, Washington. Battelle Press, Columbus, Ohio.
96. Waugh, W. J., K. L. Petersen, S. O. Link, B. N. Bjornstad, and G. W. Gee. 1994. "Natural Analogs of the Long-Term Performance of Engineered Covers." In G. W. Gee and N. R. Wing (eds.) pp. 379-410. In-Situ Remediation: Scientific Basis for Current and Future Technologies, Parts 1-2. Thirty-Third Hanford Symposium on Health and the Environment. November 7-11, 1994, Pasco, Washington. Battelle Press, Columbus, Ohio.
97. Freeman, H. D., and R. A. Romine. 1994. "Hanford Permanent Isolation Barrier Program: Asphalt Technology Development." In G. W. Gee and N. R. Wing (eds.) pp. 491-506. In-Situ Remediation: Scientific Basis for Current and Future Technologies, Parts 1-2. Thirty-Third Hanford Symposium on Health and the Environment. November 7-11, 1994, Pasco, Washington. Battelle Press, Columbus, Ohio.
98. Gilmore, B. G., and W. H. Walters. 1994. "Summary of Method Develop a Representative Equation for Soil Loss from the Hanford Permanent Isolation Barrier." In G. W. Gee and N. R. Wing (eds.) pp. 507-522. In-Situ Remediation: Scientific Basis for Current and Future Technologies, Parts 1-2. Thirty-Third Hanford Symposium on Health and the Environment. November 7-11, 1994, Pasco, Washington. Battelle Press, Columbus, Ohio.
99. Landeen, D. S. 1994. "The Influence of Small-Mammal Burrowing Activity on Water Storage at the Hanford Site." In G. W. Gee and N. R. Wing (eds.) pp. 523-544. In-Situ Remediation: Scientific Basis for Current and Future Technologies, Parts 1-2. Thirty-Third Hanford Symposium on Health and the Environment. November 7-11, 1994, Pasco, Washington. Battelle Press, Columbus, Ohio.
100. Ligothke, M. W. 1994. "Control of Eolian Soil Erosion from Waste-Site Surface Barriers." In G. W. Gee and N. R. Wing (eds.) pp. 545-560. In-Situ Remediation: Scientific Basis for Current and Future Technologies, Parts 1-2. Thirty-Third Hanford Symposium on Health and the Environment. November 7-11, 1994, Pasco, Washington. Battelle Press, Columbus, Ohio.

101. Link, S. O., W. J. Waugh, and J. L. Downs. 1994. "The Role of Plants in Isolation Barrier Systems." In G. W. Gee and N. R. Wing (eds.) pp. 561-592. In-Situ Remediation: Scientific Basis for Current and Future Technologies, Parts 1-2. Thirty-Third Hanford Symposium on Health and the Environment. November 7-11, 1994, Pasco, Washington. Battelle Press, Columbus, Ohio.
102. Myers, D. R., and N. R. Wing. 1994. "Hanford Site Protective Isolation Surface Barrier: Taking Research and Development to Engineered Application." In G. W. Gee and N. R. Wing (eds.) pp. 613-624. In-Situ Remediation: Scientific Basis for Current and Future Technologies, Parts 1-2. Thirty-Third Hanford Symposium on Health and the Environment. November 7-11, 1994, Pasco, Washington. Battelle Press, Columbus, Ohio.
103. Petersen, K. L. 1994. "The Long-Term Climate Change Task of the Hanford Permanent Isolation Barrier Development Program." In G. W. Gee and N. R. Wing (eds.) pp. 633-648. In-Situ Remediation: Scientific Basis for Current and Future Technologies, Parts 1-2. Thirty-Third Hanford Symposium on Health and the Environment. November 7-11, 1994, Pasco, Washington. Battelle Press, Columbus, Ohio.
104. Gee, G. W., H. D. Freeman, W. H. Walters, M. W. Ligothke, M. D. Campbell, A. L. Ward, S. O. Link, S. K. Smith, B. G. Gilmore, and R. A. Romine. 1994. "Hanford Prototype Surface Barrier Status Report: FY 1994." PNL-10275, Pacific Northwest Laboratory, Richland, Washington.
105. Gaylord, D. R., and L. D. Stetler. 1994. "Aeolian-Climate Thresholds and Sand Dunes at the Hanford Site, South-Central Washington, U.S.A." J. Arid Environments 28:95-116.
106. Freeman, H. D., R. A. Romine, and A. H. Zacher. 1994. "Hanford Permanent Isolation Barrier Program: Asphalt Technology Data and Status Report - FY 1994." PNL-10194, Pacific Northwest Laboratory, Richland, Washington.
107. Wing, N. R., G. W. Gee, and J. W. Cammann. 1995. "Program Management of a Multi-Year Technology Development Effort." PM Network 9(3):47-50.
108. Sackschewsky, M. R., C. J. Kemp, S. O. Link, and W. J. Waugh. 1995. "Soil Water Balance Changes in Engineered Soil Surfaces." J. Environ. Quality 24: 352-359.
109. Rockhold, M. L., M. J. Fayer, C. T. Kincaid, and G. W. Gee. 1995. "Estimation of Natural Ground Water Recharge for the Performance Assessment of a Low-Level Waste Disposal Facility at the Hanford Site." PNL-10508, Pacific Northwest Laboratory, Richland, Washington.
110. Link, S. O., M. E. Thiede, R. D. Evans, J. L. Downs, and G. W. Gee. 1995. "Responses of Big Sagebrush and Spiny Hopsage to Increasing Water Stress." In B. A. Roundy, E. D. McArthur, J. S. Haley, and D. K. Mann (eds.). Proceedings of the Wildland Shrub and Arid Land Restoration Symposium, pp. 196-201. USDA-FS, Intermountain Research Station, Ogden, Utah.

111. Wing, N. R., F. M. Corpuz, K. L. Petersen, and A. M. Tallman. 1995. "Physical Stability of Long-Term Surface Barriers-Assessment of Potentially Disruptive Natural Events." BHI-00145, Bechtel Hanford, Inc., Richland, Washington.
112. Wing, N. R., K. L. Petersen, C. Whitlock, R. L. Burk. 1995. "Long-Term Climate Change Effects Task for the Hanford Site Permanent Isolation Barrier Development Program: Final Report." BHI-00144, Bechtel Hanford, Inc., Richland, Washington.
113. Duranceau, D. A. 1995. "Site Evaluation Report for Candidate Basalt Quarry Sites." BHI-00005, Bechtel Hanford, Inc., Richland, Washington.
114. Fayer, M. J., and C. S. Simmons. 1995. Modified soil water retention functions for all matric suctions. Water Resour. Res. 31:1233-1238.
115. Petersen, K. L., S. O. Link, and G. W. Gee. 1995. Hanford Site Long-Term Surface Barrier Development Program: Fiscal Year 1994 Highlights. PNL-10605, Pacific Northwest Laboratory, Richland, Washington.
116. Link, S. O., N. R. Wing, and G. W. Gee. 1995. The development of permanent isolation barriers for buried wastes in cold deserts: Hanford, Washington. J. Arid Land Studies 4:215-224.

DISTRIBUTION

<u>No. of Copies</u>		<u>No. of Copies</u>	
	<u>OFFSITE</u>	3	Environmental Protection Agency Hanford Project Office 712 Swift, MS B5-01 Richland, WA 99352 ATTN: D. A. Faulk P. S. Innis P. R. Beaver
2	DOE/Office of Scientific and Technical Information J. Anderson Idaho State University Department of Biology Pocatello, ID 83209 B. Bede U.S. Ecology 509 E. 12th Olympia, WA 98501 R. A. Black Washington State University Botany Department Pullman, WA 99164 J. Brown Landfill Stabilization Focus Area Coordinator Savannah River National Laboratory Aiken, SC 29802 G. S. Campbell Washington State University Geology Department Pullman, WA 99164 D. E. Daniel University of Texas Dept. of Civil Eng. Austin, TX 78712 B. W. Drost U.S. Geological Survey 1201 Pacific Ave., Suite 600 Tacoma, WA 98402 M. Dunkelman Department of Health Division of Radiation Protection Airdustrial Park, Bldg. 5 P.O. Box 47827 Olympia, WA 98504-7827	3	Environmental Science and Research Foundation 101 S. Park Ave, Suite 2 P.O. Box 51838 Idaho Falls, ID 83405-1838 ATTN: O. D. Markam R. C. Morris T. E. Reynolds L. G. Everett Geraghty & Miller, Inc. 3700 State St, Suite 350 Santa Barbara, CA 93105-3128 W. A. Jury University of California at Riverside Dept. of Soils Riverside, CA 92502
		2	Lockheed Martin Idaho P.O. Box 1625 Idaho Falls, ID 83415-5218 ATTN: K. M. Kostelnik J. B. Sisson J. Lommler Jacobs Engineering Group, Inc. 2155 Louisiana Blvd. NE #1000 Albuquerque, NM 87110-5414 C. Massimino U.S. Environmental Protection Agency 1200 Sixth Avenue Seattle, WA 98101
		2	Oak Ridge National Laboratory P.O. Box 2008 Oak Ridge, TN 37831 ATTN: R. J. Luxmoore E. D. Smith K. L. Petersen 207 Benham St Richland, WA 99352

<u>No. of Copies</u>	<u>No. of Copies</u>
G. N. Richardson Hazen and Sawyer 4011 W. Chase Blvd. Suite 500 Raleigh, NC 276073	2 U.S. Ecology Inc. 5333 Westheimer Rd. Suite 1000 Houston, TX 77056-5407 ATTN: A. Palmer L. D. Irwin
Sandia National Laboratories P.O. Box 5800 Albuquerque, NM 87185 ATTN: S.F. Dwyer R.E. Finley J. Nelson	2 U.S. Geological Survey 333 W. Nye Lane Carson City, NV 89706 ATTN: B. J. Andraski D. E. Prudic
B. R. Scanlon Bureau of Economic Geology University of Texas at Austin University Station Box X Austin, TX 78713-7508	2 U.S. Nuclear Regulatory Commission Division of Engineering Safety Waste Management Branch 11555 Rockvill Pike Rockville, MD 29852 ATTN: T. J. Nicholson E. O'Donnell
S. D. Smith University of Nevada-Las Vegas Biology Department Las Vegas, NV 89154	N. Uziemblo Washington State Dept of Ecology 7601 W. Clearwater, Suite 102 Kennewick, WA 99336
E. Springer Los Alamos National Laboratory P.O. Box 1663 Los Alamos, NM 87545	2 Washington State Department of Ecology Mail Stop PV-11 Olympia, WA 98504-8711 ATTN: C. Cline R. B. Hibbard
D. Stone Hill Air Force Base Environmental Management Directorate OO-ALC/EM 7276 Wardleigh Road Hill AFB, UT 84056-5127	W.J. Waugh Chem Nuclear Geotech P.O. Box 14000 Grand Junction, CO 81502
M. J. Sully Reynolds Electric Engr. Co., Inc. 2626 Losee Rd Las Vegas, NV 89030	E. P. Weeks U.S. Geological Survey Federal Center Mail Stop 413 Denver, CO 80225
R. L. Treat Foster Wheeler Environ. 1981 Snyder Rd. Richland, WA 99352	2 Westinghouse Savannah River Company P.O. Box 616 Aiken, SC 29802 ATTN: S. R. McMullin M. G. Serrato
S. W. Tyler Desert Research Institute P.O. Box 60220 Reno, NV 89506	P. J. Wierenga University of Arizona Dept. of Soil & Water 429 Shantz Building Tucson, AZ 85721

No. of
Copies

ONSITE

5 DOE Richland Operations Office

B.L. Foley	K2-18
J. P. Hanson	K8-50
D. E. Trader	A5-90
D. D. Wodrich	S7-50
DOR-RL Reading Room 1	

5 Bechtel Hanford Incorporated

M. A. Buckmaster	H6-01
F. M. Corpuz	H4-85
D. R. Myers	H4-82
J. G. Woolard	H4-89
J.W. Darby	H4-84

Kaiser Engineers Hanford Company

D. L. Fort	E6-50
------------	-------

8 Westinghouse Hanford Company

M. R. Adams	H6-30
R. E. Lerch	S7-85
W. A. Skelly	L4-69
J. C. Sonnichsen	H6-23
A. M. Tallman	H6-30
D. E. Wood	H6-30
Environmental Data Mgmt Ctr (2)	

32 Pacific Northwest National Laboratory

K. A. Blanchard	K2-05
R.E. Clayton	K9-33
M. J. Fayer	K9-33
D. Felmy	K9-33
H. D. Freeman	P8-38
M. D. Freshley	K9-36
G. W. Gee (10)	K9-33
B. G. Gilmore	K9-33
C. T. Kincaid	K9-33
R. R. Kirkham	K9-33
M. W. Ligothke (3)	P7-59
S. O. Link	K6-84
P. D. Meyer	K9-33
T. L. Page	K9-18
R. A. Romine	P8-38
M. R. Sackschewsky	K6-84
Technical Report Files (5)	