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Hanford Prototype-Barrier Status Report FY 1996

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G.W. Gee
A. L. Ward
B. G. Gilmore
S. O. Link
G. W. Dennis
T. K. O'Neil

November 1996

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Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830
(Work Order XD 6016-Bechtel Hanford Inc.)

Pacific Northwest National Laboratory
Richland, Washington 99352

(a) Now at Washington State University

EXECUTIVE SUMMARY

A prototype surface barrier is being evaluated as part of a treatability study at the 200-BP-1 Operable Unit in the 200 East Area of the Hanford Site. Tests include the application of irrigation water to the northern half of the barrier and subsequent measurement of water balance, wind and water erosion, subsidence, plant establishment, and plant and animal intrusion. The tests are designed to evaluate both irrigated and nonirrigated sideslope and vegetated surfaces over a period of 3 yr. This report documents findings from the second year of testing.

From the first of November 1995 until the end of May 1996, the total applied water (irrigation, rainfall, snowmelt) was 392 mm, or more than 81% of the 3X target amount of 480 mm. During the last week of March, 70 mm of water was applied in 8 hours, simulating a 1000-yr storm event. In 1996 no runoff was observed, compared to 1.8 mm in 1995. The lack of runoff from the simulated 1000-yr storm is attributed to vegetation and its impact on surface stability and permeability. There has been no runoff from the non-irrigated areas of the prototype.

Soil-water storage was reduced annually by means of evapotranspiration (ET). Total ET for WY 1995 (Nov 1994 - Oct 1995) was 654 mm for irrigated surfaces and 440 mm for nonirrigated surfaces. A similar response was observed in WY 1996, where total ET for irrigated and nonirrigated surfaces was 542 mm and 283 mm, respectively. By the end of October 1996, water storage was 128 mm on irrigated tests and 102 mm on the nonirrigated tests. Water content profiles in August 1996 were very similar to those observed in August 1995, suggesting that vegetation is effectively extracting water from the entire 2-m soil profile. Water potentials were always lower than -0.2 MPa. At a water potential of -0.2 MPa, water flux rates from the soil are negligibly small (< 0.1 mm/yr), so very low drainage rates were expected from the soil surfaces.

No drainage was measured from the soil surfaces during the 2-yr test period. The lack of drainage from the soil surface is consistent with the observed water storage. A total of only 120 mm water was stored in the soil at the end of August, or 20% of the designed storage capacity of 600 mm. Even in early April 1996, during the wettest time of the year, the storage capacity for the irrigated surfaces was less than 300 mm, 50% of the designed storage capacity. For the nonirrigated surfaces, the water storage ranged from 20% to 30% of the designed storage during WY 1996.

Sideslope drainage was observed in WY 1995 and continued during WY 1996. However, sideslope drainage was much less than originally predicted. Over the past 18 months, the irrigated basalt rock sideslopes drained 25% of the applied water, while nonirrigated basalt rock drained 11% of the precipitation. Drainage from gravel sideslopes was 26% of the applied water when irrigated and 18% when not irrigated. The observed sideslope drainage was less than that measured in nearby lysimeters containing similar cover materials. The low drainage rates from the prototype sideslopes are attributed primarily to advective drying. The prototype barrier design, with large basalt rock on the sideslope connected to coarse rock in the sublayers, tends to optimize natural advective drying conditions. The enhanced drying of the sideslopes also acts to reduce water storage in the soil layers of the surface barrier.

Water content changes were measured at the outer edge of the barrier using neutron probe logging techniques and scanning a series of horizontal access tubes located at depths of 1, 2, and 3 m below the asphalt pad at the base of the prototype barrier. The subsurface water content changes were found to be confined to the edge and to the outside of the asphalt pad. The measurements confirm that no significant water content changes have occurred under the asphalt pad during the past 2 yrs.

A series of topographic surveys were completed on the prototype barrier during the past 2 yrs to assess the changes in surface elevation. Since construction in 1994, the surface has remained relatively stable. The only significant change that occurred was observed in the southeast corner of the barrier, where the soil has settled about 10 cm over an area of about 9 m^2. The settlement may be the result of a minor construction flaw resulting from faulty placement of geofabric. However, the amount of subsidence is small, and no corrective action is planned. No significant settlement or creep was observed for the rock sideslope.

Wind erosion on soil surfaces was estimated by visual inspection and measurement of gravel contents. Visually, the surfaces appeared stable overtime. The average gravel content of the soil surface remained at 14 wt percentage the past two years. The irrigated surface gravel content increased and the nonirrigated surface gravel content decreased slightly during the same time period.

Vegetation type on the prototype shifted dramatically during the past year. In August 1995, there was a prolific stand of tumbleweed *(Salsola kali)* on the surface of the barrier. In the fall of 1995 the tumbleweed died; the biomass subsequently dried and was blown off the barrier. The remaining shrubs and seeded grasses have grown rapidly, with little reinvasion of tumbleweed. During June 1996, the shrubs were counted and a survival rate determined. The survival rate for rabbitbrush (*Chrysothanmus nauseosus*) across treatments (irrigated and nonirrigated) was 57%, while survival rate for sagebrush (*Artemisia tridentata*) was 97%. There has been a significant invasion of numerous plant species. More than 33 species were identified in June 1996, 21 species more than were transplanted or seeded in 1994. The grass cover has increased significantly. Irrigated surfaces have more than 35% grass cover, while nonirrigated surfaces have about 15% grass cover. The rock sideslope was free of vegetation during the year, while vegetation on the gravel sideslope consisted of a sparse grass cover.

Animal intrusion was very limited. There was evidence of animals in only 20% of the 3-m x 3- m quadrats in the nonirrigated side and only 8% of the irrigated side of the barrier. Only nine animal burrows were found over the entire surface; they are small and appear to be from pocket mice.

Monitoring of water balance, subsidence, water and wind erosion, vegetation changes and animal intrusion will continue through FY 1997. Irrigation will continue on the north half of the prototype barrier and will include the application of an extreme event (e.g., 1000 yr-storm) during the last week of March, 1997. Drainage from sideslopes and movement of materials on or near the sideslopes will be documented over the course of the year.

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We wish to thank our support staff, Ray Clayton, Rod Davis, Jere Boudell, Traci Degerman, William Mast, Jennifer Lewinsohn, Suzanne Beall, Janelle Downs, and Sally Simmons who ably assisted in the testing and monitoring of the prototype during the year. 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 and work order XD6016 from Bechtel Hanford Company.

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1.0 INTRODUCTION

Surface barriers continue to be an option for isolating certain wastes at the Hanford Site. More than 230 wastes sites have been identified that may use surface barriers (USDOE 1996). Surface barriers are intended to isolate 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 a treatability study was initiated at the 200 BP1 Operable Unit in the East Area of the Hanford, consisting of the construction and performance testing of a prototype surface barrier (USDOE 1993). The prototype consists of a 2.5-ha surface barrier that covers an existing waste site (B-57 Crib). Figure 1.1 shows three aerial views of the completed prototype barrier as seen immediately after construction in August 1994 at yearly intervals since construction. Figure 1. 2 shows a schematic cross-section of the prototype barrier.

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-yr) 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. Figure 1.3 shows the type of measurements and the data flow for the prototype testing.

Figure 1.4 is a schematic of the PSB and shows the layout of the two precipitation treatments. Each treatment is divided into 6 plots, and includes 4 main plots (14 m x 23 m) and 2 transition plots (4 m x 23 m). The plots correspond to the drainage collection zones on the asphalt pad. Two of the main plots are located on the silt loam surface of each treatment (6W, 6E, 3W, 3E) and one on each side slope configuration within a precipitation treatment (4W, 4E, 1W, 1E). The silt loam plots are separated from the side slope plots by transition plots (5W, 5E, 2W, 2E). Each treatment is instrumented to permit direct monitoring of all the water balance components in the soil layer. The barrier is fitted with 14 monitoring stations, 7 on each treatment. On each irrigated treatment, 6 stations were located on the silt loam plots and 1 on the clean-fill sideslope. Each station is equipped with a precipitation meter, essentially a miniature weighing lysimeter. Additional climatological data are obtained from the Hanford Meteorological Station (HMS), located about 5 km NW of PSB. For measuring $\theta(z,t)$, each monitoring station is fitted with a vertical access tubes for measurements with a Campbell Pacific Nuclear (model 503) neutron probe.

The testing and monitoring of the prototype surface barrier is part of the DOE effort to provide performance data to the regulators and other interested stakeholders. 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, 1995; Petersen et al. 1995). One objective of the prototype barrier design was to use natural materials to develop a protective barrier system that isolates the waste site for at least 1000 yr by limiting water, plant, animal, and human intrusion, and minimizing erosion.

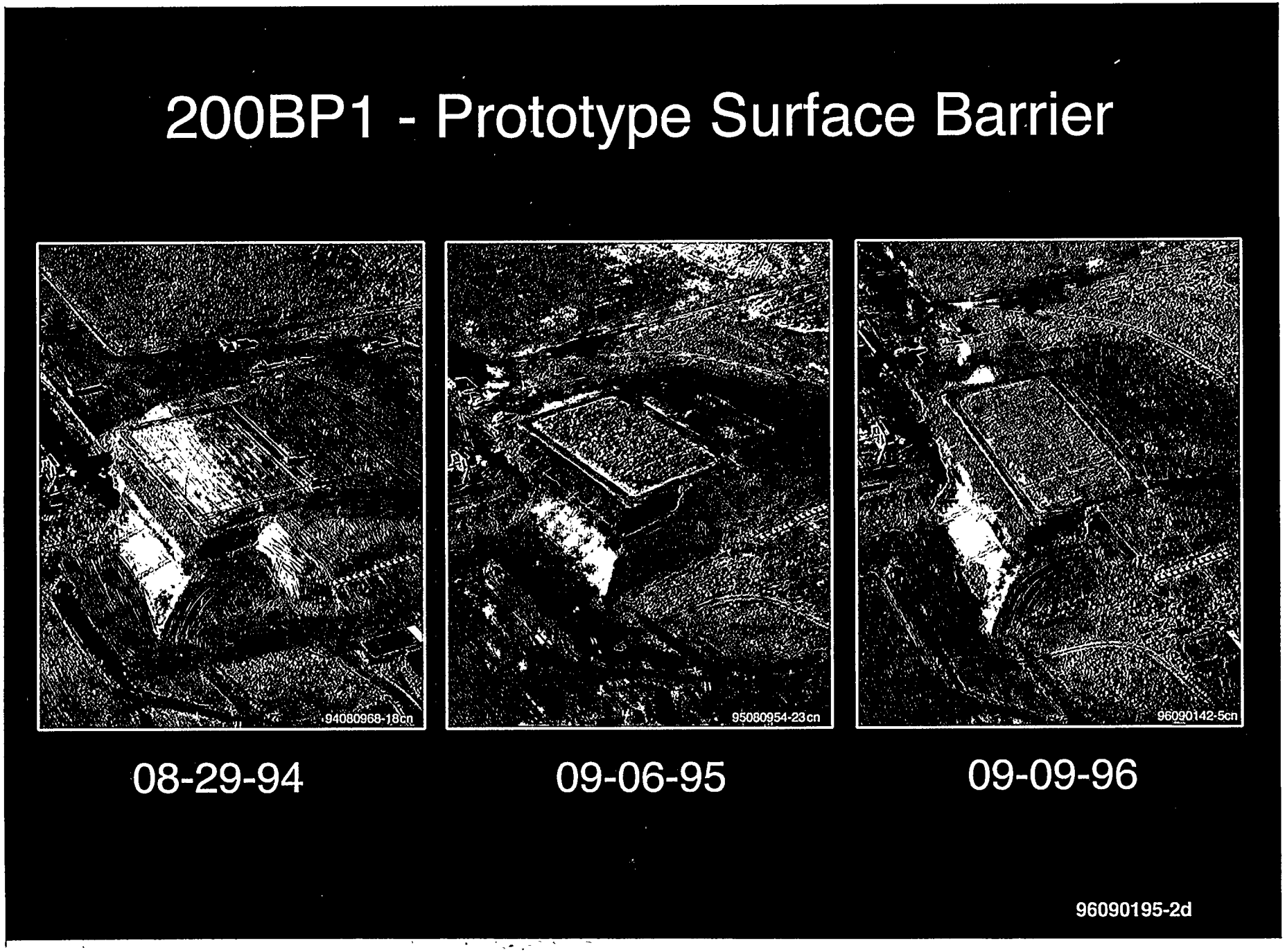

Figure 1.1. Prototype surface barrier at the 200 BP-1 Operable Unit, 200 East Area Hanford Site, Washington. Photos taken in August 1994, September 1995, and September 1996.

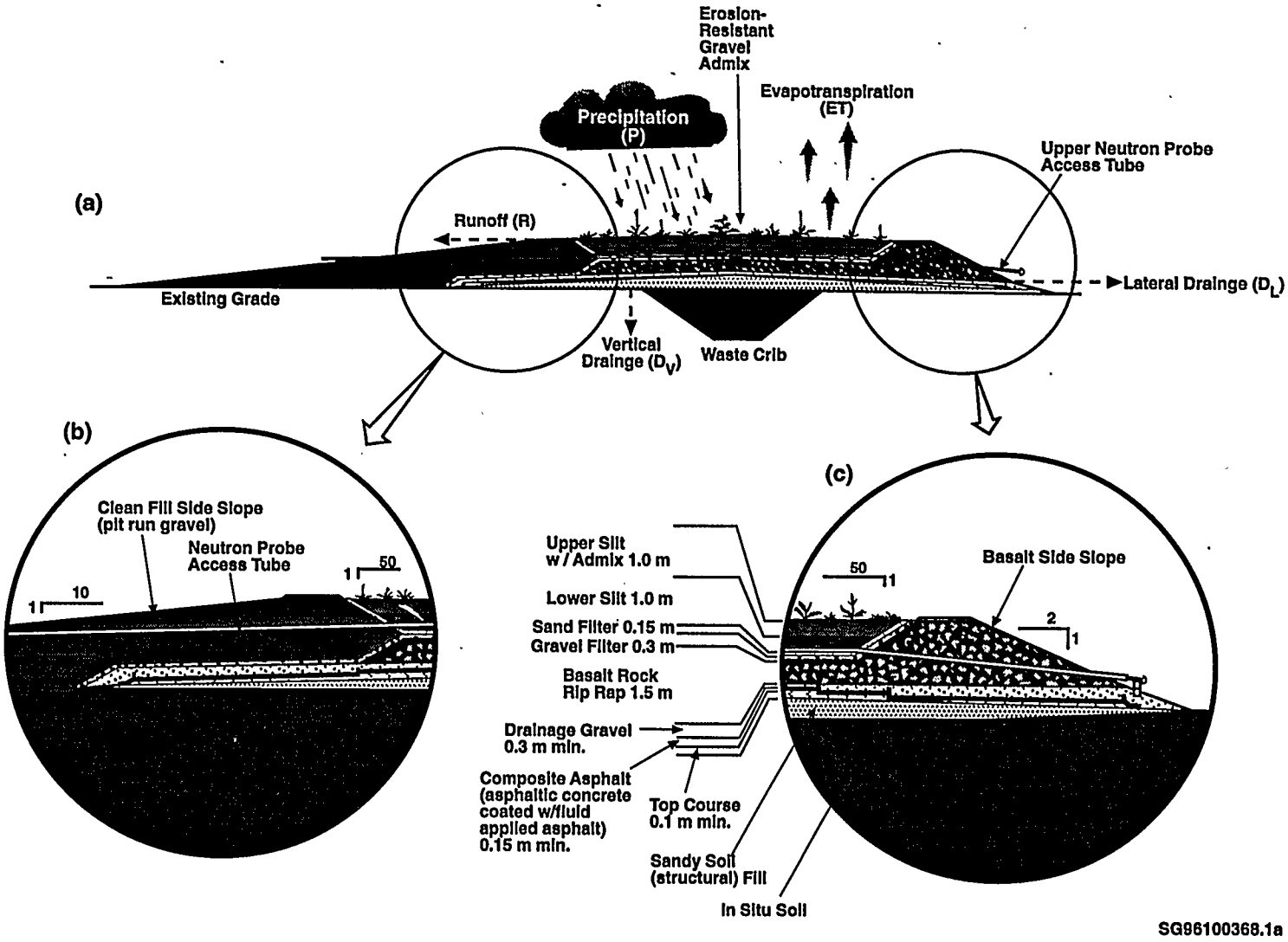

Figure 1.2. Schematic of Hanford Barrier Showing (a) Interactive Water Balance Processes and Barrier Location Relative to the Waste Zone, (b) Gravel Side Slope Showing Horizontal NP Access Tube and Asphalt Pad, and © Basalt Side Slope, Showing Horizontal NP Access Tube and Asphalt Pad.

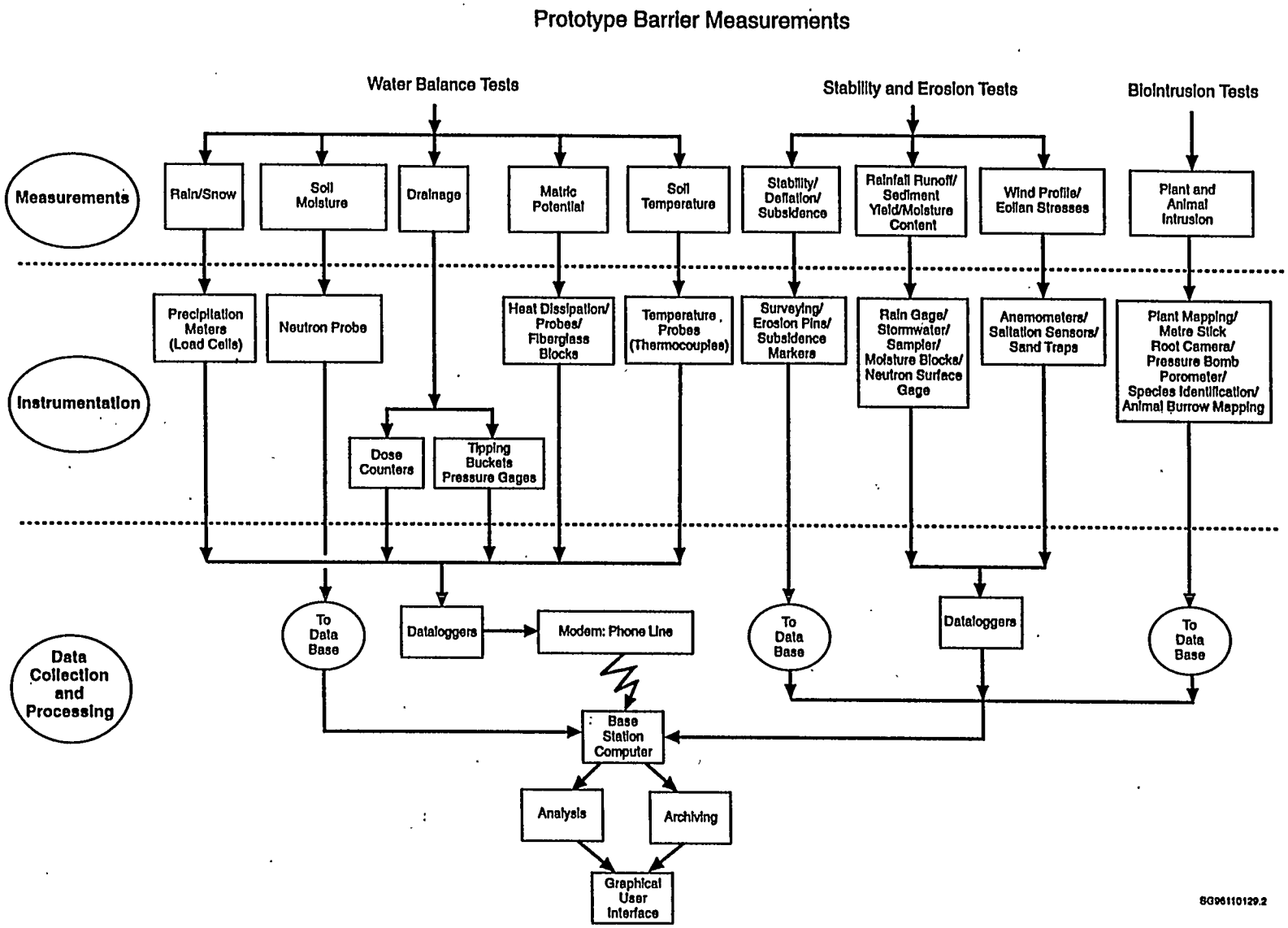

Figure 1.3. Measurement, Instrumentation, and Data Collection Flow Diagram for the Prototype Surface Barrier.

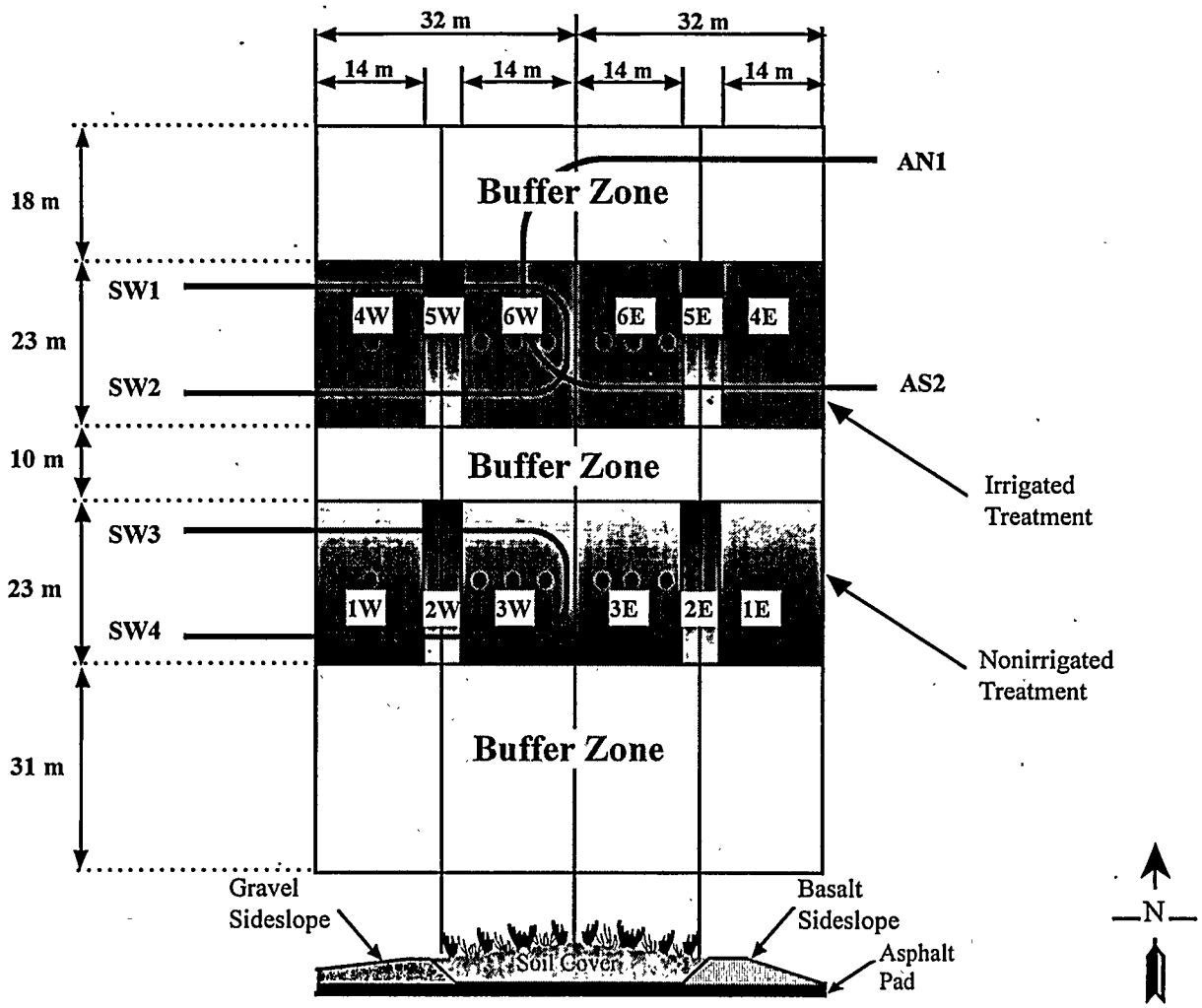

Figure 1.4. Planview of Prototype Surface Barrier. Irrigated and Nonirrigated Treatments Are Divided into Test Plots as Shown. Black Dot Represents Monitoring Stations Including Vertical Access Tubes for Neutral Probes. Horizontal Access Tubes Are Shown as Large U-tubes; SW1, SW2, SW3, SW4, AN1, and AS2.

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.

This document summarizes work completed in FY 1996 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. Section 6.0 describes quality assurance measures being used in the prototype barrier study. Planned activities for FY 1996 are summarized in Section 7.0. References are listed in Section 8.0 and a current list of barrier publications is provided in Section 9.0.

2.0 WATER BALANCE EVALUATION

The process of selecting appropriate cover technologies for Hanford and other sites demands that barrier designs be evaluated in a repeatable, objective, and scientifically sound manner, taking into account a variety of technical, regulatory, and economic factors. At present there are very few performance evaluation data from field-scale hazardous waste covers in arid regions. However, it is has been recognized that performance of hazardous waste covers is influenced by a series of interactive and dynamic water balance processes operating in the field. Water balance evaluation permits the most comprehensive measure of performance.

The purpose of this ongoing study is to quantify the energy status of water and the water balance components (i.e., precipitation, run-off, water storage, drainage, and evapotranspiration) in an effort to assess the effectiveness of the prototype Hanford surface barrier (PSB) in controlling recharge to underlying wastes. Two major issues identified in the Treatability Test Plan for the 200-BP-1 Prototype surface barrier are evaluating: 1) the effect of extreme precipitation events on water infiltration, and 2) the effect of water infiltration on side slope stability and subsurface water content (USDOE, 1993). This study is aimed at generating a complete water-balance data set during the 3-yr performance evaluation period in order to resolve the issues identified in the Test Plan.

The water balance may be described as the sum of its individual components. Since all of the components except evapotranspiration (ET) are measured directly for the PSB, the water balance may be written as

$$ET = (P + I) - (\Delta S + R + D) \qquad [1]$$

where

ΔS	= change in soil water storage
P	= natural precipitation
I	= irrigation/snow
R	= surface runoff
D	= drainage from the soil profile.

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

$$\Delta S = \int_0^L \int_{t_1}^{t_2} \frac{\partial \theta(z,t)}{\partial t} dz\, dt \qquad [2]$$

where $\theta(z,t)$ is the volumetric water content measured as a function of depth and time.

All measurements at the prototype were performed according to PNNL Technical Procedures developed for the PSB. A list of the technical procedures applicable to the Water Balance Task is provided in Section 6.0.

During the last year, changes in soil water storage were inferred from changes in soil water content measured by neutron probe. Because of project constraints, an evaluation of different techniques for monitoring water storage (capacitance probe, time domain reflectometry, ane electromagnetic induction) were discontinued. This section summarizes the results of the second year, through October 1996, of testing and monitoring performed under the Water Balance Task at the PSB.

2.1 Climatic Conditions

The FY 1996 water year (WY 1996) started on 11/01/95 and will end on 10/31/96. The PSB is equipped with a series of miniature weighing lysimeters and a tip bucket gauge for monitoring precipitation. These data, in addition to data from the Hanford Meteorological Station (HMS), were used to schedule irrigation and to calculate the water balance.

Climatic data from HMS show that 1995 was the warmest, wettest year on record (Hoitink and Burk, 1996). The winter of WY 1996 (December 1995, January 1996 and February 1996) was warmer than normal. The average temperature was 6.4 °C, compared to the normal 0.9 °C. The average temperature during the spring of WY 1996 was 21.2 °C compared to 12.4 °C in WY 1995 and the normal 11.8 °C. The trend of higher temperatures continued into the summer of WY 1996, resulting in an average temperature of 32.9 °C compared to 22.5 °C in the summer of WY 1995 and a normal 23.1 °C.

The total precipitation in calendar year 1996 was 313.9 mm, or 197 % of normal (159 mm). Total snowfall was only 55% (195.6 mm) of the normal 350.5 mm. Figure 2.1 shows a plot of cumulative precipitation over the last 2 yr, as well as the long-term average and 3X target. Apart from November, December, and February, precipitation in WY 1996 was generally lower than in WY 1995.

During the period 11/01/95 to 10/31/96 (WY 1996), the nonirrigated treatment received a total of 233 mm of from natural precipitation compared to 288 mm during the same period in WY 1995. Irrigation events started earlier in WY 1996 and, by 10/31/96, a total of 259.7 mm of irrigation water had been applied, compared to 200.6 mm in WY 1995. The sharp increase in precipitation in late March of each year represents the annual extreme precipitation event. In both WY 1995 and WY 1996, 70 mm of water was applied over an 8-hr period. The total precipitation received by the 3X irrigation treatments through 10/31/96 was 493 mm, only 13 mm more than the 3X target. In WY 1995, the irrigated treatment received a total of 488 mm.

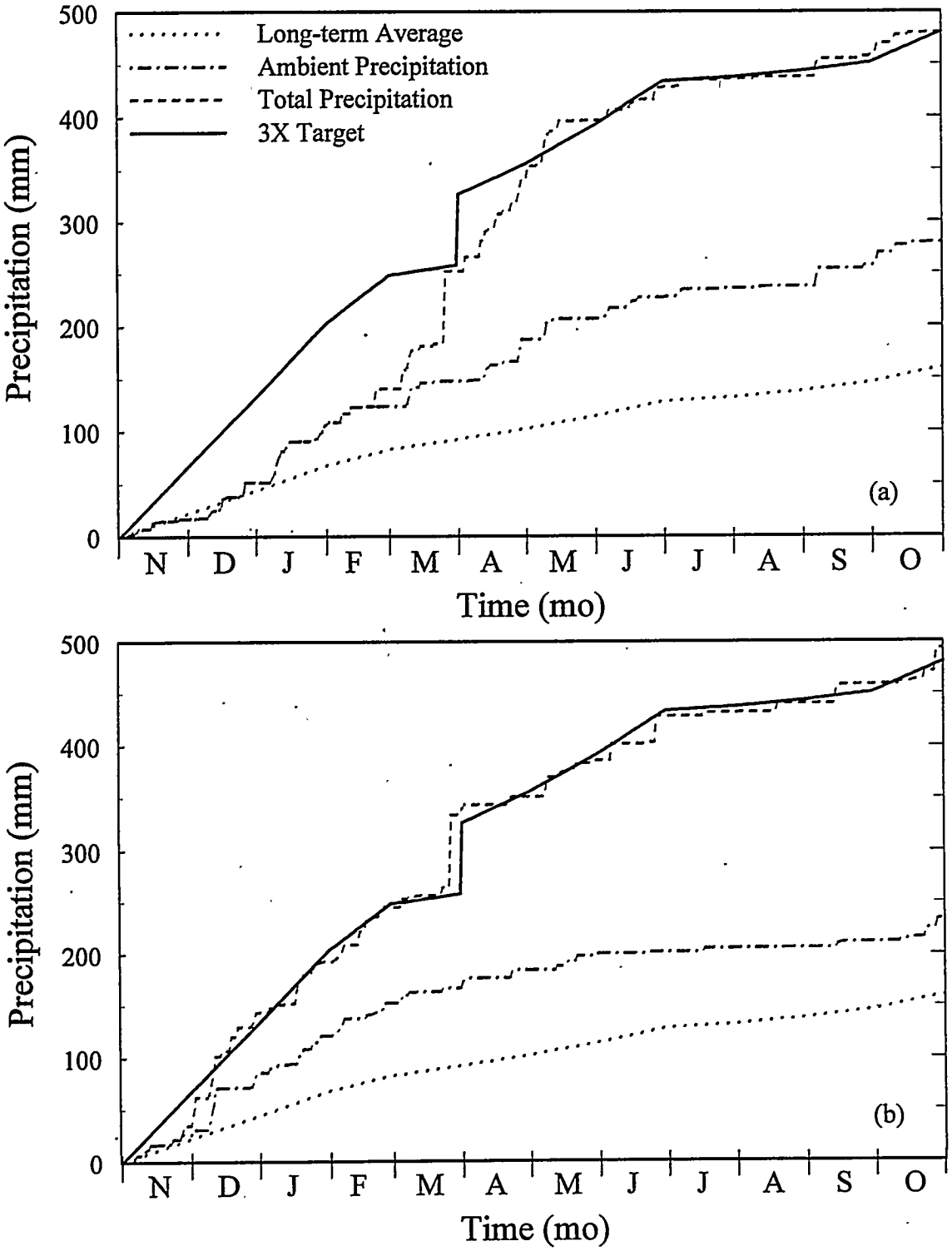

Figure 2.1. Cumulative long-term average, ambient and total precipitation data for the PSB over the last 2 yr (a) WY 1995, and (b) WY 1996.

2.2 Soil Water Storage

Neutron probe measurements were generally taken twice per month on the vertical access tubes at the PSB, according to PNL-PSB-10.0. Briefly, measurements were taken at 0.15 m increments from the surface and the data stored electronically. At the base station, data were downloaded to the database (Fig. 1.3). Figure 2.2 shows the calibration relationship used to convert vertical neutron probe counts to θ. This relationship as well as Eq. 2 were incorporated into a FORTRAN program to permit calculation of θ, S, and ΔS.

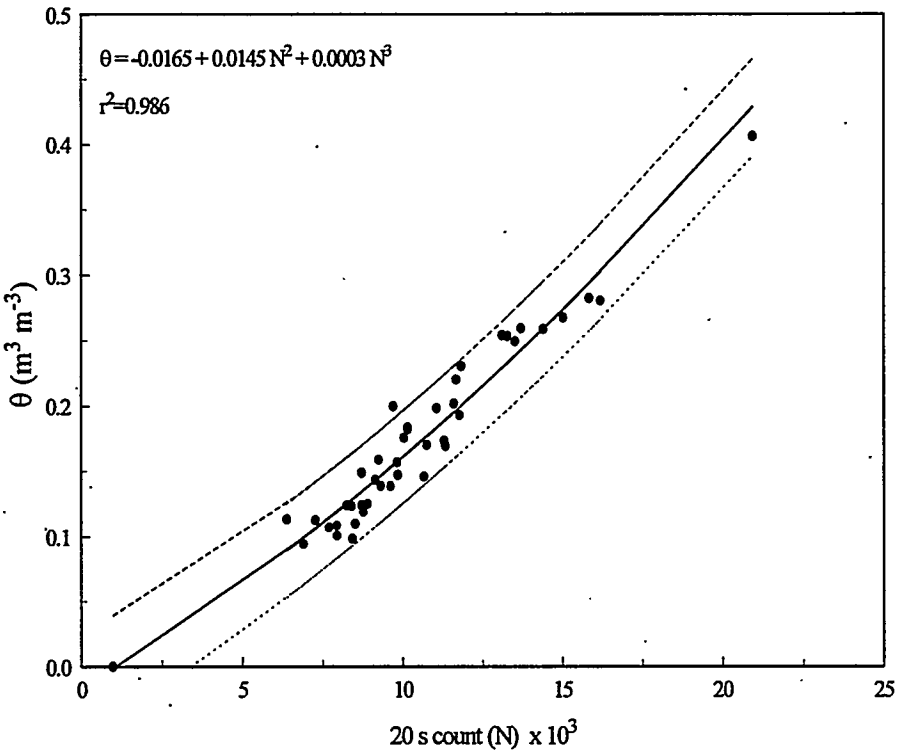

Figure 2.2. Observed and fitted (with 95% confidence intervals) calibration relationship between vertical neutron probe measurements and volumetric water content on the silt loam surface.

2.2.1 Silt Loam Plots

A comparison of S between plots within the two precipitation treatments showed very little difference. Thus, water storage values were averaged over the plots to obtain treatment averages. Neutron probe measurements of $\theta(z,t)$ were used to calculate changes in soil water storage, ΔS, for each plot within the two treatments according to Eq. [2]. There was little difference between plots within a treatment, therefore water storage values were averaged over the plots to obtain treatment averages. The temporal changes in mean S on the irrigated and unirrigated treatments, over the last 2 yr, are compared in Fig. 2.3.

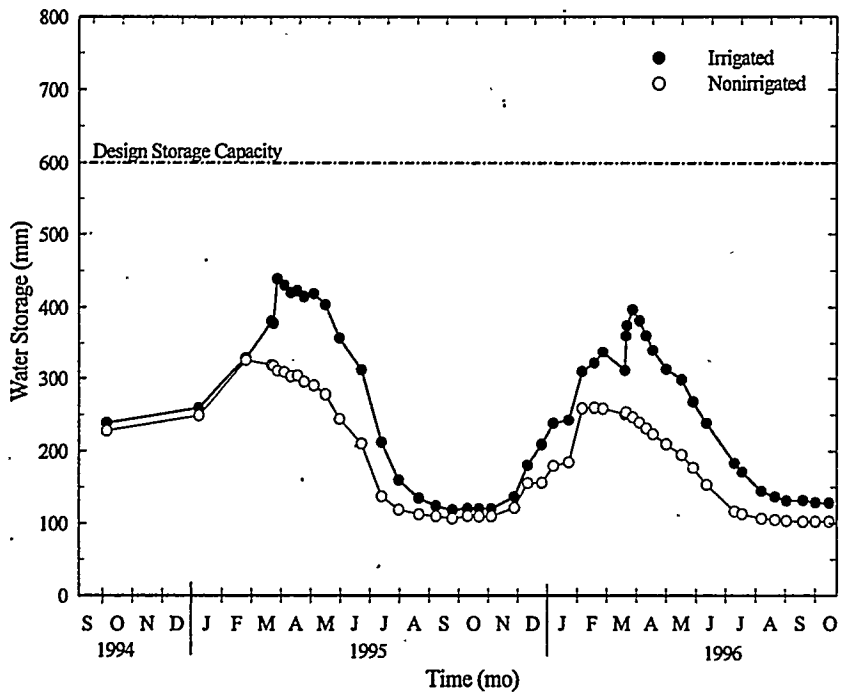

Figure 2.3. Temporal variation in soil water storage at the PSB since 09/30/94.

Shortly after PSB construction, water storage on the irrigated treatments was slightly higher than on the nonirrigated treatments. With no irrigation and a surface devoid of plants, differences in water storage between the nonirrigated and irrigated treatments remained small until the surface was revegetated in late November 1994. Irrigation started on the irrigated treatments in mid-February 1995, leading to more pronounced differences. Neither of the treatments showed any increases in storage beyond 03/27/95, when mean storage was 438.5 mm on the irrigated treatments and 310 mm on the nonirrigated treatments. Beyond this point, water storage decreased throughout the rest of WY 1995, reaching a mean value of 119.5 mm on the irrigated treatments and 109.4 mm on the nonirrigated treatment by October 1995, the end of WY 1995.

This rapid depletion in storage was attributed to evapotranspiration and led to a maximized storage capacity in time for the approaching winter precipitation.

With the onset of precipitation in the winter of 1995-1996, water storage started to increase. The rate of increase in storage, up to the extreme precipitation event, decreased by 49% on the irrigated treatment and 52% on the nonirrigated treatment. With a more developed plant community in WY 1996, a slower rate of increase in storage can be expected. At its maximum in WY 1996 (April 2), the mean water storage was 415 mm on the irrigated treatments, compared to 439 mm in WY 1995. Mean storage on the ambient treatments was 270.2 mm, compared to 310 mm in WY 1995. With the irrigated treatments receiving 5.0 mm more precipitation than last year, the 24-mm difference in storage could have been caused by increased plant activity. Climatic records show that WY 1996 was warmer than WY 1995. These conditions would have been more conducive to higher rates of water loss, mainly by transpiration, since the fully covered surfaces would have reduced evaporation losses.

As in WY 1995, there were no increases in storage beyond the extreme precipitation event. The rapid depletion in storage observed in WY 1995 is therefore being repeated. By 10/23/96, mean storage had been depleted to 128 mm on the irrigated treatment and 102 mm on the nonirrigated treatment. Compared to WY 1995, S was about 8 mm higher on the irrigated treatment and 8 mm lower on the nonirrigated treatment. Although there was a small difference in the amount of water stored relative to WY 1995, the rate of depletion after the extreme precipitation event was essentially the same on the irrigated treatment. Between the second extreme precipitation event on March 26 and the end of August 1995, the mean rate of decrease in storage was 2 mm d^{-1} on the irrigated treatment, the same as in WY 1995. In contrast, the ambient treatment showed a reduction in rate from 1.2 mm d^{-1} in WY 1995 to 0.8 mm d^{-1} in WY 1996.

These results, though contradictory in appearance, can be explained by differences in the plant community between WY 1995 and WY 1996. In WY 1995, both precipitation treatments on the silt loam surface had healthy stands of tumble weed. In contrast, there was no tumble weed on the PSB in WY 1996. On the irrigated treatment, where availability of water was nonlimiting, an unchanged rate of change in storage after the extreme precipitation event, in the absence of tumbleweed, suggests that the plants were able to utilize all available water. In WY 1996, the nonirrigated treatment received 55 mm less water than in WY 1995, resulting in less water available for transpiration. Thus, the lower rate of change in storage on the nonirrigated treatment suggest that low precipitation can be the limiting factor in the behavior of the native plant species. As in WY 1995, storage continued to decrease through the end of WY 1996, reaching 102 mm by the end of October and maximizing available storage prior to the onset of winter precipitation. As of the end of WY 1996, the design storage capacity of the PSB has not been exceeded.

2.2.2 Gravel Sideslope Plots

Neutron probe measurements of $\theta(z,t)$ on the gravel sideslope started in April 1995. Since then, measurements have been made down to a depth of 1.8 m on the irrigated treatment, but only 1.35 m on the nonirrigated treatment. Figure 2.4 shows a plot of water storage as a function of time on the two precipitation treatments of the gravel sideslope. While there was no apparent cycling in storage on the ambient

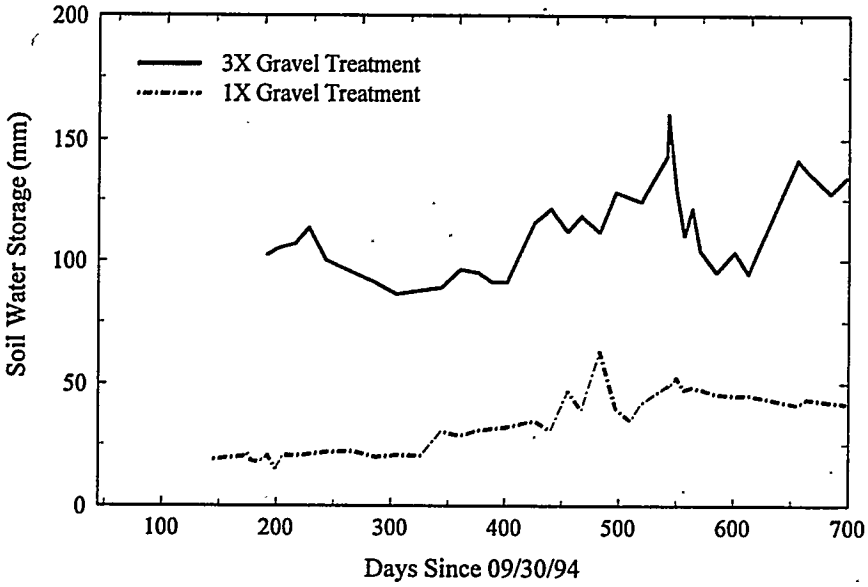

Figure 2.4. Temporal variation in mean water storage in the gravel side slope at the PSB since 09/30/94.

treatments, the irrigated treatment showed a temporal pattern similar to that of the silt loam treatments. Water storage increased in the winter months and showed rapid depletion in the summer. However, a major difference is the rapid, short-term changes in storage. The rapid increases usually occurred in response to precipitation and irrigation events and were most obvious when neutron probe readings are taken within a few hours of such events. Because of the inherently low storage capacity of the gravel, drainage was usually quite rapid, with a corresponding decrease in water stored. A good example occurs at day 543, the day of the extreme precipitation event, in which a total of 70 mm of water was applied. Neutron probe measurements were taken immediately following cessation of irrigation. By this time, water storage had increased to 160 mm in the gravel, a change of only 16 mm compared to storage on the previous day. The corresponding change in the silt loam profile was 50 mm, and it took another 7 days for storage to reach a maximum of 397 mm. The final increase in storage in response to the extreme precipitation event was 62 mm in the silt loam and 16 mm in the gravel. As will be shown in a subsequent section, there was no drainage from the silt loam, while drainage from the gravel sideslope was almost immediate.

These results should be interpreted with some caution. While it is expected that clean fill gravel would have a significantly lower storage capacity than silt loam, it should be noted that on the gravel slope, the neutron probe access tubes extend to only 1.8 m on the irrigated treatment and 1.35 on the nonirrigated treatment. The gravel profile extends down to approximately 2.5 m, and measurements to shallower depths will underestimate the water storage. Because of the shallow depth of measurements on the ambient

treatment, no attempts were made to interpret the resulting data. In FY 1997, both access tubes will be extended 2.5 m in order to better calculate the water balance on the gravel sideslopes.

2.3 Horizontal Measurements of Soil Water Content

In FY 1996, monitoring of soil water content just below the capillary break (2.0 m depth), and under the asphalt pad continued. The layout of the horizontal neutron probe access tubes is shown in Figure 1.4. Unlike FY 1995, the horizontal silt loam measurements (above asphalt) were taken twice per month and were scheduled to coincide with the silt loam vertical neutron probe measurements. The under-asphalt measurements continued on the once per month basis. The results of these activities are summarized below.

2.3.1 Horizontal Silt-Loam Measurements

Figure 2.5 shows an example of the spatial and temporal variation in θ under the irrigated section of the PSB. These data represent $\theta(x,y,t)$ for the period 09/30/94 through August 1996, taken along tubes SW1 and SE1 (Fig. 1.4). The x-axis is time, in days, since the start of neutron probe monitoring on 09/30/94. The y-axis represents horizontal distance from the center of the barrier, with a positive ordinate to the east of center (toward the basalt side slope) and a negative ordinate to the left of center (toward the gravel sideslope).

Over the last 2 yr, water accumulation showed a clearly defined cycle, with θ increasing in the winter to a maximum in late spring and decreasing over the summer. In both years, the greatest accumulation of water occurred under the transition zones (5W, 5E; Fig. 1.4) of the prototype. This was due to infiltration along the sloped interface between the silt and the crushed basalt. Lateral migration of moisture was significant during the spring and winter of the first test year, but not in the second year. The dramatic reduction in the extent of lateral migration and the maximum θ observed is a reflection of the increased ability of the plants to remove water from the profile. At the time of the first extreme precipitation event in March 1996, the surface of the PSB had been seeded for only 5 months and the plants were not well established. Thus their ability to remove water, especially from depth, was limited. Conditions at the time of the second extreme precipitation event (March 1996) were quite different, the plants having been in place for almost 2 yr.

Figure 2.6 shows a plot of the temporal variation in horizontal water content, $\theta(x)$, at the edges and midpoints of the soil covered plots (6W, 6E, 3W, and 3E). These data were obtained from measurements of θ at 7 m (midpoint of the plot) and 14 m (outer edge of the plot). On December 29, 1994, the initial θ was relatively similar, with a mean of 0.10 $m^3\ m^{-3}$ on all plots. Despite regular irrigations, the interface between the silt loam and the sand filter showed no significant increase in θ until just after the first simulated 1000-yr storm on March 26, 1995. By May 31, 1995 when the next set of measurements were made, θ had increased

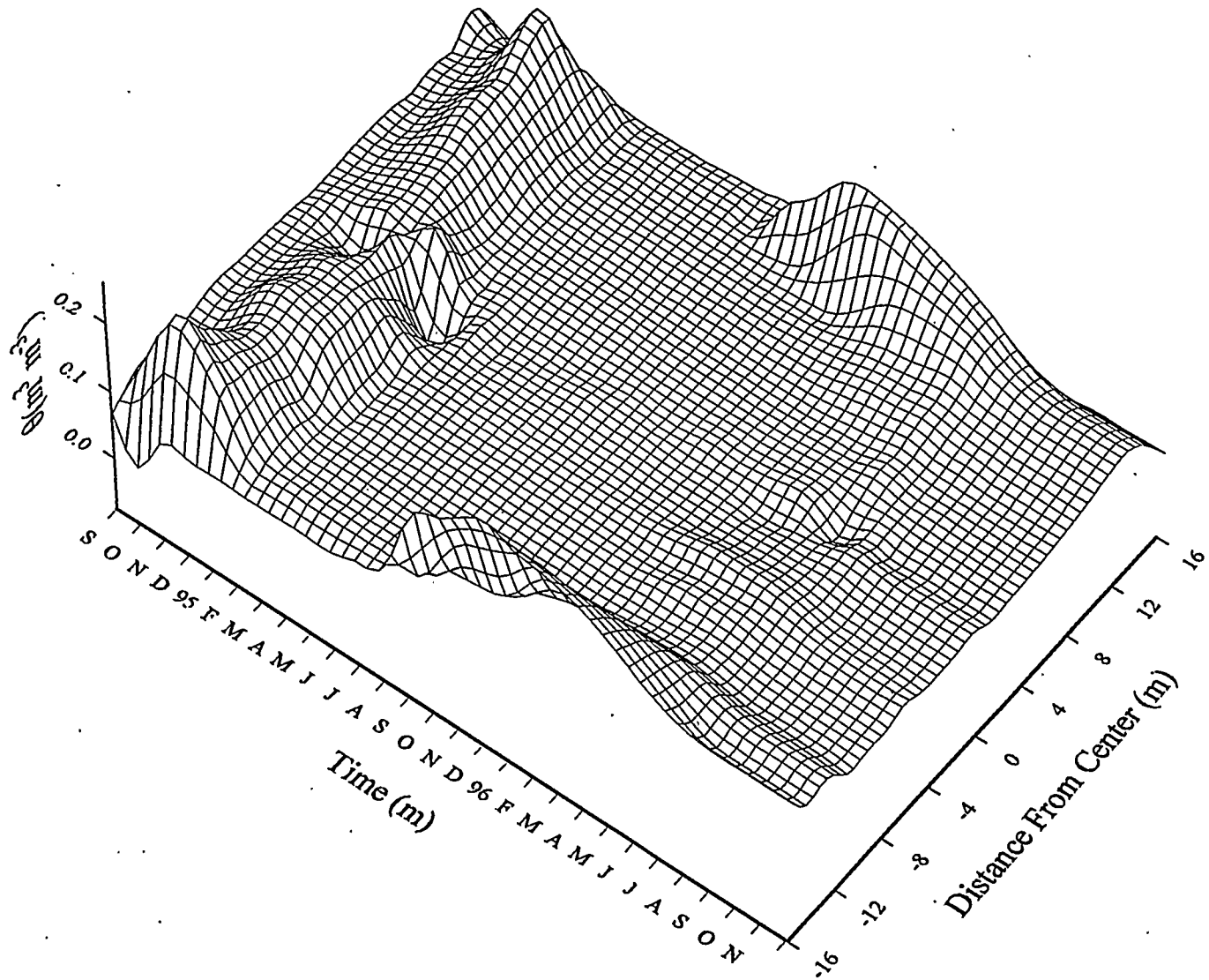

Figure 2.5. Temporal and spatial variations in soil water content at the capillary break of the irrigated treatments. Water contents were measured by neutron probe in the horizontal access tubes.

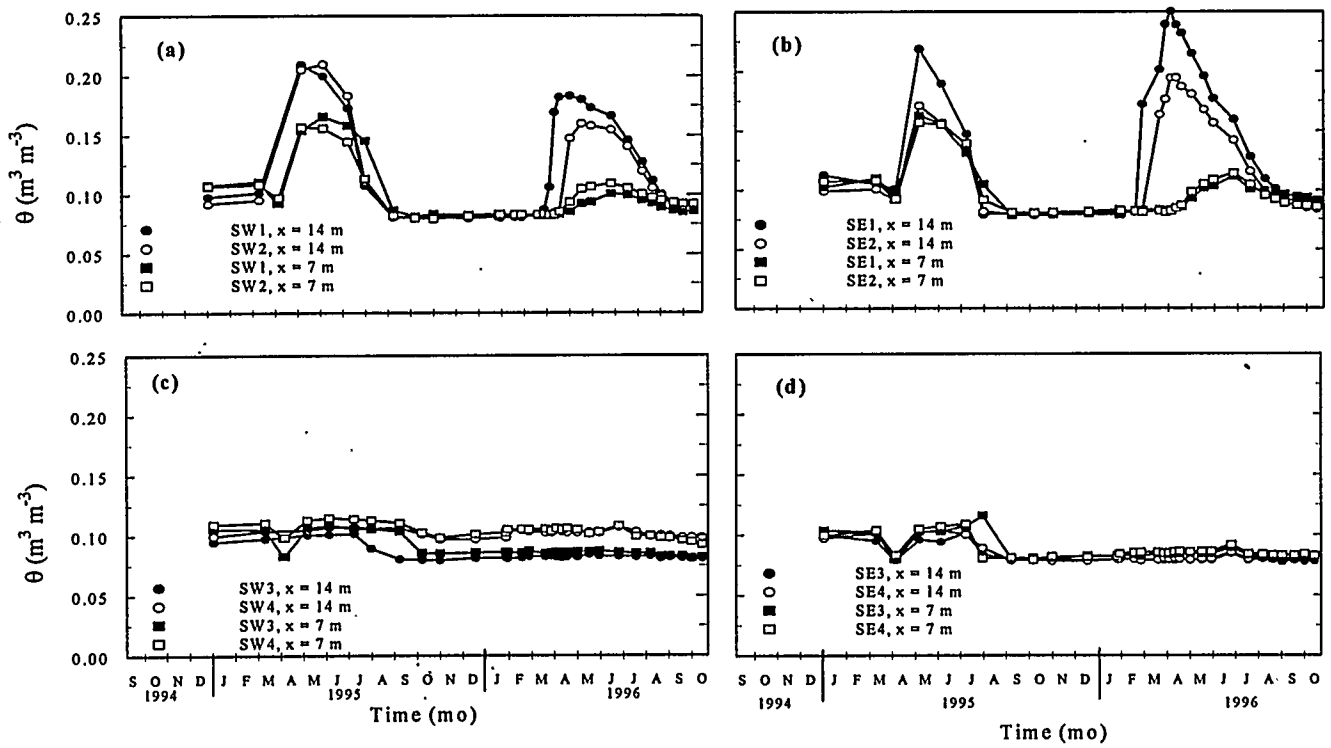

Figure 2.6. Temporal variation in θ at the capillary break under the irrigated treatment (a) Plot 6W, (b) Plot 6E, and under the nonirrigated treatment (c) Plot 3W, (d) Plot 3E. Data presented were taken at 7 and 14 m from the centerline of the barrier.

to 0.22 m^3 m^{-3} at 14 m. Because of an initially irregular monitoring schedule, the exact time of arrival of the wet front is unknown. Within a month of reaching a maximum, θ started to decline on the irrigated treatment, reaching less than 0.10 m^3 m^{-3} by late August 1995. The next significant change in θ occurred in late March 1996, in response to winter precipitation and the second simulated 1000-yr storm of March 26, 1996. The difference in the time of arrival of the wetting front on tubes 1 and 2 of each plot, and between θ on the west (Fig. 2.6a) and east (Fig. 2.6b) plots is likely due to a difference in the accumulation of water and snow during the winter and spring. During the past 2 yr, accumulation during the winter months and after the simulated 1000-yr storm was highest at the NW and NE ends of the irrigated plots (tubes SW1 and SE1).

An increase in θ at the edge of the soil-covered plots (under the transition zones) may raise some concern about failure. However, θ never reached conditions that could have resulted in drainage, and dehydration by ET was quite rapid. Also, the nature of the transition zone is such that drainage occurs toward the edge of the barrier, where it is diverted by the asphalt pad. The trend in θ at 7 m was similar to that at 14 m, only lagged in time. The peak θ was also lower and decreased from 1995 to 1996. This decrease is due to increased ET by the more mature plants in 1996. The first 1000-yr storm event occurred only 4 months after the surface was revegetated. In contrast to the irrigated treatment, θ on the ambient precipitation treatment showed no increase over the last 2 yr (Fig. 2.6c,d). Dehydration of the soil interface started in June-July, 1995 on the eastern side of the treatment (Fig. 5c), and somewhat later on the western side (Fig. 2.6c). Since then θ has remained at between 0.08 and 0.10 m^3 m^{-3} on both plots.

Data collected over the last 2 yr clearly show that the accumulation of water at the base of the silt loam profile can be controlled, even under a irrigated elevated precipitation regime. Under normal precipitation, accumulation of water at the capillary break does not appear to be a source of concern.

2.3.2 Horizontal Below-Asphalt Measurements

In WY 1996, horizontal, under-asphalt measurements of θ(x) continued on a monthly basis. These measurements, along with measurements from the under-asphalt lysimeter, provide data for quantifying the functionality of the asphalt pad as well as any underflow that might occur along the edges.

Figure 2.7 shows a plot of contour plot of θ(x,y,t) at a depth of 1 m below the uncurbed section of the asphalt pad. A positive x-coordinate represents locations to the south of the edge, i.e., under the barrier, while a negative coordinate represents locations to the east of the asphalt edge (i.e., away from the barrier). The time axis show time in days since monitoring started on 12/30/94. At the start of monitoring, water contents at the edge of the asphalt and under the asphalt pad were around 0.10 m^3 m^{-3}. Water content quickly increased to around 0.12 m^3 m^{-3}.

The increase is not surprising, since all water diverted by the asphalt pad is shed to the surrounding soil in the uncurbed region. These data show that, to date, there has been no long-term change in the moisture conditions under the soil-covered plots. The most dramatic changes in θ have been limited to the edge of the asphalt pad, extending to about 1.0 m horizontally under the asphalt pad. This is more apparent in Figure 2.8, which shows a plot of θ versus time at the edge of the asphalt (x = 0) and at a horizontal distance of 1 m

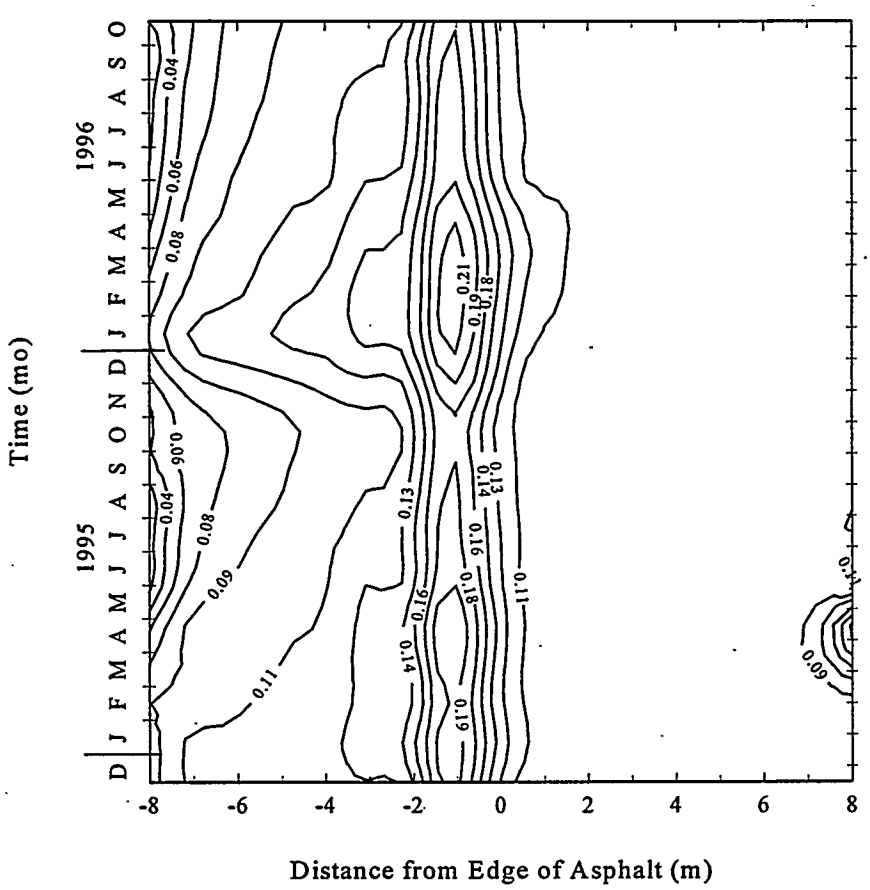

Figure 2.7. Temporal and spatial variation in the under-asphalt water content in uncurbed section of the irrigated treatment.

under the pad. The first increases in moisture along the edge occurred at the end of January 1995 and were also observed at a horizontal distance of 1 m from the edge.

Since the basalt sideslope was not irrigated in WY 1995, the extreme precipitation event had little effect on θ in this region of the barrier. Water content showed a gradual decline until early December 1995. The sharp increase in late December 1995 is due to the 72 mm of natural precipitation and 49 mm of irrigation applied since the start of WY 1996 on November 1. As with the gravel sideslope, the low storage capacity of the basalt sideslope results in rapid responses to irrigation and precipitation. As expected, it took

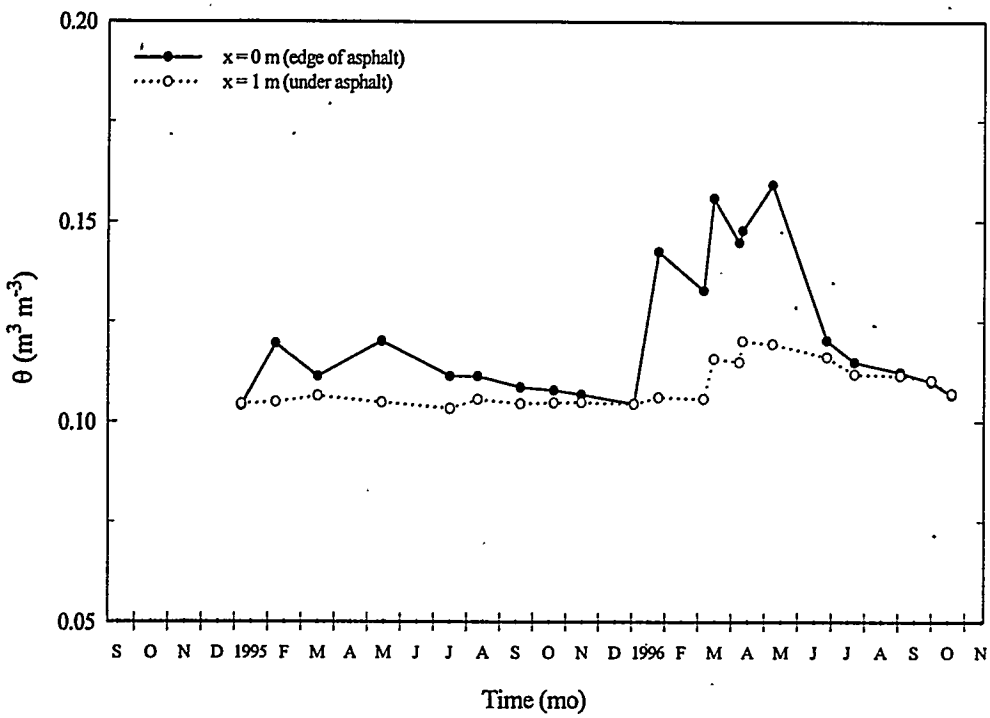

Figure 2.8. Temporal variation in soil water content along the edge and under the uncurbed section of the asphalt pad.

somewhat longer for the drainage water to migrate to the 1-m distance under the asphalt pad. Peak water contents at 1 m were also significantly lower, reaching a maximum of only 0.12 $m^3 m^{-3}$, essentially the same as in WY 1995. By mid June 1996 the soil around the edge of the asphalt had shown significant drying. This has continued through October 1996. Having completed only 2 yr of testing and monitoring, it is too early to make prediction about the long-term tendency for underflow. However, it is clear that the impact of underflow is still limited to around 1.0 m under the barrier. As shown in Figure 2.9, there has been no change in moisture content under the curbed section of the asphalt pad.

2.4 Drainage

Drainage monitoring continued through FY 1996 with hourly measurements in the siphon vaults. Drainage was recorded with a series of instruments, including tipping bucket gauges and pressure transducers. Following the extreme precipitation event in March 1996, the drainage monitoring interval was

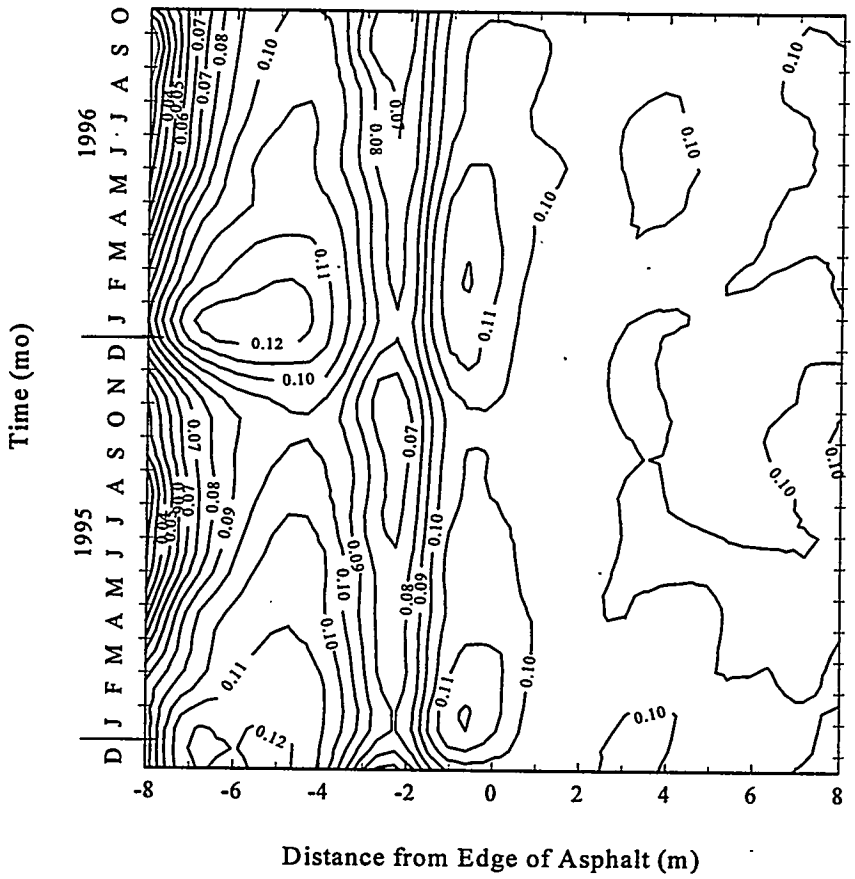

Figure 2.9. Temporal and spatial variation in the under-asphalt water content in the curbed section of the irrigated treatment.

changed from 1 hour to 30 minutes in order to improve the temporal resolution of the measurements. Measurements of evaporation from the vaults continued on a once-monthly basis. This section summarizes the drainage measurements for the past 2 yr of monitoring.

2.4.1 Sideslope Drainage

Intuitively, the amount of drainage from gravel and basalt sideslopes was expected to be high, given the low water storage capacity of the construction materials. However, the absence of a full, experimentally

based understanding of the performance of protective sideslopes for field-scale surface barriers precluded any predictions about the actual magnitude of drainage. An important aspect of this study has therefore been to investigate and document the factors influencing performance of two sideslope configurations at the prototype barrier.

Figure 2.10 shows a plot of monthly drainage from the gravel and basalt sideslopes since March 1995. These data were obtained from pressure transducer measurements of the water level in the vaults. Both sideslope configurations showed a slight increase in the volume of water drained following the start of monitoring in March 1995. During the following spring and summer, both treatments showed a reduction in the amount of water drained, with the basalt drainage decreasing at a higher rate. There was very little drainage from the basalt in the summer of 1995. In early November the trend was reversed, and drainage from the basalt exceeded that from the gravel slope. During the first year of monitoring, the sideslopes were not irrigated. Irrigation commenced in FY 1996, with the first irrigation on 12/03/95. This irrigation event is responsible for the sharp increase in drainage following 9 months of decrease. The basalt sideslope also continued to drain more water than the gravel, draining about 60% more in response to the FY 1996 extreme precipitation event (March 1996). Following this event, the trend in drainage showed another reversal in April, with the basalt starting to drain less water than the gravel. These data suggest a seasonal dependence of sideslope drainage, but one which may be confounded by irrigation.

A better understanding of the effect of sideslope configuration on drainage can be obtained from drainage measurements on the sideslopes in the ambient treatments. These data are also shown in Fig. 2.10. The trend in drainage was identical to that observed on the irrigated sideslopes, with the gravel draining more water than the basalt. The only difference is in the magnitude of drainage. Both configurations showed a reduction in drainage after March 1995, with the basalt showing no drainage beyond May 1995. This absence of drainage continued until November 1995, when the winter precipitation started. The drainage pattern was reversed for a brief period when the basalt drained more water than the gravel (November 1995 through January 1996). Drainage peaked in February 1996, in response to snowmelt and other winter precipitation. Both sideslopes drained similar amounts of water in March 1996, and by April 1996, the gravel was again draining more water than the basalt.

The data shown for the nonirrigated treatment in Fig. 2.10 remove any confounding effect of irrigation and confirm a seasonal dependence of sideslope drainage. This has led to the development of a hypothesis on the mechanisms controlling drainage on protective sideslopes. It is hypothesized that advective airflow is responsible for reducing drainage on the basalt sideslope. Each spring (March, April, May), drainage is relatively high as cool temperatures and relatively high humidity do not provide the most ideal conditions for advective airflow and evaporation from the sideslopes. In the summer months (June, July, August), higher temperatures and lower humidity lead to more ideal conditions and the rate of water loss increases, causing a corresponding decrease in drainage. As the data show, the reduction in drainage is more dramatic on the basalt sideslopes. This is due to the open structure of the sideslope resulting from the loose packing of 25-cm-diameter blocks, as well as the higher thermal gradients. The dark-colored basalt adsorbs more energy and therefore becomes hotter than the gravel. In the fall (September, October, November), lower temperatures again reduce the potential for evaporation and the drainage on the basalt slope increases.

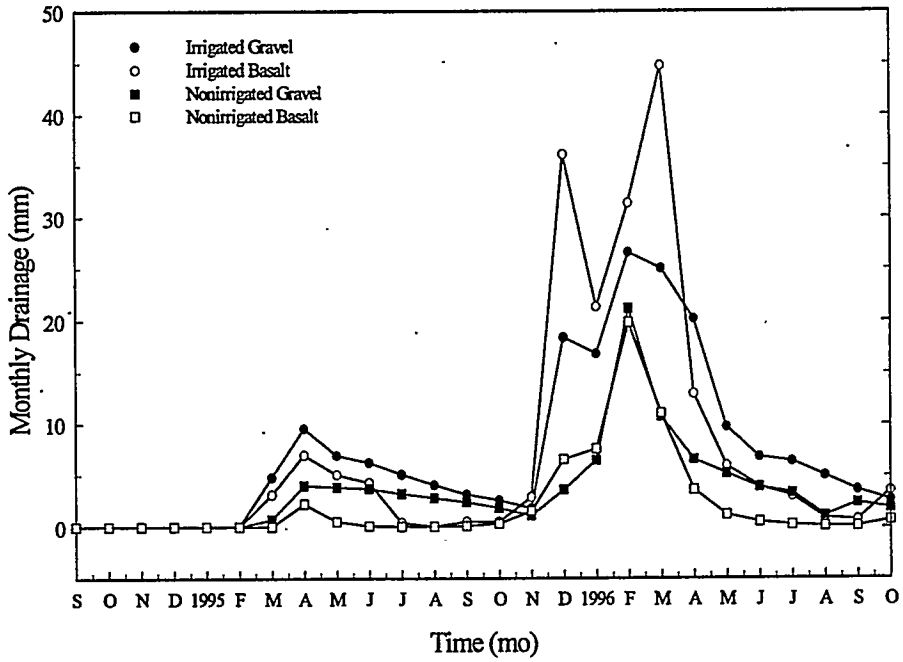

Figure 2.10. Monthly drainage from the gravel and basalt sideslopes at the PSB.

This trend generally continues until the winter months (December, January, February) , when high precipitation and low temperatures cause another reversal in drainage rates.

While these data provide some insight into the mechanisms affecting drainage, equally important to their interpretation is the overall relationship between recharge and precipitation. This relationship is best determined from a comparison of cumulative drainage with natural and enhanced precipitation.

Figure 2.11 compares cumulative drainage from the different precipitation treatments on the two sideslope configurations. In both precipitation treatments, the basalt and gravel show similar rates of drainage until 11/95, after which the rate increased on the basalt. The reason for the change in rates has already been discussed above. By the end of August 1996, the irrigated gravel had drained a total of 183 mm of water, or 24.8 % of the total precipitation received. As mentioned before, irrigation of the sideslopes did not start until 11/95. However, there were times when the sideslopes received unknown quantities of water drained from the irrigation system. The data prior to 11/95 provide another estimate of recharge and, when combined with the rest of the data, suggest a recharge of 26 to 34 % of precipitation on the irrigated gravel sideslope. Despite the seasonal reversals in drainage volumes, the basalt drained a similar amount, some 178.3 mm, or 25.5 % of total precipitation. As with the gravel, a range of recharge was

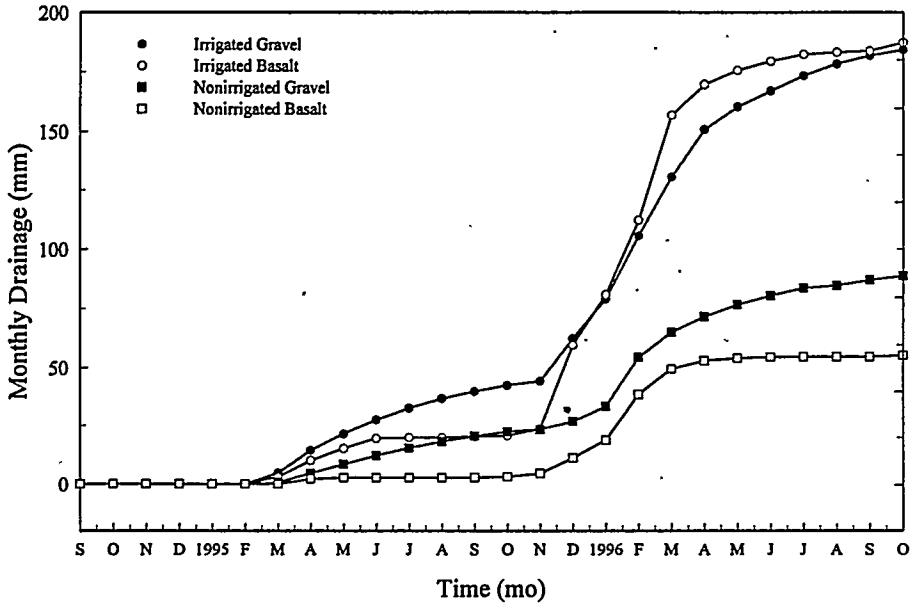

Figure 2.11. Comparison of cumulative drainage from the two sideslope configurations by precipitation treatment.

determined to be 35 to 45 % of precipitation. In contrast, the ambient gravel sideslope drained 15 to 17 % of the total ambient precipitation, while the basalt drained only 7 to 11%.

Over 10 yr of data from the Field Lysimeter Test Facility (FLTF) allow a qualitative comparison of drainage at different scales. It should be recalled that data from the FLTF formed the basis of the design of the PSB (Gee et al. 1993b). Lysimeters are intended to measure a representative sample of one-dimensional (vertical) water balance components and essentially represent point measurements. However, a common usage of lysimeter measurements is to predict or characterize water balance processes at a larger scale. An obvious question therefore is whether an extrapolation of data to larger scales is valid. When compared with drainage data from the FLTF over the same period, the data presented in Figures 2.10 and 2.11 may help to answer this question.

Figure 2.12 shows a plot of cumulative drainage from clean fill gravel and basalt treatments at the FLTF over the period March 1995 through September 1996. The precipitation regime at the FLTF was similar to that at the PSB, with one-half of the treatments receiving only ambient precipitation, and the other half receiving three times the annual average. The comparison, however, can only be qualitative at best because of differences in surface features, vegetation, and particle-size distributions. At the FLTF, there was

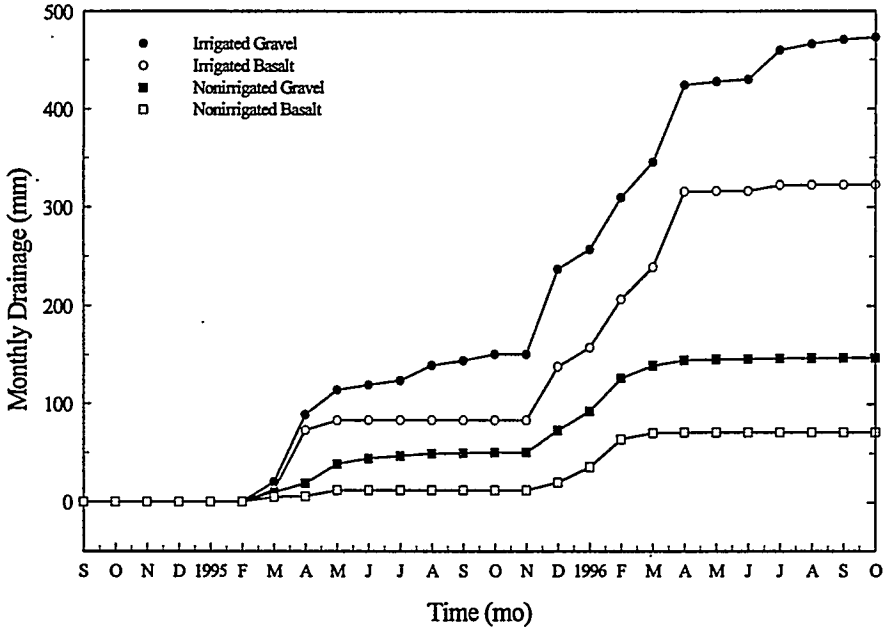

Figure 2.12. Comparison of cumulative drainage from the two sideslope configurations by precipitation treatment.

a modest but actively transpiring stand of cheatgrass on the basalt surfaces. Thus, differences observed between the two sites with the same rock surfaces are a combination of vegetation differences and advective airflow (large-scale effects). At present there is no way to differentiate the contribution of each mechanism. However, in spite of the vegetation at the FLTF, drainage was more than double that observed at the PSB, where no vegetation is present. This suggests that advective airflow is the dominant mechanism in determining drainage on basalt slopes. Similar observations have been made by Rose and Guo (1995).

The comparison is less well defined for the gravel surfaces. There are two sets of gravel surfaces at the FLTF, the prototype barrier gravel materials and washed gravel surfaces (clear-tube lysimeters). The washed gravel should represent the maximum drainage conditions expected for gravel surfaces since they are devoid of vegetation and have little or no silt. Five years of data suggest that drainage is consistently higher from the washed gravel than from any other surfaces monitored at the FLTF. In contrast, the surface of the less well sorted gravel from the PSB was covered with vegetative litter and there is a sparse but finite amount of vegetative cover. There is significantly less drainage from these two lysimeters than from washed gravel. Comparisons between the irrigated and ambient PSB gravel and washed gravel show differences which could

be attributed to differences in particle-size distribution, compounded by differences in vegetative cover (sparse vs. none).

The gravel slopes at the PSB are similar to the FLTF gravel lysimeters in that they had a very sparse vegetative cover. Any differences between the FLTF gravel and the PSB gravel slope are likely due primarily to slope, but there could be a subtle contribution from differences in transpiration from sparse vegetation. The FLTF and PSB data are compared in Table 2.1.

The following generalizations show that the surfaces we have tested can drain from 10 to 70% of the annual precipitation. The wide range in drainage is attributed to physical and biological alterations of the surface. Based on these data, the following general conclusions can be drawn: (1) Clean gravel with zero slope will likely produce the most drainage. Dirty gravel and/or gravel with sparse vegetation will produce less drainage than clean gravel. (2) Rock surfaces will produce less drainage annually than gravel surfaces because of greater advection potential in hot, dry summers. (3) Vegetation complicates the observations. Sparse amounts of vegetation appear to reduce annual drainage rates for both rock and gravel surfaces in all tests conducted to date.

Table 2.1 A comparison of the relationship between recharge and precipitation based on measurements at the FLTF and PSB.

Surface Type	Vegetation Treatment	% Slope	Precipitation Treatment	Recharge as % of precipitation	Site
Gravel	Bare	0	3X	60-70	FLTF
Gravel	Bare	0	1X	40-50	FLTF
Gravel	Vegetated	0	1X	25-35	FLTF
Gravel	Vegetated	0	3X	50-60	FLTF
Gravel	Vegetated	10	1X	15-17	PSB
Gravel	Vegetated	10	3X	25-34	PSB
Basalt	Bare	0	1X	No Data	FLTF
Basalt	Bare	0	3X	No Data	FLTF
Basalt	Bare	50	1X	7-11	PSB
Basalt	Bare	50	3X	25-40	PSB
Basalt	Vegetated	0	1X	15-20	FLTF
Basalt	Vegetated	0	3X	35-45	FLTF

2.4.2 Silt-Loam Drainage

The silt loam cover of the PSB was designed with a storage capacity of 600 mm, more than three times the long-term average precipitation for the Hanford Site. In reality, the storage capacity could be at least 20% higher due to the presence of the capillary break at the 2-m depth. The silt loam surface is also covered with native species of vegetation. In FY 1995, even when the plant cover was not well developed, plants were able to remove in excess of 600 mm of water from the soil plots. At no time did water storage approach the design capacity. Since a precursor for drainage from the silt loam profile is a level of storage in excess of the storage capacity, little drainage (≤ 0.5 mm yr^{-1}) is expected from the soil-covered plots. To date there has been no drainage from the silt loam plots. However, monthly measurements of water levels in the siphon vaults connected to the soil-covered plots have provided some insight into the error in drainage measurements. The rate of evaporation from the siphon vaults was used to calculate the error in the drainage measurements. These data are discussed in the following section.

2.4.3 The Error in Drainage Measurements

With a drainage criteria of ≤ 0.5 mm yr^{-1}, the precision with which drainage can be measured by the drainage monitoring system is critical to the correct evaluation of the water balance. During FY 1995, an incomplete set of evaporation data obtained from the siphon vaults suggested that evaporation could influence the reliability of drainage measurements. During FY 1996, estimates of evaporation rates (E) were calculated using pressure transducer measurements of water level, manual steel-tape measurements, and evaporometer measurements. Steel-tape measurements of water levels were made on a monthly basis from a fixed reference point at the top of each siphon vault. Evaporometer measurements were also taken on a monthly basis. Continuous pressure transducer measurements of the water level in the vault were recorded on an hourly basis. Water-level data collected during the period 02/95 through 08/96 were used to calculate water loss, with any loss of water being attributed to evaporation from the vault.

Figure 2.13 shows a plot of cumulative water loss from the vaults connected to the silt loam treatments (6W, 3W, 3E, and 6E) for the period 03/95 through 08/96. There is no apparent correlation between vault location and the rate of water loss. However, these data show a seasonal dependence of the rate of water loss, with the rate decreasing in the winter months. In fact, both evaporometer and pressure transducer data showed small but measurable increases in water levels during the winter months.

Table 2.2 compares the calculated evaporation rates obtained from the three types of measurements. These results show that evaporation from the closed vaults is non-zero and cannot be neglected in calculating the drainage component of the water balance evaluation. Evaporation estimated from steel tape and pressure transducer measurements is quite similar with rates of 0.26 ± 0.06 mm yr^{-1} and 0.27 ± 0.06 mm yr^{-1}, respectively. This can be expected since both techniques measure the actual height of water in the vault. However, the rate estimated from evaporometer measurements is only 0.07 ± 0.06 mm yr^{-1}, or about 25% of these rates. The disparity in calculated evaporation rates is somewhat surprising and may be due to a combination of factors.

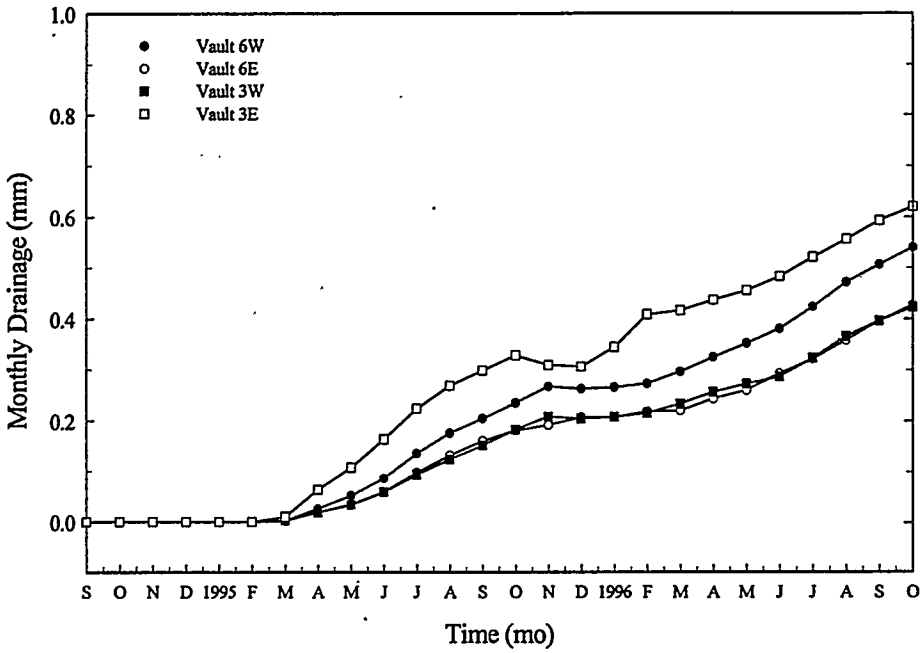

Figure 2.13. Cumulative water loss from silt loam siphon vaults.

The first factor is related to the design of the evaporometer. The evaporometer consists of a small graduated cylinder, with an internal diameter of 22.2 mm, mounted close to the top of the siphon vault. It is likely that the rate of evaporation from the relatively small surface area (386.2 mm^2) could become limited and not truly reflect evaporation from the much larger water surface (0.64 m^2) in the vault. Furthermore, as the level of water in the evaporometer dropped, further evaporation could be limited by the rate of diffusion of water vapor out of the evaporometer. A final factor that could contribute to the disparity in evaporation rates is the loss of water through the walls of the vault. The vaults are constructed of precast concrete with a fluid asphalt coating on the inside. The permeability of the vaults, while probably very low, may not be zero. Thus, the evaporation rates determined from water-level measurements probably include contributions from leakage and actual evaporation. The difference between the evaporometer and water-level measurements suggests that the mean permeability of the walls of the concrete vault is between 4.4×10^{-10} and 8.24×10^{-10} cm s^{-1}.

While it may be possible to reduce the error in evaporometer measurements by refilling the tubes on a monthly basis, differentiating between the contribution of evaporation and vault leakage will be more

difficult and is probably unnecessary. The present results show that water loss from the vaults can be accurately measured. These data represent the upper and lower bounds of water loss from the vaults. It is important to note that the mean rate of water loss is significantly less than the drainage criterion of 0.5 mm yr^{-1} and therefore should not jeopardize the reliability of drainage data and water balance evaluations at the PSB.

Table 2.2. Comparison of three measures of evaporation rates from the silt-loam siphon vaults

Measurement	6 WEST		3 WEST		3 EAST		6 EAST	
	ΔH (mm)	E (mm/yr)	ΔH (mm)	E (mm/yr)	ΔH (mm)	E (mm/yr)	ΔH (mm)	E (mm/yr)
Steel Tape†	139.7	0.31	106.9	0.22	153.55	0.32	120.65	0.19
Transducer†	142.0	0.32	111.3	0.23	153.43	0.32	121.57	0.19
Evaporometer‡	28.7	0.07	35.7	0.08	23.82	0.06	29.78	0.05

†ΔH measured between 03/09/95 and 08/29/96.
‡ΔH measured between 05/15/95 and 08/29/96.

2.5 Evapotranspiration

Evapotranspiration (ET) plays an important role in the successful performance of arid site capillary barriers. There are several techniques that can be used to determine ET at the field scale. Measurements at the Hanford Site are based on a water balance approach (Eq. [1]) and are unique in that drainage is measured with very high accuracy, thereby allowing accurate estimation of ET. Based on the results of the FY 1995 monitoring season, it was concluded that the native species of vegetation at the PSB could remove in excess of 600 mm of water in less than 12 months (Gee et al. 1995). In FY 1995, after the PSB had been revegetated for only 10 months, plants removed 615 mm from the irrigated plots and 416 mm from the ambient plots. Even after such a short period of development, the plants removed water to the same lower limit, independent of precipitation treatment. Water storage was depleted to 120 mm on the irrigated treatment and 110 mm on the nonirrigated treatment.

Data collected during FY 1996 were used to calculate ET for the two precipitation treatments at the PSB. Data for the past 2 yr of monitoring are summarized in Figure 2.14, in the form of cumulative ET. The rate of evapotranspiration was relatively low during the first 3 mo of monitoring. As the plants matured, rate of ET increased from less than 1 mm d^{-1} in January 1995 to over 2 mm d^{-1} on the irrigated and 1 mm d^{-1} on the nonirrigated treatments by early March. A dramatic increase occurred in late March, with ET increasing to about 3.2 mm d^{-1} on the irrigated treatment and 1.6 mm d^{-1} on the nonirrigated treatment. The increase in rate on the nonirrigated treatment suggests the influence of factors other than precipitation.

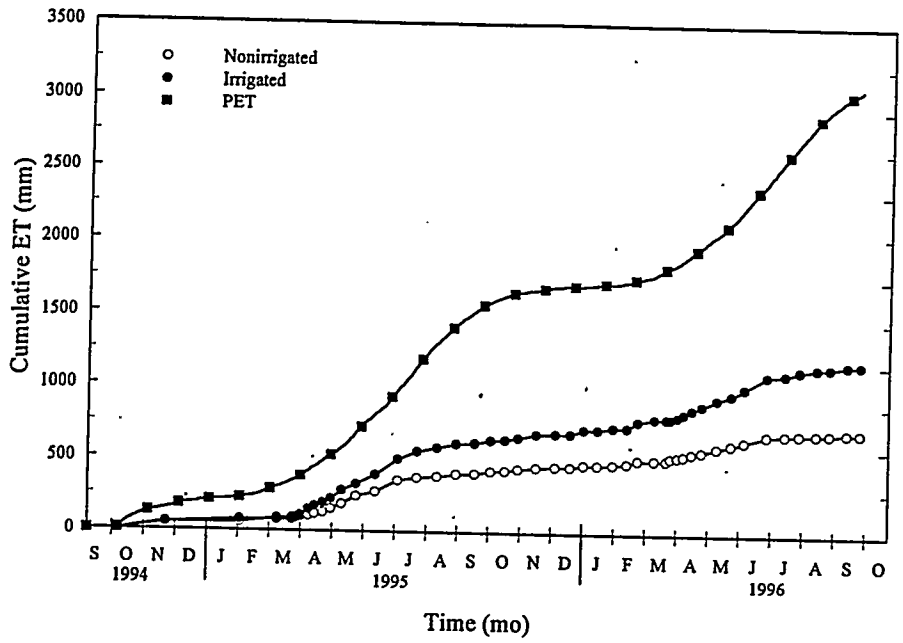

Figure 2.14. A comparison of cumulative PET with ET from the irrigated and nonirrigated treatments.

The increased rate was probably due to increasing maturity of the plants as well as climatic and soil conditions more conducive to evapotranspiration. The rate of ET continued unabated until early August 1995, when it dropped to 1.5 mm d^{-1} on the irrigated treatment and 0.6 mm d^{-1} on the nonirrigated treatment. The rate again increased in early April 1996, to 2.8 mm d^{-1} on the irrigated treatment and 1.5 mm d^{-1} on the ambient treatment. By the end of October 1996, the rate had again decreased to 2 mm d^{-1} on the irrigated and 0.8 mm d^{-1} on the nonirrigated treatments. Apart from the obvious seasonal cycling in ET rate, these data show that both the irrigated and ambient treatments respond similarly with respect to rate changes. Rate changes occurred at essentially the same time and were of a similar magnitude.

Over the last 2 yr, potential evapotranspiration (PET) was also calculated from climatological data using the Penman equation. The results are also shown in Fig. 2.14. Calculated PET was significantly higher than observed ET throughout the period of monitoring, although changes in rate occurred at essentially the same time of year. The discrepancy between ET and PET is dependent on the soil-plant-atmosphere continuum. When soil or plant surfaces are dry, as is the case much of the time at the PSB, they are unable to lose water to the atmosphere at the potential rate of evaporation. Similarly, when they are wet, ET can exceed PET even when climatological conditions predict low rates. These results suggest that PET (computed from

climatological data alone) is virtually useless in predicting actual ET and drainage at the Hanford Site and emphasizes the need for accurate measurement of the water balance components.

In WY 1995, the irrigated treatments at the PSB received 488.4 mm of water, and plants removed 134% (654.2 mm). On the ambient treatments, plants removed 153% (440.7 mm) after receiving 288 mm of precipitation. In WY 1996, plants had removed 110% (542 mm) after receiving 493 mm of precipitation. Meanwhile, plants on the ambient treatments removed 121% (283 mm) after receiving 233 mm. Thus, both treatments show a decrease in the efficiency of water loss, with the larger change occurring on the irrigated treatments. The observed reduction in the efficiency of water removal may be partly related to the change in the plant population at the PSB. In WY 1996, there were no tumbleweed plants at the PSB, compared to WY 1995 when there was a healthy stand. Although the other plants are now more mature and can transpire more water, the reduction in rate of water removal suggest that tumbleweed might have had a significant impact on the water balance. However, the fact that the irrigated treatment showed a greater reduction in the rate of water removal, while receiving slightly more water, may suggest a susceptibility of shrubs to very high levels of precipitation. In contrast, the ambient treatments received less water than in WY 1995 and the reduced efficiency suggests that water is indeed a limiting factor. It appears that the native shrub species can handle elevated precipitation, but there is a presently unknown upper limit. By the conclusion of the final year of testing, the upper limit should be more clearly defined. This behavior should not impact the long-term performance of final covers since climatic records show that the probability of ambient precipitation exceeding 160 mm yr^{-1} for an extended period of time is quite small.

2.6 Summary

The second of three planned years of testing and monitoring for Water Balance Evaluation at the prototype Hanford barrier has been completed. This study is aimed at demonstrating the effectiveness of the barrier in controlling infiltration to underlying wastes.

By the end of October 1996, the irrigated treatments had received a total of 493 mm, compared with 488 mm at the end of WY 1995. The ambient treatments had received 233 mm compared to the 287 mm at the end of August 1995. During WY 1996, water stored in the silt loam profile reached a high of 415 mm following the extreme precipitation event on the irrigated treatment. This was slightly lower than the maximum of 439 mm observed in WY 1995. On the nonirrigated treatments, water storage again peaked in late February, reaching 259 mm compared to 325 mm in WY 1995. The smaller amounts of storage are due to increased plant activity. As in WY 1995, storage showed a rapid decline after the extreme precipitation event. By the end of October 1996, mean storage had been reduced to 128 mm on the irrigated treatment and 102 mm on the nonirrigated treatment. These values are similar to the 123 mm and 110 mm observed in WY 1995 on the irrigated and nonirrigated treatments. Water storage showed no increase beyond March 1995 and 1996. Compared to WY 1995, the rate of change of storage before the extreme precipitation event decreased on both treatments but remained unchanged in the period after the event. The seasonal cycle in storage observed last year has been repeated.

Horizontal measurements of water contents at the 2-m depth in the silt loam, and under the asphalt pad, show a seasonal cycling similar to that observed in the silt loam profile. At the 2-m depth, water content changes were greatest along the edges of the barrier, in the transition zones. In WY 1995, there was an increase in moisture inward from these zones, but this was not true in FY 1996. The under-asphalt measurements showed the greatest increases along the edge of the pad, and up to 1 m inward from the edges. However, water content never exceeded 0.16 $m^3 m^{-3}$.

To date, there has been no drainage from the silt loam plots. In contrast, the two sideslope configurations continue to drain, although at different rates and in different amounts. Data collected thus far suggest that clean gravel with basalt sideslopes will produce less drainage annually than gravel surfaces because of greater advection potential in hot, dry summers. There is a small but measurable error in the drainage measurements, equal to about 0.2 mm yr^{-1}.

Water balance evaluation shows that the rate of water loss by evapotranspiration is dependent on season as well as available water. Evapotranspiration rates measured prior to the extreme precipitation event on the irrigated plots decreased in WY 1996 relative to WY 1995. However, they remained unchanged in the period after the extreme event. By the end of October 1995, plants on the irrigated treatments had transpired 110% of the precipitation received, compared to 134% at the same time last year. On the nonirrigated treatments, plants had removed 121% of total precipitation, compared to 153% last year. The reduced efficiency on the irrigated treatments suggests a susceptibility of shrubs to very high levels of precipitation. It appears that the native shrub species can handle elevated precipitation, but there is a presently unknown upper limit.

3.0 WATER EROSION

3.1 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. 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 increase, 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).

3.2 Controlled Area Testing

3.2.1 Permanent Test Plot

3.2.1.1 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 area was used to provide baseline information under natural climatic conditions. Results of the first year of monitoring indicated that no runoff was experienced, so this plot was abandoned; a similar one was constructed in the irrigated portion (north half) of the barrier. An extreme rainfall event was monitored the first year using a similar temporary test strip on the irrigated portion of the barrier. Monitoring of an extreme rainfall event was conducted over a second year with the permanent, 6-m-wide x 15-m-long flume in the 3X precipitation portion. Soil properties were monitored and recorded throughout the year as part of the effort to document the changes to the barrier surface.

3.2.1.2 Methods

Construction and instrumentation of the test plot was described in Gee et al. (1994). The second controlled area was constructed in the same manner and used the equipment from the original test plot. This plot was in the northwest quadrant of the barrier surface. Information from the dataloggers and sampling equipment was collected on a monthly basis and after every rainstorm event.

3.2.1.3 Results

There was no measurable runoff from the permanent test plot, this is not unexpected with the conditions of the northern half of the barrier surface. These conditions (vegetation coverage of 85 to 95 %, low moisture content, and no long-duration/high-intensity rainfall) were found during testing of the McGee Ranch erosion 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 having vegetation and antecedent moisture content of 1.6 and 5.6 %, respectively, had runoff of approximately 1 % for a rainstorm with an intensity of 64 mm/hr and 1 hour duration. The rainstorms that occurred at the barrier location throughout the year were generally less than 15 mm/day. Tables 3.1 and 3.2 summarize the precipitation that occurred at the barrier from January 1995 through August 1996. The records from October 1995 to the present were made after moving the rain gauge from the south half of the barrier to the north portion. Thus, the reported amounts incorporate the amount of applied irrigation in addition to the natural precipitation to the northern section. The total rainfall recorded for March 27, 1996 is the amount applied during the extreme rainfall testing.

3.2.2 Extreme Rainfall Testing

3.2.2.1 Objective

The relocation of the permanent controlled area test plot to the north portion of the barrier allowed automatic recording of the second-year extreme rainfall testing. The objectives and goals of this test were the same as in the previous year: 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-yr storm. Comparison of the first and second year extreme rainfall events was also planned. Although this testing did not simulate a natural rainfall event, it was thought that it could provide some significant insight into the expected performance of the barrier by comparison with the results of previous erosion tests (Gilmore and Walters 1993).

3.2.2.2 Methods

The first-year test incorporated 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 in the northwest quadrant of the testing and

monitoring area located on the barrier. The plot was constructed with typical plastic lawn edging around the perimeter. This allowed for minimal disturbance of the surface and aided in removal of the 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-liter sample bottles. Samples of runoff and sediment yield data were collected manually during the test from a pit dug at the south end of the collection flume. Rain gauges placed every 3 m along the north side of the test plot were read after every series of passes of the rainfall applicator. One additional gauge, placed outside of and at the longitudinal center of the plot, was used to collect the total amount of rainfall for the test.

Table 3.1. 1995 Precipitation on the Barrier Surface

1995 Rainfall on the Barrier Surface (mm)												
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
01		2.29										
02						0.51	0.25			1.78		6.60
03										5.59		15.75
04						2.54						
05												
06						5.08			8.13		1.27	
07		7.37		0.25	1.52		0.51		2.03		3.81	
08			1.52				0.76					
09		0.25	7.87		3.05		0.76					
10			3.81	1.02	0.76			1.02		1.52		
11		4.83			0.51					5.08	4.32	
12		0.25		8.38							0.76	2.54
13				1.02	0.51						3:30	
14			2.79	0.76		1.27						0.25
15						0.25		0.25				3.30
16						0.51						0.25
17						0.76				3.56	0.25	
18		0.51	0.25									
19				0.51		3.30						11.18
20			1.02	2.03								
21											0.25	
22												7.62
23			0.25								2.79	
24				0.25							1.02	
25										0.51		
26							0.51					
27				7.11					2.29		4.32	
28				9.40					0.25		8.38	
29								0.51				
30									0.25			6.35
31	0.76											2.79
Total	0.76	15.46	17.5	30.69	6.32	14.2	2.77	1.76	12.93	18	30.44	56.61

Table 3.2. 1996 Precipitation on the Barrier Surface

1996 Rainfall on the Barrier Surface (mm)												
Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
01	0.76		4.32	3.56							NR	NR
02								0.25			NR	NR
03					0.51	0.51				NR	NR	NR
04			6.10							NR	NR	NR
05			0.76							NR	NR	NR
06	0.25	0.25				13.46				NR	NR	NR
07	3.81	5.84	1.78		1.27					NR	NR	NR
08	0.25	0.51			14.99					NR	NR	NR
09	1.52									NR	NR	NR
10			0.25							NR	NR	NR
11										NR	NR	NR
12	0.25				3.05					NR	NR	NR
13										NR	NR	NR
14		10.67			0.25				11.68	NR	NR	NR
15	0.51				0.76				1.52	NR	NR	NR
16				0.25					0.25	NR	NR	NR
17	10.67	9.91			3.05		3.81			NR	NR	NR
18		1.27								NR	NR	NR
19	0.25							6.35		NR	NR	NR
20		1.02								NR	NR	NR
21		0.25			4.83					NR	NR	NR
22	0.25		3.56	4.32						NR	NR	NR
23				0.25		0.76				NR	NR	NR
24	0.25	2.03								NR	NR	NR
25		3.30								NR	NR	NR
26			59.18			20.57				NR	NR	NR
27										NR	NR	NR
28										NR	NR	NR
29					1.27					NR	NR	NR
30										NR	NR	NR
31			5.59							NR		NR
Total	18.75	35.01	81.49	8.36	29.93	35.29	3.81	6.6	13.45			

The second-year test was done with the permanent, 6.1-m-wide x 15.24-m-long flume constructed in the same area as the temporary test plot. This controlled-area flume was constructed in the same way as the first flume (Gee et al. 1994).

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 of the test area, with the sprinklers covering an area approximately 3 to 4 m wide. Each "trip" of the irrigation system comprised full travel along the test area and 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 and 17 minutes; consequently, there was a significant amount of time during the test when there was no application of rainfall on 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.

3.2.2.3 Results

There was no measurable runoff from the controlled-area test plot during the second monitoring year's extreme rainfall event. Localized surface ponding and detention were observed on the barrier surface, but no sheet flow. Near-surface antecedent moisture conditions were low (4% to 6%), with significantly more vegetation than the previous year. This condition, as previously noted, indicates that there will be little, if any, runoff from the surface.

3.3 Soil-Surface Monitoring

3.3.1 Objective

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.

3.3.2 Methods

Monitoring was conducted on a seasonal basis. 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 recorded at that time. Additional surface elevation surveys were conducted in July 1995, January 1996, and August 1996. Creep gauges were installed at 11 locations on the rock slope side, and location and elevation information was collected at the same time as the surface elevation data. With two differential settlement gauges located on the barrier gauge elevations were recorded and monitored at the same time as the other survey work. Soil properties were collected in December 1994, May 1995, and August 1996.

Survey data were collected at the location of each stake of the grid system by the use of EDM survey equipment. Vertical control was provided by the use of the four permanent survey monuments that were 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 most recent survey were also plotted with the same software.

The soil property data were collected at the approximate center of each grid cell with the use of a Troxler nuclear density gauge. The Troxler gauge provides data on moisture content and wet and dry densities. These data are indicative of near-surface conditions (<20 cm) only and do not provide information for the full soil column of the barrier. Alternative data collection techniques could be performed with the Troxler gauge to provide soil property information for depths up to 1 m if the need should arise. 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.

3.4 Elevation

3.4.1 Results

Figures 3.1 and 3.2 are topographic contour maps of the barrier surface evolution from December 1994 through September 1996. The December map was generated with the elevation data prior to the introduction of any plants on the barrier surface. The August 1995 map shows 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, there is a small overall gain in elevation apparent over the full surface from December to August.

Figure 3.3 is a surface map of the elevation changes of the barrier surface between December 1994 and August 1996. There are a number of small areas where local surface elevation changes can be seen by comparing the maps for the two periods. The lightly shaded areas are zones of small losses in elevation, and the darker shaded areas are zones of elevation gains. The area 60 m north and 5 m east is where the temporary test plot collection pit was located. When this pit was excavated, the soil was piled to the northwest; after the test, the soil was replaced in the collection pit. The elevation 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 7.5 cm and 12 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, depositing soil eroded and transported during water application. The two other areas with significant changes are in the southeast corner of the barrier, which shows a decrease in elevation of approximately 7 cm; the cause of this change has not been determined. The creep gauge nearby does not indicate any mass movement of the sideslope, and there are no other visible causes. Settlement in this area has been continuous throughout the life of the barrier and will be watched in the future.

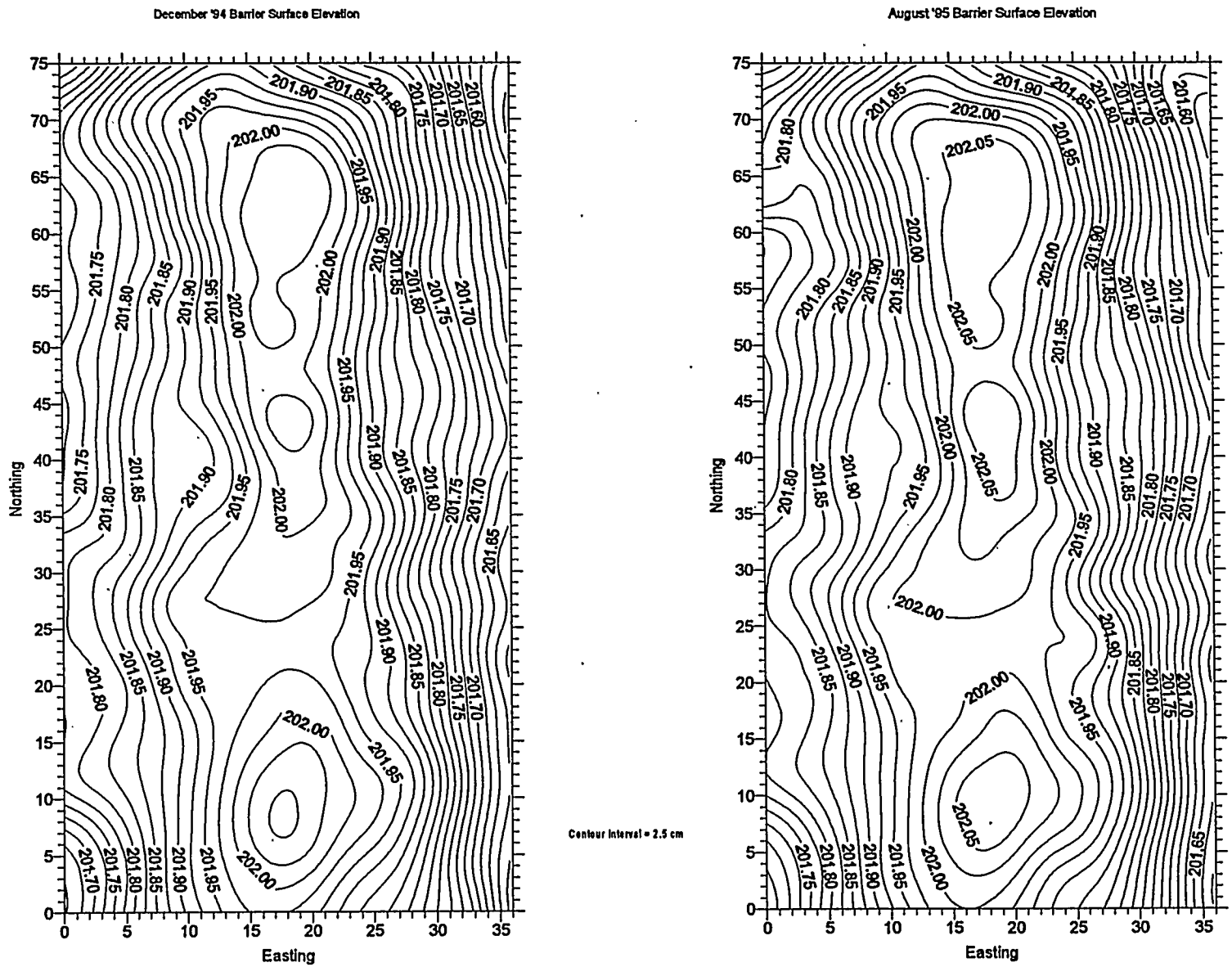

Figure 3.1 Barrier Surface Elevation Contours

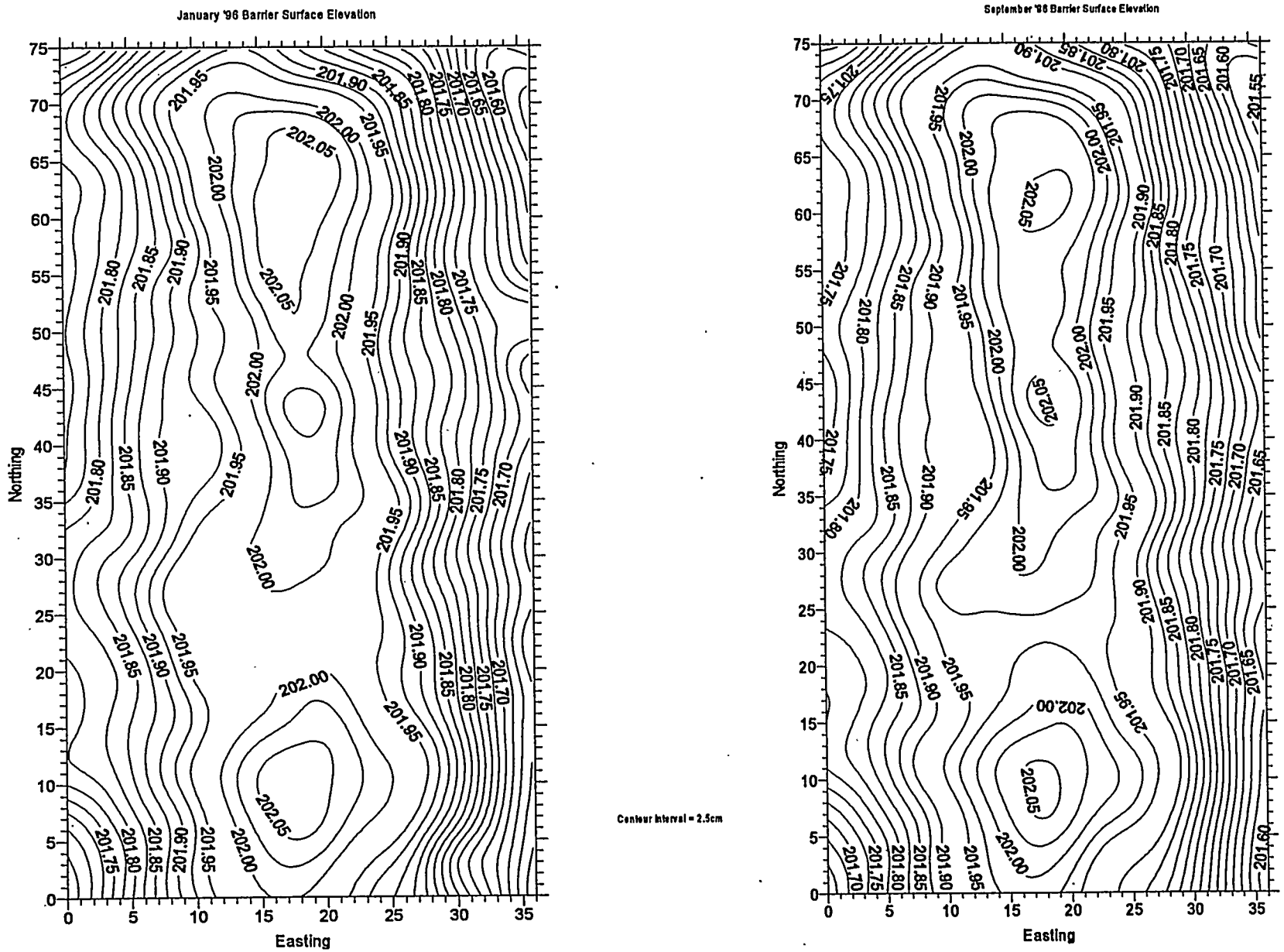

Figure 3.2 Barrier Surface Elevation Contours

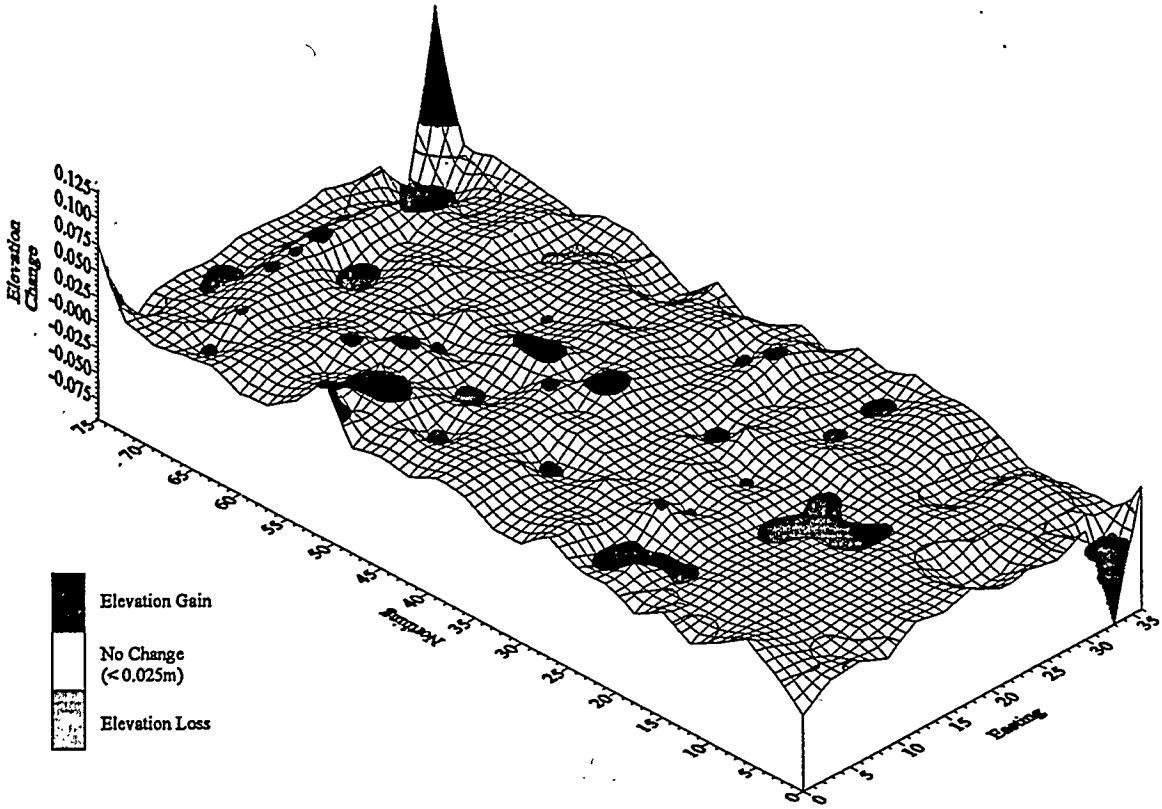

Figure 3.3 Surface Elevation Changes from December 1994 to September 1996

3.4.2 Creep and Settlement Gauges

Results of the creep gauge monitoring (Figure 3.4) indicate that all of the gauges experienced small changes in location and elevations. The directions of gauge movement (bearing) indicate that the preferred orientation of the changes is to the northwest. This movement would be expected for a sideslope failure with the lower layers slipping down and out. However, the small amount of change (< 2.5 cm) and a visual inspection of the sideslopes do not indicate any mass movement. The movement is most likely the result of the sideslope settling into a more stable and compact arrangement. This area will be closely scrutinized in the future.

The settlement gauges that were emplaced on the top of the asphalt pad were also surveyed. The results of the survey show that both have been elevation 11 mm from the initial measurements. This elevation change, which has remained constant for the past year is not understood at this time.

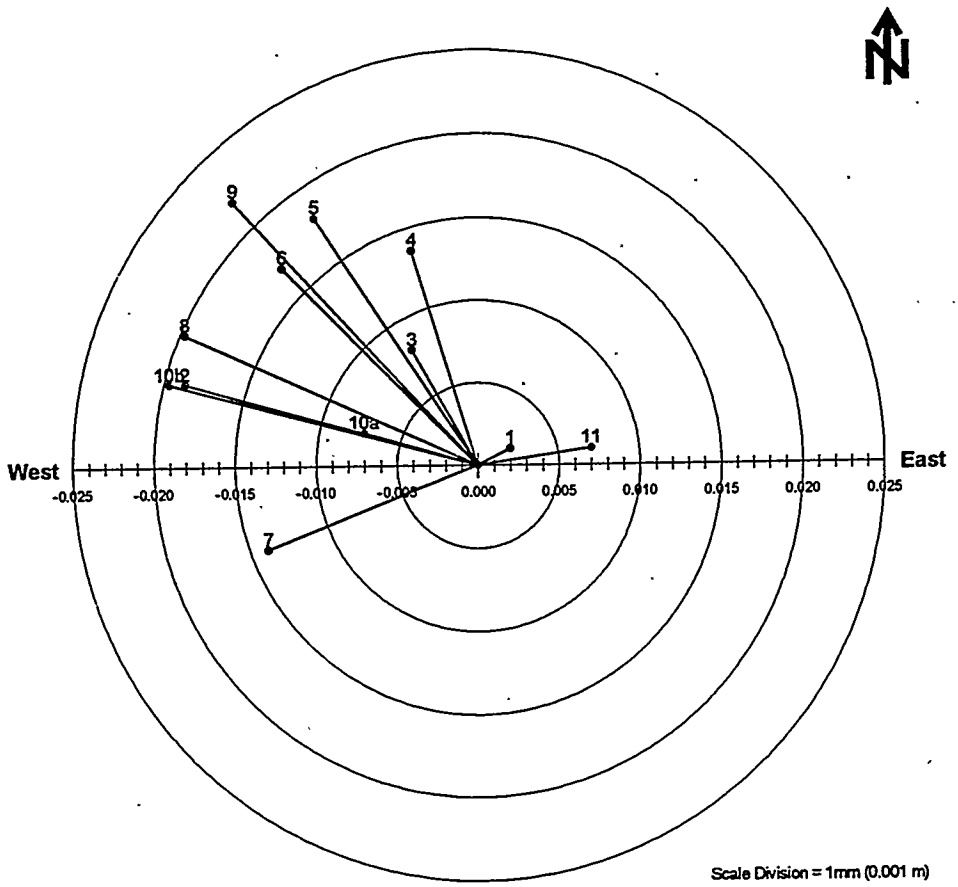

Figure 3.4 Creep gauge movement, December 1994 to September 1996

3.5 Soil Properties

3.5.1 Soil Moisture

Figures 3.5a through 3.5c are maps of the moisture contents over the past 2 yrs, showing the seasonal variations. As Figure 3.5a shows, the moisture content of the barrier surface in December 1994, after initial construction and prior to any irrigation or vegetation, was very uniform. The single high moisture point 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 was the result of recent snowfalls that melted before the soil properties data were recorded. Figure 3.5b shows the effects of applying of additional water on the north half of the barrier. The southern half has not received any additional water application, and the moisture content reflects the differences between the two halves. Also, the northeast corner has the highest water content on the barrier surface. This area is consistent with observations of water ponding in the area during the application additional water and the localized increase in elevation from December 1994 to August 1996. The southeast corner, which has the lowest water content on the barrier, is consistent with the increase in density and decrease of elevation in this area. The August

moisture content (Figure 3.5c) is extremely low, with a variation of only 0.5 %. The north half of the barrier has a near surface moisture content of 1.5 %, and the south half has a moisture content of 1.0 %. The difference is most likely the result of interference and noise from the greater amount of vegetation on the north half, rather than any real difference in moisture content. The August moisture content also shows the effects of evapotranspiration on the overall water balance.

3.5.2 Density

Figures 3.6a through 3.6c are maps of the dry densities over the past 2 yrs showing the seasonal variations. The densities of the barrier surface in December 1994 and August 1996 were fairly uniform, with an average value of 1857 kg/m^3 and 1874 kg/m^3, respectively. Figure 3.6a shows that the southern portion of the surface had a lower average density than the rest of the barrier. The change in densities from December 1994 to May 1995 is quite dramatic as can be seen from comparing Figures 3.6a and 3.6b. The average density for the barrier surface in May was 1722 kg/m^3, a decrease of 135 kg/m^3. The northern half of the barrier, the irrigated portion, shows that the effect of the additional water application is a lower dry density and is consistent with the moisture content shown in Figure 3.5b. 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 no associated increase in moisture content or elevation changes that would explain these lower densities. Figure 3.6c is a contour map of the densities for August 1996. This map shows a strip of lower densities across the south area from 18 m to 32 m east, the same area that has experienced a localized decrease in elevation.

3.6 Summary

The permanent erosion test plot indicated that the performance of the barrier was similar to that in the preliminary field erosion tests prior to construction of the prototype. This supports the conclusion that the surface will experience little erosion during extreme rainfall events. However, data have been collected for only 2 yrs, and this conclusion must be validated with further monitoring for the life of the prototype. The small movements in the rock riprap sideslope may or may not indicate some mass movement. Continued scrutiny of the creep gauges will be needed to determine if there is any potential for slope failure. The area around the southeast corner of the barrier continues to experience some settling. The root cause of this is not known at this time but it will closely watched. It would be useful to examine this area with ground-penetrating radar to determine if there is a identifiable source for the settlement.

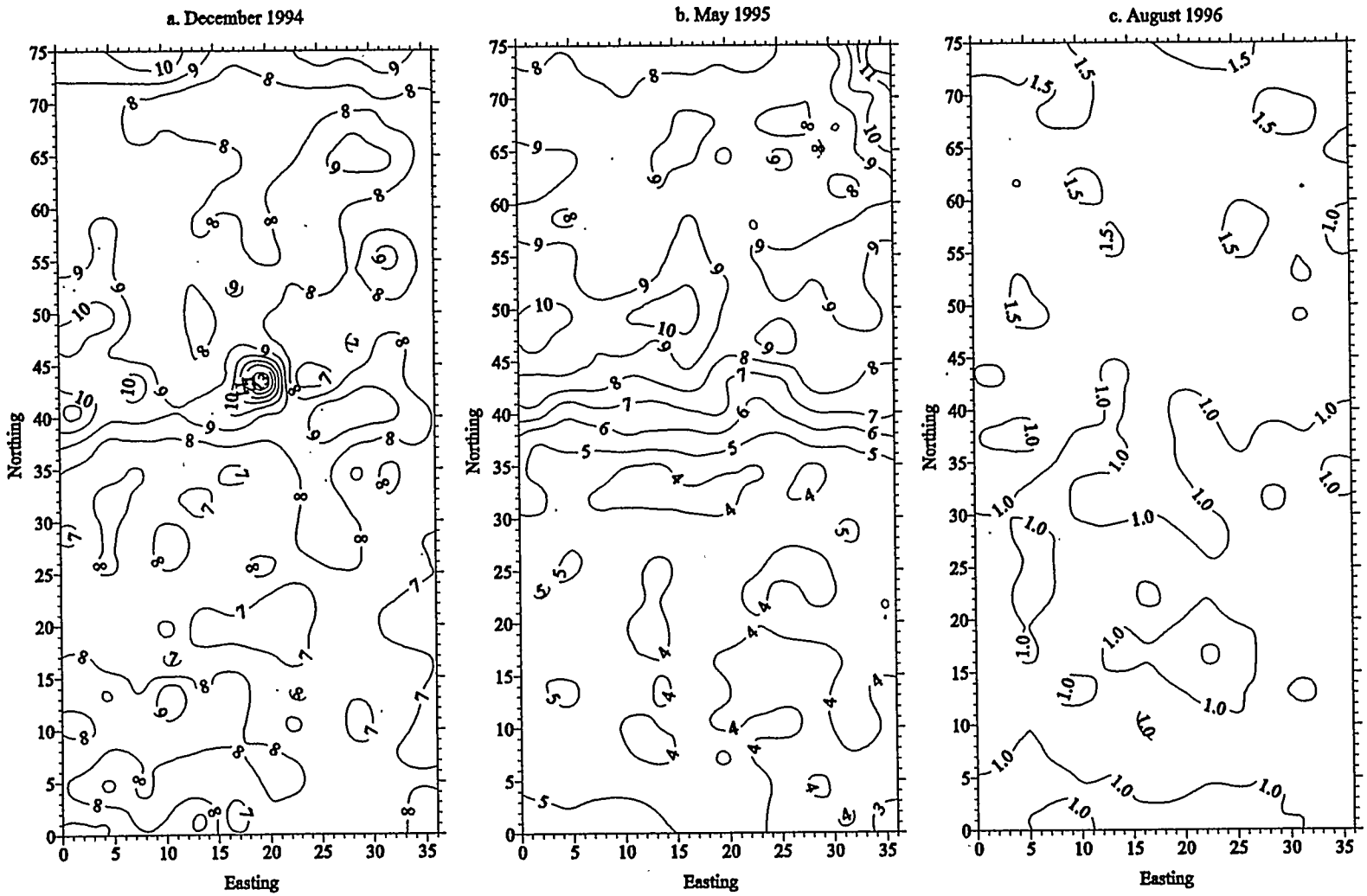

Figure 3.5 a, b, c Near Surface Moisture Contents

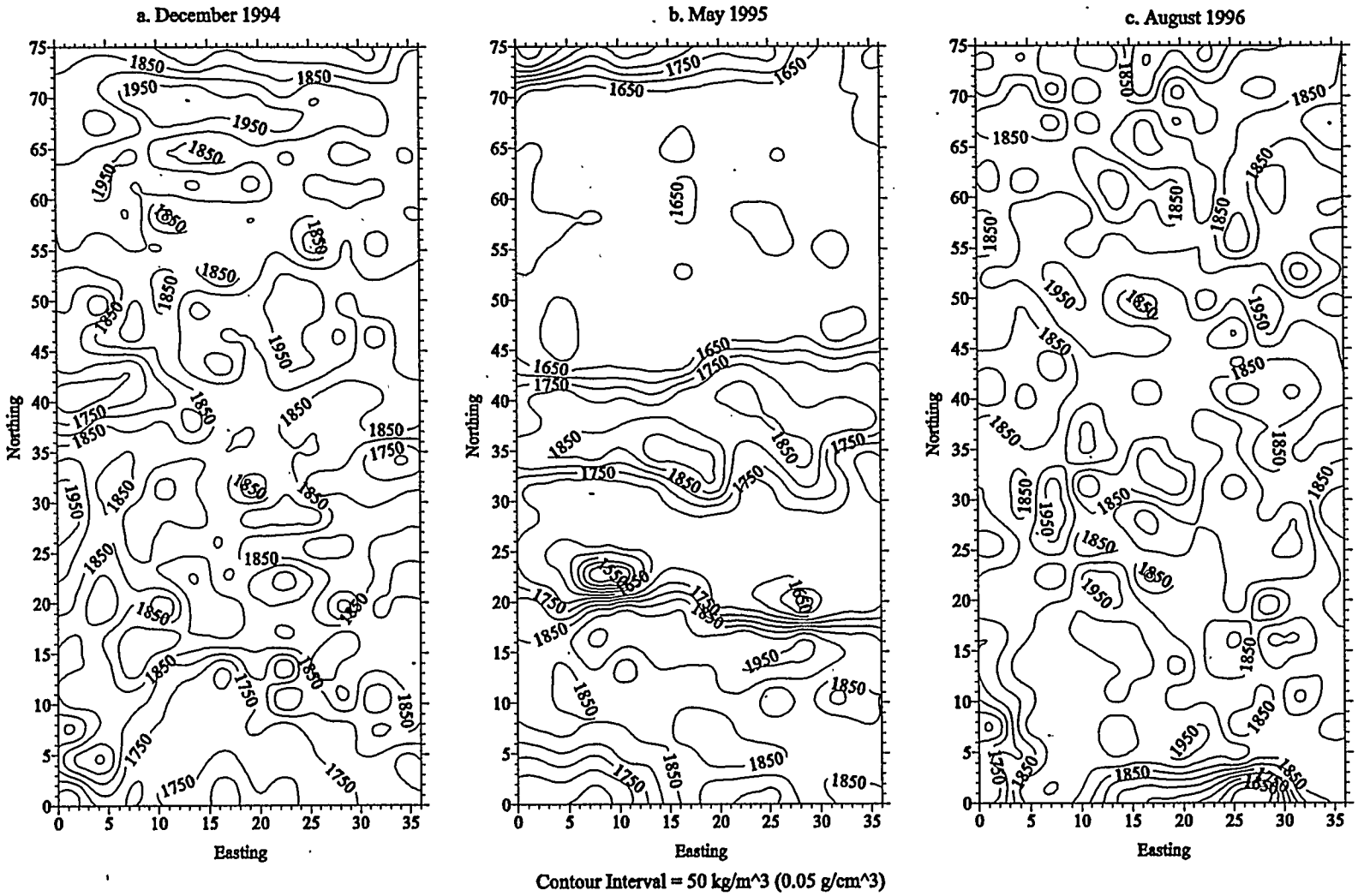

Figure 3.6 a, b, c Surface Dry Densities

4.0 WIND EROSION MONITORING

The second of three planned years of monitoring work was performed in FY 1996 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 side slopes is also being monitored. Most wind erosion monitoring work is being performed over the south, non-irrigated 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 insure 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 prototype surface barrier 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 Ligotke and Klopfer (1990) and Ligotke (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. (1993), and, in modified form, include:

- Monitor the influence of eolian stresses on the surface layer under irrigated and natural conditions.
- Obtain micrometeorological information about erosive stresses that impact the barrier
- Measure actual rates of surface deflation or inflation

In addition, two other testing and monitoring objectives are proposed for FY 1997, 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 drought.

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. (1993). 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 the addition 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 was 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) unforseen practical difficulties were not encountered during construction, and 2) it was possible to maintain a relatively uniform admixture composition.

Gravel samples were obtained in FY96 (Section 4.2.2) from the prototype barrier. It is recommended to obtain gravel samples in FY97 to allow comparison with previous studies as well as to establish a measurement for a baseline after vegetation has been well established. July or August are recommended months for sampling due to the lack of moisture. This data would be compared to data obtained in FY95 and FY96.

4.2.2 Surface Layer Composition and Deflation/Inflation

Testing and monitoring was initiated to study the suitability of 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, 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 side slopes, and how does orientation and slope influence side slope 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 once during the second year of the study on 9/23/96 and were analyzed to determine surface composition. The samples were obtained from 24 locations evenly spaced within the rectangular surface of the barrier. The soil samples were obtained by coring the soil column at 0 - 2 cm (surface) and 2 - 10 cm (bulk) depths. As the surface grid had been established by the sampling, the grid locations of each sample were also recorded.

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 13.8 ± 2.3% (September 1996) compared to the average bulk pea gravel concentration from last year of 14.1 ± 1.5% (April 95). Average pea gravel concentrations were varied for both north (irrigated) and south (non-irrigated) regions of the barrier surface. In September 1996, the bulk pea gravel concentration averaged 16.1 ± 2.8% in the north half and 11.6 ± 1.9% in the south half compared to the April 1995 bulk pea gravel concentration averages of 14.3 ± 1.6% in the north half and 13.9 ± 1.4% in the south half. This difference between the sample bulk pea gravel concentration averages is a direct result from the 1,000 extreme precipitation event that was performed on the prototype barrier in March 1996. The north half of the barrier can be expected to contain larger concentrations of bulk pea gravel than the south half because the northern section was exposed to more water (e.g. irrigation), which apparently washed out silt from the surface, leaving a higher pea gravel content.

Incidental information was also generated on moisture content (soil and admixture) from the surface samples. Similarly, information was also generated on density (wet and dry, soil and admixture) from the September 1996 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 September 1996 samples was 6.8 ± 0.7% from the bulk samples and 2.2 ± 0.2% from the surface samples (all 48 samples were dried). Separated into north (irrigated) and south (non-irrigated) regions, the dry admixture densities were: 1.38 ± 0.11 g cm^{-3} (north, bulk), 1.72 ± 0.09 g cm^{-3} (south, bulk), 1.8 ± 0.3 g cm^{-3} (north, surface) 1.8 ± 0.2 g cm^{-3} (south, surface). Again separated into north (irrigated) and south (non-irrigated) regions, the dry soil densities were: 1.16 ± 1.2 g cm^{-3} (north, bulk), 1.52 ± 0.11 g cm^{-3} (south, bulk), 1.6 ± 0.3 g cm^{-3} (north, surface), and 1.5 ± 0.2 g cm^{-3} (south, surface).

4.2.3 Wind Stress Monitoring

The second year of monitoring wind boundary layers was completed on 9/3/96. 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 09/06/94, 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 side slope. Station 03 is located west-southwest of the prototype barrier. The configuration of each wind station 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° when directed true north (18° declination), and the connection of each sensor to the dataloggers was checked and validated.

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^{-1} 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 in FY 1995. 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 second year of the study was generally characterized by normal wind. The Hanford Meteorological Station recorded nearly normal winds, 3.5 m s^{-1}, compared to a normal of 3.4 m s^{-1}. However, there were 74 days with peak wind gusts of 15.6 m s^{-1}, compared to an annual average of 55 days. The peak wind gusts at the prototype barrier between September 1995 and August 1996 were recorded as 18 m/s (measured at the 2 m level) on 2/23/96. The Hanford Meteorological Station recorded a peak gust of 55 mph on 2/23/96. 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^{-1}. The wind tunnel tests of the surface were performed at u* values between 0.4 and 2.2 m s^{-1} (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

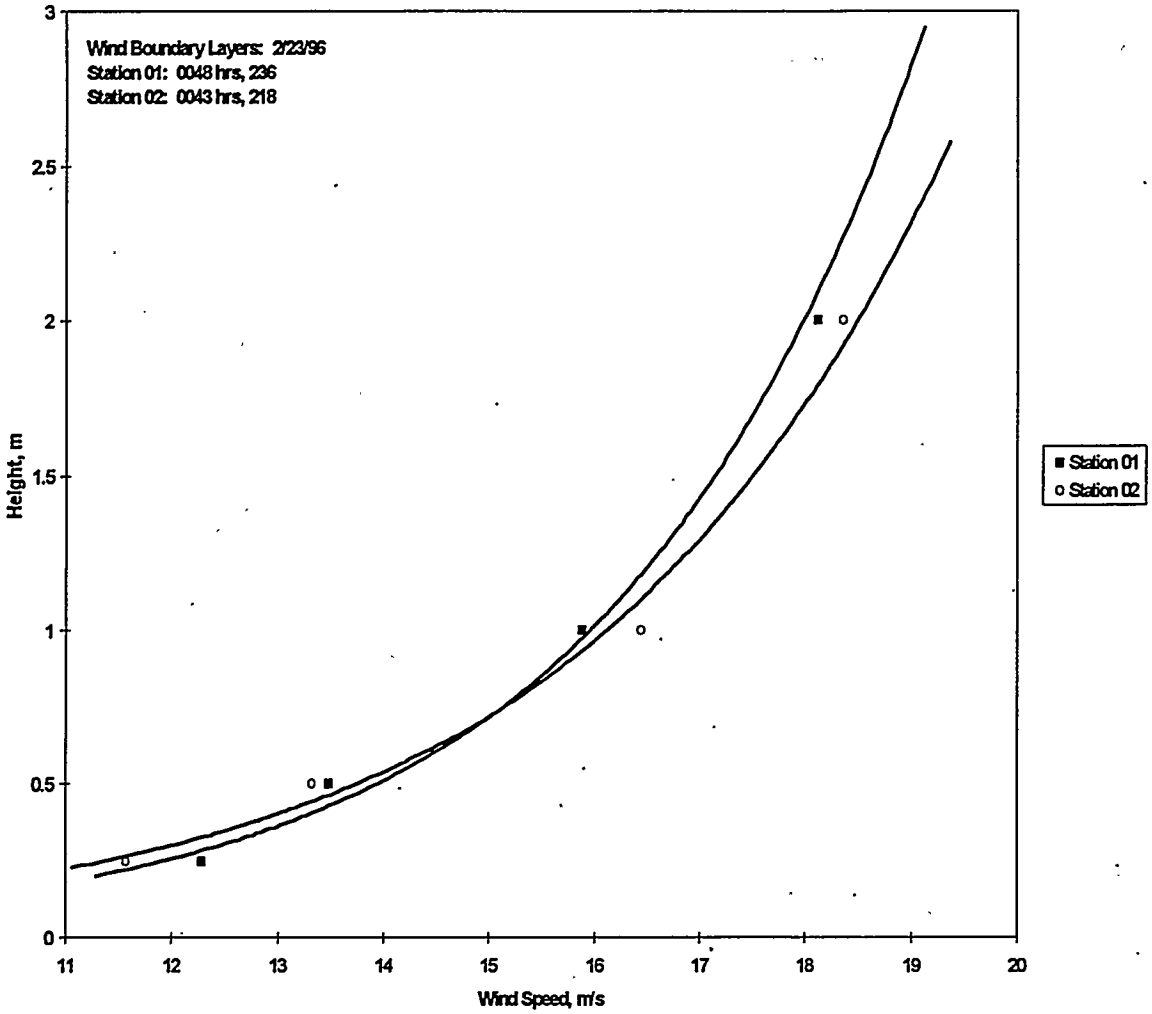

Figure 4.1. Peak gust wind profiles measured over the elevated surface of the prototype barrier on 02/23/96.

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, as well as total and hourly average solar radiation records, are available.

Wind Station 01 and Wind Station 02 experienced a loss of battery in May 1996 which resulted in the lack of wind monitoring data for approximately 10 days (May 20 - May 31). This should not have a severe impact on barrier performance evaluation since additional data, although less localized, can be obtained from the Hanford Meteorological station.

4.2.4 Monitoring Saltation Stresses and Sand Drift Rate

The dust traps that were developed and tested in FY 1994 were removed in December 1995 due to the lack of a saltation source as a result of the rapid growth rate of vegetation and the high moisture content of the soil at the prototype barrier. Results from the dust traps from the previous year including the composition and quantity of sand grains can be obtained in the Hanford Protective Barrier Project Prototype Barrier Task 2.4 Wind Erosion FY 1995 Report (Gee et al. 1995). It is possible that these experiments may be resumed in future years with the removal of dense vegetation. It is recommended that fine sand be distributed on the Southwest end of the prototype barrier to initiate a good scouring test if such a test were to be conducted in the future.

4.3 Summary and Conclusions

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. Wind boundary layer profiles and peak gusts were monitored throughout the second of three planned years of the project. 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. In FY 1997 it is planned to continue measuring the actual rates of surface deflation or inflation due to the presence of dense vegetation to obtain establish a baseline setting.

5.0 BIOINTRUSION

Plants and animals will influence hydrologic, water and wind erosion characteristics of landfill covers such as the prototype barrier (Link et al. 1995a, b). The floristic composition of the surface is documented to assess the dynamics of the plant community. Speciffically, it is important to assess possible reductions in deep-rooted perennials and increase in shallow-rooted annuals. If shallow-rooted annuals such as *Bromus tectorum* and others not yet found there should begin to dominate the surface then the long-term ability of the vegetation to extract water from the surface will be reduced. In addition, the documentation of increasing biodiversity on the surface will lend support for the proposition that increased complexity will provide increased reliability of surface to function in changing conditions. Evidence suggesting a reduction in biodiversity will bring into question the viability of the surface because of the relatively high potential for die-off of a monoculture.

Spatial distribution of plants on the surface is needed to support any evidence of spatial variation in soil water contents. An area with few deep-rooted species can lead to the potential for increased soil water. If such a condition should be observed, then it will be possible for a "lead" to occur in the future. In addition, maps of plant cover support variations observed in wind and water erosion patterns.

Plant height, activity and survivorship are measured to assess plant "health". Height is measured as an inexpensive assessment of plant size. Small plants will transpire less water than large plants. A reduction in height suggests that a particular species is experiencing a reduction in viability. If such a species is suspected of being eliminated from the surface then the consequences of such a change can be predicted for the surface. Any reduction of deep-rooted species can increase the probability for failure over time. Measurement of activities by gas exchange techniques provide immediate evidence for plant "health" status in addition to measures of transpiration. Measures of transpiration provide information that will help explain variation in surface soil water patterns. Assessment of survivorship in the deep-shrubs is done, again, as simple measure of the viability. A reduction in survivorship of either of the two shrubs planted on the surface will suggest the need to consider other plant species in revegetation of barrier structures at Hanford. If a species will not survive after a few years, then there will be no point in using the species for future revegetation efforts.

Plant water potential data were obtained as another means of providing an estimate of soil water potential in the wettest portion of the soil profile. This information supports efforts to quantify and explain soil water patterns on the surface.

Rooting patterns were assessed to document the depth of roots. If roots are found not to dominate the soil completely, then the potential of water accumulation is present. Root length density is measured to support efforts to explain soil water patterns observed with depth.

Animal evidence and burrows were assessed to document dynamics on the surface. If animal activity increases markedly, then one can expect changes in associated vegetation patterns. An increase in the number of burrows can have consequences for the hydrology and erosion protection abilities of the surface.

A surface without plants and animals will not be sustainable in the long-term and will not keep water

out of the waste. A bare rock or sterile soil surface will allow water to accumulate and increase the potential for disastrous erosional effects. A poorly revegetated surface will make the surface less viable as a means of preventing water from entering buried waste forms. A surface planted to quickly establish a sustainable and functional plant community has been the focus of biointrusion efforts for the prototype barrier program.

Revegetation of the surface was done in late fall of 1994 as discussed in Gee et al. (1995). Conclusions from the initial year's observations suggest that plants will dry out the surface even with added water and that plants have virtually eliminated wind and water erosion (Gee et al. 1995). Studies on the biological component of the prototype barrier in Fiscal Year 1996 include extensive observations of plant characteristics plus animal observations.

5.1 Vegetation

Vegetation characteristics documented include floristic composition, spatial distribution, plant height, gas exchange rates, xylem pressure potential, roots, and shrub survivorship. Analyses were done using JMP version 2.0.2 software (Sall et al. 1991). Mean data are presented with one standard error.

5.1.1 Floristic Composition

The floristic composition of engineered surfaces is dynamic (Link et al. 1994) and can influence a barrier's performance at Hanford (Link et al. 1995a, b). To document the floristic composition of the barrier requires periodic observations of the occurrence of various species.

A species list was developed in 1995 and 1996, by making inspections several times each year. Identifications were made using Hitchcock and Cronquist (1973).

The species list is given in Table 5.1 with documentation of the origination, yearly occurrence, and life-form of each species on the surface. The surface was revegetated with seedlings *of Artemisia tridentata* and *Chrysotham nusnauseosus* and seeded with native perennial grasses. The native perennial grass seed mixture included *Poa sandbergii, Agropyron dasystacyum, Oryzopsis hymenoides, Poa ampla, Stip acomata, Pseudoroegneria spicata, and Sitanion hystrix*.

A total of 34 species have been observed in 1995 and 1996. There are 12 families present, of which *Brassicaceae, Compositae, and Poaceae* account for 71% of the 34 species. Fifty-six percent of the species are native to the West; the rest are invasive aliens. Forty-seven percent of the species are annuals and 53% are biennials or perennials. There were 24 species noted in 1995 and 27 in 1996, with the assumption that the seven grasses used in revegetation germinated and thus were counted. Grass identification was not possible in 1995 and was difficult in 1996. In 1995, 55% of the species were annuals. In contrast, only 44% of the species were annuals in 1996.

In 1996 new species were observed, and some present in 1995 were not observed in 1996. Seeds of new species are likely carried to the surface by dust devils, animals, and humans. Those that are no longer present were unable to resprout or reseed themselves. We hypothesize that the vegetative

TABLE 5.1. Plant species observed on the prototype barrier surface. Native plant species (n), invasive alien species (i), and species used to revegetate the prototype barrier (r) are noted with their presence by year (0 = not present, 1 = present).

Scientific Name	Notes	Present	Life Form
(Family Species)		(1995, 1996)	
Boraginaceae			
Amsinckia tessellata	n	1,1	annual forb
Brassicaceae			
Cardaria draba	i	0,1	perennial forb
Chorispora tenella	i	1,0	annual forb
Descurainia pinnata	n	1,1	annual forb
Draba verna	i	1,1	annual forb
Sisymbrium altissimum	i	1,1	annual forb
Chenopodiaceae			
Chenopodium leptophyllum	n	1,0	annual forb
Salsola kali	i	1,1	annual forb
Compositae			
Achillaea millifolium	n	1,0	perennial forb
Ambrosia acanthicarpa	n	1,0	annual forb
Artemisia tridentata	n,r	1,1	perennial shrub
Chrysothamnus nauseosus	n,r	1,1	perennial shrub
Lactuca serriola	i	1,1	annual forb
Machaeranthera canescens	n	0,1	bien, peren forb
Tragopogon dubius	i	0,1	annual forb
Convolvulaceae			
Convolvulus arvensis	i	0,1	perennial forb
Geraniaceae			
Erodium cicutarium	i	1,1	annual forb
Hydrophyllaceae			
Phacelia linearis	n	1,0	annual forb
Leguminosae			
Melilotus alba	n	0,1	annual forb
Malvaceae			
Sphaeralcea munroana	n	0,1	perennial forb
Onagraceae			
Epilobium paniculatum	n	0,1	annual forb
Poaceae			
Agropyron cristatum	i	0,1	perennial grass
Agropyron dasytachyum	n,r	1,1	perennial grass
Agropyron intermedium	i	0,1	perennial grass
Bromus tectorum	i	1,1	annual grass
Oryzopsis hymenoides	n,r	1,1	perennial grass
Poa ampla	r	1,1	perennial grass
Poa bulbosa	i	1,1	perennial grass
Poa sandbergii	n,r	1,1	perennial grass
Pseudoroegneria spicata	n,r	1,1	perennial grass
Sitanion hystrix	n,r	1,0	perennial grass
Stipa comata	n,r	1,0	perennial grass
Triticum aestivum	i	1,0	annual grass
Verbenaceae			
Verbena bracteata	n	0,1	perennial forb

composition of the barrier will become increasingly perennial. A highly diverse mix of perennials is preferred because of their efficient use of water.

5.1.2 Spatial Distribution

In 1995 grasses were mapped and found to be highly variable in space. It was felt that the variation was due to the hydroseeding process (Gee et al. 1995).

In 1996 cover estimates of grasses, shrubs, herbaceous forbs, litter, and bare soil were made on each 9-m^2 quadrat after Daubenmire (1959). Cover was estimated by visual inspection of each quadrat. Cover was assigned values for percentage cover ranges as:

1 = 0-5%
2 = 5-25%
3 = 25-50%
4 = 50-75%
5 = 75-95%
6 = 95-100%.

Data were converted to the midpoint of the these value ranges. Statistics of these results are presented as percentages for easy interpretation. Differences between treatments for cover data were assessed using the Mann-Whitney U test (Siegel 1958).

Cover data obtained in 1996 revealed significant effects of irrigation (Figure 5.1). Percentage grass cover in the irrigated half was significantly ($p < 0.00001$) and nearly 2.5 times greater than in the ambient precipitation half of the surface. Percentage bare ground was significantly($p = 0.0071$) greater in the ambient precipitation half than in the irrigated half as was the percentage cover of herbaceous plants ($p = 0.0001$). There were no significant differences between the halves for percentage shrubs ($p = 0.3473$) or percentage litter ($p = 0.6553$) cover. The substantial increase in perennial grass cover in the irrigated half supports the concept of responsivity to limiting resources in the shrub-steppe, as noted in Link et al. (1990). It is likely that vegetation on barrier surfaces will use all available water by changing cover in concert with changing precipitation.

Mapping data for percentage grass cover reveal greater cover in the irrigated half than in the ambient precipitation half, with the greatest cover in the northeast corner of the surface (Figure 5.2). Mapping data for shrub cover reveal no particular pattern (Figure 5.3). Mapping data for herbaceous forbs reveal more cover in the ambient precipitation half than in the irrigated half, with low cover in the northeastern corner of the surface (Figure 5.4). There was a higher cover of litter in the northeastern corner of the surface than elsewhere (Figure 5.5), most likely because of the high cover of grasses in the northeastern corner. In association with grass and litter, bare soil was least in the northeastern corner (Figure 5.6).

The most impressive effect of the irrigation treatment was observed with *Salsola kali*. In 1995, *S.kali* almost completely covered the entire surface by late July. In 1996, *S. kali* was eliminated from the

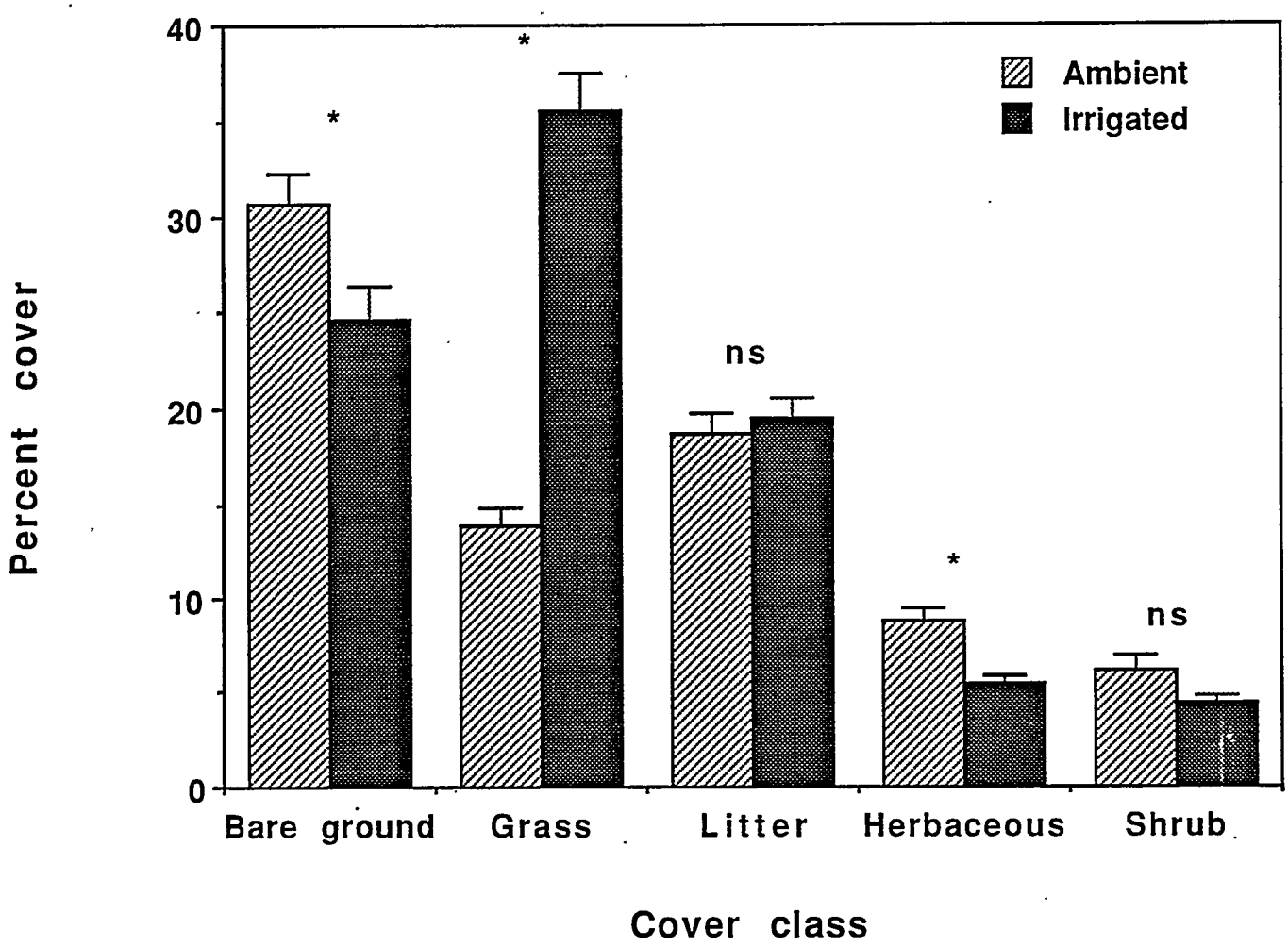

Figure 5.1. Percent cover of surface classes on the barrier surface in the irrigated and ambient precipitation treatments. Error bars are one standard error of the mean. Means within classes with asterisks are significantly different (* = 0.05).

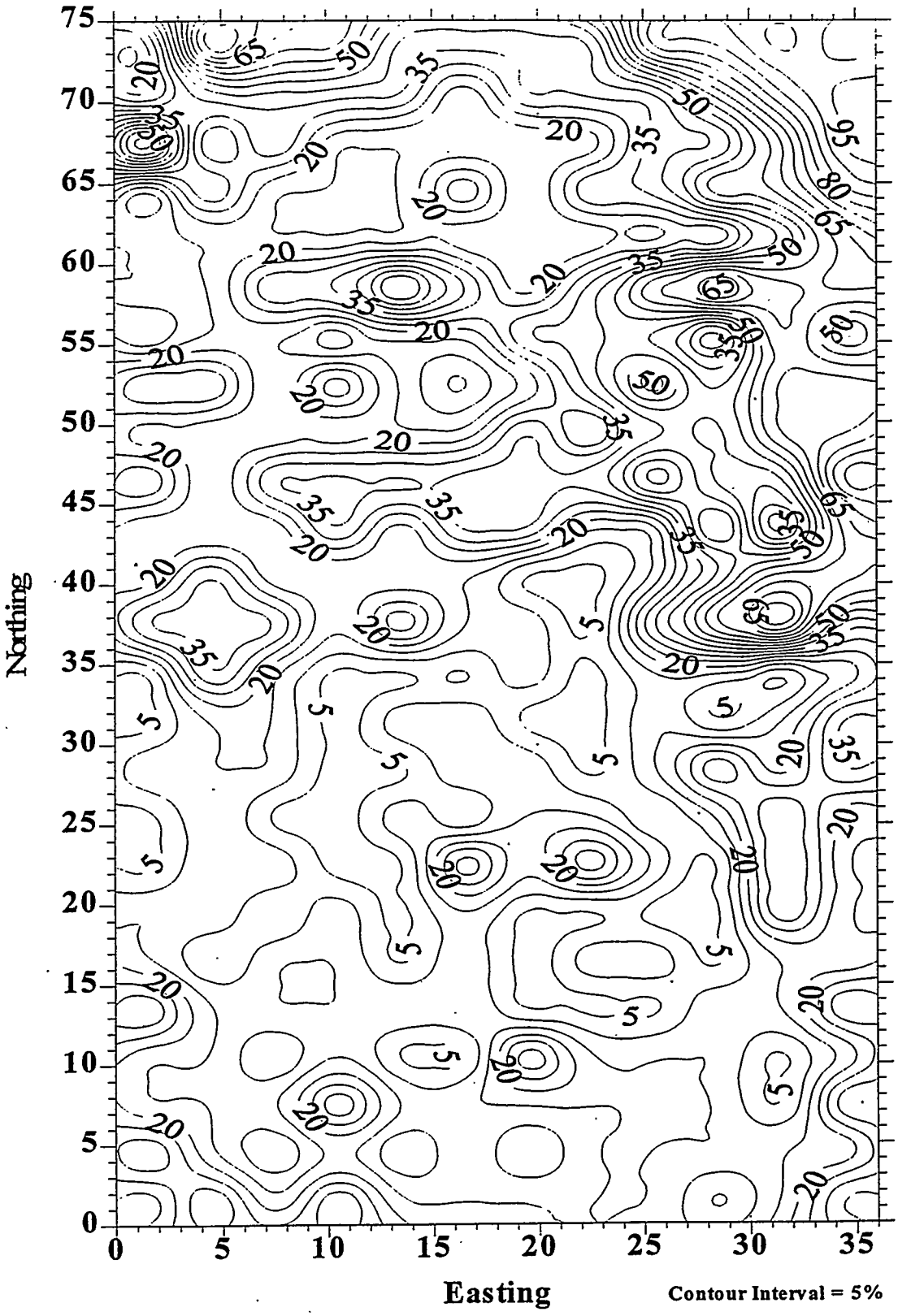

Figure 5.2. Percent cover of grasses on the surface

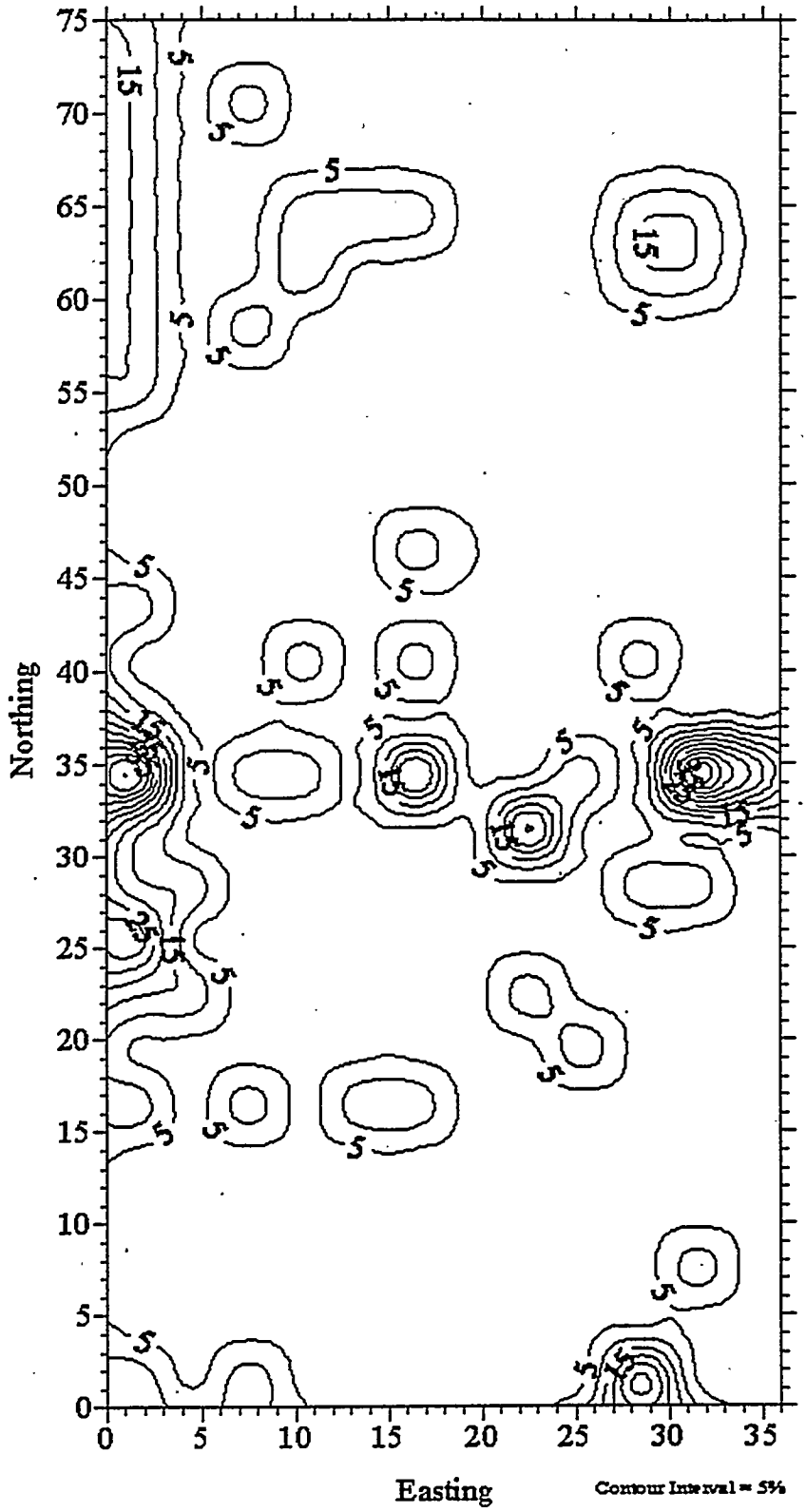

Figure 5.3. Percent cover of shrubs on the surface.

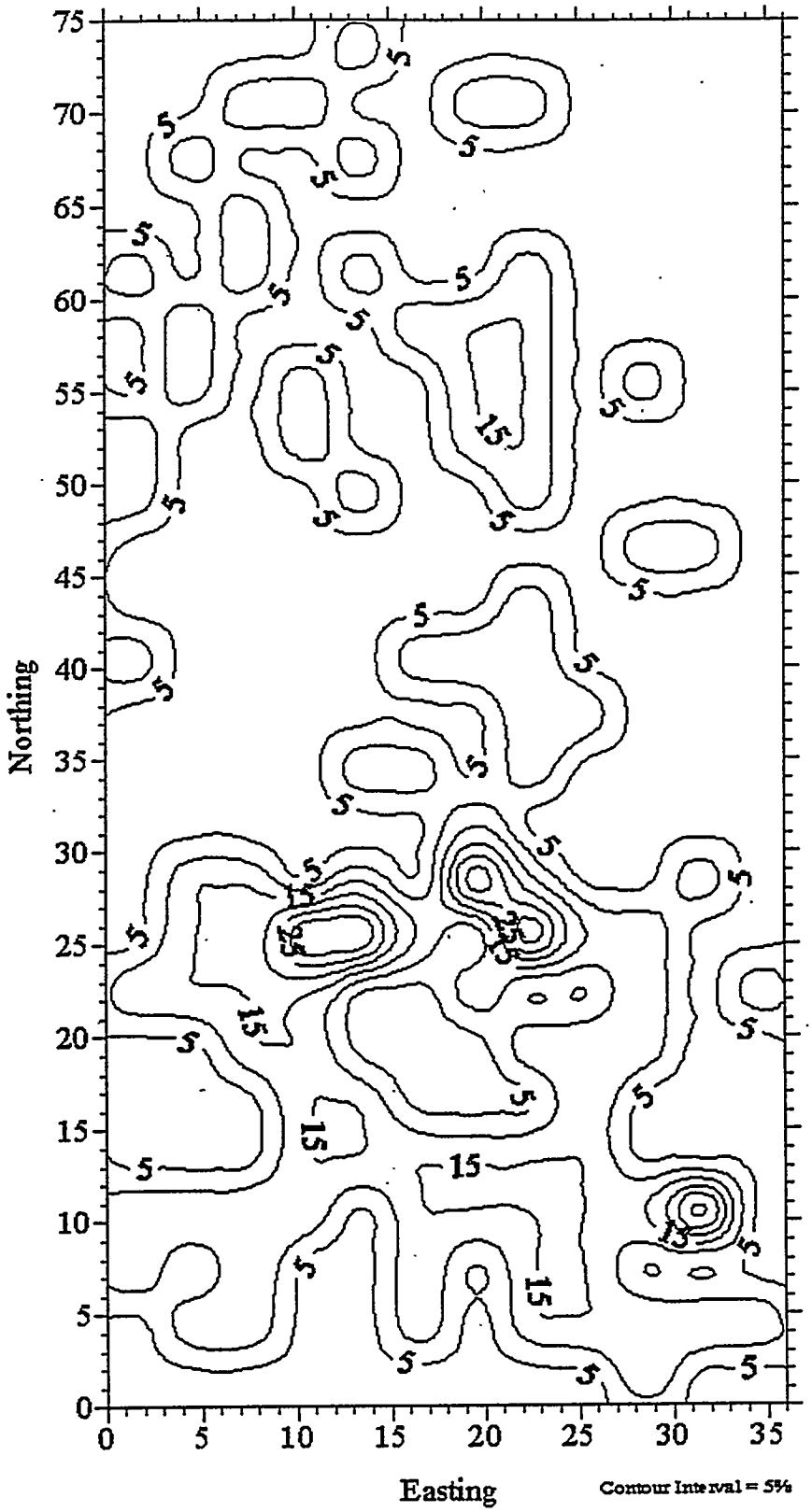

Figure 5.4. Percent cover of herbaceous forbs on the surface.

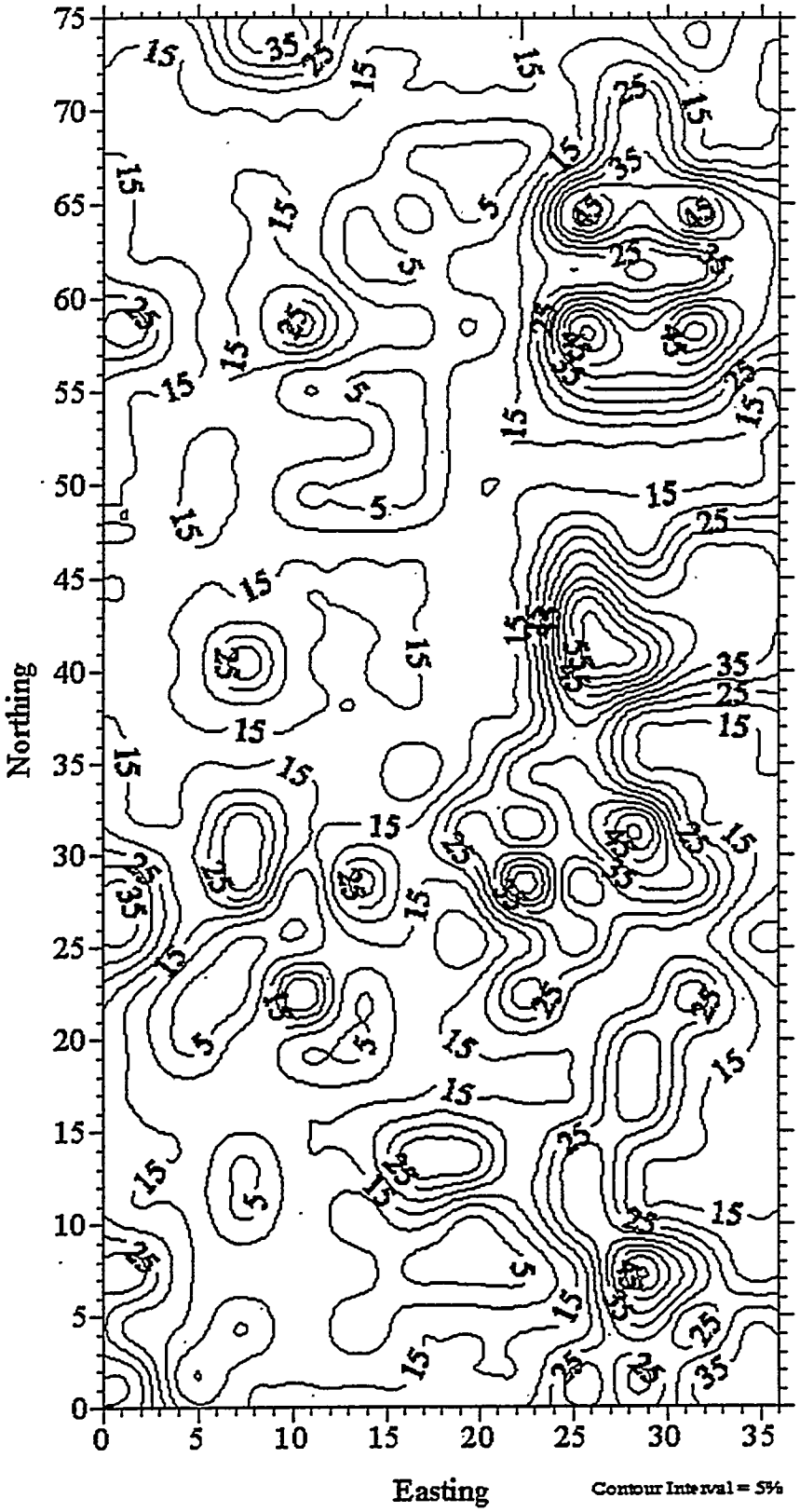

Figure 5.5. Percent cover of litter on the surface.

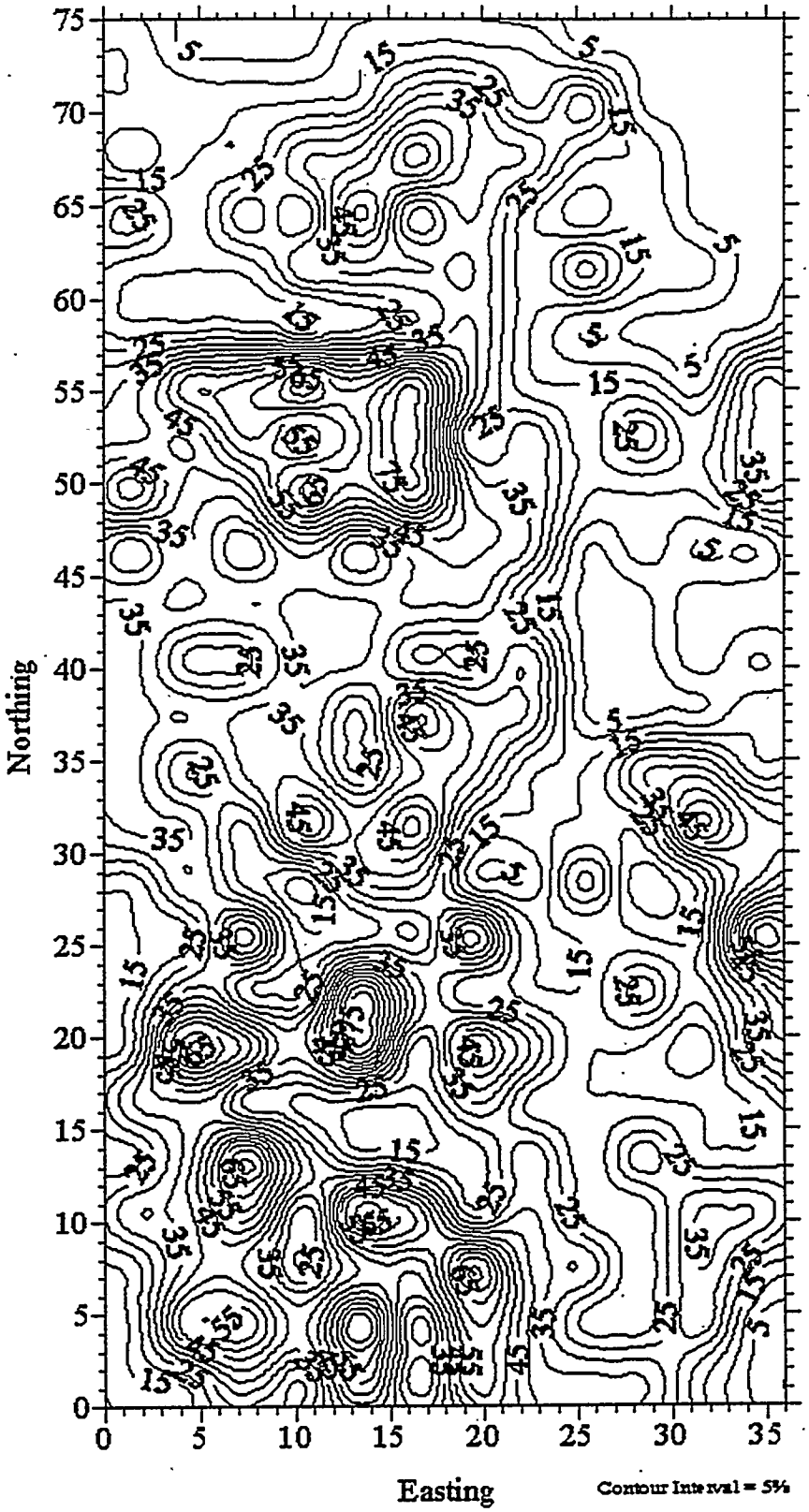

Figure 5.6. Percent cover of bare soil on the surface.

irrigated half and was only sparsely distributed on the ambient precipitation half. The irrigation apparently allows perennials to dominate the surface even though there was adequate water at depth. Perhaps seedlings of *S. kali* were not able to extend roots into the wet zones rapidly enough to survive. 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).

In 1997 we expect to observe increasing dominance of perennial grasses in the irrigated half and a general increase in litter corresponding to a decrease in bare soil cover.

5.1.3 Plant Height

The size of plants in water-limited ecosystems is positively correlated with available water (Link et al. 1990). We measured shoot height to see if plants were taller in the irrigated treatment compared with the ambient precipitation treatment. Data for 1995 and 1996 are presented to document change.

Maximum plant height was measured with a meter stick in the irrigated and unirrigated portions of the barrier in 1995 and 1996. Observations were taken on at least 9 individuals of *S. kali*, *A. tridentata*, and *C. nauseosus* in each of the treatments on July 26, 1995, *on A. dasystacyum* in each treatment on May 23, 1996 and again on *S. kali*, *A. tridentata*, *and C. nauseosus* in each of the treatments on August 1, 1996.

Differences between treatments for height data were assessed using analysis of variance (ANOVA) and comparisons based on least-squares means. The effects of the water treatment (irrigated and ambient precipitation), year (1995 and 1996), and their interaction on the height of *S. kali*, *C. nauseosus*, and *A. tridentata* were examined. Least-squares means are not presented.

The effect of the treatment was not significant on the height of *S. kali*, while the year and interaction of treatment plus year were significant (Table 5.2). Plants were shorter in 1996 than in 1995. The interaction between treatment and year was apparent in 1996. Plants in the irrigated treatment area were significantly shorter than those in the ambient precipitation treatment (Table 5.3).

The only factor having a significant effect on the height *of C. nauseosus* was the water treatment (Table 5.4). Plants in the water treatments were taller than those in the ambient precipitation treatment in 1995. There was no effect of treatment on height in 1996. Plants did not appear to gain a significant amount of height from 1995 to 1996 in either treatment (Table 5.3).

The only factor having a significant effect on the height of *A. tridentata* was the year (Table 5.5). Plants were taller in 1996 than in 1995. Treatment did not affect height across years (least-squares means not presented), yet plants in the irrigated treatment were significantly taller than those in the ambient precipitation treatment in 1995 (Table 5.3). Plant height increased 20% from 1995 to 1996 in the irrigated treatment. The increase in the ambient precipitation treatment was 40% which is an indication of a relative suppression of growth or carbon gain for *A. tridentata* when irrigated.

Table 5.2. Analysis of variance for the effects of treatment (irrigation and ambient precipitation) and year (1995, 1996) on the height of *Salsola kali.*

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**Prob>F**
Model	3	37535.019	12511.7	117.8845	0.0000
Error	35	3714.725	106.1		
C Total	38	41249.744			
Effect Test					
Source	**Nparm**	**DF**	**Sum of Squares**	**F Ratio**	**Prob>F**
Treatment	1	1	297.006	2.7984	0.1033
Year	1	1	34939.514	329.1988	0.0000
Treatment * Year	1	1	1941.233	18.2902	0.0001

Table 5.3. Mean plant height with one standard error (SE, n = 9 to 23). Means with differing letters within species and years are significantly different.

Species	Treatment	Date	Mean Height (cm)	SE
		7/26/95		
A. tridentata	irrigated ambient		45.0[a] 35.5[b]	2.9 1.9
C nauseosus	irrigated ambient		37.0[a] 30.5[b]	2.1 1.9
S. kali	irrigated ambient		76.0[a] 69.0[a]	3.8 4.2
		8/1/96		
A. tridentata	irrigated ambient		53.9[a] 49.7[a]	2.2 2.4
C. nauseosus	irrigated ambient		39.2[a] 34.0[a]	1.7 2.6
S. kali	irrigated ambient		2.6[a] 22.2[b]	0.2 3.2

Table 5.4. Analysis of variance for the effects of treatment (irrigation and ambient precipitation) and year (1995,1996) on the height of *Chrysothamnus nauseosus.*

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**Prob>F**
Model	3	405.1473	135.049	2.9531	0.0451
Error	37	1692.0722	45.732		
C Total	40	2097.2195			
Effect Test					
Source	**Nparm**	**DF**	**Sum of Squares**	**F Ratio**	**Prob>F**
Treatment	1	1	338.85454	7.4096	0.0098
Year	1	1	40.67613	0.8895	0.3517
Treatment * Year	1	1	3.41792	0.0747	0.7861

Table 5.5. Analysis of variance for the effects of treatment (irrigation and ambient precipitation) and year (1995,1996) on the height of *Artemisia tridentata.*

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**Prob>F**
Model	3	420.8199	806.873	5.8869	0.0013
Error	61	8360.826	137.063		
C Total	64	10781.446			
Effect Test					
Source	**Nparm**	**DF**	**Sum of Squares**	**F Ratio**	**Prob>F**
Treatment	1	1	507.8199	3.7050	0.0589
Year	1	1	1601.7947	11.6866	0.0011
Treatment * Year	1	1	47.7159	0.3481	0.3481

Finally, *A. dasytacyum* plants measured on May 23, 1996 were significantly ($p = 0.009$) taller in the irrigated area (71.4 cm ± 3.15) than in the ambient precipitation (60.8 cm ± 1.82) area.

5.1.4 Gas Exchange

Plant gas exchange data were collected on August 1, 1996 to continue observations made in the spring of 1995. Transpiration, stomatal conductance and net photosynthetic data are presented. Such data are useful as an indication of the ability of shrubs to remove water from the surface. Comparisons are made

for the effect of the irrigation treatment on gas exchange rates for both shrub species. These data are graphically presented with data gathered in 1995 as in Gee et al. (1995) to interpret long-term trends in plant gas exchange (Figures 5.7 - 5.9).

Gas exchange data, gathered with a Li-Cor 6200 gas exchange system, are collected by placing a chamber over stem tips and allowing water vapor and CO_2 to change over a few minutes. In 1996, a 10-cm length of stem was placed in the chamber for plants in the ambient precipitation treatment, and a shorter piece (less than 5 cm long) was used in the irrigated treatment. The amounts of exposed leaf area were varied to maintain a similar vapor pressure in the chamber between treatments. After observations were made the stem was cut and single-sided leaf area measured using a Li-Cor 3100 leaf area meter. All gas-exchange observations were taken at mid-day and in full sun.

Stomatal conductance increased from near 0.08 mol $m^{-2}s^{-1}$ in February to 0.46 mol $m^{-2}s^{-1}$ in the ambient precipitation treatment and to 0.21 mol $m^{-2}s^{-1}$ in the irrigated treatment for *A. tridentata* in July (Figure 5.7a). Stomatal conductance also increased over time *in C. nauseosus* ranging from near 0.07 mol $m^{-2}s^{-1}$ in February to 0.17 mol $m^{-2}s^{-1}$ in the irrigated treatment and to 0.10 mol $m^{-2}s^{-1}$ in the ambient precipitation treatment by July (Figure 5.7b). There were no differences between treatments within species on any of the 4 days ($p > 0.05$).

Transpiration rates increased from near 0.75 mmol $m^{-2}s^{-1}$ in February to 19.7 mmol $m^{-2}s^{-1}$ in the ambient precipitation treatment and to 8.8 mmol $m^{-2}s^{-1}$ in the irrigated treatment for *A. tridentata* in July (Figure 5.8a). Transpiration also increased over time in *C. nauseosus* ranging from near 0.75 mmol $m^{-2}s^{-1}$ in February to 5.1 mmol $m^{-2}s^{-1}$ in the ambient precipitation treatment and to 6.1 mmol $m^{-2}s^{-1}$ in the irrigated treatment by July (Figure 5.8b). There were no differences between treatments within species on any of the 4 days ($p > 0.05$) except for *A. tridentata* in July when the transpiration rate in the ambient precipitation treatment was significantly greater than in the irrigated treatment ($p = 0.033$). The higher rate of transpiration in the ambient precipitation treatment than in the irrigation treatment suggests that *A. tridentata* is under a hydration stress caused, apparently, by too much water. As discussed next, plants in the irrigated treatment had much higher predawn xylem pressure potential values than those in the ambient precipitation treatment, an indication of no apparent water stress. Yet there appears to be a restriction in the ability of water to move through *A. tridentata* when it is supplied with 3 times normal precipitation. Perhaps excess water reduces the hydraulic conductivity of *A. tridentata* leading to a reduction in transpiration rates. This effect was not observed in *C. nauseosus*.

Net photosynthetic rates increased from near 3 μmol $m^{-2}s^{-1}$ in February to 19.7 μmol $m^{-2}s^{-1}$ in the ambient precipitation treatment and to 10.1 μmol $m^{-2}s^{-1}$ in the irrigation treatment for *A. tridentata* in July (Figure 5.9a). Net photosynthesis increased for *C. nauseosus* from 1 μmol $m^{-2}s^{-1}$ in February to 6.4 μmol $m^{-2}s^{-1}$ in the irrigated treatment and to 3.5 μmol $m^{-2}s^{-1}$ in the ambient precipitation treatment by July (Figure 5.9b). There were no differences between treatments within species on any of the 4 days ($p > 0.05$).

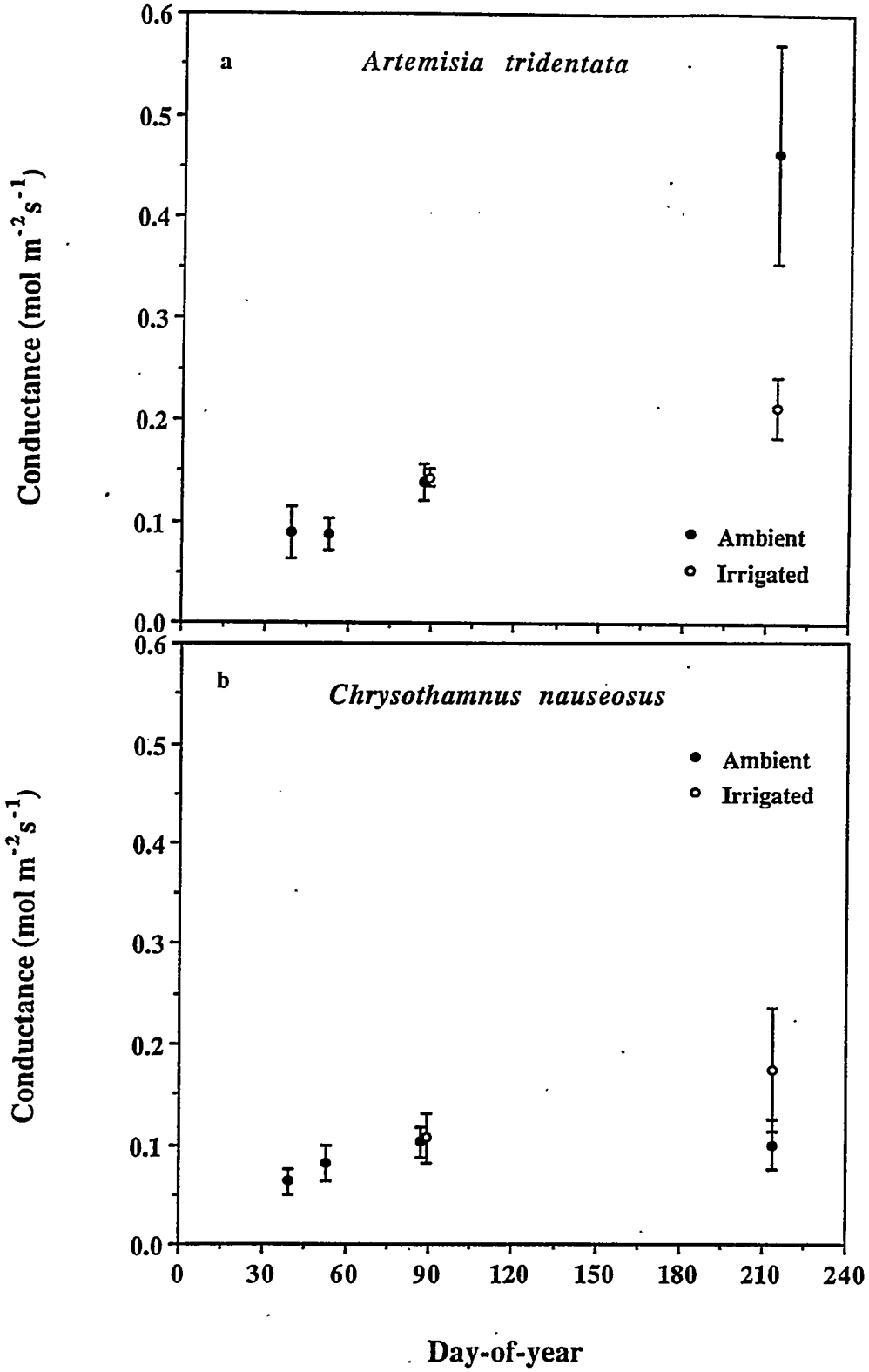

Figure 5.7. Conductance of water vapor *in Artemisia tridentata* (a) and *Chrysothamnus nauseosus* (b) in 1995 and 1996. Data collected in 1996 occurred on day 212. Error bars are one standard error of the mean.

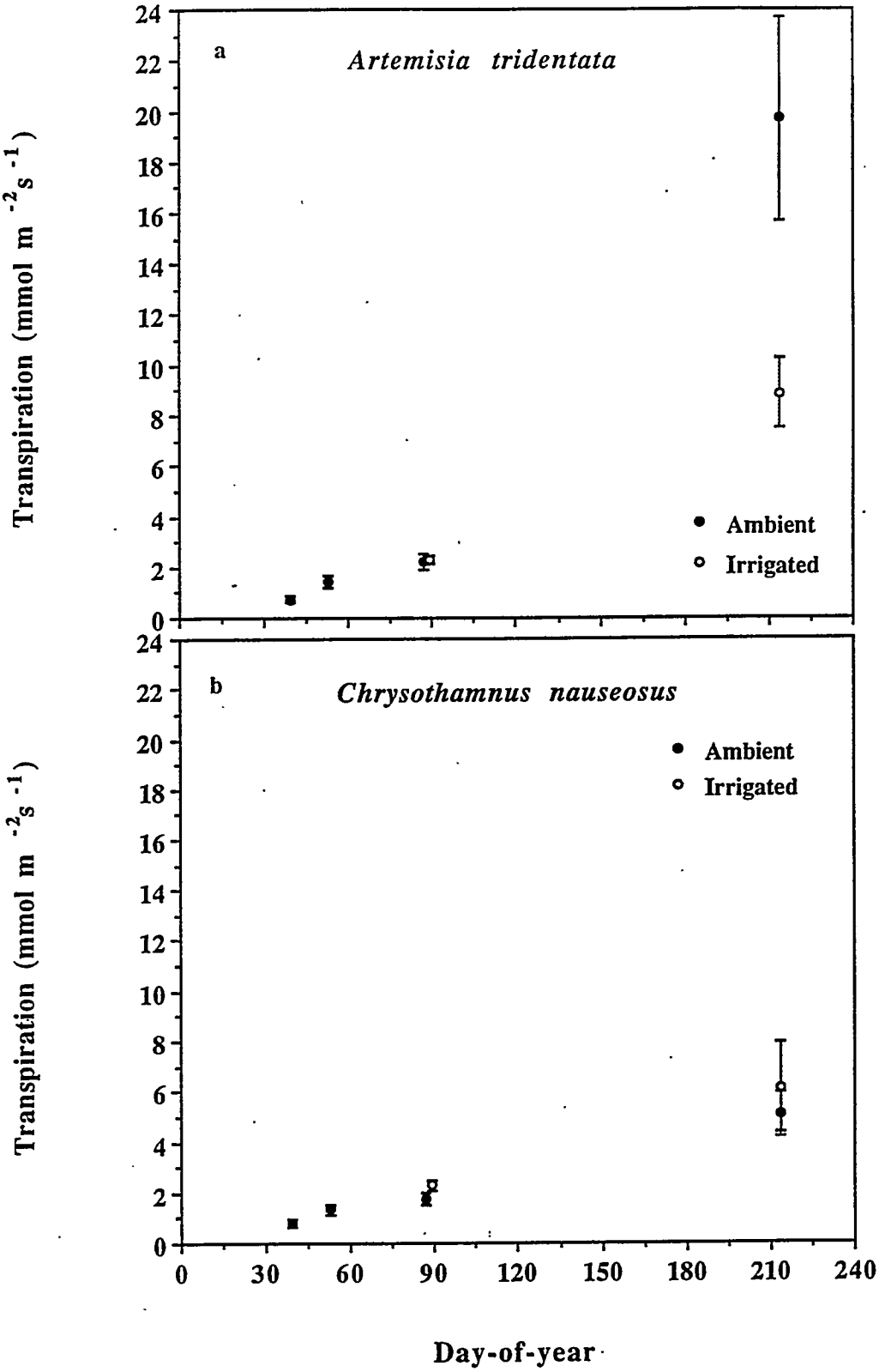

Figure 5.8. Transpiration in *Artemisia tridentata* (a) and *Chrysothamnus nauseosus* (b) in 1995 and 1996. Data collected in 1996 occurred on day 212. Error bars are 1 standard error of the mean.

5.1.5 Xylem Pressure Potential

Predawn xylem pressure potential data were gathered on August 1, 1996 with a pressure chamber (Soil Water Equipment Co.), after Scholander et al. (1965). Data were gathered on both shrub species in both irrigated and ambient precipitation treatments. Xylem pressure potential data were obtained by placing cut stems (about 10 cm in length) in the pressure chamber and slowly pressurizing with nitrogen gas until the tip of the stem first showed evidence of a color change due to expressed water. A wet paper towel was placed in the chamber to maintain a humid atmosphere around the stem and leaf material during pressurization. Treatment effects on xylem pressure potential were compared using Student's t-test (Steele and Torrie 1960) within species.

Xylem pressure potential values were significantly lower in the ambient precipitation treatment than in the irrigated treatment (Table 5.6). Both species had almost identical mean values within treatments, with more variation in the ambient precipitation treatment than in the irrigated treatment. Values ranged from -0.7 to -1.2MPa in the irrigated treatment and -2.7 to -5.5 MPa in the ambient precipitation treatment.

5.1.6 Roots

Root observations were taken using a Circon Agricultural camera in clear mini-rhizotron tubes inclined at a 45° angle. Six mini-rhizotrons were placed in the irrigated and unirrigated halves of the surface. Observations were taken from July 13 to July 21 in 1995 and in June 1996. 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 were then divided by the observation area to yield a root length density value (Upchurch and Ritchie 1983).

Root length data are presented with respect to treatment, year, and depth in Figure 5.10. Root length density increased with depth down to about 110 to 150 cm, where root length density was the greatest (Figure 5.10a,b). Below 150 cm root length density was generally lower. By 1996 roots had penetrated to the bottoms of all the tubes.

Root length density is related significantly to the treatments, year, depth, and the interaction of treatments and year by ANOVA (Table 5.7). There were no differences detectable between year and treatments at any particular depth because of the variable and relatively large error terms (Figure 5.10). Although means could not be separated, the effect of treatment was significant, with root length density in the irrigated treatment apparently greater than that in the ambient precipitation treatment in 1996. Similarly, there was an apparent increase in root length density in 1996 compared with that in 1995 in the irrigated treatment.

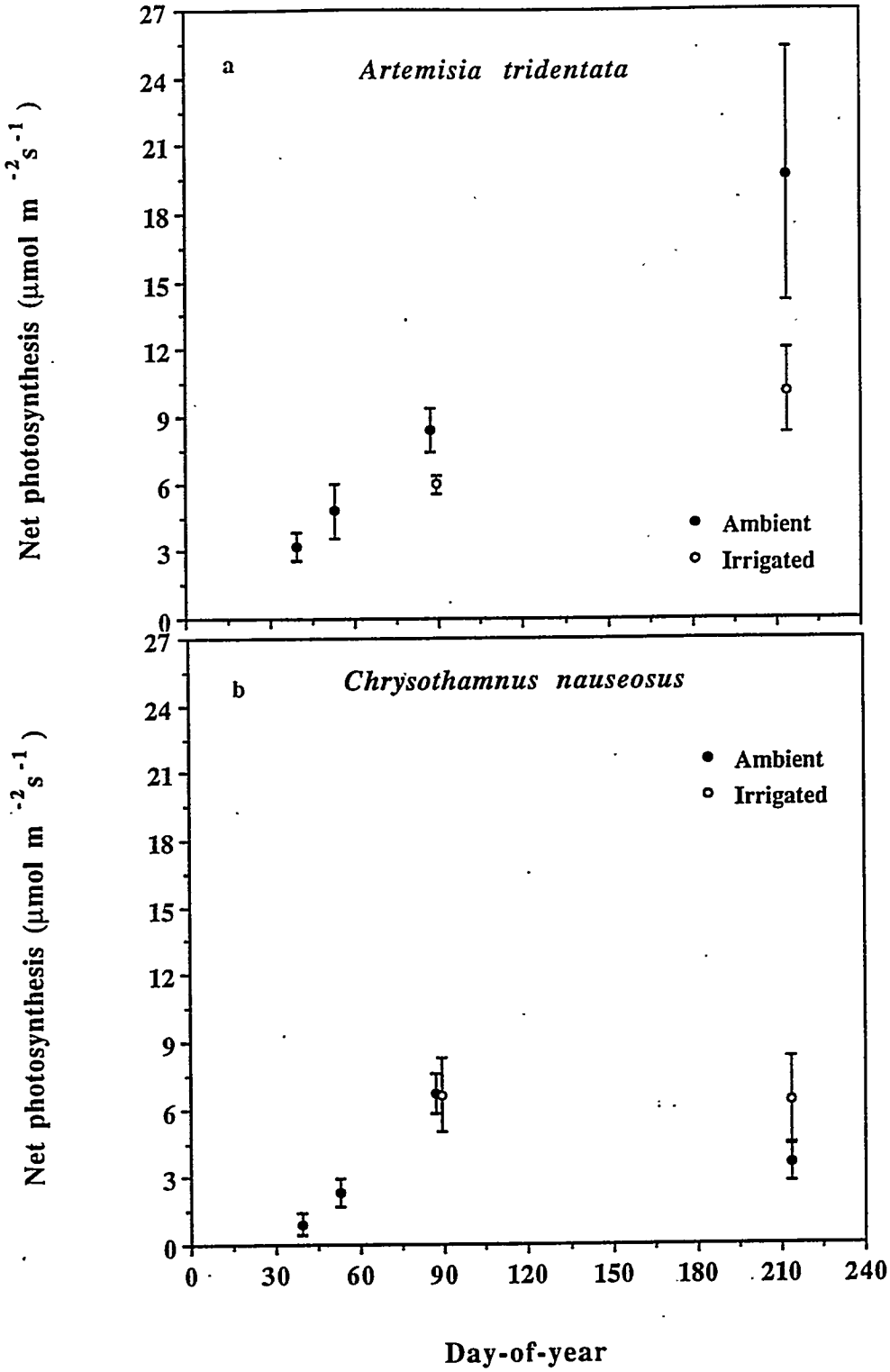

Figure 5.9. Net photosynthesis in *Artemisia tridentata* (a) and *Chrysothamnus nauseosus* (b) in 1995 and 1996. Data collected in 1996 occurred on day 212. Error bars are 1 standard error of the mean.

Table 5.6. Mean pre-dawn xylem pressure potential with one standard error (SE, n = 5 to 6). Means with differing letters within species are significantly different.

Species	Treatment	Mean xylem Pressure Potential (MPa)	SE
A. tridentata	irrigated	-0.92[a]	0.086
	ambient	-0.87[b]	0.418
C. nauseosus	irrigated	-0.92[a]	0.066
	ambient	-3.88[b]	0.305

Table 5.7. Analysis of variance for the effects of water (irrigation and ambient precipitation), year (1995, 1996) and depth on root length density.

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**	**Prob>F**
Model	4	336.37	84.09	7.37	0.0000
Error	239	2726.95	11.41		
C Total	243	3036.32			
Effect Test					
Source	**Nparm**	**DF**	**Sum of Squares**	**F Ratio**	**Prob>F**
Treatment	1	1	336.37	6.86	0.0094
Year	1	1	68.88	6.04	0.0147
Depth	1	1	55.41	4.86	0.0285
Treatment * Year	1	1	118.37	10.37	0.0015

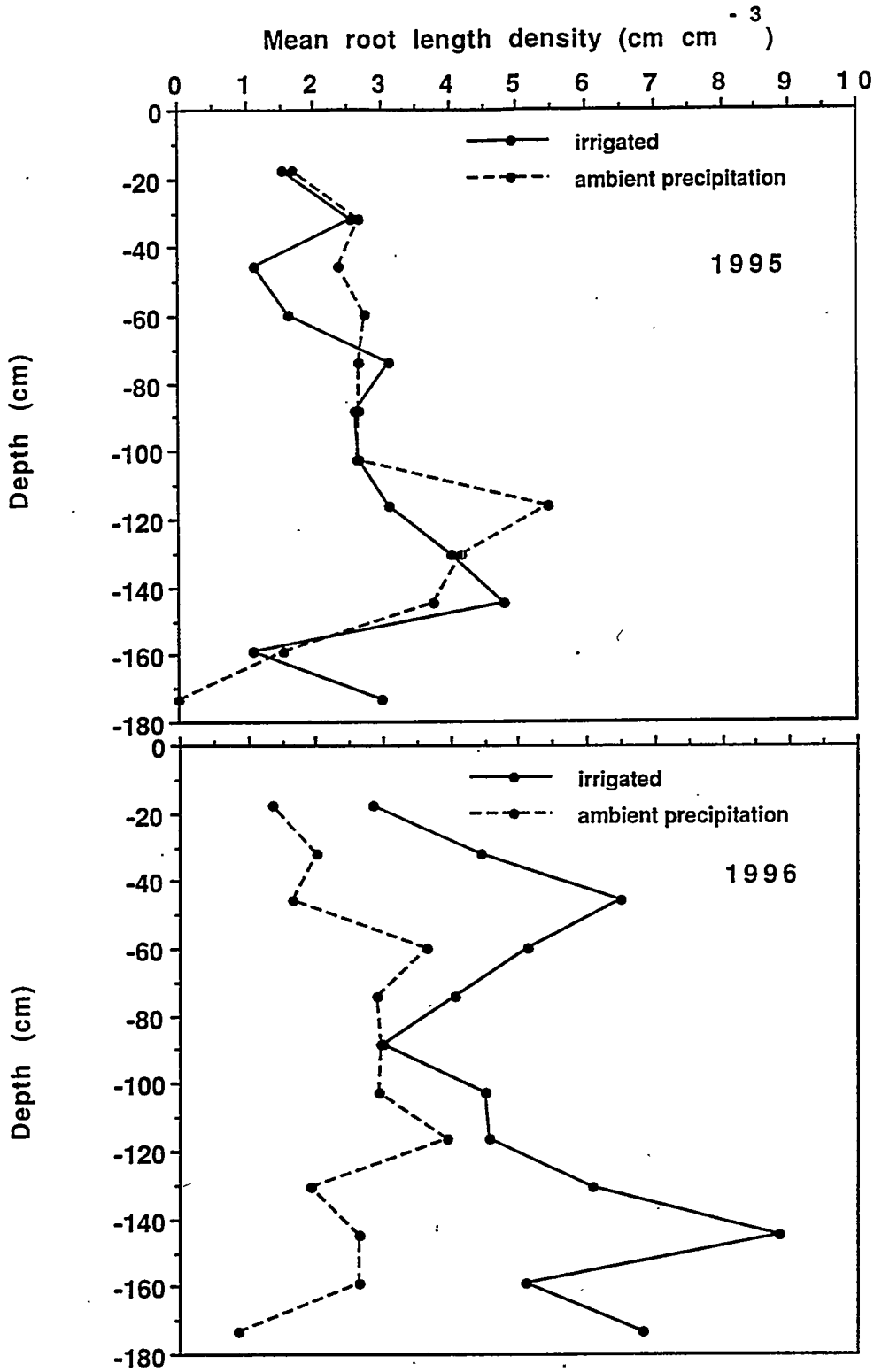

Figure 5.10. Mean root length density as a function of depth and treatment in 1995 (a) and in 1996 (b). One standard error of the mean ranged from 0.5 to 6.9 with a mean of 2.77 computed on 48 values associated with the means in the figure. Error bars are not presented.

5.1.7 Survivorship

In 1996 a census of live and dead shrubs was conducted in all 300 quadrats. The mean survivorship of the shrubs was compared with respect to the treatment (Table 5.8). *Chrysothamnus nauseosus* survivorship was significantly greater in the irrigated treatment than in the ambient precipitation treatment. In contrast, survivorship of *A. tridentata* was significantly greater in the ambient precipitation treatment than in the irrigated treatment. Survivorship of *A. tridentata* was near 97% across treatments which is much greater than survivorship of *C. nauseosus* across treatments (57%). There was little change in survivorship in *A. tridentata* from 1995 to 1996, while there was a great decrease in survivorship (from 92% in 1995 to 57% in 1996) for *C. nauseosus* (Gee et al. 1995).

Table 5.8. Shrub survivorship after 2 yrs, based on the ratio of live to live + dead individuals per 9-m^2 quadrat. Mean survivorship values are presented with one standard error (SE, n = 144) without transformation. Means with differing letters within species are significantly different after arcsin transformation.

Species	Treatment	Mean Survivorship	SE
A. tridentata	irrigated	0.959^a	0.007
	ambient	0.980^b	0.004
C. nauseosus	irrigated	0.714^a	0.028
	ambient	0.418^b	0.031

5.2 Animal Observations

Animal evidence on the surface was casually noted in 1995 and measured in 1996. In 1996 evidence of animal presence (feces, burrows) was noted by inspection in all 300 quadrats on the surface between May 24 and June 7.

There was evidence in 20% of the quadrats in the ambient precipitation half of the barrier and in 8% of the quadrats in the irrigated half. There were nine holes observed on the surface.

5.3 Conclusions

The establishment of a viable and highly diverse plant community on the surface after 2 yr continues to have a significant effect on the function of the surface. The complete coverage by deep-rooted perennials has completely dried out the soil cap even with three times normal precipitation. The plant community has accommodated the excess precipitation with more vegetative matter. 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 second year to make sure that its abilities will continue.

6.0 QUALITY ASSURANCE

The prototype barrier testing is operated under Quality Assurance plan OHE-002, Rev.5, which is a controlled document and located in the project files and with each task leader. This plan is the guiding document for the testing on the prototype surface barrier. Specific test procedures are identified in the QA plan and include procedures for irrigation applications, snow applications, dosing siphon measurements and a series of water content measurements and soil and aggregate analysis. Data reduction related to drainage and water balance measurements are emphasized both in the test plan and the quality assurance plan. Data from water infiltration, water storage measurements, wind and water erosion and biointrusion tasks are collected and input into laboratory record books (LRBs) and into data loggers and electronic data files. These files are formatted for subsequent graphical display and analysis. Detailed records are kept and hard copy files are maintained at the task level. The test results and data are compiled in data summary reports and are periodically reviewed. The QA procedures are reviewed annually.

Procedures that are specific to the prototype barrier project include the following:

PNL-PSB-2.0	Procedure for Measuring Soil Moisture Using the Neutron Probe in the Neutron Access Tube Vertical and Horizontal Arrays.
PNL-PSB-3.0	Irrigation Applications.
PNL-PSB-4.0	Snow Applications.
PNL-PSB-5.0	Dosing Siphon Monitoring.
PNL-PSB-6.0	Pan Lysimeter Under Asphalt Pad Monitoring Protocol.
PNL-PSB-7.0	Vertical Capacitance Probe Measurements.
PNL-PSB-8.0	Procedure for Measuring Soil Water Content Using the Moisture Point Soil Moisture Instrument.

Data analysis focuses on quantifying barrier performance. Quantification of water balance is made on selected test areas and reported at least on an annual basis. Beginning in FY 1997, the irrigation and water storage data will be provided to Bechtel Hanford, Inc. on a monthly basis as part of the formal reporting system. The measurement error in water storage and evapotranspiration will be reported in the annual summary report. Wind and water erosion and biotic intrusion will be reported on a more qualitative basis, but where possible, measurement error and uncertainties will be documented. The performance of the barrier under irrigated and non irrigated conditions will be compared for similar time periods and for a minimum of three years.

7.0 FUTURE TESTING AND MONITORING PLANS

FY 1997 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. A summary report documenting the status of the prototype testing and monitoring for the 3-yr study will be prepared in late August for review in September 1997.

7.1 Water Balance Monitoring and Tests

Activities will include continued testing of instrumentation to measure complete water balance on the soil surface and the sideslope plots under irrigated and ambient conditions. Irrigation will be continued in FY 1997. Irrigation will continue as planned through the winter but will not be applied under freezing conditions. During the last week of March 1996 there will be an intense water application. Two scenarios are under consideration. The first scenario is to continue with the present water application pattern, that is, by use of irrigation, we will apply 70 mm applied in an 8-hr period. This irrigation is designed to represent a 1000-yr storm event. The second scenario is to apply 200 mm by irrigation in a 24-hr period, representing a probable maximum precipitation (PMP) event. The actual amount of water applied will be determined after additional discussions with Bechtel and DOE-RL staff. In both cases, 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. The distribution of water will be altered as needed to attain the 480-mm target for the water year. One of the purposes of testing the prototype barrier with a PMP is to look at barrier response under conditions where runoff is likely. As noted, no runoff was observed in 1996 during or after the 1000-yr storm testing, suggesting that the vegetation surface features of the prototype were effective in eliminating runoff. With higher precipitation rates, runoff is more likely.

As in the previous 2 yr, water balance parameters, precipitation, water storage and drainage will all be monitored nearly continuously for the duration of 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. A study will continue to examine why more water has drained from the clean-fill (gravel) sideslope than from the rock sideslopes.

7.2 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, located on the north (irrigated) half of the prototype will be used to document both runoff water volumes and sediment loads. 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-yr storm or PMP test in March to document surface response to intense storm events. Because of past experience, the south side of the prototype barrier will not be retrofitted with a plot to document runoff under ambient (nonirrigated) conditions. Experience to date data indicates the south (ambient precipitation) side of the prototype has not and will not experience runoff. We will, however, document any snowmelt events for potential runoff conditions for the entire barrier surface and provide qualitative estimates of runoff from quadrats (sections of the barrier) that are not directly monitored.

7.3 Wind Erosion

Wind erosion will be documented using established stations to monitor peak gust winds and wind boundary layers during windstorms. 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, since our experience dictates that soil loss by wind erosion is minimal. 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. We will continue 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. Measurements of gravel content in the top 10 cm will continue through FY 1997. It is recommend that duplicate samples be taken from each of the designated quadrats to improve the reliability of the statistical analysis.

7.4 Biointrusion

Both animal and plant intrusion will continue to be documented in FY 1997. Plant community dynamics, via vegetation changes, will be documented. We have seen this past year that there was a dramatic 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. 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.

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