# Status Report for the Small-Tube Lysimeter Facility Fiscal Year 1990

Prepared for the U.S. Department of Energy
Office of Environmental Restoration and
Waste Management

**Westinghouse Hanford Company** Richland, Washington

Hanford Operations and Engineering Contractor for the
U.S. Department of Energy under Contract DE-AC06-87RL10930

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# Status Report for the Small-Tube Lysimeter Facility Fiscal Year 1990

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## EXECUTIVE SUMMARY

Westinghouse Hanford Company and Pacific Northwest Laboratory are jointly developing earthen protective barriers for the near surface disposal of radioactive and hazardous waste at the Hanford Site. The proposed barrier design consists of a blanket of fine-textured soil overlying a sequence of layers, varying from sand-to-basalt riprap. The experiments conducted at the Small-Tube Lysimeter Facility were designed to measure the influence of erosion control practices and alternative barrier layering configurations on water movement within the barrier, and extraction of water from the barrier.

This report describes the results of nearly 2 full years of data collection at the Small-Tube Lysimeter Facility. Four concurrent experiments are being performed at this facility, each of these experiments are designed to test different components of the proposed barrier. The experiments are described in the following paragraphs.

**Surface Treatment Effects (12 treatments with 5 replications).** This experiment is designed to test the effects of various erosion control practices on soil column water storage and evapotranspiration, and includes all combinations of the following main effects:

- Surface treatment (plain soil, gravel admix, gravel mulch)
- Precipitation (ambient and twice average)
- Vegetation (cheatgrass and bare).

**Layering Sequence Effects (four treatments, five replications).** This experiment is designed to test two different subsurface capillary break structures under twice the long term average precipitation. Treatment include combinations of:

- Layering treatment (pit-run or bimodal gravel versus graded sand)
- Vegetation (cheatgrass and bare).

**Surface Sand and Gravel Effects (six treatments, five replications).** This experiment is designed to assess the effects of aeolian deposition of sand on a protective barrier under twice average precipitation. The results are compared with the effects of a gravel-mulch, erosion control treatment. Treatments include combinations of the following:

- Surface layer (none, sand, gravel)
- Vegetation (cheatgrass and bare).

**Alternative Barriers (three treatments, five replications).** Low-permeability, subsurface infiltration barriers are being considered as a built-in redundancy for protection against water infiltration through the

protective barrier. The performance of these alternative barriers is being examined at the Small-Tube Lysimeter Facility. Described in this report are results for clay and chemical grout subsurface barriers. None of the lysimeters are vegetated and all receive twice average precipitation.

The results of this study are summarized in the following paragraphs.

**Surface Treatment Effects.** All three of the main factors (surface treatment, precipitation, and vegetation) had significant effects on both water storage change and cumulative evapotranspiration. Generally, lysimeters with a gravel mulch surface had significantly greater storage change and significantly less cumulative evapotranspiration than lysimeters with either a soil or gravel admix surface. The presence of vegetation generally increased the evapotranspiration and decreased the amount of storage. Lysimeters that received twice the long-term average precipitation typically had greater evapotranspiration and greater storage than lysimeters that received ambient precipitation. Drainage occurred only in the irrigated gravel mulch treatments.

**Layering Sequence Effects.** There were no significant storage or evapotranspiration differences between the bimodal and graded subsurface layering treatments. Vegetation tended to increase the evapotranspiration and decrease the total storage change only during the drier portions of the year. No drainage was found in any of the bimodal or graded layer lysimeters.

**Surface Sand and Gravel Effects.** A sand deposition layer was found to have a similar effect on soil column water balance as a gravel mulch layer. Both types of surface layers significantly decreased the amount of evapotranspiration and increased the amount of storage compared to control lysimeters that have a plain soil surface. Vegetation significantly increased the amount of cumulative evapotranspiration from the sand and gravel covered lysimeters during the second year of measurement. Drainage was detected from both the sand and gravel covered lysimeters, with no significant differences among the treatments.

**Alternative Barrier Effects.** There were no significant storage or evapotranspiration differences between the clay and grout treatments. However, the grout treatment had significantly higher amounts of evapotranspiration than the control treatments (bimodal and graded capillary breaks) at the early sampling dates. This difference might be attributable to the high water content of the grout slurry used to form this lysimeter layer. The drying of the grout slurry layer may account for the increase in evapotranspiration noted from these lysimeters. None of the clay or grout lysimeters produced detectable drainage.

All barrier configurations with or without plants, and with or without gravel admix, prevented drainage under both ambient and twice average precipitation conditions. This result indicates that the barrier, as currently designed, will prevent water infiltration under the conditions simulated. Barrier configurations that included a surface layer of either

sand or gravel did not prevent drainage. This implies that if a gravel admix surface erodes to form a gravel mulch or if sands are deposited on the barrier surface, then infiltration may be possible. The probabilities of these occurrences should be evaluated.

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## LIST OF TERMS

| | |
|---|---|
| ABS | acrylonitrile-butodiene-styrene |
| ALE | Hanford Site Arid Lands Ecology Reserve |
| ANOVA | analysis of variance |
| ET | evapotranspiration |
| FLTF | Field Lysimeter Test Facility |
| FY | fiscal year |
| HMS | Hanford Meteorological Station |
| PNL | Pacific Northwest Laboratory |
| PVC | polyvinyl-chloride |
| STLF | Small-Tube Lysimeter Facility |

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# STATUS REPORT FOR THE SMALL-TUBE LYSIMETER TEST FACILITY, FISCAL YEAR 1990

## 1.0 INTRODUCTION

The Westinghouse Hanford Company (Westinghouse Hanford) and Pacific Northwest Laboratory (PNL) are jointly developing protective barriers for the long-term isolation of low level radioactive and mixed radioactive/hazardous waste at the Hanford Site for the U.S. Department of Energy. Protective barriers have been identified as an integral part of the overall final disposal strategy for low-level defense waste at the Hanford Site (DOE 1987).

Several performance objectives have been developed for a protective barrier: (1) water infiltration to and through the waste should be limited to near-zero amounts, (2) intrusion into the waste by plants, animals, and humans should be minimized, (3) minimal wind and/or water erosion should occur during the functional lifetime of the barrier, and (4) the barrier should be maintenance free and functional for a period up to 10,000 yr. A protective barrier designed to meet these general criteria should isolate the waste, minimize the transport and release of contaminants to the environment, and could be considerable less expensive than other treatment and disposal options (DOE 1987).

The current conceptual design of the Hanford Site protective barrier is a multi-layered earthen structure consisting of a fine soil surface layer overlying a sequence of layers grading downward from sand to basalt riprap. The textural difference between the fine soil and coarser materials functions as a capillary break, which helps prevent water from flowing from the finer material to the coarser material; this allows the fine soil layer to hold more moisture. Water held above the textural interface can then be recycled to the atmosphere through the processes of soil evaporation and plant transpiration. Additional, redundant infiltration barriers of clay, chemical grout, or asphalt also may be included in the design. The basalt rip-rap layer is designed to reduce plant root and animal intrusion into the waste, and also may serve as a deterrent to human intrusion. Erosion control will be accomplished through the placement of gravel on the surface of the fine soil surface either as a mulch, or as an admixture (homogeneous mixture of gravel and soil) in the upper 20 to 30 cm, establishment of a vegetative cover, and control of the barrier surface slope angle. Preliminary wind tunnel investigations indicate that either method would provide adequate protection from wind erosion (Ligotke 1989). The conceptual protective barrier design uses only natural materials that are expected to withstand degradation for at least 10,000 yr.

The Small-Tube Lysimeter Facility (STLF) was designed and constructed to test the effects of different layering sequences, surface erosion control practices, and alternative infiltration barriers on the soil-column water balance of a simulated protective barrier (Waugh and Link 1987, Relyea et al. 1990, Freeman et al. 1989). The conceptual barrier design uses a carefully

graded series of gravel, sand, and fine soil to form a stable capillary break. An alternative structure of the capillary break is fine soil over pitrun gravel. Pitrun gravel has a bimodal particle size distribution (sand and gravel), and is hence termed bimodal gravel in this report. The bimodal gravel design would probably be less expensive to construct and would more closely resemble natural soil structures on the Hanford Site. However, the bimodal design may be less effective in minimizing infiltration; this is currently being tested at the STLF.

The addition of gravel to the barrier surface either as a mulch or as an admix will provide considerable erosion protection compared with a bare soil surface. The surface gravel also may affect infiltration and decrease the amount of soil evaporation, thus increasing the likelihood of water infiltration through the waste. These effects are being examined at the STLF and at the McGee Ranch Admix test plots (Waugh and Link 1987, Waugh 1988). An additional potential problem for a protective barrier is the eolian deposition of sand on top of the fine soil layer. This also would be expected to increase the soil surface infiltration and reduce the amount of soil evaporation. This effect is also being examined at STLF.

The inclusion of a very low permeability sublayer within the protective barrier would function as a redundant infiltration barrier, and would help to protect the underlying waste even under extremely high-intensity storm events. The efficacy of sublayers of clay, chemical grout, and various types of asphalt are being studied at the STLF. Studies involving clay and chemical grout sublayers are described in this report; the asphalt experiments are described separately (Freeman et al. 1989, Freeman and Gee 1989). This report describes the operations and results of nearly 2 yr of data collection at the STLF. Relyea et al. (1990) describe the initial conditions and fill specifications for each of the lysimeters. The results for both fiscal year (FY) 1989 and FY 1990 are analyzed and described in this report.

# 2.0 MATERIALS AND METHODS

## 2.1 THE SMALL TUBE LYSIMETER FACILITY

The STLF is located adjacent to the Hanford Meteorological Station (HMS), within the protective Barrier Field Lysimeter Complex. It consists of 105 lysimeters arranged in an array of 21 rows of 5 lysimeters each (Figure 2-1). Eighty of the lysimeters (rows 1 through 16) are used to test the effects of various erosion control practices, sand deposition, and barrier layering sequences on soil column water balance. The remaining 25 lysimeters (rows 17 through 21) are used to test alternative infiltration barriers (clay, chemical grout, asphalt) that have been proposed as impermeable components of a protective barrier system (Freeman et al. 1989).

Each lysimeter consists of a 169 cm long, 30.4 cm internal diameter acrylonitrile-butadiene-styrene (ABS) well casing placed inside a 175-cm-long, 39-cm-dia polyvinyl-chloride (PVC) sleeve. The tops of the sleeves and lysimeter tubes are placed approximately 2.5 cm abovegrade. A rubber insulating collar (36-cm-bicycle inner-tube, painted white) is placed at the upper end of each lysimeter tube in order to minimize heat transfer between the atmosphere and the airspace between the sleeve and lysimeter tube. Each lysimeter tube is fitted with a recessed cap at the bottom and an aluminum lifting collar at the top. The aluminum collar serves both as a rigging attachment point during weighing and as a coupling interface for an acrylic plant gas exchange chamber that is used for separate controlled experiments on photosynthesis and evapotranspiration (ET) (Waugh and Link 1987, Link and Waugh 1989, Link et al. 1990).

The sealed tube serves as a combined weighing and drainage lysimeter. Drainage is measured monthly by collecting water from a clear, flexible polymer tube that is fitted to a threaded drain hole at the low end of the end cap. Changes in water storage are estimated as the monthly weight change, which is measured by suspending the lysimeters from a load cell attached to a gantry crane.

The lysimeters were each filled by hand with layers of gravel, sand, silt loam soil, pit-run gravel, and impermeable barrier material. The exact materials and layering sequences for each tube depended on the assigned treatment combination for that lysimeter (Figure 2-2). The treatment combinations are described in Section 2.2, and complete descriptions of the lift thicknesses, weights, moisture contents and initial conditions for each lysimeter can be found in Relyea et al. (1990). Construction and filling were completed in mid-September 1988. A section of black-steel grating (1 by 2 m) is placed at the soil surface between the rows of lysimeters. These grating sections allow workers to move about the facility with minimal disturbance to the lysimeters.

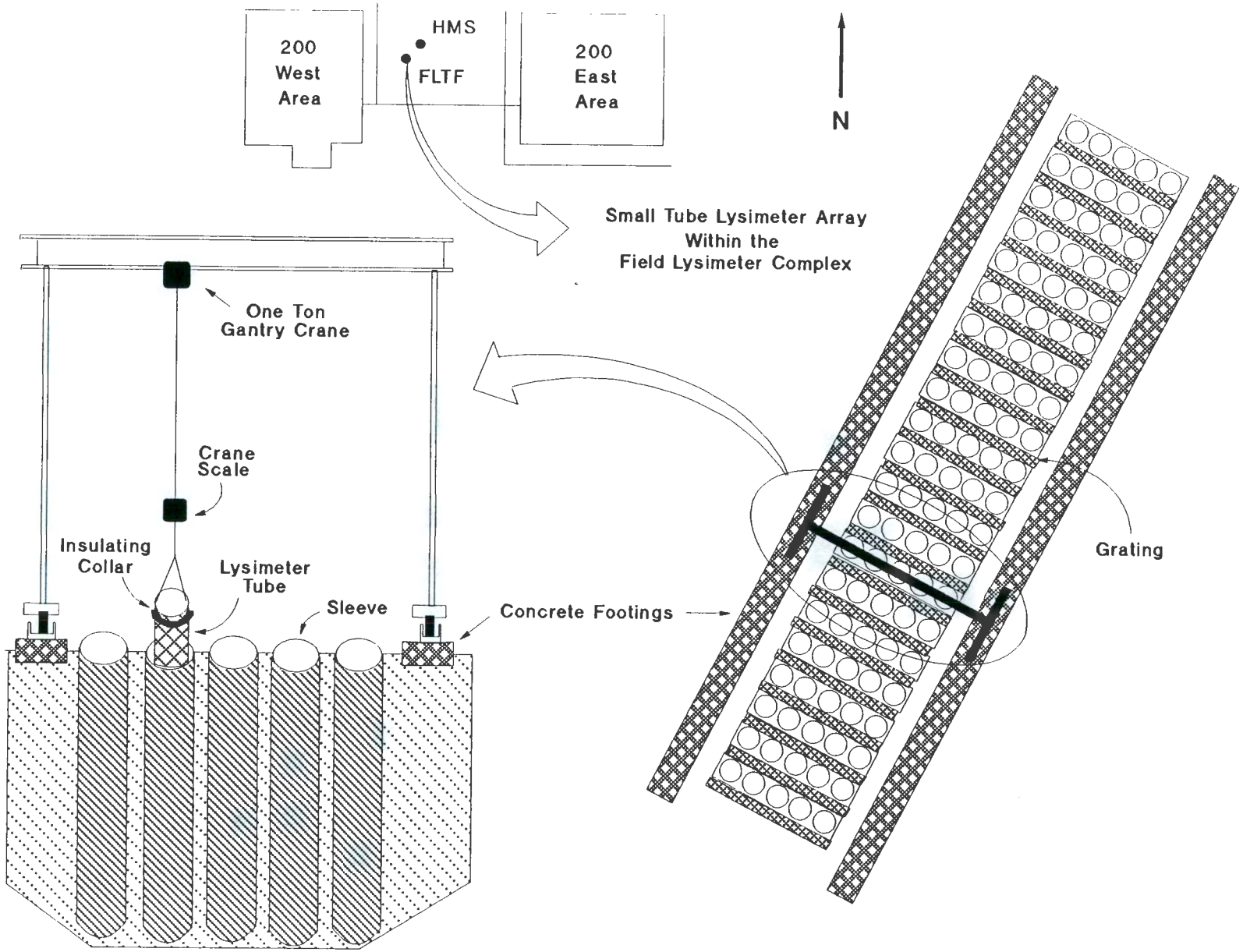


Figure 2-1. Illustration of the Small-Tube Lysimeter Facility.

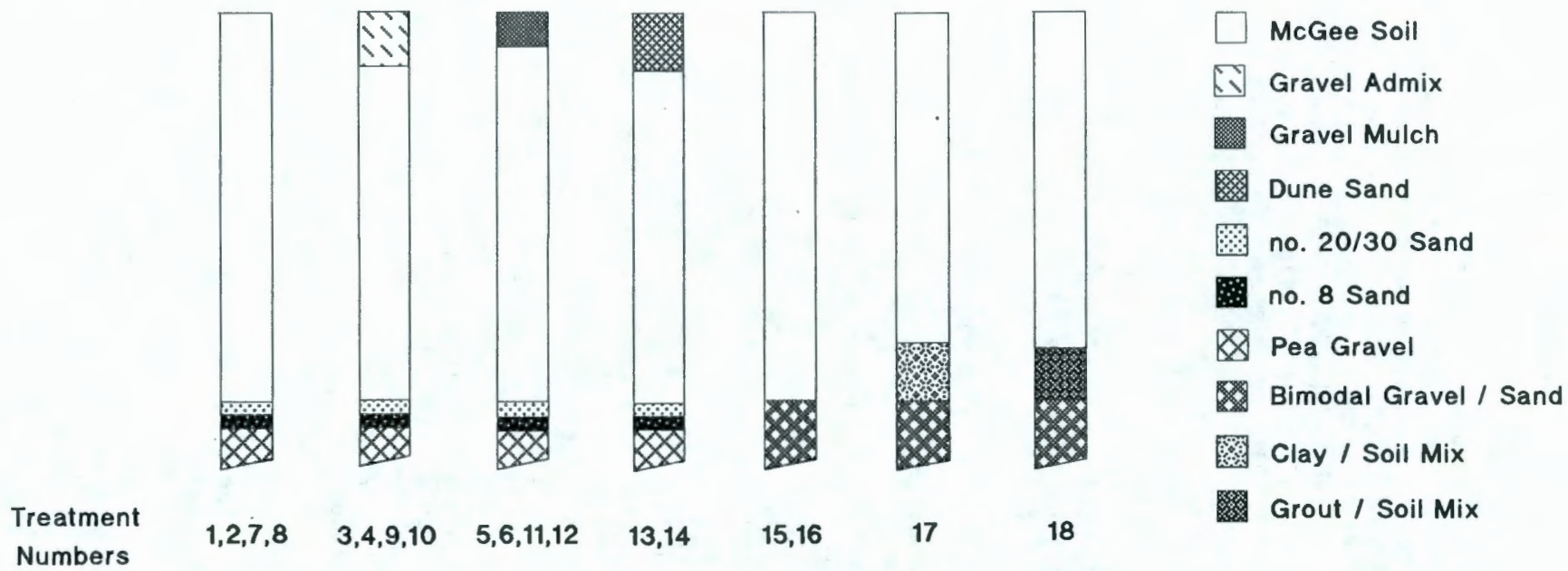


Figure 2-2. Layering Sequences of Small-Tube Lysimeter Facility Treatment Lysimeters.

## 2.2 DESCRIPTION OF EXPERIMENTS

The experiments at STLF represent an expansion of the studies conducted at the Field Lysimeter Test Facility (FTLF) (Kirkham et al. 1987). Several of the treatment combinations are in common with the treatments included in the FLTF design, and some match the conditions in previous UNSAT-H simulations of unsaturated soil water movement (Fayer et al. 1985) performed in support of the Hanford Site protective barrier program. The data acquired at SLTF will supplement the FLTF data for validation of the UNSAT-H computer code (Fayer 1990). The primary advantage of performing experiments at SLTF is the ability to greatly increase both the number of treatment combinations and the number of replicates of each treatment, thus improving the statistical power and confidence levels associated with the analysis of the resultant data (Waugh and Link 1987).

The studies conducted at STLF are primarily comparative experiments devised to measure the influence on water storage, ET, and drainage of the following factors:

- Surface gravel admix and gravel mulch
- Sand deposition
- Twice the long-term average precipitation
- Vegetation
- Structural sequence of the capillary break
- Impermeable alternative infiltration barriers.

One or more of these factors are included in the treatment combination assigned to each lysimeter. These treatment combinations are summarized in Table 2-1. Treatment descriptions and initial results of the asphalt barrier tests are provided in Freeman et al. (1989) and Freeman and Gee (1989).

The inclusion of all six of the factors (previously listed) in one experimental design would require a facility at least twice as large as the present STLF, and would result in several impractical treatment combinations. Therefore, four interconnected, but separate experiments (statistical models), are performed simultaneously to analyze the effects of the six factors of interest. A complete statistical description of these models is provided in Relyea et al. (1990). The experimental designs are briefly summarized in the following paragraphs.

**Experiment 1.** The first experiment is a 3 by 2 by 2 factorial analysis of variance (ANOVA) designed to test the effects of erosion control practices. It includes three different surface treatments (plain soil, 30% gravel admix, and surface gravel mulch), two levels of precipitation (ambient and two times the long-term average), and the presence or absence of vegetation. There are

Table 2-1. Treatment Structure for Experiments at Small-Tube Lysimeter Facility.

| Treatment combinations | Barrier layering | | Vegetation | | Surface treatments | | | Precipitation | |
|---|---|---|---|---|---|---|---|---|---|
| | Graded | Bimodal | Bare | Cheatgrass | Admix gravel | Surface gravel | Dune sand | Ambient | Twice average |
| 1 | X | - | X | - | - | - | - | X | - |
| 2 | X | - | X | - | - | - | - | - | X |
| 3 | X | - | X | - | X | - | - | X | - |
| 4 | X | - | X | - | X | - | - | - | X |
| 5 | X | - | X | - | - | X | - | X | - |
| 6 | X | - | X | - | - | X | - | - | X |
| 7 | X | - | - | X | - | - | - | X | - |
| 8 | X | - | - | X | - | - | - | - | X |
| 9 | X | - | - | X | X | - | - | X | - |
| 10 | X | - | - | X | X | - | - | - | X |
| 11 | X | - | - | X | - | X | - | X | - |
| 12 | X | - | - | X | - | X | - | - | X |
| 13 | X | - | X | - | - | - | X | - | X |
| 14 | X | - | - | X | - | - | X | - | X |
| 15 | - | X | X | - | - | - | - | - | X |
| 16 | - | X | - | X | - | - | - | - | X |
| 17 | - | X | X | - | - | - | - | - | X |
| 18 | - | X | X | - | - | - | - | - | X |

a total of 12 treatment combinations (treatments 1 through 12), with five replicates of each combination. All of the lysimeters in this experiment have a graded capillary break structure.

**Experiment 2.** This experiment is a 2 by 2 factorial analysis of variance designed to test the effects of different capillary break layering sequences. It includes two different capillary break structures (graded sand versus the bimodal or soil over pit-run gravel/sand structure), and the presence or absence of vegetation. This experiment includes four treatment combinations (treatments 2, 8, 15, and 16) with five replicates of each treatment.

**Experiment 3.** The third experiment is a 2 by 2 factorial analysis of variance designed to test the effects of a sand deposition layer and vegetation on soil column water balance. It includes two sand deposition treatments (pure soil and 20-cm surface sand layer) and two levels of vegetation (none and cheatgrass). This experiment includes four treatment combinations (treatments 2, 8, 13, and 14) with five replicates of each treatment combination. Each of these lysimeters has the graded sand capillary break. All of the lysimeters in experiments 2 and 3 receive the two times precipitation treatment.

**Experiment 4.** The fourth experiment uses a one way analysis of variance to compare the effects of a clay subsurface layer (treatment 17), a chemical grout layer (treatment 18), and the designated control treatment (bimodal capillary break - treatment 15), using five replicates of each treatment. We included an additional control treatment (graded subsurface capillary break) in some of the analyses. All of the lysimeters in this experiment receive the two times the precipitation treatment and none are vegetated.

The 80 lysimeters used in experiments 1 through 3 are arranged randomly throughout rows 1 through 16 of the SLTF array (Figure 2-3). The five lysimeters used for testing the clay layer are in row 17, and the five used for chemical grout are in row 18. Rows 19 through 21 are being used for a separate evaluation of asphalt subsurface layers (Freeman et al. 1989 ) and are not included in the main statistical design.

## 2.3 SUPPLEMENTAL APPLIED IRRIGATION

Two precipitation treatments are included in the STLF experiments. The ambient treatment lysimeters receive only natural precipitation, which is recorded at the HMS. The two times (twice average) treatment receives natural precipitation plus enough irrigation to bring the total water input twice the long-term average precipitation. Irrigation is applied over a period of 1 to 4 hours within 2 to 3 weeks following the end of each month in which rainfall is less than twice the long-term average. Table 2-2 shows the monthly average precipitation, the recorded precipitation, and the amounts of irrigation applied during each month of the study. In April 1989, some of the ambient tubes were inadvertently irrigated, so the same amount of water (2.49 cm) was subsequently added to all of the ambient tubes to preserve the statistical models previously described.

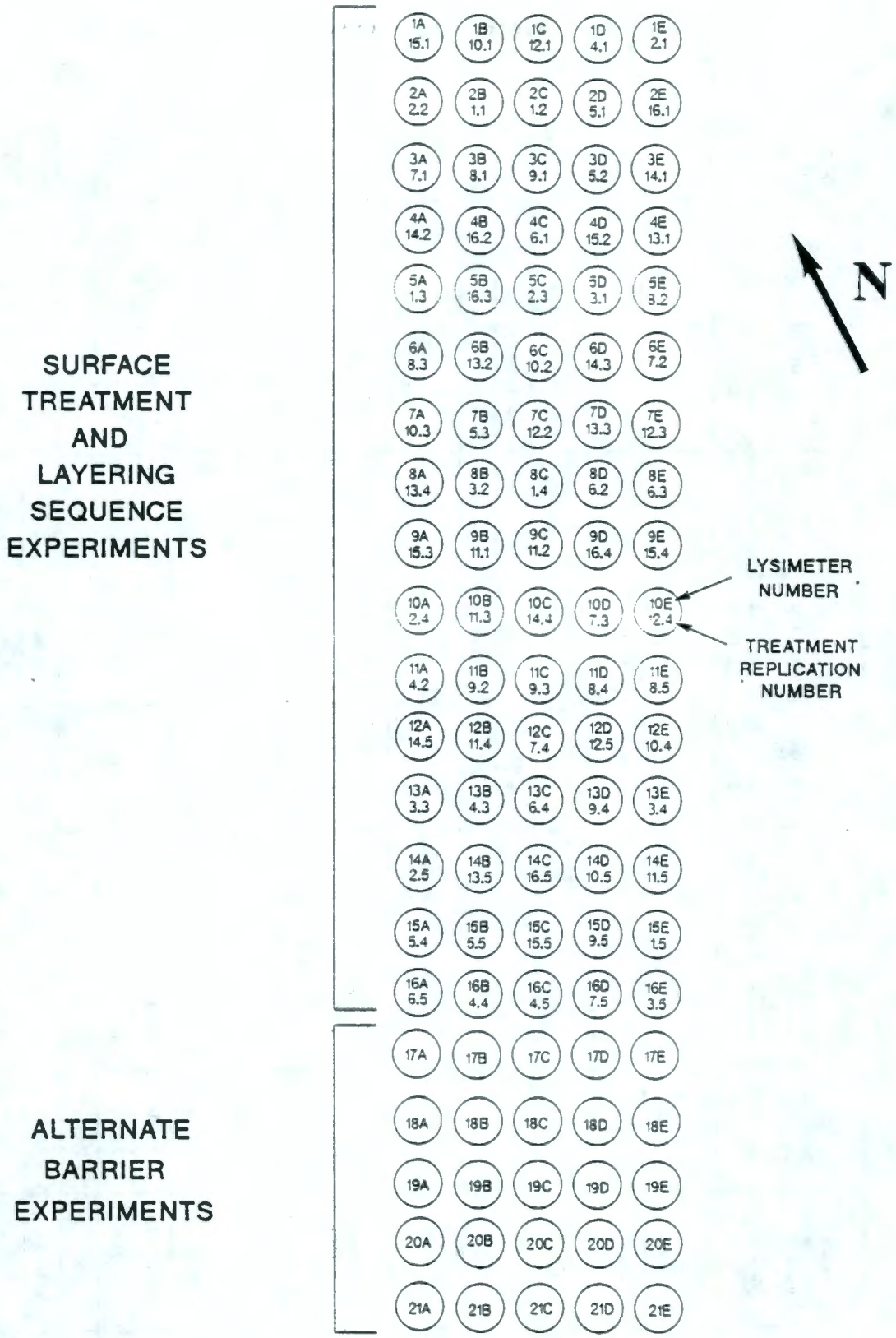


Figure 2-3. Random Assignment of Treatment Combinations.

Table 2-2. Precipitation and Irrigation Amounts Applied at Small-Tube Lysimeter Facility (in centimeters).

| Month | Monthly HMS average rainfall | Cumulative monthly average | Cumulative twice average monthly average | HMS recorded precipitation | Cumulative recorded precipitation | Irrigation applied | Cumulative irrigation applied | Sum irrigation + precipitation | Cumulative irrigation + precipitation | Cumulative in ambient tubes |
|---|---|---|---|---|---|---|---|---|---|---|
| Oct-88 | 1.42 | 1.42 | 2.84 | 0.03 | 0.03 | 0.00 | 0.00 | 0.03 | 0.03 | 0.03 |
| Nov-88 | 2.16 | 3.58 | 7.16 | 2.08 | 2.11 | 0.00 | 0.00 | 2.08 | 2.11 | 2.11 |
| Dec-88 | 2.26 | 5.84 | 11.68 | 1.02 | 3.12 | 0.00 | 0.00 | 1.02 | 3.12 | 3.12 |
| Jan-89 | 2.34 | 8.18 | 16.36 | 0.53 | 3.66 | 0.00 | 0.00 | 0.53 | 3.66 | 3.66 |
| Feb-89 | 1.52 | 9.70 | 19.40 | 4.24 | 7.90 | 3.50 | 3.50 | 7.75 | 11.40 | 7.90 |
| Mar-89 | 0.94 | 10.64 | 21.28 | 3.96 | 11.86 | 2.94 | 6.45 | 6.91 | 18.31 | 11.86 |
| Apr-89 | 0.99 | 11.63 | 23.26 | 2.13 | 14.00 | 2.97 | 9.42 | 5.10 | 23.41 | 16.48 |
| May-89 | 1.22 | 12.85 | 25.70 | 1.50 | 15.49 | 0.00 | 9.42 | 1.50 | 24.91 | 17.98 |
| Jun-89 | 1.37 | 14.22 | 28.44 | 0.03 | 15.52 | 0.79 | 10.21 | 0.81 | 25.73 | 18.01 |
| Jul-89 | 0.38 | 14.60 | 29.20 | 0.03 | 15.54 | 2.71 | 12.92 | 2.74 | 28.47 | 18.03 |
| Aug-89 | 0.61 | 15.21 | 30.42 | 0.66 | 16.21 | 0.73 | 13.66 | 1.39 | 29.86 | 18.69 |
| Sep-89 | 0.79 | 16.00 | 32.00 | 0.05 | 16.26 | 0.56 | 14.21 | 0.61 | 30.47 | 18.74 |
| Oct-89 | 1.42 | 17.42 | 34.84 | 1.07 | 17.32 | 1.53 | 15.74 | 2.60 | 33.07 | 19.81 |
| Nov-89 | 2.16 | 19.58 | 39.16 | 2.64 | 19.96 | 1.77 | 17.52 | 4.41 | 37.48 | 22.45 |
| Dec-89 | 2.26 | 21.84 | 43.68 | 0.74 | 20.70 | 1.68 | 19.20 | 2.42 | 39.90 | 23.19 |
| Jan-90 | 2.34 | 24.18 | 48.36 | 1.96 | 22.66 | 3.78 | 22.98 | 5.74 | 45.64 | 25.14 |
| Feb-90 | 1.52 | 25.70 | 51.40 | 0.23 | 22.89 | 2.72 | 25.70 | 2.95 | 48.59 | 25.37 |
| Mar-90 | 0.94 | 26.64 | 53.28 | 0.25 | 23.14 | 2.81 | 28.51 | 3.07 | 51.65 | 25.63 |
| Apr-90 | 0.99 | 27.63 | 55.26 | 1.02 | 24.16 | 1.63 | 30.14 | 2.64 | 54.30 | 26.64 |
| May-90 | 1.22 | 28.85 | 57.70 | 2.18 | 26.34 | 0.96 | 31.10 | 3.15 | 57.44 | 28.83 |
| Jun-90 | 1.37 | 30.22 | 60.44 | 0.91 | 27.25 | 0.26 | 31.36 | 1.17 | 58.61 | 29.74 |
| Jul-90 | 0.38 | 30.60 | 61.20 | 0.36 | 27.61 | 1.83 | 33.19 | 2.18 | 60.80 | 30.10 |

## 2.4 LYSIMETER PLANTINGS

The 40 lysimeters receiving a vegetated surface treatment (treatments 7 through 12, 14, and 16) were planted to cheatgrass (*Bromus tectorum*) in early October 1989. The seed used was collected from the Hanford Site Arid Lands Ecology Reserve (ALE) during early June 1989. Seeds were hand-stripped from plants selected to be as free of smut as possible. The seeds were air-dried and maintained at room temperature in paper bags until planting. Before planting, the seeds were divided into 40 aliquots of approximately 1,000 seeds each, and each aliquot was individually bagged. Just before planting, cheatgrass litter was obtained from the ALE reserve to serve as mulch.

The following planting procedures were used. On the lysimeters with a surface of plain soil or gravel admix, the soil crust was broken, the seeds contained in one bag were distributed evenly over the disturbed soil, and the seeds were then packed lightly by hand and mulched with approximately one centimeter of cheatgrass litter. On lysimeters with sand surfaces, the sand was lightly disturbed, then the same procedure was followed. Lysimeters with gravel mulch on the surface were not disturbed before planting. At planting, ambient soil moisture was generally low, because the normal autumn rains had not yet begun. In the surrounding environment, cheatgrass had not yet begun to germinate.

Unfortunately, no biomass or leaf area data was collected during FY 1990. However, visual observations indicated that the amount of plant growth on the lysimeters was considerably less than in the surrounding native stands.

## 2.5 TEMPERATURE EFFECTS

Questions concerning thermal gradients in and around the lysimeters were raised and addressed during FY 1990. Two basic issues were addressed: (1) the possibility of uneven surface temperatures because of the presence of the black-steel grating placed between the lysimeter rows, and (2) vertical gradients within the annulus between the lysimeter tubes and the sleeves that may create temperature profiles that are not reflective of the natural soil profiles.

### 2.5.1 Surface Temperatures

Surface temperatures were measured to document the extent to which the black-steel grating, which serves as a walkway above the soil and between lysimeter rows, can modify surface temperatures on the lysimeters. Temperatures were measured with a hand-held radiometer. In addition to the temperature measurements made on the grating and on the soil surface directly below the grating, the surface temperatures of selected treatment lysimeters were measured. All measurements were made on March 29, 1990, under clear-sky conditions in the early afternoon (approximately 12:45 p.m. to 1:30 p.m.).

Because the sun's rays were oblique to the vertically oriented openings in the grating at the time of the temperature measurements, the soil beneath the steel grating was shaded by the grating.

Mean temperatures of the different surfaces are listed in Table 2-3. One-way analysis of variance for the effects of surface showed significant surface-temperature differences ($F=50.95$, $p<0.0001$). Table 2-3 also shows the results of the conservative Scheffe F-test (Snedecor and Cochran 1980) comparing temperatures for the surfaces of the lysimeters, the soil below the steel grating near lysimeter rows 15 and 16, and the grating near lysimeter rows 15 and 16.

Shading by the grating caused the surface of the soil between lysimeter rows to be significantly cooler than any of the lysimeter surfaces or the grating itself, both of which were exposed to direct sunlight. Shading resulted in temperatures approximately 8 °C cooler below the grating compared with the vegetated and bare soil surfaces (Table 2-3). Although additional measurements were not taken, it would be expected that the midday temperature differences would decrease later in the summer as the solar angle increases and the relative amount of shading decreases. In general, the dark-colored surfaces (sand, gravel, and grating) were significantly warmer than the lighter-colored surfaces (soil and admix).

An additional effect that the black grating may have is the formation of a heat island around the STLF. Such a heat island could alter both the surface and surrounding air temperature patterns in a uniform manner. The higher temperatures, as well as the increased air movement across the facility that could be caused by the heat island, would increase the amount of evapotranspiration from the lysimeter surfaces. This can be addressed in the future by using infra-red photography and/or measuring air temperature profiles along a transect across the facility, and in adjacent native areas.

### 2.5.2 Subsurface Lysimeter Temperatures

Concern that lysimeter soil temperatures may differ from nearby soil temperatures outside the lysimeters prompted an investigation of lysimeter soil-temperature profiles. The ET measured in the lysimeters may not be representative of natural conditions when the temperature in the lysimeter is unlike that in the surrounding soil. Temperature-profile measurements began in October 1989, approximately 1 yr after soil water balance data collection began. The lysimeters are positioned inside parallel-walled sleeves that result in a 3- to 4-cm air gap the length of the lysimeter between the outside lysimeter wall and the inside of the sleeve. Thus, the lysimeter design allows free access of outside air to the bottom of the lysimeter.

Thermocouples were installed in lysimeters 16d and 16e at depths of 1, 10, 50, 100, and 140 cm. Holes were drilled through the lysimeter walls, and thermocouples were pushed into the soil 2 cm past the lysimeter wall. Thermocouples also were installed in the space between the lysimeter and the sleeve casing at depths corresponding to the thermocouples placed inside of the lysimeters. A control hole was dug 1 m outside the lysimeter facility to

Table 2-3. Mean Soil Surface Temperatures (March 29, 1990).

| Surface treatment | Mean temperature[a] °C (±S.D.) | Treatments with significantly different[b] temperatures |
|---|---|---|
| Bare soil (A) | 35.0 (2.0) | I,J,K |
| Bare sand (B) | 38.8 (1.2) | C,J,K |
| Bare admix (C) | 32.4 (1.4) | B,D,E,F,G,H,I,J,K |
| Bare gravel (D) | 39.3 (1.3) | B,E,J,K |
| Vegetated Soil (E) | 34.7 (2.3) | D,I,J,K |
| Vegetated admix (F) | 37.7 (2.3) | C,J,K |
| Vegetated gravel (G) | 38.1 (1.1) | C,J,K |
| Grating row 15 (H) | 37.6 (0.8) | C,J,K |
| Grating row 16 (I) | 39.9 (0.7) | A,C,E,J,K |
| Soil < grating 15 (J) | 26.5 (0.9) | A,B,C,D,E,F,G,H,I |
| Soil < grating 16 (K) | 26.2 (1.5) | A,B,C,D,E,F,G,H,I |

[a]Mean of five sample measurements.

[b]Scheffe F-test at p = 0.05.

S.D. = Standard deviation.

monitor the temperature profile of the native soil. Thermocouple depths in the control hole correspond to depths of thermocouples in the lysimeters, except that the deepest control depth was 128 cm rather than 140 cm, because rocks prevented deeper installation. Beginning October 27, 1987, hourly temperature readings were collected from all of the thermocouples with a Campbell CR7* micrologger. A Campbell CR7 micrologger was installed October 27, 1989 (to record hourly temperatures in the lysimeters) in the annulus between lysimeters and sleeves, and in the control profile.

The results of the temperature monitoring indicated that lysimeter soil temperature closely paralleled the temperatures in the air gap, and mid-winter temperatures were consistently about 3 °C cooler in the lysimeters than in the control soil at the 100-cm depth (Figure 2-4). These results prompted a decision to insulate the lysimeters.

Several insulation methods were considered but rejected because of the concern that the insulation would absorb water and therefore influence lysimeter weights, making it impossible to accurately determine soil water-balance parameters by weight change alone. Even a closed cell foam was found

*Campbell CR7 is a trademark of Campbell Scientific Instruments, Inc., Logan, Utah.

to absorb considerable amounts of water. It was determined that bicycle inner-tubes of the proper diameter were available and fit snugly over the lysimeters and when inflated would fill the interspace between the lysimeter and the sleeve. Initial trials indicated the inner-tubes are easily installed and removed, are flexible, and perform as an inflatable rubber gasket without absorbing water.

The inner-tube gaskets were installed on the lysimeters in row 16 on March 5, 1990. Figure 2-5 shows temperatures at the 100-cm depth for lysimeters 16d and for the control soil outside the lysimeters before and after the installation of the insulation gaskets. After the inner-tubes were installed the temperatures inside the lysimeters began to track the control soil temperatures more closely than before installation. Short-term fluctuations in temperature were damped, and the lysimeter temperature more closely approached the control soil temperatures. Insulating gaskets were installed on all of the lysimeters in rows 1 - 18 on April 2, 1990.

## 2.6 DATA MANAGEMENT SYSTEM

The data management system is used to store, retrieve, and analyze data from the small-tube lysimeter experiments. Data acquired routinely for the tube lysimeter studies include the following:

- Monthly rainfall measurements from the HMS
- Volume of irrigation applied
- Monthly lysimeter weights and scale calibration weights
- Soil temperature measurements
- Volume of subsurface drainage from the lysimeters
- Leaf area and biomass measurements.

The data management system consists of five basic components: (1) standardized data collection forms designed to encourage recorders to consistently enter all essential field information, (2) methods for consistent data entry into the computer and for quality control verification of the data, (3) data coding, sorting, and restructuring programs to make the system accessible to analysis and graphics programs, (4) data graphics programs, and (5) data analysis programs. Field data that are subject to rigorous analysis are maintained on a mainframe computer (ZVAX) located in the Sigma V Building at PNL. Supporting data that require only tracking and/or summarizing are kept in standard spreadsheet files on personal computers. All ZVAX programs are written in the SAS* system language for data management and analysis. The data are accessible by modem or direct link for graphics and analysis on the ZVAX and for importing to mini- and micro-computer operation systems.

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*SAS is a trademark of the SAS Institute Inc.

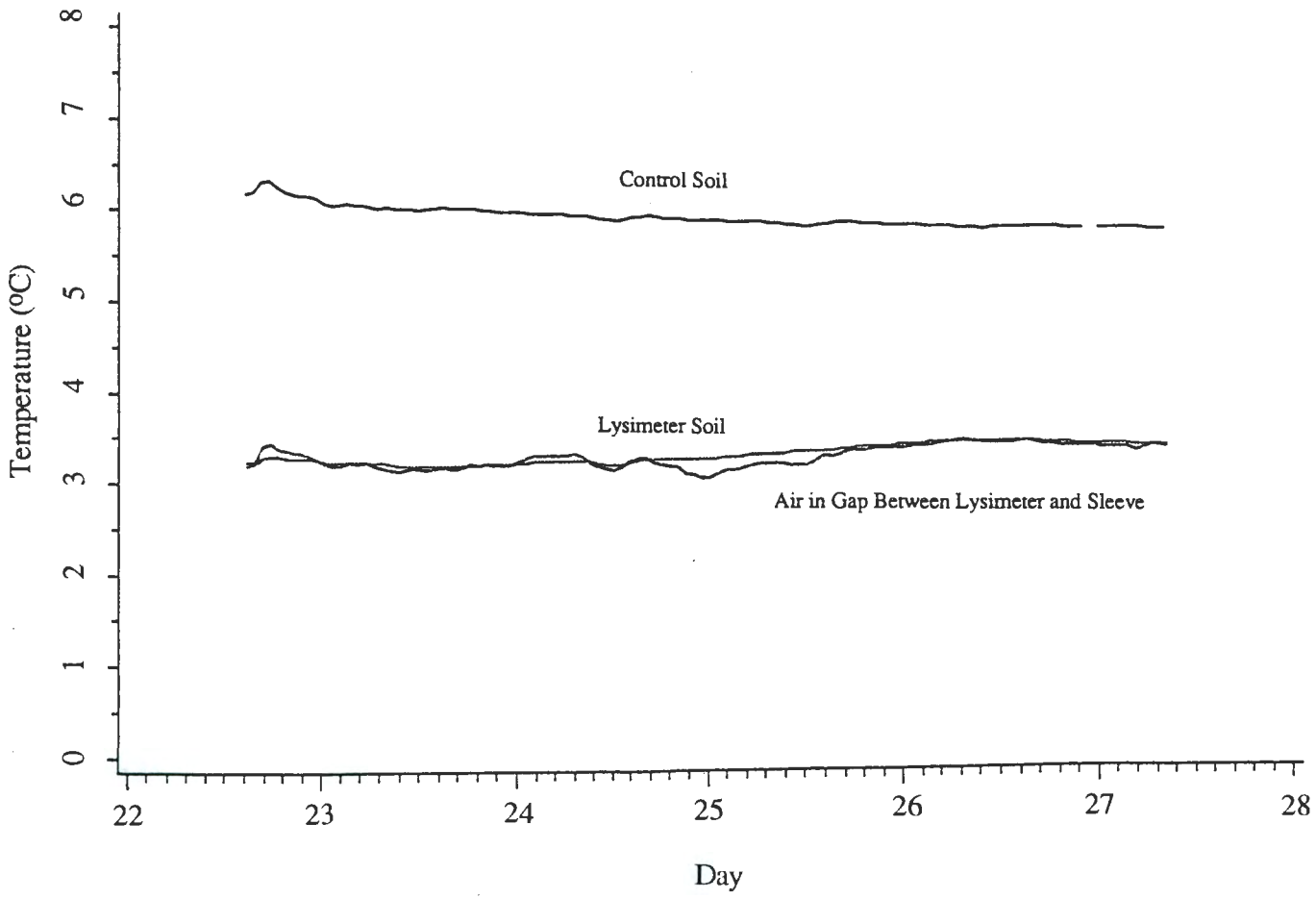


Figure 2-4. Temperatures at 100 cm in Soil in Lysimeter 16e, in the Air Gap Between the Lysimeter and the Surrounding Sleeve, and in Control Soil during December 1989.

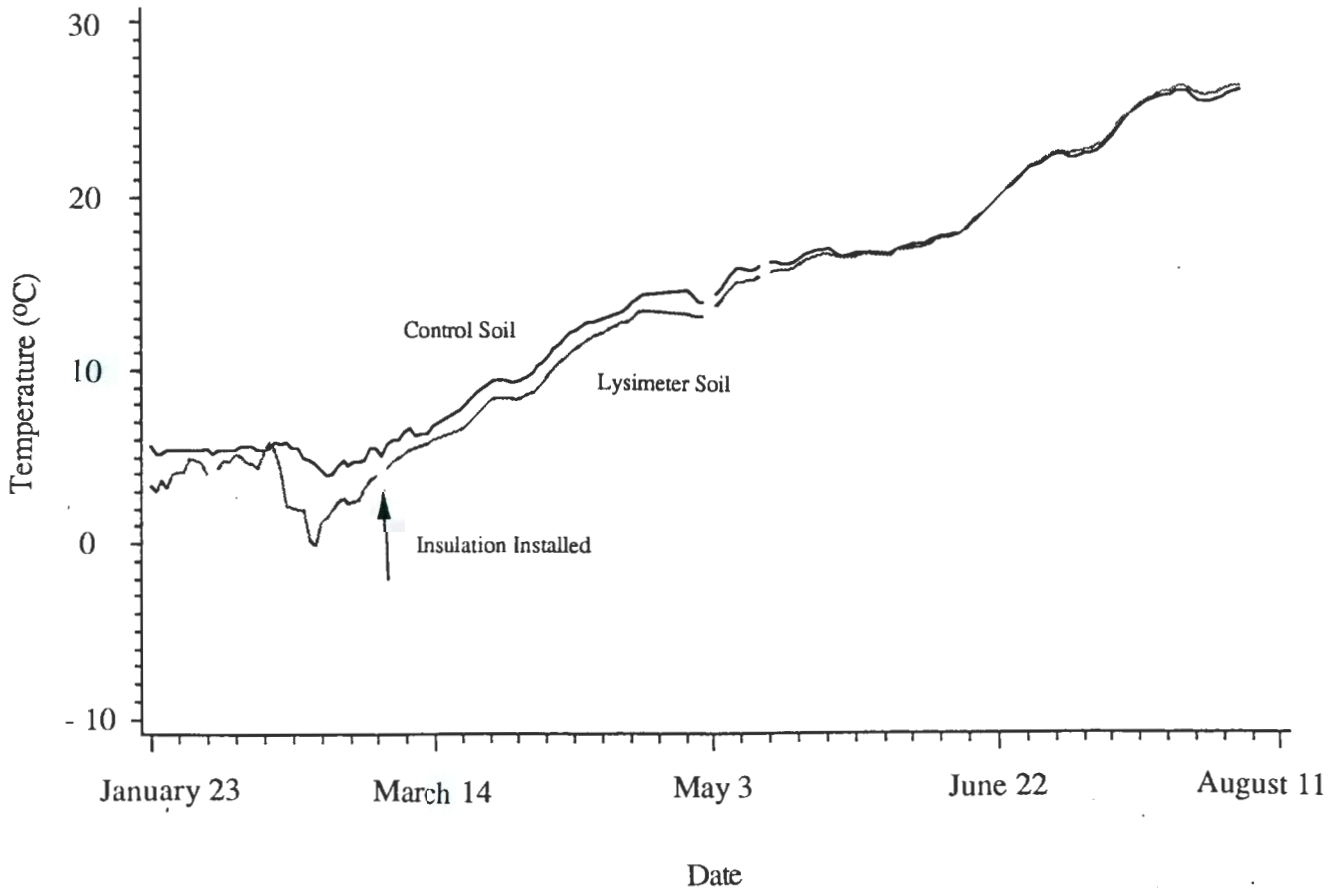


Figure 2-5. Soil Temperatures at a Depth of 100 cm in Lysimeter 16d and in Control Soil during 1990.

The data management structure is shown in Figure 2-6. All field data records are stored in a Quality Assurance (QA) impact level 3 project file in Room 35, the 331 Building, in the 300 Area of the Hanford Site. The lysimeter weight and soil temperature data are transferred to the ZVAX. Lysimeter weight data are entered on separate files for each sampling session. After editing and verifying entries, files are merged into a single file for analysis and graphics. This composite file can be accessed in the following manner:

Directory PNLZ::DISK7:[tule.lys]:tubewt.dat

Files are printed after each entry and then checked by a person other than the one who entered the data. Data entry and data verification personnel record their initials and the date of work in the following QA file:

Directory PNLZ::DISK7:[TULE.QA]:summary.dsc

After raw weight data and drainage are entered into the SAS file, the program assigns to each lysimeter the appropriate treatment number and a replicate number. Lysimeters are coded by (1) whether they receive ambient or twice average precipitation, (2) whether they are vegetated or bare, (3) the surface cover (soil, admix, gravel mulch, sand), and (4) the type of subsurface barrier (graded, bimodal, clay, grout). Sampling times are converted to Julian days and to SAS time to assist in graphing. Data are then transposed by attaching treatment qualifiers so that each data point is uniquely identified.

Standard scale weights, measured at the beginning and end of each monthly sampling session, are entered in a separate file.

Directory PNLZ::DISK7:[TULE.LYS]:caltestB.dat

To remove drift in scale electronics and changes in environmental influences among sampling sessions, the data are standardized using a new calibration factor determined by linear regression coefficients derived from the field calibration (Relyea et al. 1990) for each sampling period.

Several SAS programs were written to process changes in ET for each lysimeter. These programs include inputs such as rainfall and irrigation data, which are updated monthly on a personal computer spreadsheet and transferred to the SAS program. Collectively, the programs (1) convert lysimeter weight changes to changes in ET and storage, (2) sort ET and storage data by treatment, (3) calculate mean and standard deviation statistics for the various treatment combinations, and (4) test for treatment effects and interactions using four separate balanced statistical designs using the ANOVA models described by Relyea et al. (1990) and in Section 2.2.

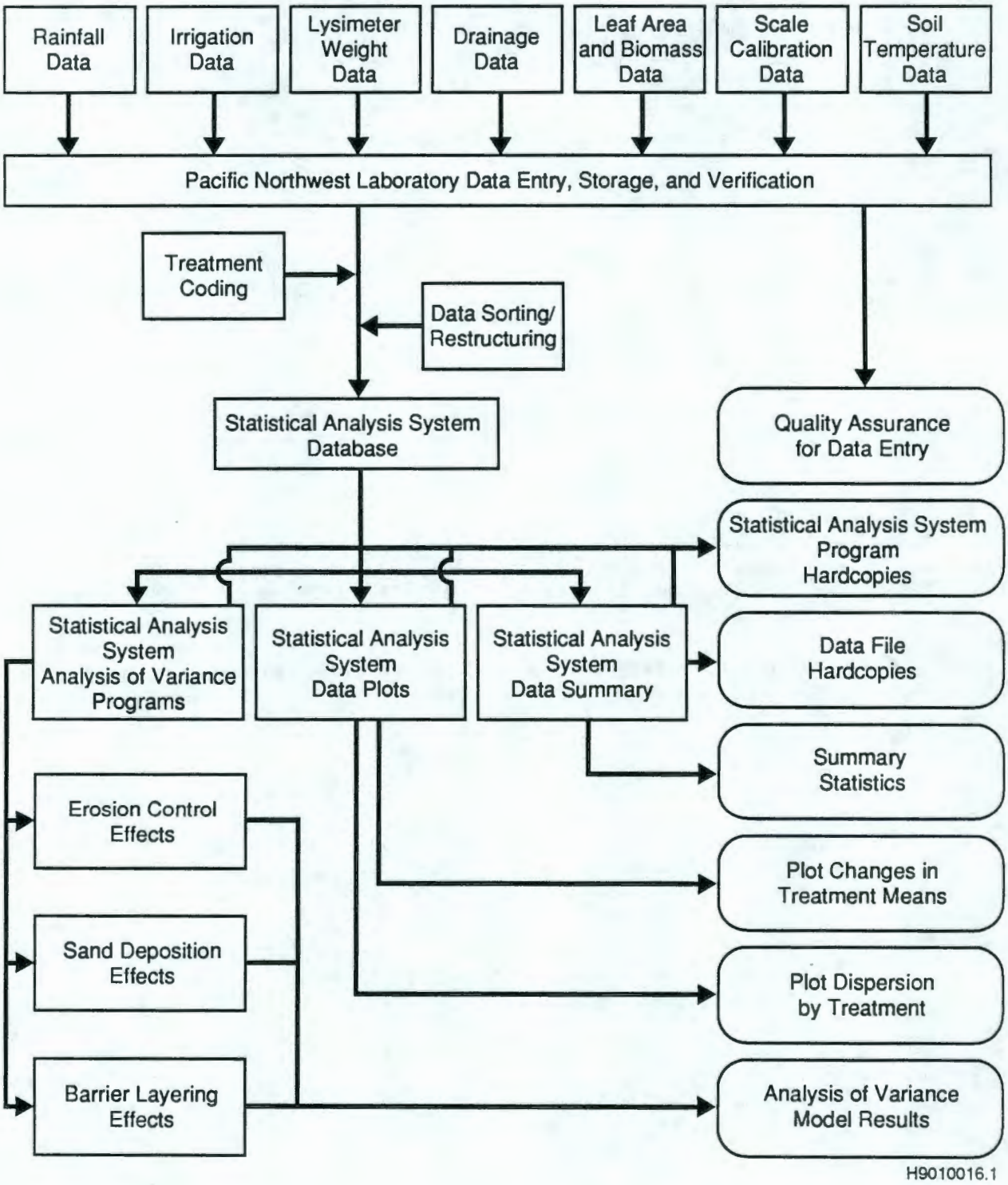


Figure 2-6. Data Analysis Structure of the Small-Tube Lysimeter Facility.

# 3.0 WATER BALANCE RESULTS

Reported here are the overall trends in water storage and ET, as well as more rigorous statistical analysis of ET and storage for four selected measurement dates (May 1989, October 1989, May 1990, and August 1990). These dates were selected because they represent the beginning of the water year (October 1989 and August 1990) when storage changes are at yearly minima, or at the latter portion of the cheatgrass growth season (May) to accentuate the effects of vegetation. In general, the treatment differences described for these selected dates are representative of the treatment differences present at the other 16 measurement dates. Treatment differences at the selected sampling dates were compared using Duncan's multiple range test (Snedecor and Cochran 1980).

## 3.1 SURFACE TREATMENTS

The long-term patterns in mean cumulative ET for the different surface treatments are presented in Figures 3-1 and 3-2. The companion long-term patterns in storage change are presented in Figures 3-3 and 3-4. In general, all three of the main factors (surface treatment, vegetation, precipitation) had significant effects on both cumulative ET and storage change. The lysimeters with a gravel mulch surface had the least amount of ET and the greatest change in storage. All of the gravel mulch treatments, except the vegetated/ambient precipitation treatment had an increase in the amount of water stored in the lysimeters after nearly 2 yr of measurements. The lysimeters with soil and admix surfaces behaved very similarly throughout the measurement period, and were affected by both vegetation and precipitation. The only lysimeters that produced drainage were those that had a gravel mulch surface and received twice average precipitation.

On the May 1989 measurement date, all of the gravel mulch treatments had significantly ($p<0.05$) less cumulative ET than any of the soil or admix surface treatment combinations (Figure 3-5). Neither vegetation nor the amount of precipitation or irrigation had a significant affect on ET when a gravel mulch surface was present. By this measurement date, the gravel mulch treatment lysimeters had evapotranspired 5 to 7 cm of water, whereas the soil and admix lysimeters had evapotranspired 15 to 20 cm of water. The amount of precipitation had a small affect on the amount of ET in the soil and admix treatment lysimeters (Figure 3-5), but the twice average precipitation treatments were significantly greater than only two of the ambient precipitation treatments (bare/admix and veg/soil). Vegetation had no real affect on ET at this measurement date.

All of the treatment combinations had either near zero or positive storage change (gained water) by the May 1989 measurement date (Figure 3-6). All of the gravel mulch treatment combinations had significantly greater storage than the soil or admix treatment combinations, and stored two to four times the amount of water. The amount of precipitation significantly affected the storage in the gravel mulch treatments, and had a slight, but for the most

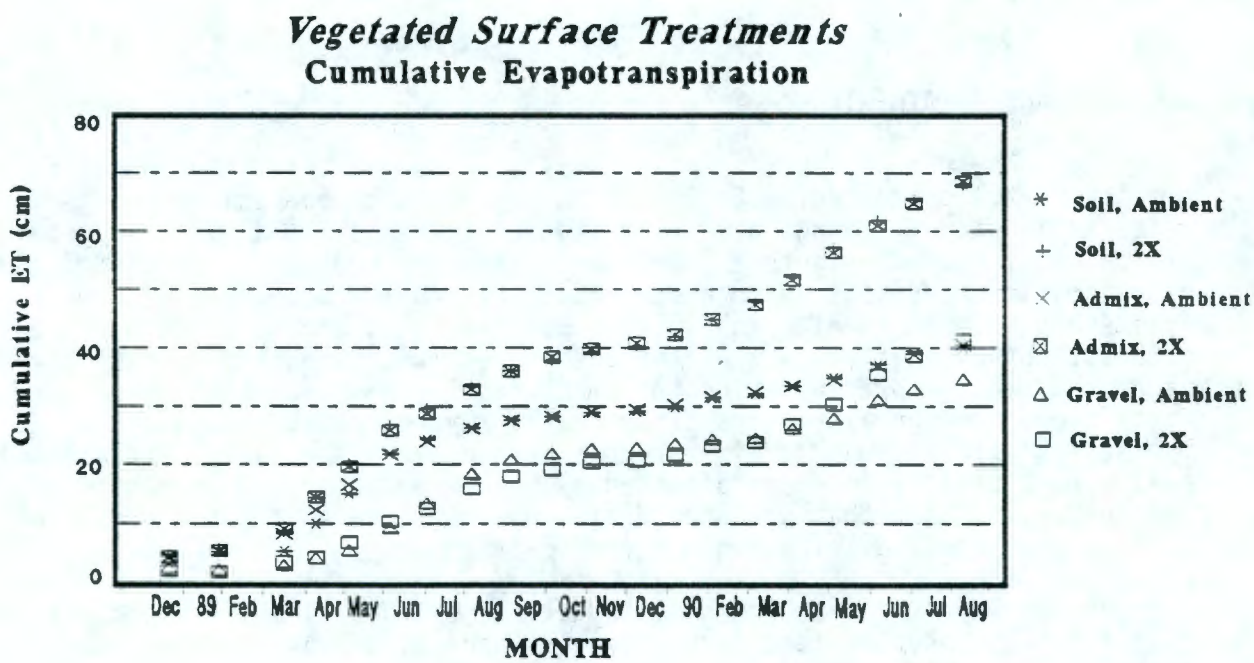


Figure 3-1. Vegetated Surface Treatments (Cumulative Evapotranspiration).

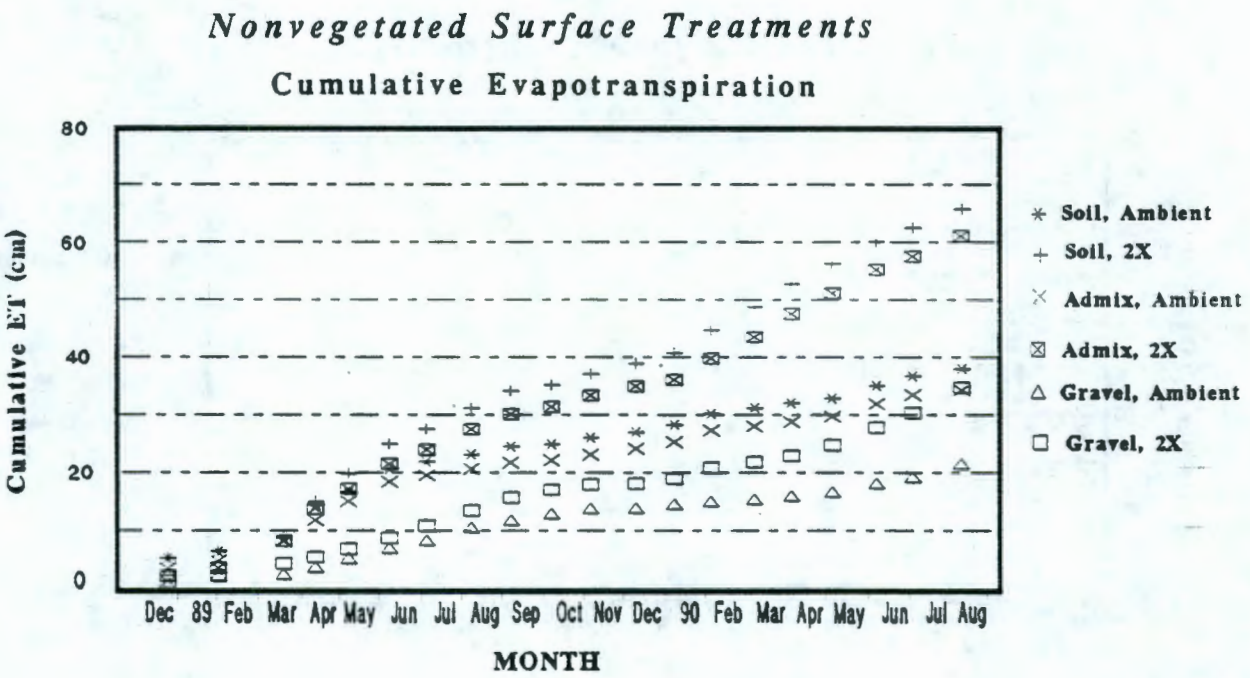


Figure 3-2. Vegetated Surface Treatments (Storage Change).

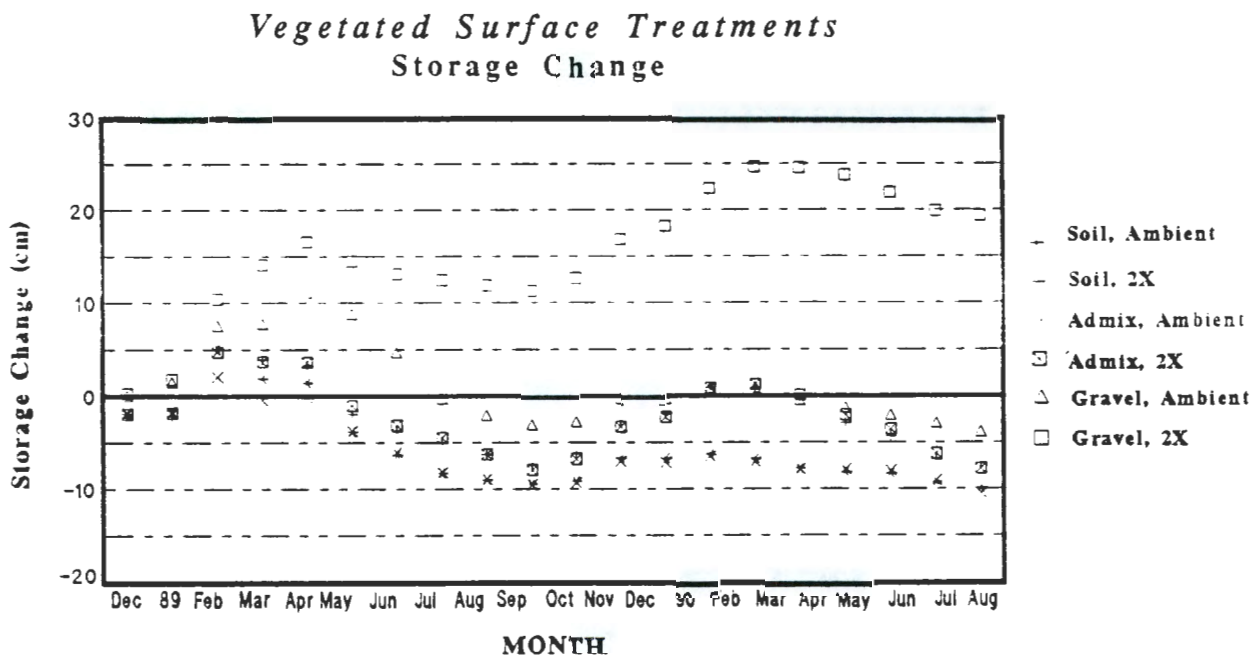


Figure 3-3. Cumulative Storage Change for Vegetated Surface Treatments.

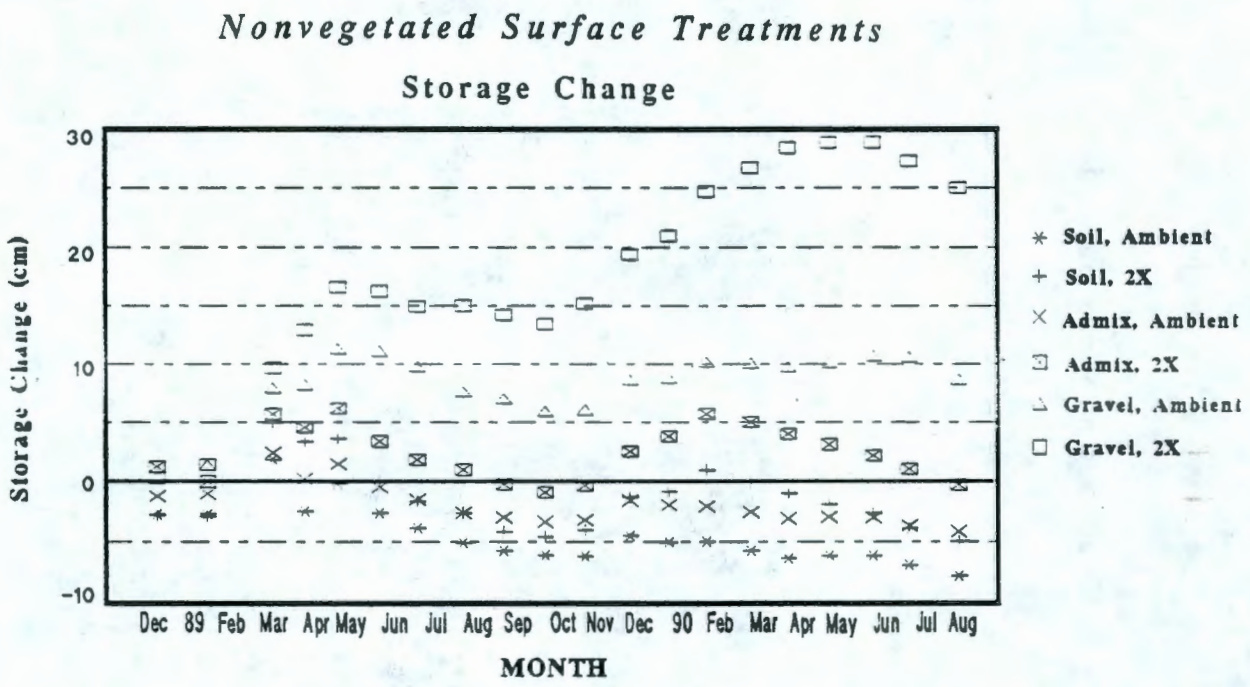


Figure 3-4. Cumulative Storage Change for Nonvegetated Surface Treatments.

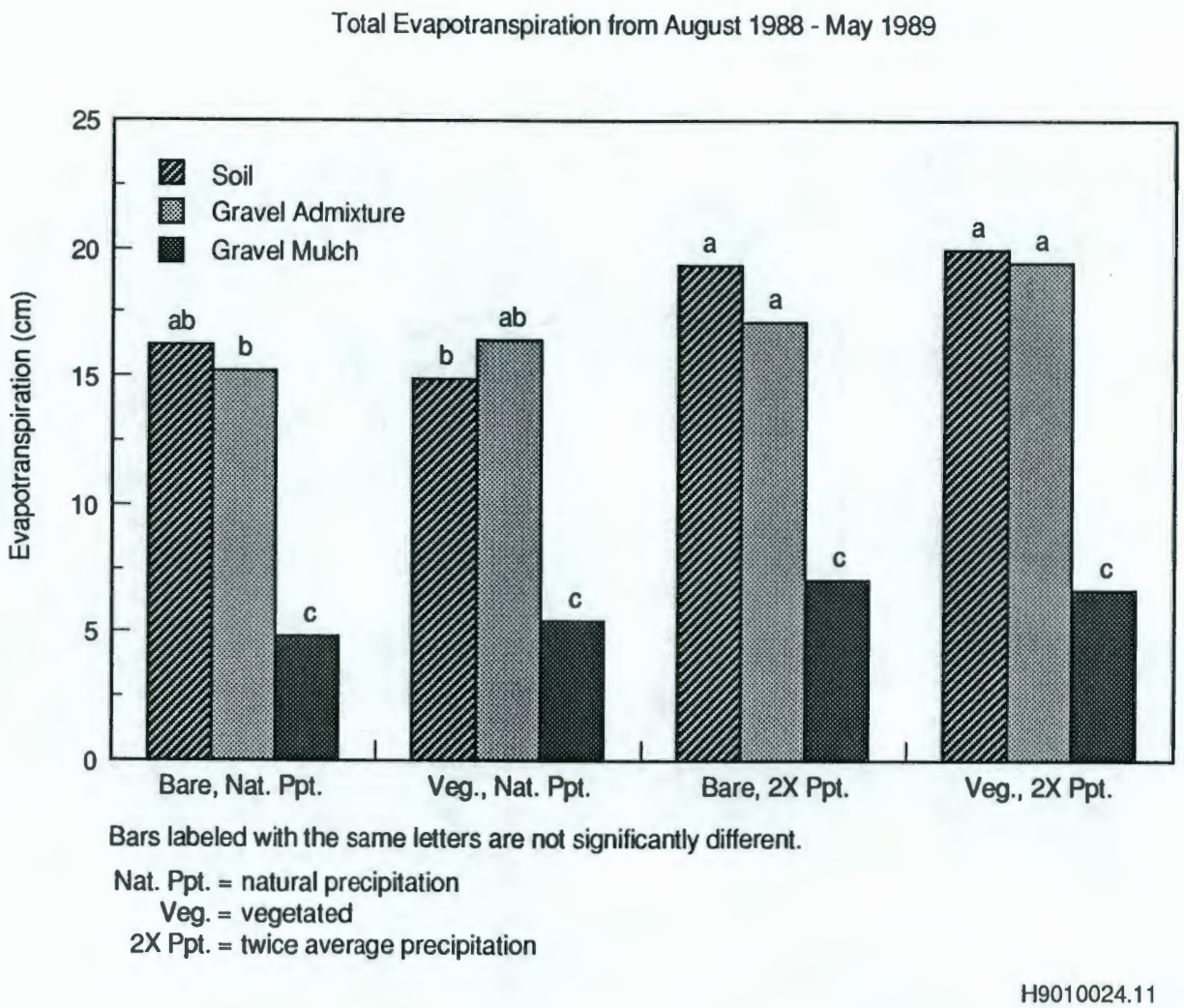


Figure 3-5. Cumulative Evapotranspiration for Three Surface Covers (May 1989).

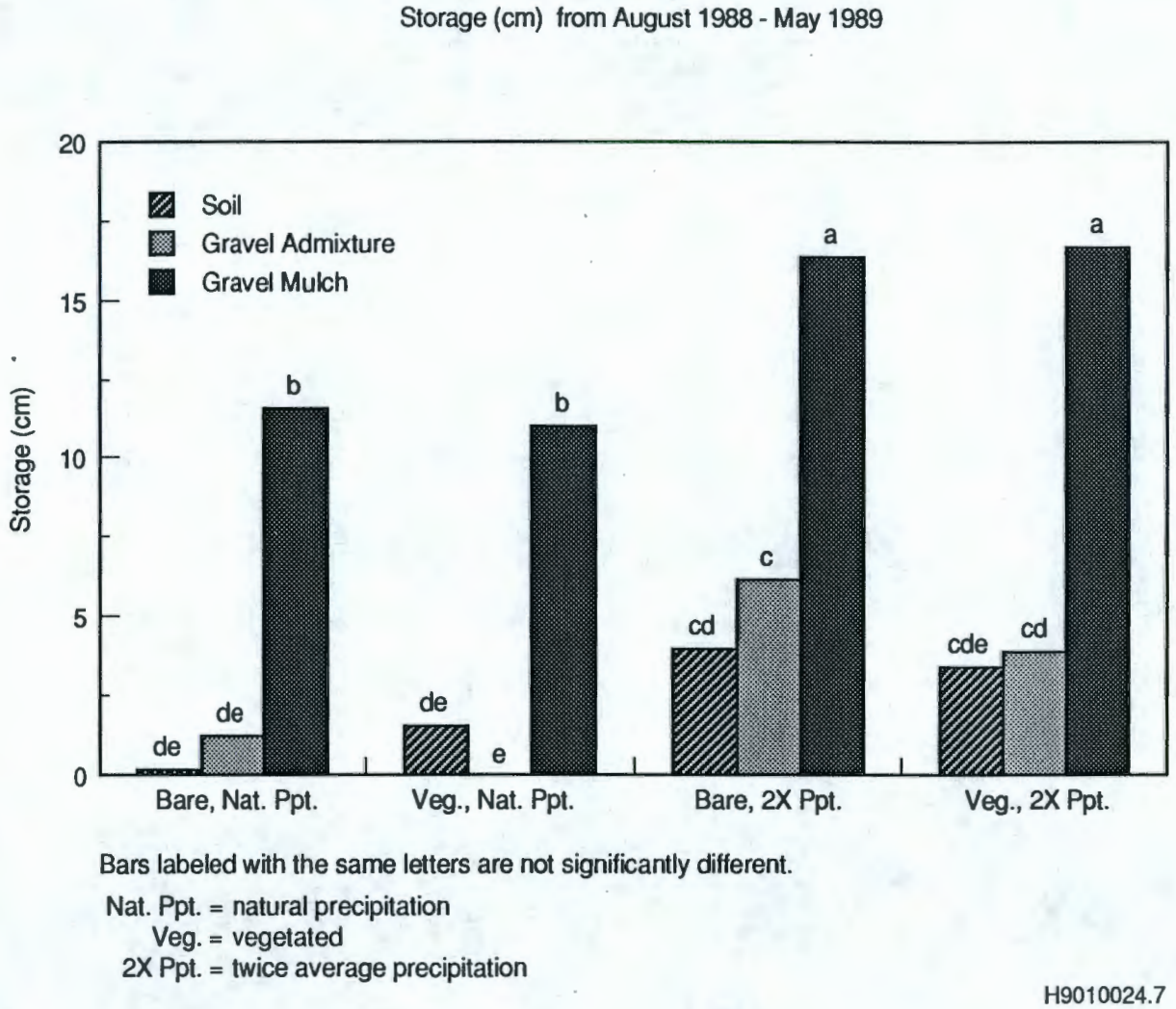


Figure 3-6. Storage Change for Three Surface Covers (May 1989).

part nonsignificant, affect on the soil and admix treatments. The presence of vegetation did not significantly affect the storage change for any of the surface treatment combinations.

On the October 1989 measurement date, after one complete water cycle, ET was affected by surface treatment, precipitation, and vegetation (Figure 3-7). The gravel mulch treatments had the least amount of cumulative ET, with the lowest value found for the bare, ambient precipitation combination. The gravel mulch/vegetated/ambient precipitation treatment combination had a similar cumulative ET value as both the soil and admix/bare/ambient precipitation treatment combinations. The remaining soil and admix treatment combinations all had significantly greater amounts of cumulative ET than any of the gravel mulch treatments. Vegetation had a significant affect on the gravel mulch/ambient precipitation and for the admix surface treatments under both ambient and twice average precipitation treatments. The amount of precipitation significantly affected the cumulative ET for both soil and admix, but not the gravel mulch treatment combinations.

Storage change at the October 1989 measurement date was positive for three of the four gravel mulch treatment combinations (Figure 3-8), the only exception being the vegetated/ambient precipitation combination. The gravel/vegetated/ambient lysimeters had storage values similar to the bare/soil and admix lysimeters. Precipitation had a significant affect on storage only in the gravel mulch treatments. Vegetation had a significant affect on storage under ambient precipitation conditions for both the gravel mulch and the admix surfaces, and under twice average precipitation for the admix surface treatment. Neither precipitation nor vegetation had significant affects on the storage change in lysimeters with a soil surface.

At the May 1990 sampling date, the cumulative ET from the gravel mulch/bare/ambient precipitation lysimeters was significantly less than from any of the other treatment combinations (Figure 3-9). The twice average precipitation/gravel mulch lysimeters behaved similarly to ambient precipitation soil and admix lysimeters suggesting that proportionately only half of the water input was lost through ET from the gravel mulch lysimeters compared to the soil and admix lysimeters. Within each vegetation/ precipitation combination, the cumulative ET amounts were significantly greater from soil and admix surfaces than from gravel mulch surfaces. The amount of precipitation significantly affected cumulative ET for the soil and admix treatments, and for the nonvegetated gravel mulch combinations. The effect of vegetation was significant for gravel mulch surfaces under both precipitation regimes and for admix surfaces under ambient precipitation conditions.

Within each vegetation/precipitation combination, storage change was significantly more positive in the gravel mulch surface lysimeters than in the soil and admix lysimeters (Figure 3-10). The storage change was significantly different among all of the four gravel mulch treatment combinations. Vegetation did not significantly affect the amount of storage change in either the soil or the admix combinations. The amount of precipitation did not significantly affect the amount of storage in the soil surface lysimeters, but did have a significant affect for the admix surface lysimeters.

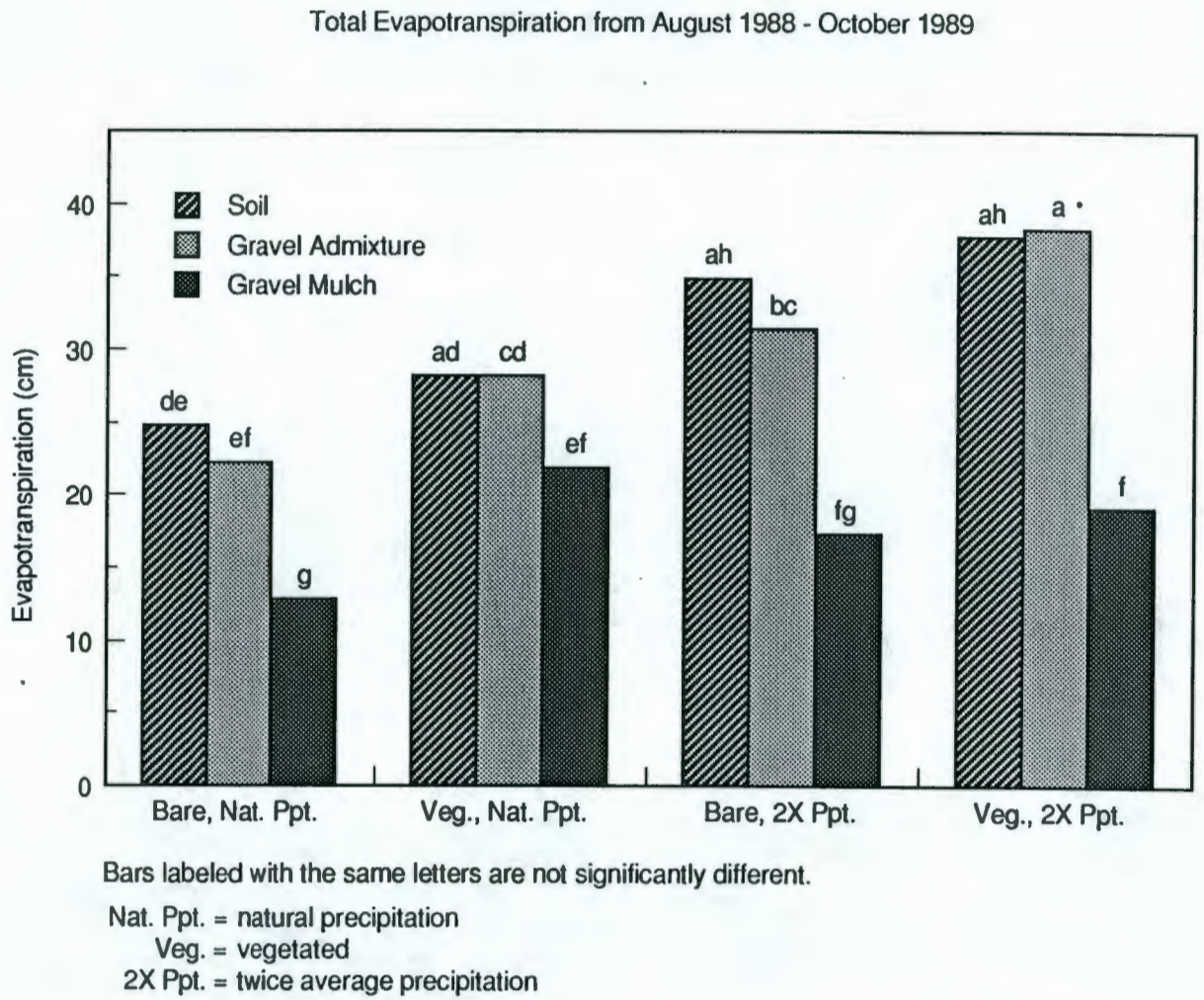


Figure 3-7. Cumulative Evapotranspiration for Three Surface Covers (October 1989).

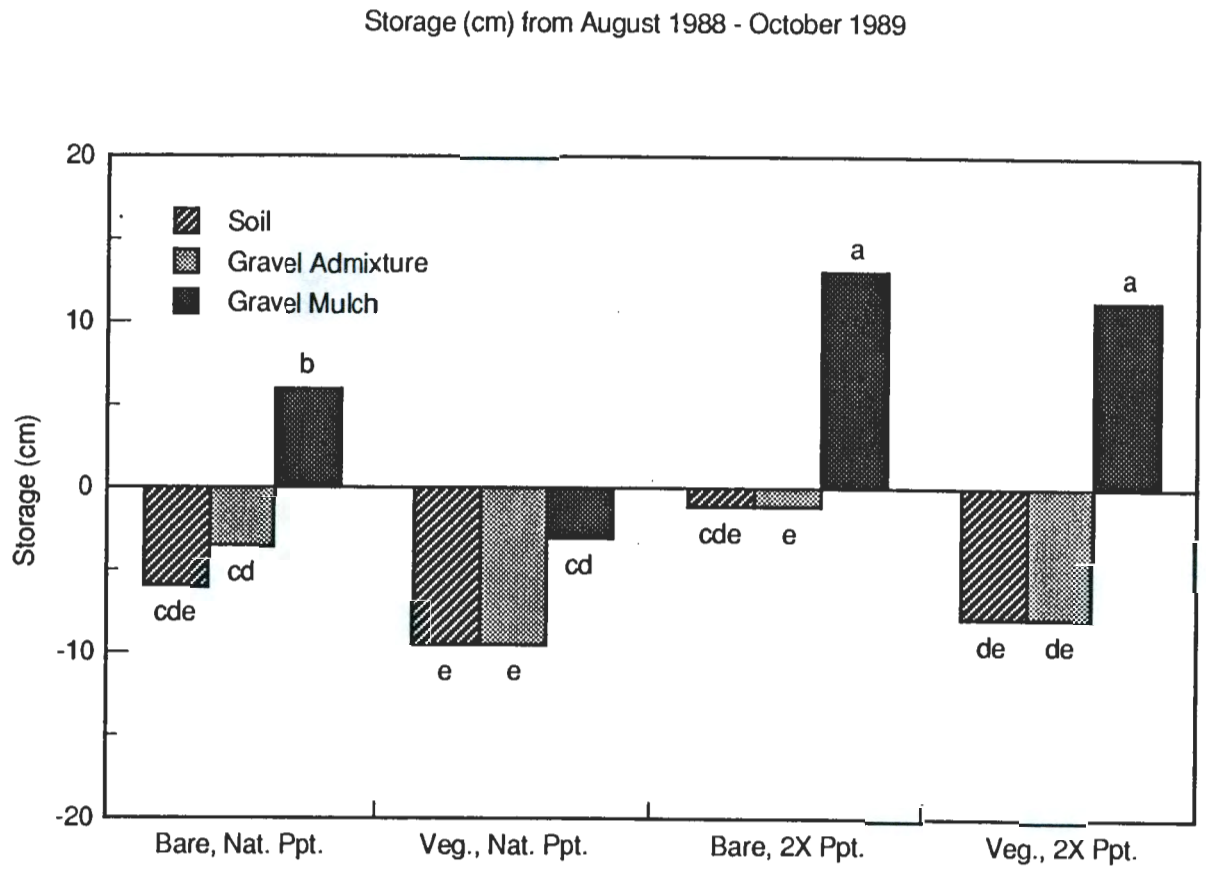


Figure 3-8. Storage Change for Three Surface Covers (October 1989).

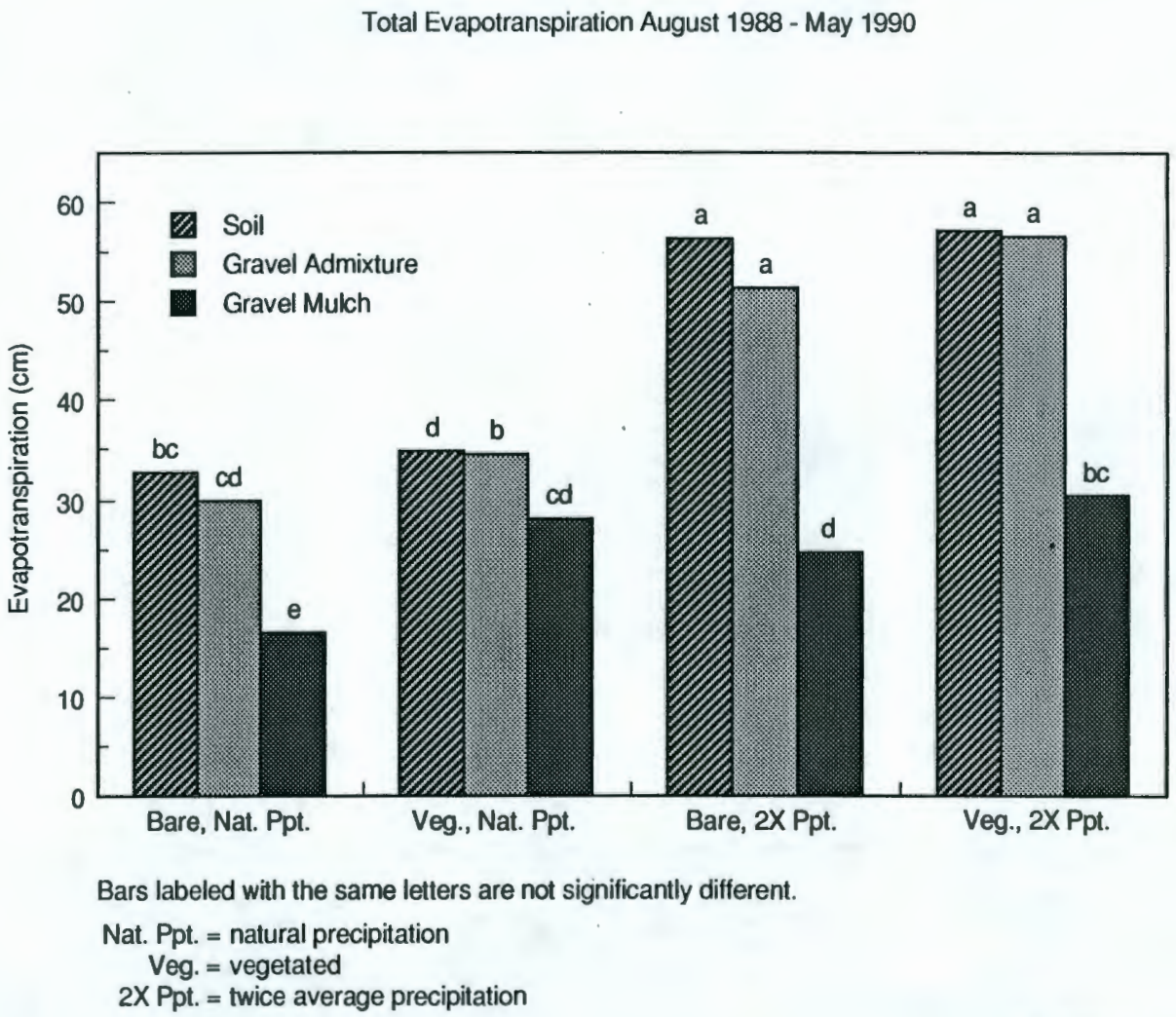


Figure 3-9. Cumulative Evapotranspiration for Three Surface Covers (May 1990).

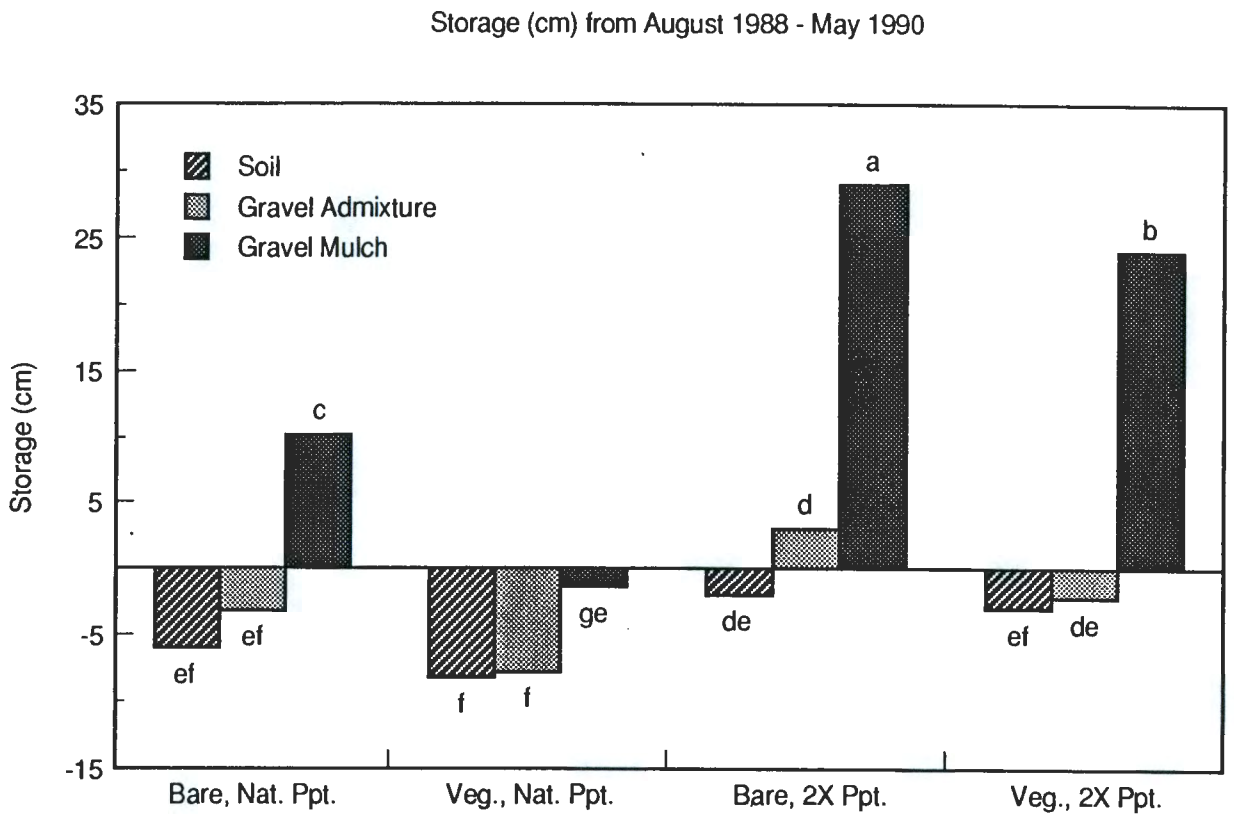


Figure 3-10. Storage Change for Three Surface Covers (May 1990).

The ET patterns at the last available sampling date (August 1990) were similar to the May 1990 patterns. Within each vegetation/precipitation treatment combination the gravel mulch surface lysimeters had significantly lower amounts of cumulative ET than either the soil or admix surface lysimeters (Figure 3-11). Vegetation significantly affected the ET in the gravel mulch and the admix surface lysimeters under both of the precipitation regimes. Precipitation had a significant affect on all surface types.

The cumulative storage change patterns at the August 1990 sampling date also were similar to the patterns observed on the May 1990 sampling date. The total storage changes for the four gravel mulch surface treatments were all significantly different from each other (Figure 3-12), with only the vegetated/ambient precipitation treatment combination showing a negative storage change. The amount of precipitation did not significantly affect the storage change for either the soil or the admix surface treatments. Vegetation had a significant affect on storage change for admix surface lysimeters under both precipitation regimes but did not significantly affect the soil surface lysimeters.

The overall conclusions concerning the results described previously include:

- Gravel mulch greatly decreases ET and increases storage compared to soil or admix surfaces
- There is essentially no difference in ET and storage change for bare soil and admix gravel treatments regardless of whether they are vegetated or not
- After about 1 yr of measurement, both the ET and the storage increase under twice average precipitation conditions
- The affects of vegetation are small but real, depending on the particular treatment combinations.

## 3.2 BARRIER LAYERING SEQUENCE EFFECTS

The treatments with the bimodal and graded capillary breaks had very similar overall patterns of cumulative ET (Figure 3-13) and total storage change (Figure 3-14). The cumulative ET was significantly affected by vegetation only at the sampling dates during the drier parts of the year, October 1989 and August 1990 (Figure 3-15). During May of both 1989 and 1990, vegetation had no significant affect, whereas this affect was significant during October 1989 and August 1990 for the bimodal treatment, and the cumulative ET was slightly higher in the vegetated versus the nonvegetated graded treatment. Within a vegetation treatment there were no significant differences between the bimodal and graded sublayer treatments at any of the analysis dates. The storage changes followed a similar pattern to the cumulative ET (Figure 3-16). All of the treatments had a positive storage change at the May 1989 sampling date and had negative values at the remaining

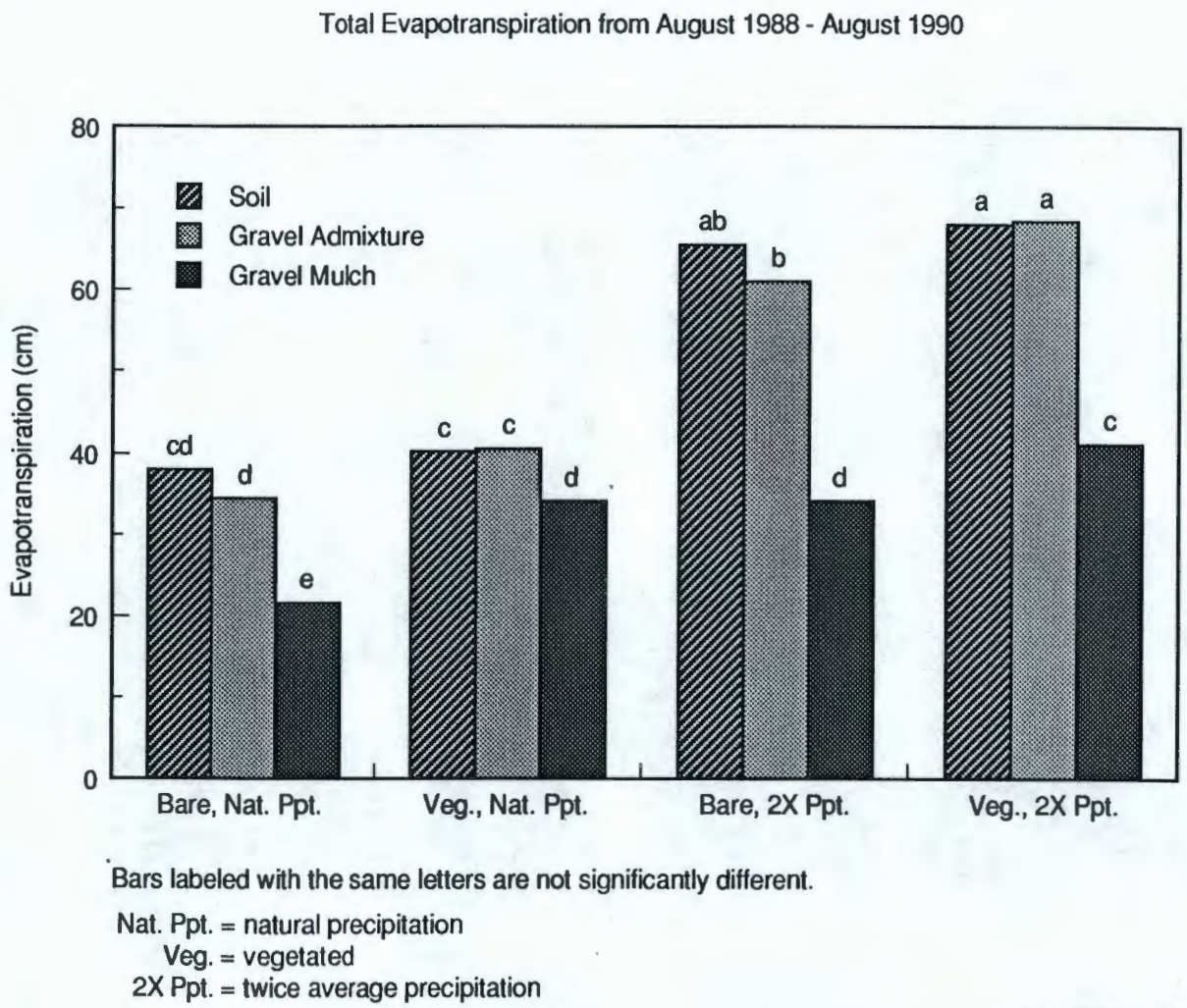


Figure 3-11. Cumulative Evapotranspiration for Three Surface Covers (August 1990).

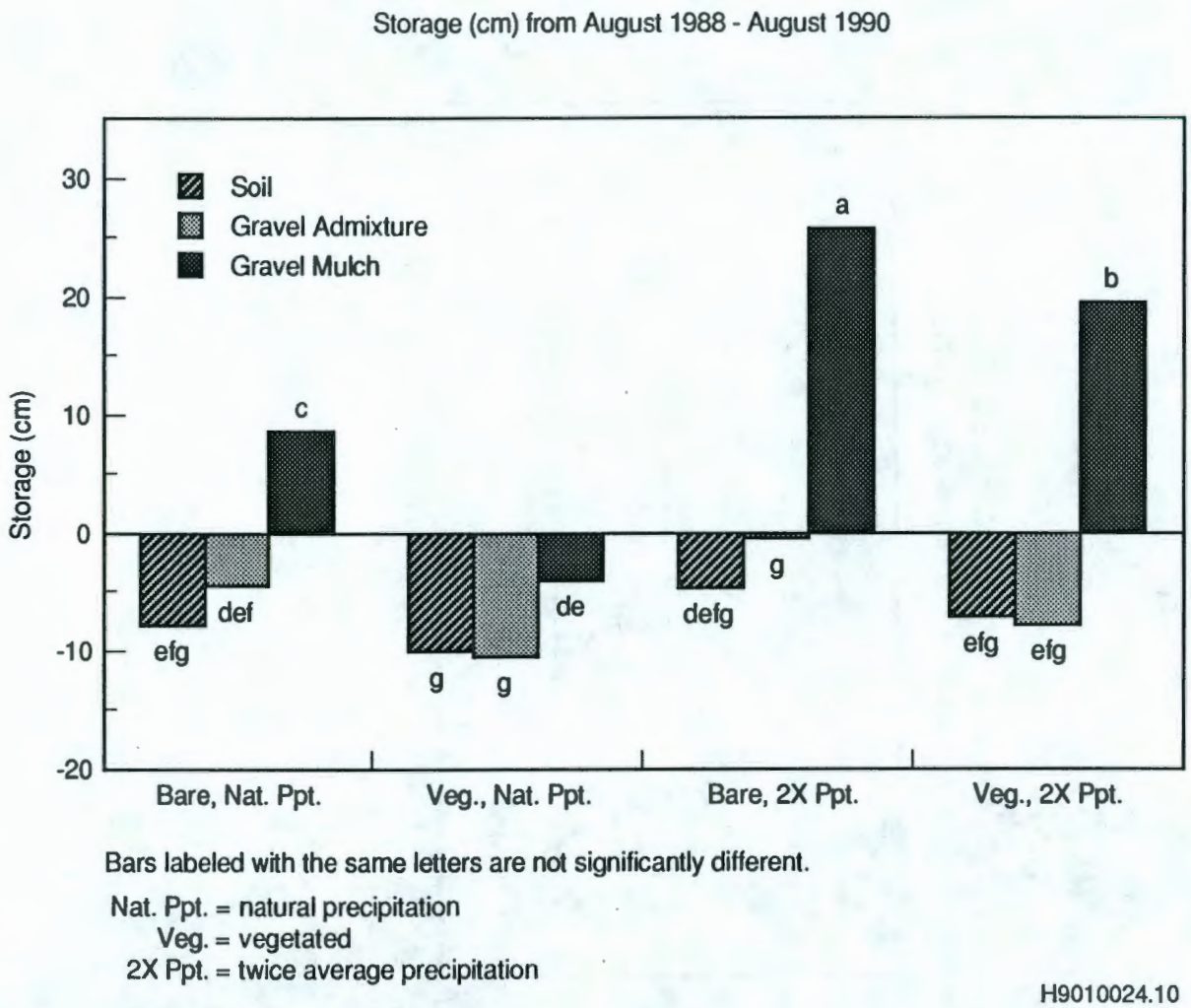


Figure 3-12. Storage Change for Three Surface Covers (August 1990).

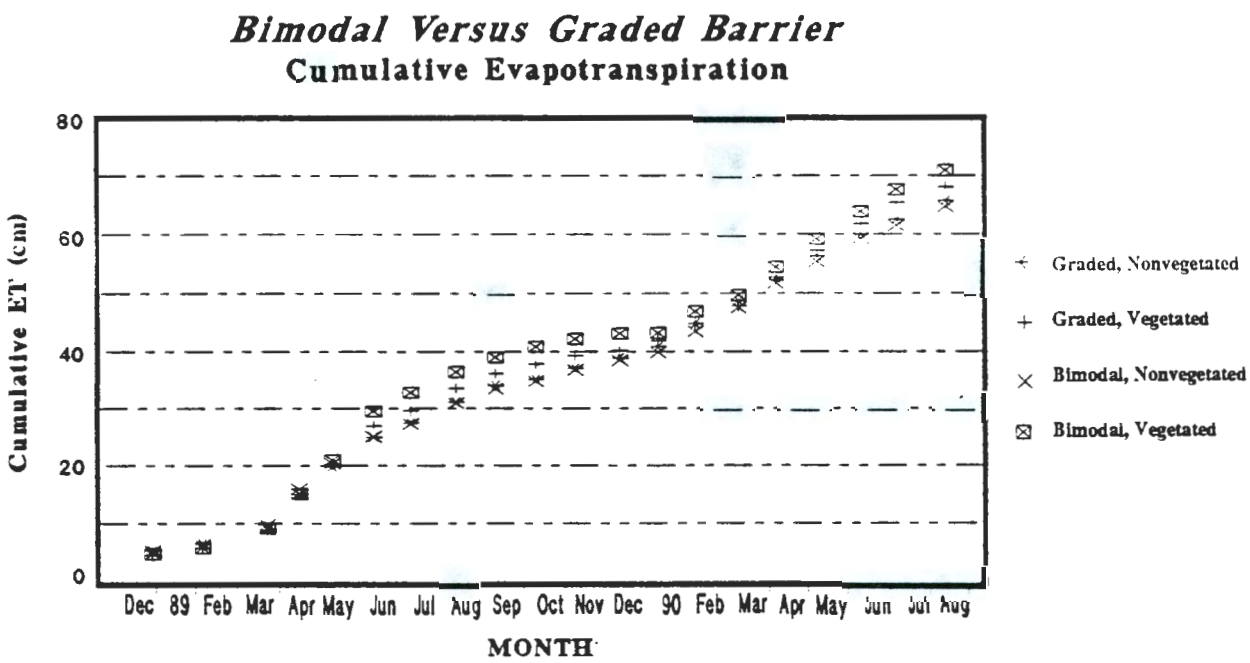


Figure 3-13. Bimodal Versus Graded Barriers (Cumulative Evapotranspiration).

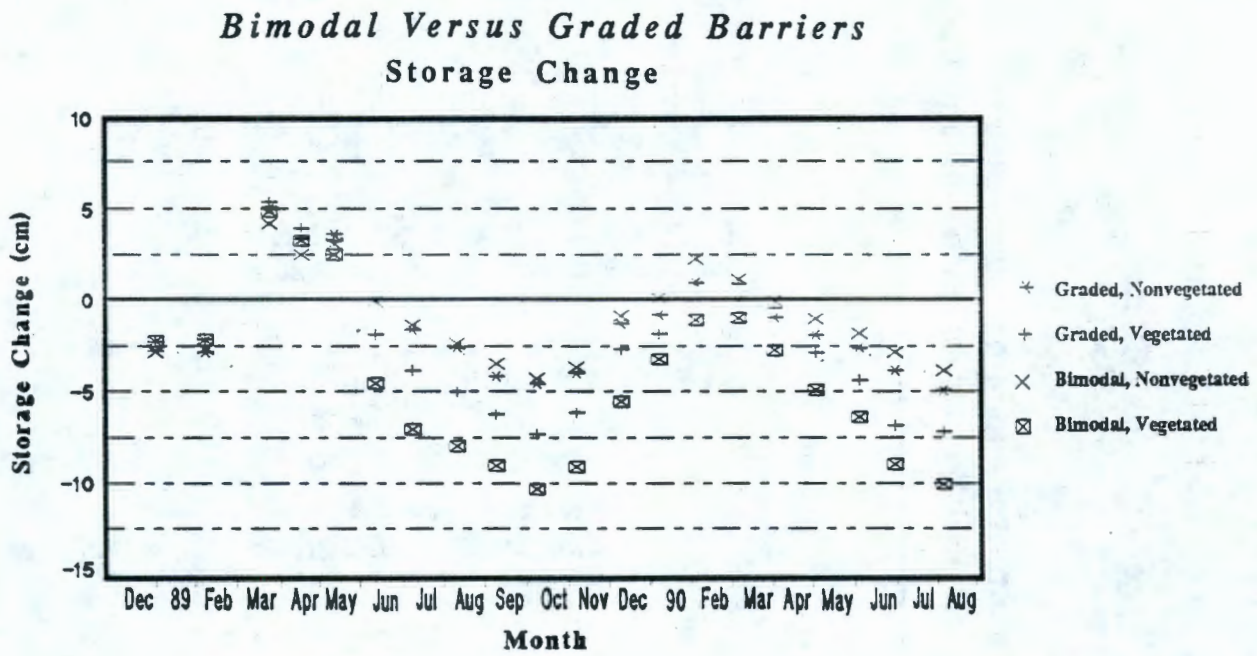


Figure 3-14. Bimodal Versus Graded Barriers (Storage Change).

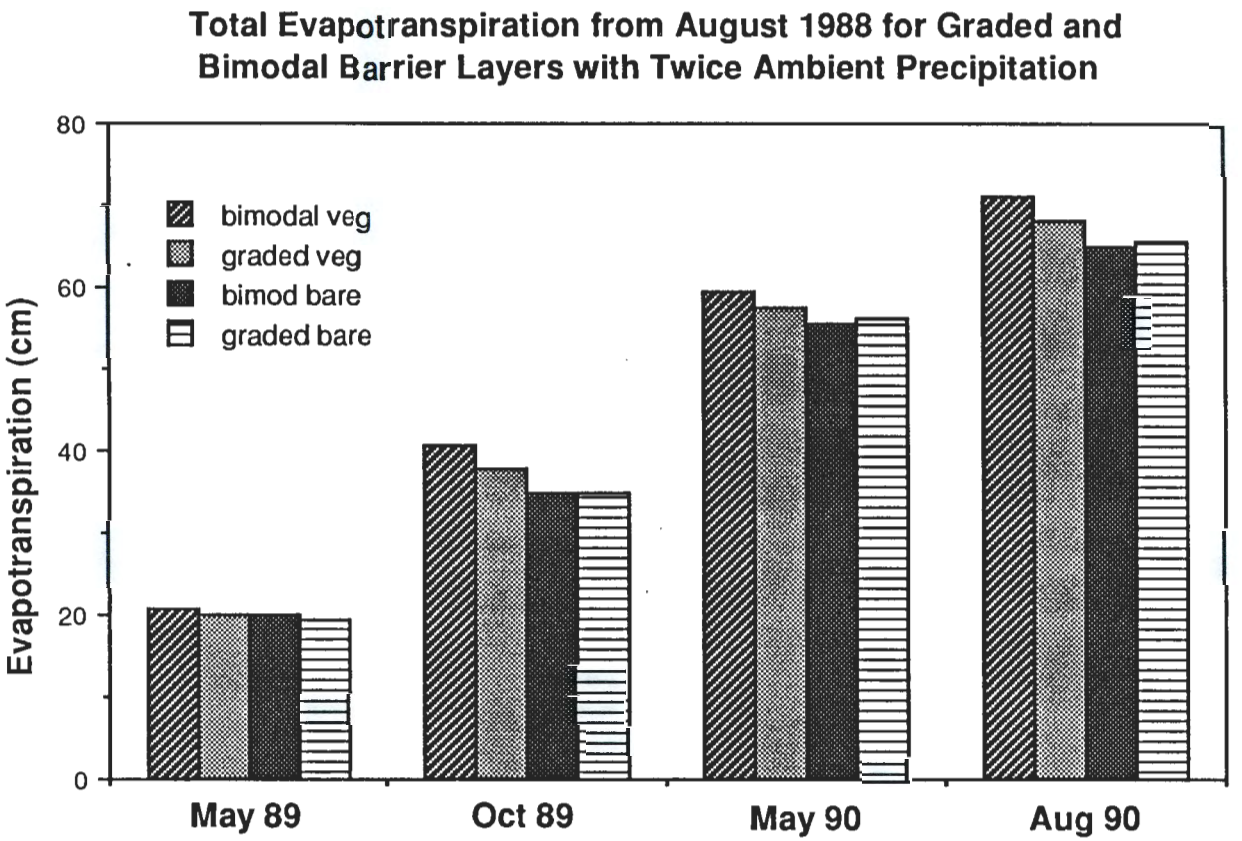


Figure 3-15. Total Evapotranspiration from August 1988 for Graded and Bimodal Barrier Layers with Twice Ambient Precipitation.

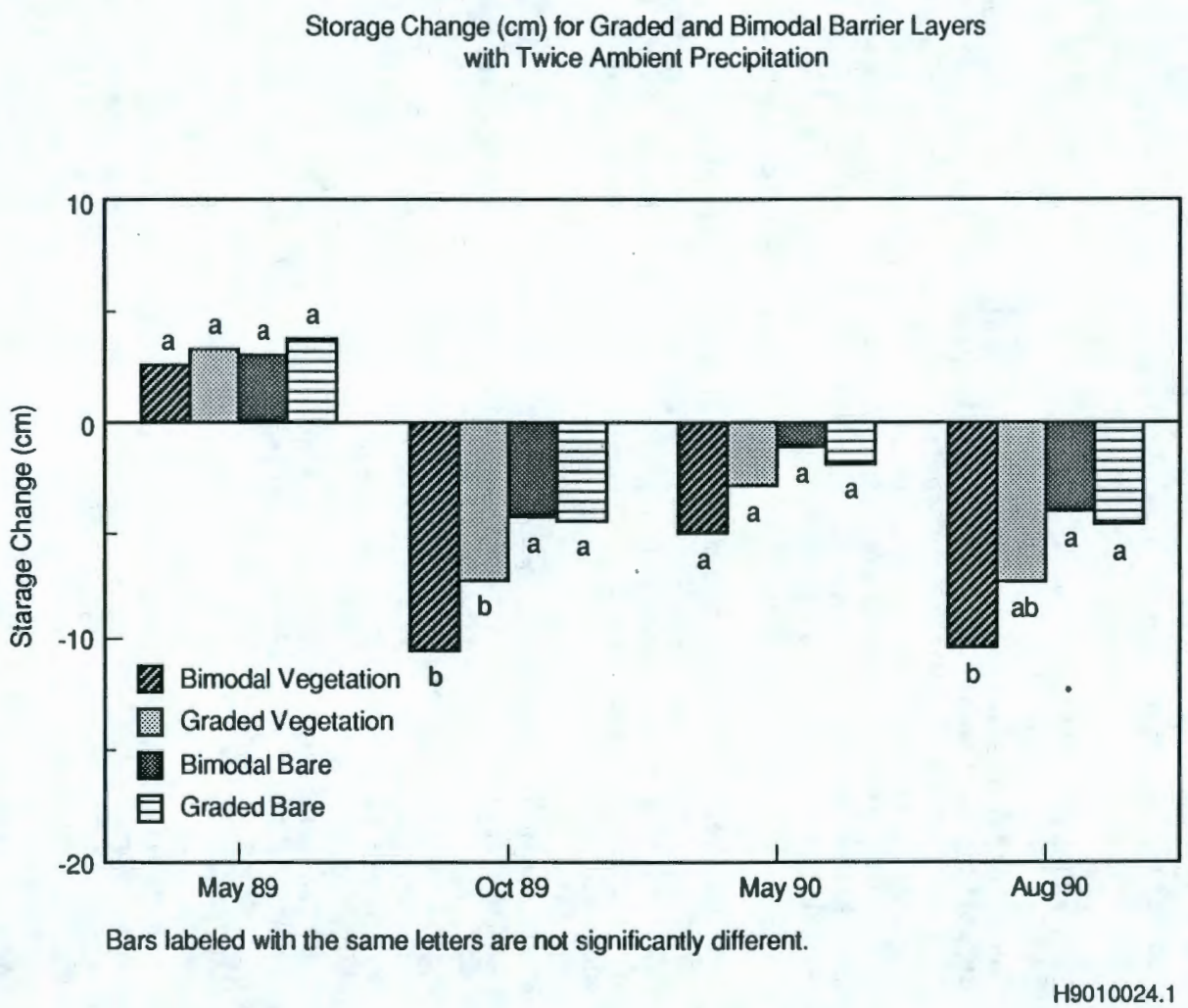


Figure 3-16. Storage Change from August 1988 for Graded and Bimodal Barrier Layers with Twice Ambient Precipitation.

analyzed dates. The vegetated lysimeters had greater storage change (decrease) than the nonvegetated lysimeters during October 1989 and August 1990. This difference was significant in the bimodal treatment but was not for the graded treatment.

The difference between the graded and bimodal treatments concerning vegetation may be attributable to the amount of plant biomass available and not to any intrinsic affect of the layering sequence itself. No drainage was detected in any of the graded or bimodal treatment lysimeters.

## 3.3 SAND AND GRAVEL DEPOSITION

The original analysis of variance model (Relyea et. al 1990) compared the sand deposition treatments with the control twice average precipitation plain soil surface treatments, with the effects of vegetation also included. During initial data analysis we were struck by the similarity between the sand treatments and corresponding gravel surface treatments. Therefore, we have included the gravel mulch treatments in this analysis, with a resulting 3 by 2 factorial ANOVA with three levels of surface treatment (sand, gravel, and control) and two levels of vegetation. This is a complete, balanced model.

The long-term patterns in cumulative ET and storage change are presented in Figures 3-17 and 3-18, respectively. From these figures it is readily apparent that compared to the control, plain soil treatments, there is considerably less ET and greater storage in all of the sand or gravel mulch treatments.

When cumulative ET values are compared at specific dates (Figure 3-19) the amounts of ET are significantly less with sand or gravel covers than with plain soil at all sampling dates. Vegetation was never a significant affect in the soil surface lysimeters, but became significant for the sand and gravel treatments during the second year of measurement. Changes in storage show a similar pattern (Figure 3-20). Decreased storage in the presence of vegetation was evident during the second year of sampling for the sand and gravel surface treatments, but vegetation was not a significant affect on the control surface treatment. When comparing the sand and gravel treatments, there were no significant differences within any vegetation treatment/sampling date combination.

Drainage was observed from the sand deposition and irrigated gravel mulch lysimeters. Cumulative drainage for these treatments ranged from about 0.6 cm to 1.1 cm as of the August 1990 sampling date, with initial drainage first being detected during January 1990 (Figure 3-21). None of the mean cumulative drainage amounts are significantly different among the gravel and sand surface treatments. These were the only lysimeter treatments that were found to produce drainage during the two years of sampling.

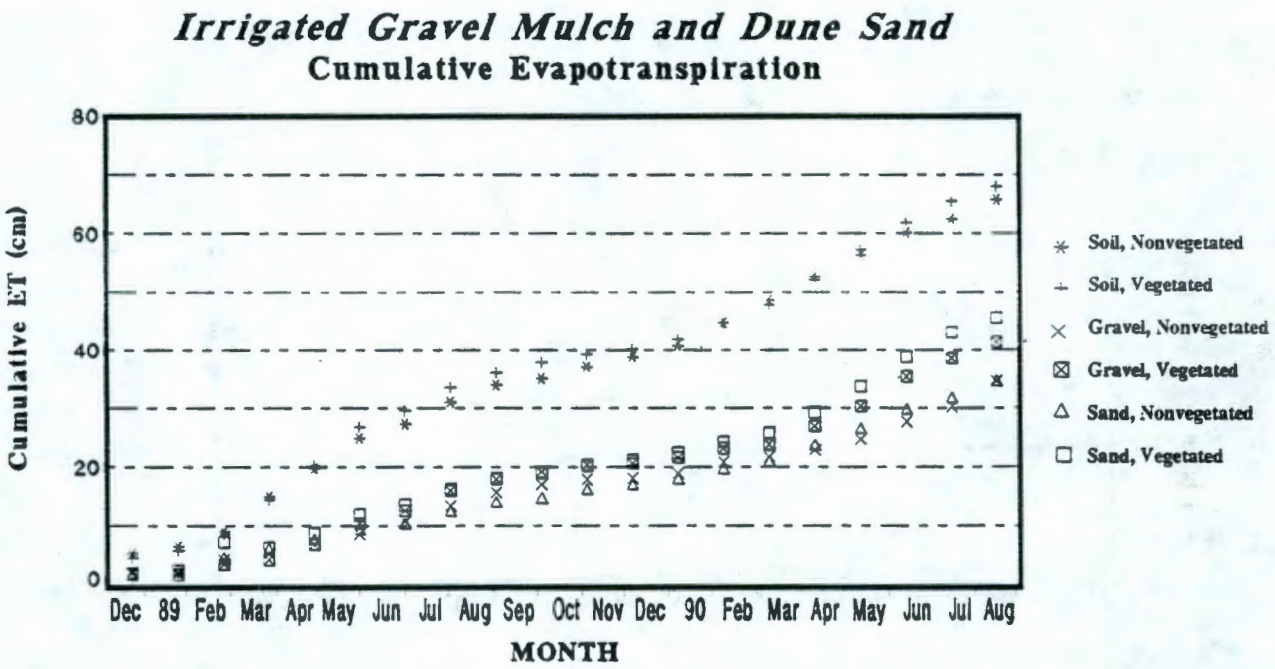


Figure 3-17. Irrigated Gravel Mulch and Dune Sand (Cumulative Evapotranspiration).

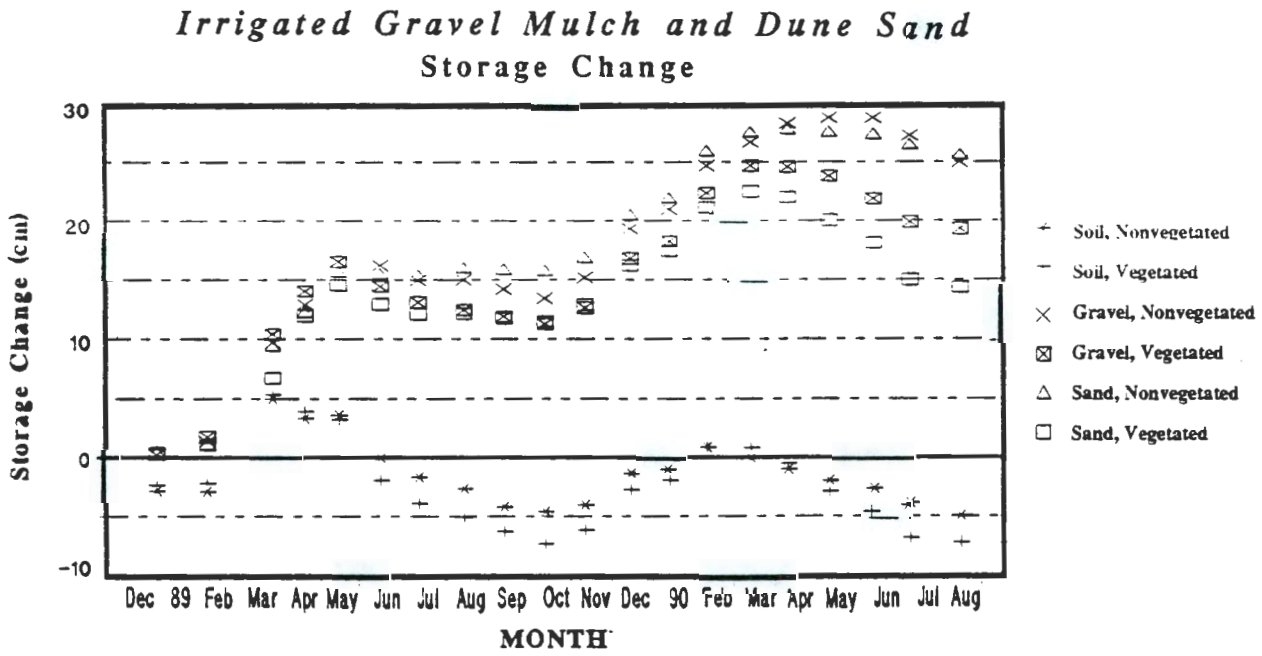


Figure 3-18. Irrigated Gravel Mulch and Dune Sand (Storage Change).

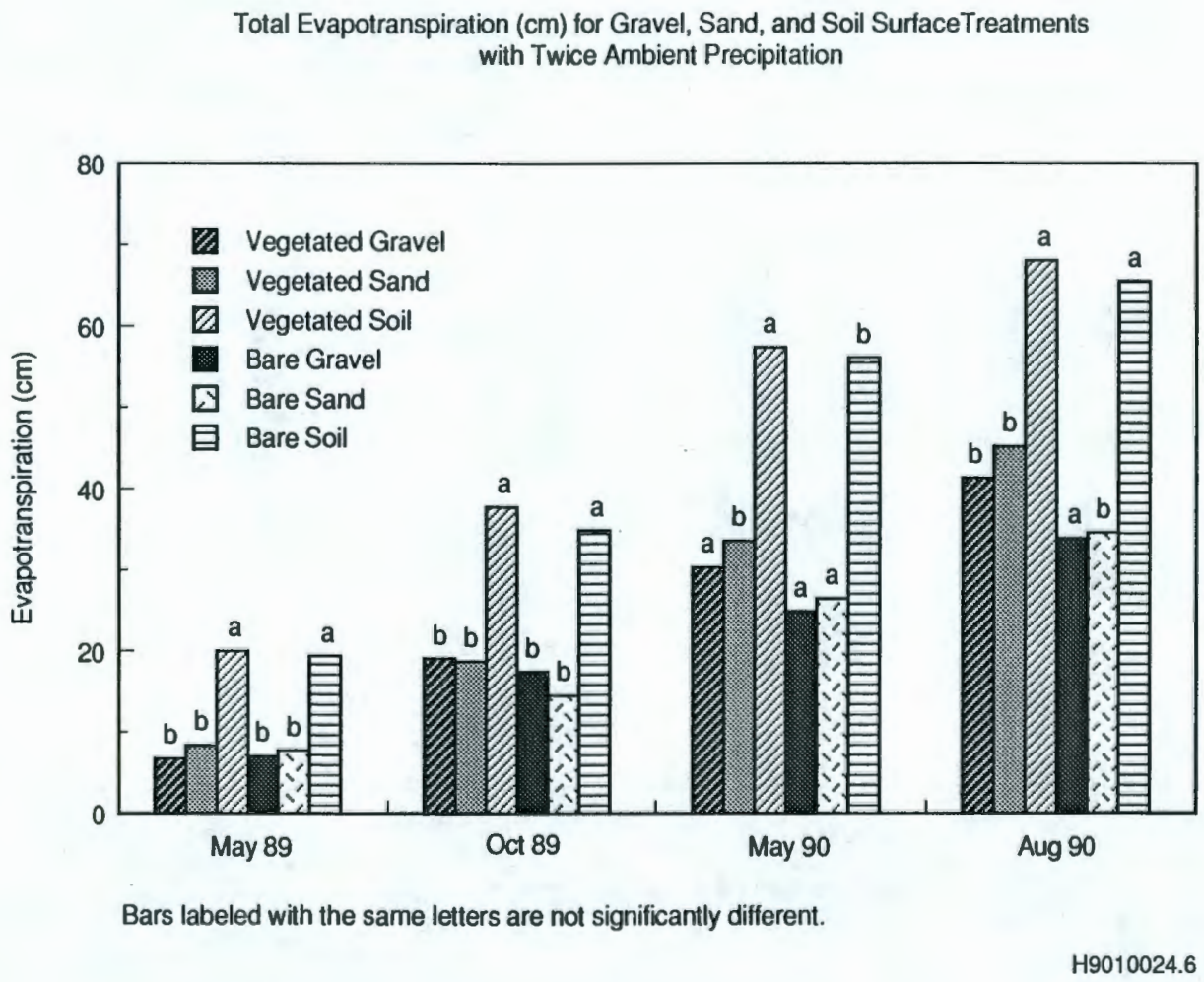


Figure 3-19. Cumulative Evapotranspiration from Gravel, Sand, and Soil Surface Lysimeters on Selected Sampling Dates.

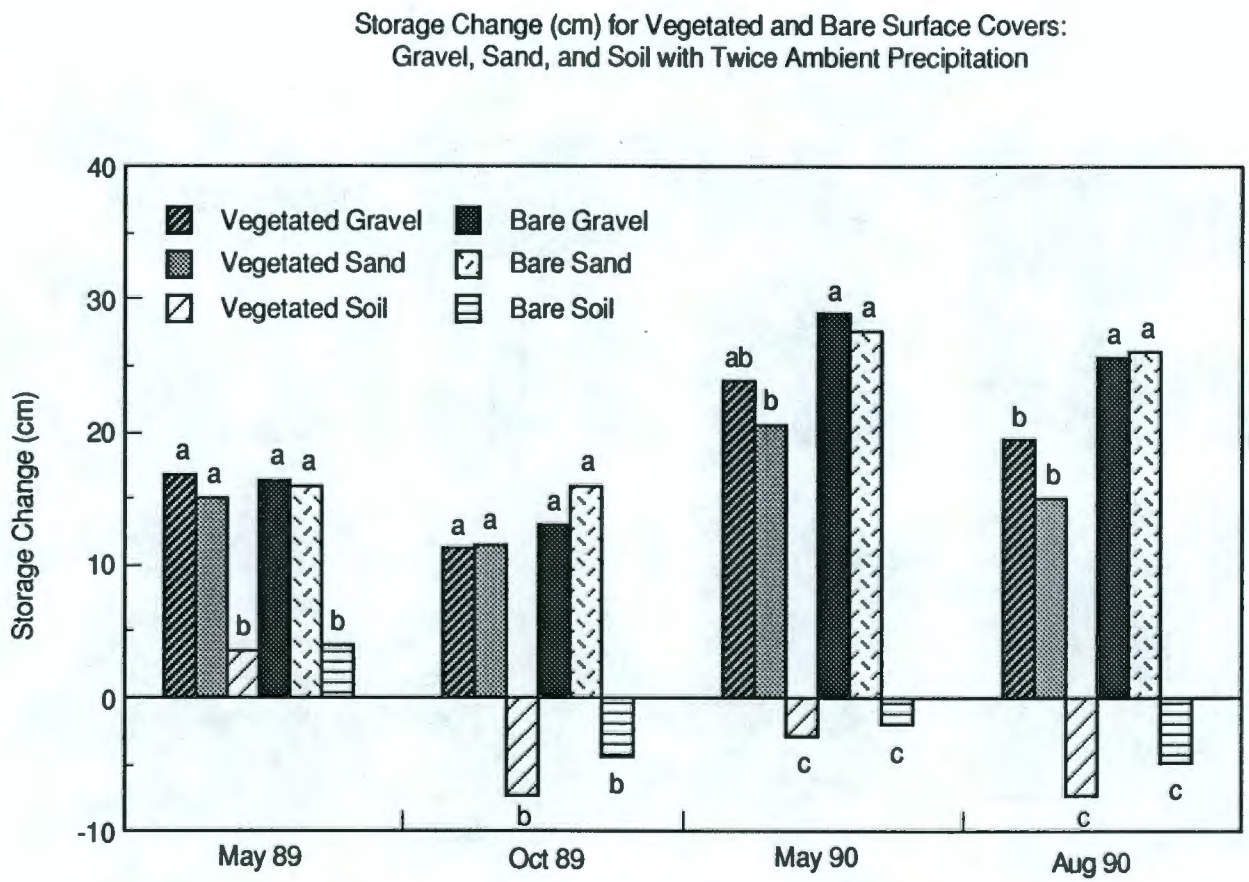


Figure 3-20. Storage Change for Gravel, Sand, and Soil Surface Lysimeters on Selected Sampling Dates.

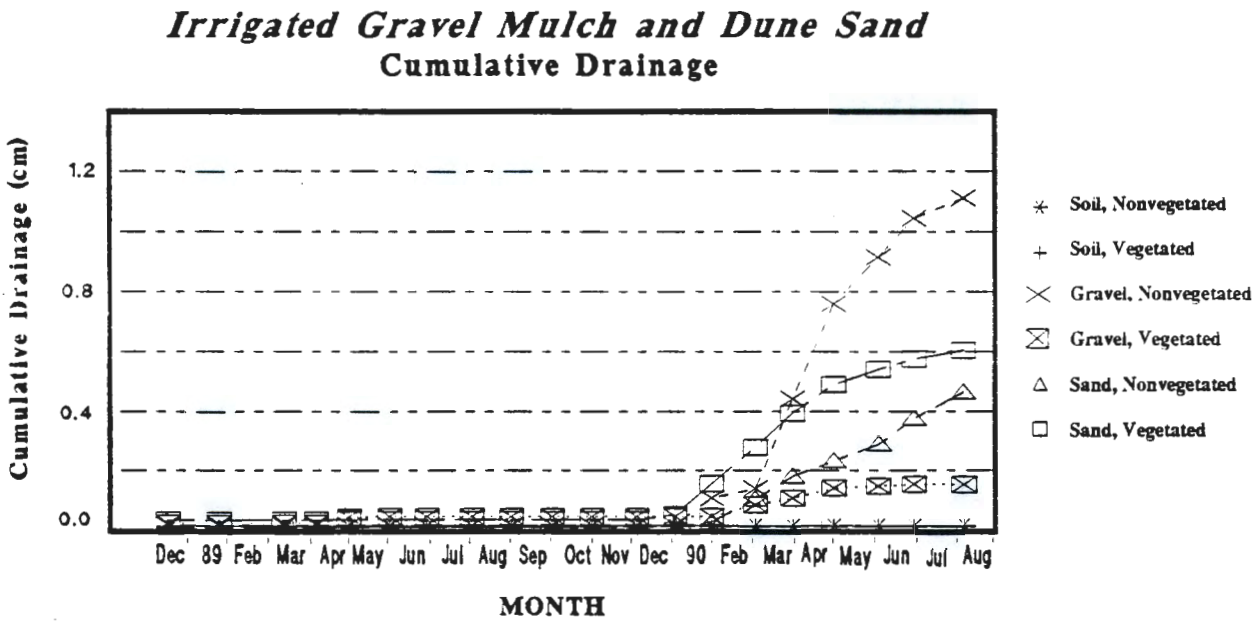


Figure 3-21. Irrigated Gravel Mulch and Dune Sand (Cumulative Drainage).

## 3.4 ALTERNATIVE INFILTRATION BARRIERS

There is little difference among the clay, grout and control treatments in the long term patterns of either cumulative ET (Figure 3-22) or in total storage change (Figure 3-23). In the analysis of the results at the selected sampling dates, the only significant difference in cumulative ET occurred early in the experiment in May 1989 (Figure 3-24). Likewise, this sampling date is the only one that showed significant storage change differences (Figure 3-25). The grout treatment had significantly higher cumulative ET and lower total storage than either the bimodal control or the graded design. The means for the clay layer lysimeters were between these two extremes and were not significantly different from either. The different appearance early on in the experiment may be the result of the high water content of the grout slurry used to form the grout layer (Relyea et al. 1990). The drying of this layer may have provided the extra moisture for the increase in ET. The same would be true to a lesser extent in the lysimeters with a clay layer. No drainage was detected in any of these alternative barrier lysimeters.

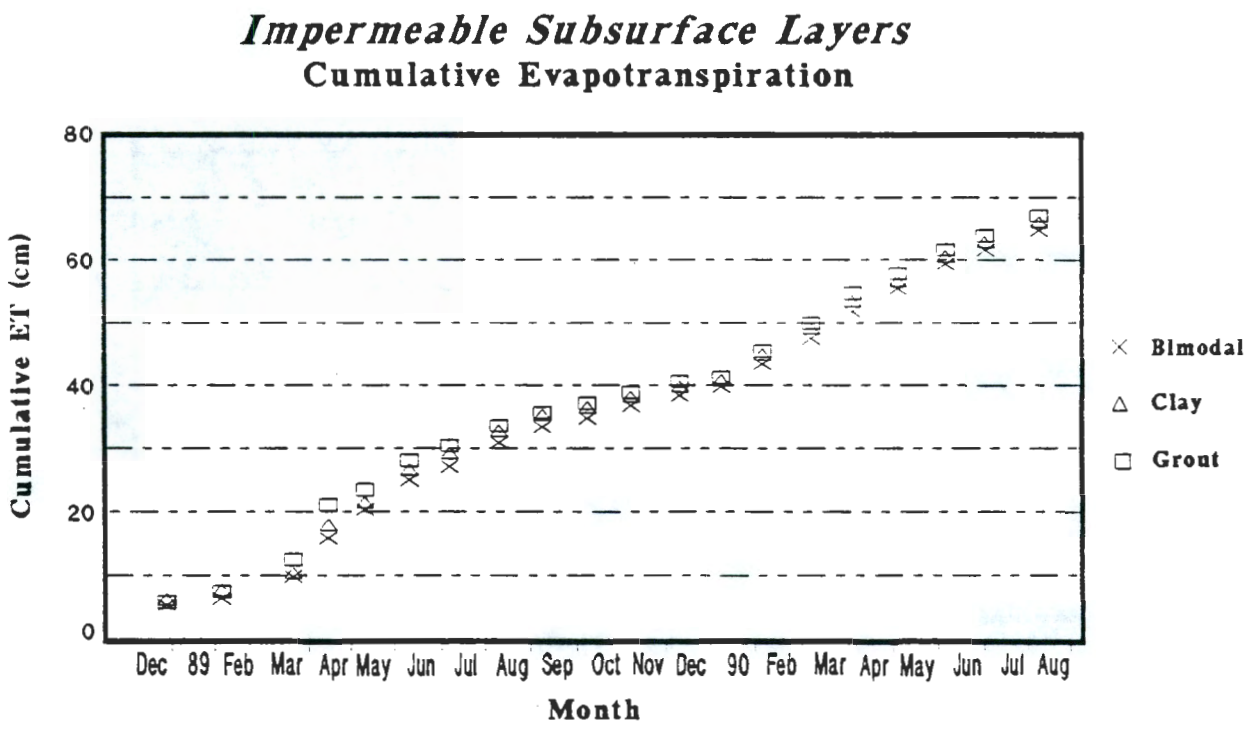


Figure 3-22. Impermeable Subsurface Layers (Cumulative Evapotranspiration).

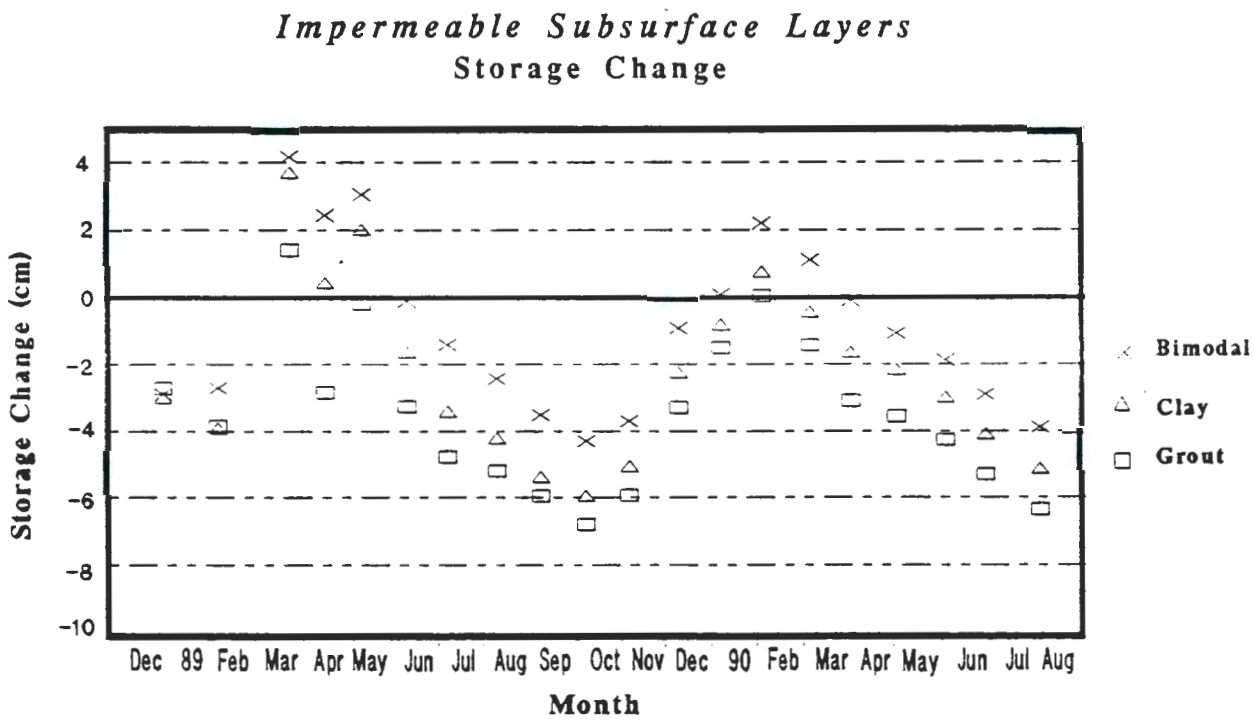


Figure 3-23. Impermeable Subsurface Layers (Storage Change).

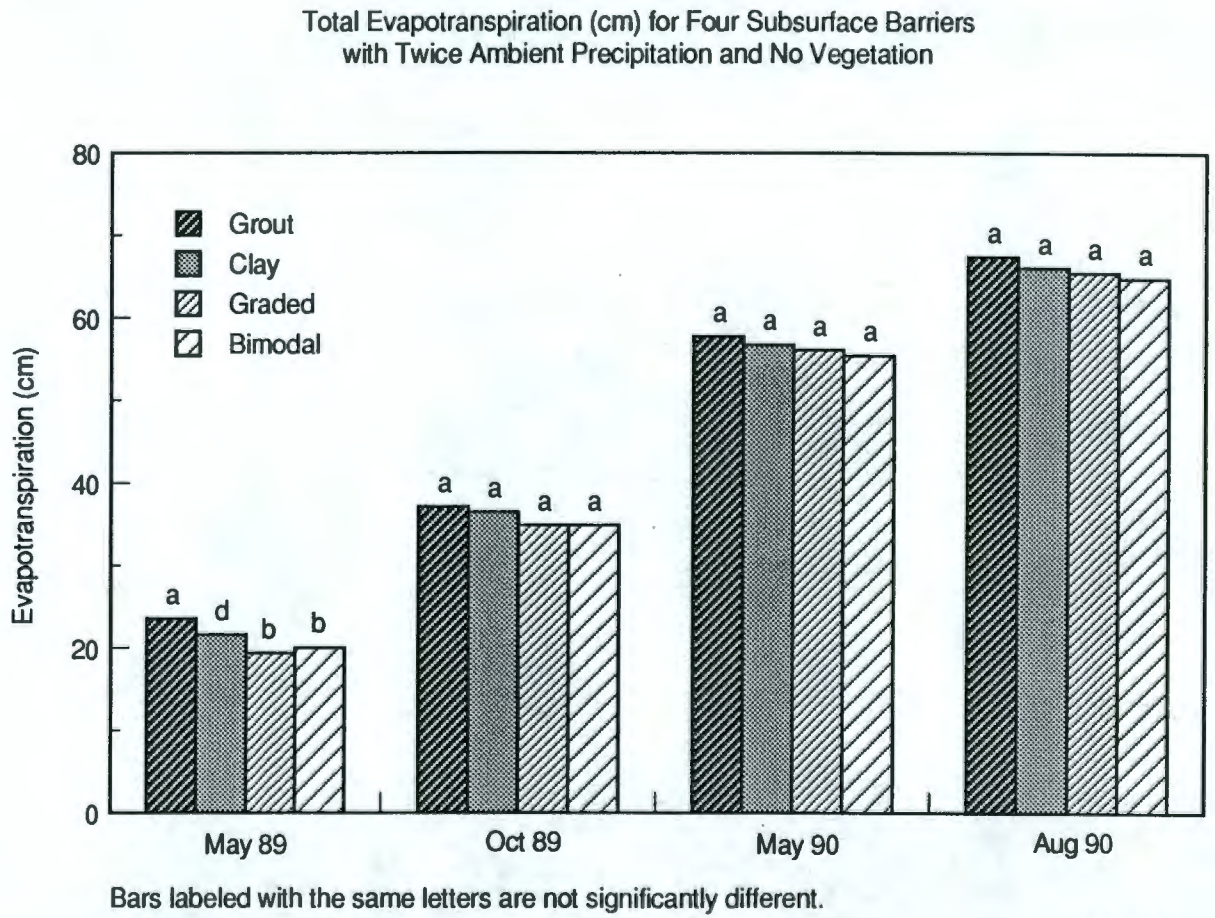


Figure 3-24. Cumulative Evapotranspiration Clay, Grout, and Control Lysimeters on Selected Sampling Dates.

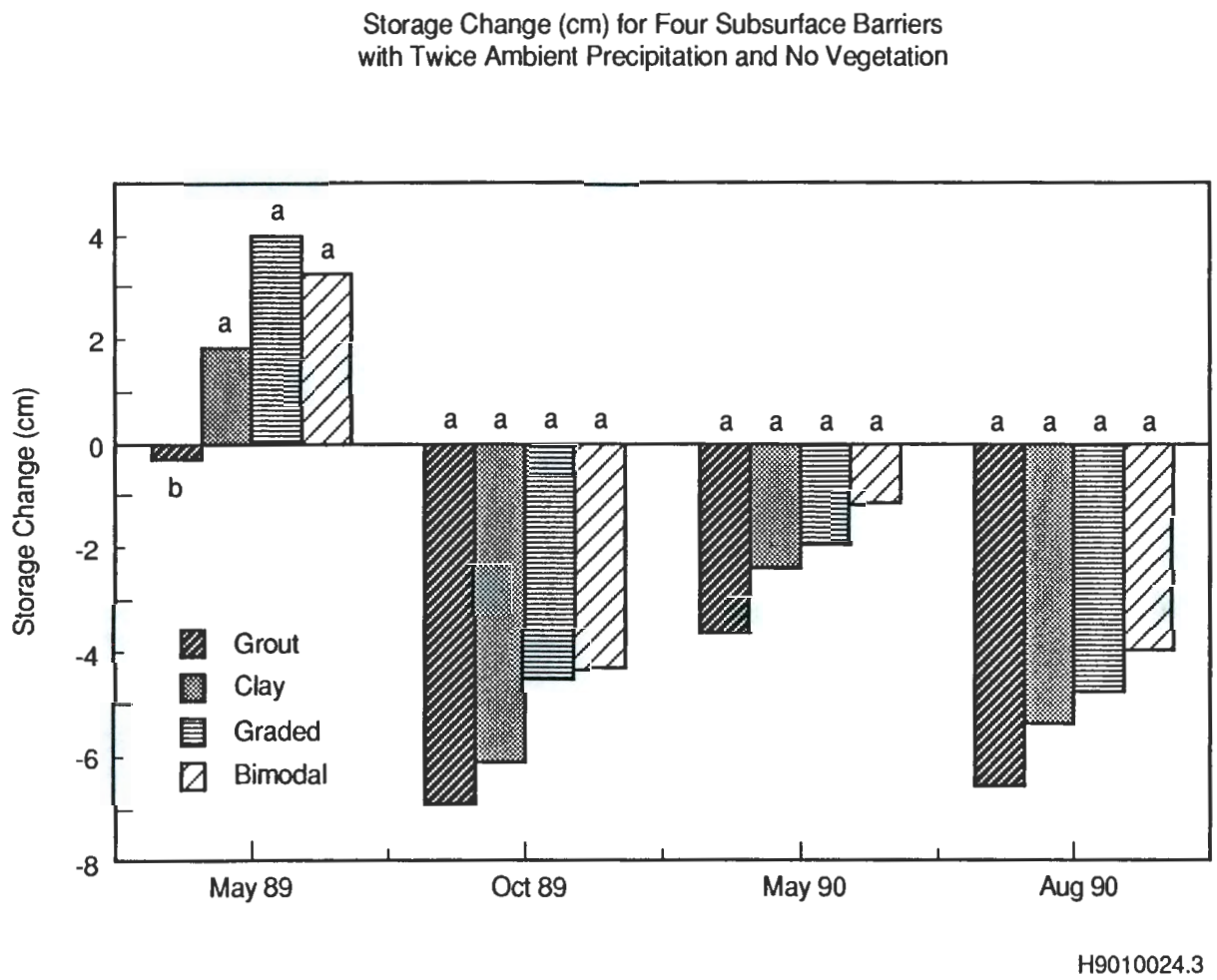


Figure 3-25. Storage Change for Clay, Grout, and Control Lysimeters on Selected Sampling Dates.

## 4.0 SUMMARY AND CONCLUSIONS

Drainage did not occur in any lysimeters with soil or gravel admix surfaces, or in lysimeters with a gravel mulch surface and ambient precipitation. Thus, total precipitation during the first 2 yr of the experiment has effectively been partitioned into ET and storage. For the bare soil and admix treatments ET, exceeded precipitation and there was a net reduction in stored water. These preliminary results suggest that soil and gravel admix (pea gravel mixed into the McGee Ranch silt loam) are equally effective in returning soil water to the atmosphere through the combined processes of evaporation and transpiration. Only the sand and gravel mulch treatments resulted in a net gain in soil water storage. This observation suggests that gravel surface mulch (that could be applied to soil surfaces to limit erosion) and sand (that might accumulate as deposition on the barrier surface) may limit ET to the extent that water will accumulate in the barrier and eventually contribute to drainage, particularly under conditions where vegetative growth is minimal or absent.

Actually, the performance of the subsurface alternative infiltration barriers and the different layering sequences was not effectively tested because the surface treatment applied (soil only) provides for the evaporation of all precipitation, even at twice the average amount. Therefore, it is anticipated that the additional water applications planned for FY 1991 may initiate increases in storage thus permitting a more complete evaluation of solution grout, clay, and bimodal layering sequences in limiting drainage.

The addition of inflatable insulating collars just below the soil surface between the lysimeter sleeves and the lysimeters was effective in moderating rapid fluctuations in lysimeter soil temperature and in causing the lysimeter soil temperatures to track temperatures in the surrounding soil instead of the air.

Although vegetation growth was not directly measured on the lysimeters in FY 1990, the relative quantity of growth was visually observed to be comparable to that in FY 1989. The vegetation quantity can best be described as sparse, and was well below the amount expected under natural field conditions. Thus, the vegetation treatments approximate a lower limit of cheatgrass productivity which suggests that transpiration in the lysimeters is low compared to potential transpiration that may occur on future barrier surfaces. Also, cheatgrass communities are relatively shallow-rooted and have been reported to use less water than a sagebrush-bunchgrass community occupying the same site (Cline et al. 1977).

Nutrient deficiencies are suspected to be a contributing factor for the limited plant growth that was observed. Nutrient deficiencies may result if the soil came from deeper zones within the native soil profile at the McGee Ranch. Future tests will compare the nutrient status of the lysimeter soil with the native soils at the McGee Ranch. Other limiting factors may include the degree of soil compaction or the abundance of mycorrhizae in the soil. These factors also may be addressed in the future. In order to obtain a more representative vegetation cover and associated vegetation responses,

the plan is to provide enhanced vegetation growth in FY 1991 by (1) adding nutrients to the lysimeters, (2) changing the vegetation by planting other species, or (3) both of the above. The establishment of normal plant cover on the lysimeters also is important if representative test results are to obtain on protective barrier performance with respect to ET, soil water storage, and drainage under enhanced (three to four times average) precipitation.

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