USEcology Nevada

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# DESIGN BASIS AND CONSTRUCTION SPECIFICATIONS FOR TRENCHES 11 AND 12 FINAL COVERS BEATTY, NEVADA FACILITY

**Supplement to:**

## TRENCH 12 CONSTRUCTION QUALITY ASSURANCE PLAN

**USEPA ID #NVT330010000**

**Nevada Hazardous Waste Treatment, Storage and Disposal Permit NEV HW0019**


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**April 2008**

# DESIGN BASIS AND CONSTRUCTION SPECIFICATIONS FOR TRENCHES 11 AND 12 FINAL COVERS

**Supplement to**

## TRENCH 12 CONSTRUCTION QUALITY ASSURANCE PLAN

**US Ecology Nevada, Inc.**

**Hazardous Waste Management Facility**

**Beatty, Nevada**

**USEPA ID #NVT330010000**

**Nevada Hazardous Waste Treatment, Storage and Disposal Permit NEV HW0019**

**April 2008**

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# CERTIFICATION

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information, the information submitted is, to be the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

**US Ecology Nevada Representative:** _____ **Date:** _____

**Printed name:** _____

**Title:** _____

**Nevada Professional Engineer** _____ **Date:** _____

# EXECUTIVE SUMMARY

This Construction Quality Assurance Plan (CQA Plan) provides the Design Basis and Construction Specifications for the final landfill covers for Disposal Trenches 11 and 12 at the US Ecology Nevada, Inc. (USEN) Hazardous Waste Management Facility located about 11 miles south of the town of Beatty in Nye County, Nevada. The CQA Plan is consistent with the requirements of HW Permit Number NEV HW0019 dated April 29, 2005. The document has been developed under the direction of a professional engineer registered in the State of Nevada and describes the design features and procedures that will be employed in the construction of final landfill covers.

## Arid Region Alternative Covers

Arid region final covers use the moisture retention properties of native soils to contain and store infiltrating moisture (precipitation) until the natural processes of evaporation and plant transpiration remove the stored moisture and release it the atmosphere. The proposed final covers for Trenches 11 and 12 will be protective of human health and the environment, and offer benefits when compared to conventional landfill cover types that incorporate compacted clay or synthetic materials as low-permeability components. These benefits include, but are not limited to, use of easily obtained construction materials, relative simplicity of construction, reduced complexity of quality assurance/quality control programs, increased long-term cover integrity and stability, and simplified cover maintenance.

## Regulatory Considerations

The final landfill covers for USEN Trenches 11 and 12 are designed to satisfy the regulatory requirements for final closure of a landfill cell. The design acknowledges and benefits from research and experience that confirms that the desired environmental protection benefits can be obtained with an alternative design. This document describes a final landfill cover system that is fully consistent with the provisions of 40 CFR 264.110, the performance standards of 40 CFR 264.111, and the following requirements of 40 CFR 264.310(a) dealing with landfill closure:

*(1) Provide long-term minimization of migration of liquids through the closed landfill;*

*(2) Function with minimum maintenance;*

*(3) Promote drainage and minimize erosion or abrasion of the cover;*

*(4) Accommodate settling and subsidence so that cover's integrity is maintained; and*

*(5) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.*

Based upon frequent discussions with the Nevada Division of Environmental Protection (NDEP) during the design process, USEN is confident that the arid-region final cover design for Trenches 11 and 12 is consistent with applicable regulatory requirements. The manner by which the arid region final cover design addresses each of these requirements is summarized below.

Long-term minimization of liquid migration. Liquid migration into and through the landfilled waste is minimized by the low effective hydraulic conductivity (permeability) of the monolithic final cover system. Unsaturated flow modeling, with site-specific input parameters (some established at the Amargosa Desert Research Site), shows that vertical liquid flux (also called percolation) is very small (much less than 10 millimeters per year). As such, little liquid is expected to move through the final cover into the disposed waste.

Minimum maintenance. The capacity of the final cover to function with minimum maintenance is provided by the combination of the simplicity of its monolithic design and the capacity of the natural soil materials that comprise the cover to resist damage from water and wind erosion. By not including multiple component layers, such as low permeability geosynthetic liner materials or geosynthetic drainage media, the monolithic soil cover is less susceptible to loss of integrity through damage to or deterioration of such components, and can be much more easily and quickly repaired if damaged. Repairs to the monolithic arid-region final cover can be completed by adding cover soil and re-establishing surface grades. Replacing or repairing multiple components of a cover reliant upon geosynthetic materials, with related quality control requirement, will be unnecessary for a monolithic arid-region final cover.

Promote drainage and minimize erosion. The final cover system incorporates slopes and natural materials that promote drainage and minimize erosion. The final covers include limited areas of flat or gentle slopes and large areas of steeper slope areas that will promote precipitation run-off while preventing run-on from areas off the cover. Erosion by water and wind is maintained at acceptable levels through the use of relatively coarse-grained native soil materials.

Accommodate settling. Little settling of waste though consolidation or degradation is expected for the largely inert waste materials that have been or are expected to be disposed in the trenches, and little subsidence of the final covers is expected. The 1996 Trench 12 design (as referenced herein) determined that the disposed waste is likely to be 85 percent soil and soil-like waste, 10 percent containerized waste, and five percent non-compressible solids. That design document established that cover settlement was expected to be 1.5 feet or less, and to occur relatively uniformly across the landfill in proportion to the thickness of disposed waste. Considering the limited amount and relatively uniform distribution of expected settlement, the monolithic arid-region final cover is expected to accommodate settlement without disrupting the integrity of the final cover or its capacity to function as an effective barrier to liquid migration. Also, the monolithic final cover does not incorporate components (such as geosynthetic liners or drainage media) whose capacity to function is more prone to negative impacts from settlement.

Low permeability. This design basis document provides technical substantiation to the fact that liquid percolation through this arid region final cover system (i.e., this cover design in this arid setting) will be much less than 10 millimeters per year, which is an effective hydraulic conductivity (permeability) that is less than $3.2 \times 10^{-8}$ centimeters per second (cm/sec). At this effective permeability, the cover is less permeable than the bottom liner system component maximum permeability of $1 \times 10^{-7}$ cm/sec that is prescribed in 40 CFR 264.301(c)(1)(i)(B). When the presence of just the uppermost portion of the thick sequence of dry waste beneath the cover also is considered, the effective permeability of the cover system is even lower.

Selected Arid and Semi-Arid Region Monolithic ET Alternate Final Covers

| Name and Location | | Landfill Type | Cover Type | Regulatory Status | Rainfall (in/yr) | Percolation (mm/yr) | Cover Description and Construction Status |
|---|---|---|---|---|---|---|---|
| Apple Valley Landfill | CA, Apple Valley | MSW | ET, monolithic | AFC research | 5.4 | NA | Demonstration, 3.0 feet thick cover installed in 2002 |
| Altamont Landfill | CA, Livermore | Nonhaz waste | ET, monolithic | AFC research | 13.4 | 1.5 | Demonstration, 3.5 feet thick cover installed in 2001 |
| Phelan Landfill | CA, Phelan | MSW | ET, monolithic | AFC research | 5.6 | 0.8 to 11.7* | Demonstration, 5.0 feet thick cover installed in 1998 |
| Milliken Landfill | CA, San Bernardino | MSW | ET, monolithic | AFC research | 12.0 | 0.8 to 6.6 | Demonstration, 5.0 feet thick cover installed in 1997 |
| Rocky Mountain Arsenal Landfill | CO, Denver | Hazwaste | ET, monolithic | AFC research | 15.6 | <1.3mm | Demonstration, 3.5-4.0 feet thick cover installed in 1998 |
| US Ecology of Idaho, Site B Test Pad | ID, Grand View | Hazwaste | ET, monolithic | AFC research | 7.1 | <<3.2 | Demonstration, 5.0 feet thick cover installed in 2000 |
| Kirtland Municipal Waste Landfill | NM, Albuquerque | MSW | ET, monolithic | AFC research | 8.5 | NA | Full scale, cover over waste installed in 2002 |
| Area 3 Radioactive Waste Management Site | NV, Nye County | Radwaste | ET, monolithic | AFC research | 5.3 | NA | Demonstration, 8.0 feet thick covers |
| Finley Buttes Regional Landfill | OR, Boardman | MSW | ET, monolithic | AFC research | 8.7 | <<1.0 | Demonstration, 4.0 feet thick cover over waste installed in 2000 |
| Lopez Canyon Sanitary Landfill | CA, Los Angeles | MSW | ET, monolithic | Approved, CA RWQCB | 17.0 | NA | Full scale, 3.0 feet thick cover over waste installed in 1999 |
| Denver Arapaho Disposal Site | CO, Aurora | MSW | ET, monolithic | Approved, CO DPHE | 14.0 | NA | Full scale, 4.0 feet thick cover over waste installed in 2002 |
| Rocky Mountain Arsenal Landfill | CO, Denver | Hazwaste | ET, monolithic | Approved, CO DPHE | 15.6 | NA | Full scale, cover construction began in 2007 |
| US Ecology of Idaho, Trenches 10 & 11 | ID, Grand View | Hazwaste | ET, monolithic | Approved, ID DEQ | 7.1 | NA | Full scale, 5.0 feet thick cover over waste installed in 2000 |
| Mr. M Landfill | MT, Lewiston | MSW | ET, monolithic | Approved, MT DEQ | 18.0 | NA | Full scale, 3.0 feet thick cover over waste installed in 2000 |
| Sandia Chemical Waste Landfill | NM, Albuquerque | Hazwaste | ET, monolithic | Approved, NM ED | 8.5 | NA | Demonstration, cover approved as a corrective measure |
| Kirtland AFB Landfill Closures | NM, Albuquerque | Hazwaste and Nonhaz waste | ET, monolithic | Approved, NM ED | 8.5 | NA | Demonstrations, covers approved as corrective measure for three landfills |
| Los Alamos County Landfill | NM, Los Alamos | MSW | ET, monolithic | Approved, NMED | 18.2 | NA | Full scale, 3.0 feet thick cover installed in 2007. |
| Operating Industries, Inc. Landfill | CA, Monterey Park | MSW | ET, monolithic | Approved, USEPA | 18.5 | NA | Demonstration, 4.0 feet (min) thick cover constructed in 2000 |

NA = information not available << = much less than * Reported value is for 1997-1998, and not a long-term average

The preceding table identifies landfills and other facilities (including hazardous, solid, and radioactive waste management units) in arid and semi-arid areas of the U.S. have incorporated monolithic evapotranspiration covers (ET Covers). These include several landfills where monolithic ET Covers have been tested and demonstrated to provide performance that is consistent with regulatory requirements are identified below. As the table indicates, full-scale monolithic ET AFCs have been constructed at several facilities in locations that, similar to the USEN Beatty facility, have annual precipitation totals that are much less than 20 inches. Arid settings with low precipitation, high average temperatures, high solar radiation, and high evaporation potential are positive factors in the long-term performance of monolithic AFCs.

**Design Considerations**

The facility location in the Amargosa Desert, acknowledged as one of the most arid areas within the continental U.S., supports the use of a monolithic ET Cover. Annual precipitation averages about 4.25 inches, while the potential evapotranspiration rate for this location is about 78 inches. Moisture migration research by the USGS at the Beatty facility location, and predictive modeling of moisture movement in this environment, strongly support the use of an ET Cover as an appropriate method for long-term minimization of infiltration of liquids through the landfill cover. The cover system will limit liquid percolation into waste, thereby minimizing the likelihood that such liquid will move through the waste, through the components of the liner system, and into the subsurface environment.

From bottom to top, the components of the arid region cover to be used for Trenches 11 and 12 are as follows.

- **Interim Cover Soil Layer**. The lower layer of the final cover is a lightly compacted native soil layer at least 12-inches (1.0 foot) thick and extending across the cover to the natural ground surface on all sides of the trenches.

- **Final Cover Soil Layer**. The upper layer of the final cover is a lightly compacted soil layer at least 24-inches (2.0 feet) thick and extending across the cover to the natural ground surface on all sides of the trenches. In conjunction with the Interim Cover Layer, it retards the downward movement of infiltrating water by providing temporary water-storage, and allowing stored water to be returned to the atmosphere by evaporation and plant transpiration.

Moisture Retention by Final Covers

The long-term performance of the arid-region final cover is determined by consideration of infiltration of precipitation, moisture retention within the cover soil, moisture removal by evapotranspiration, and potential percolation into waste. These factors were evaluated using two models, the quasi-two-dimensional water-balance HELP model and the one-dimensional Richards equation UNSAT-H model. These models simulate water flow into and out of the proposed final cover and were used to predict performance of the proposed final cover.

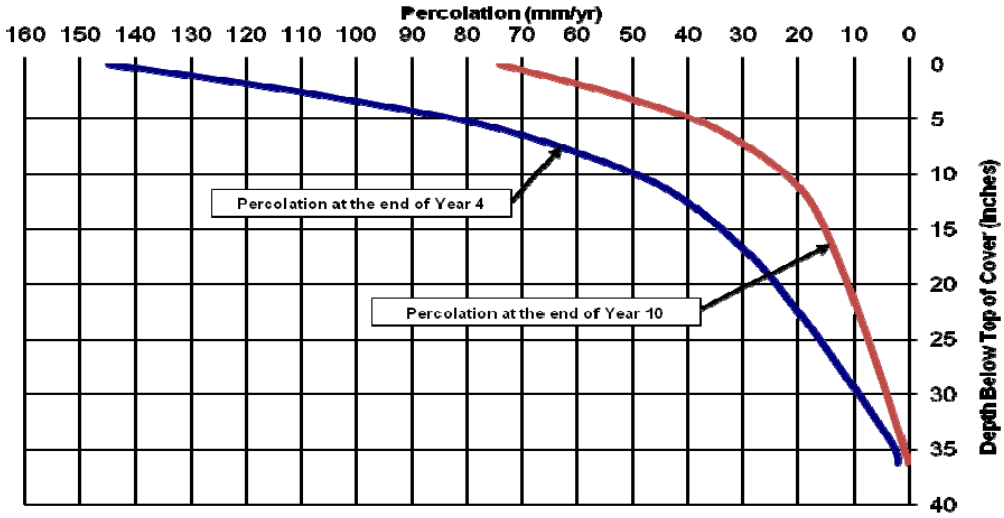
The two models predicted similar results with regard to the capacity of the final cover to limit percolation. Both models predicted that a three-feet (36-inch) thick monolithic cover will

prevent significant percolation of fluids through the cover and into waste. The results also indicate that nearly all of the precipitation that enters returns to the atmosphere through the combination of evaporation and transpiration rather than infiltrating deeply into the cover and percolating into waste. These results likely are conservative because no vegetation was considered in either the HELP or UNSAT-H models, so the evaluation of "evapotranspiration" (the combined effect of evaporation and plant transpiration) actually was limited to consideration of evaporation only. The following table summarizes HELP and UNSAT-H modeled percolation through the base of a 36-inch monolithic ET Cover as designed for the USEN facility

| Modeled Year | HELP Percolation Results (mm/year) | UNSAT-H Percolation Results (mm/year) |
|---|---|---|
| 1 | 0.00000 | 0.456 |
| 2 | 0.00000 | 0.304 |
| 3 | 0.00000 | 1.973 |
| 4 | 0.00000 | 2.029 |
| 5 | 0.00000 | 0.319 |
| 6 | 0.00000 | 0.018 |
| 7 | 0.00003 | 1.466 |
| 8 | 0.00000 | 2.028 |
| 9 | 0.00000 | 0.319 |
| 10 | 0.00000 | 0.302 |
| 11 | 0.00000 | 0.301 |
| 12 | 0.00000 | 0.301 |
| 13 | 0.00000 | 1.973 |
| 14 | 0.00000 | 2.029 |
| 15 | 0.00000 | 0.319 |
| 16 | 0.00000 | 0.018 |
| 17 | 0.00000 | 1.466 |
| 18 | 0.00000 | 2.028 |
| 19 | 0.00000 | 0.319 |
| 20 | 0.00000 | 0.302 |
| 21 | 0.00000 | 0.301 |
| 22 | 0.00003 | 0.301 |
| 23 | 0.00000 | 1.973 |
| 24 | 0.00000 | 2.029 |
| 25 | 0.00003 | 0.319 |
| 26 | 0.00000 | 0.018 |
| 27 | 0.00000 | 1.466 |
| 28 | 0.00000 | 2.028 |
| 29 | 0.00000 | 0.319 |
| 30 | 0.15776 | 0.302 |
| **Annual Average** | **0.005261 mm/year** | **0.911 mm/year** |

The graph below illustrates downward percolation rates (vertical flux) estimated by UNSAT-H at increasing depths within a three-feet (36-inch) thick final cover at two times during the 30-year period. The first, "End of Year 4," represents the moisture condition in the cover immediately following two sequential years of higher than normal (7.65 inches) precipitation. The second, "End of Year 10," represents the moisture condition after 10 years of varying precipitation amounts that average 5.2 inches per year, or about one inch greater than the normal precipitation for Beatty.

As the "End of Year 4" graph shows, vertical flux rates are relatively high, in the upper one foot of the cover and decrease to small values (about 2 mm/year) approaching the base of the cover at three feet deep. The graph, which represents conditions after two consecutive wet years, is representative of times when percolation from the base of the cover is theoretically the highest during the 30 years modeled. The nature of the curve at points deeper than about 30 inches indicates that increasing the total cover thickness to values more than 36 inches likely would not provide significant performance improvement relative to deep percolation.




VERTICAL FLUX AT INCREASING DEPTHS IN A 36-INCH FINAL COVER AFTER YEARS 4 AND 10

Although observing predicted percolation immediately after two consecutive wet years is conservative; considering a longer period of time is a better measure of final cover performance. The "End of Year 10" graph illustrates the downward percolation rates (vertical flux) at increasing depths in the cover after the first 10 years of modeling. In this instance, the nature of the curve at points deeper than about 25 inches indicates that the total cover thickness of 36 inches will provide acceptable performance relative to deep percolation.

Percolation of 10 mm/year is suggested as a reasonable point for comparison for the two scenarios. After two consecutive wet years, percolation is reduced to below 10 mm/year at a depth of 30 inches into the cover. But, after ten years of varied precipitation (including four wet years), percolation is reduced to below 10 mm/year at a depth of about 22 inches into the cover. When long-term climate conditions and moisture movement are considered, an unvegetated cover thickness of 22 inches will reduce percolation to less than 10 mm/year and a final cover that is more than 1.5 times thicker, at 36-inches, will reduce percolation to less than 1 mm/year. Adding the effect of vegetation coverage would further improve the capacity of the 36-inch thick cover to reduce percolation.

The Trench 11 and 12 final covers can be constructed using site soils that contain some fine-grained materials to aid in moisture retention and a significant gravel fraction for erosion control and stability. The proposed final covers will:

1. Capture and retain the small amounts of precipitation that occur in the arid climate at the USEN facility;

2. Limit runoff, providing native plant species the necessary moisture for establishment; and

3. Limit percolation into the waste layer by providing adequate moisture storage to be returned to the atmosphere by evaporation and transpiration.

Cover Erosion

Using regional input values believed to be a reasonable representation of site conditions, the calculated estimates of surface erosion by water and wind on the Trench 11 and 12 final covers do not exceed maximum erosion rate recommendations, in the case of water erosion, or reasonable soil thinning rates, in the case of wind erosion.

- For the material type to be used in the final covers, water erosion rates estimated using the RUSLE2 model were less than the two tons per acre per year USEPA-recommended maximum rate.

- Wind erosion was analyzed using the WEPS model. Erosion by wind is assumed to result in uniform soil removal over a broad area and not in a manner than tends to concentrate soil removal. Accordingly, consideration of the significance of surface soil removal (or cover thinning to the point of exposing waste) is pertinent. Soil loss resulting from wind erosion was estimated to be 0.022 inches per year, or 0.65 inches over 30 years.

The conclusion that cover erosion by water or wind will not exceed acceptable rates is applicable to use of native soil types in the Trench 11 and 12 final covers without special attention to placement of a surficial layer specifically intended to reduce surface erosion. In fact, with regard to water erosion, the native soil type intended for final cover construction will be sufficiently coarse-grained to be considered an "erosion reduction" layer. Also, no special attention in cover design is needed to reduce erosion potential by shortening cover slope sections. Thus, no benches or other engineered flattening of slopes is required to reduce erosion potential.

Surface-Water Runoff

Peak runoff rates expected from closed (covered) Trench 11 and Trench 12 drainage areas was estimated for two design rain storms: a 2-year, 24-hour storm resulting in approximately 1.0 inch of precipitation, and a 25-year, 24-hour storm resulting in approximately 2.1 inches of precipitation. These analyses show that ditches, berms, or swales, to intercept runoff are unnecessary on the Trench 11 and 12 final covers because of:

- Low rainfall amounts;
- Erosion-resistant cover soil;
- Down-slope flow lines that are less than 200 feet long in most instances;
- Uniform and planar cover slopes; and

- Absence of significant flow convergence areas.

After flowing off the final covers by sheet flow, design storm runoff will combine in stormwater drainage ditches that begin at the base of the Trench 11 and 12 covers and leave the USEN property to the west, north, or south. No runoff will occur in these drainages following the two-year, 24-hour storm. The 25-year, 24-hour storm results in design storm flows at the facility boundary in these drainages that range from 3.0 to 8.0 CFS. These maximum values were used to design the runoff ditches. In these channels, which are not located above disposed waste, the natural soil materials forming the channel bottoms are sufficiently coarse-grained so as to not need additional measures to reduce channel erosion.

**Construction Specifications**

Starter Berms Construction. Compacted-soil starter berms will serve as the outer shell of the above-grade waste disposal area for Trenches 11 and 12. The starter berms on the perimeter of Trench 11 were constructed previously in accordance with NDEP approval of the 1999 design and plan for above-grade waste disposal. The Trench 12 berms will be constructed of compacted native soil or compacted select soil waste (where the berm is over waste). Suitable materials will be placed in lifts not exceeding 12 inches thick and compacted to 95 percent maximum dry density (ASTM D 1557). In-situ density tests will be performed as specified in the CQA Plan.

Landfill Cover Construction. Soil materials for final cover construction will consist of natural soil obtained from USEN stockpiles and the Trench 12 excavation, supplemented as needed with imported soil materials. Native and imported materials will be screened and mixed, as needed, to obtain material of satisfactory grain size.

The Trench 11 interim soil layer has been constructed as a layer at least 12 inches thick constructed during the trench's waste disposal operations history. The Trench 12 interim soil layer will be a layer not less than 12 inches thick that is comprised of natural soil materials that contain no grain sizes larger than 6.0 inches. Lift thickness will be measured and documented, but there is no compaction specification for this material, which will be placed as above-grade waste disposal proceeds.

Soil materials for the Trench 11 and 12 final cover layer will be 90 percent smaller than 1.0 inch with not less than 5.0 percent passing the #200 sieve. No materials in this layer will be larger than 3.0 inches. Cover materials will be placed in lifts that between 12 and 24 inches thick and lightly compacted to achieve a density of about 80 percent MDD (ASTM D 1557).

The lower density compaction requirement of the soil cover is important for the moisture holding capacity of the soil. Over-compaction could lead to reduced effectiveness and should be prevented. Areas of the final cover layer that become overly compacted, such as could result from repeated vehicle or equipment passage, will be loosened by shallow ripping or disking.

**Post Closure Performance Verification**

Trench closure will be considered complete when the final design slopes have been established on the Final Cover layer. Post-closure inspection and maintenance will be performed in a

manner and on a schedule that will be similar to that for other closed landfill units at the facility. With the design features presented in this report, the closed disposal facility will provide low-maintenance waste containment and the requisite long-term environmental protections.

Verification of post-closure performance of the final cover will be provided by the combination of leachate monitoring (quality and quantity) and groundwater monitoring. Although the final cover design process has taken erosion, settlement, and slope instability into consideration and has determined that these natural processes are not expected to result in unacceptable changes to the final covers, post-closure care plans will describe the process by which any such unexpected and unacceptable changes would be identified and corrected

# 1. INTRODUCTION

This document, "Design Basis and Construction Specifications for Trenches 11 and 12 Final Covers," provides the design basis and Construction Quality Assurance (CQA) Plan for the final landfill covers for Disposal Trenches 11 and 12 at the US Ecology Nevada, Inc. (USEN) Hazardous Waste Management Facility located about 11 miles south of Beatty, Nevada, in Nye County. The Design Basis and Construction Specification document complies with the requirements of HW Permit Number NEV HW0019 dated April 29, 2005. The document has been developed under the direction of a professional engineer registered in the State of Nevada and describes the design features and procedures that will be employed in the construction of final landfill covers.

This work completes a design process that began in 1995 and received conditional approval from the Nevada Division of Environmental Protection (NDEP) in the 2005 RCRA Permit. This design document is part of the Trench 11 and 12 design documents that most recently included the October 8, 2007, "Supplement to the Landfill Report for Trench 12" and accompanying "Construction Quality Assurance Plan for Trench 12." The final cover design for Trenches 11 and 12 incorporates use of an alternative final cover that is appropriate for application at the arid location of the USEN Beatty facility. This design basis and specifications document includes the following components.

- Section 1: Introduction
- Section 2: Regulatory basis for arid region cover design.
- Section 3: Final landfill covers for Trenches 11 and 12.

  Sections 2 and 3 provide an explanation of the regulatory and technical basis for consideration of an alternate final cover design concept for Trenches 11 and 12, and present a description of the final cover design selected for use.

- Section 4: Technical basis for cover design.

  Section 4 provides a discussion of the primary technical bases for the final cover design, including the results of moisture retention modeling, erosion modeling, and surface-water runoff modeling.

- Section 5: Other cover design considerations.

  Section 5 provides a discussion of other design considerations important to the design and construction of the final landfill cover, making reference, as appropriate, to pertinent design basis information that is provided in documents previously submitted to and approved by NDEP.

- Section 6: Specifications for final cover construction.

  Section 6 is a detailed presentation of the construction specifications for the Trenches 11 and 12 final covers and is a component of the Construction Quality Assurance Plan for final cover construction. This section references the companion document, October 8, 2007, "Supplement to the Landfill Report for Trench 12" and accompanying "Construction Quality Assurance Plan for Trench 12" for description of the administrative aspects (such as responsibilities and recordkeeping details) of the CQA Plan that are applicable to final cover construction.

- Appendix 1: Trenches 11 and 12 Final Covers Design Drawings.

- Appendix 2: Trenches 11 and 12 Final Covers Supporting Calculations.

# 2. REGULATORY BASIS FOR ARID REGION FINAL COVER DESIGN

## 2.1 REGULATORY REQUIREMENTS AND FLEXIBILITY

From 40 CFR 264.111, the following general closure performance standards apply to closure of RCRA units.

> *The owner or operator must close the facility in a manner that:*
>
> *(a) Minimizes the need for further maintenance; and*
>
> *(b) Controls, minimizes or eliminates, to the extent necessary to protect human health and the environment, post-closure escape of hazardous waste, hazardous constituents, leachate, contaminated run-off, or hazardous waste decomposition products to the ground or surface waters or to the atmosphere.*

From 40 CFR 264.310, the following specific requirements apply at final closure of the entire landfill or any individual landfill cell, such as Trenches 11 and 12.

> *(a) …the owner or operator must cover the landfill or cell with a final cover designed and constructed to:*
>
> *(1) Provide long-term minimization of migration of liquids through the closed landfill;*
>
> *(2) Function with minimum maintenance;*
>
> *(3) Promote drainage and minimize erosion or abrasion of the cover;*
>
> *(4) Accommodate settling and subsidence so that the cover's integrity is maintained; and*
>
> *(5) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.*

The RCRA regulations incorporate flexibility to allow closure approaches that differ from the specific requirements of 264.310(a), but continue to provide the long-term environmental protection intended in the regulation. Specifically, at 40 CFR 264.110(c), the regulations state:

> *The Regional Administrator may replace all or part of the requirements of this subpart (and the unit-specific standards referenced in §264.111(c) applying to a regulated unit), with alternative requirements set out in a permit or in an enforceable document (as defined in 40 CFR 270.1(c)(7)), where the Regional Administrator determines that:*

*(1) The regulated unit is situated among solid waste management units (or areas of concern), a release has occurred, and both the regulated unit and one or more solid waste management unit(s) (or areas of concern) are likely to have contributed to the release, and*

*(2) It is not necessary to apply the closure requirements of this subpart (and those referenced herein) because the alternative requirements will protect human health and the environment and will satisfy the closure performance standard of § 264.111 (a) and (b).*

USEN Trenches 11 and 12 are situated among pre-RCRA solid waste management units and other areas of concern, and also is near closed low-level radioactive waste disposal trenches. A release affecting groundwater has been documented at the site that is attributed to volatile constituents in the vadose zone beneath the pre-RCRA units. The source of the volatile constituents likely is a combination of regulated units, solid waste management units, and areas of concern.

The final landfill covers for USEN Trenches 11 and 12 are presented in this Design Basis and Construction Specification document to satisfy the regulatory requirements for final closure of a landfill cell. The design acknowledges and benefits from research and experience that confirms that the desired environmental protection benefits can be obtained with an alternative design. This document describes a final landfill cover system that is fully consistent with the provisions of 264.110 cited above, the performance standards of 264.111, and the requirements of 264.310(a) dealing with landfill closure:

*(1) Provide long-term minimization of migration of liquids through the closed landfill;*

*(2) Function with minimum maintenance;*

*(3) Promote drainage and minimize erosion or abrasion of the cover;*

*(4) Accommodate settling and subsidence so that cover's integrity is maintained; and*

*(5) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.*

The functionality of the final cover system will limit liquid percolation into waste, thereby minimizing the likelihood that such liquid will move through the waste, through the components of the liner system, and into the subsurface environment. The facility's location in the Amargosa Desert further supports the use of an alternative cover. Annual precipitation averages about 4.25

inches, while the potential evapotranspiration rate for this location is about 78 inches[1]. Moisture migration research by the USGS at the Beatty facility location, and predictive modeling of moisture movement in this environment, strongly support the use of an evapotranspiration cover as an appropriate method for long-term minimization of infiltration of liquids through the landfill cover.

Based upon frequent discussions with the Nevada Division of Environmental Protection (NDEP) during the design process, USEN is confident that the arid-region final cover design for Trenches 11 and 12 is consistent with applicable regulatory requirements of 264.310(a). The manner by which the final cover design addresses each of these requirements is summarized below.

Long-term minimization of liquid migration. Liquid migration into and through the landfilled waste is minimized by the low effective permeability of the monolithic final cover system. Unsaturated flow modeling shows that vertical liquid flux (also called percolation) is very small and little liquid is expected to move through the final cover into the disposed waste.

Minimum maintenance. The capacity of the final cover to function with minimum maintenance is provided by the combination of the simplicity of its monolithic design and the capacity of the natural soil materials that comprise the cover to resist damage from water and wind erosion. Though events requiring cover repair are expected to be infrequent, most repairs to the monolithic final cover can be completed simply, by adding cover soil and re-establishing surface grades.

Promote drainage and minimize erosion. The final cover system incorporates slopes and natural materials that promote drainage and minimize erosion. The final covers include limited areas of flat or gentle slopes and large areas of steeper slopes that will promote precipitation run-off while preventing run-on from areas off the cover. Erosion by water and wind is maintained at acceptable levels through the use of relatively coarse-grained native soil materials.

Accommodate settling. Little settling of waste though consolidation or degradation is expected for the largely inert waste materials that have been or are expected to be disposed in the trenches,

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[1] Shevenell, L., 1996. Statewide Potential Evapotranspiration Maps for Nevada. Nevada Bureau of Mines and Geology, Report 48.

and little subsidence of the final cover is expected. The 1996 Trench 12 design determined that the disposed waste is likely to be 85 percent soil and soil-like waste, 10 percent containerized waste, and five percent non-compressible solids. That design document also determined that cover settlement would be 1.5 feet or less, and would occur relatively uniformly across the landfill in proportion to the thickness of disposed waste. Considering the limited amount and relatively uniform distribution of expected settlement, the monolithic arid-region final cover is expected to accommodate settlement without disrupting the integrity of the final cover or its capacity to function as an effective barrier to liquid migration.

Low permeability. This design basis document shows that liquid percolation through the final cover system will be much less than 10 millimeters per year, an effective permeability that is less than $3.2 \times 10^{-8}$ centimeters per second (cm/sec). At this effective permeability, the cover is less permeable than the maximum value of $1 \times 10^{-7}$ cm/sec prescribed for bottom liner components in 40 CFR 264.301(c)(1)(i)(B).

## 2.2 GENERAL INFORMATION FOR THE TRENCH 11 AND 12 FINAL COVER

Conventional landfill final covers utilize multiple components, including natural or man-made low permeability materials, to achieve long-term performance objectives for closure and post-closure care. The 1996 Design for the Trench 12 final cover conditionally approved by the NDEP is an example of a multi-component cover. Cover performance research conducted since the 1990s, including the USEPA-sponsored Alternate Cover Assessment Program (ACAP)[2] and alternative cover research by Sandia National Laboratory[3], has shown that alternative cover designs can perform as well as or, under some conditions, better than conventional multi-component final covers. Performance improvement is particularly evident when construction-related damage or long-term deterioration of the low-permeability components of conventional covers are considered. Alternative final covers typically use the moisture retention properties of

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[2] ACAP is part of the USEPA-National Risk Management Research Laboratory's (NRMRL) Superfund Innovative Technology Evaluation (SITE) Program established to promote the development of new and innovative technologies used to address hazardous waste. The Desert Research Institute in Reno, NV is a co-researcher for ACAP. Information at www.acap.dri.edu

[3] Large-scale field demonstration comparing final landfill cover designs at Sandia National Laboratories in Albuquerque, New Mexico. Information at http://www.sandia.gov/Subsurface/factshts/ert/alcd.pdf

native soils to contain and store infiltrating moisture (precipitation) until the natural processes of evaporation and plant transpiration remove the stored moisture and release it to the atmosphere. These alternative final covers are called evapotranspiration (or ET) covers.

Table 1 identifies landfills and other facilities (including hazardous, solid, and radioactive waste management units) in arid and semi-arid areas of the U.S. where monolithic ET covers have been tested and demonstrated to provide performance that is consistent with regulatory requirements to minimize infiltration. As noted, full-scale monolithic ET covers have been constructed at several of these facilities in locations with annual precipitation totals less than 20 inches, and in a few locations less than 10 inches. Arid settings with low precipitation, high average temperatures, high solar radiation, and high evaporation potential are positive factors in the long-term performance of a monolithic ET cover.

Vegetation becomes established slowly on disturbed areas in a hot, dry desert climate, perhaps taking 10 years or more. For example, the USEN Trench 10 cover sideslopes were regraded in 1998. Ten years later that cover does have some sideslope plant growth, but the plant density is much less than in undisturbed areas in the surrounding desert. During the vegetation establishment period in the early years after closure, performance of a landfill cover as a hydraulic barrier will rely primarily on evaporation to remove stored infiltration. The long-term performance of arid region covers that perform acceptably without vegetation during the early years undoubtedly will improve as vegetation becomes established and plant transpiration becomes significant.

Section 4, Technical Basis for Cover Design, presents the results of analytical steps undertaken to design the alternative final covers for Trenches 11 and 12.

Table 1: Selected Arid and Semi-Arid Region Monolithic ET Alternate Final Covers

| Name and Location | | Landfill Type | Cover Type | Regulatory Status | Rainfall (in/yr) | Percolation (mm/yr) | Cover Description and Construction Status |
|---|---|---|---|---|---|---|---|
| Apple Valley Landfill | CA, Apple Valley | MSW | ET, monolithic | AFC research | 5.4 | NA | Demonstration, 3.0 feet thick cover installed in 2002 |
| Altamont Landfill | CA, Livermore | Nonhaz waste | ET, monolithic | AFC research | 13.4 | 1.5 | Demonstration, 3.5 feet thick cover installed in 2001 |
| Phelan Landfill | CA, Phelan | MSW | ET, monolithic | AFC research | 5.6 | 0.8 to 11.7* | Demonstration, 5.0 feet thick cover installed in 1998 |
| Milliken Landfill | CA, San Bernardino | MSW | ET, monolithic | AFC research | 12.0 | 0.8 to 6.6 | Demonstration, 5.0 feet thick cover installed in 1997 |
| Rocky Mountain Arsenal Landfill | CO, Denver | Hazwaste | ET, monolithic | AFC research | 15.6 | <1.3mm | Demonstration, 3.5-4.0 feet thick cover installed in 1998 |
| US Ecology of Idaho, Site B Test Pad | ID, Grand View | Hazwaste | ET, monolithic | AFC research | 7.1 | <<3.2 | Demonstration, 5.0 feet thick cover installed in 2000 |
| Kirtland Municipal Waste Landfill | NM, Albuquerque | MSW | ET, monolithic | AFC research | 8.5 | NA | Full scale, cover over waste installed in 2002 |
| Area 3 Radioactive Waste Management Site | NV, Nye County | Radwaste | ET, monolithic | AFC research | 5.3 | NA | Demonstration, 8.0 feet thick covers |
| Finley Buttes Regional Landfill | OR, Boardman | MSW | ET, monolithic | AFC research | 8.7 | <<1.0 | Demonstration, 4.0 feet thick cover over waste installed in 2000 |
| Lopez Canyon Sanitary Landfill | CA, Los Angeles | MSW | ET, monolithic | Approved, CA RWQCB | 17.0 | NA | Full scale, 3.0 feet thick cover over waste installed in 1999 |
| Denver Arapaho Disposal Site | CO, Aurora | MSW | ET, monolithic | Approved, CO DPHE | 14.0 | NA | Full scale, 4.0 feet thick cover over waste installed in 2002 |
| Rocky Mountain Arsenal Landfill | CO, Denver | Hazwaste | ET, monolithic | Approved, CO DPHE | 15.6 | NA | Full scale, cover construction began in 2007 |
| US Ecology of Idaho, Trenches 10 & 11 | ID, Grand View | Hazwaste | ET, monolithic | Approved, ID DEQ | 7.1 | NA | Full scale, 5.0 feet thick cover over waste installed in 2000 |
| Mr. M Landfill | MT, Lewiston | MSW | ET, monolithic | Approved, MT DEQ | 18.0 | NA | Full scale, 3.0 feet thick cover over waste installed in 2000 |
| Sandia Chemical Waste Landfill | NM, Albuquerque | Hazwaste | ET, monolithic | Approved, NM ED | 8.5 | NA | Demonstration, cover approved as a corrective measure |
| Kirtland AFB Landfill Closures | NM, Albuquerque | Hazwaste and Nonhaz waste | ET, monolithic | Approved, NM ED | 8.5 | NA | Demonstrations, covers approved as corrective measure for three landfills |
| Los Alamos County Landfill | NM, Los Alamos | MSW | ET, Monolithic | Approved, NMED | 18.2 | NA | Full scale, 3.0 feet thick cover installed in 2007. |
| Operating Industries, Inc. Landfill | CA, Monterey Park | MSW | ET, monolithic | Approved, USEPA | 18.5 | NA | Demonstration, 4.0 feet (min) thick cover constructed in 2000 |

NA = information not available << = much less than * Reported value is for 1997-1998, and not a long-term average.

# 3. FINAL LANDFILL COVER FOR TRENCHES 11 AND 12

## 3.1 COVER DESIGN CONCEPT

The arid-region final cover design for Trenches 11 and 12 at the USEN Beatty facility, acknowledged as one of the most arid areas within the continental U.S., is consistent with applicable regulatory requirements that allow for regulatory agency approval of alternative cover designs. Based upon discussions between USEN and the Nevada Division of Environmental Protection (NDEP) during the design process, the configuration presented in this design basis and specification is consistent with these requirements.

In addition to being consistent with RCRA regulation requirements, the final covers for Trenches 11 and 12 were designed consider the following expectations.

- The cover should be constructed from a combination of natural soils selected to limit the amount of infiltration of precipitation into the waste and to provide long-term separation between the disposed waste materials and the environment.
- The cover should have stable, low-maintenance slopes, considering normal static loading and seismic-induced loading associated with the prescribed design conditions.
- The structure should be capable of being constructed by experienced contractors using conventional construction equipment.
- The disposal structure, including the final cover, should be designed and constructed to be entirely located within the legal metes and bounds of the facility property.

## 3.2 COVER DESIGN DESCRIPTION

When waste and backfill are approximately three feet below the designed top of waste elevation, final waste placement will begin. At that time, waste and backfill will be mounded toward the middle of the active area to the design maximum waste elevations. As the final waste placement and slope configuration is reached, the last portion of the first layer of the final cover (Interim Layer) will be placed over the disposed waste. When the maximum waste height has been reached, the final cover layer will be placed over the first layer. The final cover soil layers will store infiltrating precipitation and release it again to the atmosphere by evaporation and transpiration.

Control of percolation into the closed trench will be provided by constructing the cover with materials that combine to provide a final cover system that holds precipitation water that infiltrates into the cover, and returns the majority of that water to the atmosphere through the combined processes of evaporation and plant transpiration. These combined processes will control the remaining water that could percolate into the disposed waste to an amount that, given the thickness and relative dryness of disposed waste, is unlikely to result in generation of significant leachate volumes.

From bottom to top, the components of the arid region final cover are as follows.

- **Interim Cover Soil Layer**. The first layer of the final cover is a lightly compacted native soil layer that provides waste containment during disposal operations and, in conjunction with the Final Cover Layer, retards the downward movement of infiltrating water by providing temporary water-storage, which allows stored water to be returned to the atmosphere by evaporation and plant transpiration. This layer will be at least 12-inches (1.0 foot) thick and extend across the cover to the natural ground surface on all sides of the trenches.

- **Final Cover Soil Layer**. This upper layer is a lightly compacted soil layer that resists erosion and, in conjunction with the Interim Cover Layer, retards the downward movement of infiltrating water by providing temporary water-storage, and allowing stored water to be returned to the atmosphere by evaporation and plant transpiration. This layer will vary in thickness to allow the cover to be shaped; however, the layer will be least 24-inches (2.0 feet) thick. This layer will extend across the cover to the natural ground surface on all sides of the trenches.

Trench closure will be considered complete when the final design slopes have been established on the Final Cover layer. Post-closure inspection and maintenance will be performed in a manner and on a schedule that will be similar to that for other closed landfill units at the facility. With the design features presented in this report, the closed disposal facility will provide low-maintenance waste containment and the requisite long-term environmental protections.

Verification of post-closure performance of the final cover will be provided by the combination of leachate monitoring (quality and quantity) and groundwater monitoring. Leachate monitoring and response to unexpected changes in either leachate quantity or quality will be addressed in the Response Action Plan (RAP) that is to be completed 60-days before waste is accepted for disposal in Trench 12.

Other aspects of the long-term performance of the final covers will be addressed under the plans for post-closure care for Trenches 11 and 12. Although the final cover design process has taken erosion, settlement, and slope instability into consideration and has determined that these natural processes are not expected to result in unacceptable changes to the final covers, the post-closure care plans will describe the process by which any such unexpected and unacceptable changes would be identified and corrected.

# 4. TECHNICAL BASIS FOR COVER DESIGN

## 4.1 MOISTURE RETENTION PROPERTIES

The long-term performance of the arid-region alternative final cover is determined by consideration of infiltration of precipitation, moisture retention in the cover soil, moisture removal by evapotranspiration, and potential (estimated) percolation into waste. These factors have been evaluated using two models, the quasi-two-dimensional water-balance HELP model and the one-dimensional Richards equation UNSAT-H model. These models simulate water flow into and out of the proposed final cover and were used to predict performance of the proposed ET cover and the conventional RCRA cover for the Trench 12 design, as submitted to NDEP in 1996.

Climate is very important in both moisture movement models. The HELP model uses monthly data as its climate input and includes an extensive database of climatic information for different U.S. geographic locations. The regional default climate databases include precipitation, temperature, solar radiation, and evapotranspiration data. For southern Nevada, this database includes climatic data for Las Vegas. The Las Vegas area, with average annual precipitation of about 4.5 inches, is a reasonable surrogate for the USEN site area which has an annual average of 4.25 inches precipitation. HELP then uses the Las Vegas area data to develop a synthetic climate history for the period of time selected for model runs.

UNSAT-H has no internal climate database, instead requiring that site-specific, daily data be developed and entered. For these data, a synthetic climate history was developed using the results of actual daily measurements made at an on-site weather station during recent years, which included extreme dry and wet years, as well as near-normal years.

The HELP model compared long-term performance of different cover types. The UNSAT-H model, with its use of site-specific climate and soil data, provides a more accurate estimate of percolation for the monolithic ET cover under consideration[4].

### 4.1.1 Approach

Percolation estimates assess the suitability of alternate cover configurations that achieve the objective of "long-term minimization of migration of liquids through the closed landfill." Liquids first must move through the final cover and into waste and then through waste before reaching a leachate collection system. Moisture movement through dry waste will be deterred by the same processes that retain moisture within the cover soil. But, if moisture ultimately reaches the leachate collection system, its occurrence as leachate in the landfill LCRS or LDS (leachate collection and recovery system or leak detection system) does not indicate that a release to the environment is imminent. Rather, the presence and accumulation of leachate in those systems increases the potential that such a release could occur. An important step in reducing the potential for such a release to the environment is the use of a final landfill cover that reduces liquid percolation through the cover to a practical low value. For ET covers in arid regions, percolation through covers in a given year will range from much less than 10 millimeters to more than 10 millimeters per year. Annual percolation values will vary in response to the occurrence of unusually wet or dry years, so this quantifiable measure of performance is not a specific value for a single year, but an average value over a reasonably long period of time, perhaps 10 or more years.

It can be useful to use mathematical models to estimate moisture movement into and out of monolithic and multi-component covers and make simple comparisons of percolation (moisture flux) as a measure of cover performance. The important outcome of this comparison is identifying acceptable final covers that minimize percolation under a reasonable range of climatic condition variations.

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[4] Nichols, W. (1991), Comparative Simulations of a Two-Layer Landfill Barrier Using the HELP v. 2.0 and UNSAT-H v. 2.0 Codes. Pacific Northwest Laboratory, Richland, WA.

USEPA, in its 2002 Draft RCRA Guidance for Landfill Covers, entitled "Technical Guidance for RCRA/CERCLA Covers," (EPA Draft Guidance) suggests that two models be used to provide comparative results for performance of a landfill cover design. Previous modeling efforts that simulate infiltration into the waste for other cover design concepts at the Beatty facility have used the HELP model. EPA's Draft Guidance lists the HELP model for purposes of cover performance modeling. Another program listed in the EPA Draft Guidance is UNSAT-H. Recommendations have been made by other researchers that suggest the UNSAT-H model will provide more accurate estimations of deep percolation. The following publications provide further details on these models.

- UNSAT-H Version 2.03: Fayer, M.J. and T.L. Jones. 1990. UNSAT-H Version 2.0: Unsaturated Soil Water and Heat Flow Model. PNL-6779, Pacific Northwest Laboratory, Richland, Washington.
- HELP Version 3.07: Schroeder, P.R., Dozier, T.S., Zappi, P.A., McEnroe, B.M., Sjostrom, J.W. and Peton, R.L. 1994. "The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3", EPA/600/R-94/168B, U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH.

The HELP model is an "enhanced water-balance model" and the UNSAT-H model is a "Richards equation-based model"[5]. The HELP user's manual describes its model as "a quasi-two-dimensional hydrologic model for conducting water balance analysis of landfills, cover systems, and other solid waste containment facilities… The primary purpose of the model is to assist in the comparison of design alternatives." The 2003 ITRC regulatory guidance describes the UNSAT-H model as "more physically correct for characterizing water movement than [water-balance] models." Further, ITRC says that, "Richards equation models can predict flux for soil moisture values less than field capacity" and can "capture the dynamics of varying soil types and their potential impact on water flux." Both HELP and UNSAT-H yield estimates of percolation of liquid from the base of the cover components into the waste layer.

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[5] ITRC, 2003 Technical and Regulatory Guidance for Design, Installation, and Monitoring of Alternative Final Landfill Covers

Thirty (30) years was selected as the modeled time period for both models. That time period corresponds to the basic post-closure care period in RCRA regulations and provides a reasonable period of time over which long-term percolation can be estimated. The results of the modeling effort conducted are summarized below. Representative model input and output information is included in Appendix 2.

### 4.1.2 HELP Modeling Summary

#### 4.1.2.1 Climate Data

The HELP model provides default input of various weather data, including evapotranspiration, precipitation, temperature, and solar radiation. Climate data for Las Vegas, Nevada were chosen to represent conditions at the USEN facility. Data for this geographic location also were used for precipitation, temperature, and solar radiation. The HELP model stochastically generated 30 years of precipitation, temperature, and solar radiation data using a synthetic weather generator.

Evapotranspiration is addressed in HELP by choices of evaporative zone depth and maximum leaf area index. Since plant establishment on an arid region alternative cover is expected to be non-existent or sparse for the first years following cover placement, an evaporative zone depth of 24 inches and a maximum leaf area index of 0.0 were chosen (representing bare soil conditions). The model was run for a 36-inch thick monolithic ET cover, a 36-inch thick ET cover with capillary barrier, and the 1996 RCRA cap.

#### 4.1.2.2 Physical Data

The HELP model was run for each cover type for 30 years with unvegetated conditions. Since vegetation establishment actually would begin sooner than 30 years and vegetation would remove moisture from the soil through transpiration, considering unvegetated conditions for the full modeled time period adds conservatism to the percolation estimates. Soil characteristics considered in modeling included the results of testing Trench 12 area samples supplemented with soil properties reported in published studies of the Beatty facility[6]. Other soil properties used

[6] Andraski, B.J., Properties and Variability of Soil and Trench Fill at an Arid Waste-Burial Site, Published in Soil Science Soc. Am. J. 60:54-66. 1996.

included soil layer type, thickness, soil texture, and initial volumetric soil water content. The surface-water runoff curve number was determined based on cover conditions and geometry.

#### 4.1.2.3 Modeling Approach

Three cover scenarios were considered in HELP, including the prescriptive (conventional) RCRA Subtitle C cap that was conditionally approved in the 1996 Trench 12 Design submittal, an ET cover with a capillary break, and a monolithic ET cover. Modeling was performed for a total of 30 years, with the cover in the initial development stage (assuming no vegetation).

#### 4.1.2.4 Model Result

The HELP model shows that a three-feet (36-inch) thick monolithic soil ET Cover limits maximum potential percolation through the cover to 0.16 millimeters in any single year and to an average annual percolation of just 0.005 millimeters per year (mm/year) over the 30-year period modeled. These maximum and average infiltration amounts likely are too small to be measurable in the field. Also, there essentially is no run-off from the modeled flat covers in any year modeled, so the majority of precipitation is temporarily held in the cover and then lost to evapotranspiration. The monolithic cover performs better than an ET cover with capillary break (average annual percolation estimate of 0.12 mm/year). Either ET cover virtually eliminates percolation, even when the modeled scenarios do not consider vegetation. While the HELP model artificially limits water content in the soil to values that are not below the wilting point, research observations show that water content actually does decrease to values below the wilting point because of evaporation and the capacity of some native desert plants to obtain moisture at moisture tensions that exceed the typical wilting point for particular soil types. Thus, the model actually considers moisture to be present at times when soil moisture likely has been exhausted. This generates even greater conservatism in the percolation predicted by the HELP model.

HELP modeling shows that the 1996 RCRA Cover also is effective in limiting percolation. This cover profile contains a low permeability geosynthetic clay liner that theoretically blocks percolation. However, the model does not consider all possible effects on the permeability of this liner (i.e., permeability increases) that could result from construction damage, aging, or desiccation.

The predicted percolation rates for the RCRA Cover, ET Cover with capillary break, and monolithic ET Cover are shown below on Table 2, the "HELP Model Percolation Output."

The percolation estimate increase at year 30 is not an expected result, particularly since it occurs following annual precipitation events that are not unique in the 30-year synthetic climate history. Also, no buildup toward the increase is seen in the preceding modeling results. This appears to be an issue with the HELP model rather than an event that correlates with actual precipitation events or other site factors. However, the magnitude of the increase is small and has little effect on the average annual percolation volume for either of the ET Covers modeled.

Table 2: HELP Model Percolation Output – 30 Years, No Vegetation

| Year | Precipitation | RCRA Subtitle C Cover | | ET Cover with Capillary Break | | ET Monolithic Cover | |
|---|---|---|---|---|---|---|---|
| | | (inches/year) | (mm/year) | (inches/year) | (mm/year) | (inches/year) | (mm/year) |
| 1 | 2.80 | 0.000000 | 0.00000 | 0.000031 | 0.00079 | 0.000000 | 0.00000 |
| 2 | 4.81 | 0.000000 | 0.00000 | 0.000036 | 0.00091 | 0.000000 | 0.00000 |
| 3 | 3.38 | 0.000001 | 0.00003 | 0.000036 | 0.00091 | 0.000000 | 0.00000 |
| 4 | 7.19 | 0.000001 | 0.00003 | 0.000038 | 0.00097 | 0.000000 | 0.00000 |
| 5 | 3.76 | 0.000001 | 0.00003 | 0.000038 | 0.00097 | 0.000000 | 0.00000 |
| 6 | 4.98 | 0.000001 | 0.00003 | 0.000040 | 0.00102 | 0.000000 | 0.00000 |
| 7 | 3.63 | 0.000001 | 0.00003 | 0.000039 | 0.00099 | 0.000001 | 0.00003 |
| 8 | 4.03 | 0.000001 | 0.00003 | 0.000039 | 0.00099 | 0.000000 | 0.00000 |
| 9 | 3.49 | 0.000001 | 0.00003 | 0.000040 | 0.00102 | 0.000000 | 0.00000 |
| 10 | 4.23 | 0.000001 | 0.00003 | 0.000040 | 0.00102 | 0.000000 | 0.00000 |
| 11 | 8.71 | 0.000001 | 0.00003 | 0.000040 | 0.00102 | 0.000000 | 0.00000 |
| 12 | 3.33 | 0.000001 | 0.00003 | 0.000047 | 0.00119 | 0.000000 | 0.00000 |
| 13 | 2.58 | 0.000000 | 0.00000 | 0.000045 | 0.00114 | 0.000000 | 0.00000 |
| 14 | 3.92 | 0.000001 | 0.00003 | 0.000046 | 0.00117 | 0.000000 | 0.00000 |
| 15 | 4.26 | 0.000001 | 0.00003 | 0.000046 | 0.00117 | 0.000000 | 0.00000 |
| 16 | 3.66 | 0.000001 | 0.00003 | 0.000046 | 0.00117 | 0.000000 | 0.00000 |
| 17 | 2.71 | 0.000001 | 0.00003 | 0.000046 | 0.00117 | 0.000000 | 0.00000 |
| 18 | 3.73 | 0.000001 | 0.00003 | 0.000047 | 0.00119 | 0.000000 | 0.00000 |
| 19 | 3.61 | 0.000001 | 0.00003 | 0.000047 | 0.00119 | 0.000000 | 0.00000 |
| 20 | 2.05 | 0.000001 | 0.00003 | 0.000047 | 0.00119 | 0.000000 | 0.00000 |
| 21 | 2.33 | 0.000000 | 0.00000 | 0.000047 | 0.00119 | 0.000000 | 0.00000 |
| 22 | 4.05 | 0.000000 | 0.00000 | 0.000048 | 0.00122 | 0.000001 | 0.00003 |
| 23 | 2.86 | 0.000001 | 0.00003 | 0.000052 | 0.00132 | 0.000000 | 0.00000 |
| 24 | 5.62 | 0.000001 | 0.00003 | 0.000051 | 0.00130 | 0.000000 | 0.00000 |
| 25 | 3.67 | 0.000001 | 0.00003 | 0.000054 | 0.00137 | 0.000001 | 0.00003 |
| 26 | 4.54 | 0.000001 | 0.00003 | 0.000055 | 0.00140 | 0.000000 | 0.00000 |
| 27 | 4.20 | 0.000001 | 0.00003 | 0.000054 | 0.00137 | 0.000000 | 0.00000 |
| 28 | 2.55 | 0.000001 | 0.00003 | 0.000054 | 0.00137 | 0.000000 | 0.00000 |
| 29 | 5.56 | 0.000001 | 0.00003 | 0.000055 | 0.00140 | 0.000000 | 0.00000 |
| 30 | 4.90 | 0.000001 | 0.00003 | 0.141391 | 3.59133 | 0.006211 | 0.15776 |
| | **Yearly Averages:** | **(mm/year)** | **0.000021** | | **0.120815** | | **0.005261** |

### 4.1.3 UNSAT-H Modeling Summary

#### 4.1.3.1 Climate Data

EPA's Draft Guidance recommends that modeling consider critical infiltration events that could result in percolation, including instances when precipitation equals or exceeds potential evapotranspiration (PET). Site-specific meteorological data were obtained from publications of the United States Geological Survey (USGS) Amargosa Desert Research Site (ADRS) located at the USEN Beatty facility. Available meteorological data for the ADRS includes 1978 to 1980 and 1986 to 2005. These data were used to describe representative annual precipitation. These data, and pertinent ADRS publications, confirm that annual PET at the Beatty site far exceeds the annual precipitation total even in unusually wet years.

A synthetic climate history was developed and used in the UNSAT-H model by considering repetitions of an above-average precipitation year (1998, one of the highest precipitation year on record), a below-average precipitation year (2002, one of the lowest precipitation years on record), and a near-average precipitation year (2000). The recorded daily rainfall amounts for "near-average" year 2000 (totaling 3.61 inches) were adjusted to 4.25 inches, which is the 30-year average for the site[7]. Other daily climatic factors associated with the 2000 rainfall events that are input to UNSAT-H were not adjusted.

Table 3 indicates how the actual daily ADRS weather observations for 1998, 2000, and 2002 were repeated and grouped to provide a conservative synthetic 10-year climate record. To model 30 years of moisture movement in the final cover using UNSAT-H, this 10-year climate record was repeated three times.

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[7] Scanlon, B.R., K. Keese, R.C. Reedy, J. Simunek, and B.J. Andraski, 2003. "Variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing (0-90 kyr): Field measurements, modeling, and uncertainties." Water Resources Research, Vol. 39, No. 7.

Table 3: Synthetic Precipitation History Used in UNSAT-H Model

| Model Year | Precipitation Type | Precipitation Total (inches) |
|---|---|---|
| Year 1 | Normal Year (2000) | 4.25* |
| Year 2 | Normal Year 2000) | 4.25* |
| Year 3 | Wet Year (1998) | 7.65 |
| Year 4 | Wet Year (1998) | 7.65 |
| Year 5 | Normal Year (2000) | 4.25* |
| Year 6 | Dry Year (2002) | 0.14 |
| Year 7 | Wet Year (1998) | 7.65 |
| Year 8 | Wet Year (1998) | 7.65 |
| Year 9 | Normal Year (2000) | 4.25* |
| Year 10 | Normal Year (2000) | 4.25* |

* Adjusted total annual rainfall

The conservatism incorporated into this synthetic climate history can be seen if the discontinuous ADRS climate record from 1978 to 2005 is considered together with precipitation data from "Amargosa Farms Garey Nevada," to form a continuous 28-year precipitation record. The Amargosa Farms station is a private weather monitoring station located about 12 miles southeast of the USEN facility. In this combined record of actual precipitation at (or near) the USEN facility, it is seen that:

- During the 28-year period, there were only three years (1978, 1983, and 1984) that were as wet as 1998, and this much precipitation occurred in consecutive years only once; and
- During the same 28-year period, there were no other years as dry as 2002.

The 30-year synthetic climate history included six instances where "wet years" occurred sequentially, for a total of 12 "wet years," whereas the actual precipitation history included only four "wet years." Also, the synthetic climate history included three "very dry years," where the actual precipitation history included only one "very dry year." The combined effects of multiple, consecutive "wet years" and infrequent "very dry years" (once in every ten years) adds conservatism to the UNSAT-H percolation estimates.

As EPA's Draft Guidance notes, critical infiltration events that could result in percolation are those when precipitation equals or exceeds PET. Such events are rare in the Amargosa Desert, but the 1998 record, considered to have been a 'strong El Nino year,' did include rainy periods that could be characterized as such. Between January 29 and February 24, there were 13 days with measureable rainfall, and there were nine days with measurable rain during March. This series of 1998 critical infiltration events is repeated 12 times in the 30 year synthetic climate record.

#### 4.1.3.2 Physical Data

Physical data used in the UNSAT-H model include the combination of site-specific materials data for Trench 11 and 12 and materials data obtained over several years of USGS research at the ADRS. At its ADRS website (http://nevada.usgs.gov/adrs/results.htm), USGS provides examples of regulator and industry comments concerning the value of ADRS research to the evaluation of alternative landfill covers. For example, the following quote is attributed to a regulator at the Montana Department of Environmental Quality, a State where ET covers have been tested and approved for use at some sites.

> *"The ADRS studies provide valuable guidelines that help establish regulatory minimums on demonstrations of adequate design, numerical modeling, and performance monitoring for alternative evapotranspiration (ET) landfill caps. The high quality, in-situ data on long-term soil- water movement verifies the realistic range of critical model parameters for the dry and sparse-vegetation conditions that often prevail in parts of Montana. The ADRS studies also provide insights on the effects of plants and soil properties on cap performance, and suggest that ET cap performance may actually improve over the 30 years of landfill post-closure care."*

In UNSAT-H, the nature and thickness of the cover is defined by a series of nodes. The nodes are spaced vertically downward from the surface to the bottom of the cover. Nodal spacing is very small near boundaries between different material type layers and larger in areas where there are no transitions. Nodes were established through the cover profile, and properties were assigned at each node. Since a monolithic ET Cover was modeled in the arid-region cover analysis, only one set of soil properties was needed. The cover soil properties listed below are

site-specific data taken from peer-reviewed scientific journal articles, including Scanlon, et al (2003)[8].

| K (cm/hr) | α (1/cm) | N (dimensionless) | $\theta_r$ | $\theta_s$ |
|---|---|---|---|---|
| 1.79 | 0.026 | 1.42 | 0.026 | 0.29 |

K = Saturated hydraulic conductivity
α = Coefficient of van Genuchten function
N = Coefficient of van Genuchten function
$\theta_r$ = Residual water content (volumetric)
$\theta_s$ = Saturated water content (volumetric)

Additional requirements for the UNSAT-H model include initial head conditions in the soil and the hydraulic properties of the soil. The UNSAT-H model recommends runs with initial heads at wilting point pressures (15,000 cm suction head) and at a point (5,000 cm suction head) that is between wilting point and field capacity (330 cm suction head). For conservatism in modeling the Arid-Region Cover, no vegetation was modeled in the analyses.

#### 4.1.3.3 Modeling Approach

The proposed monolithic Arid-Region Cover water flux capabilities were modeled for a performance period of 30 years. All model runs were for three feet (36 inches) of ET Cover and unvegetated conditions. The suction head in near-surface soils was determined to be very high, even greater than wilting point, which would severely limit plant growth and associated transpiration.

#### 4.1.3.4 Modeling Results

The UNSAT-H model of the ET Cover showed that the three-feet (36-inch) thick monolithic ET Cover was sufficient to limit drainage (percolation) through the bottom of the cover and into the

[8] Scanlon, B.R., K. Keese, R.C. Reedy, J. Simunek, and B.J. Andraski, 2003. "Variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing (0-90 kyr): Field measurements, modeling, and uncertainties." Water Resources Research, Vol. 39, No. 7.

waste to very small amounts. The modeling was conservative since the presence of vegetation was not considered. The following table (Table 4) shows the predicted cumulative amount of percolation through the cover at the end of each year modeled.

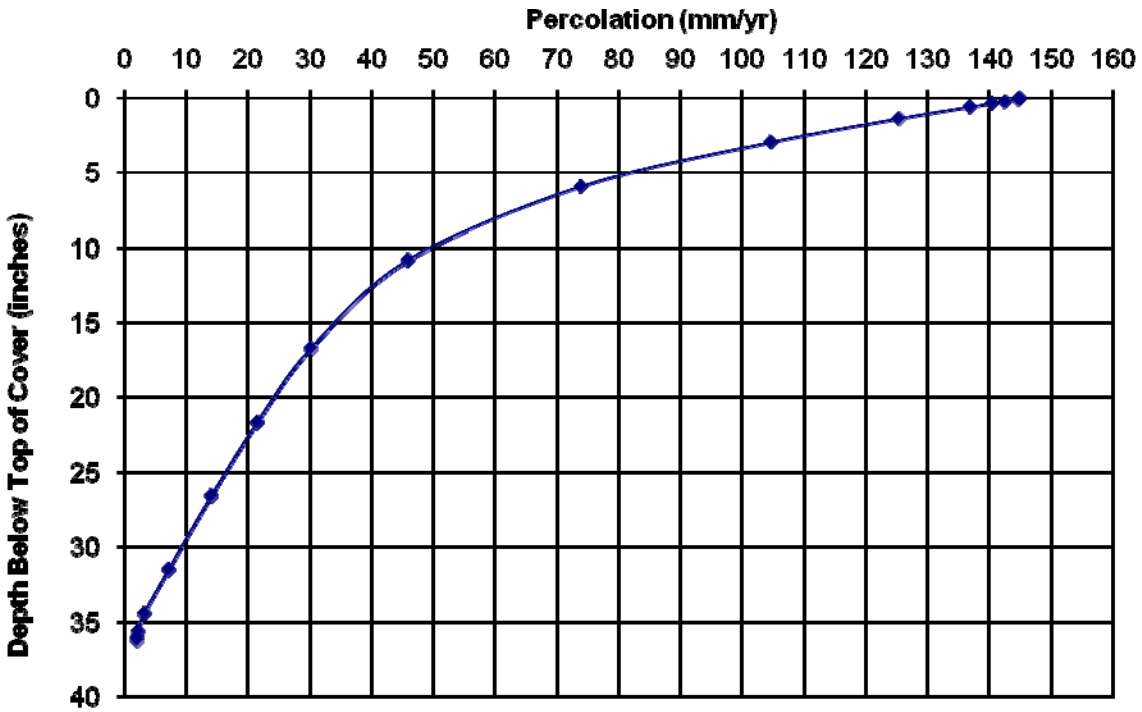
Table 4: ET Cover Percolation Predictions by UNSAT-H

| Modeled Year | Precipitation Type | Predicted Percolation (mm/year) |
|---|---|---|
| 1 | Normal | 0.456 |
| 2 | Normal | 0.304 |
| 3 | Wet | 1.973 |
| 4 | Wet | 2.029 |
| 5 | Normal | 0.319 |
| 6 | Very Dry | 0.018 |
| 7 | Wet | 1.466 |
| 8 | Wet | 2.028 |
| 9 | Normal | 0.319 |
| 10 | Normal | 0.302 |
| 11 | Normal | 0.301 |
| 12 | Normal | 0.301 |
| 13 | Wet | 1.973 |
| 14 | Wet | 2.029 |
| 15 | Normal | 0.319 |
| 16 | Very Dry | 0.018 |
| 17 | Wet | 1.466 |
| 18 | Wet | 2.028 |
| 19 | Normal | 0.319 |
| 20 | Normal | 0.302 |
| 21 | Normal | 0.301 |
| 22 | Normal | 0.301 |
| 23 | Wet | 1.973 |
| 24 | Wet | 2.029 |
| 25 | Normal | 0.319 |
| 26 | Very Dry | 0.018 |
| 27 | Wet | 1.466 |
| 28 | Wet | 2.028 |
| 29 | Normal | 0.319 |
| 30 | Normal | 0.302 |

**Average Percolation = 0.911 mm/year**

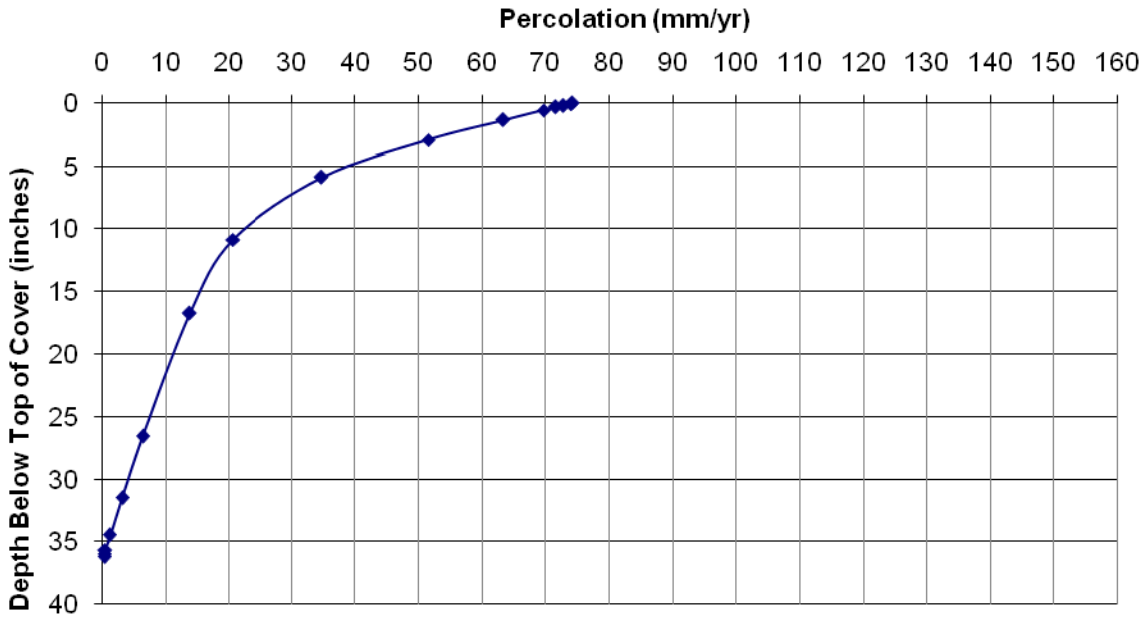
The data in the table show that the maximum percolation through a three feet (36-inch) thick cover occurs during wet years, and when wet years occur consecutively, the predicted percolation approaches 2 mm/year. The percolation prediction also shows that evaporative effects dominate during normal and dry years. The total run-off amounts predicted by UNSAT-H for each of the 30-years considered for the flat covers modeled are much less than one percent of total precipitation. Thus, essentially 100 percent of precipitation is retained in the cover soil to ultimately become either percolation or evaporation. When the 30-years of predicted annual percolation amounts are considered together, the average annual percolation through the 36-inch thick, monolithic ET cover is under 1.0 mm/year.

The graph presented below illustrates the downward percolation rates (vertical flux) at increasing depths within a three-feet (36-inch thick) final cover after the first instance of two sequential "wet years" (i.e., after modeled years three and four). As the graph shows, vertical flux rates are relatively high, in the upper one foot of the cover and decrease to small values (about 2 mm/year) approaching the base of the cover at three feet deep. The graph, which represents conditions after two consecutive wet years, is representative of times when percolation from the base of the cover is theoretically the highest during the 30 years modeled. The nature of the curve at nodes deeper than about 30 inches indicates that increasing the total cover thickness to values more than 36 inches likely would not provide significant performance improvement relative to deep percolation.




VERTICAL FLUX AT INCREASING DEPTHS IN A 36-INCH FINAL COVER AFTER YEAR 4

Observing predicted percolation immediately after two consecutive wet years is conservative. Performance over a longer period of time is a better measure of final cover performance. The graph below illustrates the downward percolation rates (vertical flux) at increasing depths within a three-feet (36-inch thick) final cover after the first 10 years of UNSAT-H modeling. Because of the repetition in the climatic history, performance is essentially identical at the end of years 10, 20 and 30. In this instance, the nature of the curve at nodes deeper than about 25 inches indicates that the total cover thickness of 36 inches will provide acceptable performance relative to deep percolation.




VERTICAL FLUX AT INCREASING DEPTHS IN A 36-INCH FINAL COVER AFTER YEAR 10

Percolation of 10 mm/year is suggested as a reasonable point for comparison for the two scenarios. After two consecutive wet years, percolation is reduced to below 10 mm/year at a depth of 30 inches into the cover. But, after ten years of varied precipitation (including four wet years), percolation is reduced to below 10 mm/year at a depth of about 22 inches into the cover. When long-term climate conditions and moisture movement are considered, an unvegetated cover thickness of 22 inches will reduce percolation to less than 10 mm/year and a final cover that is more than 1.5 times thicker, at 36-inches, will reduce percolation to less than 1 mm/year. Adding the effect of vegetation coverage would further improve the capacity of the 36-inch thick cover to reduce percolation.

### 4.1.4 Summary of Moisture Retention Modeling Results

The two models run for the Beatty ET cover design provided similar results with regard to their capacity to limit percolation through the cover. Both models predict that a three-feet (36-inch)

thick monolithic cover, without vegetation, prevents significant percolation of fluids through the cover and into waste at the USEN Beatty facility. The results also indicate that nearly all of the precipitation that enters returns to the atmosphere through the combination of evaporation and transpiration rather than infiltrating deeply into the cover and percolating into waste. The results likely are conservative because no vegetation was considered in either the HELP or UNSAT-H models, so "evapotranspiration" actually was limited to evaporation only. Also, a HELP model limitation prevented it from considering natural drying of cover soil to levels lower than the wilting point. In actuality, vegetation establishment likely will begin in less than 10 years (based on USEN experience with closed Trench 10) and moisture content likely will be drier than the wilting point during most normal and dry years. In the UNSAT-H model, weather data were used that likely overstate future precipitation.

The results of the both models suggest that a three feet (36 inch) thick soil cover will provide adequate water holding capacity when used in the arid environment of Beatty, Nevada. Further, the modeling shows that liquid movement through this final cover system will be much less than 10 mm/yr. The UNSAT-H modeling results for 10-year and 30-year periods predict that liquid percolation into the landfilled waste will not exceed 1.0 mm/yr. Considering Darcy's Law for saturated flow, percolation rates in the range between 10 and 1.0 mm/yr are equivalent to effective hydraulic conductivities (permeabilities) between $3.2 \times 10^{-8}$ and $3.2 \times 10^{-9}$ cm/sec, respectively. At these effective permeabilities, the final cover is much less permeable and will allow even less vertical liquid movement than a compacted clay or geosynthetic cover system component with a maximum permeability of $1 \times 10^{-7}$ cm/sec. When the presence of just the uppermost portion of the thick sequence of dry waste beneath the cover also is considered, the effective permeability of the cover system is even lower. In fact, when the upper part of the dry waste is considered, net fluid movement over long periods of time is likely to be vertically upward rather than downward.

The soil cover can be constructed using site soils that contain some fine-grained materials to aid in moisture retention and a significant gravel fraction for erosion control and stability. The proposed final cover will:

1. Capture and retain the small amounts of precipitation that occur in the arid climate at the USEN facility;

2. Limit runoff, providing native plant species the necessary moisture for establishment; and

3. Limit percolation into the waste layer by providing adequate moisture storage to be returned to the atmosphere by evaporation and transpiration.

Research has shown that, to facilitate vegetation rooting, final cover soil should be relatively loose, corresponding to light compaction. The concept of a "growth-limiting bulk density" (GLBD) is that cover soil should not be allowed to be placed or compacted to a density that will inhibit root development and the establishment of vegetation. The GLBD target will vary between soil types, but the recommended density range is between 1.1 and 1.5 grams per cubic centimeter[9]. Considering the soil type considered for the Trench 11 and 12 final covers (as characterized by laboratory test results presented in Attachment 1 to the October 2007 "Landfill Engineering Report for Trench 12"), the maximum bulk density target is equivalent to an in-place soil density of about 95 pounds per cubic foot (or less), which in turn is approximately equivalent to 80 percent compaction of this soil. Little compactive effort, primarily accomplished by passage of earthmoving equipment rather than use of standard soil compaction methods, will provide this level of soil compaction.

An alternate check on cover design details is a simple consideration of the ability of the soil to retain the moisture that could be expected in a single storm event. This would be those times when Potential Evapotranspiration is reduced to essentially zero during a precipitation event. The 24-hour, 25-year design storm for the USEN Beatty facility is about two inches. Using the design estimate method from the EPA Draft Guidance, the necessary minimum thickness of a cover can be estimated as:

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[9] Interstate Technical and Regulatory Council, December 2003. "Technical and Regulatory Guidance for Design, Installation, and Monitoring of Alternative Final Landfill Covers," Section 5.3.1, "Placement of Natural Materials."

Thickness of cover = (Rainfall event) ÷ (Moisture Holding Capacity)

Where the moisture holding capacity is calculated from the difference between the field capacity and wilting point.

Rearranging the equation, and considering a cover thickness of 36 inches and a 2-inch design rainfall, the moisture holding capacity (i.e., the difference between the field capacity and wilting point) that must be provided by the cover in order to hold the design rainfall should be at least:

Moisture Holding Capacity (needed) = Rainfall event ÷ Thickness of cover
= 2” ÷ 36”
= 0.0556 or 5.56% (by volume).

Soils at the US Ecology Beatty facility are anticipated to have volumetric moisture contents at field capacity of 22% and at wilting point of 11%[10]. The difference between field capacity and wilting point (i.e., moisture holding capacity) is 0.11 or 11% (by volume). Thus, a 36-inch thick soil cover made from Beatty facility soil, if at wilting point when rainfall begins, has a moisture holding capacity of about 11% of its 36 inch thickness, or about 4.0 inches. This moisture holding capacity is sufficient to retain the two-inch design storm. Since the moisture content of facility soil is often below the wilting point, additional moisture holding capacity would be available during much of a typical year.

## 4.2 SURFACE EROSION

Soil erosion occurs as the removal of soil particles at the ground surface by water or wind. In this section, water erosion and wind erosion are considered using accepted erosion estimation methods and estimates of site-specific conditions. Initial water erosion of soil occurs as sheet and rill erosion, that are defined as the removal of layers of soil from the land surface by the action of rainfall and runoff. This type of erosion occurs when rainfall exceeds infiltration.

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[10] Schroeder, P.R., et al., 1994. "The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3", EPA/600/R-94/168B, USEPA Risk Reduction Engineering Laboratory, Cincinnati, OH.

Wind erosion is the removal of soil particles by air, also a moving fluid. Wind erosion primarily affects arid and semi-arid regions because the surface in these areas frequently is poorly vegetated. The models used determine a soil erosion rate that quantifies removal of surface soil from a unit surface area per unit time.

### 4.2.1 Erosion by Water

#### 4.2.1.1 Evaluation Method

The U.S. Natural Resources Conservation Service (NRCS) Revised Universal Soil Loss Equation (RUSLE2)[11] was used to estimate soil erosion by water possible from the proposed final cover design of Trenches 11 and 12 at the USEN Beatty facility. RUSLE2 uses a region-specific database that contains a wide geographic range of values for soil properties, rainfall, slopes, and ground cover to estimate soil loss, sediment yield, and sediment characteristics from rill and inter-rill (sheet) erosion caused by rainfall and associated overland flow. The RUSLE2 equation is:

$$A = RKLSCP$$

Where

A = computed average annual soil loss
R = rainfall runoff erosivity factor
K = soil erodibility factor
LS = length-slope factor
C = cover management factor
P = supporting practices factor

Factor LS, slope angle and length, is a site-specific input added by the user. The RUSLE2 computer model uses its internal, region-specific, database information to provide the model with appropriate values for the R, K, C, and P factors, as is noted below.

[11] http://www.ars.usda.gov/Research/docs.htm?docid=6010

- Climate: RUSLE2 uses an internal database for site climatic data. For the USEN facility, the location "USA\Nevada\Nye County/NV-Nye R3" was chosen.

- Soil: The soil survey for Nye County, Southwest Part was used to determine the soil type prevalent at the USEN facility. The prevalent soil type and the one used in RUSLE2 is the Yermo, hot-Yermo-Arizo association.

- Crop Management: The crop management zone was set using the construction site template provided in RUSLE2 for CMZ Zone 31 and assumes contouring with no row grading. The construction site template assumes newly disturbed soil with no vegetation.

For modeling Trenches 11 and 12 final covers, three slopes were analyzed. Those were the 2:1, 3:1, and 20:1 slopes that are present on each cover. In each case, the longest slope length for each slope type was assumed as a worst-case scenario. The calculation in Appendix 2 identifies the longest slope lengths applicable to each cover slope segment that was considered in the RUSLE2 model.

#### 4.2.1.2 Soil Erosion Estimate

Soil erodibility by water was calculated first using soil type and hydrologic class for the Yermo, hot-Yermo-Arizo soil association (the surface soil type identified by NRCS as present at the site) and then using a generic soil type, "gravely sand 15 to 60 percent coarse fragments," that more closely approximated the soil gradation that is expected to be used for cover construction. Soil to be used to construct the Trench 11 and Trench 12 covers will be taken not only from the surface, but also from the subsurface excavation for Trench 12. Accordingly, the erosion estimate was made for the generic soil type choice within RUSLE2 rather than the Yermo surface soil.

RUSLE2 also allows the user to specify a rock cover to reduce erodibilty where the surficial soil beneath such cover is expected to be too erodible. A 100 percent rock cover surface was modeled to assess the possible benefit of such surface protection. Rock is defined by RUSLE2 as non-decomposing surface material that is sufficiently large not to be moved by raindrop impact or surface runoff. The minimum rock size considered was 10 millimeter, or 3/8-inch diameter. The analysis first was run assuming no rock cover, and then again using 100 percent

rock cover for each slope segment. The results of these analyses are shown on "RUSLE2 Erosion Calculation Record" sheets in Appendix 2.

All but one of the erosion rates calculated by RUSLE2 were less than the two tons per acre per year USEPA-recommended maximum rate[12]. The "Yermo" soil with about 200 feet of 3:1 slope eroded at 2.2 tons per acre per year, assuming that there is no rock cover. With 100 percent rock cover, all soil erosion losses were below the USEPA recommended two tons per acre per year.

### 4.2.2 Erosion by Wind

The U.S. Natural Resources Conservation Service (NRCS) Wind Erosion Prediction System (WEPS) model was used for this analysis. WEPS is intended to estimate erosion from flat-lying agricultural fields that are managed for production of various crop types. The model allows for consideration of certain topographic features that modify wind direction and velocity, but cannot consider complex geometric shapes, such as a landfill cover. Also, the agricultural nature of the surface preparation and crop management inputs to the model might not accurately reflect the early history of a closed landfill. As a result, the accuracy of the wind erosion estimate must be considered uncertain. For later comparison to the model's soil loss estimate, it is important to note that natural soil loss from desert soil type present in the site area is five tons per acre per year.[13]

#### 4.2.2.1 Evaluation Method

WEPS is used to estimate expected soil loss (as soil weight per surface area unit) based on soil properties, wind and climate history for a local weather station, and site geography. The Wind Erosion Equation (WEQ) upon which WEPS is based is widely used for estimating soil loss by wind from agricultural fields. The functional form of WEQ is:

$$E = f\,(I, C, K, L, V)$$

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[12] USEPA, October 1985. Handbook Remedial Action at Waste Disposal Sites (Revised). EPA/625/6-85/006.

[13] Bechtel SAIC Company, LLC, September 2006. Soil-Related Input Parameters for the Biosphere Model.

Where, E is the average soil loss (tons/acre/year), I is the soil erodibility, K is the soil ridge roughness, C is the climatic factor, L is the field length along the prevailing wind erosion direction, and V is the vegetative factor.

WEPS is a process-based, daily time-step model that simulates weather, field conditions, and erosion to predict wind erosion. The WEPS model allows the use of uploaded region-specific database information to determine the WEQ soil loss factors. For the Trench 11 and 12 wind erosion estimates, the following three databases were uploaded:

1. Climate Data (Beatty 8N);
2. Soil Data (Nye SW, NV785\2054 Yermo, Hot-Yermo-Arizo Association); and
3. Crop Management Template (CMZ-31)

Climate: The first WEPS input is climate data based on the location input. For the US Ecology Beatty facility, the climate factors for the monitoring station "Beatty 8N" were used.

Soil: The soil survey for Nye County was used to determine the prevalent surface soil type at the US Ecology facility. The prevalent soil type and the one used in the WEPS erosion estimate is the Yermo, hot-Yermo-Arizo association. This soil type was considered to be sufficiently similar to the expected final cover materials for use in the soil loss estimate.

Crop Management. The crop management zone was set using the construction template provided in RUSLE2 for CMZ Zone 31. The RUSLE2 database file for CMZ Zone 31 was converted to a WEPS database file. The construction site template assumes non-vegetated disturbed soil that has been modified using certain combinations of construction or agricultural equipment.

#### 4.2.2.2 Soil Erosion Estimate

The WEPS model simulation used a basic area shape (e.g., rectangle, square, circle, or quarter circle), site-specific dimensions, and an orientation (relative to wind direction) as input for the model run. For Trenches 11 and 12 at the US Ecology site, both areas were modeled as flat-lying rectangles. Trench 11 was modeled as a rectangle with an x-length of 210 meters and a y-

length of 396 meters. Trench 12 was modeled as a rectangle with an x-length of 418 meters and a y-length of 145 meters. Both simulations were run with an orientation of 0 degrees (i.e. x-length runs east-west and y-length runs north-south).

| Trench | Area (ha) | Gross Soil Loss (kg/m2) | Gross Soil Loss (tons/acre) |
|---|---|---|---|
| Trench 11 | 8.3 | 0.88 | 3.9 |
| Trench 12 | 6.1 | 0.62 | 2.8 |

The soil loss tolerance value assigned by NRCS as a standard for protecting soil as natural resource is five tons per acre per year for the Yermo, hot-Yermo-Arizo association in this natural desert setting. Both calculated values are below this NRCS soil loss tolerance value.

Wind erosion is assumed to result in uniform soil removal over a broad area and not in a manner than tends to concentrate soil removal (such as rill erosion by water). Accordingly, consideration of the significance of surface soil removal (or thinning) is pertinent. The soil loss caused by wind erosion was analyzed for the potential of thinning the cover to the point of exposing waste. Using the erosion rate estimated for the orientation of Trench 11, and assuming that cover soil is placed with a density of 100 lbs per cubic foot or approximately 1.35 tons per cubic yard, the following soil loss is estimated.

For one year: $3.9\frac{tons}{acre} * \frac{1}{1.35}\frac{yd^3}{tons} * \frac{1}{43{,}560}\frac{acre}{ft^2} * \frac{27}{1}\frac{ft^3}{yd^3} = 0.0018\, ft \;\; of\ soil\ loss\ per\ year$

or 0.022 inches of soil loss per year

For 30 years: 0.65 inches of soil loss

### 4.2.3 Erosion Conclusions

Using regional input values believed to be a reasonable representation of site conditions, the calculated estimates of surface erosion by water and wind on the Trench 11 and 12 final covers do not exceed maximum erosion rate recommendations, in the case of water erosion, or reasonable soil thinning rates, in the case of wind erosion. This conclusion is applicable to use of native soil types in the Trench 11 and 12 final covers without special attention to placement of

a surficial layer specifically intended to reduce surface erosion. In fact, with regard to water erosion, the native soil type intended for final cover construction will be sufficiently coarse-grained to be considered an "erosion reduction" layer without special treatment (such as selective particle size separation using a grizzly or screen). Also, no special attention in cover design is needed to reduce erosion potential by shortening cover slope sections. Thus, no benches or other engineered flattening of slopes is required to reduce erosion potential.

## 4.3 RUNOFF MANAGEMENT

Peak runoff rates expected from closed (covered) Trench 11 and Trench 12 drainage areas at the US Ecology Beatty Facility under the influence of design rain storms were calculated using the method of USDA Natural Resource Conservation Service Technical Release 55 (TR-55) titled "Urban Hydrology for Small Watersheds" (June 1986). The calculation is included in Appendix 2.

Two design storm events were considered in this estimation of storm runoff:

2-year, 24-hour storm, approximately 1.0 inch of precipitation, and
25-year, 24-hour storm, approximately 2.1 inches of precipitation.

For the surface properties considered, each drainage subbasin on the Trench 11 and 12 final covers generates estimated runoff amounts, per unit area of cover surface, of 0.00 inches from the two-year storm and 0.23 inches from the 25-year storm. These runoff amounts and other properties of the subbasins, including surface type, surface roughness (Manning's coefficient), flow length, rainfall, and land slope, were modeled as sheet-flow runoff over a planar surface. The highest potential runoff occurs from the 25-year, 24-hour design storm. Considering this storm in the TR-55 model resulted in peak runoff amounts in the final cover drainage subbasins ranging from less than 1.0 to about 3.0 cubic feet per second (CFS).

A commonly accepted rule-of-thumb in landfill cover design[14] is that diversion channels, usually consisting of ditches, berms, or swales, are used on the cover at approximately every 200 feet to intercept runoff before it has a chance to accumulate and cut erosion gullies. Further, such

[14] USEPA, 1995. "Decision Maker's Guide to Solid Waste Management, Volume II, (EPA 530-R-95-023).

ditches, berms, or swales usually combine at one or more "down-channels" to convey the run-off down and off long, steep cover slopes. Several design factors make such channels unnecessary on the Trench 11 and 12 final covers. These include:

- Low rainfall; design storm amount of about two inches, and typical annual rainfall of about four inches;
- Erosion-resistant surface soil on the cover;
- Down-slope flow lines on the cover that are less than 200 feet long in most instances;
- Uniform and planar cover slopes; and
- Absence of significant flow convergence areas.

The Trench 11 and 12 final cover designs do incorporate surface armoring (six-inch rip-rap) of "down-channels" in two areas where minor flow convergence might be possible, as shown on Drawing NV12-08-009. However, even in these areas, the limited run-off volumes and cover topography are such that little flow convergence is likely. In the case of the Trench 11 armored channel, this also is an area where the down-slope flow line on the 3:1 slope is about 220 feet in length, and is slightly longer than the 200-feet 'rule' cited above.

After flowing off the Trench 11 and 12 final covers by sheet flow, the design storm event runoff amounts from individual cover subbasins combine in several stormwater drainage ditches that begin at the base of the Trench 11 and 12 covers and leave the US Ecology property to the west, north, or south. The combined design storm flows in these drainages range between 3.0 and 8.0 CFS at the facility boundary for the 25-year, 24-hour storm. No runoff occurs in the same drainages from the two-year, 24-hour storm. The maximum values associated with the larger storm were used to design the runoff ditches (i.e., Reaches 1 and 2, as shown in Drawing NV12-08-013). In these channels, which are not located above disposed waste, the natural soil materials forming the channel bottoms are expected to be sufficiently coarse grained so as to not need additional measures to reduce channel erosion.

# 5. OTHER COVER DESIGN CONSIDERATIONS

## 5.1 COVER DRAINAGE

The final covers promote sheet run-off of precipitation and reduce locations where run-off concentrations will occur. However, the shape of Trenches 11 and 12 are such that there are two locations where minor flow concentrations are possible. These locations are indicated on Drawing NV12-08-009 and detailed on NV12-08-013. The cover design reduces the likelihood that deep erosion will occur in these areas by armoring the potential flow concentration areas using gravel and cobble size rocks.

These south-facing areas of possible surface-water flow convergence could be areas where soil moisture contents temporarily are increased following heavy precipitation. However, the ET cover will protect these areas against percolation through the base of the cover. Also, if soil moisture content is higher in the upper part of the cover soil in these areas, it is likely that vegetative growth will be enhanced, allowing transpiration to combine with evaporation to more rapidly remove the soil moisture. Further, any increase in vegetation density in these areas will work together with the rock armoring to help minimize erosion.

## 5.2 RUN-ON/RUN-OFF CONTROL

With regard to surface-water management, the 2007 Design final cover will prevent run-on from areas outside the final cover footprint from affecting the final cover. The final cover design, as shown on Drawing NV12-08-009, manages stormwater run-off from the cover and controls cover material erosion. Stormwater runoff leads to stormwater channels along the base of the cover that lead to natural or enhanced drainage channels outside of the facility boundaries.

The 2007 Design includes a corridor about 10-feet wide between the toe of the final Trench 12 cover and the toe of the LLRW site cover that will provide for permanent routing of surface-water runoff originating on the adjoining portions of Trench 12 and the closed LLRW disposal site.

## 5.3 FINAL COVER SLOPE STABILITY EVALUATION

### 5.3.1 Trench 11

Relative to critical slopes for stability evaluation, the final cover slopes of Trench 11 are sufficiently similar to those of the Trench 12 final cover that the stability evaluation discussion (below) for Trench 12 also applies to Trench 11 slopes. Actually, the above-grade waste disposal method initially used for Trench 11 enhances post-closure slope stability. That method was the use of a series of stacked, compacted soil perimeter berms, each 10 feet (or more) high, as shown on Drawing NV12-08-011. These stacked berms provide a strong stabilizing buttress at the toe (base) of the final cover on all sides of Trench 11.

### 5.3.2 Trench 12

The Trench 12 final cover has a maximum elevation of 2,860 feet above NGVD (National Geodetic Vertical Datum, or mean sea level), or about 80 feet above the surrounding land surface, and 3:1 (H:V) slopes over all sides, except along the south side and on all sides at the base (toe) of the cover. In those areas, the final Trench 12 cover design includes an 11-feet high perimeter ("starter berm" or "toe berm") with 2:1 (H:V) slopes that is constructed of compacted clean soil.

The "Slope Stability Evaluation with Surface Soil Improvement" calculation series included in Attachment 3, "Supplemental Engineering Calculations," to the October 8, 2007 "Landfill Report for Trench 12" includes evaluation of the stability of the Trench 12 final cover. In that calculation series, the final cover is characterized as a 4.0 feet thick monolithic soil layer with zero cohesive strength. The actual final cover thickness will be a minimum of 3.0 feet thick. For the purpose of slope stability evaluation, consideration of a 4.0 feet thick cohesionless final cover is more conservative than consideration of a 3.0 feet thick cohesionless final cover. Thus, the calculation included in the October 2007 Landfill Report is conservative and appropriate. This calculation series shows that the final cover configuration for the 2007 Design is acceptably stable under static loading and pseudo-static loading conditions. Slope failures involving cover and waste materials have factors of safety against failure that are greater than the design requirement (i.e., 1.5 or greater for static loading conditions, and 1.0 or greater for pseudo-static or seismic loading conditions considering a maximum horizontal acceleration of 0.42g.).

## 5.4 UPLIFT PRESSURES FROM WIND LOADS

The design of the covers uses only natural soil components. Uplift will not be a concern during or after cover construction.

## 5.5 THERMAL EXPANSION AND CONTRACTION

The design of the covers uses only natural soil components. Thermal expansion and contraction will not be a concern during or after cover construction.

## 5.6 POST-CLOSURE COVER SETTLEMENT

Post-closure settlement of the landfill cover attributed settlement within the soil cover, settlement (and degradation/consolidation) of the waste fill, and settlement of the foundation materials underlying the waste fill were addressed in the 1996 Design Report and supporting calculations[15].

[15] The "1996 Trench 12 Design" is comprised of the 1994 Landfill Report, 1996 Design Report, and subsequent resolution of NDEP design-related comments and questions.

# 6. SPECIFICATIONS FOR FINAL COVER CONSTRUCTION

## 6.1 COMPACTED EARTH FILL STARTER BERM CONSTRUCTION

### 6.1.1 Trench 11 Starter Berm

The starter berms on the perimeter of Trench 11 were constructed previously in accordance with NDEP approval of the 1999 design and plan for above-grade waste disposal. The Trench 11 starter berms were constructed in a manner similar to that described below for the Trench 12 starter berm, but typically the Trench 11 berms are higher and, as such, are much thicker in vertical and horizontal dimension than the Trench 12 starter berms, as shown in Drawings NV12-08-011 and NV12-08-012. Other than minor surface grading to achieve the desired surface topography, no changes to the Trench 11 starter berms are considered in this final cover design.

### 6.1.2 Trench 12 Starter Berm

Low, compacted fill berms will serve as the outer shell of the above-grade waste disposal area for Trench 12, or "starter berms". The final outer slopes of the starter berms will be 2:1. The starter berms will be constructed of native soil materials or select soil waste. Select soil waste, if used, will be placed only over lined areas and must satisfy material gradation and compaction specifications. The starter berms will be constructed on the Trench 12 perimeter (as shown in Drawing NV12-08-010) after the disposed waste surface within a particular portion of the trench has been raised to within three feet of the ground surface. The starter berms, the inner part of which will be constructed on top of waste, will be completed before waste is disposed above three feet below ground surface in the interior area adjacent to the berms.

### 6.1.3 Starter Berm Foundation

The berm will be constructed on native surface soil or select soil waste re-compacted as specified in Sections 2.1 and 3.2 of Appendix C, Construction Methods Specifications, to the October 2007 Landfill Report for Trench 12.

### 6.1.4 Starter Berm Material Specification

Native soil or select soil waste materials used for the compacted soil starter berms will contain no materials larger than six inches, 95 percent smaller than 3.0 inches, and about five percent (or more) passing the #200 sieve.

### 6.1.5 Starter Berm Construction

The berm will be constructed using native surface soil or select soil waste as specified in Sections 2.3 and 3.5 of Appendix C, Construction Methods Specifications, to the October 2007 "Landfill Report for Trench 12." Suitable materials from direct excavation or stockpiles will be placed in lifts not exceeding 12 inches thick and compacted to 95 percent MDD by ASTM D 1557 at a moisture content between the OMC minus 1 percent and OMC +2 percent.

In-situ density tests will be performed at a minimum of one test per compacted lift or one test for every 2,000 cubic yards placed, whichever is less. In the event that density testing indicates that the target density is not achieved, the berm area at the failed test location and 50 feet each way from the failing testing (along the berm axis) will be re-compacted and retested. Confirmation of satisfactory compaction in a re-compacted area will be by documented by satisfactory density tests at all three locations.

A schedule of starter berm construction requirements is attached as Table 5.

## 6.2 FINAL LANDFILL COVER CONSTRUCTION

The final Trench 11 and 12 final covers will incorporate the following soil components (from bottom to top).

- **Interim Cover Soil Layer, 12 to 24-Inches Thick**. The first layer of the final trench cover is a lightly compacted soil layer that will be at least 12-inches (1.0 feet) thick. This layer will extend across the cover to the natural ground surface on all sides of the trenches.

- **Final Cover Soil Layer, 24-Inches Thick**. The upper component of the final trench cover is a lightly compacted soil layer that will vary in thickness to allow the cover to be shaped; however, the layer everywhere will be at least 24-inches (2.0 feet) thick. This layer will extend across the cover to the natural ground surface on all sides of the trenches.

Soil materials for final cover construction will consist of the predominantly sand and gravel soils obtained from stockpiles and the Trench 12 excavation area, supplemented as needed with imported soil materials. Native and imported materials will be screened and mixed, as needed, to obtain material of satisfactory grain size. Materials that cannot be satisfactorily placed and/or compacted to a stable condition will be designated as unsuitable. Unsuitable materials will include trash, organic substances, large rocks, or other materials determined to be unsuitable by the Project Manager. These materials will be removed from the fill material and segregated from suitable soil.

### 6.2.1 Specification for Interim Cover Layer Soil

Soil materials for the Trench 12 interim soil layer will contain no materials larger than 6.0 inches. Suitable materials from direct excavation or stockpiles, or derived from on-site screening of these materials, will be placed in a single lift, not less than 12 inches thick. Lift thickness will be measured and documented, but there is no compaction specification for this material, which will be placed as above-grade waste disposal proceeds.

A low density is desirable for this layer of the final cover, as this is important to the moisture holding capacity and vegetation establishment properties of the soil. Over-compaction could lead to reduced cover effectiveness and should be prevented. Areas of the interim cover layer that become overly compacted, such as could result from repeated vehicle or equipment passage, will be loosened by shallow (12 inches or less) disking before placement of the final cover layer.

A schedule of the cover layer placement inspection requirements is attached as Table 5.

### 6.2.2 Specification for Final Cover Layer Soil

Soil materials for the final cover layer will contain no materials larger than 3.0 inches, 90 percent smaller than 1.0 inch, and not less than 5.0 percent passing the #200 sieve. Suitable materials from direct excavation or stockpiles, or derived from on-site screening of these materials, will be placed in lifts that between 12 and 24 inches thick and lightly compacted to achieve a density of about 80 percent MDD by ASTM D 1557 at a moisture content between 2.0 and 4.0 percent less than the OMC.

The lower density compaction requirement of the soil cover is important for the moisture holding capacity of the soil. Over-compaction could lead to reduced effectiveness, and should be prevented. Areas of the final cover layer that become overly compacted, such as could result from repeated vehicle or equipment passage, will be loosened by shallow ripping or disking.

The achievement of the proper compaction requirement will be determined by in-situ density tests performed at a minimum of one test per each one test for every 10,000 square feet of cover placed. In the event that density testing indicates that the target density is not achieved, the area within 100 feet of the failing testing will be re-compacted and retested. Confirmation of satisfactory compaction in a re-compacted area will be by done by three satisfactory density tests, at locations selected to represent the entire 100 by 100 feet area, passing the density specification.

A schedule of the cover layer placement inspection requirements is attached as Table 5.

## 6.3 EQUIPMENT TRAFFIC

Cover soil placement using low-ground pressure equipment, such as wide-tracked dozers, is recommended and use of heavy wheeled equipment, that could cause linear surface depressions, is not recommended. Also if tracked equipment is used, tracking perpendicular to contour (i.e., directly up or down slopes) is suggested rather than tracking parallel to contour (i.e., across slopes). Based on experience at Trench 10 at Beatty, this will reduce the potential for creating track cleat depressions that are aligned in a down-slope direction that later could favor rill erosion.

Over-compaction (i.e., exceeding the density specification for cover materials) could reduce the water-holding characteristics of the cover or the ability of the cover to establish and support vegetation. Such over-compaction could be caused by repeated passage of heavy equipment over cover materials during or after placement (such as would result from repeated use of a haul route). Such haul road will not be used, and equipment loads on the soil cover during construction will be limited to the normal equipment traffic associated with placing, spreading and compacting the cover soil. Once the cover is completed in an area, vehicular traffic on the soil cover will be limited. Also, construction materials and equipment will not be temporarily

stored on the cover during or after construction. Areas that become over-compacted because of equipment traffic will be loosened, such as by shallow disking.

## 6.4 PROCEDURE FOR CONFIRMING LINE AND GRADE

This work will consist of the layout of the final cover. Cover components will be laid out in accordance with the location, lines and grades, and construction details shown on the project plans. Staking will be done using a 100-feet grid placed using standard surveying and inspection techniques. Stake markings will denote the minimum total thickness of the full final cover system at each grid intersection.

Verification of the constructed dimensions (line, grade, and elevation) of the final cover will be accomplished by measuring the interim and final cover layer thickness, and aggregate thickness of both layers (after compactions) at each grid intersection.

Changes to line and grade requirements will have the approval of the Project Engineer prior to implementation.

Table 5: Final Cover Soil Placement Inspection Schedule

| FINAL COVER SOIL PLACEMENT INSPECTION SCHEDULE | | | | |
|---|---|---|---|---|
| **Inspection Task** | **Inspection/Test Method Reference** | **Sample/Test Quantity/Frequency** | **Observation/Sample Locations** | |
| | | | Soil Stockpile | Cover Area |
| **GENERAL REQUIREMENTS FOR FIELD INSPECTION OF FINAL COVER CONSTRUCTION** | | | | |
| General project observations | Visual observations, plus basic measurements and recordkeeping | Continuous observation, during final cover construction | Yes | Yes |
| Cover feature layout | Observation of survey staking | Continuous observation, during final cover construction | NA | Yes |
| Soil material observation | Observation of cover soil material | Continuous observation, during final cover construction | Yes | Yes |
| **SOIL TESTS TO BE DONE DURING FINAL COVER CONSTRUCTION** | | | | |
| Particle-size analysis | ASTM C 136 | 3 tests per material type, reconfirmed as needed | Yes | Yes |
| Moisture/density curve | ASTM D1557, Modified proctor moisture-density relation (or approved alternative method) | 3 tests per material type, reconfirmed as needed | Yes | Yes |
| Lift thickness | Observation/measurement before and during compaction | Random locations | NA | Yes |
| In-place density and moisture content | ASTM D6938 (or approved alternative method) | As specified | NA | Yes |

| FINAL COVER SOIL PLACEMENT INSPECTION SCHEDULE (continued) | | | | | |
|---|---|---|---|---|---|
| **Inspection Task** | **Inspection/Test Method Reference** | **Sample/Test Quantity/Frequency** | **Sample Location** | | **Acceptance Criteria** |
| | | | **Soil Stockpile** | **Cover Area** | |
| **COMPACTED FILL STARTER BERM FOR TRENCH 12** | | | | | |
| Particle-size analysis | ASTM C136 | 3 tests per material type in stockpile, reconfirm as needed, verify maximum size criterion by visual observation at placement | Yes | Yes | 95% ≤ 3.0”<br>≥5% passing #200 sieve |
| Moisture/density relation | ASTM D1557 | 3 tests per material type, reconfirmed as needed | Yes | NA | NA |
| In-place density | ASTM D6938 (or acceptable equivalent method), after compaction | 1 per lift per 200 feet of berm, minimum (as fill is placed) | NA | Yes | 95% MDD (min) by ASTM D 1557 |
| Moisture content | ASTM D6938 (after compaction) | 1 per lift per 200 feet of berm, minimum (as fill is placed) | NA | Yes | OMC-1% to OMC+2% |
| **INTERIM COVER LAYER** | | | | | |
| Particle-size analysis | ASTM C136 | 3 tests per material type, reconfirm as needed, verify by visual observation | Yes | NA | 100% <6.0” |
| Lift thickness, for interim cover layer | Measurement after loose placement | Random measurements and observation | NA | Yes | Total loose thickness ≥12.0” |

| FINAL COVER SOIL PLACEMENT INSPECTION SCHEDULE (continued) | | | | | |
|---|---|---|---|---|---|
| **Inspection Task** | **Inspection/Test Method Reference** | **Sample/Test Quantity/Frequency** | **Sample Location** | | **Acceptance Criteria** |
| | | | **Soil Stockpile** | **Cover Area** | |
| **FINAL COVER LAYER** | | | | | |
| Particle-size analysis | ASTM C136 | 3 tests per material type in stockpile, reconfirm as needed, verify maximum size criterion by visual observation at placement | Yes | Yes | 100% ≤ 3.0”<br>≤10% > 1.0”<br>≥5% passing #200 sieve |
| Moisture/density relation | ASTM D1557, Modified proctor moisture-density relation | 3 tests per material type, reconfirmed as needed | Yes | NA | NA |
| Lift thickness, final cover layer | Measurement before compaction | One measurement for each 100 ft by 100 ft grid area | NA | Yes | Loose lift thickness 12.0” to 24.0” |
| In-place density and moisture content | ASTM D1557 (after compaction) | one test per each one test for every 10,000 square feet of cover placed | NA | Yes | 80% MDD (±3%)<br>OMC minus 2-4% |

MDD = Standard Proctor (ASTM D1557) maximum dry density.

OMC = Standard Proctor (ASTM D1557) optimum moisture content

# APPENDIX 1

# TRENCHES 11 AND 12 FINAL COVERS

# DESIGN DRAWINGS

## DRAWINGS LIST

| | |
|---|---|
| NV12-08-009 | Final Covers |
| NV12-08-010 | Cross Sections A-A and B-B |
| NV12-08-011 | Cross Sections C-C and D-D |
| NV12-08-012 | Cross Sections E-E and F-F |
| NV12-08-013 | Details |

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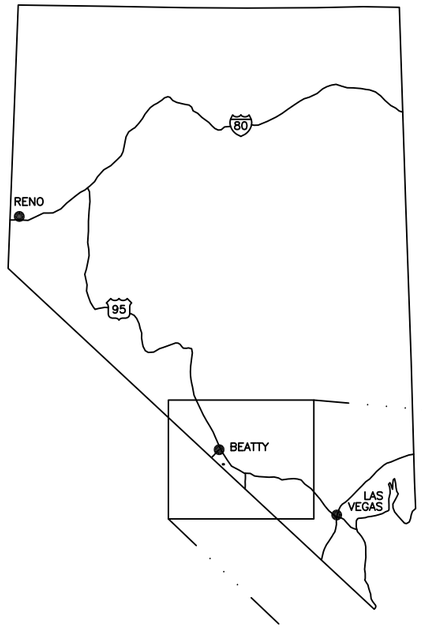
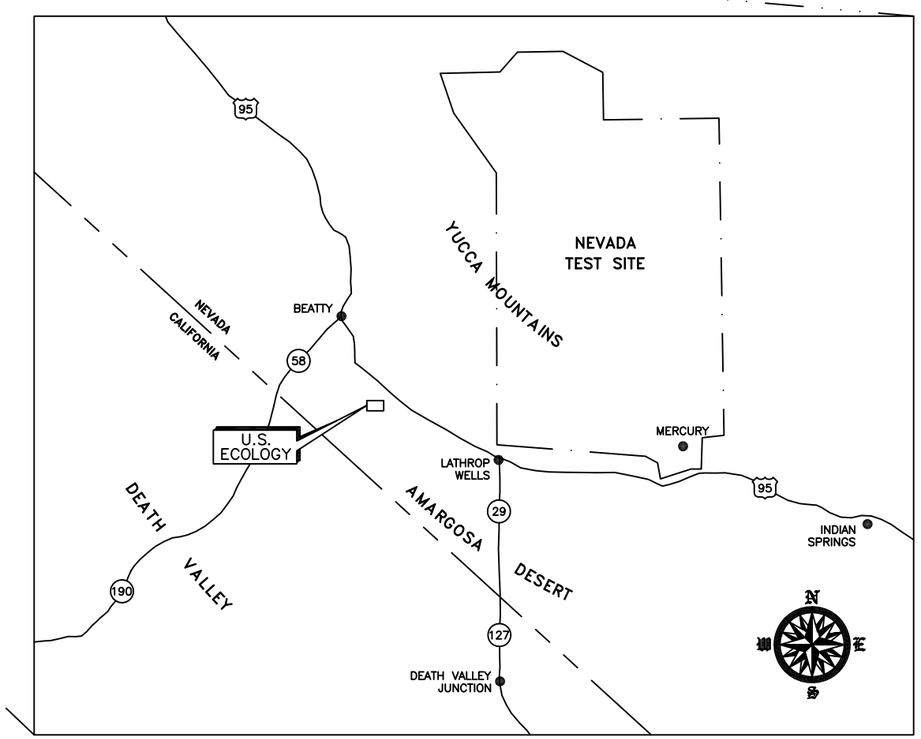
# LANDFILL TRENCH 12 DESIGN AND TRENCH 11 AND TRENCH 12 FINAL COVERS HAZARDOUS WASTE MANAGEMENT FACILITY BEATTY, NEVADA

## RCRA FACILITY ID NO. NVT330010000
## HAZARDOUS WASTE PERMIT NUMBER NV HW0019




VICINITY MAP

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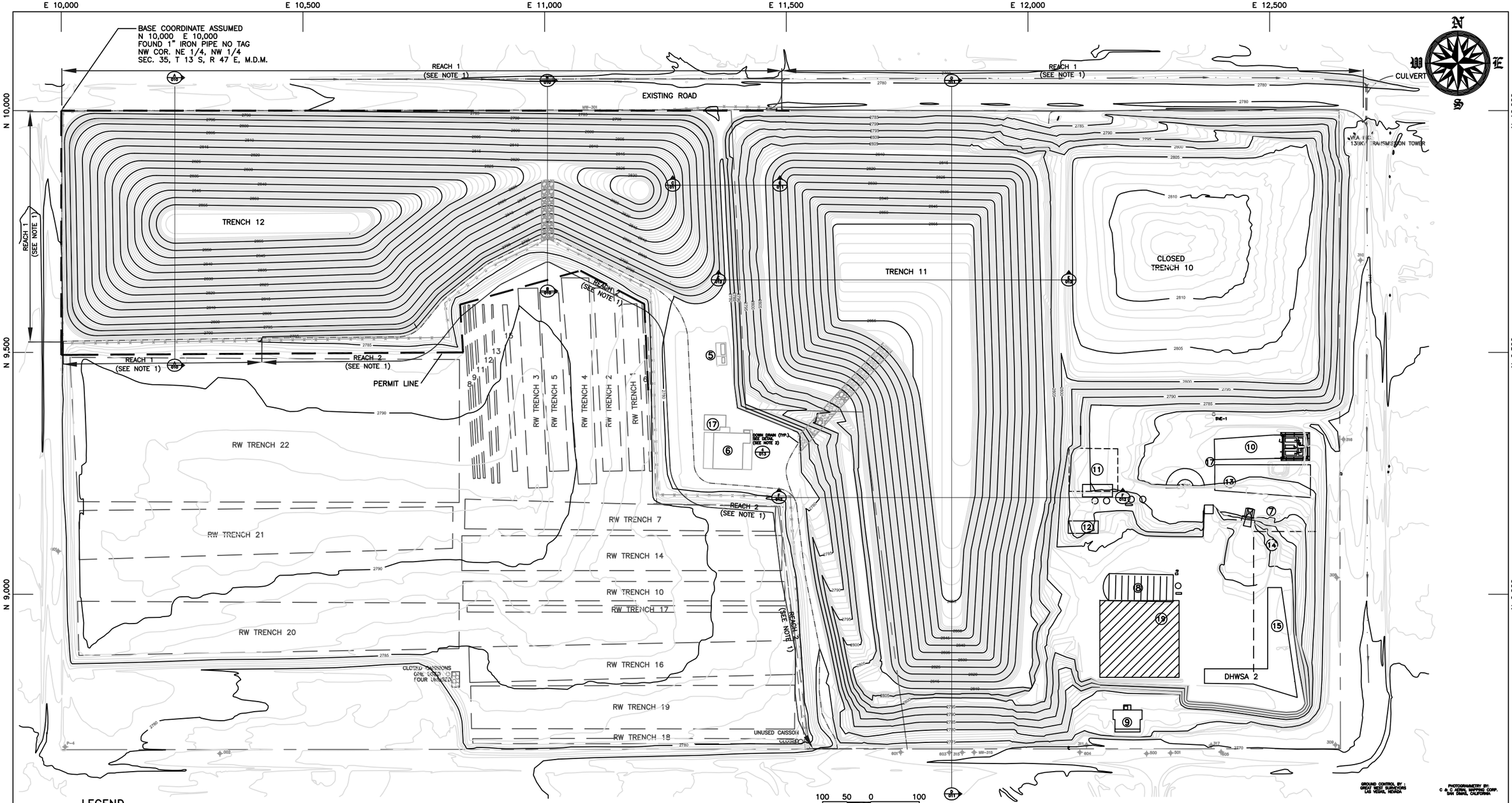
## INDEX OF DRAWINGS


| SHEET NO. | DRAWING NO. | TITLE |
|---|---|---|
| 1 | NV12-08-001 | TITLE SHEET |
| LANDFILL TRENCH 12 | | |
| 2 | NV12-07-002 | SITE PLAN |
| 3 | NV12-07-003 | EXCAVATION PLAN-PERIMETER SOILS REQUIRING RECOMPACTION |
| 4 | NV12-07-004 | EXCAVATION PLAN |
| 5 | NV12-07-005 | CROSS SECTIONS A-A AND B-B |
| 6 | NV12-07-006 | CROSS SECTIONS C-C, D-D AND LINER DETAILS |
| 7 | NV12-07-007 | SUMP DETAILS |
| 8 | NV12-07-008 | SUMP AND MISCELLANEOUS DETAILS |
| TRENCH 11 AND 12 FINAL COVERS | | |
| 9 | NV12-08-009 | FINAL COVERS |
| 10 | NV12-08-010 | CROSS SECTIONS A-A AND B-B |
| 11 | NV12-08-011 | CROSS SECTIONS C-C AND D-D |
| 12 | NV12-08-012 | CROSS SECTIONS E-E AND F-F |
| 13 | NV12-08-013 | FINAL COVER DETAILS |


NOTE: THESE TRENCH 12 PLANS ARE REVISED FROM 1996 TRENCH DESIGN DRAWINGS NV-161-001 THROUGH NV-161-010 WHICH WERE CONDITIONALLY APPROVED BY THE NEVADA DEPARTMENT OF ENVIRONMENTAL PROTECTION IN RCRA PERMIT NEV HW0019 DATED APRIL 29, 2005.




## LEGEND

- HORIZONTAL CONTROL LINE
- PERMIT LINE
- DRAINAGE DITCH AND DIRECTION OF FLOW
- PROPERTY LINE
- FENCE LINE
- 302 MONITOR WELL LOCATION AND NUMBER
- SVE-1 SOIL VAPOR EXTRACTION WELL
- 1' CONTOUR INTERVAL, FEET (MSL)
- 2780 5' CONTOUR INTERVAL, FEET (MSL)
- RW TRENCH 1 LOW LEVEL RADIOLOGICAL WASTE TRENCH

⑤ FUEL STORAGE
⑥ MAINTENANCE SHOP
⑦ LOW TEMPERATURE THERMAL DESORPTION
⑧ TRUCK PARKING
⑨ EVAPORATION TANK
⑩ PCB PROCESSING AREA
⑪ BATCH STABILIZATION TANK AND SILOS
⑫ STABILIZATION TANKS
⑬ THERMAL TREATMENT AREA
⑭ LOW TEMPERATURE THERMAL DESORPTION FUTURE EXPANSION
⑮ DRY HAZARDOUS WASTE STORAGE AREA
⑲ CONTAINER MGNT./STAB. BUILDING

100 50 0 100
SCALE FEET

NOTES:

1. REACHES ARE PERIMETER DITCHES WHICH HAVE A UNIFORM CROSS-SECTION. DITCH CONFIGURATIONS ARE SHOWN IN DETAIL 1 ON DRAWING NV-08-013.
2. DOWN DRAIN DISCHARGE LOCATION WILL DEPEND ON FINAL COVER TOPOGRAPHY.

| REV. | DESCRIPTION | DRWN. BY | DSGN. BY | CHECK BY | APP'D BY | DATE |
|---|---|---|---|---|---|---|
| 0 | ISSUED FOR REGULATORY REVIEW | LAM | CAB | SLW | SLW | 4/25/08 |

| DRWN. BY | DATE | DSGN. BY | DATE | CHKD. BY | DATE | APP'D BY |
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| LAM | 12/26/07 | CAB | 12/26/07 | SLW | 12/26/07 | SLW |

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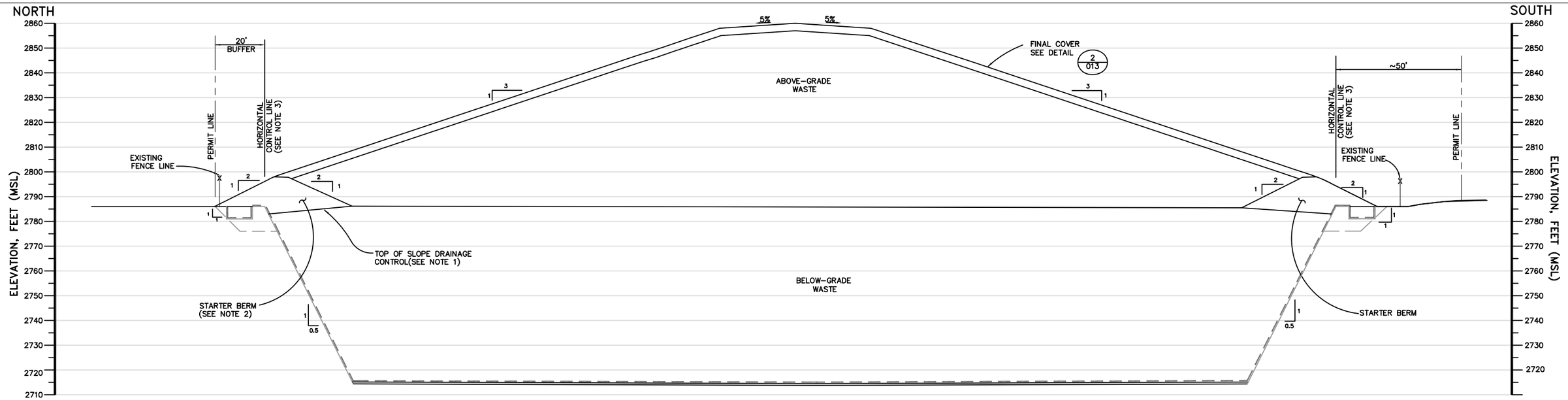
PROJECT NUMBER: 073113 DATE: 4/25/08

BEATTY NEVADA
HAZARDOUS WASTE MANAGEMENT FACILITY

FINAL COVERS
LANDFILL TRENCHES 11 & 12

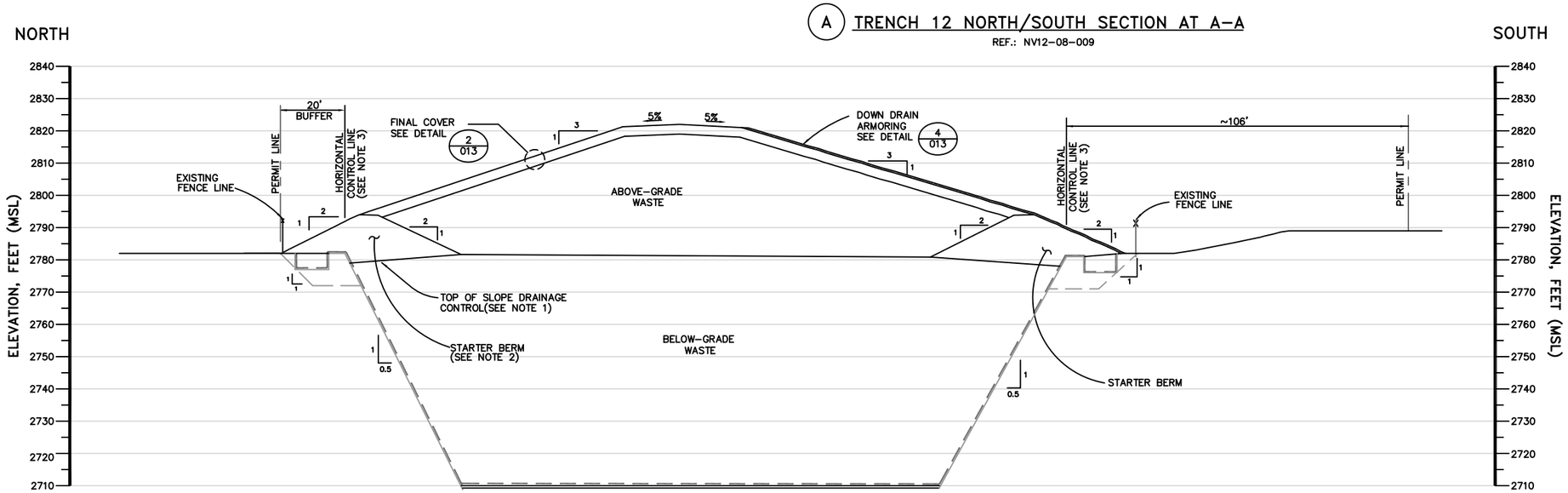
| JOB NO. | DRAWING NO. | REV. |
|---|---|---|
| 073113 | NV12-08-009 | 0 |

CAD FILE NAME: F:\Data\073113 T12 Design\T12 Design Package\Final Cover Design\Drawings\Issued for Reg Review\NV12-08-009.dwg PLOT DATE: 4/25/08




A TRENCH 12 NORTH/SOUTH SECTION AT A–A

REF.: NV12–08–009




B TRENCH 12 NORTH/SOUTH SECTION AT B–B

REF.: NV12–08–009

## SECTION LEGEND

LINER SYSTEM

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SCALE FEET

NOTES:

1. KEEP WASTE 3' BELOW TOP OF SLOPE UNTIL CONSTRUCTION OF STARTER BERM.
2. STARTER BERM IS COMPACTED SOIL. FILL MATERIAL CAN INCLUDE CLEAN, NATIVE SOIL AND SELECT SOIL WASTE. SELECT SOIL WASTE, IF USED, MUST BE PLACED ONLY OVER LINED AREAS AND MUST SATISFY MATERIAL GRADATION AND COMPACTION SPECIFICATIONS. (SEE DETAIL 3, NV12–08–013).
3. HORIZONTAL CONTROL LINE MARKS THE PERIMETER OF THE TRENCH EXCAVATION.

| REV. | DESCRIPTION | DRWN. BY | DSGN. BY | CHECK BY | APP'D BY | DATE |
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HAZARDOUS WASTE MANAGEMENT FACILITY

CROSS SECTIONS A–A AND B–B
TRENCH 12

| DRWN. BY | DATE | DSGN. BY | DATE | CHKD. BY | DATE | APP'D BY |
|---|---|---|---|---|---|---|
| LAM | 12/26/07 | CAB | 12/26/07 | SLW | 12/26/07 | SLW |

| JOB NO. | DRAWING NO. | REV. |
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| 073113 | NV12–08–010 | 0 |

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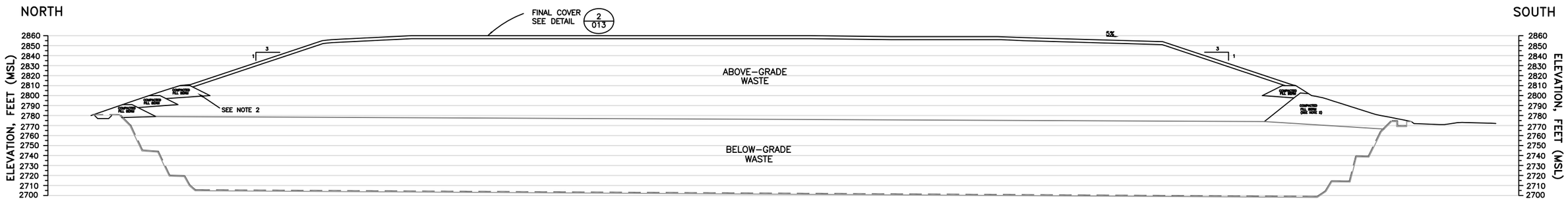


D TRENCH 11 NORTH/SOUTH SECTION AT D-D

REF.: NV12-08-009

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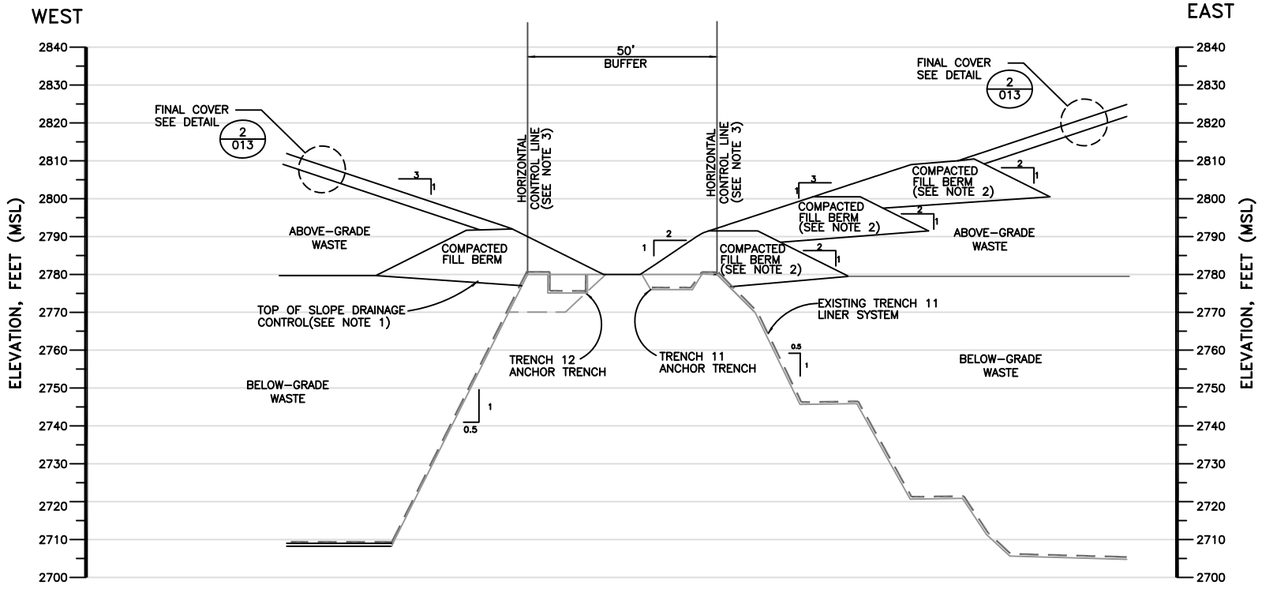


C TYPICAL SECTION-TRENCH 12/TRENCH 11 TIE-IN

REF.: NV12-08-009

20 10 0 20
SCALE FEET

NOTES:

1. KEEP WASTE 3' BELOW TOP OF SLOPE UNTIL CONSTRUCTION OF STARTER BERM TO PREVENT RUN-OFF.
2. TRENCH 11 FEATURES, OTHER THAN FINAL COVER LAYER, INCLUDING COMPACTED SOIL BERMS, ALREADY HAVE BEEN CONSTRUCTED
3. HORIZONTAL CONTROL LINE MARKS THE PERIMETER OF THE TRENCH EXCAVATION.

SECTION LEGEND

— — — — — BASE LINER SYSTEM

| REV. | DESCRIPTION | DRWN. BY | DSGN. BY | CHECK BY | APP'D BY | DATE |
|---|---|---|---|---|---|---|
| 0 | ISSUED FOR REGULATORY REVIEW | LAM | CAB | SLW | SLW | 4/25/08 |

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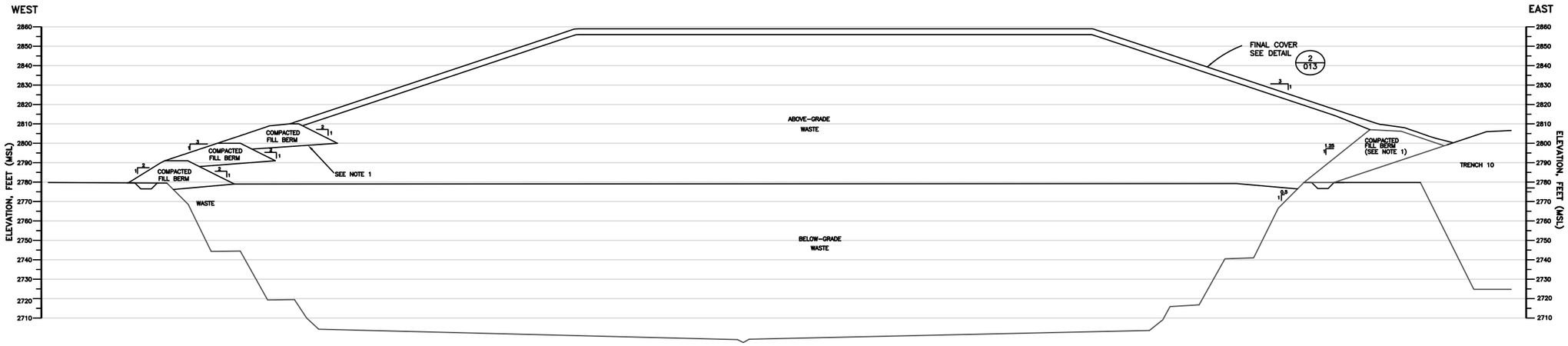
BEATTY NEVADA
HAZARDOUS WASTE MANAGEMENT FACILITY

CROSS SECTIONS C-C, D-D
TRENCH 12

| DRWN. BY | DATE | DSGN. BY | DATE | CHKD. BY | DATE | APP'D BY |
|---|---|---|---|---|---|---|
| LAM | 12/26/07 | CAB | 12/26/07 | SLW | 12/26/07 | SLW |

| JOB NO. | DRAWING NO. | REV. |
|---|---|---|
| 073113 | NV12-08-011 | 0 |

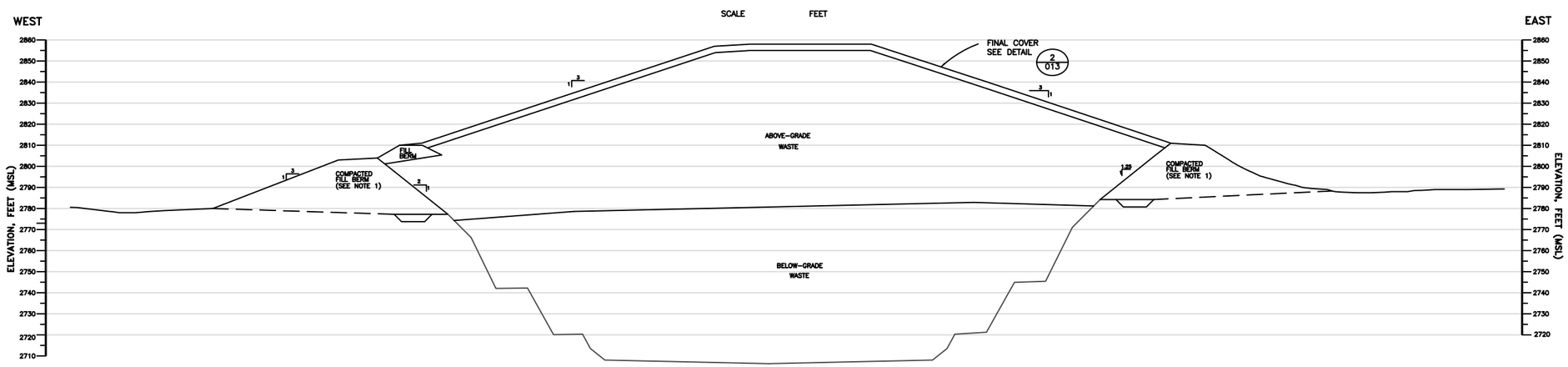
CAD FILE NAME: F:\Data\073113 T12 Design\T12 Design Package\Final Cover Design\Drawings\Issued for Reg Review\NV12-08-011.dwg PLOT DATE: 4/25/08




E TRENCH 11 NORTH/SOUTH SECTION AT E-E

REF.: NV12-08-009

0 30 60
SCALE FEET




F TRENCH 11 NORTH/SOUTH SECTION AT F-F

REF.: NV12-08-009

0 30 60
SCALE FEET

NOTES:

1. TRENCH 11 FEATURES, OTHER THAN FINAL COVER LAYER, INCLUDING COMPACTED SOIL BERMS, ALREADY HAVE BEEN CONSTRUCTED

| REV. | DESCRIPTION | DRWN. BY | DSGN. BY | CHECK BY | APP'D BY | DATE |
|---|---|---|---|---|---|---|
| 0 | ISSUED FOR REGULATORY REVIEW | LAM | CAB | SLW | SLW | 4/25/08 |

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|---|---|---|---|---|---|---|
| LAM | 12/26/07 | CAB | 12/26/07 | SLW | 12/26/07 | SLW |

USEcology Nevada
*an American Ecology company*

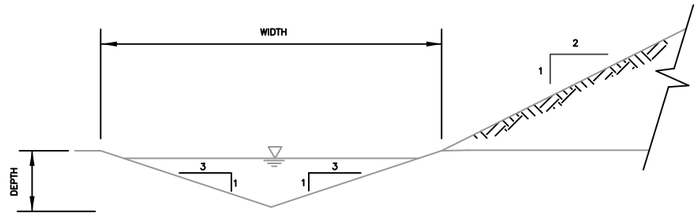
PROJECT NUMBER: 073113 DATE: 4/25/08

BEATTY NEVADA
HAZARDOUS WASTE MANAGEMENT FACILITY

CROSS SECTIONS E-E AND F-F
TRENCH 11

| JOB NO. | DRAWING NO. | REV. |
|---|---|---|
| 073113 | NV12-08-012 | 0 |

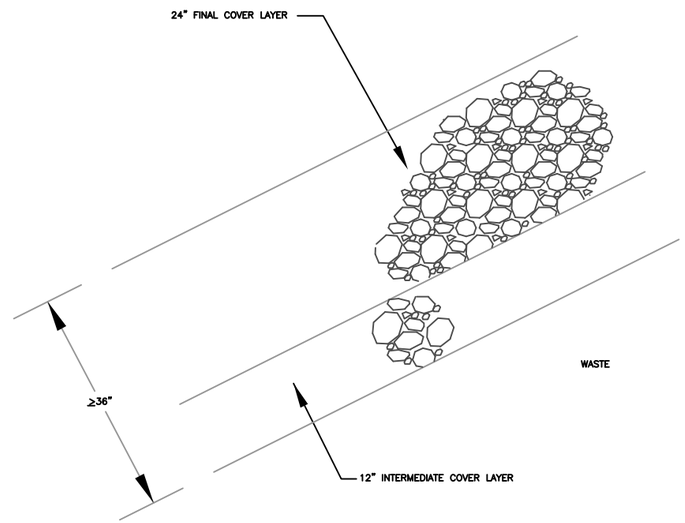
CAD FILE NAME: F:\Data\073113 T12 Design\T12 Design Package\Final Cover Design\Drawings\Issued for Reg Review\NV12-08-012.dwg PLOT DATE: 4/25/08




| REACH (SEE DRAWING 009) | Q 25 (cfs) | SLOPE (ft/ft) | DEPTH (feet) | WIDTH (feet) |
|---|---|---|---|---|
| 1 | 3 | 0.005 | 0.7 | 4.2 |
| 2 | 8 | 0.005 | 1.0 | 6.0 |

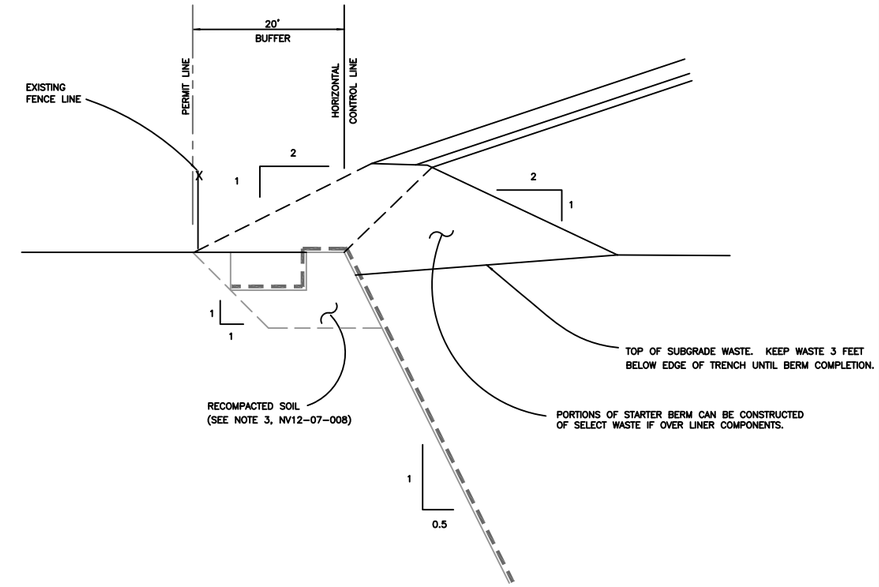
1 TYPICAL PERIMETER DITCH
REACHES 1 AND 2

REF.: NV12-08-009




2 TYPICAL COVER SYSTEM

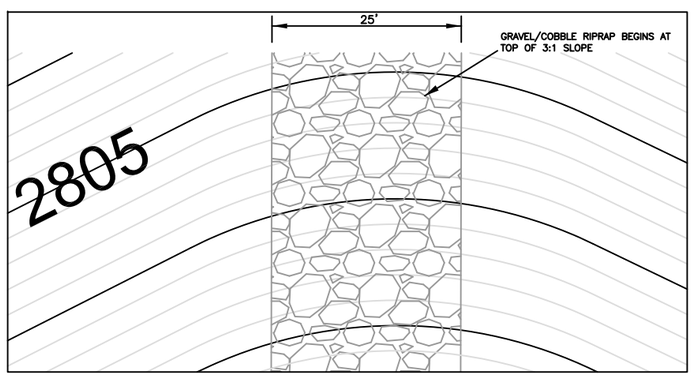
0 2 4
SCALE FEET




3 BERM CONSTRUCTION DETAIL

REF: NV12-08-010

0 10 20
SCALE FEET




4 DOWN DRAIN DETAIL

REF: NV12-08-009

0 10 20
SCALE FEET

| REV. | DESCRIPTION | DRWN. BY | DSGN. BY | CHECK BY | APP'D BY | DATE |
|---|---|---|---|---|---|---|
| 0 | ISSUED FOR REGULATORY REVIEW | LAM | CAB | SLW | SLW | 4/25/08 |

| DRWN. BY | DATE | DSGN. BY | DATE | CHKD. BY | DATE | APP'D BY |
|---|---|---|---|---|---|---|
| LAM | 12/26/07 | CAB | 12/26/07 | SLW | 12/26/07 | SLW |

USEcology Nevada
*an American Ecology company*

PROJECT NUMBER: 073113 DATE: 4/25/08

BEATTY NEVADA
HAZARDOUS WASTE MANAGEMENT FACILITY

FINAL COVER LANDFILL
TRENCH 11 & 12

| JOB NO. | DRAWING NO. | REV. |
|---|---|---|
| 073113 | NV12-08-013 | 0 |

CAD FILE NAME: F:\Data\073113 T12 Design\T12 Design Package\Final Cover Design\Drawings\Issued for Reg Review\NV12-08-011.dwg PLOT DATE: 4/25/08

# APPENDIX 2

# TRENCHES 11 AND 12 FINAL COVERS

# SUPPORTING CALCULATIONS

AquAeTer

*optimizing environmental resources - water; air; earth*

# CALCULATION SUMMARY SHEET



PROJECT NUMBER: 073113

PROJECT NAME: USEN – Trench 12 Design, Supplemental Calculations

DATE: November 8, 2007

CALCULATION NUMBER: NA Revision:

**CALCULATION TITLE: Alternative Final Cover Modeling**

**DESCRIPTION OF CALCULATION:**

This calculation is the modeling of the long-term performance of an arid region alternative landfill cover to predict percolation into waste using the water balance models, HELP and UNSAT-H

**REFERENCES USED:** Reference Pages Attached: Yes

UNSAT-H Version 2.03

HELP Version 3.07

HELP User's Manual

Variation in flow and transport in thick desert vadose zones (Andraski 2003)

Properties and variability of soil and trench fill at an arid waste burial site (Andraski 1996)

Characterizing the dependence of gas diffusion coefficient on soil properties (Jury 1996)

Selected micrometeorological and soil-moisture–Amargosa Desert Research Site 1998-2000 (USGS 2002)

Selected micrometeorological and soil-moisture–Amargosa Desert Research Site 2001-05 (USGS)

**REVIEW COMMENTS:**

Calculation revision made to adjust 'normal year' rainfall amounts to 4.25 inches

CALCULATION MADE BY: CAB DATE: November 7, 2007

CALCULATION CHECKED BY: APM DATE: November 11, 2007

CALCULATION REVISED BY: APM DATE: December 21, 2007

CALCULATION REVIEWED BY: SLW DATE: December 21, 2007

# CALCULATION

## PURPOSE

US Ecology is applying for a RCRA Permit Modification that will allow it to incorporate an arid-region alternate final cover (AFC) into the design for final closure of Trench 11 and 12 at the Beatty facility. An arid-region AFC is an Evaportranspirative Cover (ET Cover) that is not vegetated in the early years after construction, and does not release water by plant transpiration.

At the Beatty facility, Trench 11 has been (and still is) used to dispose of RCRA hazardous waste, but is expected to be filled in the near future. Trench 12 has been designed and will be constructed beginning in 2008 for disposal of RCRA hazardous waste. Both Trenches must satisfy the RCRA Subtitle C (40 CFR 264) requirements for land disposal of hazardous waste and final closure. To evaluate the long-term performance of alternate final cover designs for infiltration, evapotranspiration, and percolation, the quasi-two-dimensional enhanced water-balance model HELP and one-dimensional Richards' equation model UNSAT-H were used to simulate water flow into and out of the proposed final cover and compare the performance of the proposed cover to that of the conventional RCRA Cover for the Trench 12 design, as submitted to NDEP in 1996.

## APPROACH

The 2002 USEPA Draft RCRA Guidance for Landfill Covers, entitled "Technical Guidance for RCRA/CERCLA Covers," (EPA Draft Guidance) suggests that two models be used to provide comparative results for performance of a landfill cover design. Previous modeling efforts that simulate infiltration into the waste for other cover design concepts at the Beatty facility have used the HELP model. The HELP model is listed in the EPA Draft Guidance as a model that can be used for cover performance modeling. Another program also listed in the EPA Draft Guidance is UNSAT-H. Recommendations have been made by other researchers (e.g., Nichols, 1991) that suggest the UNSAT-H model will provide more accurate estimations of deep percolation.

Both HELP and UNSAT-H models were used in the analysis. A discussion of these analyses and their results is included in this calculation.

- UNSAT-H Version 2.03: Fayer, M.J. and T.L. Jones. 1990. UNSAT-H Version 2.0: Unsaturated Soil Water and Heat Flow Model. PNL-6779, Pacific Northwest Laboratory, Richland, Washington.

- HELP Version 3.07: Schroeder, P.R., Dozier, T.S., Zappi, P.A., McEnroe, B.M., Sjostrom, J.W. and Peton, R.L. 1994. "The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3", EPA/600/R-94/168B, U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH

The HELP model is an "enhanced water-balance model" and the UNSAT-H model is a "Richards' equation-based model" (ITRC, 2003 Technical and Regulatory Guidance for Design, Installation, and Monitoring of Alternative Final Landfill Covers). As such, there are fundamental differences between the models. The recent ITRC regulatory guidance (2003) considers the UNSAT-H model to be of a type that is "more physically correct for characterizing water movement than [water-balance] models." Further, ITRC says that, "Richards' equation models can predict flux for soil moisture values less than field capacity" and can "capture the dynamics of varying soil types and their potential impact on water flux." Both HELP and UNSAT-H yield estimates of percolation of liquid from the base of the cover components into the waste layer. For the purposes of this evaluation, the waste is modeled as a free-draining medium.

The development of percolation estimates is one method to assess the suitability of alternate cover configurations to achieve the RCRA cover performance objective of "long-term minimization of migration of liquids through the closed landfill" as such liquids first must move through the final cover and into waste and then through waste before reaching a leachate collection system. Moisture movement through dry waste will be deterred by the same processes that retain moisture within the cover soil. But, if moisture ultimately reaches the leachate collection system, its mere occurrence of leachate in the landfill LCRS or LDS (leachate collection and recovery system or leak detection system) does not indicate that a release to the environment is imminent. Rather, the presence and accumulation of leachate in those systems increases the potential that such a release could occur. An important step toward reducing the potential for such a release to the environment is the use of a final landfill cover type that will reduce liquid percolation into waste to a practical, low value. For ET covers in arid regions, practical, low values have been determined to range from less than 10 to a few 10s of millimeters per year, or the equivalent of a few percent of the annual precipitation total. Annual percolation values will vary in response to the occurrence of unusually dry, average, and unusually wet years, so this measure of performance is not a specific value for a single year, but a low average value for a reasonably long period of time, perhaps 10 or more years.

USEPA has not promulgated regulations or published guidance regarding percolation (also called flux rates), so there is no certain criterion by which to judge this aspect of alternative cover performance. It can be useful, to use mathematical models to estimate moisture movement into and out of monolithic and multi-component covers and make simple comparisons of moisture flux as a measure of cover performance. However, the one-to-one comparison of modeling results for different cover types can be problematic since the model might not be capable of considering the actual effect that construction damage, aging, and desiccation can have on some components of a multi-component final cover (such as compacted clay, flexible membrane liners, and thinly layered expansive clay materials). The important outcome of this comparison is not that one cover type provides a numerical measure of moisture flux that is the same as or better than that of another cover type, but that any acceptable final cover type provide long-term (average) percolation values that remain low under a reasonable range of climatic condition variations.

The results of the modeling effort are summarized below. Representative model input and output information is appended to the calculation summary.

Thirty (30) years was selected as the modeled time period for both models. That time period corresponds to the basic post-closure care period in RCRA regulations and provides a reasonable period of time over which long-term percolation could be estimated.

## HELP MODELING DISCUSSION

### Climate Data

The HELP model provides default input of various weather data, including evapotranspiration, precipitation, temperature, and solar radiation. As was noted previously, climate data for Las Vegas, Nevada were chosen to represent conditions at the USEN facility. Data for this geographic location also were used for precipitation, temperature, and solar radiation. The HELP model stochastically generated 30 years of precipitation, temperature, and solar radiation data using a synthetic weather generator.

Evapotranspiration is addressed by choices of evaporative zone depth and maximum leaf area index. Since plant establishment on an arid region alternative cover is expected to be non-existent or sparse for the first years following cover placement, an evaporative zone depth of 24 inches and a maximum leaf area index of 0.0 were chosen (representing bare soil conditions). The model also was run for the 1996 RCRA cap assuming an evaporative zone depth of 24 inches and a maximum leaf area index of 0.0.

### Physical Data

The HELP model was run for each cover type for 30 years with unvegetated conditions. Since vegetation establishment actually would begin sooner than 30 years and vegetation would remove moisture from the soil through transpiration, considering unvegetated conditions for the full modeled time period adds conservatism to the percolation estimates. Soil characteristics approximating those identified during soil testing on the USEN property were used. Other soil properties used included soil layer type, thickness, soil texture, and initial volumetric soil water content. The surface-water runoff curve number information was determined based on cover conditions and geometry.

### Modeling Approach

HELP modeling was performed for a total of 30 years, conservatively assuming no vegetation. HELP modeling in this manner assumes there is little or no plant transpiration during the first 30 years following cover placement.

Three scenarios were run in HELP including a prescriptive (conventional) RCRA Subtitle C cap, as conditionally approved in the 1996 Trench 12 Design submittal, an ET Cover with a capillary break, and a monolithic ET Cover. The three scenarios are further described in the following table, which also provides the file name, cover type, and components of each scenario.

| File Name | Cover Type | Components |
|---|---|---|
| B-DES1AR | RCRA Subtitle C cap | 0.5 feet erosion layer (gravel ¾ inch to 3 inch) |
| | | 1.5 feet soil layer (granular soil < 1 inch) |
| | | Drainage layer (double-sided geocomposite) |
| | | 60-mil HDPE |
| | | GCL |
| | | 2.0 feet foundation layer (clean site soil) |
| B-DES2AR | ET cover with capillary break | 2.0 feet final cover (SM) |
| | | 1.0 feet of intermediate soil cover (SM) |
| | | 0.5 feet capillary break (gravel) |
| MONO36AR | ET monolithic cover | 2.0 feet final cover (SM) |
| | | 1.0 feet of intermediate cover (SM) |

Analyses were performed to compare the results for ET Covers to the 1996 RCRA Subtitle C Cover. The properties of the geomembrane and the GCL were taken from the HELP manual as representative of a typical "good installation" that acknowledges the presence of liner material defects (the result of damage before, during, and after construction).

| | |
|---|---|
| Thickness | 0.06 inches (60 mil) |
| Porosity | 0.0 |
| Field Capacity | 0.0 |
| Wilting Point | 0.0 |
| Initial Water Content | 0.0 |
| Effective saturated hydraulic conductivity | 2E-13 cm/sec |
| FML Pinhole Density | 0.75 holes/acre |
| FML Installation Defects | 2.00 holes/acre |
| FML Placement Quality | 3 (good) |

The ET Cover simulations include a final cover thickness and an intermediate soil cover modeled as one monolithic unit in HELP. The model runs are for 30 years with unvegetated conditions. Soil characteristics approximating those identified during soil testing on the US Ecology property were used.

It is noted that the HELP program, when attempting to resolve the steady-state initial moisture conditions does not allow calculations for moisture content below the wilting point, and in fact, returns initial conditions that typically are between the wilting point and field capacity.

However, it is recognized that at the Beatty site, near-surface soils can have moisture contents that are well below the wilting point. As such, the initial moisture content was set at the wilting point in the modeling runs. This model limitation of restricting initial moisture content conditions to a higher than actual value might result in unrealistically high infiltration results in this very arid environment.

The results suggest that a three-feet (36-inch) monolithic ET Cover will perform comparably to both the approved RCRA Subtitle C Cover and a three-feet thick ET Cover with and additional 6-inch thick capillary break between the waste and cover materials. The monolithic ET Cover includes 1 foot of intermediate cover and 2.0 feet of final cover.

**Model result**

The HELP model shows that a three-feet (36-inch) thick monolithic soil ET Cover is sufficient to prevent significant percolation into the waste, limiting maximum potential percolation to 0.16 millimeters in a single year and average annual percolation over 30 years to just 0.005 millimeters per year (mm/year). In this comparison, the monolithic cover actual performs better than the ET cover with capillary break (average annual percolation estimate of 0.12 mm/year). However, both ET covers perform very well with regard to estimated percolation, even when the modeled scenarios do not consider vegetation.

## HELP MODEL PERCOLATION OUTPUT – 30 YEARS, NO VEGETATION

| Year | Precipitation | RCRA Subtitle C Cover | | ET Cover with Capillary Break | | ET Monolithic Cover | |
|---|---|---|---|---|---|---|---|
| | | (inches/year) | (mm/year) | (inches/year) | (mm/year) | (inches/year) | (mm/year) |
| 1 | 2.80 | 0.000000 | 0.00000 | 0.000031 | 0.00079 | 0.000000 | 0.00000 |
| 2 | 4.81 | 0.000000 | 0.00000 | 0.000036 | 0.00091 | 0.000000 | 0.00000 |
| 3 | 3.38 | 0.000001 | 0.00003 | 0.000036 | 0.00091 | 0.000000 | 0.00000 |
| 4 | 7.19 | 0.000001 | 0.00003 | 0.000038 | 0.00097 | 0.000000 | 0.00000 |
| 5 | 3.76 | 0.000001 | 0.00003 | 0.000038 | 0.00097 | 0.000000 | 0.00000 |
| 6 | 4.98 | 0.000001 | 0.00003 | 0.000040 | 0.00102 | 0.000000 | 0.00000 |
| 7 | 3.63 | 0.000001 | 0.00003 | 0.000039 | 0.00099 | 0.000001 | 0.00003 |
| 8 | 4.03 | 0.000001 | 0.00003 | 0.000039 | 0.00099 | 0.000000 | 0.00000 |
| 9 | 3.49 | 0.000001 | 0.00003 | 0.000040 | 0.00102 | 0.000000 | 0.00000 |
| 10 | 4.23 | 0.000001 | 0.00003 | 0.000040 | 0.00102 | 0.000000 | 0.00000 |
| 11 | 8.71 | 0.000001 | 0.00003 | 0.000040 | 0.00102 | 0.000000 | 0.00000 |
| 12 | 3.33 | 0.000001 | 0.00003 | 0.000047 | 0.00119 | 0.000000 | 0.00000 |
| 13 | 2.58 | 0.000000 | 0.00000 | 0.000045 | 0.00114 | 0.000000 | 0.00000 |
| 14 | 3.92 | 0.000001 | 0.00003 | 0.000046 | 0.00117 | 0.000000 | 0.00000 |
| 15 | 4.26 | 0.000001 | 0.00003 | 0.000046 | 0.00117 | 0.000000 | 0.00000 |
| 16 | 3.66 | 0.000001 | 0.00003 | 0.000046 | 0.00117 | 0.000000 | 0.00000 |
| 17 | 2.71 | 0.000001 | 0.00003 | 0.000046 | 0.00117 | 0.000000 | 0.00000 |
| 18 | 3.73 | 0.000001 | 0.00003 | 0.000047 | 0.00119 | 0.000000 | 0.00000 |
| 19 | 3.61 | 0.000001 | 0.00003 | 0.000047 | 0.00119 | 0.000000 | 0.00000 |
| 20 | 2.05 | 0.000001 | 0.00003 | 0.000047 | 0.00119 | 0.000000 | 0.00000 |
| 21 | 2.33 | 0.000000 | 0.00000 | 0.000047 | 0.00119 | 0.000000 | 0.00000 |
| 22 | 4.05 | 0.000000 | 0.00000 | 0.000048 | 0.00122 | 0.000001 | 0.00003 |
| 23 | 2.86 | 0.000001 | 0.00003 | 0.000052 | 0.00132 | 0.000000 | 0.00000 |
| 24 | 5.62 | 0.000001 | 0.00003 | 0.000051 | 0.00130 | 0.000000 | 0.00000 |
| 25 | 3.67 | 0.000001 | 0.00003 | 0.000054 | 0.00137 | 0.000001 | 0.00003 |
| 26 | 4.54 | 0.000001 | 0.00003 | 0.000055 | 0.00140 | 0.000000 | 0.00000 |
| 27 | 4.20 | 0.000001 | 0.00003 | 0.000054 | 0.00137 | 0.000000 | 0.00000 |
| 28 | 2.55 | 0.000001 | 0.00003 | 0.000054 | 0.00137 | 0.000000 | 0.00000 |
| 29 | 5.56 | 0.000001 | 0.00003 | 0.000055 | 0.00140 | 0.000000 | 0.00000 |
| 30 | 4.90 | 0.000001 | 0.00003 | 0.141391 | 3.59133 | 0.006211 | 0.15776 |
| | **Yearly Averages:** | **(mm/year)** | **0.000021** | | **0.120815** | | **0.005261** |

## UNSAT-H MODELING DISCUSSION

### Climate Data

The UNSAT-H model can be more site-specific than the HELP model with regard to climate. UNSAT-H requires the user to prepare inputs of these data, generally based on nearby weather station information. Site-specific meteorological data were available from the United States Geological Survey (USGS) for the Beatty site and were used in the UNSAT-H model runs.

One of the EPA Draft Guidance recommendations for cover design is that critical infiltration events that may result in percolation be identified. It is recommended that the meteorological record for the site be evaluated for times when precipitation equals or exceeds potential evapotranspiration (PET). USGS meteorological data available for the Beatty station includes 1977 to 1980 and 1986 to 2005 and were evaluated for years representing normal, wet, and dry years. PET is not exceeded at Beatty under precipitation conditions that reasonably can be assumed to occur, including even the wettest years. An above-average precipitation year (1998, one of the highest precipitation year on record), a below-average precipitation year (2002, one of the lowest precipitation years on record), and a near-average precipitation year (2000) were identified and used as inputs in the UNSAT-H model. The recorded daily rainfall amounts for "near-average" year 2000 (totaling 3.61 inches) were adjusted by multiplication by 1.18 (4.25 ÷ 3.61) so that the year's rainfall total equaled 4.25 inches, which is the 30-year average for the site[1]. Other climatic factors associated with the 2000 rainfall events that are input to UNSAT-H, were not adjusted.

The following table indicates how the actual daily weather observations for 1998, 2000, and 2002 were repeated and grouped to provide a conservative synthetic 10-year climate record. The modeling scheme developed includes a ten-year period with five normal years, two episodes of consecutive wet years, and only one dry year.To model 30 years of moisture movement in the final cover using UNSAT-H, this 10-year climate record was repeated three times.

| Model Year | Precipitation Type | Precipitation Total (inches) |
|---|---|---|
| Year 1 | Normal Year (2000*) | 4.25* |
| Year 2 | Normal Year (2000*) | 4.25* |
| Year 3 | Wet Year (1998) | 7.70 |
| Year 4 | Wet Year (1998) | 7.70 |
| Year 5 | Normal Year (2000*) | 4.25* |

[1] Scanlon, B.R., K. Keese, R.C. Brady, J. Simunek, and B.J. Andraski, 2003. "Variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing (0-90 kyr): Field measurements, modeling, and uncertainties." Water Resources Research, Vol. 39, No. 7.

| Model Year | Precipitation Type | Precipitation Total (inches) |
|---|---|---|
| Year 6 | Dry Year (2002) | 0.14 |
| Year 7 | Wet Year (1998) | 7.70 |
| Year 8 | Wet Year (1998) | 7.70 |
| Year 9 | Normal Year (2000*) | 4.25* |
| Year 10 | Normal Year (2000*) | 4.25* |

* 2000 daily rainfall amounts were multiplied by 1.18 (as discussed above)

**Physical Data**

In UNSAT-H, the nature and thickness of the cover is defined by a series of nodes. The nodes are spaced vertically downward from the cover surface. The UNSAT-H user guidance suggests nodal spacing should be very small near boundaries or at interfaces between layers and can be larger in areas where there are no transitions. Nodes were established through the soil profile, and properties assigned to each node. Using the nodal arrangement, soil properties can be assigned to specific nodes to account for different soil types or layers. Since a monolithic ET Cover was modeled in the analysis, only one set of soil properties was needed. The Beatty cover soil properties were taken from peer-reviewed scientific journal articles that provide the results of various studies of the soils present at the site. Copies of these journal articles are attached as references.

Additional requirements for the UNSAT-H model include initial head conditions in the soil and the hydraulic properties of the soil. Hydraulic properties of soil have been described by many different relationships (for example Brooks-Corey, Haverkamp, van Genuchten). The UNSAT-H model recommends runs with initial heads at wilting point pressures (15,000 cm suction head), and at a point in between wilting point and field capacity (5,000 cm suction head). For conservatism in modeling the arid-region cover, no vegetation was modeled in the analyses.

The following table shows the site-specific physical soil parameters that were entered into the UNSAT-H model for the monolithic ET cover soil. Site specific physical soil parameters from Andraski, et. al. 2003 (reference attached).

| K (cm/hr) | $\alpha$ (1/cm) | N (dimensionless) | $\theta_r$ | $\theta_s$ |
|---|---|---|---|---|
| 1.79 | 0.026 | 1.42 | 0.026 | 0.29 |

K = Saturated hydraulic conductivity

$\alpha$ = Coefficient of van Genuchten function

N = Coefficient of van Genuchten function

$\theta_r$ = Residual water content (volumetric)

$\theta_s$ = Saturated water content (volumetric)

**Modeling Approach**

The proposed monolithic arid-region cover (ET Cover) water flux capabilities were modeled for a performance period of 30 years. All model runs were for three feet (36 inches) of ET Cover and unvegetated conditions. The suction head in near-surface soils was determined to be very high, even greater than wilting point, which would severely limit plant growth and associated transpiration.

UNSAT-H does not have a method to model the performance of the RCRA cover proposed in the 1996 design. UNSAT-H does not allow the modeling of geomembranes or barrier layers; therefore, UNSAT-H was only run for a monolithic three feet thick ET cover and the results compared to HELP output.

**Modeling Results**

The UNSAT-H model of the ET Cover showed that the 36-inch thick monolithic ET Cover was sufficient to limit drainage (percolation) through the bottom of the cover and into the waste to very small amounts. The modeling was conservative since no vegetation was considered. The following table shows the cumulative amount of percolation through the cover at the end of each year modeled.

| Modeled Year | Precipitation Type | Predicted Percolation (mm/year) |
|---|---|---|
| 1 | Normal | 0.456 |
| 2 | Normal | 0.304 |
| 3 | Wet | **1.973** |
| 4 | Wet | **2.029** |
| 5 | Normal | 0.319 |
| 6 | Very Dry | 0.018 |
| 7 | Wet | **1.466** |
| 8 | Wet | **2.028** |
| 9 | Normal | 0.319 |
| 10 | Normal | 0.302 |
| 11 | Normal | 0.301 |
| 12 | Normal | 0.301 |
| 13 | Wet | **1.973** |
| 14 | Wet | **2.029** |
| 15 | Normal | 0.319 |
| 16 | Very Dry | 0.018 |
| 17 | Wet | **1.466** |

| Modeled Year | Precipitation Type | Predicted Percolation (mm/year) |
|---|---|---|
| 18 | Wet | **2.028** |
| 19 | Normal | 0.319 |
| 20 | Normal | 0.302 |
| 21 | Normal | 0.301 |
| 22 | Normal | 0.301 |
| 23 | Wet | **1.973** |
| 24 | Wet | **2.029** |
| 25 | Normal | 0.319 |
| 26 | Very Dry | 0.018 |
| 27 | Wet | **1.466** |
| 28 | Wet | **2.028** |
| 29 | Normal | 0.319 |
| 30 | Normal | 0.302 |

**Average Percolation = 0.911 mm/year**

The data in the table show that the maximum percolation through a three feet (36-inch) thick cover (**bold** values) occurs during wet years, and when wet years occur consecutively, the predicted percolation approaches 2 mm/year. The percolation prediction also shows that evaporative effects dominate during normal and dry years. When the 30-years of predicted annual percolation amounts are considered together, the average annual percolation through the 36-inch thick, monolithic ET cover is under 1.0 mm/year.

## SUMMARY OF MODELING RESULTS

The two models run for the Beatty ET Cover design provided similar results with regard to the capacity of the cover design to limit percolation from the cover into waste

Both models predict that a three feet (36 inch) thick monolithic cover, without vegetation is sufficient to prevent significant percolation of fluids through the arid region cover and into waste at the Beatty facility, and indicate that nearly all of the precipitation is lost to evapotranspiration rather than infiltration into the cover and percolation into waste. The results likely are conservative, because no vegetation was included in the model runs, so the evapotranspiration was limited to evaporation only. Also, a HELP model limitation prevented considering natural drying of cover soil to levels lower than the wilting point.

Both models predict that a three-feet (36-inch) thick monolithic cover, without vegetation is sufficient to prevent significant percolation of fluids through the arid region ET cover and into waste at the USEN Beatty facility. The soil cover should be made up of site soils that are as silty as possible, but also contain a significant gravel fraction for erosion control and stability. Finer-grained soils (i.e., soils with minus-200 fines making up more than 10 percent of the material) will provide a greater water holding capacity, and should be used as possible. Additional fine-grained material could be added to improve the moisture holding capacity.

An alternate cover details check is a simple consideration of the ability of the soil to retain the moisture that could be expected in a single design event. This would be those times when PET is reduced to essentially zero during a precipitation event. The 24-hour, 25-year storm for the Beatty facility is about 2 inches. Using the design estimate from the EPA Draft Guidance, the necessary minimum thickness of a cover can be estimated as:

Thickness of cover = (Rainfall event) ÷ (Moisture Holding Capacity)

Where the moisture holding capacity is calculated from the difference between the field capacity and wilting point.

Rearranging the equation, and considering a cover thickness of 36 inches and a 2-inch design rainfall, the moisture holding capacity (i.e., the difference between the field capacity and wilting point) to hold the design rainfall should be at least:

Moisture Holding Capacity (needed) = rainfall event / thickness of cover

= 2" / 36"

= 0.0556 or 5.56% (by volume)

= 2.00 inches needed in the 36" cover

Soils at the US Ecology Beatty facility are anticipated to have volumetric moisture contents at field capacity of 22% and at wilting point of 11%[2]. The difference between field capacity and wilting point (i.e., moisture holding capacity) is 0.11 or 11% (by volume). Thus, a 36-inch thick soil cover made from Beatty facility soil, if at wilting point when rainfall begins, has a moisture holding capacity of about 11% of its 36 inch thickness, or about 4.0 inches. This moisture holding capacity is sufficient to retain the design storm. Since the moisture content of facility soil is often below the wilting point, additional moisture holding capacity would be available during much of a typical year.

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2 Schroeder, P.R., et al., 1994. "The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3", EPA/600/R-94/168B, USEPA Risk Reduction Engineering Laboratory, Cincinnati, OH.

# HELP MODEL

## INPUTS & USER GUIDANCE

United States
Environmental Protection
Agency

Office of
Solid Waste &
Emergency Response

EPA/530-SW-84-009
June 1984

Solid Waste

EPA

# The Hydrologic Evaluation of Landfill Performance (HELP) Model

CALCULATION
REFERENCE

## Volume I. User's Guide for Version I

## Technical Resource Document for Public Comment

CALCULATION REFERENCE

# THE HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL

## Volume I. User's Guide for Version 1

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# THE HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL

## *USER'S GUIDE FOR VERSION 3*

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## ABSTRACT

The Hydrologic Evaluation of Landfill Performance (HELP) computer program is a quasi-two-dimensional hydrologic model of water movement across, into, through and out of landfills. The model accepts weather, soil and design data and uses solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane or composite liners. Landfill systems including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners may be modeled. The program was developed to conduct water balance analysis of landfills, cover systems, and solid waste disposal and containment facilities. As such, the model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may be expected to result from the operation of a wide variety of landfill designs. The primary purpose of the model is to assist in the comparison of design alternatives as judged by their water balances. The model, applicable to open, partially closed, and fully closed sites, is a tool for both designers and permit writers.

This report explains how to use Version 3 of the HELP model. Section 1 provides background and overview of the model, and lists software and hardware requirements. Section 2 describes basic landfill design and liquids management concepts. Section 3 presents definitions, options and limitations for input parameters as well as detailed guidance for selecting their input values. Section 4 provides detailed instructions on how to enter input, run the simulation and view or print output. Appendix A provides assistance for estimating material properties for moisture retention and saturated hydraulic conductivity.

The user interface or input facility is written in the Quick Basic environment of Microsoft Basic Professional Development System Version 7.1 and runs under DOS 2.1 or higher on IBM-PC and compatible computers. The HELP program uses an interactive and a user-friendly input facility designed to provide the user with as much assistance as possible in preparing data to run the model. The program provides weather and soil data file management, default data sources, interactive layer editing, on-line help, and data verification and accepts weather data from the most commonly used sources with several different formats.

HELP Version 3 represents a significant advancement over the input techniques of Version 2. Users of the HELP model should find HELP Version 3 easy to use and should be able to use it for many purposes, such as preparing and editing landfill profiles and weather data. Version 3 facilitates use of metric units, international applications, and designs with geosynthetic materials.

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This report should be cited as follows:

Schroeder, P. R., Aziz, N. M., Lloyd, C. M. and Zappi, P. A. (1994). "The Hydrologic Evaluation of Landfill Performance (HELP) Model: User's Guide for Version 3," EPA/600/R-94/168a, September 1994, U.S. Environmental Protection Agency Office of Research and Development, Washington, DC.

This report was submitted in partial fulfillment of Interagency Agreement Number DW21931425 between the U.S. Environmental Protection Agency and the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. This report covers a period from November 1988 to June 1994 and work was completed as of June 1994.

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# MODEL INFORMATION

The following text is from the PDF User's Manual for HELP, and outlines the program function and requirements.

The Hydrologic Evaluation of Landfill Performance (HELP) computer program is a quasi-two-dimensional hydrologic model of water movement across, into, through and out of landfills. The model accepts weather, soil and design data and uses solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane or composite liners. Landfill systems including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners may be modeled. The program was developed to conduct water balance analysis of landfills, cover systems, and solid waste disposal and containment facilities. As such, the model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may be expected to result from the operation of a wide variety of landfill designs. The primary purpose of the model is to assist in the comparison of design alternatives as judged by their water balances. The model, applicable to open, partially closed, and fully closed sites, is a tool for both designers and permit writers.

## 3.1 OVERVIEW

The HELP model requires general climate data for computing potential evapotranspiration; daily climatologic data; soil characteristics; and design specifications to perform the analysis. The required general climate data include growing season, average annual wind speed, average quarterly relative humidities, normal mean monthly temperatures, maximum leaf area index, evaporative zone depth and latitude. Default values for these parameters were compiled or developed from the "Climates of the States" (Ruffner, 1985) and "Climatic Atlas of the United States" (National Oceanic and Atmospheric Administration, 1974) for 183 U.S. cities. Daily climatologic (weather) data requirements include precipitation, mean temperature and total global solar radiation. Daily rainfall data may be input by the user, generated stochastically, or taken from the model's historical data base. The model contains parameters for generating synthetic precipitation for 139 U.S. cities. The historical data base contains five years of daily precipitation data for 102 U.S. cities. Daily temperature and solar radiation data are generated stochastically or may be input by the user.

Necessary soil data include porosity, field capacity, wilting point, saturated hydraulic conductivity, initial moisture storage, and Soil Conservation Service (SCS) runoff curve number for antecedent moisture condition II. The model contains default soil characteristics for 42 material types for use when measurements or site-specific estimates are not available. The porosity, field capacity, wilting point and saturated hydraulic conductivity are used to estimate the soil water evaporation coefficient and Brooks-Corey soil moisture retention parameters. Design specifications include such items as the slope and maximum drainage distance for lateral drainage layers; layer thicknesses; layer

description; area; leachate recirculation procedure; subsurface inflows; surface characteristics; and geomembrane characteristics.

## 3.2 SYNTHETIC WEATHER GENERATION

The HELP program incorporates a routine for generating daily values of precipitation, mean temperature, and solar radiation. This routine was developed by the USDA Agricultural Research Service (Richardson and Wright, 1984) based on a procedure described by Richardson (1981). The HELP user has the option of generating synthetic daily precipitation data rather than using default or user-specified historical data. Similarly, the HELP user has the option of generating synthetic daily mean temperature and solar radiation data rather than using user-specified historical data. The generating routine is designed to preserve the dependence in time, the correlation between variables and the seasonal characteristics in actual weather data at the specified location.
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correlation coefficients were found to be negligible. The elements of the A and B matrices are therefore treated as constants.

## 3.3 MOISTURE RETENTION AND HYDRAULIC CONDUCTIVITY PARAMETERS

The HELP program requires values for the total porosity, field capacity, wilting point, and saturated hydraulic conductivity of each layer that is not a liner. Saturated hydraulic conductivity is required for all liners. Values for these parameters can be specified by the user or selected from a list of default values provided in the HELP program. The values are used to compute moisture storage, unsaturated vertical drainage, head on liners and soil water evaporation.

### 3.3.1 Moisture Retention Parameters

Relative moisture retention or storage used in the HELP model differs from the water contents typically used by engineers. The soil water storage or content used in the HELP model is on a per volume basis ($\theta$), volume of water ($V_w$) per total (bulk--soil, water and air) soil volume ($V_t = V_s + V_w + V_a$), which is characteristic of practice in agronomy and soil physics. Engineers more commonly express moisture content on a per mass basis ($w$), mass of water ($M_w$) per mass of soil ($M_s$). The two can be related to each other by knowing the dry bulk density ($\rho_{db}$) and water density ($\rho_w$), the dry bulk specific gravity ($\Gamma_{db}$) of the soil (ratio of dry bulk density to water density), ($\theta = w\,\Gamma_{db}$), or the wet bulk density ($\rho_{wb}$), wet bulk specific gravity ($\Gamma_{wb}$) of the soil (ratio of wet bulk density to water density), ($\theta = [w\,\Gamma_{wb}] / [1 + w]$).

Total porosity is an effective value, defined as the volumetric water content (volume of water per total volume) when the pores contributing to change in moisture storage are at saturation. Total porosity can be used to describe the volume of active pore space present in soil or waste layers. Field capacity is the volumetric water content at a soil water suction of 0.33 bars or remaining after a prolonged period of gravity drainage without additional water supply. Wilting point is the volumetric water content at a suction of 15 bars or the lowest volumetric water content that can be achieved by plant transpiration (See Section 4.11). These moisture retention parameters are used to define moisture storage and relative unsaturated hydraulic conductivity.

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The HELP program requires that the wilting point be greater than zero but less than the field capacity. The field capacity must be greater than the wilting point and less than the porosity. Total porosity must be greater than the field capacity but less than 1

The HELP user can specify the initial volumetric water contents of all non-liner layers. Soil liners are assumed to remain saturated at all times. If initial water contents are not specified, the program assumes values near the steady-state values (allowing no long-term change in moisture storage) and runs a year of simulation to initialize the moisture contents closer to steady state. The soil water contents at the end of this year are substituted as the initial values for the simulation period. The program then runs the complete simulation, starting again from the beginning of the first year of data. The results of the volumetric water content initialization period are not reported in the output.

### 3.3.2 Unsaturated Hydraulic Conductivity

Darcy's constant of proportionality governing flow through porous media is known quantitatively as hydraulic conductivity or coefficient of permeability and qualitatively as permeability. Hydraulic conductivity is a function of media properties, such as particle size, void ratio, composition, fabric, degree of saturation, and the kinematic viscosity of the fluid moving through the media. The HELP program uses the saturated and unsaturated hydraulic conductivities of soil and waste layers to compute vertical drainage, lateral drainage and soil liner percolation. The vapor diffusivity for geomembranes is specified as a saturated hydraulic conductivity to compute leakage through geomembranes by vapor diffusion.

The following text is from the PDF User's Manual for UNSAT-H, and outlines the program function and requirements.

### 2.2 Code Summary

The UNSAT-H code is designed to simulate water and heat flow processes in one dimension (typically vertical). UNSAT-H can simulate the isothermal flow of liquid water and water vapor, the thermal flow of water vapor, the flow of heat, the surface energy balance, soil-water extraction by plants, and deep drainage. Information about where to find the code, updates, and lessons learned can be found at http://hydrology.pnl.gov/.

### 2.2.1 Processes

**Infiltration**. The UNSAT-H model simulates infiltration in a two-step process. First, infiltration is set equal to the precipitation rate during each time step. Second, if the surface soil saturates, the solution of that time step is repeated using a Dirichlet boundary condition (with the surface node saturated). The resulting flux from the surface into the profile is the infiltration rate.

**Runoff**. The UNSAT-H model does not simulate runoff explicitly. Instead, it equates runoff to the precipitation rate that is in excess of the infiltration rate. There is no provision for run-on or surface detention.

**Soil Water and Heat Flow**. The UNSAT-H model simulates liquid water flow using the Richards equation, water vapor diffusion using Fick's law, and sensible heat flow using the Fourier equation. Convective airflow is not considered. Options for describing soil water retention include linked polynomials, the Haverkamp function, the Brooks and Corey function, the van Genuchten function, and several special functions that account for water retention of very dry soils. In addition, the van Genuchten

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function can also be treated hysteretically. Options for describing hydraulic conductivity include linked polynomials, the Haverkamp model, the Mualem model, and the Burdine model.

**Drainage and Lower Boundary Heat Flow**. The UNSAT-H model has several options for the boundary conditions. For water flow, the user can specify Dirichlet or Neumann conditions, or a unit hydraulic gradient condition. For heat flow, the user can specify Dirichlet or Neumann conditions, or a temperature gradient.

**Evaporation**. The UNSAT-H model simulates evaporation in two ways. In the isothermal mode, UNSAT-H uses the PET concept. The user supplies either daily values of PET or daily weather data, with which the code calculates daily PET values using the Penman equation. During each time step, the code attempts to apply the potential evaporation rate. If the soil surface dries to or above a user-defined matric potential limit, the time step is re-solved using a Dirichlet condition at the surface. In this situation, the surface potential is held constant at the matric potential limit and evaporation is set equal to the flux from below.

In the thermal mode, UNSAT-H calculates evaporation as a function of the vapor density difference between the soil and the reference height (the height at which air temperature and wind speed are measured) and the resistance to vapor transport. The resistance to vapor transport is a function of several factors, including air temperature, wind speed, and atmospheric stability.

2.3

**Transpiration**. The UNSAT-H model simulates the effects of plant transpiration using the PET concept. There is no provision to simulate both water and heat flow in a plant canopy. Plant information is supplied to the code to partition the PET into potential evaporation and potential transpiration. The potential transpiration is applied to the root zone using the root distribution to apportion it among the computational nodes that have roots. The withdrawal of water from a particular node is dependent on the suction head of the node. The user provides suction head values that define how the potential transpiration rate applied to a particular node is reduced. Below the minimum value, sometimes known as the wilting point, transpiration is unable to remove any water. When all nodes with roots reach this level of suction head, transpiration is reduced to zero.

### 2.2.2 Numerical Implementation

The mathematical equations that describe the state and dynamics of the modeled system are written in an implicit finite-difference form. The user must specify an averaging scheme for internodal hydraulic and vapor conductivities; choices include arithmetic (and arithmetic-weighted), geometric, and harmonic. Heat internodal conductances are calculated as arithmetic means. The resulting equations are solved using an iteration technique (either standard or modified Picard) with the Thomas algorithm. The solution strategy for each iteration is to solve the water flow equations, then solve the heat flow equations. After the second and subsequent iterations, the convergence criteria are checked.

The user controls the spatial detail of the solution by specifying the node spacing in the input file. The user also controls the temporal detail by specifying the minimum and maximum time step size. The user can control the solution accuracy by specifying acceptance criteria for the solution to a particular time step. The available criteria include change in water content, mass balance error, absolute change in head, relative change in head, and heat balance error.

### 2.2.3 Input Requirements

The following list is a subset of the information needed to run UNSAT-H (see Appendix A for a complete list). Not all of these inputs are needed for every simulation. Instructions for formulating a problem to be solved and running the code are given in Section 6.0. The format for entering the data is listed in Appendix A.

**Simulation Information**. This information includes simulation options. Simulation options include number of nodes (up to 250 nodes in the compiled version), node depths and associated material types (up to 10 materials in the compiled version), boundary condition choices, output frequencies, and maximum and minimum time step size.

**Constitutive Relationships**. This information includes the parameters needed to describe the hydraulic, hysteretic, and thermal properties of each material, depending on the options chosen.

**Initial Conditions**. This information includes the initial suction head profiles and soil temperature profiles (if simulating heat flow).

2.4

**Plant Parameters**. This information includes details about the seasonal variation of leaf area index and maximum rooting depth, root density variations with depth, and suction head limits that impact the withdrawal efficiency of plants. UNSAT-H also has a specific function for partitioning PET into evaporation and transpiration for *Bromus tectorum* (cheatgrass).

**Boundary Conditions**. This information includes daily PET values; daily weather conditions (e.g., temperature, wind speed, solar radiation, precipitation); and lower boundary condition choices (e.g., water fluxes, temperature gradient).

### 2.2.4 User Interface

The UNSAT-H code comprises three programs. DATAINH is used to read the text input file, process the information, and create a binary input file. UNSATH is the main program; it reads the binary input file, performs the simulation, and creates a binary output file. The user runs DATAOUT to read the binary output file. The output file contains daily (and less-than-daily if selected by the user) summaries of water content, suction head, water flow, temperature, heat flow, and plant water use as a function of depth. The file also contains cumulative totals of the water and heat balance components (e.g., storage, precipitation, evaporation, transpiration, drainage, net radiation, and the sensible, latent, and soil heat fluxes). The user can then view the output on screen or write the output to a text file for manipulation with a spreadsheet or graphics program.

### 2.2.5 System Requirements (not important, text removed)

### 2.2.6 General Limitations

Features of UNSAT-H that may limit its application include one dimensionality, the use of empirical plant transpiration algorithms, and the lack of algorithms for snowmelt, freezing soil, and the temperature dependence of soil properties. Use of UNSAT-H is considered valid where flow is assumed to be strictly vertical, such as in fairly level terrain or the central portion of a landfill surface cover. For steeper terrain or the edge of an elevated surface cover with sideslopes, lateral flow could be significant and thus not be amenable to analysis with a one-dimensional model. Although the one-dimensional nature of UNSAT-H

2.5

constitutes a well-defined limitation on the types of problems that can be solved, the other limitations listed above do not. The severity of each of these limitations with respect to the intended uses of the code is being evaluated by validation testing, which is the process by which model predictions are objectively compared to field or laboratory data. Testing by Fayer et al. (1992), Fayer and Gee (1997), and Khire et al. (1997) has begun to demonstrate the reliability of UNSAT-H predictions.

## 2.3 Example Applications

UNSAT-H can be used to solve a variety of water and heat flow problems in unsaturated soils and sediments. With proper accounting for site-specific features, recharge can be estimated as a function of variations in soil type or layering, plant cover and type, and climate. The applications described below represent a small sample of those available. These examples are intended to give the reader a sense of what has been accomplished.

The first major use of UNSAT-H was for the cover analyses used to support the Hanford Defense Waste Environmental Impact Statement (DOE 1987). The simulations illustrated the impact of soil type and layer thickness, the presence of plants, and weather variations on drainage through the cover. For all of these simulations, the precipitation rate was increased to twice normal (30.1 cm/yr) to evaluate what was then considered a worst-case situation. The results showed that coarse-textured soils such as sands were ineffective at preventing drainage under these conditions whereas fine-textured soils were effective. The results also showed that a coarse-textured layer was needed beneath the fine-textured layer to create a capillary break. If this "break" was too deep (e.g., 3.0 m) or not present at all, the fine-textured soil could not prevent significant drainage from occurring.

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## TABLE 4. DEFAULT SOIL, WASTE, AND GEOSYNTHETIC CHARACTERISTICS

| Classification | | | Total Porosity | Field Capacity | Wilting Point | Saturated Hydraulic Conductivity |
|---|---|---|---|---|---|---|
| HELP | USDA | USCS | vol/vol | vol/vol | vol/vol | cm/sec |
| 1 | CoS | SP | 0.417 | 0.045 | 0.018 | $1.0 \times 10^{-2}$ |
| 2 | S | SW | 0.437 | 0.062 | 0.024 | $5.8 \times 10^{-3}$ |
| 3 | FS | SW | 0.457 | 0.083 | 0.033 | $3.1 \times 10^{-3}$ |
| 4 | LS | SM | 0.437 | 0.105 | 0.047 | $1.7 \times 10^{-3}$ |
| 5 | LFS | SM | 0.457 | 0.131 | 0.058 | $1.0 \times 10^{-3}$ |
| 6 | SL | SM | 0.453 | 0.190 | 0.085 | $7.2 \times 10^{-4}$ |
| 7 | FSL | SM | 0.473 | 0.222 | 0.104 | $5.2 \times 10^{-4}$ |
| 8 | L | ML | 0.463 | 0.232 | 0.116 | $3.7 \times 10^{-4}$ |
| 9 | SiL | ML | 0.501 | 0.284 | 0.135 | $1.9 \times 10^{-4}$ |
| 10 | SCL | SC | 0.398 | 0.244 | 0.136 | $1.2 \times 10^{-4}$ |
| 11 | CL | CL | 0.464 | 0.310 | 0.187 | $6.4 \times 10^{-5}$ |
| 12 | SiCL | CL | 0.471 | 0.342 | 0.210 | $4.2 \times 10^{-5}$ |
| 13 | SC | SC | 0.430 | 0.321 | 0.221 | $3.3 \times 10^{-5}$ |
| 14 | SiC | CH | 0.479 | 0.371 | 0.251 | $2.5 \times 10^{-5}$ |
| 15 | C | CH | 0.475 | 0.378 | 0.265 | $1.7 \times 10^{-5}$ |
| 16 | Barrier Soil | | 0.427 | 0.418 | 0.367 | $1.0 \times 10^{-7}$ |
| 17 | Bentonite Mat (0.6 cm) | | 0.750 | 0.747 | 0.400 | $3.0 \times 10^{-9}$ |
| 18 | Municipal Waste (900 lb/yd$^3$ or 312 kg/m$^3$) | | 0.671 | 0.292 | 0.077 | $1.0 \times 10^{-3}$ |
| 19 | Municipal Waste (channeling and dead zones) | | 0.168 | 0.073 | 0.019 | $1.0 \times 10^{-3}$ |
| 20 | Drainage Net (0.5 cm) | | 0.850 | 0.010 | 0.005 | $1.0 \times 10^{+1}$ |
| 21 | Gravel | | 0.397 | 0.032 | 0.013 | $3.0 \times 10^{-1}$ |
| 22 | L* | ML | 0.419 | 0.307 | 0.180 | $1.9 \times 10^{-5}$ |
| 23 | SiL* | ML | 0.461 | 0.360 | 0.203 | $9.0 \times 10^{-6}$ |
| 24 | SCL* | SC | 0.365 | 0.305 | 0.202 | $2.7 \times 10^{-6}$ |
| 25 | CL* | CL | 0.437 | 0.373 | 0.266 | $3.6 \times 10^{-6}$ |
| 26 | SiCL* | CL | 0.445 | 0.393 | 0.277 | $1.9 \times 10^{-6}$ |
| 27 | SC* | SC | 0.400 | 0.366 | 0.288 | $7.8 \times 10^{-7}$ |
| 28 | SiC* | CH | 0.452 | 0.411 | 0.311 | $1.2 \times 10^{-6}$ |
| 29 | C* | CH | 0.451 | 0.419 | 0.332 | $6.8 \times 10^{-7}$ |
| 30 | Coal-Burning Electric Plant Fly Ash* | | 0.541 | 0.187 | 0.047 | $5.0 \times 10^{-5}$ |
| 31 | Coal-Burning Electric Plant Bottom Ash* | | 0.578 | 0.076 | 0.025 | $4.1 \times 10^{-3}$ |
| 32 | Municipal Incinerator Fly Ash* | | 0.450 | 0.116 | 0.049 | $1.0 \times 10^{-2}$ |
| 33 | Fine Copper Slag* | | 0.375 | 0.055 | 0.020 | $4.1 \times 10^{-2}$ |
| 34 | Drainage Net (0.6 cm) | | 0.850 | 0.010 | 0.005 | $3.3 \times 10^{+1}$ |

* Moderately Compacted

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**TABLE 4 (continued). DEFAULT SOIL, WASTE, AND GEOSYNTHETIC CHARACTERISTICS**

| Classification | | Total Porosity | Field Capacity | Wilting Point | Saturated Hydraulic Conductivity |
|---|---|---|---|---|---|
| HELP | Geomembrane Material | vol/vol | vol/vol | vol/vol | cm/sec |
| 35 | High Density Polyethylene (HDPE) | | | | $2.0 \times 10^{-13}$ |
| 36 | Low Density Polyethylene (LDPE) | | | | $4.0 \times 10^{-13}$ |
| 37 | Polyvinyl Chloride (PVC) | | | | $2.0 \times 10^{-11}$ |
| 38 | Butyl Rubber | | | | $1.0 \times 10^{-12}$ |
| 39 | Chlorinated Polyethylene (CPE) | | | | $4.0 \times 10^{-12}$ |
| 40 | Hypalon or Chlorosulfonated Polyethylene (CSPE) | | | | $3.0 \times 10^{-12}$ |
| 41 | Ethylene-Propylene Diene Monomer (EPDM) | | | | $2.0 \times 10^{-12}$ |
| 42 | Neoprene | | | | $3.0 \times 10^{-12}$ |

(concluded)

user-defined soil option accepts non-default soil characteristics for layers assigned soil type numbers greater than 42. This is especially convenient for specifying characteristics of waste layers. User-specified soil characteristics can be assigned any soil type number greater than 42.

When a default soil type is used to describe the top soil layer, the program adjusts the saturated hydraulic conductivities of the soils in the top half of the evaporative zone for the effects of root channels. The saturated hydraulic conductivity value is multiplied by an empirical factor that is computed as a function of the user-specified maximum leaf area index. Example values of this factor are 1.0 for a maximum LAI of 0 (bare ground), 1.8 for a maximum LAI of 1 (poor stand of grass), 3.0 for a maximum LAI of 2 (fair stand of grass), 4.2 for a maximum LAI of 3.3 (good stand of grass) and 5.0 for a maximum LAI of 5 (excellent stand of grass).

The manual option requires values for porosity, field capacity, wilting point, and saturated hydraulic conductivity. These and related soil properties are defined below.

*Soil Water Storage (Volumetric Content)*: the ratio of the volume of water in a soil to the total volume occupied by the soil, water and voids.

*Total Porosity*: the soil water storage/volumetric content at saturation (fraction of total volume).

The ***Alt D*** combination causes the program to delete a layer from the list of layers. For example, to delete the layer on line 3, the user should move the cursor to line 3, hold the ***Alt*** key down and press ***D***. The program will delete all information on line 3 and will shift the layers on lines 4 to 20 upward one line (i.e., layer on line 4 moves to line 3, layer on line 5 moves to line 4, etc.), and line 20 becomes a blank line. The user is cautioned that the deleted layer cannot be recovered without quitting and losing all changes (***F9*** or ***Esc***).

The copy command allows the user to place a layer that is identical to another layer on another line. For example, to copy the layer on line 7 to line 2, move the cursor to line 7 and press the ***Alt C*** combination, then move the cursor to line 2 and press the ***Alt A*** combination. This action will cause the program to insert a layer with values the same as those formerly found at line 7 above the layer formerly found at line 2. The layers formerly at and below line 2 will be moved downward one line. (The user may obtain the same result after the ***Alt C*** combination by moving to line 1 and pressing the combination ***Alt B***).

The move command allows the user to move a layer from one row on the screens of layer data to another row. For example, to move the layer on line 3 above the layer on line 6, move the cursor to line 3, press the ***Alt M*** combination, and move the cursor to line 6 and press the ***Alt A*** combination. This action will cause the layer on line 3 to be deleted and be placed directly above the layer on line 6. This will cause line 4 to move up one line to line 3, line 5 to move to line 4 and line 3 to move to line 5; the other lines will be unchanged. (The user may obtain the same result after the ***Alt M*** combination by moving to line 5 and pressing the combination ***Alt B***).

The ***Esc*** key can be used to quit the move and copy functions (after pressing ***Alt M*** or ***Alt C*** and before pressing ***Alt A*** or ***Alt B***). By editing the data as discussed above, the user may arrange the order of the layers and run the model to test several possible configurations.

If the user has 20 lines completely filled with layers and then decides to add or copy a layer, the layer that is already in line 20 will disappear and cannot be recovered. Therefore, care must be taken not to add layers that will cause the loss of the layers at the bottom of the spreadsheet.

When all the layers of the profile are entered, press ***Page Down*** from the third layer spreadsheet to proceed with the rest of the soil and design data entry. Pressing ***Page Up*** from the first layer spreadsheet passes control to the "Landfill General Information" screen.

### 4.6.4 Runoff Curve Number

The "Runoff Curve Number Information" screen may be reached from the third layer spreadsheet by pressing ***Page Down***, or from the "Landfill General Information" Screen

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by pressing ***Page Up***. A schematic of the options associated with the "Runoff Curve Number Information" screen is shown in Figure 16. This screen is composed of three options that can be used to specify the runoff curve number. The first option is to use an ***user-specified curve number*** that the HELP model will use without modification. The second option is to request the HELP model to ***modify a user-specified curve number*** according to the surface slope and surface slope length. In the third option the user requests a ***HELP model computed runoff curve number*** based on surface slope, slope length, soil texture of the top layer in the landfill profile, and vegetation. To select one of these three options, the user should move the cursor to the desired option and press ***Enter***. This action will cause the program to transfer control down to the box for the option selected. For each option, the user must input all required information. Although the user can move from one box to the other (use ***Tab*** and ***Shift Tab*** keys), care should be taken to insure that the desired method is the one that will be used by HELP. The HELP model uses that option in which data was last entered; this option is marked by a small arrow in front of the option.

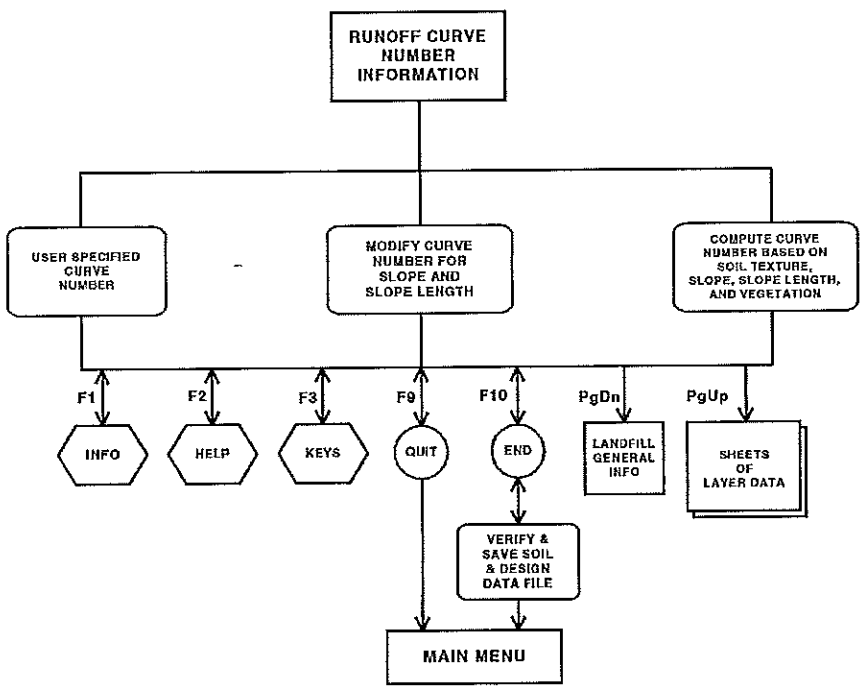


Figure 16. Schematic of "Runoff Curve Number Information" Screen Options

The user should refer to the HELP model documentation for Version 3 for the techniques used in the computation of the curve number based on slope and slope length. The value of the slope must be input in percent, and slope length must be input in the units indicated. If the top layer in the landfill is obtained from the default soil/material

textures, the soil texture number for that layer will be displayed in the appropriate cell on the screen. The user can solicit help on the ***vegetation cover*** by pressing the ***F2*** key. The only valid entries for the vegetation are 1 through 5, according to the following:

1. Bare ground
2. Poor stand of grass
3. Fair stand of grass
4. Good stand of grass
5. Excellent stand of grass

If the user selects the option that requires the HELP model to compute the curve number, the program first calculates the SCS runoff curve number for landfills with mild surface slopes (2 to 5 percent) based on the vegetation type and the soil texture on the top layer if one of the default soil/material textures is selected (soil texture types 1 through 18, 20 and 22 through 29) in the same manner as Version 2 (Schroeder et al., 1988b). HELP Version 3 then adjusts the SCS runoff curve number based on the surface slope and the length of the slope.

### 4.6.5 Verifying and Saving Soil and Design Data

Pressing ***F10*** anywhere in the soil and design option transfers control to the "Verification and Saving" screen. This screen provides the user with several options: verify landfill general design data, verify soil layer/geomembrane properties, verify layer arrangement, review/save user-defined soil textures, and save soil and design data. The user can select any of these options by moving the cursor to the option and pressing ***Enter***. Figure 17 shows the verify and save soil and design data options.

The user can verify the data before attempting to save the data by exercising the first three options on the "Verification and Saving" screen. These options are available mainly for the convenience of the new user since experienced users will be familiar with data requirements and the data will always be verified before saving. To check the data entered on the general landfill and runoff information screens, the user should select the first option, "Verify Landfill General Information Design Data." If there are no violations or warnings, the program will write "OK" to the right of the option; otherwise the program will list the problems and then write "BAD" to the right of the option.

The user can check the layer descriptions (the values on a row of the third screens

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# TECHNICAL NOTE ON USING HELP MODEL (VER. 3.07)

## I: INPUT STEPS GUIDE

The purpose of this document is to help the users of HELP Model through the input procedures, and interpretation of the output results . All information contained herein are from HELP "User's Guide" and "Engineering Documentation" for version 3. Included is a step-by-step example, which is a part of the GRI report # 19, page 34- 37 (leachate collection system).

### INSTALLATION NOTE

You can download the latest version of HELP Model 3.07 from the following web-site address: http://www.wes.army.mil/el/elmodels/index.html. You will save the downloaded file (zhelp3w.exe or zhelp3p.exe) onto a temporary subdirectory, after you execute the file it will be self extracted into some files needed for the setup. From the files that have been self extracted, you run the setup file follow the steps that will show on the screen.

Whether you download HELP Model program from the internet or install it from a floppy, the files should be installed (or copied) in a subdirectory directly under the root, i.e. C:\ or D:\. The executable file is called "Help3.bat".

### INPUT STEPS

### 1. Weather Data

From the main menu you choose option 1 "**Enter/ Edit Weather Data**", this will prompt you to another screen with the following four options:

Evapotranspiration; Precipitation; Temperature; and Solar radiation

For each you hit "PgDn" to start new file, or "F4" to choose from a list of saved files. Below is a description of the input data required for each of the four weather selections.

#### 1.1 Evapotranspiration

Evapotranspiration is the first weather option the program is going to prompt you for if you are starting a new project. However, if you're editing an existing project you'll be prompted to the screen corresponding to your selection of either of the four weather data.

a) Units: with up or down arrows you select either 1 Customary (English), or 2 Metric. In the current example we selected **Metric.**

b) City: If you're going to select **default** option, you hit "F5" to select a "State" first and then a "City" that is closest to the landfill location, then all the corresponding required data will be filled except for the following two data:

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"**Evaporative Zone Depth**" in centimeters which is at least equal to the expected average depth of root penetration. To the right of the screen a table with three columns will appear that indicates the input value, you choose a value depending on the condition of vegetation expected.

| Bare | Fair | Excellent |
|---|---|---|
| 25 | 55 | 101 |

In our example we'll select **Texas, Austin, 25 cm** (for no vegetation)

**"Leaf Area Index"** (LAI), LAI is a dimensionless ratio of the leaf area that is actively transpiring vegetation to the nominal surface area of the land on which the vegetation is growing. Below is a table that lists the LAI values for different conditions of vegetation.

INPUT

| Bare | Poor Stand of Grass | Fair Stand of Grass | Good Stand of Grass | Excellent Stand of Grass |
|---|---|---|---|---|
| 0.0 | 1.0 | 2.0 | 3.5 | 5.0 |

In our example we'll choose **0.0** for no vegetation condition.

If you're going to select the **manual** option, in addition to the above two parameters you'll be asked to input the following parameters: location (city and state), dates of starting and ending the growing season, normal average annual wind speed, and Normal average quarterly relative humidity. The last three data are available from "Climatic Atlas of the United States" (NOAA, 1974)

**1.2** Precipitation, Temperature, Solar Radiation

The input options for the above three weather data are: **Synthetic, Create/Edit, NOAA tape, Climatedata, ASCII file, HELP Version 2, and Canadian Climatological**. Only Precipitation has an extra option which is **Default**. Below is a description of the input options:

**Default** (Precipitation only): The user may select any of the stored 102 cities for which the historical precipitation data are recorded during 5 years from 1974 to 1978. In the current example this option is chosen and the city of **San Antonio, Texas** is selected.

**Synthetic:** the program will generate from 1 to 100 years of daily Precipitation, Temperature, or Solar Radiation data stochastically for the selected location using a synthetic weather generator. The user may enter normal mean monthly precipitation values for the location to improve the statistical characteristics of the resulted daily values. For that option user needs to specify a location from 139 stored cities, number of years of data to be generated, and normal mean monthly value (optional).
For the current example the synthetic option is chosen for both temperature and solar radiation data where the city of **Austin, Texas**, and **5** years are selected.

**Create/Edit, NOAA tape, Climatedata, ASCII file, HELP Version 2, and Canadian Climatological:** all of these 6 options require the user to input the location (city and state), and the corresponding daily precipitation, temperature, or solar radiation data stored in a saved file(s) name, the format of the file(s) differs from option to the other. All options accept customary or metric units.

After completing entering the weather data input, you hit "F10" to end and save by typing the path and the name of each of the four saved files. The files will take automatically a default extensions as: D4; D7; D13; and D11 for Precipitation; Temperature; Solar radiation; and Evapotranspiration respectively (do not attempt to change the default extensions). After saving the files, you'll be prompted to the main menu screen. The program will prompt you to a warning screen if one or more of the data is missed or incorrect.

**2. Soil Data**

From the main menu you choose option 2 "**Enter/ Edit Soil Data**", this will prompt you to another screen where you either hit "PgDn" to start new file, or "F4" to choose from a list of saved files. Below is a description of the input soil data:

**2.1** Initial Information

The first screen of soil data input contains the following required information:

**Unit System**: on the same screen you are prompted to select a unit system, in the current example we selected **Metric**, Then you're prompted to another screen where you input;

**Project Title**: in the current example: "**Example in GRI Report # 19**"

**Landfill Area**: in the current example: **4 hectares**

**Percent of landfill where runoff is possible**: in the current example **100%**

**Method of initialization of moisture storage**: you have two options: 1) to choose to enter the initial moisture content for the soil layers in the analyzed profile as per the available soil information, and then at the following screen you'll input the corresponding values. 2) to let the program initialize the moisture content to the near steady-state condition, **option (2)** is selected in the current example.

**Initial Snow/Water Storage**: this piece of information is optional and needed when moisture storage is user-defined.

**2.2** Layers Information

The second, third, and fourth screens contain the layers information as follows:

**2.2.1** General Soil Information

**Layer Type:** four types of layers are supported by HELP model; 1)vertical percolation, 2) lateral drainage, 3) barrier soil liner, and 4) geomembrane liner

**Layer thickness**: in customary or Metric systems

**Soil Texture**: the soil texture information contains four properties;

- Porosity (vol/vol)
- Field Capacity (vol/vol)
- Witlting point (vol/vol), and
- Saturated hydraulic conductivity (cm/sec)

The user has the option to select from a 42 default soil/ material textures, select from user-built soil texture library where the properties will be automatically assigned, or to enter the above information manually. To learn more about the above properties refer to section "3.5 Soil Characteristics" of HELP Model User's Guide.

**Initial moisture storage**: vol/vol, optional if you choose option (1) of "Method of initialization of moisture storage" in section 2.1.

**Rate of subsurface inflow to layer**: optional, customary or Metric unit systems (mm or inch/year).

**2.2.2** Layer Specific Information

The four types of layers that are supported by HELP model are explained below:

**Vertical Percolation Layer**: waste and vegetation support layers are examples of vertical percolation layer. The downward flow in the vertical percolation layer is modeled by the unsaturated vertical gravity drainage. The upward flux due to evapotranspiration is modeled as an extraction.

**Lateral Drainage Layer**: the lateral drainage layer is designed to promote drainage laterally to a collection and removal system. The vertical flow in this layer is modeled as in the vertical percolation layer, however, a saturated lateral drainage is also allowed. In addition to the soil data in section 2.2.1, the following information are also required to model the lateral drainage layer:

- Max drainage length: customary or Metric. The horizontal projection of the slope, rather than the distance along the slope.
- Drain slope: percent. From 0 to 50 percent

- Percentage of recirculated to collected leachate. From 0 to 100%
- Layer No. to receive the recirculated leachate. Vertical percolation or lateral drainage. Layer number.

**Barrier soil liners**: are intended to restrict vertical drainage/ leakage/ percolation. These layers should have significantly lower hydraulic conductivity than the other layers. The barrier soil layer is assumed to be saturated all time but leak only when there is a positive head on the top surface of the liner. HELP model allows only downward saturated flow through the barrier soil layer, thus any water moving into the liner will eventually percolate through it. Evapotranspiration and lateral drainage are not permitted.

**Geomembrane liners:** are virtually impermeable synthetic membranes that reduce the area of vertical drainage/ leakage/ percolation to a very small fraction of the area locatednear manufacturing flaws and installation defects. Also a small quantity of vapor transport is modeled by specifying the vapor diffusivity of the geomembrane liner. In addition to data listed in section 2.2.1, the following information is required:

- Pinhole density: (#/acre or hectare). Defects of a diameter equal or smaller than the membrane thickness (estimated as 1 mm in diameter). Typical geomembranes may have from 0.5 to 1 pinhole per acre (1 to 2 per hectare).

- Installation defects density: (#/acre or hectare). Defects of a diameter greater than the membrane thickness (estimated as 1 $cm^2$ in area).

INPUTS *

| Installation Quality | Defect Density (#/acre) | Frequency (%) |
|---|---|---|
| Excellent | Up to 1 | 10 |
| Good | 1 to 4 | 40 |
| Fair | 4 to 10 | 40 |
| Poor | 10 to 20 (old landfills) | 10 |

- Placement quality: addresses the quality of contact between geomembrane and the underneath soil that limits the drainage rate. The table below explains the 6 cases supported by HELP model:

| | |
|---|---|
| 1. Perfect | Assumes perfect, (no gap, "sprayed-on" seal) |
| 2. Excellent | Assumes exceptional contact (typically achievable only in the lab ) |
| 3. Good | Assumes good field installation with well-prepared, smooth soil surface and geomembrane wrinkle control |
| 4. Poor | Assumes poor field installation with a less well-prepared soil surface and/ or geomembrane wrinkling control |
| 5. Worst Case | Assumes that contact between geomembrane and the underneath does not limit drainage rate |

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6. Separating Geotextile — Assumes leakage spreading and rate is controlled by the in-plane transmissivity of the geotextile separating the geomemebrane and the adjacent soil layer. This quality does not apply to GCL where bentonite swells upon wetting and extrudes into the geotextile significantly reducing its ability to spread the leakage.

- Saturated hydraulic conductivity: (vapor diffusivity), cm/sec
- Geotextile in-plane transmissivity, $cm^2/sec$ (optional when placed with geomembrane)

In the current example two layers are simulated, the following is the information required from the user as input. Other information is set up as default values corresponding to the layer's texture number:

1) Lateral drainage layer

- Type 2
- thickness 45 cm
- texture number 21
- slope length 10 m
- slope: 33%
- percent of recirculated leachate; zero%

2) Geomembrane liner

- Type 4
- thickness 0.15 cm
- texture number 35
- zero pinholes and zero installation defects
- placement quality: 1 (perfect)

**2.3** Site Characteristics

The third screen contains the runoff curve number information, the user has three options to input the SCS runoff curve number: 1) defined by the user, 2) defined by the user and modified

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by HELP model for slope surface and length, and 3) computed by HELP model based on top layer texture, slope length and slope.
In the current example **option 3** is selected and the corresponding slope %, slope length, soil texture and vegetation conditions (1: bare, 2:poor, 3: fair, 4:good, 5: excellent stand of grass) are input as in the previous step for the top layer (drainage layer). The SCS runoff curve number calculated by HELP model is **75.9**.

After completing entering the soil data input, you hit "F10" to end and save by typing the path and name of the file, the file will take automatically a default extension as: D10 (do not attempt to change the default extensions). After saving the file, you'll be prompted to the main menu screen. The program will prompt you to a warning screen if one or more of the data is missed or incorrect.

**3. Execution, Viewing and Printing Results**

From the main menu you choose option 3 "**Execute Simulation**" which will prompt you to a screen where you type the five files' names which contain weather and soil data information. Then to another screen where the program asks for the unit system wanted for the output (regardless of the system used in the input data), number of years during which the output is generated, and the intervals of the generated output; annual, monthly, or daily. The program will take few minuets (variable depending on your computer speed) to execute the project information, then it'll prompt to the main menu. To view or to print* the out put you choose either option 4 "**View Results**", or option 5 "**Print Results**".

A printout of the example discussed above is included.

*Since HELP model is DOS operated program, a conflict in the printing command may occur. It's recommended to open and print the output file "**filename.out**" through the program "**Notepad**" found in your Windows 95 system under: "start/programs/accessories/notepad".

**4. Flux Calculations**

Referring to the output table: "Peak Daily Values for Years 1974 Through 1978", drainage collected from layer 1= 61.12513 mm ( 0.061 m/day)

Hourly Flux ( $m^3$/hr)/ width (m) = Depth of Liquid Collected Daily (m/day) x Slope length (m) / 24 (hr/day)
=(0.061)*(10)/24 = 0.025 $m^3$/hr-m width

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# II: DRAINAGE GEOCOMPOSITE INPUT DATA

As discussed in section I, the input data for the lateral drainage Layer (Layer Type 2) could be divided into two categories; 1) project specific , and 2) product specific. The properties under the project specific category are listed on page 4 of section I. This section discusses the product specific properties for the lateral drainage layer with an emphasis on geosynthetic drainage geocomposites. In general, it should be noted that unlike the conventional soil drainage layer (sand or aggregate), the physical and hydraulic properties of geosynthetic materials are highly dependent on project's design criteria, such as anticipated normal load, hydraulic gradient, and boundary conditions. The five required properties for the drainage layer are as follows:

**1. Thickness (mm, inch)**
The layer thickness determined at the anticipated normal load.

**2. Porosity (vol/vol)**
The volume of space/total volume.

**3. Field Capacity (vol/vol)**
Field capacity as defined in HELP Model is the amount of water that the product will accept before gravity flow could commence in the layer.

**4. Wilting Point (vol/vol)**
Wilting point by definition is the maximum amount of moisture in the material that can not be drawn by plants

**5. Saturated Hydraulic Conductivity (cm/sec)**
The saturated hydraulic conductivity of the geonets are determined by dividing the transmissivity measured under the required design and field conditions by the corresponding thickness of the geonet.

The table below presents the above discussed properties for two of Tenax's geocomposites; Tenflow and Tendrain used typically for landfill capping and lining applications respectively.

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**Tenax's Lateral Drainage Layer Input Data for HELP Model**

| Geonet Type | Thickness* (mm/mils) | Porosity (vol/vol) | Field Capacity+ (vol/vol) | Wilting Point+ (vol/vol) | Saturated Hydraulic Conductivity++ (cm/sec) |
|---|---|---|---|---|---|
| Tenflow | 7.30/ 287 | 0.86 | 0.01 | 0.005 | 15.8 |
| Tendrain | 5.14/ 202 | 0.70 | 0.01 | 0.005 | 12.4 |

*Measured at anticipated stress level of 1,000 psf for Tenflow, and 15,000 for Tendrain (geonet only)
+ Per HELP Model default value for drainage geonets
++Determining the Design Hydraulic Conductivity for Drainage Geocomposites.

*Equations:*

$$T_{all} = \frac{T_{ult}}{RFin*RFcr*RFcc*RFbc} \quad (1)$$

Where, $T_{all}$ = allowable Transmissivity [$cm^2/s$]

$T_{ult}$ = ultimate Transmissivity measured in the lab [$cm^2/s$]

$RF_{in}$ = reduction factor for intrusion of adjacent geotextile

$RF_{cr}$ = reduction factor for creep deformation

$RF_{cc}$ = reduction factor for chemical clogging

$RF_{bc}$ = reduction factor for biological clogging

$$T_{dsg} = \frac{T_{all}}{FS} \quad (2)$$

Where, $T_{dsg}$ = design Transmissivity used in calculations [$cm^2/s$]

FS = overall factor of safety

$$T_{dsg} = k_{dsg} * t_{dsg} \quad (3)$$

Where, $k_{dsg}$ = design hydraulic conductivity used in calculations [$cm^2/s$]

$t_{dsg}$ = design thickness used in calculations [cm]

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*Solution:*

*Landfill Final Closure*:

1) Estimated design load on landfill foundation = 1,000 psf

2) Ultimate Transmissivity = $T_{ult}$ = 4.0 * 10E-3 $m^2$/sec = 40 $cm^2$/s

**(geocomposite tested in soil boundary condition under 1,000 psf, a hydraulic gradient of 0.33, and a seating period of 100 hours)**

3) Using Table 1 for typical values of reduction factors, *Giroud, Zornberg, and Zhao, 2000, "Hydraulic Design of Liquid Collection Layers", Geosynthetics International*: RFin = 1.1, RFcc = 1.1, RFbc = 1.4

4) Using RFcr = 1.02 (determined value for Tenflow)

5) FS = 2.0 (state of practice typical value)

6) **$t_{dsg}$ = 0.730 cm (0.287 inches)**

Substituting in Equation (1): $T_{all}$ = 23.1 $cm^2$/sec

Substituting in Equation (2): $T_{dsg}$ = 11.6 $cm^2$/sec

Substituting in Equation (3): **$k_{dsg}$ = 15.8 cm/sec**

*Landfill Liner Prior to Final Closure*:

1) Estimated design load on landfill foundation = 15,000 psf

2) Ultimate Transmissivity = $T_{ult}$ = 5.0 * 10E-3 $m^2$/sec = 50 $cm^2$/s

**(geocomposite tested in soil boundary condition under 15,000 psf, a hydraulic gradient of 0.02, and a seating period of 100 hours)**

3) Using Table 1 for typical values of reduction factors, *Giroud, Zornberg, and Zhao, 2000, "Hydraulic Design of Liquid Collection Layers", Geosynthetics International*: RFin = 1.2, RFcc = 1.75, RFbc = 1.75

4) Using RFcr = 1.07 (determined value for Tendrain)

5) FS = 2.0 (state of practice typical value)

6) **$t_{dsg}$ = 0.514 cm (0.202 inches)**

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Substituting in Equation (1): $T_{all}$ = 12.7 $cm^2$/sec

Substituting in Equation (2): $T_{dsg}$ = 6.4 $cm^2$/sec

Substituting in Equation (3): **$k_{dsg}$ = 12.4 cm/sec**

**Please note that the above calculations were done assuming typical information for the design requirements of a landfill liner and a landfill cap systems, as well as product design data for specific drainage geocomposites. The design engineer should implement the design data that are representative to the project in design and the considered products.**

# HELP MODEL

## Ø OUTPUTS

```
******************************************************************************
******************************************************************************
**                                                                          **
**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)                **
**                  DEVELOPED BY ENVIRONMENTAL LABORATORY                   **
**                    USAE WATERWAYS EXPERIMENT STATION                     **
**             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY              **
**                                                                          **
**                                                                          **
******************************************************************************
******************************************************************************


PRECIPITATION DATA FILE:     C:\HELP\DATA4A.D4
TEMPERATURE DATA FILE:       C:\HELP\DATA7A.D7
SOLAR RADIATION DATA FILE:   C:\HELP\DATA13A.D13
EVAPOTRANSPIRATION DATA:     C:\HELP\DATA11A.D11
SOIL AND DESIGN DATA FILE:   C:\HELP\B-DES1AR.D10
OUTPUT DATA FILE:            C:\HELP\B-DES1AR.OUT


TIME:  12:41     DATE:   1/18/2008


******************************************************************************

  TITLE:  Beatty T11 and T12 Cover 1996 Design
******************************************************************************


     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                  LAYER  1
                                  --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER  21
          THICKNESS                    =      6.00   INCHES
          POROSITY                     =      0.3970 VOL/VOL
          FIELD CAPACITY               =      0.0320 VOL/VOL
          WILTING POINT                =      0.0130 VOL/VOL
          INITIAL SOIL WATER CONTENT   =      0.0130 VOL/VOL
          EFFECTIVE SAT. HYD. COND.    =  0.300000012000     CM/SEC


                                  LAYER  2
                                  --------
```

```
          TYPE 1 - VERTICAL PERCOLATION LAYER
              MATERIAL TEXTURE NUMBER   7
THICKNESS                    =     18.00   INCHES
POROSITY                     =      0.4730 VOL/VOL
FIELD CAPACITY               =      0.2220 VOL/VOL
WILTING POINT                =      0.1040 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.1040 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.520000001000E-03 CM/SEC


                        LAYER  3
                        --------

            TYPE 2 - LATERAL DRAINAGE LAYER
              MATERIAL TEXTURE NUMBER  20
THICKNESS                    =      0.50   INCHES
POROSITY                     =      0.8500 VOL/VOL
FIELD CAPACITY               =      0.0100 VOL/VOL
WILTING POINT                =      0.0050 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.0050 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =   10.0000000000     CM/SEC
SLOPE                        =     33.00   PERCENT
DRAINAGE LENGTH              =    250.0    FEET


                        LAYER  4
                        --------

            TYPE 4 - FLEXIBLE MEMBRANE LINER
              MATERIAL TEXTURE NUMBER  35
THICKNESS                    =      0.06   INCHES
POROSITY                     =      0.0000 VOL/VOL
FIELD CAPACITY               =      0.0000 VOL/VOL
WILTING POINT                =      0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.199999996000E-12 CM/SEC
FML PINHOLE DENSITY          =      0.75   HOLES/ACRE
FML INSTALLATION DEFECTS     =      2.00   HOLES/ACRE
FML PLACEMENT QUALITY        =  3 - GOOD


                        LAYER  5
                        --------

             TYPE 3 - BARRIER SOIL LINER
             MATERIAL TEXTURE NUMBER  17
THICKNESS                    =      0.20   INCHES
POROSITY                     =      0.7500 VOL/VOL
FIELD CAPACITY               =      0.7470 VOL/VOL
WILTING POINT                =      0.4000 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.7500 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.300000003000E-08 CM/SEC
```

COEFFICIENTS FOR LAS VEGAS NEVADA

NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

| JAN/JUL | FEB/AUG | MAR/SEP | APR/OCT | MAY/NOV | JUN/DEC |
|---|---|---|---|---|---|
| 0.50 | 0.46 | 0.41 | 0.22 | 0.20 | 0.09 |
| 0.45 | 0.54 | 0.32 | 0.25 | 0.43 | 0.32 |

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR LAS VEGAS NEVADA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

| JAN/JUL | FEB/AUG | MAR/SEP | APR/OCT | MAY/NOV | JUN/DEC |
|---|---|---|---|---|---|
| 44.60 | 50.10 | 55.30 | 63.50 | 73.30 | 83.60 |
| 90.30 | 88.00 | 80.10 | 67.60 | 53.60 | 45.40 |

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR LAS VEGAS NEVADA
AND STATION LATITUDE = 36.08 DEGREES

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ANNUAL TOTALS FOR YEAR 1

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 2.80 | 335412.031 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 2.083 | 249483.547 | 74.38 |
| DRAINAGE COLLECTED FROM LAYER 3 | 0.7148 | 85629.133 | 25.53 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000000 | 0.014 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0000 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000000 | 0.014 | 0.00 |
| CHANGE IN WATER STORAGE | 0.002 | 299.368 | 0.09 |
| SOIL WATER AT START OF YEAR | 4.598 | 550854.250 | |
| SOIL WATER AT END OF YEAR | 4.601 | 551153.625 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.042 | 0.00 |

| | | | |
|---|---|---|---|
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.080 | 0.00 |
| CHANGE IN WATER STORAGE | 0.165 | 19739.014 | 4.88 |
| SOIL WATER AT START OF YEAR | 4.908 | 587955.437 | |
| SOIL WATER AT END OF YEAR | 5.073 | 607694.437 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.023 | 0.00 |

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ANNUAL TOTALS FOR YEAR 4

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 7.19 | 861290.187 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 6.023 | 721453.875 | 83.76 |
| DRAINAGE COLLECTED FROM LAYER 3 | 1.1264 | 134926.125 | 15.67 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.095 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0000 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.095 | 0.00 |
| CHANGE IN WATER STORAGE | 0.041 | 4910.063 | 0.57 |
| SOIL WATER AT START OF YEAR | 5.073 | 607694.437 | |
| SOIL WATER AT END OF YEAR | 5.114 | 612604.500 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.024 | 0.00 |

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ANNUAL TOTALS FOR YEAR 5

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|

| | | | |
|---|---|---|---|
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.004 | 0.00 |

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ANNUAL TOTALS FOR YEAR 7

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.63 | 434837.719 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 2.923 | 350114.094 | 80.52 |
| DRAINAGE COLLECTED FROM LAYER 3 | 1.0189 | 122056.547 | 28.07 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.094 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0000 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.094 | 0.00 |
| CHANGE IN WATER STORAGE | -0.312 | -37333.102 | -8.59 |
| SOIL WATER AT START OF YEAR | 5.512 | 660303.187 | |
| SOIL WATER AT END OF YEAR | 5.201 | 622970.062 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.063 | 0.00 |

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ANNUAL TOTALS FOR YEAR 8

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.03 | 482753.719 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.125 | 374394.625 | 77.55 |
| DRAINAGE COLLECTED FROM LAYER 3 | 0.9855 | 118057.812 | 24.46 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.104 | 0.00 |

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.23 | 506711.687 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.351 | 401369.031 | 79.21 |
| DRAINAGE COLLECTED FROM LAYER 3 | 0.8794 | 105342.469 | 20.79 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.085 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0000 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.085 | 0.00 |
| CHANGE IN WATER STORAGE | 0.000 | 0.000 | 0.00 |
| SOIL WATER AT START OF YEAR | 5.073 | 607694.437 | |
| SOIL WATER AT END OF YEAR | 5.073 | 607694.437 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.115 | 0.00 |

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ANNUAL TOTALS FOR YEAR 11

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 8.71 | 1043371.000 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 6.878 | 823919.125 | 78.97 |
| DRAINAGE COLLECTED FROM LAYER 3 | 1.6914 | 202607.266 | 19.42 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.155 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0001 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.155 | 0.00 |
| CHANGE IN WATER STORAGE | 0.141 | 16844.154 | 1.61 |
| SOIL WATER AT START OF YEAR | 5.073 | 607694.437 | |
| SOIL WATER AT END OF YEAR | 5.214 | 624538.562 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |

| | | | |
|---|---|---|---|
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000000 | 0.058 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0000 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000000 | 0.058 | 0.00 |
| CHANGE IN WATER STORAGE | 0.055 | 6543.761 | 2.12 |
| SOIL WATER AT START OF YEAR | 5.073 | 607694.437 | |
| SOIL WATER AT END OF YEAR | 5.128 | 614238.187 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.015 | 0.00 |

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ANNUAL TOTALS FOR YEAR 14

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.92 | 469576.750 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.146 | 376901.469 | 80.26 |
| DRAINAGE COLLECTED FROM LAYER 3 | 0.8283 | 99218.852 | 21.13 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.096 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0000 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.096 | 0.00 |
| CHANGE IN WATER STORAGE | -0.055 | -6543.761 | -1.39 |
| SOIL WATER AT START OF YEAR | 5.128 | 614238.187 | |
| SOIL WATER AT END OF YEAR | 5.073 | 607694.437 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.082 | 0.00 |

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| | | | |
|---|---|---|---|
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.015 | 0.00 |

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ANNUAL TOTALS FOR YEAR 17

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 2.71 | 324630.875 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 2.097 | 251201.703 | 77.38 |
| DRAINAGE COLLECTED FROM LAYER 3 | 0.6442 | 77170.758 | 23.77 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.079 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0000 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.079 | 0.00 |
| CHANGE IN WATER STORAGE | -0.031 | -3741.724 | -1.15 |
| SOIL WATER AT START OF YEAR | 5.104 | 611436.187 | |
| SOIL WATER AT END OF YEAR | 5.073 | 607694.437 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.064 | 0.00 |

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ANNUAL TOTALS FOR YEAR 18

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.73 | 446816.656 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 2.931 | 351122.219 | 78.58 |

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ANNUAL TOTALS FOR YEAR 20

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 2.05 | 245569.500 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 1.468 | 175866.141 | 71.62 |
| DRAINAGE COLLECTED FROM LAYER 3 | 0.5819 | 69703.281 | 28.38 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.068 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0000 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.068 | 0.00 |
| CHANGE IN WATER STORAGE | 0.000 | 0.000 | 0.00 |
| SOIL WATER AT START OF YEAR | 5.073 | 607694.437 | |
| SOIL WATER AT END OF YEAR | 5.073 | 607694.437 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.011 | 0.00 |

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ANNUAL TOTALS FOR YEAR 21

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 2.33 | 279110.687 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 1.776 | 212694.953 | 76.20 |
| DRAINAGE COLLECTED FROM LAYER 3 | 0.5544 | 66415.672 | 23.80 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000000 | 0.055 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0000 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000000 | 0.055 | 0.00 |
| CHANGE IN WATER STORAGE | 0.000 | 0.000 | 0.00 |
| SOIL WATER AT START OF YEAR | 5.073 | 607694.437 | |

| | | | |
|---|---|---|---|
| EVAPOTRANSPIRATION | 2.081 | 249307.359 | 72.77 |
| DRAINAGE COLLECTED FROM LAYER 3 | 0.7284 | 87259.531 | 25.47 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.086 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0000 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.086 | 0.00 |
| CHANGE IN WATER STORAGE | 0.050 | 6032.363 | 1.76 |
| SOIL WATER AT START OF YEAR | 5.073 | 607694.437 | |
| SOIL WATER AT END OF YEAR | 5.123 | 613726.812 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.014 | 0.00 |

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ANNUAL TOTALS FOR YEAR 24

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 5.62 | 673219.812 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.211 | 504397.344 | 74.92 |
| DRAINAGE COLLECTED FROM LAYER 3 | 1.4597 | 174854.703 | 25.97 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.116 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0001 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.116 | 0.00 |
| CHANGE IN WATER STORAGE | -0.050 | -6032.363 | -0.90 |
| SOIL WATER AT START OF YEAR | 5.123 | 613726.812 | |
| SOIL WATER AT END OF YEAR | 5.073 | 607694.437 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.031 | 0.00 |

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| | | | |
|---|---|---|---|
| SOIL WATER AT START OF YEAR | 5.073 | 607694.437 | |
| SOIL WATER AT END OF YEAR | 5.073 | 607694.437 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.018 | 0.00 |

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ANNUAL TOTALS FOR YEAR 27

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.20 | 503117.906 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.239 | 387957.406 | 77.11 |
| DRAINAGE COLLECTED FROM LAYER 3 | 0.9614 | 115160.391 | 22.89 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.106 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0000 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.106 | 0.00 |
| CHANGE IN WATER STORAGE | 0.000 | 0.000 | 0.00 |
| SOIL WATER AT START OF YEAR | 5.073 | 607694.437 | |
| SOIL WATER AT END OF YEAR | 5.073 | 607694.437 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.015 | 0.00 |

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ANNUAL TOTALS FOR YEAR 28

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 2.55 | 305464.437 | 100.00 |

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ANNUAL TOTALS FOR YEAR 30

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.90 | 586970.937 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.821 | 457736.625 | 77.98 |
| DRAINAGE COLLECTED FROM LAYER 3 | 1.4909 | 178600.766 | 30.43 |
| PERC./LEAKAGE THROUGH LAYER 5 | 0.000001 | 0.088 | 0.00 |
| AVG. HEAD ON TOP OF LAYER 4 | 0.0001 | | |
| PERC./LEAKAGE THROUGH LAYER 6 | 0.000001 | 0.088 | 0.00 |
| CHANGE IN WATER STORAGE | -0.412 | -49366.523 | -8.41 |
| SOIL WATER AT START OF YEAR | 5.485 | 657060.937 | |
| SOIL WATER AT END OF YEAR | 5.073 | 607694.437 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.002 | 0.00 |

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AVERAGE MONTHLY VALUES IN INCHES FOR YEARS 1 THROUGH 30

| | JAN/JUL | FEB/AUG | MAR/SEP | APR/OCT | MAY/NOV | JUN/DEC |
|---|---|---|---|---|---|---|
| PRECIPITATION | | | | | | |
| TOTALS | 0.37 | 0.42 | 0.27 | 0.27 | 0.21 | 0.06 |
| | 0.43 | 0.73 | 0.31 | 0.14 | 0.48 | 0.35 |
| STD. DEVIATIONS | 0.42 | 0.44 | 0.31 | 0.21 | 0.30 | 0.11 |
| | 0.65 | 0.56 | 0.48 | 0.15 | 0.53 | 0.50 |

RUNOFF

| | | | | |
|---|---|---|---|---|
| PRECIPITATION | 4.04 | ( 1.403) | 483712.0 | 100.00 |
| RUNOFF | 0.000 | ( 0.0000) | 0.00 | 0.000 |
| EVAPOTRANSPIRATION | 3.137 | ( 1.1447) | 375761.66 | 77.683 |
| LATERAL DRAINAGE COLLECTED FROM LAYER 3 | 0.88535 | ( 0.28878) | 106055.562 | 21.92535 |
| PERCOLATION/LEAKAGE THROUGH LAYER 5 | 0.00000 | ( 0.00000) | 0.084 | 0.00002 |
| AVERAGE HEAD ON TOP OF LAYER 4 | 0.000 | ( 0.000) | | |
| PERCOLATION/LEAKAGE THROUGH LAYER 6 | 0.00000 | ( 0.00000) | 0.084 | 0.00002 |
| CHANGE IN WATER STORAGE | 0.016 | ( 0.1557) | 1894.67 | 0.392 |

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FINAL WATER STORAGE AT END OF YEAR 30

| LAYER | (INCHES) | (VOL/VOL) |
|---|---|---|
| 1 | 0.1690 | 0.0282 |
| 2 | 2.2530 | 0.1252 |
| 3 | 0.0050 | 0.0100 |
| 4 | 0.0000 | 0.0000 |
| 5 | 0.1500 | 0.7500 |
| 6 | 2.4960 | 0.1040 |
| SNOW WATER | 0.000 | |

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**                                                                          **
**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)                **
**                  DEVELOPED BY ENVIRONMENTAL LABORATORY                   **
**                    USAE WATERWAYS EXPERIMENT STATION                     **
**             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY              **
**                                                                          **
**                                                                          **
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PRECIPITATION DATA FILE:     C:\HELP\DATA4A.D4
TEMPERATURE DATA FILE:       C:\HELP\DATA7A.D7
SOLAR RADIATION DATA FILE:   C:\HELP\DATA13A.D13
EVAPOTRANSPIRATION DATA:     C:\HELP\DATA11A.D11
SOIL AND DESIGN DATA FILE:   C:\HELP\B-DES2AR.D10
OUTPUT DATA FILE:            C:\HELP\B-DES2AR.OUT


TIME:  12:46     DATE:   1/18/2008


******************************************************************************

  TITLE:  Beatty T11 and T12 ET COVER With Capillary Break
******************************************************************************


     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                  LAYER  1
                                  --------

                 TYPE 1 - VERTICAL PERCOLATION LAYER
                     MATERIAL TEXTURE NUMBER   7
          THICKNESS                  =     36.00   INCHES
          POROSITY                   =      0.4730 VOL/VOL
          FIELD CAPACITY             =      0.2220 VOL/VOL
          WILTING POINT              =      0.1040 VOL/VOL
          INITIAL SOIL WATER CONTENT =      0.1040 VOL/VOL
          EFFECTIVE SAT. HYD. COND.  =  0.520000001000E-03 CM/SEC


                                  LAYER  2
                                  --------
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TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 21

| | | | |
|---|---|---|---|
| THICKNESS | = | 6.00 | INCHES |
| POROSITY | = | 0.3970 | VOL/VOL |
| FIELD CAPACITY | = | 0.0320 | VOL/VOL |
| WILTING POINT | = | 0.0130 | VOL/VOL |
| INITIAL SOIL WATER CONTENT | = | 0.0130 | VOL/VOL |
| EFFECTIVE SAT. HYD. COND. | = | 0.300000012000 | CM/SEC |

## GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS USER-SPECIFIED.

| | | | |
|---|---|---|---|
| SCS RUNOFF CURVE NUMBER | = | 68.00 | |
| FRACTION OF AREA ALLOWING RUNOFF | = | 100.0 | PERCENT |
| AREA PROJECTED ON HORIZONTAL PLANE | = | 33.000 | ACRES |
| EVAPORATIVE ZONE DEPTH | = | 24.0 | INCHES |
| INITIAL WATER IN EVAPORATIVE ZONE | = | 2.496 | INCHES |
| UPPER LIMIT OF EVAPORATIVE STORAGE | = | 11.352 | INCHES |
| LOWER LIMIT OF EVAPORATIVE STORAGE | = | 2.496 | INCHES |
| INITIAL SNOW WATER | = | 0.000 | INCHES |
| INITIAL WATER IN LAYER MATERIALS | = | 3.822 | INCHES |
| TOTAL INITIAL WATER | = | 3.822 | INCHES |
| TOTAL SUBSURFACE INFLOW | = | 0.00 | INCHES/YEAR |

## EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
LAS VEGAS NEVADA

| | | | |
|---|---|---|---|
| STATION LATITUDE | = | 36.08 | DEGREES |
| MAXIMUM LEAF AREA INDEX | = | 0.00 | |
| START OF GROWING SEASON (JULIAN DATE) | = | 62 | |
| END OF GROWING SEASON (JULIAN DATE) | = | 321 | |
| EVAPORATIVE ZONE DEPTH | = | 24.0 | INCHES |
| AVERAGE ANNUAL WIND SPEED | = | 9.10 | MPH |
| AVERAGE 1ST QUARTER RELATIVE HUMIDITY | = | 39.00 | % |
| AVERAGE 2ND QUARTER RELATIVE HUMIDITY | = | 21.00 | % |
| AVERAGE 3RD QUARTER RELATIVE HUMIDITY | = | 24.00 | % |
| AVERAGE 4TH QUARTER RELATIVE HUMIDITY | = | 36.00 | % |

NOTE: PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR LAS VEGAS NEVADA

NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

| JAN/JUL | FEB/AUG | MAR/SEP | APR/OCT | MAY/NOV | JUN/DEC |
|---|---|---|---|---|---|
| 0.50 | 0.46 | 0.41 | 0.22 | 0.20 | 0.09 |

| | | | |
|---|---|---|---|
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.689 | 561686.375 | 97.48 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000036 | 4.343 | 0.00 |
| CHANGE IN WATER STORAGE | 0.121 | 14499.395 | 2.52 |
| SOIL WATER AT START OF YEAR | 3.823 | 458009.844 | |
| SOIL WATER AT END OF YEAR | 3.944 | 472509.250 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.202 | 0.00 |

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ANNUAL TOTALS FOR YEAR 3

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.38 | 404890.187 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.446 | 412823.406 | 101.96 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000036 | 4.298 | 0.00 |
| CHANGE IN WATER STORAGE | -0.066 | -7937.583 | -1.96 |
| SOIL WATER AT START OF YEAR | 3.944 | 472509.250 | |
| SOIL WATER AT END OF YEAR | 3.878 | 464571.656 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.072 | 0.00 |

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ANNUAL TOTALS FOR YEAR 4

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|

| | | | |
|---|---|---|---|
| PRECIPITATION | 4.98 | 596554.125 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.587 | 549456.875 | 92.11 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000040 | 4.738 | 0.00 |
| CHANGE IN WATER STORAGE | 0.393 | 47092.508 | 7.89 |
| SOIL WATER AT START OF YEAR | 4.270 | 511458.000 | |
| SOIL WATER AT END OF YEAR | 4.663 | 558550.500 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.003 | 0.00 |

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ANNUAL TOTALS FOR YEAR 7

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.63 | 434837.719 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.151 | 497241.656 | 114.35 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000039 | 4.708 | 0.00 |
| CHANGE IN WATER STORAGE | -0.521 | -62408.578 | -14.35 |
| SOIL WATER AT START OF YEAR | 4.663 | 558550.500 | |
| SOIL WATER AT END OF YEAR | 4.142 | 496141.937 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.081 | 0.00 |

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ANNUAL TOTALS FOR YEAR 8

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.23 | 506711.687 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.276 | 512167.312 | 101.08 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000040 | 4.732 | 0.00 |
| CHANGE IN WATER STORAGE | -0.046 | -5460.389 | -1.08 |
| SOIL WATER AT START OF YEAR | 3.874 | 464070.437 | |
| SOIL WATER AT END OF YEAR | 3.828 | 458610.062 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.037 | 0.00 |

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ANNUAL TOTALS FOR YEAR 11

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 8.71 | 1043371.000 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 7.976 | 955385.375 | 91.57 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000040 | 4.795 | 0.00 |
| CHANGE IN WATER STORAGE | 0.734 | 87980.492 | 8.43 |
| SOIL WATER AT START OF YEAR | 3.828 | 458610.062 | |
| SOIL WATER AT END OF YEAR | 4.563 | 546590.562 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.345 | 0.00 |

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ANNUAL TOTALS FOR YEAR 14

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.92 | 469576.750 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.902 | 467428.344 | 99.54 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000046 | 5.513 | 0.00 |
| CHANGE IN WATER STORAGE | 0.018 | 2142.955 | 0.46 |
| SOIL WATER AT START OF YEAR | 3.987 | 477603.094 | |
| SOIL WATER AT END OF YEAR | 4.005 | 479746.062 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.058 | 0.00 |

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ANNUAL TOTALS FOR YEAR 15

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.26 | 510305.375 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.330 | 518717.031 | 101.65 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000046 | 5.564 | 0.00 |
| CHANGE IN WATER STORAGE | -0.070 | -8417.223 | -1.65 |
| SOIL WATER AT START OF YEAR | 4.005 | 479746.062 | |
| SOIL WATER AT END OF YEAR | 3.935 | 471328.844 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.006 | 0.00 |

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ANNUAL TOTALS FOR YEAR 18

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.73 | 446816.656 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.814 | 456844.062 | 102.24 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000047 | 5.606 | 0.00 |
| CHANGE IN WATER STORAGE | -0.084 | -10033.128 | -2.25 |
| SOIL WATER AT START OF YEAR | 4.566 | 546933.750 | |
| SOIL WATER AT END OF YEAR | 4.482 | 536900.625 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.106 | 0.00 |

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ANNUAL TOTALS FOR YEAR 19

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.61 | 432441.844 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.643 | 436430.406 | 100.92 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000047 | 5.602 | 0.00 |
| CHANGE IN WATER STORAGE | -0.033 | -3994.139 | -0.92 |
| SOIL WATER AT START OF YEAR | 4.482 | 536900.625 | |
| SOIL WATER AT END OF YEAR | 4.449 | 532906.500 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.004 | 0.00 |

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ANNUAL TOTALS FOR YEAR 22

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.05 | 485149.531 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.194 | 502356.562 | 103.55 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000048 | 5.697 | 0.00 |
| CHANGE IN WATER STORAGE | -0.144 | -17212.809 | -3.55 |
| SOIL WATER AT START OF YEAR | 3.991 | 478095.375 | |
| SOIL WATER AT END OF YEAR | 3.847 | 460882.562 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.072 | 0.00 |

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ANNUAL TOTALS FOR YEAR 23

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 2.86 | 342599.344 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 2.122 | 254242.047 | 74.21 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000052 | 6.177 | 0.00 |
| CHANGE IN WATER STORAGE | 0.738 | 88351.062 | 25.79 |
| SOIL WATER AT START OF YEAR | 3.847 | 460882.562 | |
| SOIL WATER AT END OF YEAR | 4.585 | 549233.625 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.078 | 0.00 |

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ANNUAL TOTALS FOR YEAR 26

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.54 | 543846.625 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.089 | 489777.875 | 90.06 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000055 | 6.578 | 0.00 |
| CHANGE IN WATER STORAGE | 0.451 | 54061.930 | 9.94 |
| SOIL WATER AT START OF YEAR | 4.051 | 485258.906 | |
| SOIL WATER AT END OF YEAR | 4.502 | 539320.812 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.220 | 0.00 |

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ANNUAL TOTALS FOR YEAR 27

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.20 | 503117.906 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.517 | 541072.062 | 107.54 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.000054 | 6.481 | 0.00 |
| CHANGE IN WATER STORAGE | -0.317 | -37960.566 | -7.55 |
| SOIL WATER AT START OF YEAR | 4.502 | 539320.812 | |
| SOIL WATER AT END OF YEAR | 4.185 | 501360.281 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.026 | 0.00 |

| | | | |
|---|---|---|---|
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.053 | 0.00 |

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ANNUAL TOTALS FOR YEAR 30

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.90 | 586970.937 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 6.066 | 726662.250 | 123.80 |
| PERC./LEAKAGE THROUGH LAYER 2 | 0.141391 | 16937.199 | 2.89 |
| CHANGE IN WATER STORAGE | -1.308 | -156628.203 | -26.68 |
| SOIL WATER AT START OF YEAR | 6.565 | 786438.625 | |
| SOIL WATER AT END OF YEAR | 5.258 | 629810.375 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.280 | 0.00 |

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AVERAGE MONTHLY VALUES IN INCHES FOR YEARS 1 THROUGH 30

| | JAN/JUL | FEB/AUG | MAR/SEP | APR/OCT | MAY/NOV | JUN/DEC |
|---|---|---|---|---|---|---|
| PRECIPITATION | | | | | | |
| TOTALS | 0.37 | 0.42 | 0.27 | 0.27 | 0.21 | 0.06 |
| | 0.43 | 0.73 | 0.31 | 0.14 | 0.48 | 0.35 |
| STD. DEVIATIONS | 0.42 | 0.44 | 0.31 | 0.21 | 0.30 | 0.11 |
| | 0.65 | 0.56 | 0.48 | 0.15 | 0.53 | 0.50 |
| RUNOFF | | | | | | |
| TOTALS | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| STD. DEVIATIONS | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

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PEAK DAILY VALUES FOR YEARS 1 THROUGH 30

| | (INCHES) | (CU. FT.) |
|---|---|---|
| PRECIPITATION | 1.94 | 232392.609 |
| RUNOFF | 0.000 | 0.0000 |
| PERCOLATION/LEAKAGE THROUGH LAYER 2 | 0.000773 | 92.63312 |
| SNOW WATER | 0.99 | 118629.8280 |

| | |
|---|---|
| MAXIMUM VEG. SOIL WATER (VOL/VOL) | 0.2714 |
| MINIMUM VEG. SOIL WATER (VOL/VOL) | 0.1040 |

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**                                                                          **
**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)                **
**                  DEVELOPED BY ENVIRONMENTAL LABORATORY                   **
**                    USAE WATERWAYS EXPERIMENT STATION                     **
**             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY              **
**                                                                          **
**                                                                          **
******************************************************************************
******************************************************************************


PRECIPITATION DATA FILE:     C:\HELP\DATA4A.D4
TEMPERATURE DATA FILE:       C:\HELP\DATA7A.D7
SOLAR RADIATION DATA FILE:   C:\HELP\DATA13A.D13
EVAPOTRANSPIRATION DATA:     C:\HELP\DATA11A.D11
SOIL AND DESIGN DATA FILE:   C:\HELP\MONO36AR.D10
OUTPUT DATA FILE:            C:\HELP\MONO36AR.OUT


TIME:  12:37     DATE:   1/18/2008


******************************************************************************
*  TITLE:  Beatty T11 and T12 ET Monolithic Cover
******************************************************************************


     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                  LAYER  1
                                  --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER   7
          THICKNESS                    =     36.00   INCHES
          POROSITY                     =      0.4730 VOL/VOL
          FIELD CAPACITY               =      0.2220 VOL/VOL
          WILTING POINT                =      0.1040 VOL/VOL
          INITIAL SOIL WATER CONTENT   =      0.1040 VOL/VOL
          EFFECTIVE SAT. HYD. COND.    =  0.520000001000E-03 CM/SEC


                   GENERAL DESIGN AND EVAPORATIVE ZONE DATA
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NOTE: SCS RUNOFF CURVE NUMBER WAS USER-SPECIFIED.

| | | | |
|---|---|---|---|
| SCS RUNOFF CURVE NUMBER | = | 68.00 | |
| FRACTION OF AREA ALLOWING RUNOFF | = | 100.0 | PERCENT |
| AREA PROJECTED ON HORIZONTAL PLANE | = | 33.000 | ACRES |
| EVAPORATIVE ZONE DEPTH | = | 24.0 | INCHES |
| INITIAL WATER IN EVAPORATIVE ZONE | = | 2.496 | INCHES |
| UPPER LIMIT OF EVAPORATIVE STORAGE | = | 11.352 | INCHES |
| LOWER LIMIT OF EVAPORATIVE STORAGE | = | 2.496 | INCHES |
| INITIAL SNOW WATER | = | 0.000 | INCHES |
| INITIAL WATER IN LAYER MATERIALS | = | 3.744 | INCHES |
| TOTAL INITIAL WATER | = | 3.744 | INCHES |
| TOTAL SUBSURFACE INFLOW | = | 0.00 | INCHES/YEAR |

## EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
LAS VEGAS NEVADA

| | | | |
|---|---|---|---|
| STATION LATITUDE | = | 36.08 | DEGREES |
| MAXIMUM LEAF AREA INDEX | = | 0.00 | |
| START OF GROWING SEASON (JULIAN DATE) | = | 62 | |
| END OF GROWING SEASON (JULIAN DATE) | = | 321 | |
| EVAPORATIVE ZONE DEPTH | = | 24.0 | INCHES |
| AVERAGE ANNUAL WIND SPEED | = | 9.10 | MPH |
| AVERAGE 1ST QUARTER RELATIVE HUMIDITY | = | 39.00 | % |
| AVERAGE 2ND QUARTER RELATIVE HUMIDITY | = | 21.00 | % |
| AVERAGE 3RD QUARTER RELATIVE HUMIDITY | = | 24.00 | % |
| AVERAGE 4TH QUARTER RELATIVE HUMIDITY | = | 36.00 | % |

NOTE: PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR LAS VEGAS NEVADA

NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

| JAN/JUL | FEB/AUG | MAR/SEP | APR/OCT | MAY/NOV | JUN/DEC |
|---|---|---|---|---|---|
| 0.50 | 0.46 | 0.41 | 0.22 | 0.20 | 0.09 |
| 0.45 | 0.54 | 0.32 | 0.25 | 0.43 | 0.32 |

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR LAS VEGAS NEVADA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

| JAN/JUL | FEB/AUG | MAR/SEP | APR/OCT | MAY/NOV | JUN/DEC |
|---|---|---|---|---|---|
| 44.60 | 50.10 | 55.30 | 63.50 | 73.30 | 83.60 |
| 90.30 | 88.00 | 80.10 | 67.60 | 53.60 | 45.40 |

| | | | |
|---|---|---|---|
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.223 | 0.00 |

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ANNUAL TOTALS FOR YEAR 3

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.38 | 404890.187 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.446 | 412822.375 | 101.96 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.054 | 0.00 |
| CHANGE IN WATER STORAGE | -0.066 | -7932.385 | -1.96 |
| SOIL WATER AT START OF YEAR | 3.867 | 463169.656 | |
| SOIL WATER AT END OF YEAR | 3.800 | 455237.281 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.146 | 0.00 |

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ANNUAL TOTALS FOR YEAR 4

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 7.19 | 861290.187 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 7.018 | 840628.375 | 97.60 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.007 | 0.00 |
| CHANGE IN WATER STORAGE | 0.172 | 20661.535 | 2.40 |
| SOIL WATER AT START OF YEAR | 3.800 | 455237.281 | |
| SOIL WATER AT END OF YEAR | 3.973 | 475898.812 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |

| | | | |
|---|---|---|---|
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.122 | 0.00 |

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ANNUAL TOTALS FOR YEAR 7

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.63 | 434837.719 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.151 | 497241.781 | 114.35 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000001 | 0.062 | 0.00 |
| CHANGE IN WATER STORAGE | -0.521 | -62404.125 | -14.35 |
| SOIL WATER AT START OF YEAR | 4.585 | 549220.562 | |
| SOIL WATER AT END OF YEAR | 4.064 | 486816.406 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.005 | 0.00 |

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ANNUAL TOTALS FOR YEAR 8

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.03 | 482753.719 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.038 | 483766.000 | 100.21 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.001 | 0.00 |
| CHANGE IN WATER STORAGE | -0.008 | -1012.458 | -0.21 |
| SOIL WATER AT START OF YEAR | 4.064 | 486816.406 | |
| SOIL WATER AT END OF YEAR | 4.055 | 485803.937 | |

| | | | |
|---|---|---|---|
| SOIL WATER AT END OF YEAR | 3.751 | 449299.781 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.215 | 0.00 |

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ANNUAL TOTALS FOR YEAR 11

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 8.71 | 1043371.000 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 7.976 | 955396.437 | 91.57 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.037 | 0.00 |
| CHANGE IN WATER STORAGE | 0.734 | 87974.039 | 8.43 |
| SOIL WATER AT START OF YEAR | 3.751 | 449299.781 | |
| SOIL WATER AT END OF YEAR | 4.485 | 537273.812 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.477 | 0.00 |

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ANNUAL TOTALS FOR YEAR 12

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.33 | 398900.687 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.311 | 396570.875 | 99.42 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.003 | 0.00 |
| CHANGE IN WATER STORAGE | 0.019 | 2329.595 | 0.58 |
| SOIL WATER AT START OF YEAR | 4.485 | 537273.812 | |

| | | | |
|---|---|---|---|
| SOIL WATER AT START OF YEAR | 3.909 | 468295.500 | |
| SOIL WATER AT END OF YEAR | 3.927 | 470387.531 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.050 | 0.00 |

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ANNUAL TOTALS FOR YEAR 15

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.26 | 510305.375 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.330 | 518642.937 | 101.63 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.011 | 0.00 |
| CHANGE IN WATER STORAGE | -0.070 | -8337.311 | -1.63 |
| SOIL WATER AT START OF YEAR | 3.927 | 470387.531 | |
| SOIL WATER AT END OF YEAR | 3.857 | 462050.219 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.268 | 0.00 |

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ANNUAL TOTALS FOR YEAR 16

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.66 | 438431.406 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.280 | 392958.031 | 89.63 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.014 | 0.00 |
| CHANGE IN WATER STORAGE | 0.380 | 45473.176 | 10.37 |

| | | | |
|---|---|---|---|
| CHANGE IN WATER STORAGE | -0.084 | -10037.012 | -2.25 |
| SOIL WATER AT START OF YEAR | 4.488 | 537642.812 | |
| SOIL WATER AT END OF YEAR | 4.404 | 527605.812 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.098 | 0.00 |

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ANNUAL TOTALS FOR YEAR 19

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 3.61 | 432441.844 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 3.643 | 436438.406 | 100.92 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.004 | 0.00 |
| CHANGE IN WATER STORAGE | -0.033 | -3996.709 | -0.92 |
| SOIL WATER AT START OF YEAR | 4.404 | 527605.812 | |
| SOIL WATER AT END OF YEAR | 4.371 | 523609.094 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.168 | 0.00 |

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ANNUAL TOTALS FOR YEAR 20

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 2.05 | 245569.500 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 1.821 | 218119.031 | 88.82 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.005 | 0.00 |

| | | | |
|---|---|---|---|
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000001 | 0.108 | 0.00 |
| CHANGE IN WATER STORAGE | -0.144 | -17220.721 | -3.55 |
| SOIL WATER AT START OF YEAR | 3.914 | 468881.469 | |
| SOIL WATER AT END OF YEAR | 3.770 | 451660.719 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.035 | 0.00 |

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ANNUAL TOTALS FOR YEAR 23

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 2.86 | 342599.344 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 2.122 | 254224.219 | 74.20 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.005 | 0.00 |
| CHANGE IN WATER STORAGE | 0.738 | 88375.078 | 25.80 |
| SOIL WATER AT START OF YEAR | 3.770 | 451660.719 | |
| SOIL WATER AT END OF YEAR | 4.508 | 540035.812 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.052 | 0.00 |

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ANNUAL TOTALS FOR YEAR 24

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 5.62 | 673219.812 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 5.130 | 614570.250 | 91.29 |

| | | | |
|---|---|---|---|
| EVAPOTRANSPIRATION | 4.090 | 489916.562 | 90.08 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.000 | 0.00 |
| CHANGE IN WATER STORAGE | 0.450 | 53929.754 | 9.92 |
| SOIL WATER AT START OF YEAR | 3.972 | 475860.687 | |
| SOIL WATER AT END OF YEAR | 4.423 | 529790.437 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.285 | 0.00 |

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ANNUAL TOTALS FOR YEAR 27

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 4.20 | 503117.906 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 4.516 | 540925.875 | 107.51 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.000000 | 0.000 | 0.00 |
| CHANGE IN WATER STORAGE | -0.316 | -37808.172 | -7.51 |
| SOIL WATER AT START OF YEAR | 4.423 | 529790.437 | |
| SOIL WATER AT END OF YEAR | 4.107 | 491982.250 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | 0.228 | 0.00 |

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ANNUAL TOTALS FOR YEAR 28

| | INCHES | CU. FEET | PERCENT |
|---|---|---|---|
| PRECIPITATION | 2.55 | 305464.437 | 100.00 |
| RUNOFF | 0.000 | 0.000 | 0.00 |

| | | | |
|---|---|---|---|
| RUNOFF | 0.000 | 0.000 | 0.00 |
| EVAPOTRANSPIRATION | 6.070 | 727185.125 | 123.89 |
| PERC./LEAKAGE THROUGH LAYER 1 | 0.006211 | 743.990 | 0.13 |
| CHANGE IN WATER STORAGE | -1.177 | -140957.828 | -24.01 |
| SOIL WATER AT START OF YEAR | 6.488 | 777193.937 | |
| SOIL WATER AT END OF YEAR | 5.311 | 636236.062 | |
| SNOW WATER AT START OF YEAR | 0.000 | 0.000 | 0.00 |
| SNOW WATER AT END OF YEAR | 0.000 | 0.000 | 0.00 |
| ANNUAL WATER BUDGET BALANCE | 0.0000 | -0.340 | 0.00 |

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AVERAGE MONTHLY VALUES IN INCHES FOR YEARS 1 THROUGH 30

| | JAN/JUL | FEB/AUG | MAR/SEP | APR/OCT | MAY/NOV | JUN/DEC |
|---|---|---|---|---|---|---|
| **PRECIPITATION** | | | | | | |
| TOTALS | 0.37 | 0.42 | 0.27 | 0.27 | 0.21 | 0.06 |
| | 0.43 | 0.73 | 0.31 | 0.14 | 0.48 | 0.35 |
| STD. DEVIATIONS | 0.42 | 0.44 | 0.31 | 0.21 | 0.30 | 0.11 |
| | 0.65 | 0.56 | 0.48 | 0.15 | 0.53 | 0.50 |
| **RUNOFF** | | | | | | |
| TOTALS | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| STD. DEVIATIONS | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **EVAPOTRANSPIRATION** | | | | | | |
| TOTALS | 0.321 | 0.448 | 0.400 | 0.303 | 0.261 | 0.139 |
| | 0.345 | 0.439 | 0.397 | 0.218 | 0.398 | 0.316 |
| STD. DEVIATIONS | 0.329 | 0.388 | 0.356 | 0.226 | 0.239 | 0.095 |
| | 0.637 | 0.443 | 0.563 | 0.138 | 0.446 | 0.252 |
| **PERCOLATION/LEAKAGE THROUGH LAYER 1** | | | | | | |
| TOTALS | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 |
| | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

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PEAK DAILY VALUES FOR YEARS 1 THROUGH 30

| | (INCHES) | (CU. FT.) |
|---|---|---|
| PRECIPITATION | 1.94 | 232392.609 |
| RUNOFF | 0.000 | 0.0000 |
| PERCOLATION/LEAKAGE THROUGH LAYER 1 | 0.000643 | 77.03716 |
| SNOW WATER | 0.99 | 118629.8280 |

| | |
|---|---|
| MAXIMUM VEG. SOIL WATER (VOL/VOL) | 0.2715 |
| MINIMUM VEG. SOIL WATER (VOL/VOL) | 0.1040 |

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# UNSAT-H

## Soil References:

INPUTS

WATER RESOURCES RESEARCH, VOL. 39, NO. 7, 1179, doi:10.1029/2002WR001604, 2003

CALCULATION
REFERENCE

# Variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing (0–90 kyr): Field measurements, modeling, and uncertainties

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[1] An understanding of unsaturated flow and potential recharge in interdrainage semiarid and arid regions is critical for quantification of water resources and contaminant transport. We evaluated system response to paleoclimatic forcing using water potential and Cl profiles and modeling of nonisothermal liquid and vapor flow and Cl transport at semiarid (High Plains, Texas) and arid (Chihuahuan Desert, Texas; Amargosa Desert, Nevada) sites. Infiltration in response to current climatic forcing is restricted to the shallow (~0.3–3 m) subsurface. Subsurface Cl accumulations correspond to time periods of 9–90 kyr. Bulge-shaped Cl profiles generally represent accumulation during the Holocene (9–16 kyr). Lower Cl concentrations at depth reflect higher water fluxes (0.04–8.4 mm/yr) during the Pleistocene and earlier times. Low water potentials and upward gradients indicate current drying conditions. Nonisothermal liquid and vapor flow simulations indicate that upward flow for at least 1–2 kyr in the High Plains and for 12–16 kyr at the Chihuahuan and Amargosa desert sites is required to reproduce measured upward water potential gradients and that recharge is negligible (<0.1 mm/yr) in these interdrainage areas. *INDEX TERMS:* 1809 Hydrology: Desertification; 1815 Hydrology: Erosion and sedimentation; 1833 Hydrology: Hydroclimatology; *KEYWORDS:* paleoclimate, chloride mass balance, unsaturated zone, unsaturated flow modeling

**Citation:** Scanlon, B. R., K. Keese, R. C. Reedy, J. Simunek, and B. J. Andraski, Variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing (0–90 kyr): Field measurements, modeling, and uncertainties, *Water Resour. Res.*, *39*(7), 1179, doi:10.1029/2002WR001604, 2003.

## 1. Introduction

[2] Quantification of water resources is a critical issue for many desert regions, particularly in the southwestern United States, where water demand is increasing with increasing populations. Interdrainage semiarid and arid regions represent significant portions of watersheds; therefore evaluating whether there is diffuse recharge or no recharge in these regions is important for water resources. Waste disposal is also an important issue for semiarid and arid regions because they are considered much more suitable than humid regions for this purpose [*Reith and Thompson*, 1992]. Determining whether water is moving up or down is critical for recharge and contaminant transport. This basic question is difficult to resolve in many interdrainage, semiarid and arid regions because water fluxes are extremely low (~mm/yr [*Phillips*, 1994]]. The low fluxes result in thick vadose zones providing an archive of system response to paleoclimatic fluctuations [*Tyler et al.*, 1996]. Understanding the current system at different depths requires evaluation of system response to past climate fluctuations, which, in turn, requires an understanding of the following issues: (1) How deep does water penetrate under current climatic fluctuations? (2) What is the spatial and temporal variability in estimated water fluxes and ages from Cl profiles? (3) What timescales are represented by upward water potential gradients? (4) How important is vapor flow?

[3] The purpose of this study was to evaluate variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing using field measurements and modeling analysis. Water potential and Cl profiles from several sites (High Plains and Chihuahuan Desert, Texas, and Amargosa Desert, Nevada) were used in the analysis. This study addresses many of the above issues, including penetration depths of wetting fronts in response to seasonal and annual climatic forcing using long-term (5–12 yr) water potential monitoring records, variability in water fluxes and ages calculated from Cl profiles at the different sites, and timescales of upward flow related to upward water potential

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gradients and relative importance of liquid and vapor flow using numerical modeling. Unique aspects of this study include the range of current climatic conditions (mean annual precipitation 108–500 mm/yr) and of sediment types (clay loam to sand) at the different sites, length of water potential monitoring records (5–12 yr), and collocation of water potential and Cl profiles. Numerical modeling of nonisothermal liquid and vapor flow plays a critical role in evaluating system response to paleoclimatic fluctuations and assessing important processes (upward versus downward flux, liquid and vapor flux) and controls (e.g., climate, vegetation, and sediment texture) on subsurface flow and transport. Uncertainties in all aspects of the study, including measurements, monitoring, and modeling, are evaluated to identify gaps in our knowledge and areas of future research.

### 1.1. Background

[4] Direction of water movement can be determined using potential energy gradients in isothermal systems because water moves from regions of high energy to regions of low energy [*Jury et al.*, 1991]. Gravitational potential is equal to the elevation above a datum, such as the water table. Matric potential describes the forces related to the soil matrix and is dominated by capillary forces under wet conditions and adsorptive forces under dry conditions. Osmotic potential results from the addition of solutes to the pore water. Water potential includes matric and osmotic potential and can be measured by thermocouple psychrometers. Typical water potentials in many semiarid and arid settings are lowest near the surface (~−400 to −1000 m) and increase exponentially with depth, indicating an upward driving force for water movement [*Scanlon*, 1994; *Andraski*, 1997; *Izbicki et al.*, 2000; *Walvoord et al.*, 2002]. Relating water potential profiles to paleoclimatic forcing requires an understanding of how water potential variations are related to seasonal and annual climatic fluctuations.

[5] Chloride concentrations in unsaturated zone pore water have been measured at many of the sites where water potentials have been measured [*Andraski and Prudic*, 1997; *Scanlon et al.*, 1999; *Izbicki et al.*, 2000; *Walvoord et al.*, 2002]. The Cl mass balance (CMB) approach was used to quantify water fluxes on millennial timescales at these sites. Water flux is calculated by dividing the Cl input (precipitation × Cl concentration in precipitation and dry fallout) by the Cl concentration in unsaturated zone pore water. The age represented by Cl is calculated by dividing the cumulative mass of Cl from the surface to the depth of interest by the Cl input. One of the primary assumptions of the CMB approach is that water is moving downward through the unsaturated zone. Bulge-shaped Cl profiles at these sites are characterized by increasing concentrations to a maximum near the base of the root zone and decreasing to much lower concentrations at depth. These profiles are typical of desert regions in the southwestern United States [*Phillips*, 1994]. The low Cl concentrations beneath the bulges have been attributed to higher water fluxes during pluvial conditions (mesic vegetation) in the Pleistocene (≥10 to 15 ka [thousand years ago]) [*Scanlon*, 1991; *Phillips*, 1994]. The Cl bulges have been attributed to a reduction in water fluxes during more arid conditions (xeric vegetation) in the Holocene (0 to 10–15 ka). There is an apparent inconsistency between the downward-flow assumption required by the CMB approach to estimate water fluxes and upward flow suggested by the upward water potential gradients. This inconsistency was reconciled in some previous studies by assuming that the Cl data represented much longer timescales than the upward water potential gradients [*Scanlon et al.*, 1999]. From a waste-containment standpoint, assuming downward water fluxes provided a conservative estimate of water flux, and most interpretations assumed that the Cl bulges represented a reduction in water flux or zero water flux since the Pleistocene [*Scanlon*, 1991; *Phillips*, 1994; *Prudic*, 1994; *Tyler et al.*, 1996].

[6] The timescales represented by the upward water potential gradients were evaluated using numerical modeling by *Walvoord et al.* [2002] for typical arid interdrainage sites in the southwestern United States. A reversal in the direction of water movement from downward to upward was attributed to changes from mesic vegetation during Pleistocene pluvial periods to xeric vegetation during Holocene arid conditions [*van Devender*, 1990]. Downward water fluxes of 2–5 mm/yr, estimated from deep Cl concentrations, were simulated for the pluvial period (≥15 ka). The transition to xeric vegetation was simulated by setting the matric potential head at ~−400 m at the base of the root zone (~4 m depth), which represents the ability of plants to capture infiltrated water in the root zone. These simulations demonstrated that downward propagation of drying fronts over time periods of ~15 kyr would be required to reproduce the measured upward water potential gradients. The Cl bulges were simulated by downward diffusion of Cl driven by concentration gradients. Simulated current water fluxes at depth are much lower than the paleofluxes estimated using the CMB approach.

[7] The importance of vapor flow in semiarid and arid regions was evaluated by *Ross* [1984], who indicated that it should be very important in areas of little or no recharge (≤0.03 mm/yr). In systems with no recharge, under isothermal conditions at steady state, the matric potential should balance the gravitational potential, resulting in a matric potential gradient of unity. Under nonisothermal conditions, upward vapor flow driven by the geothermal gradient would result in a matric potential gradient much less than unity. Conservation of mass would require a downward liquid flux to balance the upward vapor flux because thermal vapor flux varies with elevation. *Ross* [1984] predicted an upward vapor flux and corresponding downward liquid flux of 0.03 mm/yr for a system with a geothermal gradient of 33°C/km. The modeling studies by *Walvoord et al.* [2002] also indicate that upward geothermally driven vapor flow would provide water through condensation for upward isothermal liquid and isothermal vapor flow near the land surface and for downward liquid flow at depth.

[8] This study builds on previous work by evaluating water potential and Cl profiles at a number of semiarid and arid sites in the southwestern United States that represent different current climates, vegetation, and sediment textures. Detailed nonisothermal liquid and vapor flow simulations, similar to those conducted by *Walvoord et al.* [2002], were applied to the sites in this study to evaluate processes and controls on subsurface flow over millennia.

### 1.2. Site Descriptions

[9] The analysis of subsurface flow focuses on four different sites: the High Plains (HP) site near Amarillo in

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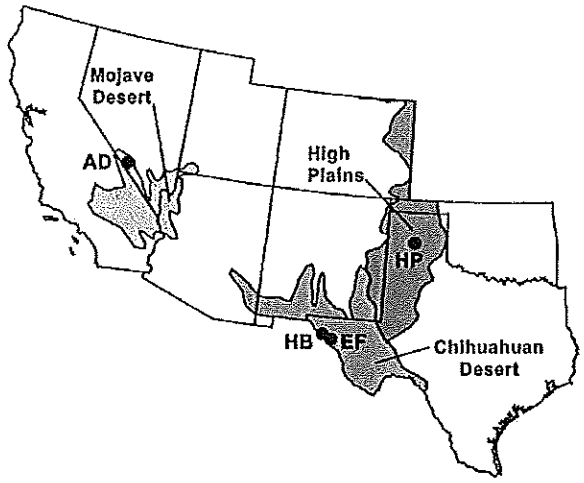


**Figure 1.** Study locations: Amargosa Desert site (AD) in the Mojave Desert, High Plains site (HP), and Hueco Bolson (HB) and Eagle Flat (EF) sites in the Chihuahuan Desert.

the Texas Panhandle; the Eagle Flat (EF) and Hueco Bolson (HB) sites in the Chihuahuan Desert in West Texas; and the Amargosa Desert (AD) site in the Mojave Desert near Beatty, Nevada (Figure 1 and Table 1). Detailed descriptions of these sites are given by *Scanlon* [1991, 1994], *Andraski* [1997], *Scanlon and Goldsmith* [1997], and *Scanlon et al.* [1999]. Sediment textures range from coarse grained (loamy sand (AD) and sand (shallow HB $\leq$ 8 m)) to fine grained (sandy clay loam (EF); clay loam (HP and deep HB ($\geq$8 m))) (Table 2). Long-term mean annual precipitation varies from 108 mm (AD) to 500 mm (HP) (Table 1). Vegetation is variable and is sparse at most sites (creosote bushes, AD; grasses, HP; grasses and shrubs, EF) and dense at the HB site (mesquite trees and creosote bushes). The water table depth varies from 75 m (HP) to 200 m (EF) (Table 1).

**Table 1.** Attributes for the High Plains (HP), Eagle Flat (EF), Hueco Bolson (HB), and Amargosa Desert (AD) Sites

4.25"

| | HP | EF | HB | AD |
|---|---|---|---|---|
| Precipitation (mm/yr) (30-yr average) | 500 | 320 | 280 | 108 |
| Water table depth (m) | 75 | 200 | 150 | 110 |
| Profile depth (wp) (m)[a] | 22.1 | 19.3 | 24 | 47.5 |
| Profile depth (Cl) (m)[b] | 17.6 | 17.5 | 10.5 | 85 |
| Cl precipitation (mg/L)[c] | 0.3 | 0.27 | 0.29 | 1.6 |
| Cl input (mg/m$^2$/yr) | 157 | 87 | 80 | 173 |
| CMB flux base (mm/yr)[d] | 1.3 | 0.04 | 0.2 | 8.4 |
| Cl peak (mg/L) | 2,515 | 6,575 | 9,343 | 9,000 |
| Cl peak depth (m) | 1.6 | 0.5 | 2.8, 4.7 | 2.3 |
| Cl base (mg/L) | 118 | 2,600 | 460 | 20 |
| CMB age (kyr)[e] | 9 | 12 | 13 | 16 |
| CMB age base (kyr)[f] | 9 | 90 | 17 | 18 |
| Matric potential (root sink) (m)[g] | −250 | −450 | −450 | −500 |
| Root sink depth (m) | 1.6 | 0.5 | 2.8 | 2.3 |
| Geothermal gradient (°C/km) | 25 | 25 | 35 | 40 |

[a]Depth of water potential profile.
[b]Depth of Cl profile.
[c]Cl concentration in precipitation and dry fallout.
[d]CMB flux at the base of the profile.
[e]CMB age at the base of the Cl bulge.
[f]CMB age at the base of the Cl profile.
[g]Matric potential assigned to root sink term in numerical model.

**Table 2.** Soil Texture, Saturated Hydraulic Conductivity ($K_s$), Saturated ($\theta_s$) and Residual ($\theta_r$) Water Content, and van Genuchten Parameters $\alpha$ and n[a]

| Site | Texture | Percent Sand, Silt, Clay | $K_s$ m/d | $\theta_s$ m$^3$/m$^3$ | $\theta_r$ m$^3$/m$^3$ | $\alpha$, 1/m | n |
|---|---|---|---|---|---|---|---|
| HP/HB | clay loam | 21,51,28 | 0.14 | 0.43 | 0.06 | 0.8 | 1.25 |
| EF | sandy clay loam | 56,23,21 | 0.41 | 0.35 | 0.04 | 0.8 | 1.21 |
| HB | sand | 92,7,1 | 5.87 | 0.38 | 0.03 | 5.0 | 1.95 |
| AD | loamy sand | 80,14,6 | 0.43 | 0.29 | 0.026 | 2.6 | 1.42 |

[a]Texture for the AD site represents the $\leq$2 mm fraction; the whole sample contained 22% gravel [*Andraski*, 1996] (Table 1). The HB profile consists of sand in the upper 8 m and clay loam at greater depth.

[10] Paleoclimate and paleovegetation of the different regions have been reconstructed from records of fluvial and lacustrine systems, speleothems (cave calcite formations), pollen, and packrat middens. Evidence of cooler and wetter conditions during the Pleistocene in the High Plains is provided by geologic records of water-filled playas and flowing streams. The transition to semiarid conditions on the High Plains during the Holocene is marked by a shift from erosion to deposition in fluvial channels and sediment aggradation (12 ka, $^{14}$C dating [*Holliday*, 1995]). Speleothems in Central Texas caves record up to two orders of magnitude higher growth rates from 24 to 12 ka (U series isotope dating), which were attributed to wetter conditions during the Pleistocene than during the Holocene [*Musgrove et al.*, 2001]. Information from paleolake shorelines within the Salt Basin in the Chihuahuan Desert in Texas reflects highstands ranging from 23 to 16 ka ($^{14}$C [*Wilkins and Currey*, 1997]). Packrat midden data record a shift from mesic pinon-juñiper woodlands to xeric desert scrub containing creosote bushes and mesquite trees ~1–8 ka [*van Devender*, 1990]. The paleoclimate near the Amargosa Desert has been reconstructed from lacustrine and marsh deposits and packrat midden data. Significantly wetter conditions from 150 and 120 ka and later from 24 and 10 ka caused Searles Lake (130 km southwest of the AD site) to overflow. Marsh deposits were recorded south of the AD site between 60 and 40 ka and between 30 and 15 ka [*Quade*, 1986]. *Benson et al.* [1990] and *Morrison* [1991] recorded variations in lake levels in western Nevada ~14–13 ka. Packrat midden data record a shift in vegetation from mesic woodlands to xeric scrublands ~14–9 ka in southern Nevada [*Spaulding*, 1990]. The paleoclimate and paleovegetation indicators are consistent and record cooler, wetter conditions during the Pleistocene and warmer, drier conditions during the Holocene.

## 2. Methods

[11] Detailed descriptions of the methods used at the HP, EF, and HB sites are given by *Scanlon et al.* [1991, 1999, 2000] and in *Scanlon and Goldsmith* [1997], and those for the AD site can be found in *Fischer* [1992], *Prudic* [1994], *Andraski* [1996, 1997], and *Andraski and Prudic* [1997]. Sediment samples from shallow excavations and deep boreholes were collected for laboratory analyses of sediment texture, bulk density, water content, water potential, and Cl concentration. Laboratory measurements of water potential

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were made using a thermocouple psychrometer sample changer (SC10A; Decagon Devices, Inc., Pullman, WA) or a water activity meter (CX1; Decagon Devices Inc) [*Andraski and Scanlon*, 2002; *Scanlon et al.*, 2002].

[12] In situ water potentials were monitored using thermocouple psychrometers (Model 74, J.R.D. Merrill Specialty Equipment, Logan, UT) [*Andraski and Scanlon*, 2002] installed in the sidewall of hand-dug pits (~1.5 m deep), in deep boreholes, and laterally out from an experimental instrument shaft. For each of the four sites, all samples and data were collected at locations that were in close proximity (i.e., ≤70 m).

### 2.1. Numerical Modeling

[13] Numerical simulations were done to evaluate the timescales represented by upward water potential profiles. The simulations used a modified version of the HYDRUS-1D computer code [*Simunek et al.*, 1998] that includes coupled liquid water, water vapor, and energy transport. The basic water flow equations are provided by *Simunek et al.* [1998]. Because vapor flow is discussed in detail in this study, the equations for vapor flow are provided here and are similar to those of *Fayer* [2000]. Liquid water flux is described by Darcy's law. Water vapor flux ($q_v$) is described by Fick's law of diffusion:

$$q_v = q_{vh} + q_{vT} = -K_{vh}\frac{\partial h}{\partial z} - K_{vT}\frac{\partial T}{\partial z}$$

$$= -\frac{D}{\rho_w}\rho_{vs}\frac{Mg}{RT}H_r\frac{\partial h}{\partial z} - \frac{D}{\rho_w}\eta H_r\frac{\partial \rho_{vs}}{\partial T}\frac{\partial T}{\partial z} \quad (1)$$

where $q_{vh}$ is isothermal vapor flux (L T$^{-1}$), $q_{vT}$ is thermal vapor flux (L T$^{-1}$), $K_{vh}$ is isothermal vapor conductivity (L T$^{-1}$), $K_{vT}$ is thermal vapor conductivity (L$^2$ K$^{-1}$ T$^{-1}$), $D$ is vapor diffusivity in soil (L$^2$ T$^{-1}$), $\rho_w$ is density of liquid water (M L$^{-3}$), $\rho_{vs}$ is saturated vapor density (M L$^{-3}$), $M$ is molecular weight of water (kg mol$^{-1}$), $g$ is gravitational acceleration (L T$^{-2}$), $R$ is gas constant (J mol$^{-1}$K$^{-1}$), $H_r$ is relative humidity, $h$ is matric potential head (L), $\eta$ is enhancement factor, and $T$ is temperature (K). The vapor diffusivity in soil is

$$D = \tau\theta_a D_a = \frac{\theta_a^{7/3}}{\theta_s^2}\theta_a D_a; \quad D_a = 2.12\times10^{-5}\left(\frac{T}{273.15}\right)^2 \quad (2)$$

where $\tau$ is tortuosity described by *Millington and Quirk* [1961], $\theta_a$ is volumetric air content, $D_a$ is diffusivity of water vapor in air (L$^2$ T$^{-1}$), and $\theta_s$ is saturated water content. HYDRUS-1D includes enhancements for thermal vapor flux as a result of liquid islands and increased temperature gradients in the air phase relative to the average temperature gradient [*Philip and de Vries*, 1957]. The *Cass et al.* [1984] formulation for the enhancement factor [*Campbell*, 1985] is used in HYDRUS-1D:

$$\eta = 9.5 + 3\frac{\theta}{\theta_s} - 8.5\exp\left(-\left(\left(1+\frac{2.6}{\sqrt{f_c}}\right)\frac{\theta}{\theta_s}\right)^4\right) \quad (3)$$

where $f_c$ is mass fraction of clay in soil.

[14] The modeling approach used in this study was similar to that used by *Walvoord et al.* [2002]. The pluvial period was approximated by simulating downward water fluxes, estimated from Cl concentrations beneath the bulge, until steady state was achieved. The resultant matric potentials provided initial conditions for simulations of the Holocene that included a constant head root sink at the base of the root zone to represent xeric vegetation. The base of the root zone was assumed equal to the depth of the Cl peak. The matric potential at the sink was assigned on the basis of measured water potentials just below the root zone (Table 1). The transient simulations therefore consisted of a step change from downward flux in the Pleistocene to upward flux during the Holocene. This simplified approach assumes that the assigned conditions are representative of long-term average conditions and avoids the complexities of simulating diurnally and seasonally varying water flux dynamics in the upper few meters, which were considered in previous studies [*Scanlon and Milly*, 1994]. The top boundary condition consisted of an applied water and solute flux equal to precipitation and Cl in precipitation and dry deposition. The entire unsaturated zone from the ground surface to the water table was simulated. The lower boundary condition was assigned zero pressure equal to the water table. The geothermal gradient was incorporated by specifying the temperature at the surface and in the groundwater. The surface temperature was set equal to the average temperature monitored at depths of 10 to 15 m, which is below the zone of seasonal fluctuations. In areas where accurate temperature data were not available, the geothermal gradient was estimated from the literature (HB site) [*Henry and Gluck*, 1981]. The grid cell size generally varied from 0.1 m at the surface to a maximum of 2 m within the profile and decreased to a minimum value of 0.05 m at the water table. Adaptive time stepping is used in HYDRUS-1D, and a minimum initial time step was generally set at 0.01 day. There was no limit on the maximum time step size.

### 2.2. Hydraulic Properties

[15] Profiles for most sites were represented using a single sediment type generally based on the dominant texture in the profiles, with the exception of the HB site, which was simulated using coarse-textured sand in the upper 8 m (Camp Rice Formation) underlain by clay loam (Fort Hancock Formation) that extends to the water table (150 m). Hydraulic properties were based on field or laboratory measurements of samples with the exception of the HB site. Hydraulic properties for the sand layer at the HB site were derived from the UNSODA database (UNSODA 4650 [*Leij et al.*, 1996]), and the underlying clay-loam properties were based on measurements at the HP site. The AD site was represented by layer 1 material properties described in *Andraski* [1996]. Water retention measurements were made over a maximum pressure range of 0.2 to 18,000 m. *Van Genuchten* [1980] water retention functions were fitted to the laboratory-measured water retention data (Figure 2 and Table 2). The $R^2$ values for measured versus fitted water contents ranged from 0.96 to 0.99. Unsaturated hydraulic conductivity was estimated from field or laboratory measurements of saturated hydraulic conductivity and water retention functions using the Mualem hydraulic conductivity model [*Mualem*, 1976] (Figure 3). The enhancement factors for thermal vapor diffusion for materials at each of the sites are shown in

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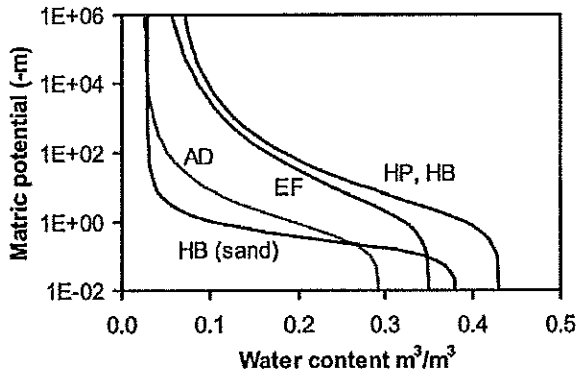


**Figure 2.** van Genuchten water retention functions for sediment textures used to model each site. Values for van Genuchten parameters are listed in Table 2.

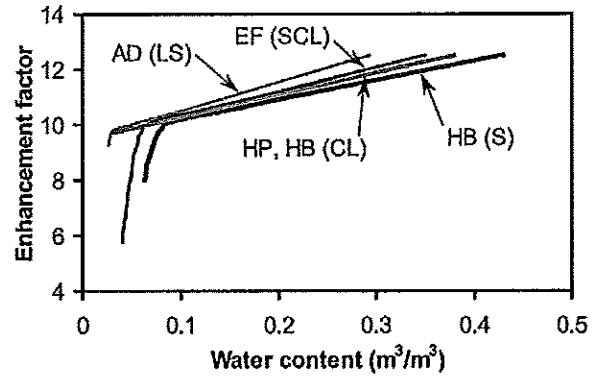


**Figure 4.** Enhancement factors for different sediment textures (LS, loamy sand; SCL, sandy clay loam; CL, clay loam; S, sand) at the High Plains (HP), Eagle Flat (EF), Hueco Bolson (HB), and Amargosa Desert (AD) sites. Water content ranges from saturated to residual for each texture.

Figure 4. Thermal conductivity for each sediment texture as a function of water content was based on data from *Chung and Horton* [1987].

## 3. Results and Discussion

### 3.1. Water Potential Monitoring

[16] Long-term (5 to 12 yr) monitoring of water potentials at each site indicates that penetration of wetting fronts in response to seasonal and annual fluctuations in precipitation is restricted to the shallow subsurface. The wetting front is defined as water potential close to zero. Wetting fronts penetrated to a maximum depth of <0.3 m (EF), 0.8 m (HB), 1.2 m (AD), and 2.9 m (HP) (Figure 5). Deeper penetration of water at the HB site compared with the EF site in the Chihuahuan Desert is attributed to coarser textured soils at the HB site (Table 1). Infiltration occurs primarily in response to winter precipitation at all sites and also in response to summer monsoonal precipitation in the Chihuahuan Desert (EF and HB sites). Winter infiltration often results in water potential increases for several months because ET is low. Rapid removal of this water generally occurs in the spring in response to increased ET. In contrast, the duration of summer increases in water potential is much shorter (≤1 month) because ET rates are high. Temporal variability in water potentials at each site reflects the complex interplay between seasonal changes in climate forcing, sediment texture, and vegetation.

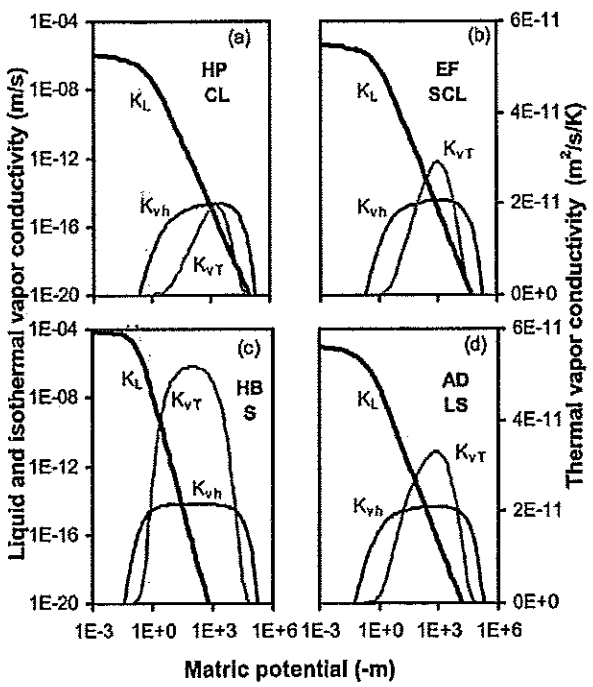


**Figure 3.** Liquid ($K_L$), isothermal vapor ($K_{vh}$), and thermal vapor ($K_{vT}$) conductivity calculated by HYDRUS-1D for sediment textures at each site. Hueco Bolson sand properties represent the upper 8 m depth, and clay loam at greater depth is represented by the High Plains properties. (CL, clay loam: SCL, sandy clay loam; S, sand; LS, loamy sand).

[17] Data from most sites indicate predominantly piston flow with progressive increases in water potential with depth after precipitation events. Water potential increases in a gravel layer at 1.2 m depth at the AD site during high precipitation in 1987 are attributed to preferential flow down the instrument borehole because water potentials increased at this depth prior to those at shallower depths. Data from the HP site also suggested that preferential flow might have resulted from instrument installation. Water potentials were low during the first 3 years, suggesting dry conditions. Water potential fluctuations then became spiky at depths of 1.7 to 2.9 m, suggesting preferential flow. Ultimately water potentials at these depths remained uniformly high, indicating percolation of water to these depths; however, coring and analysis of Cl profiles in a nearby borehole after this time indicated steadily increasing Cl concentrations from an average value of 40 mg/L in the top meter to a peak value (1550 mg/L) at 4 m depth. Heat-dissipation sensors were also installed within a 2-m radius of the original thermocouple psychrometer installations and indicated much lower matric potentials in the upper 6 m

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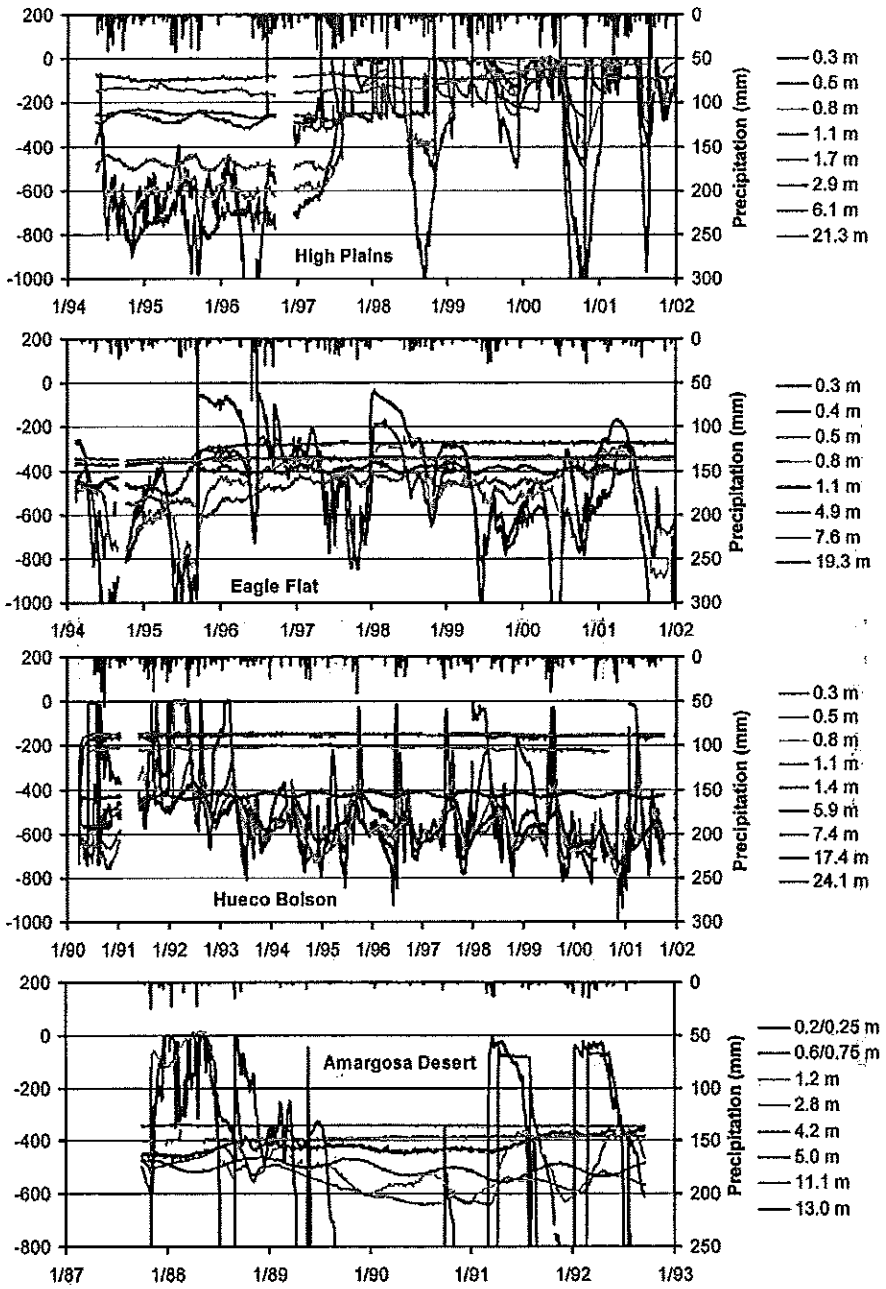


**Figure 5.** Temporal variability in water potential monitored in situ at various depths at each site. Daily precipitation is also shown. See color version of this figure at back of this issue.

than the thermocouple psychrometer data. These results underscore the difficulties of monitoring structured soils without artificially creating preferential pathways.

[18] Temporal variations in water potential decrease with depth. Seasonal water potential fluctuations occur to depths of ~5 to 7 m and can be seen most clearly in data from the HB site. These fluctuations are attributed to seasonal temperature fluctuations similar to those recorded in another nearby profile [*Scanlon*, 1994]. Large seasonal fluctuations in water potentials at the AD site (e.g., 1.2 m depth) could not be explained by temperature effects on water potential and were attributed to seasonality of vapor fluxes [*Andraski and Jacobson*, 2000].

### 3.2. Comparison of Field- and Laboratory-Measured Water Potentials

[19] Many previous studies of flow in semiarid and arid regions are based on laboratory-measured water potentials [*Prych*, 1998; *Izbicki et al.*, 2000; *Walvoord*, 2002]; however, these measurements may be biased because of the possibility of sample drying during field collection. Field monitoring should accurately record in situ water potentials.

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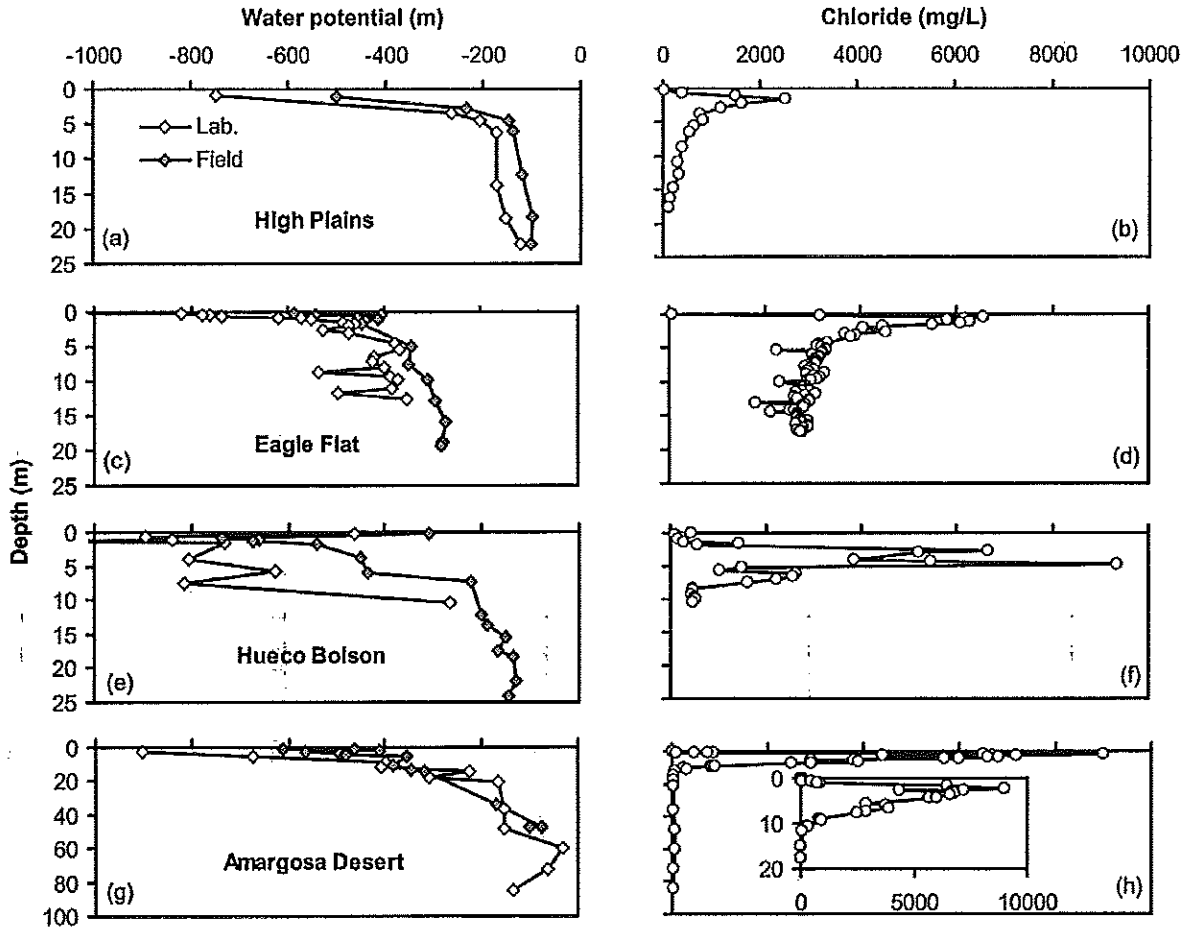


**Figure 6.** Water potential profiles (laboratory measured and field monitored) and Cl concentration profiles for each site. The inset in the Amargosa Desert Cl profile shows more detail in the upper 20 m zone.

Comparison of laboratory- and field-measured water potentials indicates that the trends in both are similar; lowest water potentials at the surface indicate very dry conditions, and exponentially increasing water potentials with depth indicate progressively wetter conditions (Figure 6). However, laboratory-measured water potentials were generally lower (more negative) than field-measured water potentials. Water loss from coarse-textured and low water content soils can be most problematic because a small change in water content can result in a large change in water potential. Laboratory- and field-measured water potentials (Figure 6) indicate that core drying can result in errors as great as 250 to 600 m.

### 3.3. Chloride Profiles

[20] All Cl profiles are bulge shaped with low Cl concentrations near the surface, increasing to peak concentrations that ranged from 2,515 mg/L (1.6 m depth, HP) to 9,343 mg/L (4.7 m depth, HB), and decreasing to lesser concentrations of 20 mg/L (AD) to ~2,600 mg/L (EF) (Figure 6). The low Cl concentrations near the surface are attributed to leaching of Cl by seasonal infiltration. Peak Cl concentrations were lowest in the semiarid HP site and much higher in the arid sites. Peak Cl concentrations at the AD and HB sites were similar (~9000 mg/L). The Cl profile at the HB site is multipeaked. Cl concentrations at depth were one to two orders of magnitude lower than peak values, with the exception of the EF site, which has high Cl concentrations at depth (~2600 mg/L).

[21] The bulge-shaped Cl profiles have generally been interpreted as representing accumulation of Cl since the Pleistocene (Figure 7). Total profile CMB ages were calculated using the best available estimates of average Cl input during the Holocene. CMB ages for the entire profile ranged from 9 to 18 kyr for HP, AD, and HB sites (Table 1). In contrast, CMB age for the EF site was much higher (90 kyr). This high CMB age raises the question about whether there are additional sources of Cl at the EF site. The EF site is located ~25 km southwest of a Salt Flat playa; however, Cl/Br ratios (92–150) in subsurface profiles are similar to Cl/Br ratios in precipitation at this site (24–167) and are typical of meteoric Cl [*Davis et al.*, 1998]. Cl/Br ratios in samples affected by halite dissolution typically range from 1000 to 10,000 [*Davis et al.*, 1998]. Cl/Br ratios remain fairly uniform with depth at the EF site (Figure 8). Prebomb $^{36}$Cl/Cl ratios in different profiles at the EF site (383 ×

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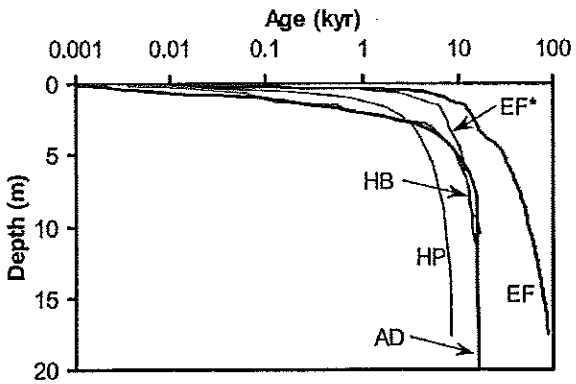


**Figure 7.** Chloride mass balance age versus depth for profiles at the Hueco Bolson (HB), High Plains (HP), Amargosa Desert (AD), and Eagle Flat (EF) sites. EF* represents Eagle Flat profile after the background concentration of 2800 mg/L was subtracted from shallow bulge.

$10^{-15}$ to $723 \cdot \times 10^{-15}$) are significantly higher than those in the Salt Flat ($\sim 90 \times 10^{-15}$) and suggest that Cl input from the Salt Flat is unlikely [*Scanlon*, 2000]. A Cl bulge can be identified in the EF profile, and the Cl inventory of this bulge was estimated by subtracting the background concentration of 2600 mg/L from the Cl concentrations. The CMB age of this bulge is ~12 kyr, which is similar to the ages estimated for the bulges in the other profiles (9 kyr, HP to 16 kyr, AD) (Table 1).

[22] Water fluxes were estimated from Cl concentrations below the Cl bulge and range from 0.04 mm/yr (EF) to 8.4 mm/yr (AD) (Table 1). These water fluxes are interpreted to represent fluxes during the cooler, wetter climate of the Pleistocene for most profiles and much longer time periods for the EF site (~12 to 90 kyr). Water fluxes were highest at the AD (8.4 mm/yr) and HP (1.3 mm/yr) sites, which may reflect wetter conditions during the Pleistocene at these sites relative to the Chihuahuan Desert sites. The proximity of the EF and HB sites in the Chihuahuan Desert suggests that the paleoclimatic forcing at these two sites should have been similar. The difference in Pleistocene water fluxes between the two sites (EF, 0.04 mm/yr; HB, 0.2 mm/yr) may be attributed to coarser grained sediments at the HB site, which allowed this system to respond much more to wetter conditions during the Pleistocene than did the EF site. This negligible response to Pleistocene conditions at the EF site is also consistent with the shallowest penetration of the wetting front at the EF site under current climatic forcing (Figure 5). These data demonstrate the importance of sediment texture in controlling system response to paleoclimatic forcing.

### 3.4. Numerical Modeling

#### 3.4.1. Simulated Versus Measured Water Potential and Cl Profiles

[23] Simulated matric potential profiles agree reasonably well with measured water potential profiles (Figure 9). The wet initial conditions corresponding to mesic vegetation during the Pleistocene pluvial period were based on downward simulations of water fluxes estimated from Cl concentrations beneath the bulge. A constant matric potential sink was assigned to the base of the root zone to represent the transition to xeric vegetation during the Holocene period, which is approximated by the CMB age at the base of the Cl bulge at each site (Table 1). Simulated matric potentials are similar to current measured water potentials at the end of this time period. The time required to reproduce the measured water potential profile at the HP site (~1–2 kyr) is much shorter than the CMB age at the base of the Cl bulge (~9 kyr) at this site. Simulated matric potentials at the EF site overestimate measured water potentials but are similar to estimated matric potentials from field data calculated by subtracting the osmotic potential. These data are discussed in more detail in section 3.5.2. Simulated matric potentials and measured water potentials at the HB site are similar in magnitude; however, the simulated minimum matric potential is deeper than the measured minimum because the depth of the root zone was based on the peak Cl concentration. The simulations of the AD site overestimate measured water potentials, even after 16 kyr of upward flow related to xeric vegetation.

[24] There is also fairly good agreement between simulated and measured Cl profiles. Simulations of the HP, EF, and AD sites underestimate the Cl peak by up to 25%, whereas simulations of the HB site overestimate the peak by 75%. Simulated Cl concentrations at depth below the peak underestimate measured values at the HB site. The Cl bulges result primarily from addition of Cl to the system from precipitation, with the exception of the EF site, where upward flow from depth contributes about 70% of the Cl to the bulge because of the high Cl concentrations at depth. Because water movement is upward below the root sink, diffusion driven by the concentration gradient is the only process that can transport Cl below the sink. These results demonstrate that it is possible to generally reproduce measured water potential and Cl profiles by simulating the transition from mesic to xeric vegetation and associated upward flow for long time periods (1–16 kyr).

[25] Cl bulges are excellent indicators of low water flux, and their formation process is similar to that of calcic soils. Both Cl profiles and calcic soils indicate low water flux; however, Cl is much more readily flushed out of the soil profile under increased downward fluxes than calcium carbonate, which can remain in a relict calcic horizon for

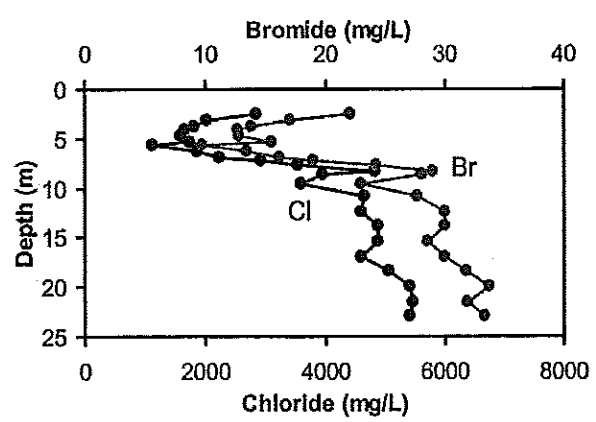


**Figure 8.** Chloride and bromide concentrations in an EF site profile.

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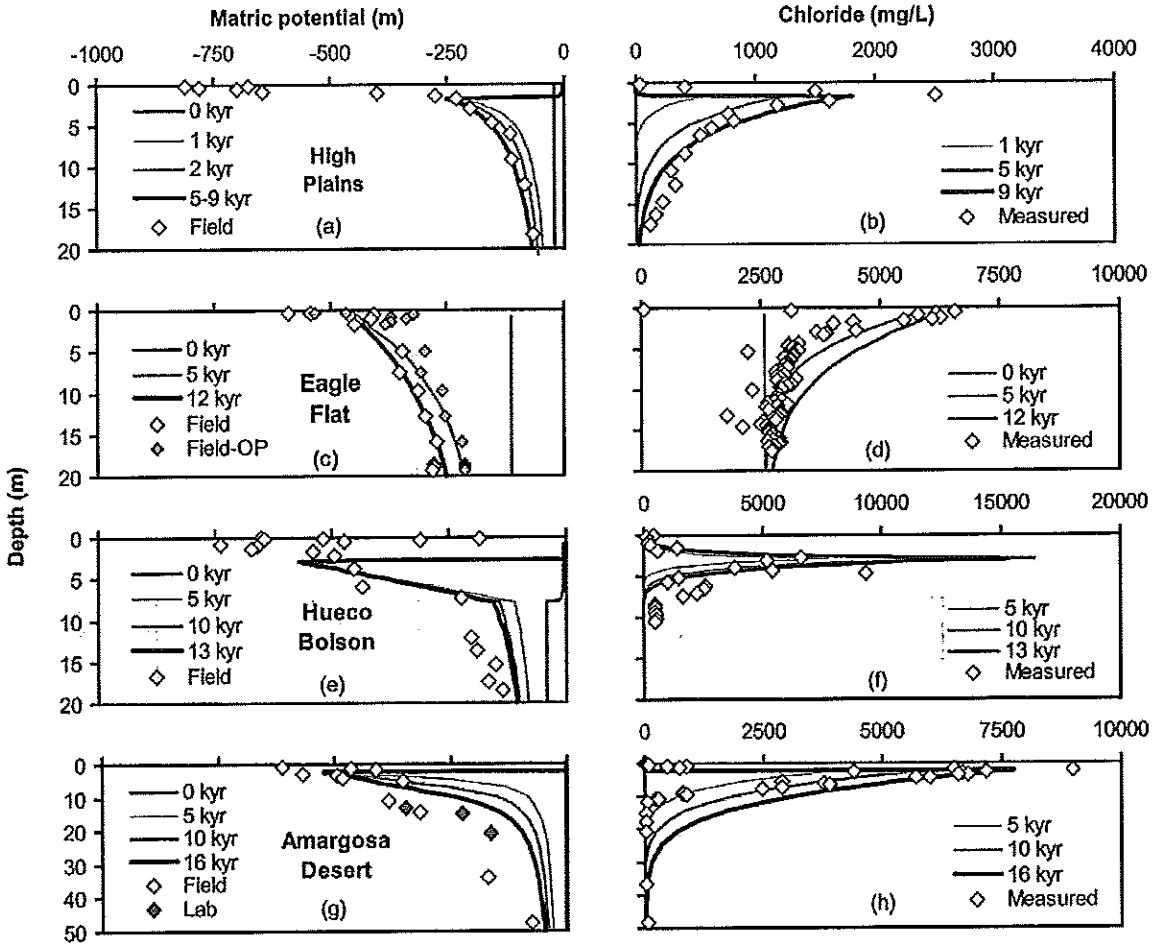


**Figure 9.** Simulated matric potentials and Cl concentrations for each site. Time 0 kyr represents wet initial conditions (Pleistocene pluvial period). The remaining times represent different periods of upward flow to a maximum time based on CMB age at the base of the Cl bulge for each site. Measured water potential and Cl profiles are shown for comparison with simulated profiles. Estimated matric potentials are also shown for the EF site after subtracting the osmotic potential (Field - OP). Laboratory-measured water potentials are also included in the AD profile to fill a gap in the field-measured data.

a long time. This can be shown by flushing of the AD Cl profile with a flux of 10 mm/yr (Figure 10). The Cl bulge moves deeper with time, and the peak concentration decreases with time. After 2000 yr, the Cl bulge was completely flushed out of the profile.

### 3.4.2. Relative Importance of Liquid and Vapor Flow

[26] Simulated water-flux profiles for each site reveal differences in flux regimes among the sites (Figure 11). All of the simulations include enhanced vapor flux. Total water flux includes liquid and vapor flux components. The flux profiles at the HP site show propagation of the drying front with time (Figure 11a). Vapor flux is negligible at this site; therefore liquid water and total water (liquid + vapor) fluxes are approximately equivalent. After 1 kyr of drying, total water flux is divergent, with upward water flux (positive) in the top ~25 m controlled by matric potential forces and downward water flux (negative) at greater depth

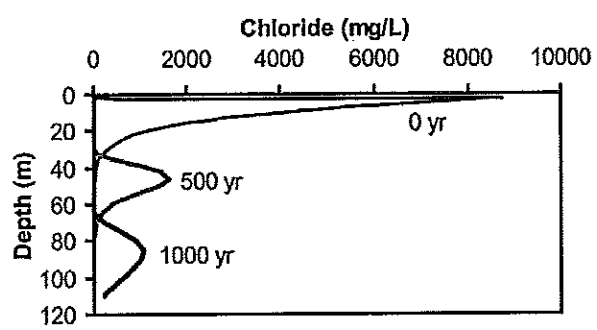


**Figure 10.** Flushing of Cl caused by a downward water flux of 10 mm/yr. The 0 yr profile represents the measured Cl concentration at the AD site.

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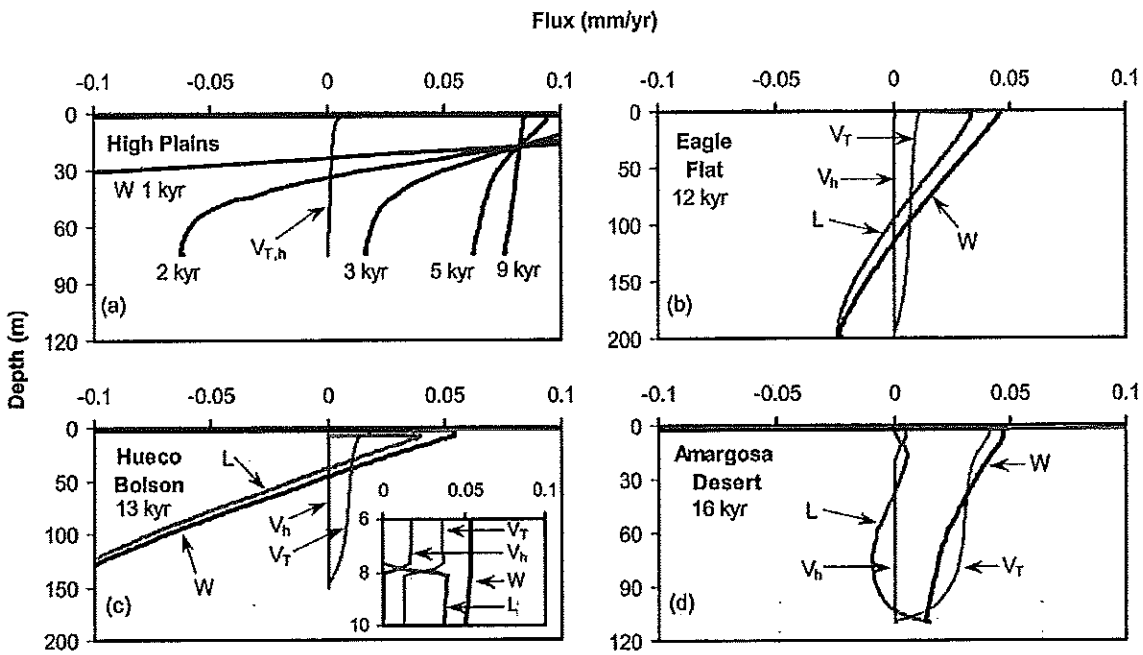


**Figure 11.** Simulated total water (W), liquid (L), isothermal ($V_h$), and thermal ($V_T$) vapor flux profiles that represent current conditions after drying for different time periods since Pleistocene pluvial conditions. Downward fluxes are negative and upward fluxes are positive. The propagation of the drying front is shown for the HP site by including results after 1, 2, 3, 5, and 9 kyr of drying. Liquid flux at the HP site is approximately equal to total water flux.

controlled by gravity. The plane of divergence can exist in the profile because of the transient nature of flow. The plane of divergence reaches a depth of ~35 m after 2 kyr of drying. After ~3 kyr of drying the plane of divergence has reached the water table, and water flux is upward throughout the entire profile. The profile has almost reached steady state after 9 kyr of drying with a uniform upward water flux of ~0.08 mm/yr. This upward flux differs in magnitude and direction from the water flux estimated according to the CMB approach (1.3 mm/yr downward).

[27] The total water flux profile at the AD site after 16 kyr of drying is upward throughout the unsaturated zone (Figure 11d). Simulated total water flux at the base of the profile is ~0.01 mm/yr upward, which is in the opposite direction and much lower than the downward CMB flux of 8.4 mm/yr. In contrast to the HP site, vapor flux is dominant at the AD site. Thermal vapor flux is dominant throughout most of the profile, whereas isothermal vapor flux is negligible except near the surface where matric potential gradients are steep. Thermal vapor flux is fairly uniform throughout much of the profile (~0.03 mm/yr) and decreases to zero at the water table because the sediments become saturated. Liquid water flux is upward in the upper ~40 m, controlled by matric potential gradients, and generally downward at greater depth, controlled by gravity.

[28] The plane of divergence for total water flux is within the unsaturated zone for the two deeper profiles (EF and HB) in the Chihuahuan Desert (Figures 11b and 11c). The plane of divergence of total water flux is ~115 m deep in the EF profile after 12 kyr of drying. Liquid flux is upward in the upper 95 m as a result of matric potential gradients and downward below 95 m as a result of gravity. Thermal vapor flux is upward throughout the profile and ranges from 0 at the water table to 0.01 mm/yr near the surface. The flux profiles at the HB site are similar to those at the EF site except that the planes of divergence of liquid and total water flux are shallower (~40–45 m deep). Vapor flux is dominated by thermal vapor flux, which ranges from 0 at the water table to 0.01 mm/yr at the base of the shallow sand zone (8-m depth). Isothermal and thermal vapor fluxes increase in the sand zone by a factor of ~2 to 4, whereas liquid water flux decreases to ~0. Simulated downward water fluxes at the base of the EF and HB profiles (0.02 and 0.13 mm/yr, respectively) are less than the CMB-calculated fluxes (0.04, 0.2 mm/yr).

[29] The magnitude of vapor fluxes varied among sites. Negligible vapor fluxes at the HP site are attributed to high water contents associated with fine-grained sediments and to the higher matric potential assigned to the root sink (Table 1). Although sediments at the HP site are similar to those at the HB site below the sand zone, vapor fluxes are higher at the HB site because the matric potential at the root sink is much lower at this site relative to the HP site. Vapor fluxes are similar in the fine-grained sediments at the HB and EF sites. High vapor fluxes in the upper 8 m at the HB site and throughout the AD profile are attributed to coarse-grained sediments and extremely low water contents.

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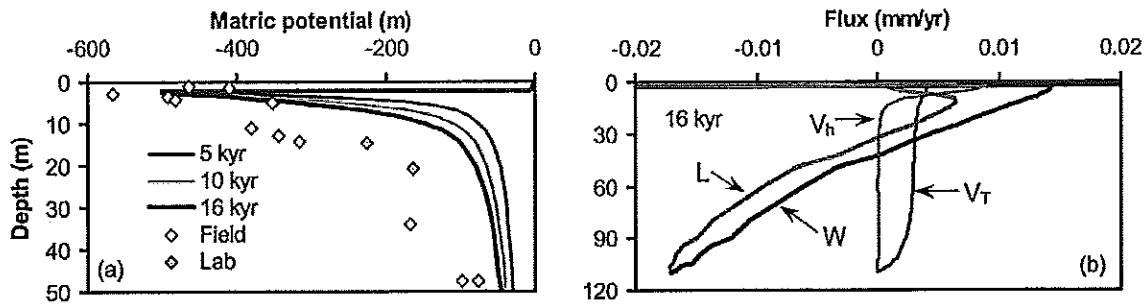


**Figure 12.** Simulated matric potentials and fluxes (total water (W), liquid (L), isothermal ($V_h$), and thermal ($V_T$) vapor) for unenhanced vapor flux at the AD site. For comparison with enhanced vapor flux, see Figure 9g for simulated water potential and Figure 11d for simulated fluxes. Field- and laboratory-measured water potentials are also shown.

[30] The effect of the enhancement factor on thermal vapor diffusion was evaluated in simulations of the AD profile where vapor flux was highest throughout the profile. The enhancement factor increases with water content (Figure 4). Neglecting the enhancement factor in simulations resulted in up to 30% higher (less negative) matric potentials and much lower thermal vapor fluxes by almost an order of magnitude (Figure 12). Similar results were found at the EF site. The flux regime for the AD site changes from upward total water flux throughout the profile under enhanced vapor-flux conditions (Figure 11d) to a divergent flux regime at 35-m depth under unenhanced vapor-flux conditions (Figure 12b). Simulated Cl profiles were similar for enhanced and unenhanced vapor flux.

[31] With the exception of the HP site, which almost reached steady state after ~9 kyr of drying, none of the other profiles had reached steady state at the end of the drying period (Figure 11). To evaluate steady state fluxes, a simpler simulation was conducted with a constant pressure head at the surface equal to that assigned to the root sink. Pressure and flux profiles are shown for the EF and AD sites (Figure 13). The flux profile had almost reached steady state after 60 kyr of drying at the EF site and after 100 kyr of drying at the AD site. However, it is unlikely that these profiles will ever reach steady state in the natural system because the timescales for climate change (~10 kyr) are much shorter than the time required to reach steady state. Total water flux is upward throughout the profile at steady state (EF ~0.03 mm/yr; AD ~0.05 mm/yr). Liquid water fluxes decrease with elevation above the water table as the sediments become drier. Decreasing upward liquid water fluxes are balanced by increasing upward thermal vapor fluxes. Thermal vapor fluxes were expected to decrease with elevation above the water table because temperature decreases with elevation; however, the effect of decreasing water content on thermal vapor conductivity ($K_{vT}$) outweighs the effect of decreasing temperature in these profiles. For example, the change in $K_{vT}$ with water content throughout much of the AD profile (water content 0.040–0.075 $m^3\ m^{-3}$; T = 24°C) was about two times greater than the change in $K_{vT}$ with temperature (22–26°C; water content 0.06 $m^3\ m^{-3}$). Isothermal vapor fluxes are negligible throughout both profiles at steady state.

[32] Flux profiles described in this study were compared with typical flux profiles that were described by *Walvoord et al.* [2002] using the deep arid system hydrodynamics (DASH) model for the southwestern United States. Vapor flow was considered an integral part of the DASH model; however, in this study it was found that fine-grained sediments and wetter conditions at the HP site resulted in negligible vapor flux. The flux profile at the AD site after 16 kyr of drying without enhanced vapor flux (Figure 12b) is most similar to the typical profile described by the DASH

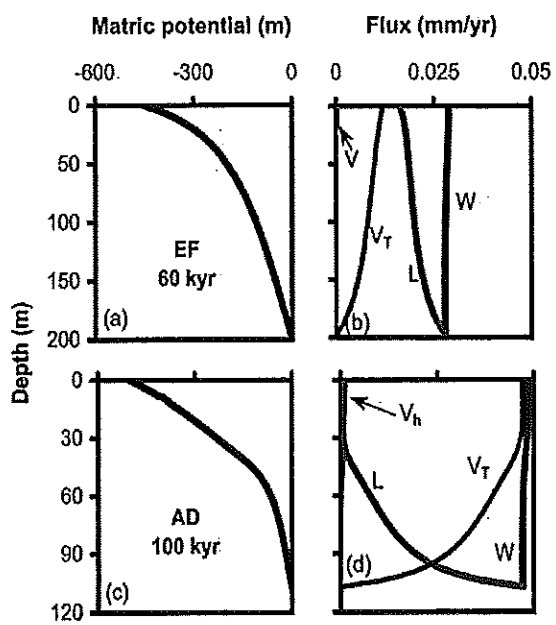


**Figure 13.** Simulated matric potentials and fluxes (W, total water flux; L, liquid water flux; $V_T$, thermal vapor flux; $V_h$, isothermal vapor flux) at steady state at the EF and AD sites. Matric potentials in equilibrium with the gravitational potential field under isothermal conditions are shown for comparison with simulated matric potentials.

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model because both profiles have coarse-grained sediments and matric potentials at the root sink are similar. The steady state flux profile for the AD site, however, differs significantly from the steady state base case profile for the DASH model simulated using the FEHM code. The differences cannot be attributed to the use of different codes because the patterns in fluxes and heads in the DASH base case could be reproduced using HYDRUS-1D that used unenhanced vapor flux. The differences in flux profiles between the two sites can be attributed to differences in water retention functions. Thermal vapor flux at the AD site is dominated by the effect of water content, which decreases by up to a factor of 2 with elevation throughout much of the profile and results in increasing thermal vapor flux with elevation. In contrast, water content remains fairly uniform with elevation in the DASH base case; therefore temperature is the dominant driving force for thermal vapor flux, which decreases with elevation as temperature decreases and is balanced by downward liquid water flux at depth. This comparison underscores the difficulties of developing general profiles because of variability in climatic conditions and hydraulic properties from site to site.

### 3.5. Uncertainty Analysis

[33] Evaluation of uncertainties is important in order to identify gaps in our knowledge and areas of future research. Uncertainty analysis conducted by *Walvoord et al.* [2002] addressed the effects of varying water table depths, saturated hydraulic conductivities, geothermal gradients, and vapor diffusion enhancement. The current study builds on the uncertainty analysis of *Walvoord et al.* [2002] and addresses uncertainties in CMB ages, osmotic component of water potentials, and numerical modeling. Uncertainties in numerical modeling include those related to conceptual models, hydraulic parameterization, and solute diffusion coefficients. Improving understanding of these uncertainties is critical to evaluating subsurface flow and transport in response to paleoclimatic forcing.

#### 3.5.1. Chloride Mass Balance Ages and Fluxes

[34] In assessing the response of subsurface flow and transport to past climate fluctuations, we rely on the chloride mass balance (CMB) approach to determine the age of the water and to compare water fluxes during different climatic conditions. The Pleistocene/Holocene climate and associated vegetation transition generally occurred about 10 to 15 ka. CMB ages for the base of the Cl bulges vary from ~9 kyr for HP to 16 kyr for AD (Table 1). Water fluxes (0.04–8.4 mm/yr) were also estimated from Cl concentrations beneath the bulge representing the Pleistocene. What are the uncertainties in these CMB ages and fluxes? Uncertainties in various parameters in the CMB equation linearly translate to uncertainties in calculated ages and fluxes because the equations for estimating ages and fluxes are linear. Detailed analysis of uncertainties related to the CMB approach is described by *Scanlon* [2000]. In this section, we focus on uncertainties in Cl input, which was estimated from prebomb $^{36}Cl/Cl$ ratios for the HP, EF, and HB sites [*Scanlon*, 1991, 2000; *Scanlon and Goldsmith*, 1997]. Uncertainty in these estimates has previously been assigned ±35% [*Scanlon*, 2000]. Accurate estimates of Cl input are not available for the AD site. The CMB age previously estimated at the base of the AD site's Cl bulge (16.5 kyr [*Phillips*, 1994]) was based on incorrectly calculated Cl concentrations [*Fouty*, 1989] that differed from true Cl concentrations by a factor of 1.7 (bulk density of the soil) [*Prudic*, 1994]. Applying the same Cl input (100 mg/m$^2$/yr) used by *Phillips* [1994] with the correct Cl concentrations would result in an age of 28 kyr. If we assume that the Cl bulge generally represents accumulation after the Pleistocene, a CMB age of ~16 kyr would require a Cl input of 173 mg/m$^2$/yr. This Cl input value is similar to the upper range of values suggested by *Prudic* [1994] and may reflect additional Cl from run-on. Increasing the Cl input will also increase the estimated water flux during the Pleistocene.

[35] Estimation of Cl inputs in many areas has been somewhat arbitrary. For example, the Cl input at Frenchman Flat at the Nevada Test site was increased by a factor of 1.5 to account for increased precipitation during the Pleistocene [*Tyler et al.*, 1996]; however, this increased input has also been applied to the Holocene record, which would underestimate the age of the Pleistocene/Holocene transition by 1.5. Cl inventories estimated from Cl bulges generally are locally variable. For example, profiles in interstream settings in the Hueco Bolson have inventories that correspond to ages of 13 to 25 kyr at the base of the Cl bulge [*Scanlon*, 1991]. *Walvoord* [2002] also noted differences in Cl inventories of up to a factor of two in a study of the Trans-Pecos region in Texas. This variability may reflect variations in input related to subtle differences in topography or run-on. CMB ages may not be sufficiently accurate to locate the Pleistocene/Holocene transition; however, the Cl bulges in many cases can generally be assumed to correspond to Cl accumulation during the Holocene and appropriate ages calculated by varying the Cl input within the range of uncertainties.

#### 3.5.2. Osmotic Component of Water Potential

[36] Thermocouple psychrometers at each site monitor water potentials, which include matric and osmotic potentials. However, the HYDRUS-1D code simulates only matric potentials and does not include osmotic potentials. Isothermal vapor flux driven by osmotic potentials was estimated for the AD site, which has the steepest Cl concentration gradient (Figure 6h). Osmotic potentials were estimated from the Cl concentration data [*Campbell*, 1985; *Scanlon*, 1994] and the gradient resulted in an isothermal vapor flux that was about an order of magnitude less than the average isothermal vapor flux driven by the matric potential gradient in this zone. Simulated isothermal vapor fluxes driven by matric potentials are close to zero at most sites; therefore osmotically driven vapor fluxes are negligible. However, osmotic potentials also affect the simulated time required to reproduce the measured water potentials and ignoring osmotic potentials may result in overestimation of this time.

[37] It is difficult to estimate osmotic potentials. Estimates of osmotic potentials based on Cl concentrations should provide a lower boundary on osmotic potentials because many more ions are in solution than Na and Cl. Osmotic potentials based on NaCl data at the sites examined in this study are generally less than 10 to 20% of the measured water potentials because the depths where osmotic potentials are most negative generally correspond to the depths where water potentials are also most negative [*Fischer*, 1992; *Scanlon*, 1994]. Osmotic potentials may be

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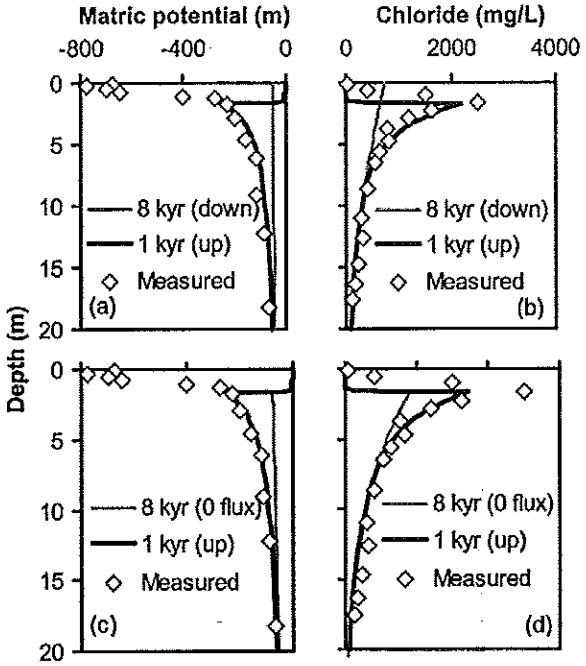


**Figure 14.** Alternative conceptual models for simulating measured water potentials and Cl profiles at the HP site. Simulations based on downward flux ~0.1 mm/yr (a and b) and zero flux (c and d) for 8 kyr followed by upward flux for 1 kyr are shown. Measured water potentials are also shown.

important at the EF site where Cl concentrations at the base of the profile are ~2600 mg/L (Figures 9c and 9d). Studies by *Izbicki et al.* [2000] indicate that osmotic potentials calculated using only NaCl data differ from those based on total ion chemistry by a factor of ~4. Differences in measured water potentials between HB (−140 m) and EF (−300 m) sites at depth may be explained by osmotic potentials if we increase, by a factor of 4, the osmotic potentials based on NaCl (−40 m) for the EF site. Osmotic potentials are difficult to estimate accurately because soil-solution samplers do not function at these low water potentials and it is difficult to extract water using centrifugation. The effect of bound water may also be important.

### 3.5.3. Numerical Modeling

#### 3.5.3.1. Conceptual Model Uncertainty

[38] The conceptual model used in this study is relatively simple and assumes downward water flux associated with mesic vegetation during the Pleistocene and upward water flux near the root zone associated with xeric vegetation during the Holocene. Upward flow creates a drying front that propagates deeper into the profile with time and results in matric potentials similar to field-measured water potentials.

[39] Alternative conceptual models to upward flow may be appropriate for the High Plains site, where field-monitored water potentials can be simulated after 1 to 2 kyr of drying (Figure 14). Reduction in water flux from the Pleistocene (~1.3 mm/yr) to the Holocene (~0.1 mm/yr) or zero flux for 8 kyr, followed by upward flux for 1 kyr, also reproduced the measured water potential and Cl profiles at this site. Therefore at this site a variety of alternative conceptual models are feasible. These alternative models are not appropriate for the other sites because long times are required to simulate the measured low water potentials.

[40] The conceptual model of xeric vegetation during the Holocene assumes that the root zone is fixed at a single time and remains at a fixed depth during the time required to accumulate Cl bulges (~9–16 kyr). Fixing the root zone at a single time assumes that the transition from mesic to xeric vegetation occurred over a short timescale relative to the timescale for climate change. Assuming uniform rooting depth during the Holocene may not be appropriate because water potential and Cl profiles in some settings indicate that roots may extend to greater depths than represented in our models. In an ephemeral stream setting with extremely dense mesquite trees in the Eagle Flat Basin, low water potentials, with the typical curved exponential shape and very low Cl concentrations, suggest that deep-rooted mesquite trees can extract water from the subsurface and create low water potential profiles in shorter times than required to accumulate Cl (Figure 15). Roots of mesquite trees have been found to depths of ≥6 m in fissured sediments at the HB site [*Scanlon*, 1992]. Similar results were found by *Walvoord* [2002] in an area where juniper trees occur. Therefore, if the assumption of constant rooting depth over the Holocene fails, dense vegetation with much deeper roots may be able to create upward water potential gradients over much shorter time periods than required to accumulate Cl bulges.

#### 3.5.3.2. Hydraulic Parameterization

[41] Hydraulic parameterization was relatively simplistic for the simulations in this study. Most sites are represented by a homogenous sediment profile. The effect of varying sediment texture at the AD site was evaluated by replacing layer 1 with layer 3 material properties [*Andraski and Jacobson*, 2000]. Layer 3 has lower saturated water content (0.22) than layer 1 (0.29) and higher saturated hydraulic conductivity (3.2 m/d) by about an order of magnitude than layer 1 (0.4 m/d). Because of the linear effect of varying water content on simulated Cl concentrations, varying the porosity by ~25% resulted in varying the simulated Cl concentrations by the same amount. Increasing the saturated hydraulic conductivity had little impact on simulated matric potentials because the drying process is controlled primarily by thermal vapor flux.

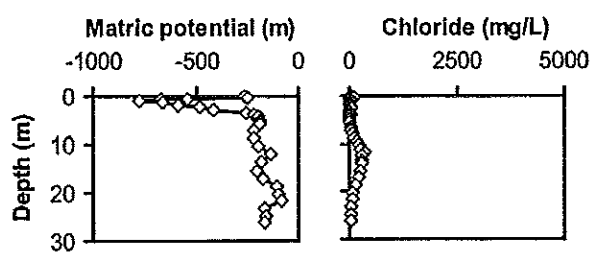


**Figure 15.** Water potential and Cl profiles in an area of dense mesquite trees in an ephemeral stream setting in the Eagle Flat Basin.

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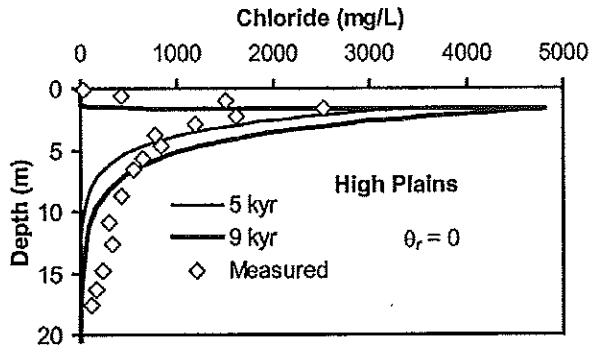


**Figure 16.** Simulated Cl profile for the HP site using a water retention function with zero residual water content. For comparison with nonzero residual water content (0.06 $m^3/m^3$), see Figure 9b.

[42] Although residual water content is treated as a fitting parameter in many retention functions, *Ross et al.* [1991] and *Rossi and Nimmo* [1994] indicated that it is more appropriate to set residual water content to zero at a finite matric potential ($10^5$ m, equivalent to oven drying at 105°C at a room relative humidity of 50%). All simulations were rerun with zero residual water content, which resulted in water content at a matric potential of $10^5$ m being reduced from 3–8% to 0–3% for the different materials. Simulated matric potentials were similar for zero and nonzero residual water contents. However, reducing residual water content reduced simulated water content and increased simulated Cl concentrations. The effect of reducing residual water content was greatest at the HP site because the original residual water content (0.06 $m^3/m^3$) was highest at this site and the resultant simulated peak Cl concentration increased by up to a factor of 2.6 (Figure 16).

[43] Simulated Cl profiles are also sensitive to varying other parameters in the water retention function, such as the van Genuchten n parameter. For example, varying n from 1.3 to 1.5 for the AD site had little impact on simulated matric potentials, but it decreased simulated water content and doubled simulated peak Cl concentration (Figure 17). These results demonstrate that simulated Cl profiles are very sensitive to water retention functions because of their dependence on simulated water content.

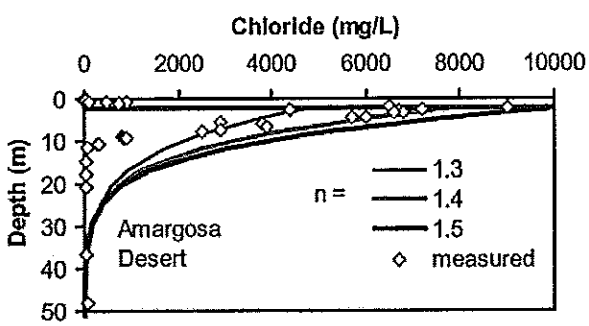


**Figure 17.** Effect of varying the water retention function (van Genuchten n parameter) on simulated Cl profiles at the AD site.

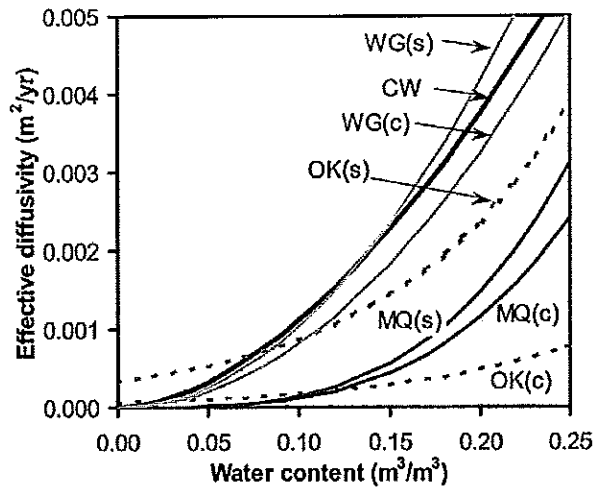


**Figure 18.** Effective diffusivity ($D_e$) for Cl calculated using expressions from *Millington and Quirk* [1961] (MQ), *Wilson and Gelhar* [1974] (WG), and *Olsen and Kemper* [1968] (OK) for sand (s) and clay (c) and from *Conca and Wright* [1992] (CW; independent of sediment texture).

#### 3.5.3.3. Cl Diffusion

[44] The main scenario evaluated in the modeling study was upward flow during the Holocene related to the root sink, which requires diffusion driven by concentration gradients to transport Cl below the root zone. Uncertainties related to Cl diffusion result primarily from uncertainties in the calculation of effective diffusivities ($D_e$). Several expressions are described in the literature for calculating $D_e$ (Figure 18). The *Millington and Quirk* [1961] equation ($D_e = D_0\theta^{10/3}/\phi$) was used to calculate $D_e$ for most sites where $D_0$ is Cl diffusivity in pure water ($2.03 \times 10^{-9}$ $m^2/s$ [*Cussler*, 1984]) and $\phi$ is porosity. The *Conca and Wright* [1992] equation ($D_e = D_0\theta^{1.76}$) was used for the AD site because it resulted in a better fit to the measured Cl concentrations. To evaluate the impact of different $D_e$ values on simulated Cl profiles, Cl profiles for the AD and HB sites were simulated using both Millington and Quirk and Conca and Wright diffusion equations. The much higher $D_e$ values estimated using the Conca and Wright equation result in more diffuse Cl profiles with lower peaks than those simulated using the Millington and Quirk equation (Figure 19). Recent studies by *Schaefer et al.* [1995] indicate that $D_e$ values using a parallel liquid phase diffusion resistance model were up to two orders of magnitude greater than those based on the Millington and Quirk equation. The Schaefer model includes interparticle and intraparticle diffusion and indicates that diffusion becomes negligible at low water contents ($\theta \sim 1$ to 2%), when only intraparticle diffusion occurs. Large uncertainties in $D_e$ coefficients, particularly at low water contents, underscore the need for rigorous testing of existing models and possible development of new models.

### 3.6. Future Studies

[45] Results of the uncertainty analysis identify gaps in our knowledge and the need for additional research. The

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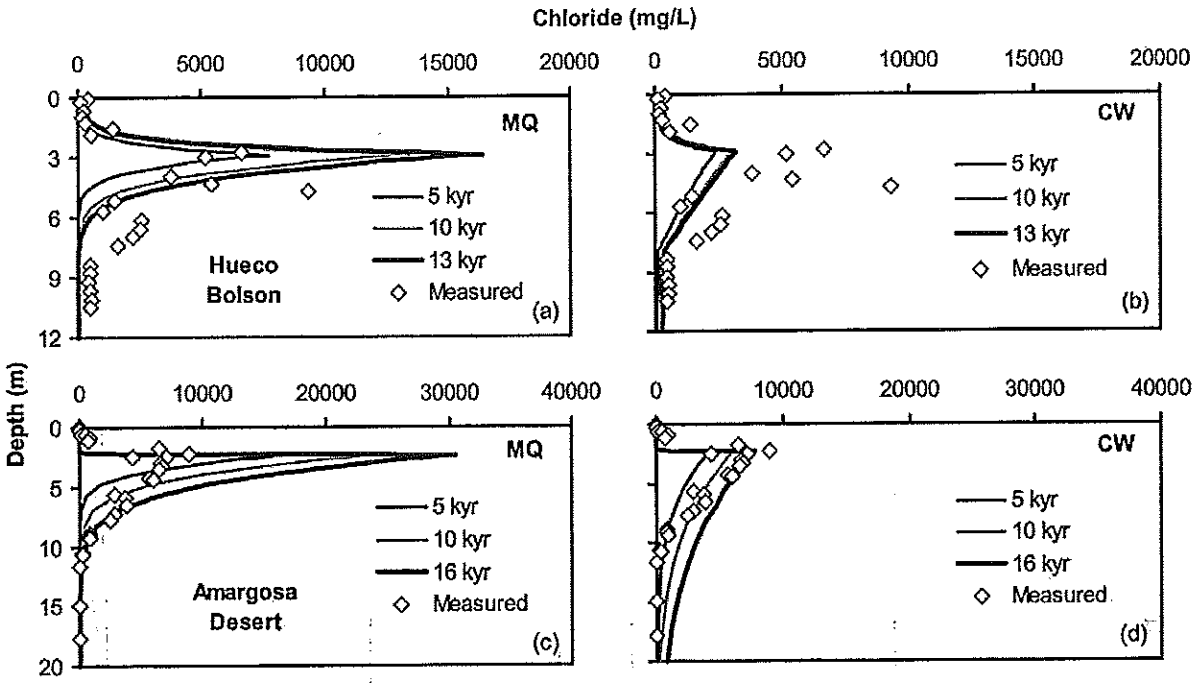


**Figure 19.** Effect of using *Millington and Quirk* [1961] (MQ) versus *Conca and Wright* [1992] (CW) effective diffusivities on simulated Cl profiles at the (a and b) Hueco Bolson and (c and d) Amargosa Desert sites. Measured Cl concentrations are shown for reference.

main sources of uncertainty evaluated in this study include (1) Cl input for the CMB estimated fluxes and ages, (2) osmotic component of water potential, (3) conceptual model, and (4) parameterization of the numerical models. Studies are currently being conducted by the U.S. Geological Survey to quantify spatial variability in Cl inputs at a number of sites in the southwestern United States (Izbicki, personal communication, 2000). However, it is much more difficult to determine whether Cl inputs have been temporally uniform over the timescales evaluated in this study. Uncertainties in the osmotic component of water potential should be evaluated by quantifying the osmotic potential and using codes that simulate osmotic potentials, such as that described by *Nassar and Horton* [1992]. The impact of the development of osmotic potentials on subsurface flow as Cl accumulated in the profile could be examined using these simulations.

[46] The modeling results from this study indicate that the formation of upward water potential gradients requires time periods at the same scale as those required to accumulate Cl. However, some profiles in areas of dense vegetation indicate that low water potentials and upward gradients can be developed over much shorter timescales than those required to accumulate Cl. Additional profiling should be conducted in similar settings to determine the prevalence of such conditions.

[47] The *Philip and de Vries* [1957] enhancement factor for thermal vapor conductivity is based on theory developed in the late 1950's. Because the enhancement factor based on experimental data from *Cass et al.* [1984] significantly increased thermal vapor fluxes at many of the sites considered in this study, the theoretical basis for the enhancement factor should be reexamined, and additional laboratory studies should be conducted to evaluate the enhancement factor.

[48] Simulations in this study were relatively simplistic. The profiles at most sites were approximated using a single soil type. Future simulations should consider the effect of heterogeneity and layering on simulation results. The wide range of models available to estimate effective diffusivities ($D_e$) for Cl transport and large uncertainties in $D_e$, particularly at low water contents, underscores the need for additional research on this topic. The importance of Cl diffusion at sites examined in this study can be tested further by measuring $^{37}Cl/^{35}Cl$ ratios because the lighter $^{35}Cl$ isotope should diffuse faster than the heavier $^{37}Cl$ isotope [*Walvoord*, 2002]. Natural $^{37}Cl/^{35}Cl$ ratios are fairly uniform (±1 per mil from standard mean ocean Cl [*Eggenkamp*, 1997]). If diffusive Cl transport is dominant beneath the Cl bulge, then $^{37}Cl/^{35}Cl$ ratios should differ markedly from natural ratios. This approach was evaluated to a limited extent by *Walvoord* [2002] in Trans Pecos, Texas; however, the results were equivocal. Comparing the $^{37}Cl/^{35}Cl$ ratios beneath the bulge at the EF site where the profile looks highly diffusive with those at the HB site, where the multipeaked Cl profile suggests low diffusion, would help in evaluating the importance of diffusion in these settings. These proposed studies should help to better constrain simulation results and provide more insight into flow and transport in thick desert vadose zones.

### 3.7. Implications

[49] The results of this analysis have important implications for water resources. Simulation results suggest that

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deep water potential and Cl profiles are out of equilibrium with current climatic forcing. Water fluxes estimated from Cl profiles at depth represent paleofluxes during the Pleistocene (Table 1) and should not be used to estimate current water fluxes at depth. Simulation results indicate that current water fluxes at the base of the unsaturated zone differ in direction at some sites (HP and AD) and magnitude at all sites from CMB-calculated paleofluxes. Simulated water fluxes at the base of the unsaturated zone are almost three orders of magnitude less than that estimated by the CMB approach at the AD site. Therefore using the CMB approach to estimate recharge at this site would greatly overestimate water resource availability. In contrast, the similarity in CMB water fluxes and simulated water fluxes at the EF site is attributed to low water fluxes during Pleistocene and earlier times at this site, which were controlled by the fine-grained sediments.

[50] The results also have implications for waste disposal. Modeling results indicate that under present climatic conditions, the natural soil-plant system limits deep percolation of precipitation and contributes to upward water fluxes below the root zone. Thus waste cover systems that replicate the natural system could decrease the potential for precipitation to percolate downward and transport contaminants to underlying aquifers. However, changes in climate, disposal of liquids, and disturbances caused by construction of waste trenches and removal or replacement of native vegetation could negate positive waste isolation features of the natural system.

## 4. Conclusions

[51] Unsaturated flow and transport were evaluated in thick desert vadose zones beneath native vegetation in the High Plains (HP), Texas; in the Hueco Bolson (HB) and Eagle Flat (EF) Basins in the Chihuahuan Desert, Texas; and in the Amargosa Desert (AD), Nevada. Upward water potential gradients indicate that current water fluxes in the shallow subsurface of interdrainage semiarid and arid regions are upward. Minimum water potentials measured near the surface were extremely low (down to −1000 m), indicating very dry conditions. Long-term water potential monitoring (5–12 yr) shows that penetration of wetting fronts is restricted to the upper 0.3 to 3 m in response to seasonal fluctuations in precipitation. Low Cl concentrations beneath the Cl bulge at depths of ~10 to 25 m represent higher water fluxes during the Pleistocene.

[52] The response of subsurface flow to paleoclimatic forcing varied among the sites as a function of sediment texture. The Cl inventory in fine-grained sediments at the EF site represents ~90 kyr of accumulation in a 17.5-m-deep profile. High Cl concentrations (~2600 mg/L) at depth at this site represent low water fluxes (0.04 mm/yr) that persisted through the Pleistocene. In contrast, Cl inventories in coarse-grained sediments in the Chihuahuan and Amargosa Deserts represent ~12 to 16 kyr of accumulation within the Cl bulge. Low Cl concentrations at depth (20–460 mg/L) represent higher water fluxes (8.4 to 0.2 mm/yr) during the Pleistocene. The site in the High Plains has fine-grained sediments; however, Cl concentrations are low at depth, which suggests high water fluxes during the Pleistocene (1.3 mm/yr).

[53] Numerical modeling of nonisothermal liquid and vapor flow indicates that development of upward water potential gradients requires thousands of years and that the water potential and Cl profiles at depth are out of equilibrium with current climatic forcing but reflect Pleistocene climate conditions. The simulations suggest that the drying front that was initiated during the Pleistocene/Holocene climate shift has propagated downward slowly with time. Downward Cl transport occurs by diffusion against upward water flux in the shallow subsurface. The shallower profiles (water table depth ~100 m; HP and AD sites) have simulated upward total water flux throughout the unsaturated zone, whereas deeper profiles in the Chihuahuan Desert (water table depth ~200 m) have a divergent total water flux pattern with upward water fluxes in the upper 40 to 115 m depth and downward water fluxes below this zone. The relative importance of liquid and vapor flux varies among the sites as a result of variations in climate and sediment textures. Vapor flux is negligible at the HP site, where the sediments are fine grained and climate is wetter, whereas vapor fluxes are higher in the AD profile and in the upper 8 m of the HB profile, where the sediments are coarse grained and dry. Vapor fluxes at these sites are dominated by thermal vapor fluxes.

[54] Integration of soil-physics monitoring and environmental-tracer profiles with numerical modeling provided a comprehensive understanding of subsurface flow processes under current and past climatic conditions. The results of this study have important implications for water resources and indicate that current recharge in interdrainage desert regions is negligible. These results also suggest that soil-plant-atmosphere interactions should be considered in the design and evaluation of waste-disposal sites in interdrainage desert settings.

[55] **Acknowledgments.** This project was funded in part by the U.S. Department of Energy. The senior author benefited from many helpful discussions with Michelle Walvoord. We gratefully acknowledge reviews provided by Mitchell Plummer, David Stonestrom, and two anonymous reviewers.

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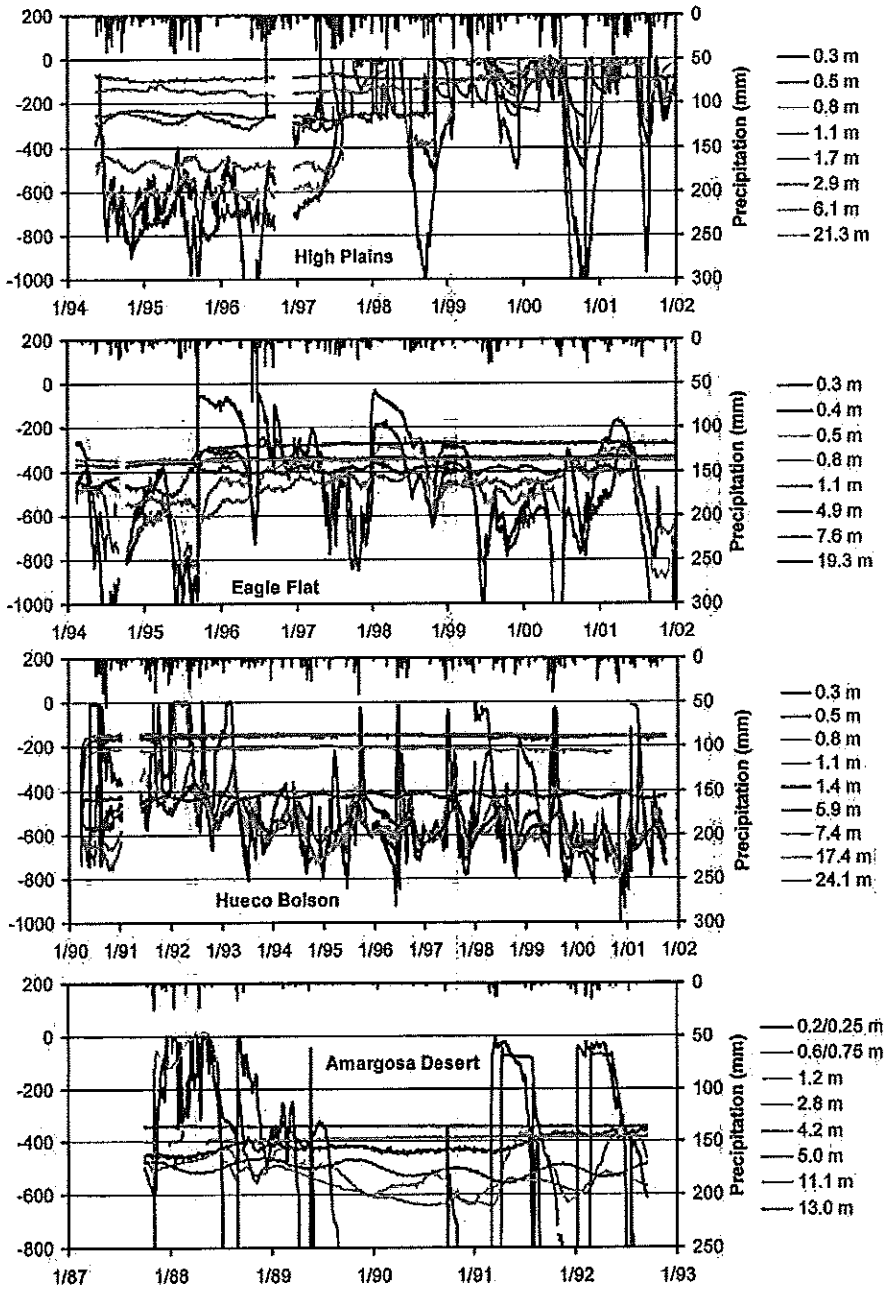


**Figure 5.** Temporal variability in water potential monitored in situ at various depths at each site. Daily precipitation is also shown.

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# Properties and Variability of Soil and Trench Fill at an Arid Waste-Burial Site

B. J. Andraski *


## ABSTRACT

Arid sites commonly are assumed to be ideal for long-term isolation of wastes. Information on properties and variability of desert soils is limited, however, and little is known about how the natural site environment is altered by installation of a waste facility. During fall construction of two test trenches next to the waste facility on the Amargosa Desert near Beatty, NV, samples were collected to: (i) characterize physical and hydraulic properties of native soil (upper 5 m) and trench fill, (ii) determine effects of trench construction on selected properties and vertical variability of these properties, and (iii) develop conceptual models of vertical variation within the soil profile and trench fill. Water retention was measured to air dryness ($\psi = 2 \times 10^6$ cm water suction). The 15 300-cm pressure-plate data were omitted from the analysis because water-activity measurements showed the actual suction values were significantly less than the expected 15 300-cm value (avg. difference = 8550 ± 2460 cm water). Trench construction significantly altered properties and variability of the natural site environment. For example, water content ranged from 0.029 to 0.041 $m^3\ m^{-3}$ for fill vs. 0.030 to 0.095 $m^3\ m^{-3}$ for soil; saturated hydraulic conductivity was $\approx 10^{-4}$ cm $s^{-1}$ for fill vs. $10^{-2}$ to $\approx 10^{-4}$ cm $s^{-1}$ for soil. Statistical analyses showed that the native soil may be represented by three major horizontal components and the fill by a single component. Under initial conditions, calculated liquid conductivity ($K_l$) plus isothermal vapor conductivity ($K_v$) for the upper two soil layers and the trench fill was $\approx 10^{-13}$ cm $s^{-1}$, and $K_l$ was $\leq K_v$. For the deeper (2–5 m) soil, total conductivity was $\approx 10^{-10}$ cm $s^{-1}$, and $K_l$ was $> K_v$. This study quantitatively describes hydraulic characteristics of a site using data measured across a water-content range that is representative of arid conditions, but is seldom studied.


INCREASING VOLUMES of radioactive and other hazardous wastes produced each year are of major concern in that new sites will be required for disposal of these wastes. The primary objective for waste-burial facilities is to limit exposure of the public to hazardous wastes for 100 to 10 000 yr.

Sites in arid regions commonly are assumed to be ideal for long-term isolation of wastes (Reith and Thomson, 1992) because the natural environment has features that can reduce the potential for waste migration (e.g., low precipitation, high evapotranspiration, thick unsaturated zone). The complex processes and interacting factors affecting water flow at arid sites, however, are not well understood (Gee and Hillel, 1988; Nativ, 1991; Andraski, 1992). Depending on specific but commonly transient conditions, water movement through either liquid or vapor flow may occur in response to matric suction and temperature gradients. Under dry conditions, movement in the vapor phase is likely to be an important transport mechanism for certain contaminants (e.g., tritium, $^{14}C$, radon). Evaluation of flow processes at arid sites requires the use of numerical models (Fayer and Gee, 1992; Scanlon and Milly, 1994) because of these complexities. Adequate and complete data needed for numerical simulation of flow processes generally are lacking, however, because of difficulties in characterizing the physical and hydraulic properties of the commonly dry, stony desert soils (Mehuys et al., 1975; Russo, 1983; Andraski, 1991). Few attempts have been made to measure hydraulic properties across the extreme range of water content observed at arid sites. Although recent work at active or proposed arid waste-burial sites has increased our knowledge of soil properties and flow processes in undisturbed arid settings (Fischer, 1992; Istok et al., 1994; Scanlon and Milly, 1994), little is known about how, or to what degree, the natural site environment is altered by the installation of a waste-burial facility.

This work was prompted by the need to better define and quantify the factors and processes affecting waste isolation at a representative arid waste-burial site. The specific objectives of this study were to: (i) characterize the physical and hydraulic properties of native soil (upper 5 m) and trench fill, (ii) determine the effects of burial-trench construction on selected physical and hydraulic properties and vertical variability of these properties, and (iii) quantitatively develop preliminary conceptual models of vertical variation within the native soil profile and the trench fill for use in numerical simulations of unsaturated flow at the site.

## MATERIALS AND METHODS

The study site is adjacent to the commercial waste-burial facility on the Amargosa Desert, about 17 km southeast of Beatty, NV, and 20 km east of Death Valley National Park. On the basis of disposal-facility records (R. Marchand, US Ecology, Inc., 1991, personal communication) and data collected at the study site (Wood and Andraski, 1995), annual precipitation during 1981 to 1992 averaged 108 mm. Depth to the water table ranges from 85 to 115 m below land surface (Fischer, 1992). Sediments in the area are largely alluvial and fluvial deposits (Nichols, 1987). Surface soils are mapped as the Yermo–Arizo association (W.E. Dollarhide, USDA-SCS, 1987, personal communication). The Yermo soils are loamy-skeletal, mixed (calcareous), thermic Typic Torriorthents, and the Arizo soils are sandy-skeletal, mixed, thermic Typic Torriorthents. Vegetation in the area is sparse; creosote bush [*Larrea tridentata* (DC.) Cov.] is the dominant species. The waste facility has been used for the burial of low-level radioactive waste (1962–1992) and hazardous chemical waste (1970–present). The low-level radioactive waste facility was the first such commercially operated site in the USA. Steps used in construction of the low-level radioactive waste burial trenches include excavation and stockpiling of native soil, emplacement of waste, and backfilling with previously stockpiled, uncompacted soil. Dimensions of the trenches have changed since the facility opened in 1962. Until the mid-1970s, trenches were about 1 to 3 m wide, 2 to 6 m deep, and 100 to 200 m long. Trenches constructed later are 30 to 90 m wide, 15 m deep, and 250 m long.

Two test trenches were constructed during September 1987 using methods that simulate those used during active disposal at the low-level radioactive waste-burial facility. The test trenches were excavated by backhoe to about 4 m in all three dimensions

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and soil-filled drums were used to simulate containers of waste (Fig. 1). Additional details on construction and instrumentation of the test trench site are given by Andraski (1990).

During excavation of the trenches and instrumentation of soil below the 4-m depth, five soil deposits within the upper 5 m were visually identified by texture, cohesiveness, and color. Layers were designated 1 (surface) to 5 (deepest). Soil Layer 1 is about 0.75 to 1 m thick and each of the four underlying layers is ≈1 m thick. Five 0.5-m-thick trench-fill layers were defined: 1, cover; 2 and 3, upper and lower half of the upper fill, respectively; 4 and 5, upper and lower half of the lower fill, respectively. The 0.5-m thickness corresponds with the thickness of layers produced during backfilling. For each trench, three to nine volumetric and associated bulk samples were collected from each layer of native soil and trench fill. A total of 92 volumetric samples and 92 associated bulk samples were collected. Volumetric determinations were based on the rubber-balloon method, except that those for the native soil between 4.4 and 5 m deep were based on core data (Andraski, 1991). Although undisturbed core samples are preferred for subsequent laboratory analyses, the rubber-balloon method was chosen because it is more reliable for the extreme ranges of rock-fragment content and soil cohesiveness at the site.

The bulk density of soil plus rock fragments, $\rho_T$ (referred to hereafter as field bulk density), was calculated by dividing oven-dry mass by sample volume. Field volumetric water content ($\theta_T$) was calculated as the product of gravimetric water content and $\rho_T$. Particle-size distribution was measured by sieve and hydrometer methods (Gee and Bauder, 1986). Rock-fragment bulk density ($\rho_r$) was determined from rock-fragment particle density and porosity. Rock-fragment particle density was measured by water pycnometry (Blake and Hartge, 1986) and porosity was determined by oven drying the sample for 24 h after vacuum saturation. Rock-fragment particle density and $\rho_r$ averaged ($n$ = 92) 2.50 ± 0.04 and 2.33 ± 0.05 Mg m$^{-3}$, respectively. Volumetric rock-fragment content ($R_v$) was calculated by $R_v = \rho_T(R_g/\rho_r)$, where $R_g$ is total gravimetric rock-fragment content. Fine-soil bulk density ($\rho_b$) was calculated by $\rho_b = \rho_T(1 - R_g)/(1 - R_v)$.

Rock fragments were removed and hydraulic properties were measured on the fine-soil (<2-mm diam.) fraction. Each sample was packed to its calculated fine-soil bulk density prior to analysis. Saturated hydraulic conductivity of the fine soil ($K_s$) was measured by the constant-head method (Klute and Dirksen, 1986) using samples (6 cm long, 5.4-cm diam.) that had been slowly wetted from the bottom up. Saturated hydraulic conductivity of soil plus rock fragments, $K_{sT}$ (referred to hereafter as field saturated conductivity)] was estimated using an empirical equation proposed by A.J. Peck and J.D. Watson, 1979, unpublished data:

$$K_{sT} = K_s\,2(1 - R_v)/(2 + R_v) \qquad [1]$$

Equation [1] was derived using a heat-flow analogy for soil with noninteracting spherical inclusions and assumes zero hydraulic conductivity for the inclusions (i.e., rock fragments). Dunn and Mehuys (1984) evaluated the Peck and Watson equation and found good agreement between estimated and measured decreases in $K_{sT}$ with increasing $R_v$ values. Soil-water retention functions were determined using desorption data. Because matric suctions at the field site range from near zero to >80 000 cm of water (Andraski, 1990), water retention was measured using different methods to cover the entire range. Pressure-plate methods (Klute, 1986) on 3-cm-long by 5.4-cm-diam. samples

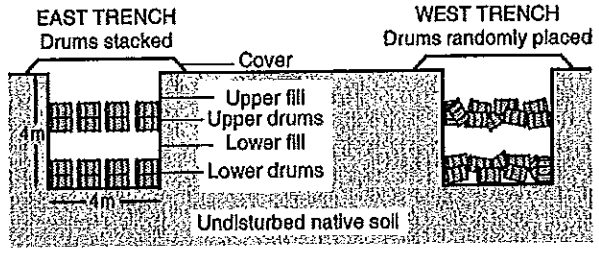


**Fig. 1. General design of two test trenches constructed using methods that simulate those used during active disposal at the low-level radioactive waste burial facility on the Amargosa Desert near Beatty, NV.**

were used to determine water content at pressures of 20, 41, 82, 336, 1020, 5100, and 15 300 cm of water. Immediately following the 15 300-cm pressure-plate measurement, a water-activity meter (Gee et al., 1992) and a series of air-drying steps (0, 4, 8, and 504 h) were used to extend water-retention measurements to air dryness (2 × 10$^6$ cm of water). Water-activity measurements made immediately after the 15 300-cm pressure-plate measurements showed that the actual suction values averaged 8550 ± 2460 cm of water less than the expected 15 300-cm value. A paired $t$-test (Steel and Torrie, 1980) showed that the difference between measurement methods was significant ($P > |t| = 0.001$). This discrepancy is assumed to be due to lack of equilibration for the pressure-plate measurement. Thus, the 15 300-cm pressure-plate data were not used in further analysis.

Water retention was described using the two-parameter junction model of Rossi and Nimmo (1994):

$$\begin{aligned} \theta/\theta_s &= \theta_I = 1 - c(\psi/\psi_o)^2 && 0 \le \psi \le \psi_i \\ \theta/\theta_s &= \theta_{II} = (\psi_o/\psi)^\lambda && \psi_i \le \psi \le \psi_j \\ \theta/\theta_s &= \theta_{III} = \alpha \ln(\psi_d/\psi) && \psi_j \le \psi \le \psi_d \end{aligned} \qquad [2]$$

where $\theta$ is volumetric water content and $\psi$ is suction expressed as a pressure head (cm of water). The parameter $\theta_s$ was measured and, here, it represents the water content of fine soil obtained at $\psi = 0$ following slow upward wetting. The parameter $\psi_d$, which represents a finite value of suction where $\theta = 0$, was calculated (9.2 × 10$^5$ cm of water) by applying the Kelvin equation to the conditions of oven drying (Ross et al., 1991)

$$\psi_d = -(RT/Mg)\ln(h_a p_{sa}/p_{so}) \qquad [3]$$

where $R$ is the ideal gas constant (8.31 × 10$^7$ ergs mol$^{-1}$ K$^{-1}$; erg = 10$^7$ J), $T$ is temperature (K), $M$ is molecular weight of water (18.01 g mol$^{-1}$), $g$ is gravitational constant (980.6 cm s$^{-2}$), $h_a$ is humidity of air outside the oven (dimensionless ratio), and $p_{sa}$ and $p_{so}$ are saturated vapor pressures of water at ambient laboratory air and oven temperatures (kPa), respectively. The model was fit to retention data of each sample and $\psi_o$ and $\lambda$ were optimized using nonlinear least squares analysis (SAS Institute, 1988). The $\psi_o$ parameter may be regarded as a scaling factor related to air-entry suction and $\lambda$ is a shape factor. The parameters $c$, $\psi_i$, $\psi_j$, and $\alpha$ were determined as analytical functions of $\psi_o$ and $\lambda$. Field water content ($\theta_T$) and field-saturated water content ($\theta_{sT}$) then were estimated using

$$\theta_T = \theta\,(1 - R_v)$$

and

$$\theta_{sT} = \theta_s\,(1 - R_v) \qquad [4]$$

where rock fragments are assumed to hold negligible water.

The experiment for determining the effects of burial-trench

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construction on selected physical and hydraulic properties and their vertical (layer to layer) variability was a 2 × 5 factorial (two materials: soil and trench fill; five layers) with two replicates (trenches) in a completely random design (Steel and Torrie, 1980). Presence and orientation of waste drums were not considered factors in the experimental design. Analysis of variance (ANOVA) procedures and contrasts (SAS Institute, 1988) were applied to test main-factor and interaction effects on the physical and hydraulic properties by using a split-plot model, with material as the main-plot factor and layer as the split-plot factor (Steel and Torrie, 1980). Analyses were done using subsample averages, with three to nine subsamples for each material and layer combination. In addition to testing the overall interaction effect, orthogonal (linearly independent) contrasts were used to partition the overall interaction effect and test individual interactions between materials and contiguous layers. The $P = 0.05$ significance level was used for testing material, layer, and material × layer interaction effects.

Prior to applying ANOVA procedures, residual analyses were used to test the assumptions of normally distributed and homogeneous error and to determine the need for data transformation. The Shapiro–Wilk $W$ statistic was used to test the assumption of normally distributed experimental errors and residual plots were used to test error homogeneity as described by Fernandez (1992). Within materials, layers were assumed independent (no autocorrelated error) because of the randomness of the processes that formed the native soil profile and the random backfilling process.

Means were compared using Fisher's least significant difference test (LSD) (Steel and Torrie, 1980). The split-plot experimental design generally gives higher precision for split-plot (layer) comparisons, but at the cost of lower precision for main-plot (material) comparisons. For this experiment, however, the increased precision for tests between layers is beneficial for assessing vertical variability, which can greatly affect water movement. If the ANOVA indicates significant interactions, then factors cannot be interpreted independently and paired comparisons are made between the mean values for specific material and layer combinations. Under these conditions, (i) LSD is used to determine significance of the difference between two layer means within a material, (ii) LSD′ is used to determine significance of the difference between two material means within the same layer or different layers, and (iii) the $P = 0.01$ significance level is used to control the error rate of multiple-mean comparisons. For the experimental design used in this study, the calculation of LSD′ is necessary because comparisons across materials involve two error terms, one associated with material and one with layer (Steel and Torrie, 1980). For comparisons within materials, however, LSD is the appropriate test statistic because it accounts only for the error associated with layer.

Results of the statistical analyses were used to quantitatively develop preliminary conceptual models of vertical variation within the native soil profile and trench fill. Hydraulic properties measured in the study then were described for each component of the conceptual models.

## RESULTS AND DISCUSSION

### Characteristics of Native Soil and Trench Fill Layers

Descriptive statistics for physical properties of the native soil layers are given in Table 1. Fine-soil texture of the five soil layers is: 1, loamy sand; 2, coarse sand; 3, 4, and 5, coarse sandy loam. Layer 4, with a clay content of 18.3%, approached the texture of a sandy clay loam. Compared with Layer 1, $R_g$ and $R_v$ values

**Table 1. Descriptive statistics for particle-size distribution, total gravimetric and volumetric rock-fragment contents ($R_g$ and $R_v$), field (soil plus rock fragments) and fine-soil bulk densities ($\rho_T$ and $\rho_b$), and field water content ($\theta_T$) during sampling for layers within native soil.**

| | | | Sand† | | | | | | Rock-fragment content | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Clay | Silt | Total | Very fine | Fine | Medium | Coarse | Very coarse | $R_g$ total | 2–4.75 mm | 4.75–12.5 mm | >12.5 mm | $R_v$ total | $\rho_T$ | $\rho_b$ | $\theta_T$ |
| | % of <2-mm diam. | | | | | | | | % of total | | | | | Mg/m³ | | m³/m³ |
| | | | | | | | | Layer 1 ($n$ = 18) | | | | | | | | |
| Mean | 6.1 | 14.1 | 79.8 | 16.4 | 27.2 | 15.1 | 11.9 | 9.2 | 21.9 | 8.7 | 9.9 | 3.3 | 14.0 | 1.46 | 1.31 | 0.030 |
| Min. | 2.5 | 10.4 | 73.5 | 9.0 | 14.0 | 11.1 | 6.5 | 3.3 | 8.7 | 3.7 | 3.8 | 0.0 | 4.9 | 1.23 | 1.08 | 0.011 |
| Max. | 8.0 | 19.0 | 85.6 | 24.4 | 36.2 | 23.1 | 21.7 | 17.4 | 42.9 | 17.1 | 19.0 | 8.6 | 29.6 | 1.63 | 1.42 | 0.060 |
| SD | 1.5 | 2.6 | 3.4 | 4.6 | 7.2 | 3.1 | 4.2 | 4.3 | 11.4 | 5.0 | 5.1 | 2.6 | 8.1 | 0.11 | 0.09 | 0.016 |
| | | | | | | | | Layer 2 ($n$ = 6) | | | | | | | | |
| Mean | 2.8 | 2.5 | 94.7 | 1.5 | 6.0 | 23.8 | 37.4 | 26.0 | 58.6 | 21.2 | 27.6 | 9.8 | 49.1 | 1.91 | 1.54 | 0.043 |
| Min. | 1.7 | 0.0 | 90.8 | 1.0 | 4.2 | 20.5 | 32.1 | 23.5 | 38.3 | 18.6 | 15.3 | 4.4 | 27.2 | 1.70 | 1.29 | 0.038 |
| Max. | 5.0 | 7.1 | 96.7 | 2.2 | 7.5 | 27.9 | 45.4 | 27.3 | 73.6 | 23.8 | 39.7 | 14.7 | 66.5 | 2.09 | 1.78 | 0.050 |
| SD | 1.2 | 2.6 | 2.6 | 0.4 | 1.4 | 3.3 | 5.0 | 1.4 | 14.6 | 2.1 | 9.4 | 4.5 | 15.4 | 0.14 | 0.17 | 0.005 |
| | | | | | | | | Layer 3 ($n$ = 6) | | | | | | | | |
| Mean | 13.6 | 5.7 | 80.7 | 1.8 | 9.1 | 28.2 | 24.3 | 17.3 | 59.9 | 21.2 | 28.3 | 10.4 | 45.4 | 1.77 | 1.30 | 0.071 |
| Min. | 8.2 | 3.5 | 73.0 | 1.0 | 4.1 | 19.4 | 20.5 | 9.6 | 49.4 | 19.0 | 17.8 | 6.9 | 37.9 | 1.65 | 1.11 | 0.058 |
| Max. | 18.8 | 9.0 | 88.4 | 3.5 | 14.7 | 37.7 | 26.8 | 22.3 | 68.8 | 24.1 | 36.7 | 18.1 | 51.9 | 1.93 | 1.48 | 0.085 |
| SD | 4.6 | 2.5 | 5.6 | 0.9 | 4.1 | 7.2 | 2.6 | 4.9 | 7.3 | 2.3 | 6.5 | 4.3 | 5.7 | 0.10 | 0.18 | 0.009 |
| | | | | | | | | Layer 4 ($n$ = 6) | | | | | | | | |
| Mean | 18.3 | 6.0 | 75.7 | 1.9 | 6.8 | 20.7 | 27.4 | 18.9 | 62.7 | 20.4 | 29.7 | 12.6 | 51.0 | 1.86 | 1.41 | 0.095 |
| Min. | 14.8 | 4.2 | 72.8 | 0.7 | 2.6 | 14.2 | 19.9 | 14.0 | 45.1 | 13.8 | 21.4 | 6.0 | 36.5 | 1.74 | 1.10 | 0.076 |
| Max. | 20.3 | 6.9 | 79.7 | 3.4 | 11.8 | 27.9 | 34.0 | 30.6 | 74.0 | 24.1 | 40.0 | 21.3 | 59.7 | 2.07 | 1.86 | 0.137 |
| SD | 2.1 | 1.1 | 2.4 | 1.1 | 3.6 | 5.2 | 5.9 | 6.4 | 11.0 | 3.6 | 6.2 | 6.2 | 8.9 | 0.14 | 0.29 | 0.022 |
| | | | | | | | | Layer 5 ($n$ = 14) | | | | | | | | |
| Mean | 12.9 | 4.9 | 82.2 | 1.7 | 6.3 | 14.6 | 31.4 | 28.2 | 54.8 | 19.2 | 22.1 | 13.5 | 36.7 | 1.56 | 1.10 | 0.078 |
| Min. | 8.9 | 2.3 | 74.6 | 0.7 | 3.3 | 8.2 | 21.4 | 18.5 | 33.1 | 14.0 | 9.9 | 1.4 | 22.6 | 1.33 | 0.85 | 0.062 |
| Max. | 19.6 | 8.5 | 88.2 | 3.0 | 9.6 | 23.8 | 37.1 | 38.0 | 66.0 | 38.2 | 31.3 | 27.3 | 46.0 | 1.62 | 1.41 | 0.101 |
| SD | 3.2 | 1.9 | 4.0 | 0.7 | 2.1 | 5.2 | 4.8 | 6.1 | 10.5 | 6.3 | 6.6 | 8.1 | 7.6 | 0.09 | 0.16 | 0.011 |

† Particle diameters are clay, <0.002 mm; and silt, 0.002–0.05 mm; sand fractions are very fine, 0.05–0.1 mm; fine, 0.1–0.25 mm; medium, 0.25–0.5 mm; coarse, 0.5–1 mm; and very coarse, 1–2 mm.

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were at least 2.5 times greater for the four gravelly subsurface layers. The layer-to-layer differences in particle-size distribution are indicative of the processes active in forming the soil profile. In relation to subsurface layers, the high silt and fine sand contents and low rock-fragment content of Layer 1 reflect eolian deposition and cumulate soil development beneath a desert pavement (McFadden et al., 1987). Textural stratification below Layer 1 reflects alluvial and fluvial processes. Mean $\rho_T$ values ranged from 1.46 to 1.91 Mg m$^{-3}$ and, within layers, values were quite uniform (CVs <10%). Mean $\theta_T$ at the time of sampling ranged from 0.030 to 0.095 m$^3$ m$^{-3}$ and was least for the surface layer. The small $\theta_T$ value for soil Layer 1 is related to the time of sampling (September; high antecedent plant water use, low antecedent precipitation) and the small value for Layer 2 reflects the coarse texture. For subsurface layers, $\theta_T$ increased with clay content.

Descriptive statistics for physical properties of the trench fill layers are given in Table 2. Textural classification for each of the five fill layers is gravelly loamy coarse sand. Among layers, mean $\rho_T$ values ranged from 1.59 to 1.74 Mg m$^{-3}$ and, within layers, values showed little variation (CVs <10%). Mean $\theta_T$ at the time of sampling ranged from 0.029 to 0.041 m$^3$ m$^{-3}$.

Descriptive statistics for hydraulic properties of the native soil layers are given in Table 3. Application of Eq. [1] to account for $R_v$ resulted in $K_{sT}$ values that were 21 to 65% less than the associated $K_s$ values. Within layers, $K_{sT}$ was highly variable (CVs ≈70–180%), but the variation was consistent with that reported by Istok et al. (1994) for other alluvial soils in southern Nevada (CVs ≈70–205%). Mean $\theta_{sT}$ for Layer 1 was about 25 to 75% greater than $\theta_{sT}$ for the subsurface layers. Mean values for the Rossi–Nimmo fitting parameter $\psi_o$ ranged from near zero to about 20 cm of water and $\lambda$ ranged from 0.13 to 0.27.

Descriptive statistics for hydraulic properties of the trench fill layers are given in Table 4. Within layers, $K_{sT}$ was about 40% less than $K_s$, and $K_{sT}$ showed less variation (CVs ≈47–69%) than that observed for native soil. For the remaining hydraulic properties, values were relatively uniform among and within layers. Mean $\psi_o$ values were from 12 to 17 cm of water and $\lambda$ was 0.21 or 0.22.

The retention-curve fitting parameters were positively correlated with silt content of the materials. Correlation coefficients ($r$) determined using the mean values given in Tables 1 through 4 ($n$ = 10), were $r$ = 0.855 ($P > |r|$ = 0.002) for $\psi_o$ and silt content, and $r$ = 0.881 ($P > |r|$ = 0.0007) for $\lambda$ and silt content.

## Trench Construction Effects on Soil Properties and Vertical Variability

The effects of burial-trench construction on selected physical and hydraulic properties and vertical variability of these properties were tested using ANOVA procedures. Physical properties evaluated were clay, silt, sand, $R_v$, $\rho_T$, and $\theta_T$ at time of sampling and hydraulic properties were $K_{sT}$, $\theta_{sT}$, $\psi_o$, and $\lambda$.

Table 2. Descriptive statistics for particle-size distribution, total gravimetric and volumetric rock-fragment contents ($R_g$ and $R_v$), field (soil plus rock fragments) and fine-soil bulk densities ($\rho_T$ and $\rho_b$), and field water content ($\theta_T$) during sampling for layers within trench fill.

| | | | Sand† | | | | | | Rock-fragment content | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Clay | Silt | Total | Very fine | Fine | Medium | Coarse | Very coarse | $R_g$ total | 2–4.75 mm | 4.75–12.5 mm | >12.5 mm | $R_v$ total | $\rho_T$ | $\rho_b$ | $\theta_T$ |
| | % of <2-mm diam. | | | | | | | | % of total | | | | | Mg/m$^3$ | | m$^3$/m$^3$ |
| **Layer 1 ($n$ = 12)** | | | | | | | | | | | | | | | | |
| Mean | 6.4 | 9.4 | 84.2 | 5.5 | 17.7 | 21.4 | 21.5 | 18.1 | 36.8 | 12.6 | 16.9 | 7.3 | 25.5 | 1.61 | 1.36 | 0.029 |
| Min. | 4.2 | 6.3 | 78.2 | 2.8 | 7.4 | 14.6 | 17.0 | 11.0 | 16.6 | 4.3 | 6.7 | 3.3 | 11.7 | 1.29 | 1.11 | 0.016 |
| Max. | 8.9 | 15.0 | 86.8 | 10.5 | 24.4 | 28.0 | 28.6 | 26.8 | 48.2 | 19.3 | 22.8 | 13.0 | 37.3 | 1.79 | 1.56 | 0.042 |
| SD | 1.2 | 2.4 | 2.4 | 1.8 | 5.4 | 3.8 | 3.6 | 5.0 | 10.8 | 4.8 | 5.1 | 2.4 | 8.4 | 0.14 | 0.16 | 0.009 |
| **Layer 2 ($n$ = 12)** | | | | | | | | | | | | | | | | |
| Mean | 5.6 | 8.9 | 85.5 | 5.1 | 17.5 | 23.1 | 21.0 | 18.8 | 40.9 | 14.3 | 18.2 | 8.4 | 29.3 | 1.65 | 1.38 | 0.031 |
| Min. | 3.4 | 6.3 | 81.7 | 3.0 | 9.6 | 18.8 | 16.8 | 13.5 | 24.6 | 8.1 | 10.9 | 3.9 | 14.5 | 1.40 | 1.14 | 0.021 |
| Max. | 8.9 | 11.6 | 88.4 | 7.6 | 24.6 | 29.0 | 28.0 | 22.6 | 50.4 | 18.4 | 24.1 | 13.0 | 38.9 | 1.79 | 1.60 | 0.043 |
| SD | 1.6 | 1.6 | 2.1 | 1.6 | 4.7 | 3.3 | 3.2 | 3.1 | 7.2 | 3.0 | 3.9 | 3.0 | 6.0 | 0.12 | 0.14 | 0.008 |
| **Layer 3 ($n$ = 6)** | | | | | | | | | | | | | | | | |
| Mean | 6.7 | 8.6 | 84.7 | 5.7 | 20.9 | 21.3 | 19.5 | 17.3 | 38.9 | 13.9 | 16.6 | 8.4 | 28.8 | 1.74 | 1.49 | 0.030 |
| Min. | 5.9 | 6.8 | 83.3 | 3.7 | 15.5 | 17.8 | 15.9 | 13.0 | 30.0 | 11.4 | 13.9 | 4.7 | 20.6 | 1.68 | 1.46 | 0.021 |
| Max. | 7.7 | 10.7 | 86.9 | 7.9 | 24.6 | 24.7 | 23.1 | 21.4 | 44.9 | 16.7 | 20.7 | 11.6 | 34.7 | 1.80 | 1.54 | 0.047 |
| SD | 0.7 | 1.6 | 1.6 | 1.4 | 3.9 | 2.6 | 3.1 | 3.3 | 5.3 | 2.1 | 2.3 | 2.8 | 4.8 | 0.04 | 0.03 | 0.010 |
| **Layer 4 ($n$ = 6)** | | | | | | | | | | | | | | | | |
| Mean | 8.3 | 7.6 | 84.1 | 4.5 | 10.4 | 26.1 | 23.6 | 19.5 | 49.4 | 17.3 | 24.1 | 8.0 | 36.0 | 1.69 | 1.34 | 0.038 |
| Min. | 5.5 | 3.4 | 78.5 | 3.1 | 6.9 | 24.4 | 20.2 | 14.2 | 37.4 | 15.1 | 18.8 | 3.4 | 28.5 | 1.57 | 1.06 | 0.032 |
| Max. | 10.5 | 12.2 | 89.9 | 5.6 | 14.3 | 28.5 | 26.5 | 26.0 | 59.6 | 23.0 | 29.6 | 11.0 | 44.0 | 1.92 | 1.61 | 0.043 |
| SD | 2.3 | 3.2 | 4.7 | 1.0 | 2.4 | 1.7 | 2.4 | 4.5 | 7.7 | 3.0 | 4.2 | 2.6 | 6.1 | 0.12 | 0.19 | 0.004 |
| **Layer 5 ($n$ = 6)** | | | | | | | | | | | | | | | | |
| Mean | 7.3 | 6.8 | 85.9 | 4.0 | 11.3 | 25.6 | 23.6 | 21.4 | 37.3 | 14.7 | 17.7 | 4.9 | 25.2 | 1.59 | 1.34 | 0.041 |
| Min. | 6.0 | 4.4 | 83.4 | 2.6 | 8.2 | 17.1 | 19.4 | 14.6 | 32.6 | 11.3 | 15.7 | 2.9 | 21.4 | 1.52 | 1.21 | 0.037 |
| Max. | 8.9 | 10.6 | 88.4 | 5.2 | 13.9 | 34.8 | 26.5 | 28.9 | 47.0 | 18.8 | 22.6 | 6.9 | 31.4 | 1.68 | 1.44 | 0.046 |
| SD | 1.3 | 2.5 | 1.7 | 0.9 | 2.2 | 6.5 | 2.8 | 5.0 | 5.0 | 2.9 | 2.6 | 1.5 | 3.5 | 0.07 | 0.08 | 0.004 |

† Particle diameters are clay, <0.002 mm, and silt, 0.002–0.05 mm; sand fractions are very fine, 0.05–0.1 mm; fine, 0.1–0.25 mm; medium, 0.25–0.5 mm; coarse, 0.5–1 mm; and very coarse, 1–2 mm.

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Table 3. Descriptive statistics for fine-soil and field (soil plus rock fragments) saturated hydraulic conductivities ($K_s$ and $K_{sT}$), fine-soil and field saturated water contents ($\theta_s$ and $\theta_{sT}$), and Rossi–Nimmo retention model fitting parameters ($\psi_o$, $\lambda$) for layers within native soil.

| | $K_s$ | $K_{sT}$ | $\theta_s$ | $\theta_{sT}$ | $\psi_o$ | $\lambda$ |
|---|---|---|---|---|---|---|
| | cm/s | | m³/m³ | | cm water | |
| | | | Layer 1 ($n$ = 18) | | | |
| Mean | $1.0 \times 10^{-3}$ | $7.9 \times 10^{-4}$ | 0.339 | 0.293 | 20.2 | 0.27 |
| Min. | $3.0 \times 10^{-4}$ | $2.5 \times 10^{-4}$ | 0.259 | 0.204 | 15.9 | 0.22 |
| Max. | $8.6 \times 10^{-3}$ | $6.4 \times 10^{-3}$ | 0.391 | 0.366 | 27.6 | 0.35 |
| SD | $1.9 \times 10^{-3}$ | $1.4 \times 10^{-3}$ | 0.034 | 0.049 | 3.7 | 0.04 |
| | | | Layer 2 ($n$ = 6) | | | |
| Mean | $4.5 \times 10^{-2}$ | $2.3 \times 10^{-2}$ | 0.324 | 0.165 | 0.03 | 0.13 |
| Min. | $6.3 \times 10^{-3}$ | $1.6 \times 10^{-3}$ | 0.270 | 0.106 | 0.001 | 0.09 |
| Max. | $1.1 \times 10^{-1}$ | $6.2 \times 10^{-2}$ | 0.365 | 0.240 | 0.09 | 0.17 |
| SD | $4.0 \times 10^{-2}$ | $2.4 \times 10^{-2}$ | 0.036 | 0.054 | 0.04 | 0.02 |
| | | | Layer 3 ($n$ = 6) | | | |
| Mean | $1.0 \times 10^{-2}$ | $4.7 \times 10^{-3}$ | 0.373 | 0.205 | 1.1 | 0.14 |
| Min. | $1.8 \times 10^{-3}$ | $7.1 \times 10^{-4}$ | 0.308 | 0.162 | 0.01 | 0.08 |
| Max. | $2.5 \times 10^{-2}$ | $1.2 \times 10^{-2}$ | 0.426 | 0.254 | 2.5 | 0.17 |
| SD | $8.6 \times 10^{-3}$ | $4.1 \times 10^{-3}$ | 0.044 | 0.041 | 1.0 | 0.03 |
| | | | Layer 4 ($n$ = 6) | | | |
| Mean | $1.1 \times 10^{-2}$ | $3.9 \times 10^{-3}$ | 0.469 | 0.231 | 2.9 | 0.13 |
| Min. | $3.8 \times 10^{-3}$ | $1.2 \times 10^{-3}$ | 0.383 | 0.161 | 0.2 | 0.10 |
| Max. | $2.5 \times 10^{-2}$ | $8.8 \times 10^{-3}$ | 0.583 | 0.298 | 10.0 | 0.16 |
| SD | $8.9 \times 10^{-3}$ | $2.9 \times 10^{-3}$ | 0.065 | 0.054 | 3.6 | 0.02 |
| | | | Layer 5 ($n$ = 14) | | | |
| Mean | $1.7 \times 10^{-2}$ | $9.4 \times 10^{-3}$ | 0.344 | 0.220 | 4.0 | 0.15 |
| Min. | $7.0 \times 10^{-4}$ | $4.0 \times 10^{-4}$ | 0.301 | 0.162 | 0.2 | 0.11 |
| Max. | $6.6 \times 10^{-2}$ | $3.6 \times 10^{-2}$ | 0.435 | 0.337 | 11.8 | 0.19 |
| SD | $1.8 \times 10^{-2}$ | $1.0 \times 10^{-2}$ | 0.044 | 0.051 | 3.8 | 0.02 |

Table 4. Descriptive statistics for fine-soil and field (soil plus rock fragments) saturated hydraulic conductivities ($K_s$ and $K_{sT}$), fine-soil and field saturated water contents ($\theta_s$ and $\theta_{sT}$), and Rossi–Nimmo retention model fitting parameters ($\psi_o$, $\lambda$) for layers within trench fill.

| | $K_s$ | $K_{sT}$ | $\theta_s$ | $\theta_{sT}$ | $\psi_o$ | $\lambda$ |
|---|---|---|---|---|---|---|
| | cm/s | | m³/m³ | | cm water | |
| | | | Layer 1 ($n$ = 12) | | | |
| Mean | $4.4 \times 10^{-4}$ | $2.8 \times 10^{-4}$ | 0.315 | 0.236 | 15.4 | 0.22 |
| Min. | $7.0 \times 10^{-5}$ | $5.8 \times 10^{-5}$ | 0.244 | 0.176 | 7.4 | 0.19 |
| Max. | $9.1 \times 10^{-4}$ | $5.5 \times 10^{-4}$ | 0.365 | 0.318 | 21.6 | 0.25 |
| SD | $2.6 \times 10^{-4}$ | $1.5 \times 10^{-4}$ | 0.037 | 0.047 | 3.9 | 0.02 |
| | | | Layer 2 ($n$ = 12) | | | |
| Mean | $5.7 \times 10^{-4}$ | $3.6 \times 10^{-4}$ | 0.324 | 0.228 | 13.4 | 0.22 |
| Min. | $1.2 \times 10^{-4}$ | $7.6 \times 10^{-5}$ | 0.255 | 0.180 | 9.2 | 0.21 |
| Max. | $1.5 \times 10^{-3}$ | $9.0 \times 10^{-4}$ | 0.372 | 0.265 | 19.5 | 0.24 |
| SD | $4.0 \times 10^{-4}$ | $2.5 \times 10^{-4}$ | 0.028 | 0.022 | 3.6 | 0.01 |
| | | | Layer 3 ($n$ = 6) | | | |
| Mean | $4.0 \times 10^{-4}$ | $2.4 \times 10^{-4}$ | 0.331 | 0.236 | 16.8 | 0.22 |
| Min. | $2.0 \times 10^{-4}$ | $1.4 \times 10^{-4}$ | 0.299 | 0.205 | 11.5 | 0.20 |
| Max. | $9.8 \times 10^{-4}$ | $5.4 \times 10^{-4}$ | 0.359 | 0.258 | 22.6 | 0.26 |
| SD | $2.9 \times 10^{-4}$ | $1.6 \times 10^{-4}$ | 0.022 | 0.021 | 4.3 | 0.02 |
| | | | Layer 4 ($n$ = 6) | | | |
| Mean | $5.4 \times 10^{-4}$ | $3.0 \times 10^{-4}$ | 0.311 | 0.199 | 16.6 | 0.21 |
| Min. | $2.9 \times 10^{-4}$ | $1.3 \times 10^{-4}$ | 0.257 | 0.153 | 14.5 | 0.19 |
| Max. | $8.6 \times 10^{-4}$ | $5.3 \times 10^{-4}$ | 0.371 | 0.265 | 20.3 | 0.23 |
| SD | $2.2 \times 10^{-4}$ | $1.4 \times 10^{-4}$ | 0.048 | 0.038 | 2.7 | 0.02 |
| | | | Layer 5 ($n$ = 6) | | | |
| Mean | $9.6 \times 10^{-4}$ | $6.2 \times 10^{-4}$ | 0.330 | 0.247 | 12.9 | 0.22 |
| Min. | $4.4 \times 10^{-4}$ | $2.9 \times 10^{-4}$ | 0.293 | 0.211 | 6.6 | 0.19 |
| Max. | $2.0 \times 10^{-3}$ | $1.2 \times 10^{-3}$ | 0.374 | 0.278 | 16.1 | 0.25 |
| SD | $7.0 \times 10^{-4}$ | $4.2 \times 10^{-4}$ | 0.028 | 0.024 | 4.2 | 0.02 |

Prior to applying ANOVA procedures, residual analyses were used to test ANOVA assumptions of normally distributed and homogeneous error and to determine the need for data transformation. Failure to meet one or more of the assumptions can affect significance levels and the sensitivity of the $F$ test. Thus, without preliminary evaluation of residuals and, if needed, the application of appropriate remedial measures, ANOVA results could lead to incorrect conclusions. Except for clay content ($P < W = 0.007$) and $K_{sT}$ ($P < W = 0.0001$), the physical and hydraulic properties had normally distributed error: $P < W$ values were 0.396 for silt, 0.593 for sand, 0.143 for $R_v$, 0.835 for $\rho_T$, 0.992 for $\theta_T$, 0.967 for $\theta_{sT}$, 0.272 for $\psi_o$, and 0.838 for $\lambda$. Residual plots (data not shown) also indicated variance heterogeneity for clay content and $K_{sT}$. Application of a log transformation to clay and $K_{sT}$ data resulted in normal error distributions ($P < W = 0.562$ for log[clay]; $P < W = 0.781$ for log[$K_{sT}$]) and more homogeneous errors. The method of Box et al. (1978) confirmed that the log transformation was most appropriate for both properties.

The ANOVA results for physical properties are summarized in Table 5 and material × layer interaction means are shown in Fig. 2. The overall material × layer interaction effect was significant for each property except sand ($P > F = 0.072$). Orthogonal contrasts, which partition the overall interaction effect into four components, were used to provide more powerful tests of the specific layer-to-layer interactions that are of interest in this study. These contrasts show that at least one of the

Table 5. Summary of analysis of variance and orthogonal contrasts for testing effects of burial-trench construction on selected physical properties and vertical variability of these properties: log(clay), silt, sand, volumetric rock-fragment content ($R_v$), field (soil plus rock fragments) bulk density ($\rho_T$), and field water content ($\theta_T$) during sampling.

| Source of variation or contrast | df | Probability level ($P > F$) log(clay) | Silt | Sand | $R_v$ | $\rho_T$ | $\theta_T$ |
|---|---|---|---|---|---|---|---|
| Material (M) | 1 | 0.033 | 0.048 | 0.105 | 0.043 | 0.244 | 0.020 |
| Main-plot error | 2 | – | – | – | – | – | – |
| Layer (L) | 4 | 0.0004 | 0.016 | 0.037 | 0.002 | 0.0001 | 0.001 |
| M × L | 4 | 0.004 | 0.048 | 0.072 | 0.023 | 0.0001 | 0.008 |
| Orthogonal contrast† | | | | | | | |
| (M1L1 − M2L1) = (M1L2 − M2L2) | 1 | 0.059 | 0.005 | 0.031 | 0.004 | 0.0001 | 0.392 |
| (M1L2 − M2L2) = (M1L3 − M2L3) | 1 | 0.002 | 0.263 | 0.035 | 0.692 | 0.0006 | 0.038 |
| (M1L3 − M2L3) = (M1L4 − M2L4) | 1 | 0.607 | 0.652 | 0.421 | 0.838 | 0.011 | 0.208 |
| (M1L4 − M2L4) = (M1L5 − M2L5) | 1 | 0.377 | 0.911 | 0.384 | 0.662 | 0.001 | 0.124 |
| Split-plot error | 8 | – | – | – | – | – | – |
| Total | 19 | – | – | – | – | – | – |

† Material × layer interaction means denoted by $M_iL_j$ for the $i$th level of material (1 = soil; 2 = fill) and the $j$th level of layer ($j$ = 1, 2, 3, 4, or 5).

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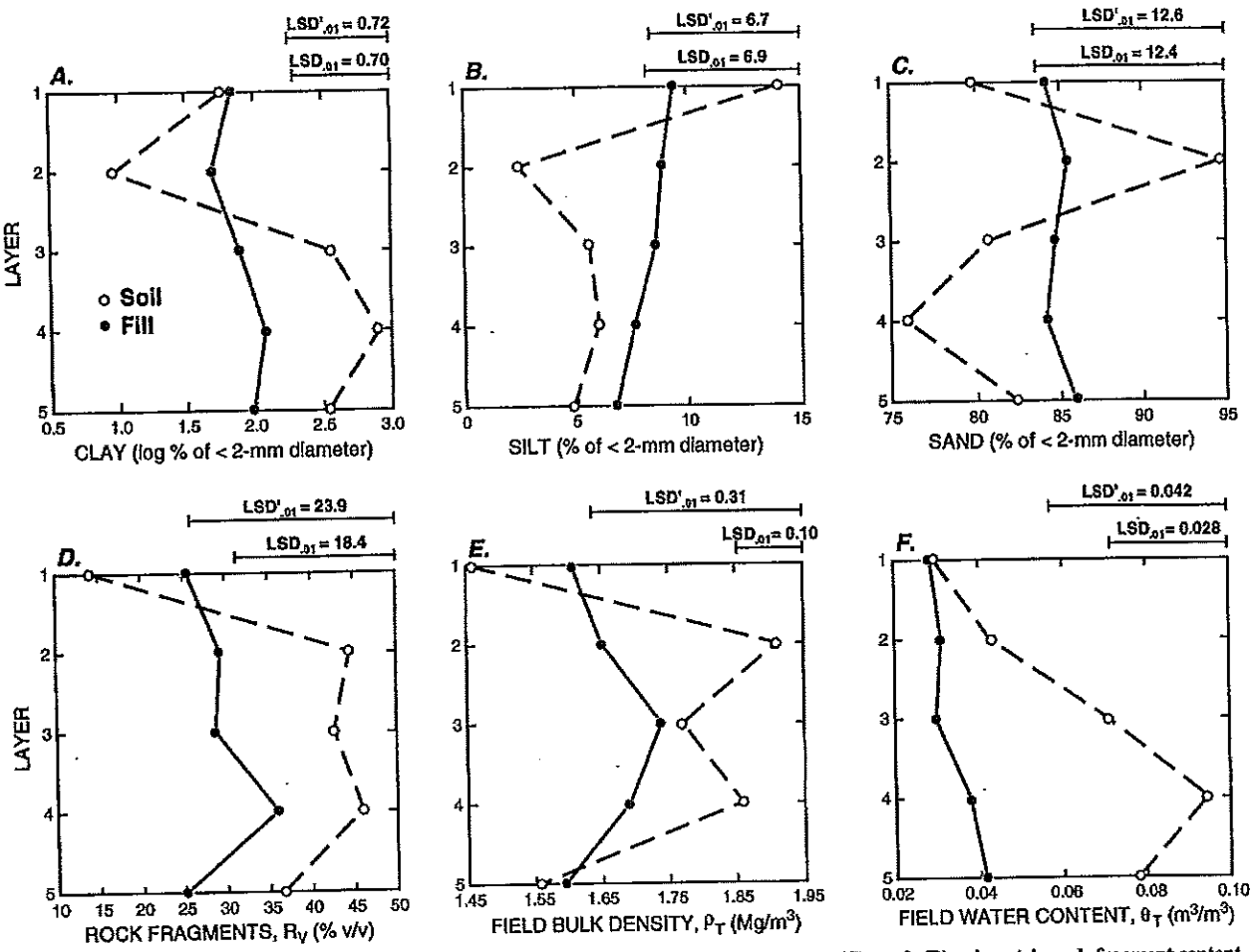


**Fig. 2. Material × layer interaction means for selected physical properties: (A) log(clay), (B) silt, (C) sand, (D) volumetric rock-fragment content, (E) field (soil plus rock fragments) bulk density, and (F) field water content at time of sampling. Test statistics are: LSD(0.01) for comparing layer means within a material, and LSD'(0.01) for comparing material means within the same layer or different layers.**

four individual material × contiguous layer interactions was significant for each of the physical properties considered under the ANOVA model (Table 5). For log(clay), silt, sand, $R_v$, and $\theta_T$, the significant contrasts are attributed to large differences observed between contiguous soil Layers 1 and 2 or 2 and 3 (Fig. 2A, 2B, 2C, 2D, and 2F). Compared with the other physical properties, $\rho_T$, which is affected by both $R_v$ and $\rho_b$, had the most significant layer-to-layer variability (four significant contrasts for $\rho_T$ in Table 5; Fig. 2E).

Because of significant interactions, the material and layer effects on physical properties cannot be interpreted independently and differences between pairs of material × layer interaction mean values are evaluated using LSD and LSD'. For log(clay), silt, sand, $R_v$, and $\theta_T$, no significant differences were observed among layers within trench fill (Fig. 2A, 2B, 2C, 2D, and 2F). The log(clay) value for soil Layer 2 was less than those for fill, whereas the value for soil Layer 4 was greater than those for fill (Fig 2A). For sand content, differences between soil and fill layers were not significant (Fig. 2C). Silt content and $R_v$ values for soil Layer 1 were significantly different from values for the underlying soil layers, but differences between soil and fill layers typically were not significant (Fig 2B and 2D). Differences between $\theta_T$ values for the three deep soil layers and those for all other soil and fill layers typically were significant (Fig. 2F). Although the magnitude of variation in $\rho_T$ values for the trench fill was less than for native soil, fill Layer 3 was significantly denser than Layers 1 and 5, and Layer 4 was denser than Layer 5.

The ANOVA results for hydraulic properties are summarized in Table 6 and material × layer interaction means are shown in Fig. 3. The overall material × layer interaction effect was not significant for $\log(K_{sT})$ and $\theta_{sT}$, but was significant for $\psi_o$ and $\lambda$. For each hydraulic property, however, contrasts indicated significant interaction between materials and contiguous Layers 1 and 2. The significance of these interactions is attributed to large differences between soil Layers 1 and 2 (Fig. 3). Within the native soil, differences between $\log(K_{sT})$ and $\theta_{sT}$ values for Layers 1 and 2 were significant and values for Layers 3, 4, and 5 were intermediate (Fig. 3A and 3B). In comparison with $\log(K_{sT})$ values for the soil, trench fill values were similar to soil Layer 1, but, in most cases, fill values were significantly less than those

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Table 6. Summary of analysis of variance and orthogonal contrasts for testing effects of burial-trench construction on hydraulic properties and vertical variability of these properties: log(field [soil plus rock fragments] saturated hydraulic conductivity) ($K_{sT}$), field saturated water content ($\theta_{sT}$), and Rossi–Nimmo retention model fitting parameter ($\psi_o$, $\lambda$).

| Source of variation or contrast | df | Probability level ($P > F$) | | | |
|---|---|---|---|---|---|
| | | $\log(K_{sT})$ | $\theta_{sT}$ | $\psi_o$ | $\lambda$ |
| Material (M) | 1 | 0.002 | 0.374 | 0.002 | 0.009 |
| Main-plot error | 2 | – | – | – | – |
| Layer (L) | 4 | 0.084 | 0.186 | 0.0004 | 0.002 |
| M × L | 4 | 0.178 | 0.201 | 0.0005 | 0.003 |
| Orthogonal contrast† | | | | | |
| (M1L1 – M2L1) = (M1L2 – M2L2) | 1 | 0.023 | 0.044 | 0.0002 | 0.0006 |
| (M1L2 – M2L2) = (M1L3 – M2L3) | 1 | 0.381 | 0.536 | 0.430 | 0.893 |
| (M1L3 – M2L3) = (M1L4 – M2L4) | 1 | 0.793 | 0.252 | 0.496 | 0.678 |
| (M1L4 – M2L4) = (M1L5 – M2L5) | 1 | 0.863 | 0.280 | 0.120 | 0.685 |
| Split-plot error | 8 | – | – | – | – |
| Total | 19 | – | – | – | – |

† Material × layer interaction means denoted by $M_iL_j$ for the $i$th level of material (1 = soil; 2 = fill) and the $j$th level of layer ($j$ = 1, 2, 3, 4, or 5).

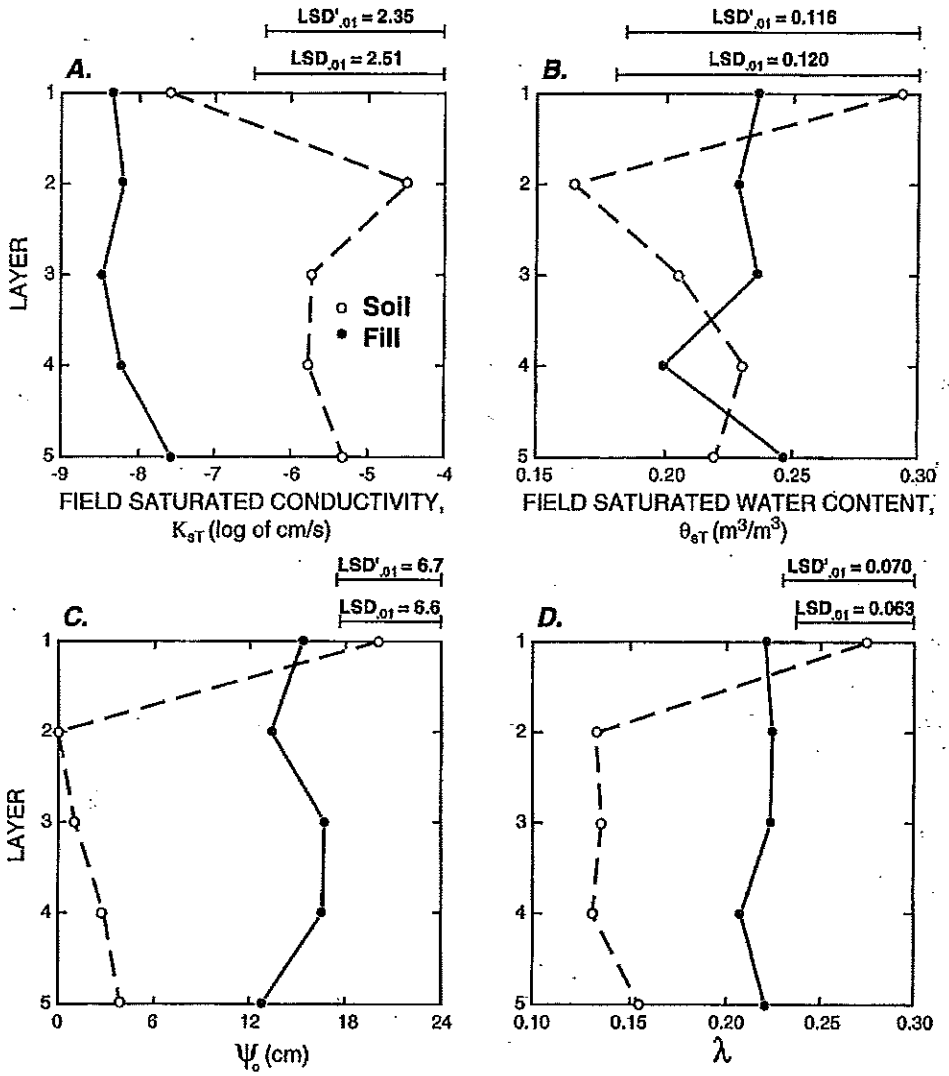


Fig. 3. Material × layer interaction means for hydraulic properties: (A) log(field [soil plus rock fragments] saturated hydraulic conductivity), (B) field saturated water content and fitting parameters for the Rossi–Nimmo retention model: (C) $\psi_o$ is related to air-entry suction and (D) $\lambda$ is a shape factor. Test statistics are: LSD(0.01) for comparing layer means within a material, and LSD′(0.01) for comparing material means within the same layer or different layers.

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for the soil subsurface layers. Differences between soil and fill $\theta_{sT}$ values were not significant. For both water-retention fitting parameters, the soil Layer 1 value was significantly greater than those for the subsurface soil layers (Fig. 3C and 3D). Trench-fill values for $\psi_o$ and $\lambda$ typically were similar to those for soil Layer 1, but were significantly greater than those for soil subsurface layers.

Results of the statistical analyses clearly show that construction of waste-burial trenches had substantial effects on physical and hydraulic properties and their vertical variability. Steps used in the construction of burial trenches (excavation, stockpiling excavated materials, and backfilling) produced a fill material that was significantly less variable than the native soil. In addition, exposure of excavated soil to air produced a fill material that, on average, was drier than the undisturbed native soil (fill, 0.034 $m^3\ m^{-3}$; soil, 0.063 $m^3\ m^{-3}$). Surprisingly, such changes typically are not considered in the evaluation of proposed waste-burial sites. Most often, a great deal of effort is placed on characterizing flow and transport in the natural system with little regard as to whether the actual disposal facility will mimic the natural system. How changes to the natural system may affect flow processes at the Amargosa Desert site are discussed below under hydraulic properties of the conceptual model components.

## Preliminary Conceptual Models of Vertical Variation within the Native Soil Profile and Trench Fill

The results of statistical analyses were used to quantitatively develop preliminary conceptual models of vertical variation within the native soil profile and trench fill. For the native soil profile, all the physical and hydraulic properties considered under the ANOVA model, except for $\theta_T$ measured during sampling, showed significant differences between Layers 1 and 2. Values for these two contiguous layers commonly represented the extremes for the soil profile. Differences between soil Layer 2 and the underlying layers were significant for several physical properties: log(clay), sand, $\rho_T$, and $\theta_T$. Although means comparisons showed no differences between $\log(K_{sT})$ values for Layer 2 vs. Layer 3, 4, or 5, the trend was toward decreased conductivity for the three underlying layers ($P > |t| = 0.130$, 0.119, and 0.290, respectively). Similarly, comparisons between $\theta_{sT}$ values for Layer 2 vs. Layers 3, 4, and 5 showed a trend toward increased $\theta_{sT}$ for the three underlying layers ($P > |t| = 0.294$, 0.103, 0.163, respectively). Among the three deep soil layers, however, only $\rho_T$ was found to differ significantly. Thus, on the basis of these statistical results, the preliminary conceptual model for the native soil profile is represented by three major components: Layer 1, Layer 2, and a composite of Layers 3, 4, and 5.

For the trench fill, except for $\rho_T$, none of the properties considered under the ANOVA model showed significant differences among layers. Therefore, the conceptual model of vertical variation within the trench fill is represented by a single composite of Layers 1, 2, 3, 4, and 5.

## Hydraulic Properties of the Conceptual Model Components

Water-retention data and the Rossi–Nimmo retention model fitted with mean parameters for each component of the native soil profile and the trench fill conceptual models are shown in Fig. 4. Within the individual plots shown in Fig. 4, each symbol represents the mean of (A) 18, (B) 6, (C) 26, and (D) 42 subsample values determined using pressure-plate or water-activity meter methods. The 15 300-cm pressure-plate data, which were omitted from the hydraulic-property analysis, are shown to further demonstrate the apparent lack of equilibration for these measurements. For each of the conceptual model components, the water-activity meter measurements made immediately after the 15 300-cm pressure-plate measurements were significantly less than the expected 15 300-cm value ($P > |t| = 0.001$). Average differences were 8380 cm water for soil Layer 1, 5270 cm water for soil Layer 2, 9040 cm water for soil composite Layers 3, 4, and 5, and 8860 cm water for trench fill. Greater differences corresponded with finer textured material. Gee et al. (1992) suggested that the water-activity meter is best adapted for measurement of soils drier than 4080 cm water suction. Although water-activity measurements were not made immediately following the 5100-cm pressure-plate measurement, the data appear to be fairly continuous across this region. The results suggest that use of standard, 15 300-cm pressure-plate data for the lower limit of water-retention measurements may lead to significant errors in the description of hydraulic properties and prediction of water flow in dry soils.

Among the conceptual model components, soil Layer 2, the component with the coarsest texture, retained the least water. For suctions $<1 \times 10^3$ cm water, soil Layer 1 retained the greatest volume of water. For suctions $>1 \times 10^3$ cm water, however, the high clay content of soil composite Layers 3, 4, and 5 resulted in this component holding the greatest volume of water. The retention curve for trench fill was intermediate between soil Layer 1 and soil composite Layers 3, 4, and 5.

The $\psi_j$ value determined for the Rossi–Nimmo model represents the second junction point where the fitted function deviates from the power law and becomes completely logarithmic. For each component of the conceptual models, the mean value for this analytically determined point [$\psi_j = \psi_d \exp(-1/\lambda)$] was: $2.4 \times 10^5$ cm water for soil Layer 1; $4.8 \times 10^3$ cm water for soil Layer 2; $8.2 \times 10^3$ cm water for soil composite Layers 3, 4, and 5; $9.8 \times 10^4$ cm water for trench fill.

As a check of the adequacy of the laboratory-derived water-retention functions, suction values for the Rossi–Nimmo model that correspond with $\theta_T$ values measured at the time of sampling were compared with suction values measured at the field site using psychrometers. For soil Layer 1 (initial $\theta_T = 0.030\ m^3\ m^{-3}$), the calculated suction value of $9.8 \times 10^4$ cm water (Fig. 4A) is consistent with field values that ranged from about $4.5 \times 10^4$ to $>8 \times 10^4$ cm water (upper limit of psychrometer calibration) (1987, unpublished data). For fill

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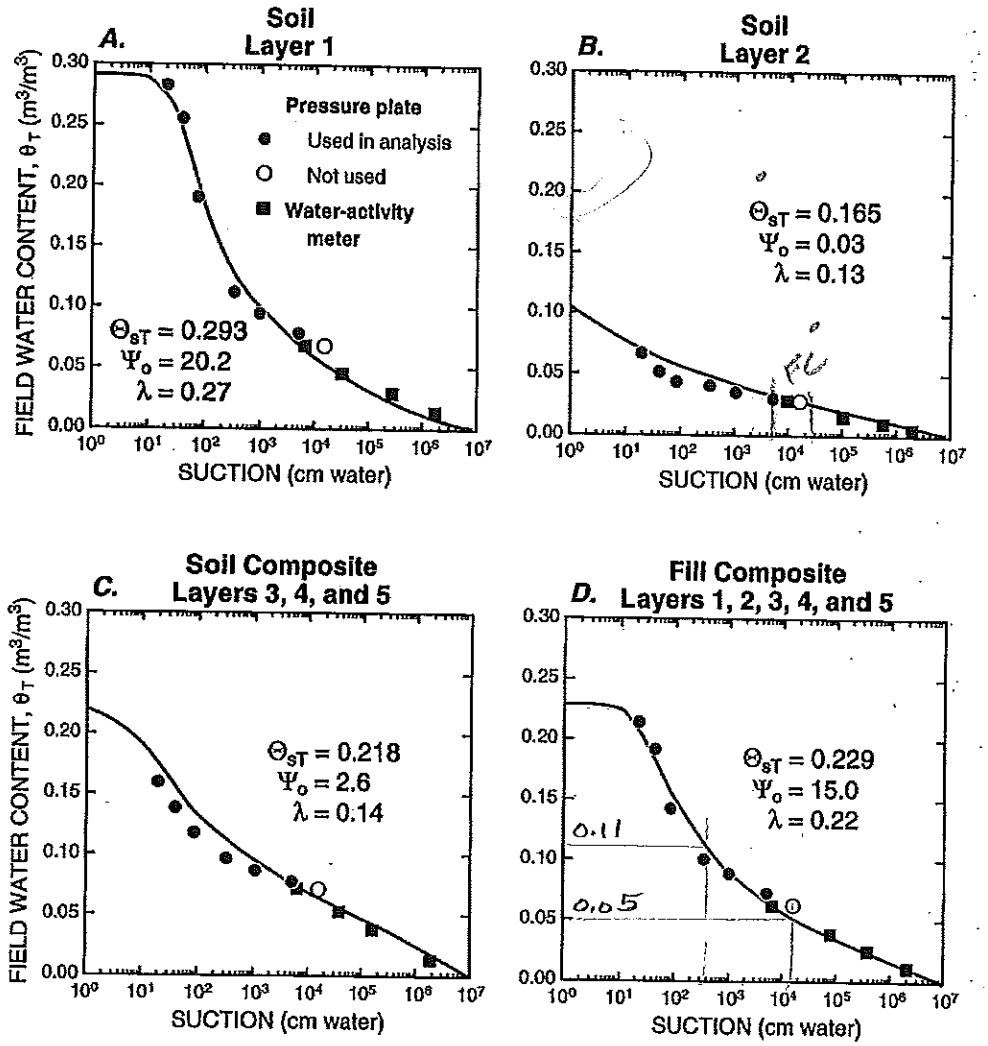


**Fig. 4. Water-retention data and the Rossi–Nimmo model fitted with mean parameters and reported on a field (soil plus rock fragments) basis for each component of the conceptual models for native soil profile and trench fill. (A) soil, Layer 1; (B) soil, Layer 2; (C) soil, composite Layers 3, 4, and 5; and (D) fill, composite Layers 1, 2, 3, 4, and 5.**

composite Layers 1, 2, 3, 4, and 5 (avg. initial $\theta_T$ = 0.034 $m^3\ m^{-3}$), the calculated suction value of 8.7 × $10^4$ cm water (Fig. 4D) also is consistent with field values of >8 × $10^4$ cm (Andraski, 1990). For the two components that show more rapid release of water at low suctions (soil Layer 2, initial $\theta_T$ = 0.043 $m^3\ m^{-3}$; soil composite Layers 3, 4, and 5, avg. initial $\theta_T$ = 0.081 $m^3\ m^{-3}$), the agreement is not as good. Calculated suction values for these components are 9.3 × $10^2$ and 3.1 × $10^3$ cm water, respectively (Fig. 4B and 4C) compared with field values between 4 × $10^4$ and 5 × $10^4$ cm water (Fischer, 1992). Although this evaluation is limited to single points (initial values) on the respective retention curves, the agreement between laboratory-derived suction values and those measured in the field is reasonable, especially when considering that values are approaching the logarithmic part of the retention curve, where a small change in water content corresponds with a large change in suction.

Describing liquid hydraulic conductivity and vapor conductivity is important because of the low water contents measured at the site. Liquid hydraulic conductivity ($K_l$) of the fine soil may be described as a function of $\theta$ using the Rossi–Nimmo junction model (Eq. [2]) in combination with the capillary bundle model of Mualem (1976)

$$K_l(\theta) = K_s(\theta/\theta_s)^{1/2}\,[I(\theta)/I(\theta_s)]^2 \qquad [5]$$

where $I(\theta)$ is the integral for any value of $\theta$ between $\theta = 0$ and $\theta_s$ and $I(\theta_s)$ is the total integral from $\theta = 0$ to $\theta_s$ (Rossi and Nimmo, 1994). Mehuys et al. (1975) have shown that, if hydraulic conductivity is expressed as a function of $\psi$, unsaturated $K_l$ values do not need to be corrected for rock-fragment content. Thus, the Mualem model was solved in terms of $\psi$ by substituting Eq. [2] into Eq. [5] and expressing saturated hydraulic conductivity as $K_{sT}$ (Eq. [1]). For this substitution, the integral for each of the three components of the retention

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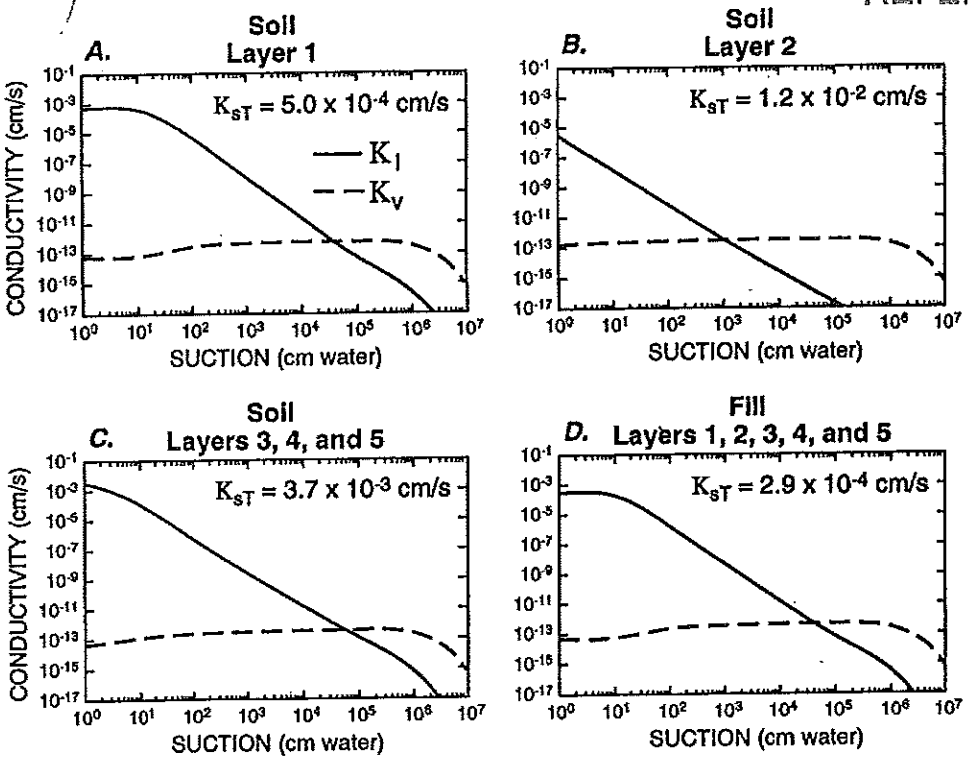


**Fig. 5. Field (soil plus rock fragments) saturated hydraulic conductivity ($K_{sT}$), liquid hydraulic conductivity ($K_l$), and isothermal (20°C) vapor conductivity ($K_v$) as a function of suction for each component of the conceptual models for native soil profile and trench fill: (A) soil, Layer 1; (B) soil, Layer 2; (C) soil, composite Layers 3, 4, and 5; and (D) fill, composite Layers 1, 2, 3, 4, and 5.**

model ($I_{III}$, $I_{II}$, and $I_I$) is expressed as

$$I_{III}(\psi) = (\alpha/\psi) - (\alpha/\psi_d) \quad \psi_d \geq \psi \geq \psi_j$$

$$I_{II}(\psi) = \{\lambda/[\psi_o(\lambda + 1)]\}\,[(\psi_o/\psi)^{\lambda+1} - (\psi_o/\psi_j)^{\lambda+1}] \quad \psi_j \geq \psi \geq \psi_i$$

$$I_I(\psi) = (2c/\psi_o^2)(\psi_i - \psi) \quad \psi_i \geq \psi \geq 0 \qquad [6]$$

Combining $I_{III}$, $I_{II}$, and $I_I$ gives the integral $I(\psi)$ for any value of $\psi$,

$$\begin{aligned} I(\psi) &= I_{III}(\psi) && \psi_d \geq \psi \geq \psi_j \\ I(\psi) &= I_{III}(\psi_j) + I_{II}(\psi) && \psi_j \geq \psi \geq \psi_i \\ I(\psi) &= I_{III}(\psi_j) + I_{II}(\psi_i) + I_I(\psi) && \psi_i \geq \psi \geq 0 \end{aligned} \qquad [7]$$

and the total integral from $\psi = \psi_d$ to 0 cm water suction is

$$I(\psi_{total}) = I_{III}(\psi_j) + I_{II}(\psi_i) + I_I(0) \qquad [8]$$

Isothermal vapor conductivity ($K_v$) was described as a function of $\psi$ using

$$K_v(\psi) = (D_v \rho_s Mg/\rho_w RT)\mathrm{RH} \qquad [9]$$

The derivation of Eq. [8] is described by Fayer et al. (1992). In Eq. [9], $K_v(\psi)$ is expressed in cm s$^{-1}$, $D_v$ is diffusion coefficient for water vapor in soil (cm$^2$ s$^{-1}$), $\rho_s$ is saturated water vapor density (g cm$^{-3}$), $\rho_w$ is density of liquid water (g cm$^{-3}$), RH is relative humidity [RH = $\exp(-\psi Mg/RT)$], and $M$, $g$, $R$, and $T$ are as defined in Eq. [3]. The diffusion coefficient accounts for tortuosity of the diffusion path and the reduced cross-sectional area for flow by $D_v = D_a\tau\varphi$, where $D_a$ is diffusivity of water vapor in bulk air, $\tau$ is a tortuosity factor (assumed to be 0.66; Penman, 1940), and $\varphi$ is air-filled porosity (total porosity minus $\theta_T$). Calculations of $K_v$ reported here are based on the assumption that $\theta_{sT}$ is 90% of total porosity.

The $K_l$ and $K_v$ functions for each component of the native soil profile and trench fill conceptual models are shown in Fig. 5. Accuracy of $K_l$ calculated through Eq. [5] to [8] has not been tested. Comparison with the few data in the literature on hydraulic conductivity of dry soils, however, indicates the calculated values are quite reasonable. Mehuys et al. (1975) used a transient-outflow method to measure total hydraulic conductivity ($K_l$ plus $K_v$) of three desert soils (a gravelly loamy sand and two gravelly sandy loam soils) within a suction range from 50 to 50 000 cm water. Their measured conductivity values ranged from about $10^{-4}$ to $10^{-11}$ cm s$^{-1}$. Conductivities calculated in this range of suction for soil Layer 1 (loamy sand), soil composite Layers 3, 4, and 5 (gravelly coarse sandy loam), and trench fill (gravelly loamy coarse sand) typically are within an order of magnitude of the values measured by Mehuys et al. (1975). For a sandy soil, Nimmo et al. (1992) used steady-state centrifuge methods to measure $K_l$ values that ranged from about $10^{-6}$ cm s$^{-1}$ at 100 cm water suction to $10^{-9}$ cm s$^{-1}$ at 430 cm water suction. Recently, Mehta et al. (1994) measured total hydraulic conductivity of a dune sand from saturation to $2.5 \times 10^5$ cm water ($\theta$ = 0.01 m$^3$ m$^{-3}$) using a steady-state flux control and an instantaneous-profile method in two suction ranges. Across the

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full suction range, their measured values ranged from about $10^{-2}$ to $10^{-13}$ cm $s^{-1}$. At suctions near 100 and 430 cm water, conductivity values measured by Mehta et al. (1994) ($\approx 10^{-9}$ and $10^{-10}$ cm $s^{-1}$, respectively) were less than those reported by Nimmo et al. (1992). At the lower and upper extremes of the suction range covered by Mehta et al. (1994), the sum of calculated $K_l$ and $K_v$ values for soil Layer 2, the coarse sand (Fig. 5B), duplicates their measured values within a factor of $\leq 2.3$. At intermediate suctions, calculated values typically are about one to two orders of magnitude less than conductivities measured by Mehta et al. (1994) and three to four orders of magnitude less than those measured by Nimmo et al. (1992). Additional studies specifically designed to test the accuracy of predictive equations against direct measurements of unsaturated conductivity in dry soils are needed.

Among the conceptual model components for the Amargosa Desert site, $K_{sT}$ was greatest for soil Layer 2, but with increased suction, values rapidly decreased to two to four orders of magnitude less than those for the other components (Fig. 5). The shape of the $K_l$ functions for soil Layer 1 and the trench fill was similar, but across a suction range from 0 to about $1 \times 10^4$ cm water, $K_l$ values for soil Layer 1 were about twice those for the trench fill.

The textural discontinuity between the two uppermost soil layers has been noted as important in impeding continued downward flow of water in the undisturbed native soil profile at the Amargosa Desert site (Gee et al., 1994). Although hydraulic conductivity typically is less for the trench fill than for the native surface soil, lack of textural discontinuity in the fill increases the potential for meteoric water to come in contact with and transport buried waste.

The $K_v$ functions were similar for all model components, except at suctions <100 cm water, where $K_v$ values were greater for soil Layer 2 (Fig. 5). The suction value at which $K_v$ begins to exceed $K_l$ differed among the conceptual model components: about $4 \times 10^4$ cm water for soil Layer 1 and the trench fill; $1 \times 10^3$ cm water for soil Layer 2; $6 \times 10^4$ cm water for soil composite Layers 3, 4, and 5. Thus, during trench construction, $K_v$ was $\geq K_l$ for each of the model components except the deep (2–5 m) soil composite. Total hydraulic conductivity, however, was greater for the soil composite layer ($\approx 10^{-10}$ cm $s^{-1}$) than for the other model components ($\approx 10^{-13}$ cm $s^{-1}$).

Exposure of excavated soil to air during trench construction produced a fill material that was drier than the undisturbed native soil profile. Although this effect is considered transient, these dry initial conditions have strong implications concerning the relative importance of liquid flow vs. vapor flow processes in the body of burial trenches. Such initial conditions can be markedly altered, however, by the timing and quantity of precipitation and the subsequent redistribution and evaporation of infiltrated water. For example, results from field monitoring at the Amargosa Desert site (first 3 yr of a 5-yr study) showed that during the first year following trench construction, redistribution of infiltrated water caused suction values to decrease rapidly to about $1 \times 10^3$ cm water at depths of 0.6 to 0.75 m in native soil and to about $4.8 \times 10^4$ cm water at a depth of 0.75 m in the fill of the east trench (Gee et al., 1994). In the absence of vegetation, these decreased suction values persisted for the next 2 yr. Thus, depending on specific but commonly transient conditions, the relative importance of liquid flow and vapor flow as transport mechanisms for buried contaminants may differ dramatically.

Both liquid and vapor flow can occur as a consequence of matric suction and temperature gradients. Thermally induced liquid flow usually is not large enough to require consideration, but thermally induced vapor flow may be important where soils are dry and large temperature fluctuations occur (Campbell, 1985). Recently, Scanlon and Milly (1994) used numerical simulations to evaluate liquid- and vapor-flow processes in response to an annual climate cycle at an undisturbed site in the Chihuahuan Desert of Texas. Changes in water storage associated with individual rainfall events and subsequent evaporation were confined mainly to the top 0.3 m of soil. Total water flow in this soil zone was dominated by downward and upward liquid fluxes, which were driven by matric-suction gradients. Upward, isothermal-vapor flux dominated only in the top several millimeters of soil during periods of evaporation. Below the 0.3-m depth, simulated water fluxes varied relatively little. The dominant flow component, however, was thermal-vapor flux, which varied with season and depth in accordance with changes in the temperature gradient. The results of Scanlon and Milly (1994) demonstrate the complexity of flow processes that may occur in an undisturbed arid setting. Additional study is needed to evaluate how the natural flow system may be altered by the installation of a waste-burial facility.

## SUMMARY AND CONCLUSIONS

Physical and hydraulic properties were determined for five layers within both the native soil profile (upper 5 m) and trench fill. Steps used in trench construction (excavation and stockpiling of native soil, backfilling with stockpiled soil) had a significant effect on soil properties and their variability. Surprisingly, such changes typically are not considered in the evaluation of proposed waste-burial sites. Most often, a great deal of effort is placed on characterizing flow and transport in the natural system with little regard as to whether the actual disposal facility will mimic the natural system. Results of statistical analyses were used to quantitatively develop preliminary conceptual models of vertical variation within the native soil profile and trench fill. The conceptual model for native soil is represented by three major horizontal components and the trench fill is represented by a single component.

Water retention measurements were extended to air dryness ($\psi = 2 \times 10^6$ cm water suction). Water-activity meter measurements made immediately after the 15 300-cm pressure-plate measurements showed the actual suction values were significantly less than the expected 15 300-cm value (avg. difference = 8550 ± 2460

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cm water). This discrepancy is assumed to be due to lack of equilibration for the pressure-plate measurement and, therefore, the 15 300-cm pressure-plate data were omitted from hydraulic-property analysis. Water retention was modeled to oven dryness using the Rossi and Nimmo (1994) junction model. The junction model described the measured values well, and predicted suction values were consistent with field values. Calculated hydraulic conductivities also were in reasonable agreement with the few measured values of conductivity in dry soils that are reported in the literature.

Backfilling with the very dry material produced by the trench construction process, at least initially, will increase the importance of vapor flow as a transport mechanism in the trench fill. Although liquid hydraulic conductivity for the trench fill is about half that for the native surface soil at suctions $\leq 1 \times 10^4$ cm water, the lack of textural discontinuity in the fill may allow infiltrated water to continue downward, increasing the potential for meteoric water to come in contact with and transport buried waste.

Results of this study show that construction of waste-burial trenches can markedly alter the natural site environment. Such alterations must be considered in siting and designing arid waste-burial and monitoring systems and also in predicting the effectiveness of proposed sites and facilities for long-term waste isolation. This study quantitatively describes the hydraulic properties and vertical variations at a site using data measured across a water-content range that is representative of arid conditions, but is seldom studied. The data suggest that use of standard, 15 300-cm pressure-plate data for the lower limit of water-retention measurements may lead to significant errors in the description of hydraulic properties and prediction of water flow in dry soils. Results of the study provide data for physically based flow and solute-transport models intended to simulate processes in the near surface and at depth at a representative arid waste-burial site.

## ACKNOWLEDGMENTS

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# Characterizing the Dependence of Gas Diffusion Coefficient on Soil Properties

Yan Jin and William A. Jury*

## ABSTRACT

**Knowledge of the gaseous diffusion coefficient is necessary to properly model gas movement in porous media. In this study, a nonreactive tracer (freon-12) and a reactive tracer (hexafluorobenzene) were used to evaluate the relationship between the ratio of the gas diffusion coefficient in soil ($D_g^s$) to that in free air ($D_g^a$) and the volumetric air content ($a$) with a two-chamber diffusion system. The measured $D_g^s/D_g^a$ values in our experiments (i.e., the relative gas diffusion coefficients) showed a similar relationship to air content as data obtained from various studies reported in the literature. Our data and values taken from other studies were used to test the validity of various models. When compared with data obtained from experiments with disturbed soils, the Penman model $D_g^s/D_g^a = 0.66\,a$ was found to overestimate the measured relative diffusion coefficient, whereas the Millington-Quirk model $D_g^s/D_g^a = a^{10/3}/\varphi^2$, where $\varphi$ is the soil porosity, underestimated it. Another Millington-Quirk relationship $D_g^s/D_g^a = a^2/\varphi^{2/3}$, which has been largely overlooked in the literature, was found to provide significantly better agreement with measured relative diffusion coefficients in various disturbed soils of different texture. On the contrary, no universal relationship was found when data from both disturbed and undisturbed soil experiments were evaluated. The Troeh model $D_g^s/D_g^a = [(a - u)/(1 - u)]^r$ had the flexibility to fit all of the experimental data when both of the model parameters were varied simultaneously; however, no obvious correlation was found between soil properties and the parameters. The limitations of any universal form for gas tortuosity model in natural soils were analyzed with percolation theory.**

The movement of gases in soil occurs by two major transport mechanisms: advection and diffusion. Gas phase diffusion dominates advection when the pressure difference is small, and when the vapor pressure and molecular weight of the chemical are low or at dilute concentrations (Falta et al., 1989). Unlike water flow, gas phase diffusion also dominates dispersion because the diffusion coefficient in air is $10^4$ to $10^5$ times greater than that in water (Jury et al., 1983; Gierke et al., 1990).

Transport modeling of gas movement in soil requires knowledge of the gaseous diffusion coefficient. Gas diffusion models are useful in analyzing a variety of transport processes such as $O_2$ and $CO_2$ exchange between plant roots and the atmosphere, distribution of fumigants applied to soil for pest control, and movement of volatile organic contaminants through soil.

The diffusion coefficient of a gas through soil ($D_g^s$) is less than that through free air ($D_g^a$) because of the reduced cross-sectional area and increased path length caused by the presence of solid and liquid obstacles. The combined effect of these reductions is embodied in the relative diffusion coefficient $\xi_g = D_g^s/D_g^a$. Many attempts have been made to find a relationship between $\xi_g$ and the volumetric air content ($a$) of the soil (Penman, 1940; Millington, 1959; Millington and Quirk, 1960; Troeh et al., 1982; Sallam et al., 1984; Collin and Rasmuson, 1988; Shimamura, 1992; Areh et al., 1994; Freijer, 1994; Steele and Nieber, 1994). However, a simple and unique relationship between $\xi_g$ and $a$ that can be used for various porous media has never been found.

Moreover, the existence of such a relationship has recently been rejected by some investigators. Bruckler et al. (1989) concluded from a laboratory experiment that there is no unique relationship between the gas diffusion coefficient and air-filled porosity for all porous media, because such a relationship would necessarily be highly dependent on pore size, pore continuity, morphology, and tortuosity. While the existence of a unique relationship is debatable, it is clear that some sort of generalized functional form relating tortuosity to static, measurable properties of soil would be very useful, and this explains why so much effort has been directed toward finding one in the past.

The two most commonly used gas diffusion models in soil are the Penman model (Penman, 1940)

$$\xi_g(a) = 0.66a \qquad [1]$$

and the Millington-Quirk model (Millington, 1959; Millington and Quirk, 1960)

$$\xi_g(a) = \frac{a^{10/3}}{\varphi^2} \qquad [2]$$

where $\varphi$ is soil porosity.

The above two models have been widely used due to their simplicity and minimum parameter requirements. However, only limited testing has been performed against experimental data to support claims for a given model's validity or generality (Troeh et al., 1982; Sallam et al., 1984). In fact, Eq. [2] was found to significantly

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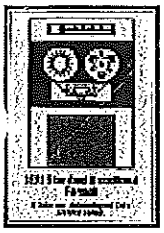
Abbreviations: HFB, hexafluorobenzene; GC, gas chromatograph; FID, flame ionization detector.

# UNSAT-H

## Meteorological Refences



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# Standard Broadband Format Manual

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## Appendix B

# Unit Conversions

The following table converts other common units to the measurement units specified by the SERI Stan dard Broadband Format. Both energy-flux units and power-flux units are given for solar radiation measurements, thereby allowing conversion between types of units. For example, an average power density of 1.0 W/m^2 over 1 min is equal to 0. 06 kJ/m of energy density.

Common solar radiation measurement units are langleys, Btus per square foot, kilojoules per square meter, and watts per square meter. In order to adhere to standard international (SI) units, only kilojoules per square meter and watts per square meter were considered for SBF. The energy-flux unit, kilojoules per square meter, causes scaling problems that are typically resolved by altering the magnitude of the unit. Thus, l-min and hourly data can be recorded compactly as kilojoules per square meter, but daily data would be recorded in megajoules per square meter and yearly data in gigajoules per square meter. This situation creates an unwanted ambiguity. In addition, recording in kilojoules per square meter causes an additional problem. The units of energy, as integrals, do not lend themselves to comparisons between measurement time intervals. For example, it is not immediately obvious that a l-min radiation measurement of 48 kJ/m^2 is equivalent to a 15-min radiation measurement of 720 kJ/m^2.

Recording with the power-flux unit, watts per square meter, removes both the ambiguity and comparison problems. It is no longer necessary for the user to maintain multiple units for various measurement time intervals. All radiation values can be expressed in the same range (0-2000 W/m^2). Also, comparison is simplified because the user is not comparing apples and oranges. With the example given for kilojoules, it is readily apparent to the user that a l-min radiation measurement is equivalent to a 15-min measurement when the values are given in watts per square meter (in this case, both equal 800 W/m ). A daily, value in SBF can be converted from an average daily value (watts per square meter) to an integrated daily value (watts per square meter) by multiplying by 24 (hours).

# One Minute* Solar Radiation Conversions

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| To Convert From | To | Multiply By |
|---|---|---|
| W/m^2 | kJ/m^2 | 0.06 |
| W/m^2 | langley/min | 0.001433 |
| w/m^2 | cal/cm^2 min | 0.001433 |
| w/m^2 | Btu/ft^2 min | 0.005285 |
| kJ/m^2 | W/m^2 | 16.66667 |
| langley/min | W/m^2 | 697.3 |
| cal/cm^2 min | W/m^2 | 697.3 |
| Btu/ft^2 min | w/m | 189.1 |

# One-Hour*Solar Radiation Conversions

| To Convert From | To | Multiply By |
|---|---|---|
| W/m^2 | kJ/m^2 | 3.6 |
| W/m^2 | langley/hour | 0.0858 |
| W/m^2 | cal/cm^2 hour | 0.0858 |
| W/m^2 | Btu/ft^2 hour | 0.317 |
| W/m^2 | kWh/m^2 | 0.024 |
| kJ/m^2 | W/m^2 | 0.27 |
| langley/hour | W/m^2 | 11.22 |
| cal/cm^2 hour | W/m^2 | 11.622 |
| Btu/ft^2 hour | W/m^2 | 3.152 |
| kWh/m^2 | W/m^2 | 41.66 |

# Pressure Conversions

| To Convert From | To | Multiply By |
|---|---|---|
| kPa | millibars | 10. |

# MET3A CALCULATION OF DEW POINT

## Summary

This report describes the calculations required for determining the dew point temperature, using the measured temperature of the RTD sensor and relative humidity sensor. The algorithm is based on the Magnus-Tetens formula, over the range

0° C < T < 60° C
0.01 < RH < 1.00
0° C < Td < 50° C

where T is the measured temperature [°C]

RH is the measured relative humidity

and Td is the calculated dew point temperature [°C]

The dew point temperature is

$$T_d = \frac{b \cdot \alpha(T, RH)}{a - \alpha(T, RH)} \quad (1)$$

$$\alpha(T, RH) = \frac{a \cdot T}{b + T} + \ln(RH) \quad (2)$$

with a = 17.27
and b=237.7 [°C]

The uncertainty in the calculated dew point temperature is ±0.4° C.

## Background

The MET3A provides three measured meteorological parameters: the atmospheric pressure, the temperature and the relative humidity. A fourth parameter is often requested, the dew point temperature. This quantity can be calculated from the three measured parameters.

The measured atmospheric pressure is the sum of two terms, the partial pressure of dry air (pa) and the partial pressure of

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$$p_w = RH \cdot p_{ws}$$

$$\Rightarrow 0.6105 \cdot \exp\left[\frac{a \cdot T_d}{b + T_d}\right] = 0.6105 \cdot RH \cdot \exp\left[\frac{a \cdot T}{b + T}\right]$$

$$\Rightarrow T_d(T, RH) = \frac{b \cdot \alpha(T, RH)}{a - \alpha(T, RH)}$$

where

$$\alpha(T, RH) = \ln(RH) + \frac{a \cdot T}{b + T}$$

**Uncertainty of Dew Point Temperature**

The uncertainty in the measured dew point temperature is a function of the measured temperature and relative humidity and the uncertainties associated with those measurements.

The uncertainty in the measured dew point temperature is

$$\sigma_{Td}^2 = \sigma_T^2 \left(\frac{\partial T_d}{\partial T}\right)^2 + \sigma_{RH}^2 \left(\frac{\partial T_d}{\partial RH}\right)^2$$

where σ2Td is the uncertainty in the calculated dew point temperature

σ2T is the uncertainty in the measured temperature

σ2RH is the uncertainty in the measured relative humidity

and assuming no cross-correlated uncertainties.

Taking the appropriate derivatives and collecting the terms, we find the uncertainty in the calculated dew point temperature to be

$$\sigma_{Td}^2 = \sigma_T^2 \left(\frac{a \cdot b}{a \cdot b - (b + T)\ln(RH)}\right)^4 + \sigma_{RH}^2 \left(\frac{a \cdot b(b + T)^2}{RH \cdot (a \cdot b - (b + T)\ln(RH))^2}\right)^2$$

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# Selected Micrometeorological and Soil-Moisture Data at Amargosa Desert Research Site in Nye County Near Beatty, Nevada, 1998–2000

*By* Michael J. Johnson, Charles J. Mayers, and Brian J. Andraski

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## CONVERSION FACTORS AND VERTICAL DATUM

| Multiply | By | To obtain |
|---|---|---|
| | **Length** | |
| centimeters (cm) | 0.3937 | inch |
| millimeter (mm) | 0.03937 | inch |
| micrometer (µm) | 0.000039 | inch |
| kilometer (km) | 0.6214 | mile |
| meter (m) | 3.281 | foot |
| | **Volume** | |
| liter (L) | 0.2642 | gallon |
| | **Volume per unit time (includes flow)** | |
| meter per second (m/s) | 3.281 | foot per second |
| millimeter per hour (mm/h) | 0.03937 | inch per hour |
| | **Pressure** | |
| kilopascal (kPa) | 0.1450 | pound-force per square inch |
| | **Radioactivity** | |
| becquerel per liter (Bq/L) | 27.027 | picocurie per liter |
| Watts per square meter ($W/m^2$) | 0.005290 | British Thermal Unit per square foot per minute |

**Temperature:** Degrees Celsius ($^{o}C$) can be converted to degrees Fahrenheit ($^{o}F$) by using the formula $^{o}F = [1.8\ (^{o}C)] + 32$. Degrees Fahrenheit can be converted to degrees Celsius by using the formula $^{o}C = 0.556\ (^{o}F - 32)$. Degrees Kelvin ($^{o}K$) can be converted to degrees Fahrenheit ($^{o}F$) by using the formula $^{o}F = [1.8\ (^{o}K - 273)] + 32$. Degrees Fahrenheit can be converted to degrees Kelvin by using the formula $^{o}K = [0.556\ (^{o}F - 32)] + 273$.

**Radiation:** A unit of activity is a Curie (Ci), which is equivalent to $37 \times 10^{10}$ disintegrations per second (dps); the standard disintegration rate of 1 gram of Radium. In International Units a Bequerel (Bq) is equivalent to 1 disintegration per second (dps). Thus, 10 milliCuries (mCi) equals 370 megaBequerels (MBq).

**Sea level:** In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

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# Selected Micrometeorological and Soil-Moisture Data at Amargosa Desert Research Site in Nye County Near Beatty, Nevada, 1998–2000

*By* Michael J. Johnson, Charles J. Mayers, and Brian J. Andraski

## ABSTRACT

Selected micrometeorological and soil-moisture data were collected at the Amargosa Desert Research Site adjacent to a low-level radioactive waste and hazardous chemical waste facility near Beatty, Nev., 1998–2000. Data were collected in support of ongoing research studies to improve the understanding of hydrologic and contaminant-transport processes in arid environments.

Micrometeorological data include precipitation, air temperature, solar radiation, net radiation, relative humidity, ambient vapor pressure, wind speed and direction, barometric pressure, soil temperature, and soil-heat flux. All micrometeorological data were collected using a 10-second sampling interval by data loggers that output daily mean, maximum, and minimum values, and hourly mean values. For precipitation, data output consisted of daily, hourly, and 5-minute totals. Soil-moisture data included periodic measurements of soil-water content at nine neutron-probe access tubes with measurable depths ranging from 5.25 to 29.75 meters.

The computer data files included in this report contain the complete micrometeorological and soil-moisture data sets. The computer data consists of seven files with about 14 megabytes of information. The seven files are in tabular format: (1) one file lists daily mean, maximum, and minimum micrometeorological data and daily total precipitation; (2) three files list hourly mean micrometeorological data and hourly precipitation for each year (1998–2000); (3) one file lists 5-minute precipitation data; (4) one file lists mean soil-water content by date and depth at four experimental sites; and (5) one file lists soil-water content by date and depth for each neutron-probe access tube.

This report highlights selected data contained in the computer data files using figures, tables, and brief discussions. Instrumentation used for data collection also is described. Water-content profiles are shown to demonstrate variability of water content with depth. Time-series data are plotted to illustrate temporal variations in micrometeorological and soil-water content data. Substantial precipitation at the end of an El Niño cycle in early 1998 resulted in measurable water penetration to a depth of 1.25 meters at one of the four experimental soil-monitoring sites.

## INTRODUCTION

Research at the Amargosa Desert Research Site (ADRS) is intended to develop a fundamental understanding of hydrologic and contaminant-transport processes in arid regions. Research objectives are to advance the state of hydrologic science and to provide scientific information for those making decisions concerning waste isolation and water management in desert environments. Information on the ADRS is available on the internet at: <http://nevada.usgs.gov/adrs/>.

In support of ongoing research, micrometeorological and soil-moisture data were collected at the ADRS adjacent to a low-level radioactive and hazardous chemical waste facility near Beatty, Nev. The waste facility has been used for the burial of low-level

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radioactive waste from 1962 through 1992 and hazardous-chemical waste from 1970 to present. The ADRS was incorporated into the U.S. Geological Survey (USGS) Toxic Substances Hydrology Program in 1997. Investigations at the ADRS began in 1983 and have produced long-term benchmark data on hydrologic characteristics and soil-water movement for undisturbed conditions and for simulated waste-disposal conditions in arid environments (Andraski and Stonestrom, 1999).

This report includes selected micrometeorological data and soil-moisture data collected for the period 1998–2000. Soil-moisture data collected during November and December 1997 also are included. Instrumentation used to collect the data is described. This report is the seventh in a series of meteorological reports published for this site (Wood and Fischer, 1991, 1992; Wood and others, 1992; Wood and Andraski, 1992, 1995; Wood, 1996). These previous reports include meteorological data collected during a 7-year period (1986–92). Meteorological data were not reported for a 5-year period (1993–97) due to funding constraints.

The micrometeorological data collected for a 3-year period (1998–2000) include precipitation, air temperature, solar radiation, relative humidity, ambient vapor pressure, wind speed and direction, and barometric pressure. In addition, net radiation data collection started in July 1998, and soil temperature and soil-heat-flux data collection started in September 1999. The soil-moisture data were collected periodically during the 3-year period and consist of volumetric soil-water content measurements made using a neutron probe.

Computer data files contain the complete micrometeorological (apps. A and B) and soil-moisture (app. C) data sets summarized in this report. These data consist of seven tabular files with about 14 megabytes of information. The tabular, computer data files (hereafter referred to as data tables) include: (1) one file of daily mean, maximum, and minimum micrometeorological data and daily total precipitation; (2) three files of hourly mean micrometeorological data and hourly precipitation for each year (1998–2000); (3) one file of 5-minute precipitation data; (4) one file of mean soil-water content by date and depth for four experimental sites; and (5) one file of soil-water content by time and depth for each neutron-probe access tube.

## SITE DESCRIPTION

The ADRS is near a waste-burial facility about 17 km south of Beatty, Nev., and 20 km east of Death Valley, Calif. (fig. 1*A*). The ADRS is in the Mojave Desert ecosystem, one of the most arid regions in the United States. Vegetation in the area is sparse; creosote bush [*Larrea tridentata*], an evergreen shrub, is the dominant species. The Amargosa Desert is in the Basin and Range physiographic province. Sediments beneath the study area and the waste-burial facility primarily are basin fill consisting of unconsolidated alluvial fan, fluvial, and marsh deposits (Clebsch, 1968). The basin fill is estimated to be more than 170 m thick (Nichols, 1987, p. 8). Depth to the water table ranges from 85 to 115 m (Fischer, 1992, p. 12).

Other studies at the ADRS facility have been established to support research of flow and transport processes within the thick unsaturated zone above the water table. The research site has two fenced areas; one enclosing an instrument shaft (figs. 1*B* and 2; Fischer, 1992), and the other enclosing simulated waste trenches (figs. 1*B* and 3; Andraski, 1990). A weather station with two precipitation gages and three neutron-probe access tubes are within the instrument shaft area (fig. 2). These instruments are used for monitoring soil-water content in a vegetated, native-soil profile. Six neutron-probe access tubes and a single precipitation gage are within the simulated waste trenches (fig. 3). The tubes are used to measure soil-water content under nonvegetated, simulated waste-trench conditions and under devegetated, but undisturbed native-soil conditions. Ground-water levels have been measured periodically since 1987 at well MR-3 (fig. 1*B*). Deep test holes (UZB-1, -2, -3; fig. 1*B*) have been used for measurements of temperature, water potential, and air pressure; and for collection of soil-gas samples throughout the thick unsaturated zone (Prudic and Striegl, 1995; Prudic and others, 1999; Andraski and Prudic, 1997). Not shown in the figures is an array of soil-gas sampling tubes that are used for periodic collection and analysis of the chemical composition of unsaturated-zone air to a depth of about 1.5 m (Healy and others, 1999; Striegl and others, 1998). Similarly, numerous plant-sampling sites have been established to evaluate soil-plant-atmosphere interactions and ultimately to determine how those interactions affect the potential release of contaminants.

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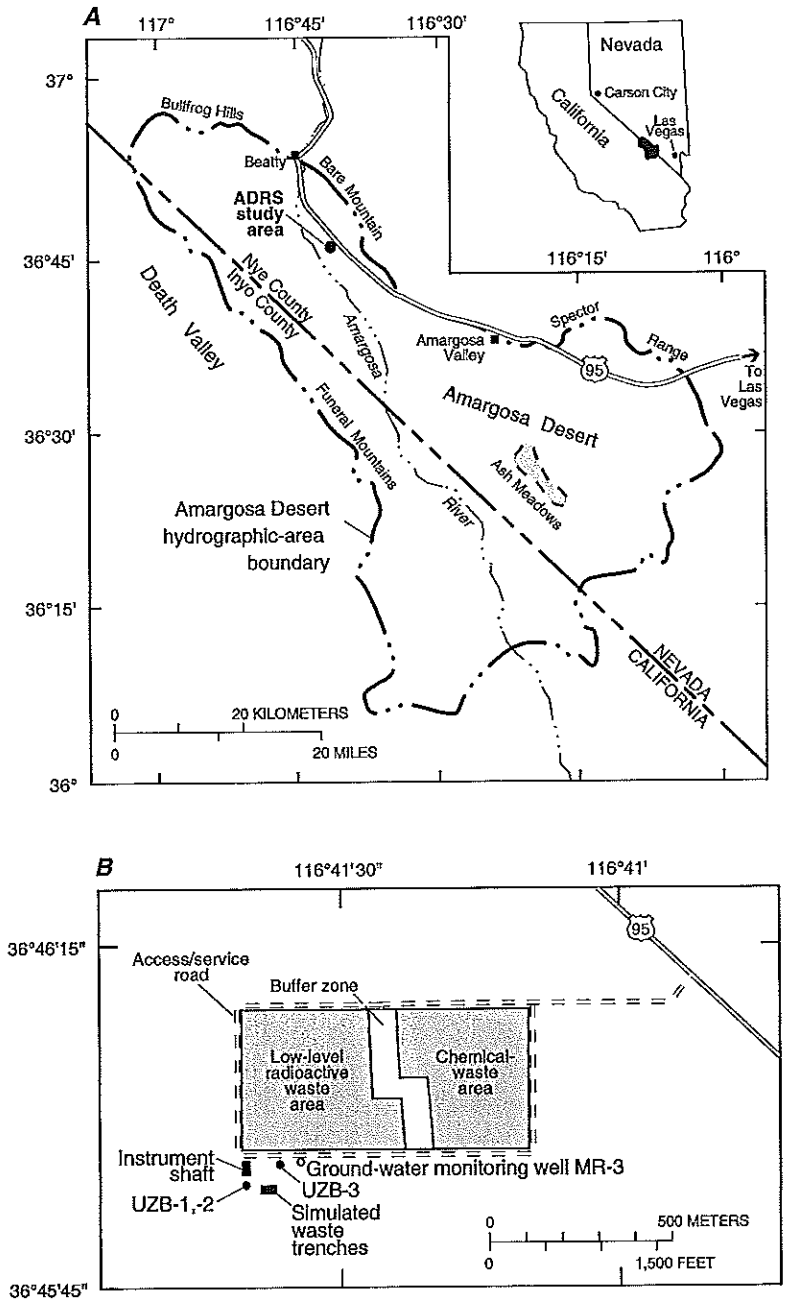


**Figure 1.** Location of (*A*) Amargosa Desert Research Site near Beatty, Nev., and (*B*) instrument shaft and simulated waste trenches adjacent to waste-disposal facility.

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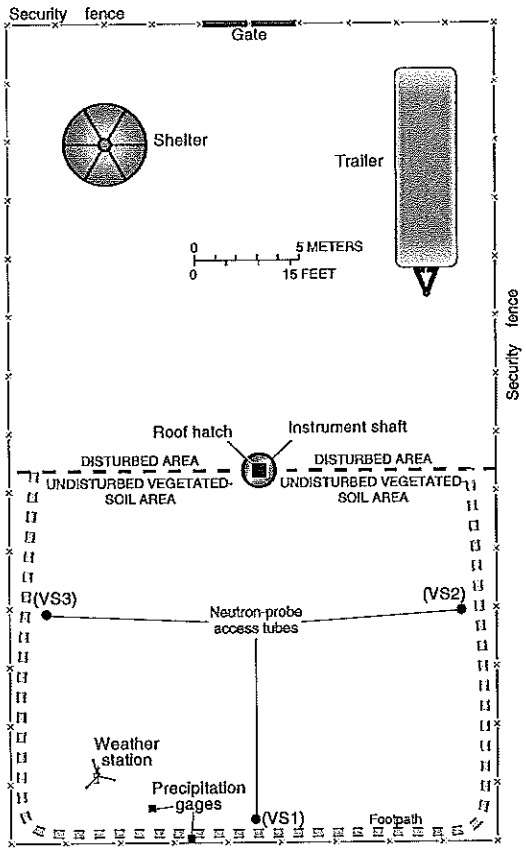


**Figure 2.** Fenced area of instrument shaft showing location of weather station, neutron-probe access tubes, and precipitation gages at Amargosa Desert Research Site near Beatty, Nev.

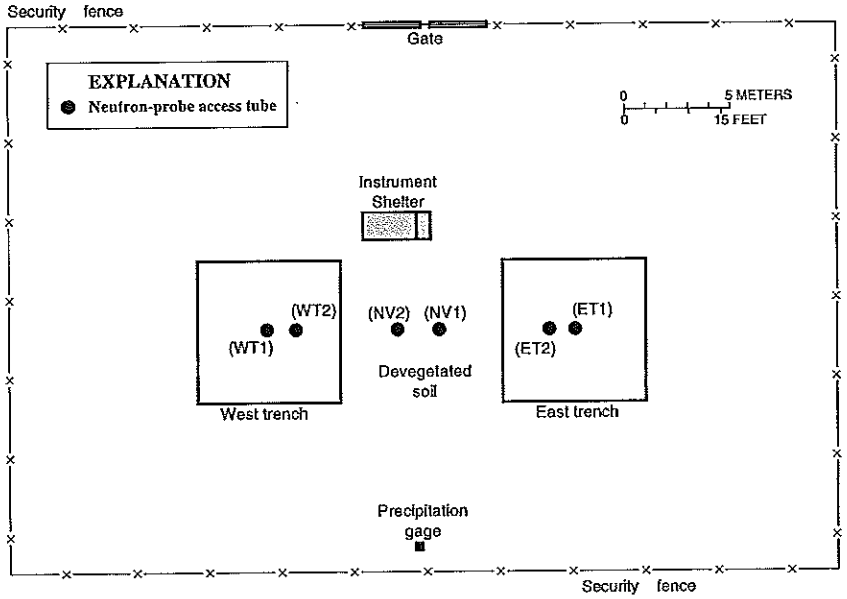


**Figure 3.** Fenced area of simulated waste trenches showing location of neutron-probe access tubes and precipitation gage at Amargosa Desert Research Site near Beatty, Nev.

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## MICROMETEOROLOGICAL INSTRUMENTATION

Micrometeorological sensors consisting of a tipping-bucket rain gage, an air-temperature and relative-humidity probe, a barometric-pressure sensor, a pyranometer, and an anemometer with wind vane were installed in December 1997. A radiometer was installed at the site in July 1998. Soil-temperature probes and two soil-heat-flux plates were installed in September 1999. Two accumulating rain gages periodically were read after storm events to check the data values obtained by the tipping-bucket rain gage.

Data from all the sensors except the net radiometer were recorded using a Campbell Scientific, Inc. (CSI), 23X data logger[1] with a 10-second sampling interval. The logger was programmed to output data in three formats: daily output of mean, maximum, and minimum values (but totals for precipitation); hourly output of mean values (but totals for precipitation); and 5-minute totals for precipitation. The data for the net radiometer were recorded using a CSI 21X data logger with a 10-second sampling interval and programmed to output hourly mean values. Both data loggers are interfaced to a telephone modem permitting automated communication and data retrieval using an off-site computer. The data loggers reference Pacific Standard Time (PST) throughout the year.

The weather station used a CSI 10 tripod to mount the temperature-relative-humidity sensor, pyranometer, and anemometer with wind vane. Mounted on the tripod above the ground were the air temperature-relative humidity sensor at 1.5 m; the solar-radiation sensor at 3 m; and the anemometer with wind vane mounted on a horizontal arm with the center of the wind cups at 3 m. The barometric-pressure sensor was mounted 1 m above the ground and housed with the CSI 23X data logger in a shelter about 30 m from the tripod (fig. 2). The net radiometer was mounted 1.5 m above the ground and about 10 m from the tripod within the undisturbed vegetated area. The precipitation tipping-bucket rain gage was installed on its own mount about 5 m from the tripod at a height of 1 m. Adjacent to the tipping-bucket rain gage was an accumulating plastic rain gage made by Tru-Chek mounted at a height of 1 m along the south fence of the instrument shaft area (fig. 2), and a second Tru-Chek rain gage was at the south end of the waste-trench area (fig. 3). Two soil-heat-flux plates were buried in the soil at a depth of 0.08 m about 2 m from the weather-station tripod. Between the flux plates and the soil surface, the averaging soil-temperature probes were buried at depths of 0.02 m and 0.06 m.

The accuracy of the data is dependent on the sensors being used. The tipping-bucket rain gage is a WeatherMeasure model P-501 with a resolution of 0.25 mm representing one tip of the bucket, and an accuracy of 0.5 percent at 12.7 mm/h. The air temperature-relative humidity probe is a Vaisala HMP35C from CSI with a temperature accuracy of $\pm$ 0.4°C over a range from –24 to 48°C, and with a relative humidity accuracy of $\pm$ 2 percent within the range from 0 to 90 percent and $\pm$ 3 percent within the range from 90 to 100 percent. The Vaisala probe was mounted inside a 12-plate gill radiation shield. Solar radiation is measured with a LI-COR LI200X silicon pyranometer calibrated against an Eppley Precision Spectral Pyranometer, which has a maximum error of $\pm$ 5 percent. The net radiometer was a Radiation and Energy Balance Systems (REBS) Q7.1 net radiometer, which has a spectral response from 0.25 to 60 µm with a nominal resistance of 4 ohms. Wind speed and direction was measured by a Met One 034A-L Windset with a wind speed accuracy of $\pm$ 0.12 m/s and a threshold of 0.28 m/s, and with a wind direction accuracy of $\pm$ 4 degrees. The barometric-pressure sensor is a CSI SBP270 with a pressure range from 800 to 1,100 mbar and an accuracy of $\pm$ 0.2 mbar. Soil temperature was measured with a TCAV-L averaging soil temperature probe manufactured by CSI with two junctions at two depths and constructed with Type-E thermocouple (chromel-constantan) wire. The four thermocouples and associated reference temperature define an averaged soil temperature with a typical uncertainty of 0.5°C, but the uncertainty can be as high as 1.6°C. The soil-heat flux was measured with two REBS HFT3 plates with a nominal resistance of 2 ohms and a thermal conductivity of 1.00 W/m/°K. The soil-heat-flux plates have an error of about $\pm$ 5 percent.

## SOIL-MOISTURE INSTRUMENTATION

Measurements of soil-water content were collected from neutron-probe access tubes using a CPN 503 Hydroprobe manufactured by Campbell Pacific

[1] Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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Nuclear International, Inc. The probe uses a 50 mCi Americum-241:Beryllium neutron source; or in System International units, a 1,850 mBq source. The fast neutrons propagate through the soil, collide with hydrogen atoms in soil water, become thermalized or slowed, and are then reflected back. The reflected slow neutrons are detected in the tube of the probe and the surface electronic sensor counts each event. Soil-water content is proportional to the number of neutron reflections counted. Counts were accumulated over a period of 30 seconds. Because the neutron source and its detector tube can vary in radiation-flux emissions and detections with time, count ratios are used to normalize the field counts for a given set of measurements. Count ratios are calculated by dividing the field counts by standard counts obtained while the neutron probe is within its shield above the ground.

Access tubes at both the vegetated-soil profile (tubes VS1, VS2, and VS3; fig. 2) and the devegetated-soil profile (tubes NV1 and NV2; fig. 3) were large-steel tubes with a 140-mm outside diameter and a 6.4-mm wall thickness. These access tubes were installed at the vegetated-soil site (July 1988) and the devegetated-soil site (September 1988) using a pneumatically driven downhole-hammer system (Abeele, 1987). Access tubes at the two simulated waste trenches (tubes ET1, ET2, WT1, and WT2; fig. 3) were small-steel tubes with a 51-mm outside diameter and a 3.0-mm wall thickness. These access tubes were installed during trench construction (September 1987) with tubes placed in holes that were hand-augered below the trench floor prior to backfilling (Andraski, 1996). Three access tubes (tubes VS1, VS2, and VS3; fig. 2) were used at the vegetated-soil profile with measurable neutron probe depths of 13.75 m, 29.75 m, and 13.75 m, respectively. Two access tubes were used at each of the other sites (fig. 3) with measurable neutron probe depths of about 5.25 m.

Neutron counts were obtained over a period of 30 seconds at each depth. At the vegetated-soil profile (within the fenced shaft area, fig. 2), single readings were obtained at each depth, with readings typically obtained at intervals of every 0.25 m to a depth of 10.75 m and then 0.5 m below that depth. At the devegetated-soil profile and the two trenches (within the fenced simulated trench area, fig. 3) two readings were obtained at each depth, with readings typically obtained at intervals of 0.25 m.

Using count ratios, calibration equations were developed that had coefficients of determination greater than 0.96 (Andraski, 1997, p. 1904). The standard error of estimate for small-diameter tubes ranged from 0.017 $m^3/m^3$ for measurements at the 15 m depth to 0.012 $m^3/m^3$ for measurements at depths greater then 15 m. For large-diameter tubes the standard error of estimate was less than 0.009 $m^3/m^3$ at all depths.

## SELECTED MICROMETEOROLOGICAL DATA

Because of the length of tables 3–5, which summarizes selected micrometeorological data collected at the ADRS facility for 1998, 1999, and 2000, they are at the back of the report following the Basic Data section.

### Precipitation

Daily total precipitation is listed in table 1, and monthly total precipitation is shown in figure 4. Complete data for precipitation totals by daily, hourly, and 5-minute periods are in appendices A and B (tables A1–A4 and B1). The tipping-bucket rain gage malfunctioned in November 2000; thus, the daily precipitation data are based on waste-facility records (L.E. Sanders, U.S. Ecology, Inc., written commun., 2001).

Total annual precipitation measured 194.4 mm in 1998, 68.4 mm in 1999, and 91.7 mm in 2000 (table 1). Based on a combination of waste-facility and ADRS precipitation records for the 20-year period (1981–2000), annual precipitation averaged 108 mm. Precipitation during 1998 was about 180 percent of the 20-year annual average and corresponded with the end of an El Niño cycle. Precipitation during 1999 and 2000 was about 63 and 85 percent, respectively, of the long-term average. Winter frontal systems typically account for 70 percent of the ADRS precipitation (Andraski and Stonestrom, 1999, p. 459), whereas summer storms typically account for 30 percent of the precipitation. In the Amargosa Desert the predominant winter precipitation comes from regional winter frontal systems moving in from the west coast. However this precipitation is reduced and variable within the desert, due to the rain shadow effect of the Sierra Nevada mountains, which similarly shadow Death Valley to the west of the Amargosa Desert. Summer precipitation is even more variable, coming mainly from localized convective storms. Summer storm generation is dependent on water vapor transported into the area by southwesterly winds bringing water vapor principally from subtropi-

7.65"
2.69"
3.61"

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**Table 1.** Daily total precipitation at Amargosa Desert Research Site near Beatty, Nev., 1998–2000

[Values are in millimeters. All unlisted dates had no precipitation]

| Date | Julian day | Total precipitation | Date | Julian day | Total precipitation |
|---|---|---|---|---|---|
| 01/04/1998 | 4 | 0.25 | 01/25/1999 | 25 | 14.90 |
| 01/09/1998 | 9 | .25 | 01/26/1999 | 26 | 5.56 |
| 01/10/1998 | 10 | .25 | 02/09/1999 | 40 | 1.26 |
| 01/29/1998 | 29 | .51 | 04/03/1999 | 93 | .51 |
| 02/02/1998 | 33 | 1.77 | 04/06/1999 | 96 | 5.05 |
| 02/03/1998 | 34 | 14.64 | 04/07/1999 | 97 | 2.53 |
| 02/04/1998 | 35 | 4.80 | 04/08/1999 | 98 | .51 |
| 02/06/1998 | 37 | 3.79 | 04/12/1999 | 102 | 2.02 |
| 02/07/1998 | 38 | 3.28 | 04/23/1999 | 113 | .51 |
| 02/08/1998 | 39 | .76 | 04/24/1999 | 114 | 2.78 |
| 02/14/1998 | 45 | 14.14 | 04/29/1999 | 119 | 2.02 |
| 02/17/1998 | 48 | 12.12 | 04/30/1999 | 120 | 1.26 |
| 02/19/1998 | 50 | 2.53 | 05/24/1999 | 144 | .25 |
| 02/20/1998 | 51 | .76 | 05/27/1999 | 147 | 2.78 |
| 02/23/1998 | 54 | 19.69 | 07/09/1999 | 190 | 4.29 |
| 02/24/1998 | 55 | 3.54 | 07/13/1999 | 194 | 1.26 |
| 03/05/1998 | 64 | .25 | 07/14/1999 | 195 | 4.29 |
| 03/06/1998 | 65 | 1.01 | 07/15/1999 | 196 | 1.01 |
| 03/13/1998 | 72 | 7.83 | 08/10/1999 | 222 | 1.26 |
| 03/16/1998 | 75 | 7.32 | 09/17/1999 | 260 | 13.13 |
| 03/17/1998 | 76 | .25 | 09/18/1999 | 261 | 1.26 |
| 03/25/1998 | 84 | 6.31 | 01/17/2000 | 17 | 1.26 |
| 03/26/1998 | 85 | 14.14 | 01/25/2000 | 25 | .51 |
| 03/28/1998 | 87 | 2.78 | 01/26/2000 | 26 | 1.26 |
| 03/29/1998 | 88 | .25 | 02/10/2000 | 41 | 9.59 |
| 04/01/1998 | 91 | 2.27 | 02/12/2000 | 43 | 2.53 |
| 04/12/1998 | 102 | .76 | 02/16/2000 | 47 | 3.28 |
| 04/25/1998 | 115 | 4.29 | 02/20/2000 | 51 | 5.56 |
| 05/05/1998 | 125 | 5.56 | 02/21/2000 | 52 | 5.81 |
| 05/07/1998 | 127 | 1.77 | 02/23/2000 | 54 | 8.08 |
| 05/12/1998 | 132 | 4.80 | 02/28/2000 | 59 | 2.78 |
| 05/13/1998 | 133 | 2.02 | 02/29/2000 | 60 | 5.30 |
| 06/03/1998 | 154 | 3.28 | 03/05/2000 | 65 | 5.81 |
| 06/08/1998 | 159 | .51 | 03/08/2000 | 68 | 5.30 |
| 06/09/1998 | 160 | .51 | 04/14/2000 | 105 | 1.52 |
| 06/10/1998 | 161 | .25 | 04/17/2000 | 108 | 3.79 |
| 06/11/1998 | 162 | 1.26 | 08/28/2000 | 241 | 2.02 |
| 06/12/1998 | 163 | 9.85 | 08/29/2000 | 242 | 8.59 |
| 07/21/1998 | 202 | 11.87 | 08/30/2000 | 243 | 5.81 |
| 08/13/1998 | 225 | .76 | 08/31/2000 | 244 | 3.79 |
| 08/30/1998 | 242 | 7.83 | 09/08/2000 | 252 | .51 |
| 08/31/1998 | 243 | .76 | 10/11/2000 | 285 | .25 |
| 09/04/1998 | 247 | 9.59 | 10/23/2000 | 297 | .51 |
| 09/06/1998 | 249 | .51 | 10/29/2000 | 303 | 1.01 |
| 09/08/1998 | 251 | .51 | 10/30/2000 | 304 | 2.53 |
| 10/24/1998 | 297 | 2.27 | 11/20/2000 | 310 | 4.32 |

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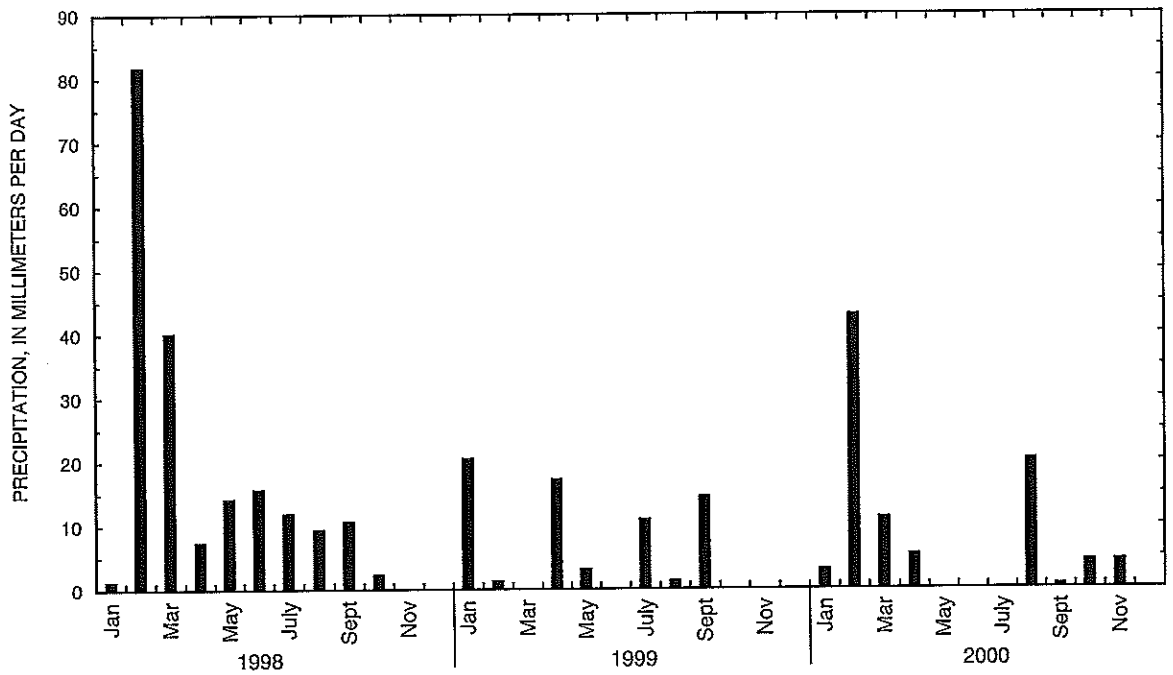


**Figure 4.** Monthly total precipitation at Amargosa Desert Research Site near Beatty, Nev., 1998–2000, computed from 10-second sampling intervals of daily totals.

cal low-pressure systems off the west coast of Mexico or southern California. Previous comparisons between the ADRS weather station and two National Oceanic and Atmospheric Administration (NOAA) sites (Wood and Andraski, 1995, p. 15) indicate monthly values also differ considerably between sites within the Amargosa Desert.

Monthly total precipitation is highly variable from year to year for a given month, and from month to month in a given year as shown in figure 4. For example, in 1998, January had little precipitation whereas February and March were wet. In 1999, January received considerable precipitation whereas February received little and March was dry. Then in 2000, January had little precipitation whereas February was wet and March was moderate. Other months also show monthly variability.

## Air Temperature

Monthly maximum, minimum, and mean air temperatures are listed in table 2. Daily mean, maximum, and minimum air temperatures are listed in table 3 and shown in figure 5. Complete data for daily and hourly air temperatures are in appendix A (tables A1–A4). From 1998 through 2000 the maximum temperature recorded was 45.6°C in July of 1998 and the minimum temperature recorded was –14.1°C in December of 1998. During the 3-year period air temperatures averaged about 30°C during July and about 7°C during December.

Daily and seasonal temperature fluctuations are large at the study site. Differences between daily maximum and minimum temperatures commonly exceed 20°C. Differences between winter minimum and summer maximum temperatures average more than 50°C. The desert environment, with its high percentage of clear skies, has a large heating capacity from incoming solar (short-wave) radiation during the day, and a proportionally large heat discharge by terrestrial (long-wave) radiation during the night. The large gains and losses in energy on a daily basis and their relative variation on a seasonal basis determine the temperatures that occur in this environment.

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**Table 2.** Monthly maximum, minimum, and mean air temperatures measured at Amargosa Desert Research site near Beatty, Nev., November 1998–December 2000

[Temperatures are in degrees Celsius. Maximum and minimum based on daily individual values determined from 8,640 samples per day (10-second sampling interval). Monthly mean obtained by averaging mean daily values]

| Date | Maximum | Day | Minimum | Day | Mean |
|---|---|---|---|---|---|
| January 1998 | 19.3 | 24 | -8.1 | 6 | 6.9 |
| February 1998 | 17.6 | 22 | -2.1 | 1 | 7.1 |
| March 1998 | 28.2 | 23 | -1.5 | 8 | 11.1 |
| April 1998 | 30.5 | 22 | -1.0 | 2 | 13.5 |
| May 1998 | 30.5 | 31 | 4.3 | 13 | 17.3 |
| June 1998 | 39.6 | 29 | 8.3 | 13 | 23.4 |
| July 1998 | 45.6 | 18 | 14.8 | 4 | 30.8 |
| August 1998 | 43.4 | 5 | 13.9 | 20 | 30.7 |
| September 1998 | 37.9 | 3 | 9.0 | 29 | 23.9 |
| October 1998 | 29.5 | 13 | 2.0 | 18 | 16.1 |
| November 1998 | 22.9 | 23 | -5.0 | 10 | 10.1 |
| December 1998 | 24.1 | 16 | -14.1 | 22 | 6.5 |
| January 1999 | 21.4 | 10 | -4.7 | 4 | 7.7 |
| February 1999 | 22.7 | 28 | -6.8 | 12 | 9.0 |
| March 1999* | 26.1 | 29 | -2.6 | 8 | 12.4 |
| April 1999 | 32.0 | 19 | -2.7 | 10 | 13.5 |
| May 1999 | 35.9 | 27 | 5.9 | 17 | 21.7 |
| June 1999 | 42.5 | 30 | 8.6 | 3 | 26.7 |
| July 1999 | 43.4 | 1 | 14.8 | 25 | 29.2 |
| August 1999 | 40.0 | 26 | 15.0 | 11 | 28.7 |
| September 1999 | 38.2 | 8 | 7.2 | 29 | 25.1 |
| October 1999 | 35.7 | 1 | 1.9 | 31 | 19.0 |
| November 1999 | 29.1 | 13 | -6.3 | 23 | 12.2 |
| December 1999 | 21.3 | 17 | -5.8 | 4 | 7.4 |
| January 2000 | 21.2 | 18 | -7.4 | 29 | 7.8 |
| February 2000 | 22.0 | 7 | -1.5 | 24 | 9.4 |
| March 2000 | 26.1 | 26 | -1.3 | 7 | 12.5 |
| April 2000 | 34.6 | 27 | 2.0 | 15 | 19.0 |
| May 2000 | 40.5 | 29 | 6.2 | 12 | 24.6 |
| June 2000 | 43.4 | 15 | 11.5 | 9 | 29.2 |
| July 2000 | 43.6 | 4 | 16.0 | 9 | 30.6 |
| August 2000 | 42.5 | 1 | 15.6 | 21 | 29.8 |
| September 2000 | 39.9 | 16 | 6.0 | 25 | 24.7 |
| October 2000 | 35.6 | 1 | 2.8 | 13 | 17.3 |
| November 2000 | 22.4 | 24 | -7.1 | 13 | 8.6 |
| December 2000 | 21.6 | 28 | -6.4 | 19 | 7.1 |

* 30 days of record.

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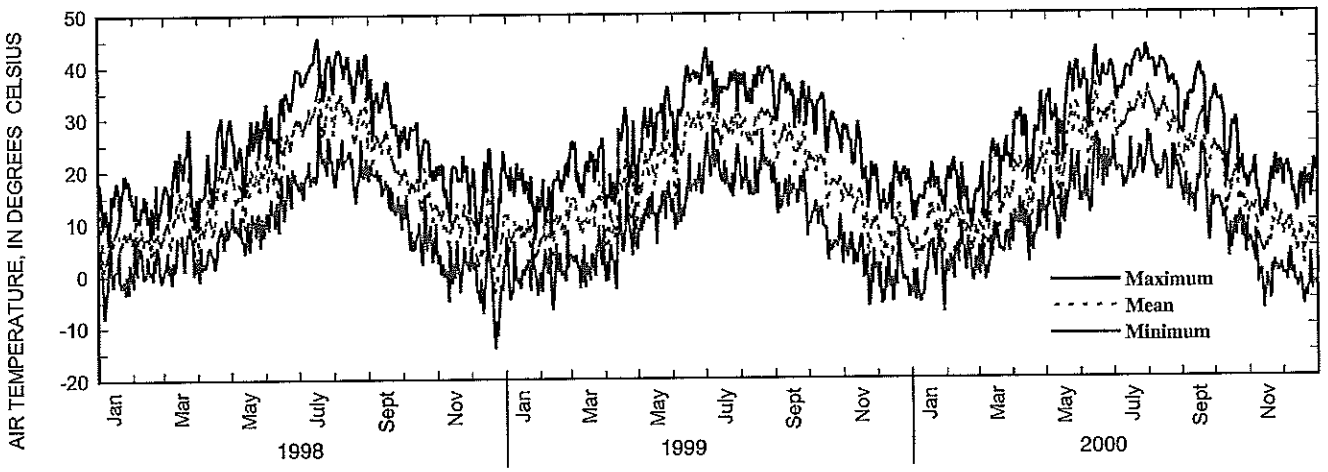


**Figure 5.** Daily maximum, minimum, and mean air temperature at Amargosa Desert Research Site near Beatty, Nev., 1998–2000, computed from 10-second sampling intervals.

## Solar Radiation

Daily mean and maximum solar radiation are listed in table 3 and shown in figure 6. Complete daily and hourly solar-radiation data are in appendix A (tables A1–A4). Solar radiation is the amount of incident radiation from the sun that reaches the surface of the earth at the point of detection. Both daily and hourly mean and maximum solar-radiation data in this report are based on a 10-second sampling interval. Previous ADRS publications (Wood and Fischer, 1991, 1992; Wood and others, 1992; Wood and Andraski, 1992, 1995; Wood, 1996) also reported hourly mean and maximum solar radiation based on a 10-second sampling interval, but reported daily mean and maximum solar radiation derived from hourly mean values.

The daily maximum and mean solar-radiation curves (fig. 6) show the annual solar-energy cycle and the difference between the daily maximum and mean for any given day in the year. The maximum radiation for the year occurs during the summer solstice period in late June during clear sky days with maximum daily values generally exceeding 1,020 W/m$^2$. Conversely, during the winter solstice period in late December during clear sky days maximum daily values generally decrease to about 520 W/m$^2$. The downward spikes in figure 6 show the limited number of days where extended periods of cloud cover occurred during the day. As indicated in figure 6, the difference between the daily maximum and daily mean time-series values varies from over 750 W/m$^2$ in the summer to a minimum of about 370 W/m$^2$ in the winter.

## Net Radiation

Daily mean, maximum, and minimum net radiation are listed in table 4. Daily values were based on hourly mean values. Complete daily and hourly net-radiation data are in appendix A (tables A1–A4). Net radiation is the difference between all downward and upward radiation fluxes of both short- and long-wave radiation. Net radiation is a measure of the energy available at the surface of the Earth that can be partitioned into such energy-consuming processes as heating the soil and air, plant growth, and water evaporation. By convention, net radiation is defined as positive when downward components (incoming radiation) exceed upward components (outgoing radiation), and this occurs after sunrise and before sunset. Allocation of this net available energy varies with seasonal surface conditions. For example, in late spring after a rainstorm, more energy is used to evaporate water from wet soils and for plant photosynthesis than is used to heat the air and soil. Later in the summer under dry conditions almost all of the available energy goes to heat the air and soil.

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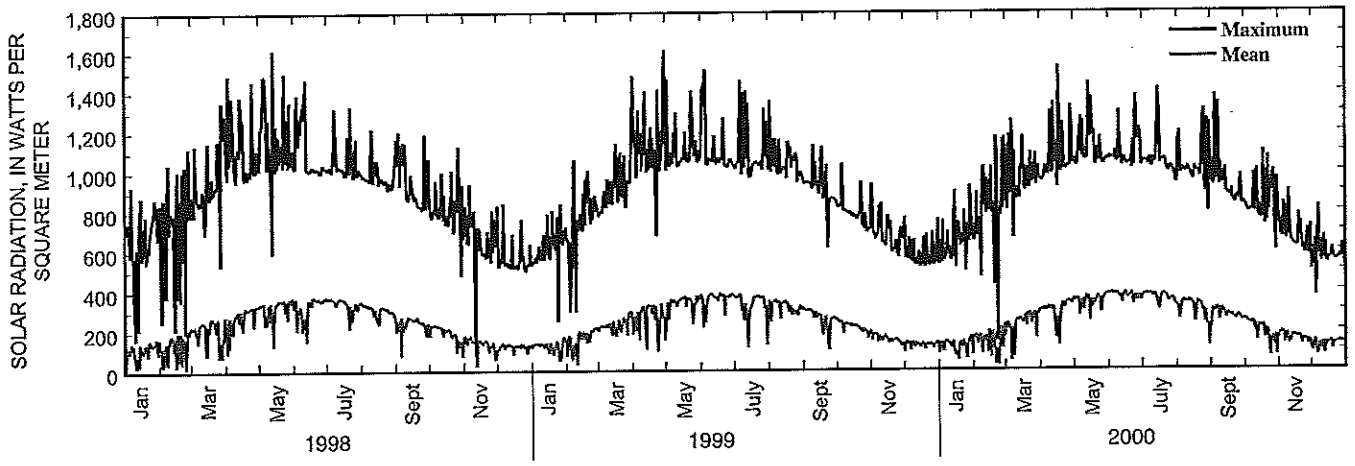


**Figure 6.** Daily maximum and mean solar radiation at Amargosa Desert Research Site near Beatty, Nev., 1998–2000, computed from 10-second sampling intervals.

Daily maximum and daily mean net-radiation curves are shown in figure 7. During a 3-year period (1998–2000), the 24-hour daily mean value generally fluctuated from 0 W/m$^2$ in early winter to about 150 W/m$^2$ in mid-summer. The daily maximum fluctuated from a low of about 250 W/m$^2$ in early winter to a high of about 550 W/m$^2$ in mid-summer. The mean net radiation that occurs from 8 a.m. to 4 p.m. PST also is shown to illustrate that a large part of daily net radiation available to the site occurs during the 4 hours before and after the near-solar noon. This daily 8 a.m. to 4 p.m. mean radiation is within 100 W/m$^2$ of the daily maximum radiation.

## Relative Humidity

Daily mean, maximum, and minimum relative humility are listed in table 3. Daily mean relative-humidity values are shown in figure 8. Complete daily and hourly relative-humidity data are in appendix A (tables A1–A4). Relative humidity is the ratio of the amount of water vapor in the air at a specific temperature to the maximum amount of water vapor that the air can hold at that temperature and is expressed as a percent. Daily mean values ranged from 4 to 96 percent. In contrast, hourly mean values ranged from 1 percent during the drier summer months to 100 percent during winter storms. During mid-day hours in the summer, relative-humidity values of less than 10 percent are common in the Amargosa Desert.

## Ambient Vapor Pressure

Daily mean, maximum, and minimum ambient vapor pressures are listed in table 3. Daily mean vapor pressures are shown in figure 9. Complete daily and hourly data are in appendix A (tables A1–A4). Ambient vapor pressure is the partial pressure exerted by water vapor present in the air and it indicates the water-vapor content of the air under prevailing atmospheric conditions. The ambient vapor pressure is the product of the saturated vapor pressure and the relative humidity. Saturated vapor pressure is the highest concentration of water vapor that can exist in equilibrium over a free-water surface at that temperature. The data logger calculates the saturated vapor pressure in kilopascals from measured air temperature using an algorithm from Lowe (1977).

Ambient vapor pressures generally are higher during the summer months and lower during winter months (fig. 9) because warm air can hold considerably more water mass than cold air. For this reason, the summer precipitation events cause high ambient vapor pressures, but larger winter precipitation events do not have comparable pressures (fig. 9). In 1998, daily mean values ranged from 2.1 kPa on September 4 after an evening rain to 0.089 kPa on December 19. For the 3 years of record (1998–2000), the maximum logged vapor pressure was 2.59 kPa on July 21, 1998, and the minimum was 0.048 kPa on May 14, 2000.

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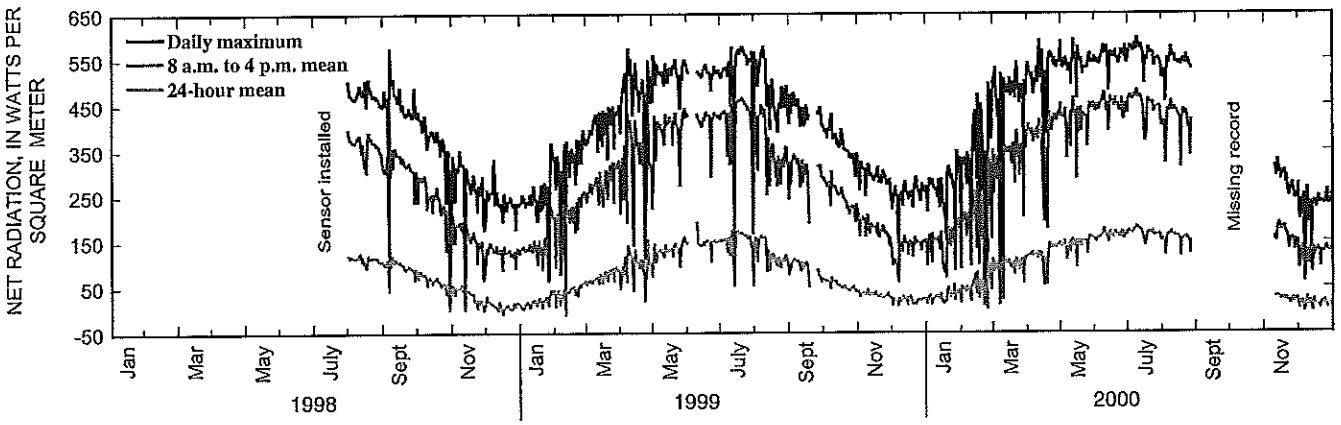


**Figure 7.** Daily maximum, mean, and mean from 8 a.m. to 4 p.m. of net radiation at Amargosa Desert Research Site near Beatty, Nev., 1998–2000, computed from 10-second sampling intervals.

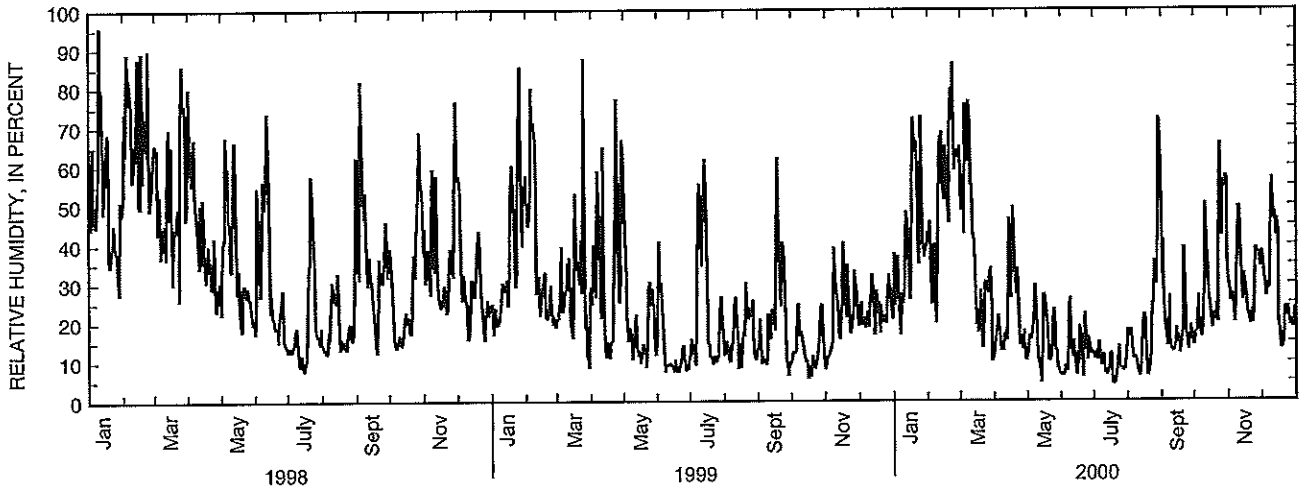


**Figure 8.** Daily mean relative humidity at Amargosa Desert Research Site near Beatty, Nev., 1998–2000, computed from 10-second sampling intervals.

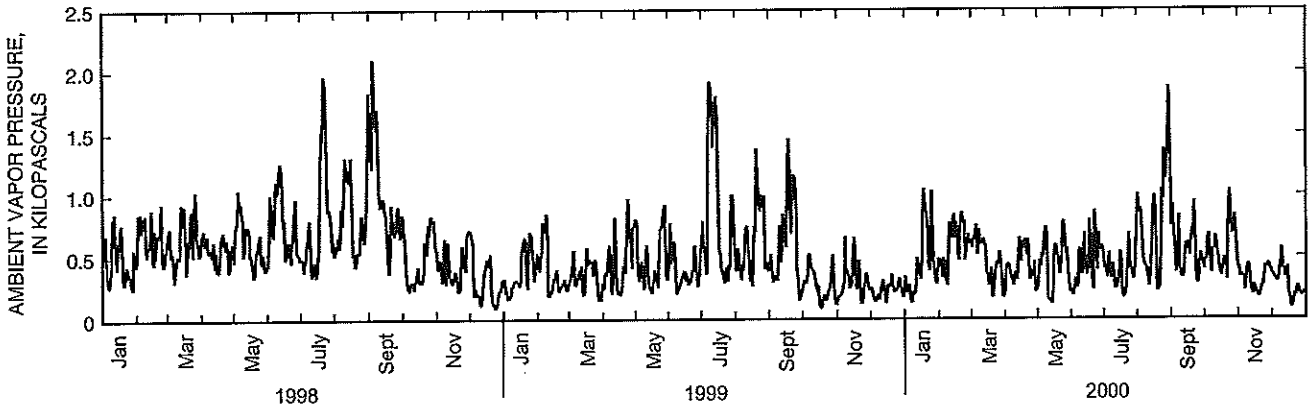


**Figure 9.** Daily mean ambient vapor pressure at Amargosa Desert Research Site near Beatty, Nev., 1998–2000, computed from 10-second sampling intervals.

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## Wind Speed and Direction

Daily mean, maximum, and minimum wind speed are listed in table 3. Daily mean wind speeds are shown in figure 10. Complete daily and hourly wind speed data are in appendix A (tables A1–A4). Annual mean wind speed computed from daily mean wind speeds (1998–2000) was 2.8, 2.8, and 2.9 m/s, respectively. During the 3-year period, the maximum, daily mean wind speed was 9.2 m/s on March 20, 2000 (fig. 10). The maximum, hourly mean wind speed was 13.0 m/s and occurred at 12 a.m. (midnight) PST on December 2, 1999. The single-highest recorded wind speed was 19.1 m/s on December 2, 1999. The distribution of hourly mean wind speed for the 3-year monitoring period for all values is shown in figure 11. For example, 4 percent of the time the wind speed was below 1.0 m/s, and 80 percent of the time the wind speed was under 4.0 m/s. Hourly mean wind speeds of 0.0 m/s occurred only 1.6 percent of the time during the 3 years of record. However, most days had at least one 10-second sampling interval with wind speeds below instrument threshold giving most days a daily minimum of 0.0 m/s.

Daily mean and standard deviation of wind-vector direction, in degrees Azimuth of true north, are listed in table 3. Complete daily and hourly wind-vector data are in appendix A (tables A1–A4). Mean horizontal wind-vector direction was calculated by vectorially summing the individual wind vectors consisting of wind magnitude and direction using available data logger commands. The daily mean wind-vector directions are shown in figure 12. Daily wind directions indicate seasonal variability and annual recurrent patterns for 1998–2000. Wind at the ADRS predominantly was from the northwest from September through February, and generally associated with regional frontal systems moving in from the west coast during the autumn and winter seasons. Winds from March to September are more evenly distributed from the northwest, southwest, and southeast. Southwest and southeast winds typically are associated with the counter-clockwise rotation of subtropical lows moving inland from off the west coast of Mexico or southern California.

## Barometric Pressure

Daily mean, maximum, and minimum barometric pressures are listed in table 5. Complete daily and hourly barometric pressure data are in appendix A (tables A1–A4). Barometric pressures at the ADRS facility are corrected to sea level using an altitude of 847.2 m. Daily mean barometric-pressure values are shown in figure 13. The mean barometric pressure for the 3-year period (1998–2000) was 101.5 kPa. Higher pressures generally occurred during clear winter days and lower pressures occurred during storm periods and summer. The daily maximum barometric pressure measured was 103.57 kPa on December 18, 2000, and the minimum was 99.47 kPa on February 3, 1998.

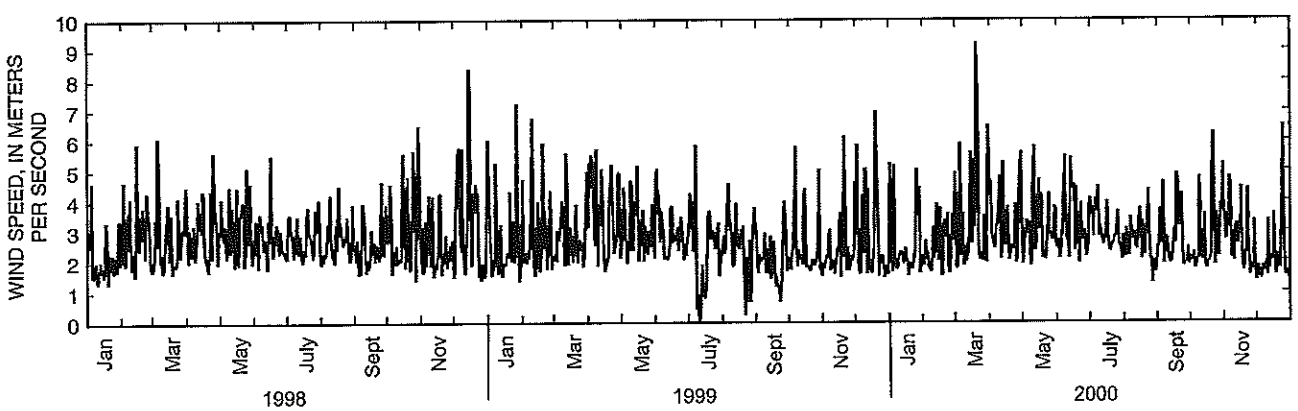


**Figure 10.** Daily mean wind speed at Amargosa Desert Research Site near Beatty, Nev., 1998–2000, computed from 10-second sampling intervals.

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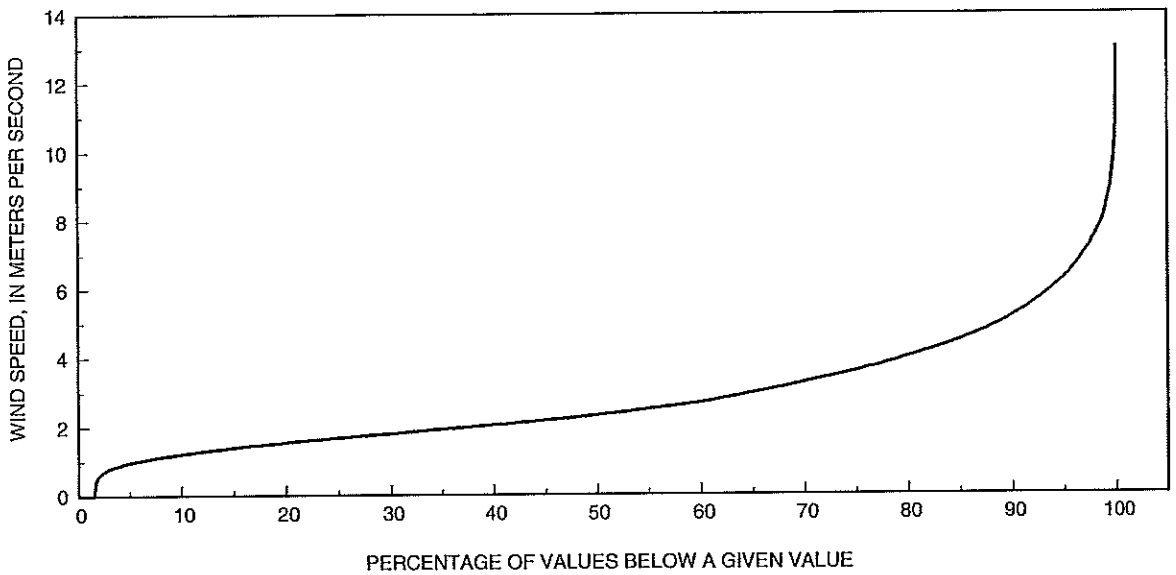


**Figure 11.** Distribution of hourly mean wind speed as a percentage of all hourly mean values at Amargosa Desert Research Site near Beatty, Nev., 1998–2000.

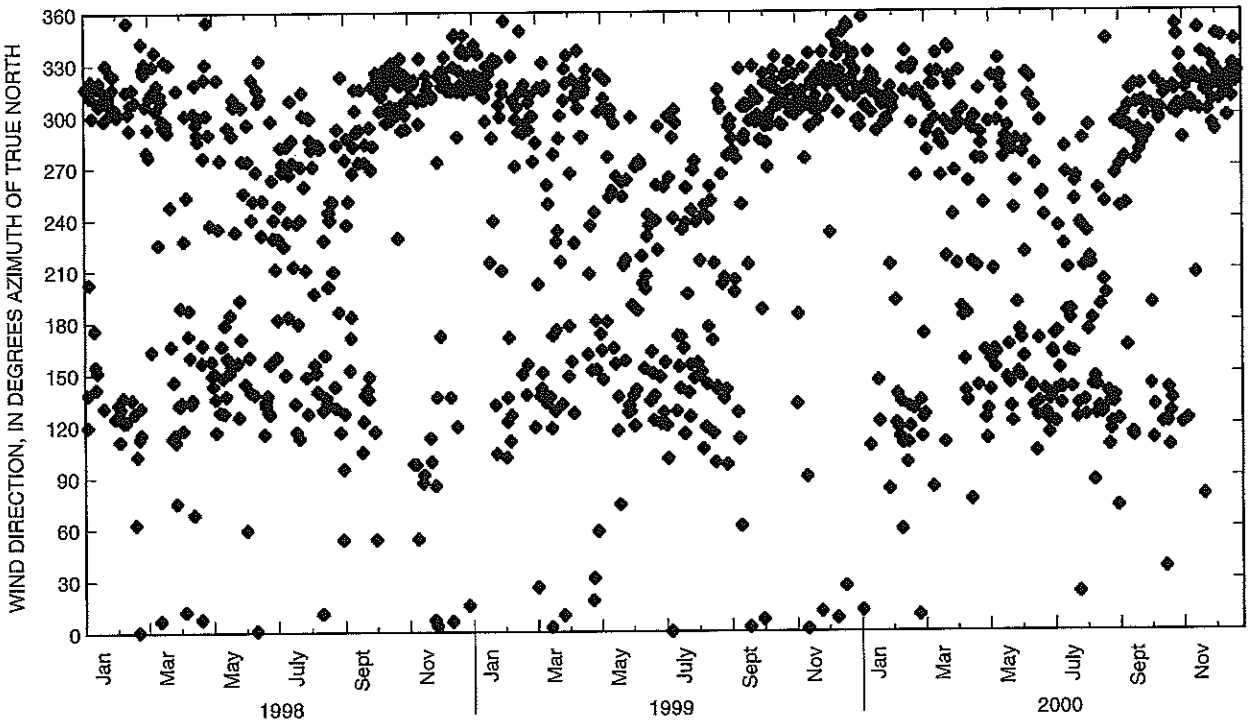


**Figure 12.** Daily mean wind-vector direction in degrees Azimuth of true north at Amargosa Desert Research Site near Beatty, Nev., 1998–2000.

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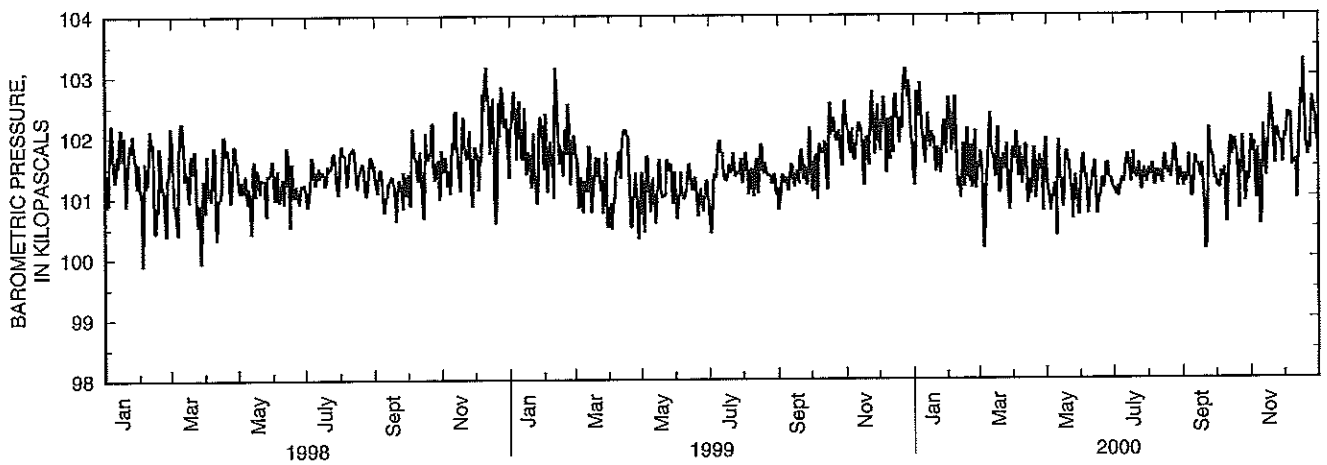


**Figure 13.** Daily mean barometric pressure at Amargosa Desert Research Site near Beatty, Nev., 1998–2000, computed from 10-second sampling intervals.

### Soil Temperature and Soil-Heat Flux

Daily mean, maximum, and minimum values of soil temperature and soil-heat flux are listed in table 4. Daily soil temperatures and soil-heat flux are shown in figures 14 and 15, respectively. Complete soil temperature and soil-heat-flux data are in appendix A (tables A1–A4). The averaging soil-thermocouple probe measures the temperature in the soil between the 8-cm depth and the soil surface. The soil-heat-flux plates measure long-wave radiation in Watts per square meter that enters or leaves the soil. Soil-heat flux entering the soil is defined as positive and leaving the soil as negative. Daily mean soil temperature ranged from 2.6°C on December 19, 2000, to 40.9°C on August 1, 2000. Daily mean values of soil-heat flux ranged from –19.7 $W/m^2$ on March 5, 2000, to 15.8 $W/m^2$ on May 23, 2000.

## SELECTED SOIL-MOISTURE DATA

Soil-water content under natural-site and simulated waste-trench conditions was monitored at four experimental sites: one vegetated, native-soil profile, one devegetated native-soil profile, and two non-vegetated, simulated waste trenches with disturbed soil used as back fill (figs. 2 and 3). The simulated waste trenches have 208-L soil-filled drums buried at depths from 1.5 to 2.5 m and 3.5 to 4.5 m; soil-water content is not determined for these depths because of the influence of simulated waste on neutron-probe readings. Soil-water content is reported in volumetric units of cubic meter per cubic meter.

### Water-Content Profiles

Variations in volumetric water content measured in the deepest access tube at the vegetated, native-soil profile (tube VS2, 29.75 m) are shown in figure 16. Variations in water content in the upper 5.5 m for the four experimental sites are shown in figure 17. The changes in water content with time at selected depths for the four experimental sites are shown in figure 18. Complete soil-water-content data and the associated calibration equations are in appendix C (tables C1–C2). Table C1 lists the mean water-content data by date and depth for each of the four experimental sites. Table C2 lists the water-content data by date and depth for each of the nine neutron-probe access tubes.

Figure 16 shows the variability of water content with depth in the vegetated, native-soil profile. The water content within the upper meter of the soil profile ranged from a low of about 0.02 $m^3/m^3$ at the shallowest monitored depth of 0.15 m on August 3, 2000, to a high of about 0.12 $m^3/m^3$ at a depth of 0.5 m on March 15, 1998. The highest water content within the entire soil profile of about 0.15 $m^3/m^3$ was measured at a depth of 25.25 m for all dates measured. Temporal changes in water content are limited to the upper 1 m, whereas below 1 m the variation in depth reflects

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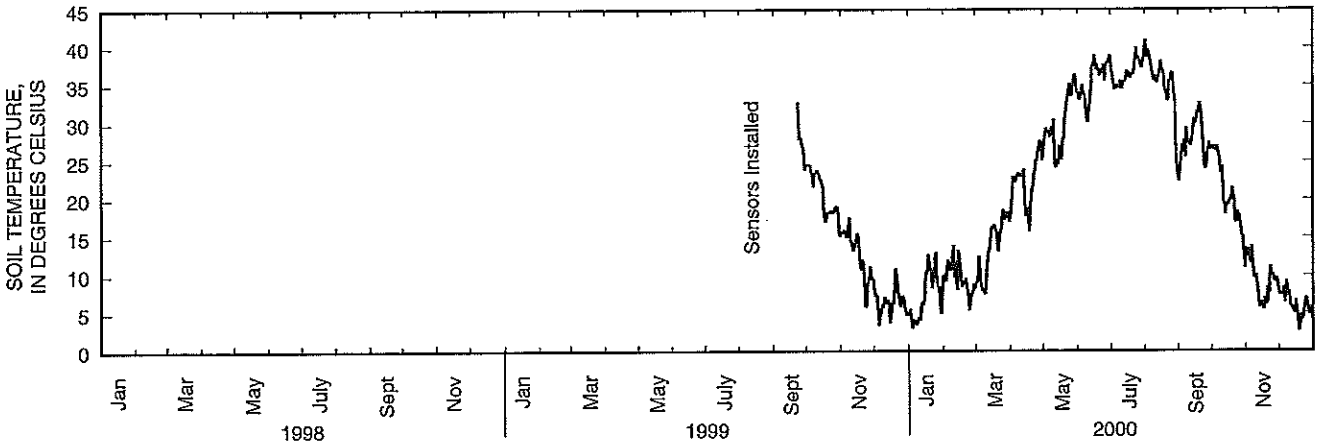


**Figure 14.** Daily mean soil temperature at Amargosa Desert Research Site near Beatty, Nev., 1998–2000, computed from 10-second sampling intervals.

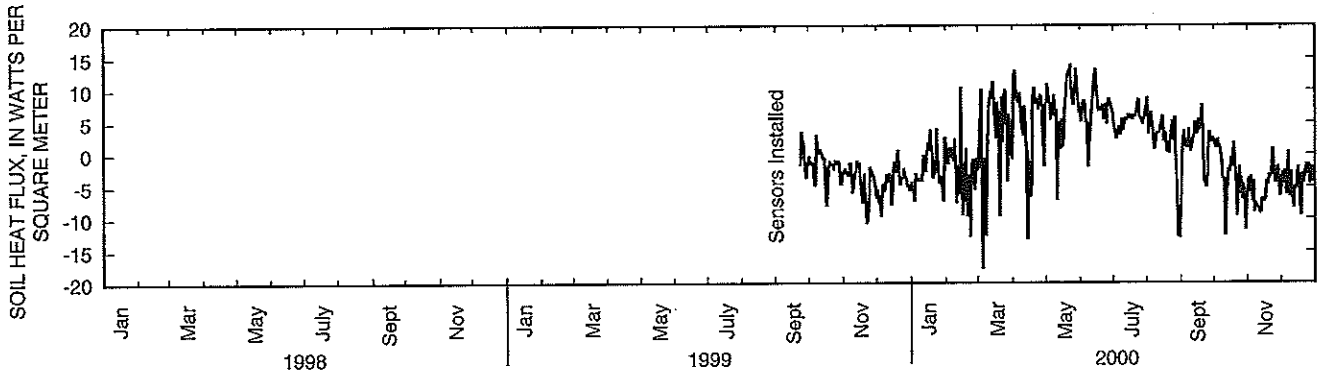


**Figure 15.** Daily mean soil-heat flux at Amargosa Desert Research Site near Beatty, Nev., 1998–2000, computed from 10-second sampling intervals.

changes in lithology and not time. At depth, moisture retention appears to be principally a function of grain size within the varying basin fill. Clay lenses within the sediments tend to have higher water content, whereas gravel layers have lower water content.

Figure 17 shows the temporal variation in soil-profile moisture in the upper 5.5 m. In the upper 1 m of the soil profile, the spring soil-water contents tend to be greater than late summer or autumn values. These variations can be accounted for by the redistribution of the soil-water with time and by increased soil-water discharge by evapotranspiration during summer.

Temporal variations in soil-water content for selected depths in the upper 3 m are shown in figure 18. All four experimental sites show measurable water penetration in response to precipitation at depths above 1.0 m (fig. 18*E*). The east trench shows measurable water penetration to a depth of 1.25 m (fig. 18*F*) peaking about May 5, 1998. That increase in water content at 1.25 m occurred in response to a series of late winter and spring storms that produced a total of 122 mm of precipitation during February and March 1998 and is associated with the latter part of an El Niño cycle. At the 3 m depth (fig, 18*G*), no measurable variation in water content exists at the four experimental sites.

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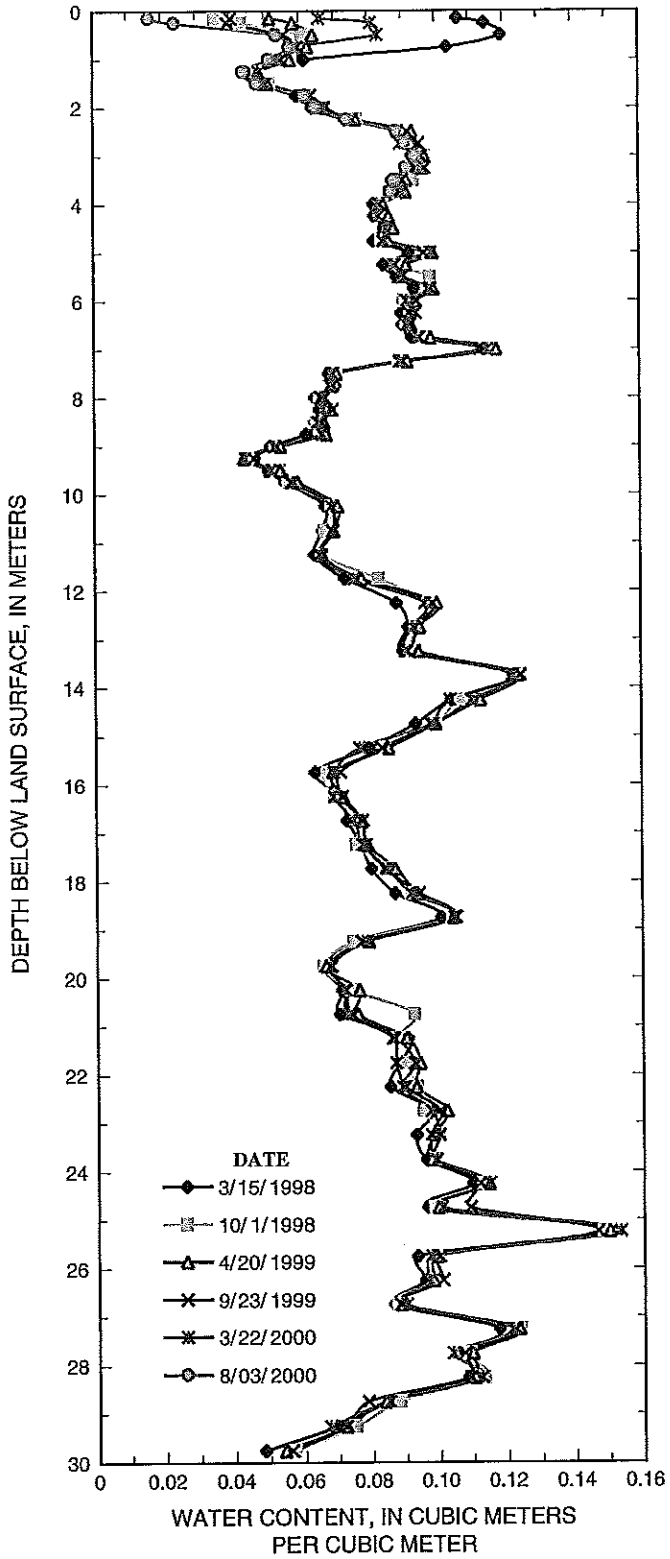


**Figure 16.** Water-content variations in the upper 30 meters for selected dates for the vegetated, native soil profile at Amargosa Desert Research Site near Beatty, Nev., 1998–2000.

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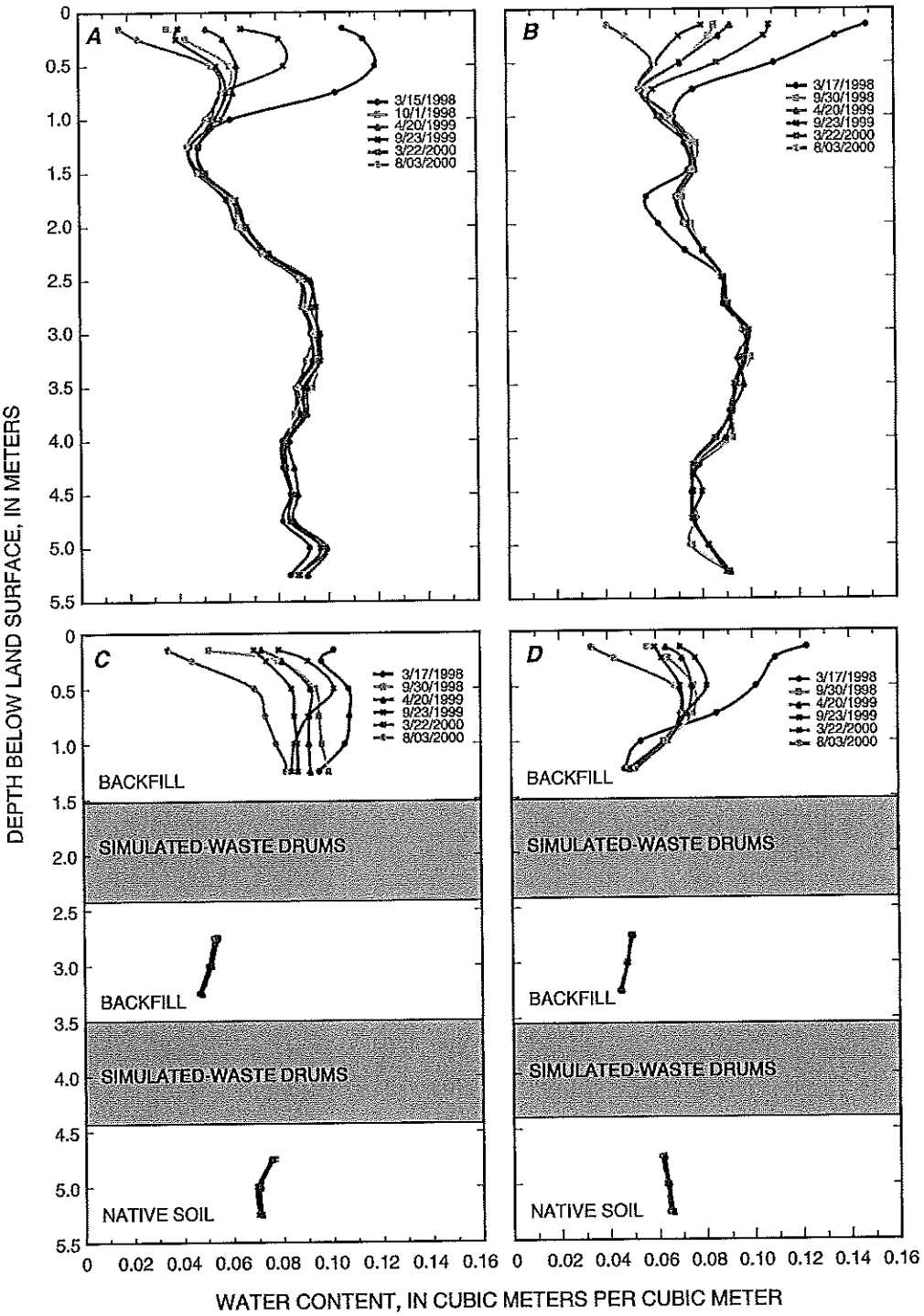


**Figure 17.** Water-content variations with depth in upper 5.5 meters of soil for selected dates at four experimental sites at Amargosa Desert Research Site near Beatty, Nev.: (*A*) vegetated, native-soil profile, (*B*) devegetated, native-soil profile, (*C*) non-vegetated, east trench, and (*D*) non-vegetated, west trench.

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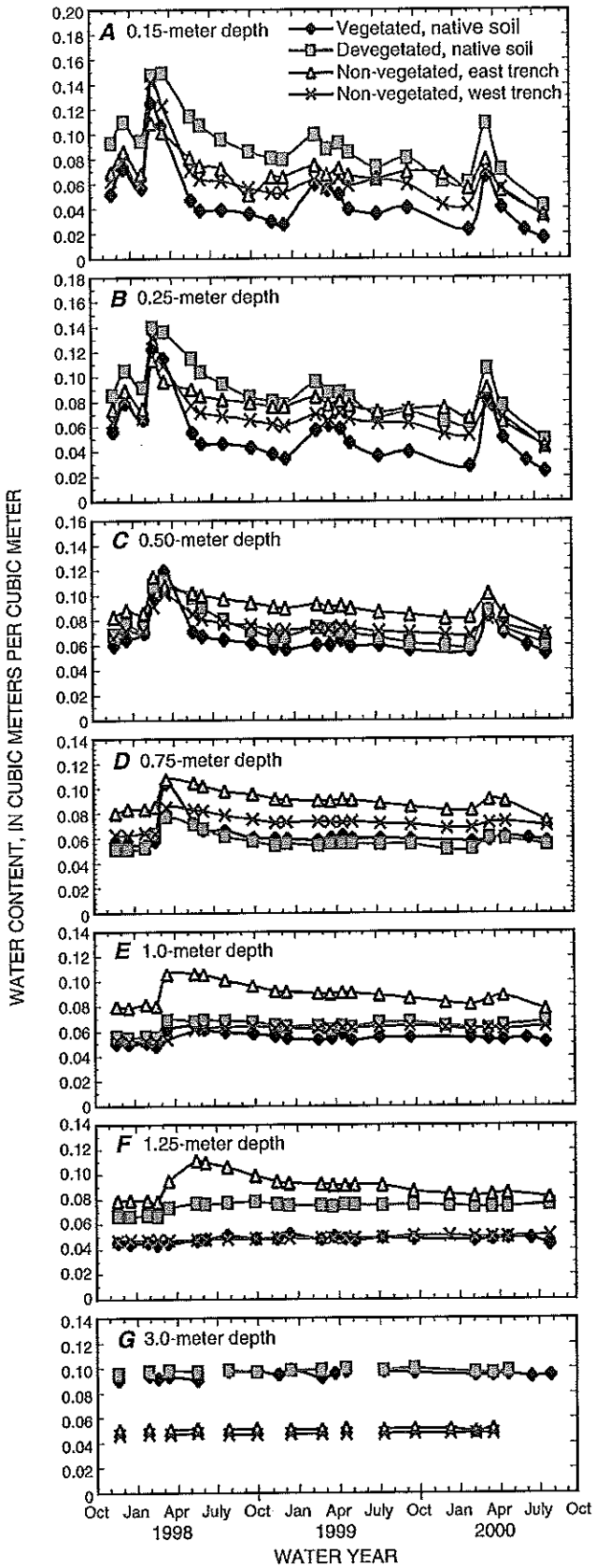


**Figure 18.** Cumulative changes in water content with time for selected depths at four experimental sites at Amargosa Desert Research Site near Beatty, Nev.: (A) 0.15-meter depth, (*B*) 0.25-meter depth, (*C*) 0.5-meter depth, (*D*) 0.75-meter depth, (*E*) 1.0-meter depth, (*F*) 1.25-meter depth, and (*G*) 3.0-meter depth.

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## SUMMARY

Micrometeorological and soil-moisture data were collected at the Amargosa Desert Research Site facility adjacent to a low-level radioactive and hazardous-chemical waste facility near Beatty, Nev. (1998–2000). Data were collected in support of ongoing research studies to improve the understanding of hydrologic and contaminant-transport processes in arid environments.

Micrometeorological data include precipitation, air temperature, solar radiation, net radiation, relative humidity, ambient vapor pressure, wind speed and direction, barometric pressure, soil temperature, and soil-heat flux. All micrometeorological data were collected using a 10-second sampling interval by data loggers that output daily mean, maximum, and minimum values, and hourly mean values. For precipitation, data output included daily totals, hourly totals, and 5-minute totals. Soil-moisture data include periodic measurements of soil-water content at nine neutron-probe access tubes with measurable depths ranging from 5.25 to 29.75 m.

Complete micrometeorological and soil-moisture data summarized in this report are in computer data files consisting of seven tabular files with about 14 megabytes of information. The data contained in the data files are summarized in figures and tables, and the instrumentation used for data collection is discussed. Data collection in 1998 occurred during the end of an El Niño cycle with above normal precipitation and measurable water penetration to a depth of 1.25 m at one of the four experimental soil-monitoring sites.

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## BASIC DATA

This section contains tables 3-5, which summarizes selected micrometeorological data collected at the ADRS facility for 1998, 1999, and 2000. Table 3 lists daily mean, maximum, and minimum values of air temperature, solar radiation, relative humidity, ambient vapor pressure, wind speed and wind vector direction. Table 4 lists daily mean, maximum, and minimum values of soil temperature and soil-heat flux starting in September 1999, and net radiation starting in July 1998. Table 5 lists daily mean, maximum, and minimum barometric pressure.

For a complete listing of field data sets containing the meteorological and soil-moisture data, refer to the computer data files included with this report. The computer data files contain seven files with about14 megabytes of information in tabular format consisting of five different computer-data tables. The field data sets include: (1) one file (data table A1) listing daily mean, maximum, and minimum micrometeorological data and daily total precipitation; (2) three files (data tables A2, A3, and A4) listing hourly mean micrometeorological data and hourly precipitation for each year (1998-2000); (3) one file (data table B1) listing 5-minute precipitation data; (4) one file (data table C1) with four worksheets listing soil-water content by date and depth at four experimental sites; and (5) one file (data table C2) with nine worksheets listing soil-water content by date and depth for each neutron-probe access tube.

Table 3 (Microsoft Excel File, 902K)

Table 4 (Microsoft Excel File, 419K)

Table 5 (Microsoft Excel File, 76K)

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# Selected Micrometeorological, Soil-Moisture, and Evapotranspiration Data at Amargosa Desert Research Site in Nye County near Beatty, Nevada, 2001–05

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# Selected Micrometeorological, Soil-Moisture, and Evapotranspiration Data at Amargosa Desert Research Site in Nye County near Beatty, Nevada, 2001–05

By Michael J. Johnson, C. Justin Mayers, C. Amanda Garcia, and B.J. Andraski

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# Conversion Factors and Datum

## Conversion Factors

| Multiply | By | To obtain |
|---|---|---|
| becquerel per liter (Bq/L) | 27.027 | picocurie per liter |
| centimeters (cm) | 0.3937 | inch |
| cubic meter ($m^3$) | 35.31 | cubic foot |
| kilometer (km) | 0.6214 | mile |
| kilopascal (kPa) | 0.1450 | pound-force per square inch |
| liter (L) | 0.2642 | gallon |
| meter (m) | 3.281 | foot |
| meter per second (m/s) | 3.281 | foot per second |
| micrometer (µm) | 0.000039 | inch |
| millibar (mbar) | 0.0145 | pound per square inch |
| millimeter (mm) | 0.03937 | inch |
| millimeter per day (mm/d) | 0.0397 | inch per day |
| millimeter per hour (mm/h) | 0.03937 | inch per hour |
| Watts per square meter ($W/m^2$) | 0.005290 | British Thermal Unit per square foot per minute |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

**Radiation:** A unit of activity is a Curie (Ci), which is equivalent to $3.7 \times 10^{10}$ disintegrations per second (dps); the standard disintegration rate of 1 gram of Radium. In International Units a Becquerel (Bq) is equivalent to 1 disintegration per second (dps). Thus, 1 Curie (Ci) equals $3.7 \times 10^{10}$ Becquerels (Bq) or 37 gigaBecquerels (GBq).

## Datum

In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

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# Selected Micrometeorological, Soil-Moisture, and Evapotranspiration Data at Amargosa Desert Research Site in Nye County near Beatty, Nevada, 2001–05

By Michael J. Johnson, C. Justin Mayers, C. Amanda Garcia, and B.J. Andraski

## Abstract

Selected micrometeorological and soil-moisture data were collected at the Amargosa Desert Research Site adjacent to a low-level radioactive waste and hazardous chemical waste facility near Beatty, Nevada, 2001–05. Evapotranspiration data were collected from February 2002 through the end of December 2005. Data were collected in support of ongoing research to improve the understanding of hydrologic and contaminant-transport processes in arid environments.

Micrometeorological data include solar radiation, net radiation, air temperature, relative humidity, saturated and ambient vapor pressure, wind speed and direction, barometric pressure, precipitation, near-surface soil temperature, soil-heat flux and soil-water content. All micrometeorological data were collected using a 10-second sampling interval by data loggers that output daily and hourly mean values. Daily maximum and minimum values are based on hourly mean values. Precipitation data output includes daily and hourly totals. Selected soil-moisture profiles at depth include periodic measurements of soil volumetric water-content measurements at nine neutron-probe access tubes to depths ranging from 5.25 to 29.25 meters. Evapotranspiration data include measurement of daily evapotranspiration and 15-minute fluxes of the four principal energy budget components of latent-heat flux, sensible-heat flux, soil-heat flux, and net radiation. Other data collected and used in equations to determine evapotranspiration include temperature and water content of soil, temperature and vapor pressure of air, and covariance values. Evapotranspiration and flux estimates during 15-minute intervals were calculated at a 0.1-second execution interval using the eddy covariance method.

Data files included in this report contain the complete micrometeorological, soil-moisture, and evapotranspiration field data sets. These data files are presented in tabular Excel spreadsheet format.

This report highlights selected data contained in the computer generated data files using figures, tables, and brief discussions. Instrumentation used for data collection also is described. Water-content profiles are shown to demonstrate variability of water content with depth. Time-series data are plotted to illustrate temporal variations in micrometeorological, soil-water content, and evapotranspiration data.

## Introduction

Research at the Amargosa Desert Research Site (ADRS) is intended to develop a fundamental understanding of hydrologic and contaminant-transport processes in arid environments. Research objectives are to advance the understanding of hydrologic science and to provide scientific information for those making decisions concerning waste isolation and water management in desert environments. Information on ADRS is available on the internet at http://nevada.usgs.gov/adrs/.

In support of ongoing research, micrometeorological, soil-moisture, and evapotranspiration (ET) data were collected at the ADRS adjacent to a low-level radioactive and hazardous-chemical waste facility near Beatty, Nev. The waste facility has been used for the burial of low-level radioactive waste from 1962 through 1992 and hazardous-chemical waste from 1970 to present. The ADRS was incorporated into the U.S. Geological Survey (USGS) Toxic Substances Hydrology Program in 1997. Research at the ADRS began in 1983 and has produced long-term benchmark data on hydrologic characteristics and soil-water movement in undisturbed conditions and in simulated waste-disposal conditions in arid environments (Andraski and Stonestrom, 1999).

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This report includes selected micrometeorological, soil-moisture, and ET data collected during 2001–05. Instrumentation used to collect the data is described herein. This report is the eighth in a series of meteorological reports published for the ADRS (Wood and Fischer, 1991, 1992; Wood and others, 1992; Wood and Andraski, 1992, 1995; Wood, 1996, Johnson and others, 2002). These previous reports include meteorological data collected during 1986–92 and during 1998–2000. Meteorological data were not reported for 1993–97.

The micrometeorological data collected for 2001–05 include solar radiation, net radiation, air temperature, relative humidity, saturated and ambient vapor pressure, wind speed and direction, barometric pressure, precipitation, near-surface soil temperature, soil-heat-flux and soil-water content. Soil-moisture profiles collected periodically during 2001-05 consist of volumetric soil-water content measurements made using a neutron probe. ET data were collected from February 14, 2002, through December 31, 2005, and included daily totals and 15-minute energy fluxes of net radiation, soil-heat flux, latent-heat flux, and sensible-heat flux along with other soil and air parameters collected and used in equations to derive ET.

Data files that contain the complete micrometeorological (appendixes A–F), soil-moisture (appendixes G and H), and ET (appendixes I–M) field data sets are summarized in this report. These data consist of 13 tabular files (in Excel spreadsheet format) with about 62 megabytes of information. Appendix A lists daily mean micrometeorological data and daily total precipitation for 2001–05. Appendixes B–F list hourly mean micrometeorological and hourly precipitation data for 2001–05. Appendix G lists soil-water content by date and depth at four experimental sites. Appendix H lists soil-water content by date and depth for each neutron-probe access tube. Appendix I lists the daily ET. Appendixes J–M list the 15-minute fluxes and other variables for each year (2002–05).

## Site Description

The ADRS is near a waste-burial facility about 17 km south of Beatty, Nev., and 20 km east of Death Valley, Calif. (fig. 1*A*). The ADRS is in the Mojave Desert ecosystem, one of the most arid regions in the United States. Vegetation in the area is sparse, covering about 6 to 8 percent of the land surface at the ADRS (Andraski and others, 2005) based on 2001 and 2003 data collected using the line-transect method (Smith, 1974). Creosote bush (*Larrea tridentata*), an evergreen shrub, is the dominant species. At the site, creosote bush averages about 0.7 m in height, with a major and minor axial diameter of 1 m and 0.7 m, respectively. The Amargosa Desert is in the Basin and Range physiographic province. Sediments beneath the study area and the waste-burial facility primarily are basin fill consisting of unconsolidated alluvial fan, fluvial, and marsh deposits (Clebsch, 1968). The basin fill is estimated to be more than 170-m thick (Nichols, 1987, p. 8). Depth to the water table ranges from 85 to 115 m below land surface (Fischer, 1992, p. 12).

Other studies at the ADRS facility have been established to support research of flow and transport processes within the thick unsaturated zone above the water table. The research site has two fenced areas; one encloses a vertical, 13.7-m instrument shaft (figs. 1*B* and 2; Fischer, 1992), and the other encloses simulated waste trenches (figs. 1*B* and 3; Andraski, 1990). A weather station, two precipitation gages, and three neutron-probe access tubes are within the instrument-shaft area (fig. 2). The instrument-shaft area is used for monitoring soil-water content in a vegetated, native-soil profile. Six neutron-probe access tubes and a single precipitation gage are within the simulated waste-trench area (fig. 3). The tubes are used to measure soil-water content under nonvegetated, simulated waste-trench conditions and under devegetated, but undisturbed native-soil conditions. Ground-water levels have been measured periodically since 1987 at well MR-3 (fig. 1*B*). Throughout the thick unsaturated zone, deep test holes (UZB-1, 2, and 3; fig. 1*B*) have been used for obtaining measurements of soil temperature, water potential, air pressure, and for collecting soil-gas samples (Prudic and Striegl, 1995; Andraski and Prudic, 1997; Prudic and others, 1999; Mayers and others, 2005). An ET station (fig. 1*B*) is located approximately 200 m south of the fenced area enclosing the instrument shaft area. Not shown in the figures is an array of soil-gas sampling tubes that are used for periodic collection and analysis of the chemical composition of unsaturated-zone air to a depth of about 1.5 m (Striegl and others, 1998; Healy and others, 1999). Similarly, numerous plant-sampling sites have been established to evaluate soil-plant-atmosphere interactions and ultimately to determine how those interactions affect the potential release of contaminants (Andraski and others, 2005).

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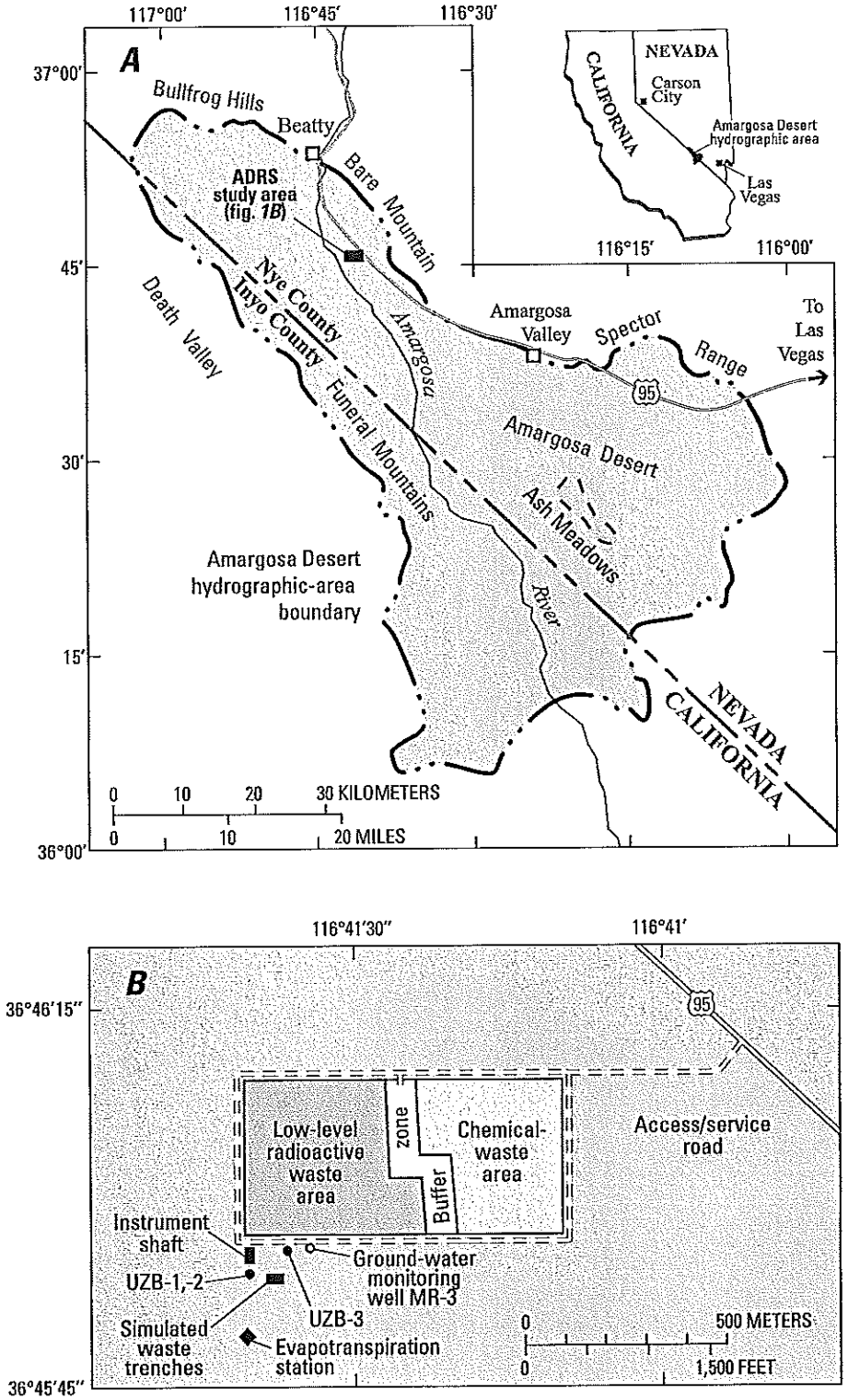


**Figure 1.** Location of (*A*) Amargosa Desert Research Site (ADRS) near Beatty, Nevada, and (*B*) instrument shaft and simulated waste trenches adjacent to waste-disposal facility.

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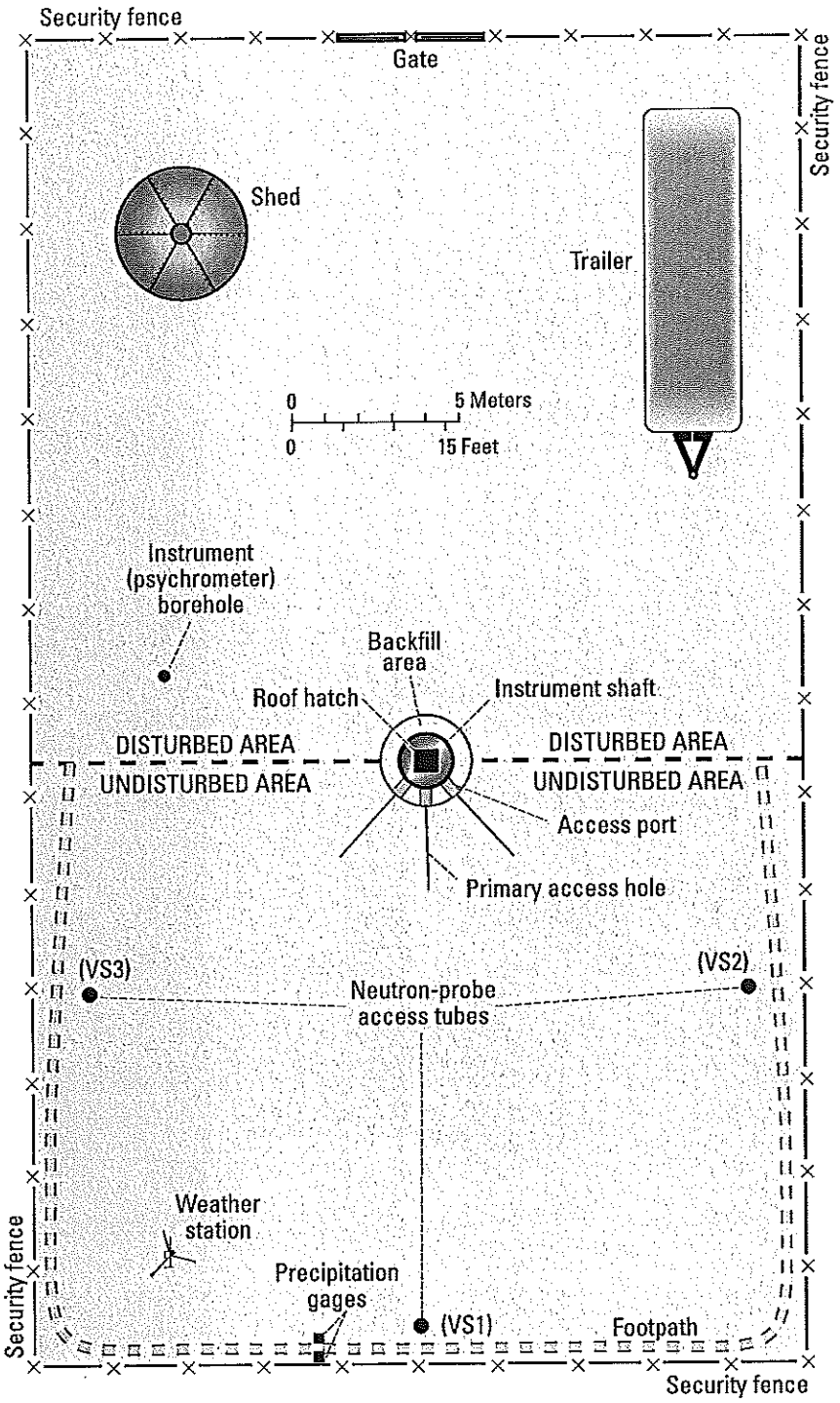


**Figure 2.** Fenced area of instrument shaft, location of weather station, neutron-probe access tubes VS1, VS2, and VS3 in vegetated native soil, and precipitation gages at Amargosa Desert Research Site near Beatty, Nevada.

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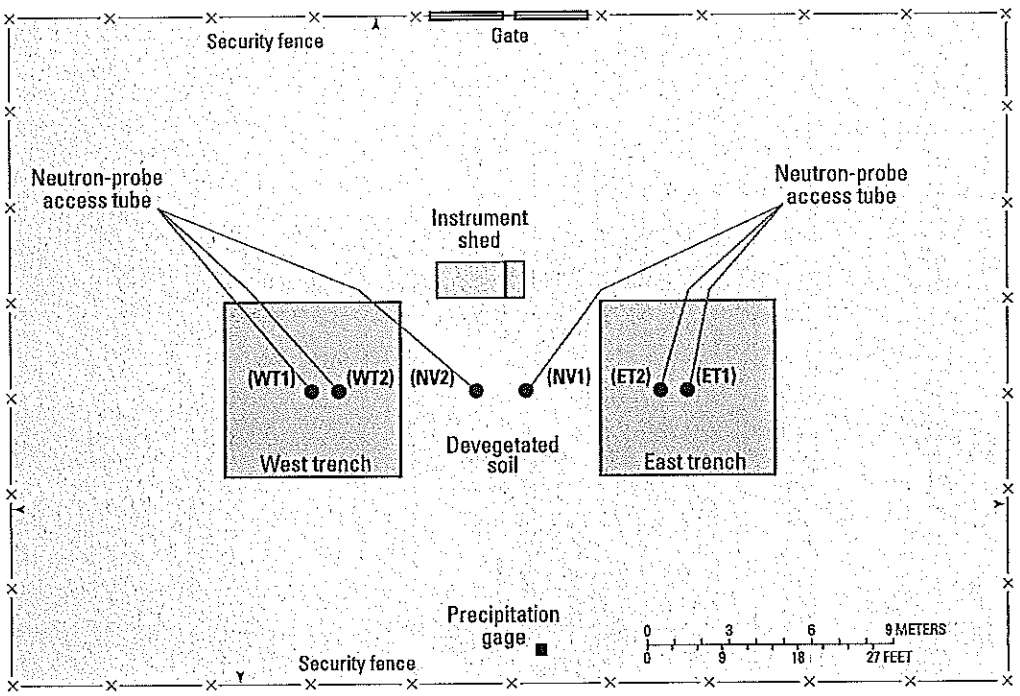


**Figure 3.** Fenced area of simulated waste trenches and location of neutron probe access tubes NV1 and NV2 in devegetated native soil; neutron-probe access tubes ET1, ET2, WT1, and WT2 in simulated waste trenches; and precipitation gage at Amargosa Desert Research Site near Beatty, Nevada.

# Micrometeorological Instrumentation

Micrometeorological sensors consisting of a tipping-bucket precipitation gage, an air-temperature and relative-humidity probe, a barometric-pressure sensor, a pyranometer, and an anemometer with wind vane were installed in December 1997. A net radiometer was installed at the site in July 1998. Soil-temperature probes and two soil-heat-flux plates were installed in September 1999. A soil-moisture probe was installed in January 2002. Data from two accumulating precipitation gages periodically were read after storm events to verify the data values obtained by the tipping-bucket precipitation gage.

Data from all the sensors were recorded using a Campbell Scientific, Inc. (CSI), 23X data logger using a 10-second sampling interval. The logger was programmed to output data in three formats: daily mean values (except for precipitation where only daily accumulated totals are output); hourly mean values (except for precipitation where only hourly accumulated totals are output); and 5-minute totals for precipitation (to define storm event timing rather than to collect data values and are not included in this data report). The data logger is interfaced to a telephone modem permitting automated communication and data retrieval using an off-site computer. The data logger reference is Pacific Standard Time (PST) throughout the year.

The air-temperature relative-humidity sensor, pyranometer, and anemometer with wind vane are mounted on a CM10 tripod at heights of 1.5 m, 3 m, and 3 m above the ground surface, respectively. The barometric-pressure sensor is mounted 1 m above the ground and housed with the data logger in a shed approximately 30 m north of the tripod (fig. 2). The net radiometer is mounted 1.5 m above the ground and approximately 10 m from the tripod. The net radiometer monitors principally bare soil radiation within the undisturbed vegetated area. The precipitation tipping-bucket precipitation gage was installed on its own mount approximately 5 m from the tripod at a height of 1 m. Adjacent to the tipping-bucket precipitation gage is an accumulating plastic precipitation gage made by Tru-Chek mounted at a height of 1 m along the south fence of the instrument shaft area (fig. 2), and a second Tru-Chek precipitation gage was at the south end of the waste-trench area (fig. 3). Two soil-heat-flux plates are buried in the near-surface soil at a depth of about 0.08 m approximately 2 m from the weather-station tripod. Between the flux plates and the soil surface, the averaging soil-temperature probes are buried at depths of 0.02 and 0.06 m. The soil-moisture probe is buried to measure average soil moisture in the depth interval between the flux plate depth of 0.08 m and the soil surface. The probe has two 0.3 m rods spaced about 0.03 m apart. The rods are inserted into the ground at a slight angle to integrate the water content of soil over the depth interval.

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The accuracy of the data is dependent on the sensors being used. Instrumentation manuals from the manufacturers (vendors) contained the following sensor specifications. The tipping-bucket precipitation gage is a WeatherMeasure model P-501 with a resolution of 0.25 mm representing one tip of the bucket, and an accuracy of 0.5 percent at 12.7 mm/h. The air-temperature relative-humidity sensor is a Vaisala HMP35C from CSI with a temperature accuracy of ±0.4°C over a range of -24 to 48°C, and measures a relative humidity accuracy of ±2 percent within the range from 0 to 90 percent and ±3 percent within the range from 90 to 100 percent. The Vaisala temperature and humidity sensor is mounted inside a 12-plate gill radiation shield. Solar radiation is measured with a LI-COR LI200X silicon pyranometer calibrated against an Eppley Precision Spectral Pyranometer, and has a maximum error of ±5 percent. The net radiometer is a Radiation and Energy Balance Systems (REBS) Q7.1 net radiometer, which has a spectral response from 0.25 to 60 μm, with a nominal resistance of 4 ohms. Wind speed and direction are measured by a Met One 034A-L Windset with a wind speed accuracy of ±0.12 m/s, a threshold of 0.28 m/s, and wind direction accuracy of ±4 degrees. The barometric-pressure sensor is a CSI SBP270 with a pressure range from 800 to 1,100 mbar and an accuracy of ±0.2 mbar. Soil temperature is measured with a TCAV-L averaging soil-temperature probe manufactured by CSI with two junctions at two depths and constructed using a Type-E thermocouple (chromel-constantan) wire. The four thermocouples and associated reference temperature define an averaged soil temperature with a typical uncertainty of 0.5°C, but the uncertainty can be as high as 1.6°C. The soil-heat flux is measured with two REBS HFT3.1 heat-flow transducer plates with a nominal resistance of 2 ohms and a thermal conductivity of 1.00 Watt per meter per degrees Kelvin (W/m/K). The soil-heat-flux plates have an error of about ±5 percent. The near-surface soil moisture is measured using a CS615 water content reflectometer designed to measure volumetric water content derived from the probe sensitivity to the unique dielectric content of the soil which changes with changing moisture conditions. The soil-moisture probe has an accuracy of ±2 percent when calibrated for a specific soil. The soil moisture values have been calibrated to the specific soil at the site by periodic field sampling of soil between the 8-cm flux-plate depth and the soil surface. Samples were analyzed to determine gravimetric water, bulk density, and volumetric water content.

## Soil-Moisture Profile Instrumentation

Measurements of soil-water content were collected at depth from neutron-probe access tubes using a CPN 503 Hydroprobe manufactured by Campbell Pacific Nuclear International, Inc. The probe uses a 50 mCi Americium-241: Beryllium neutron source, or in System International units, a 1.85 GBq source. This source emits fast neutrons that are not detected by the neutron detectors in the probe. The fast neutrons propagate through the soil, collide with hydrogen atoms in soil water, become thermalized or slowed, and are then reflected back as slow neutrons. The reflected slow neutrons are detected in the tube of the probe and the surface electronic sensor counts each slow neutron event. Counts are accumulated for a specified time interval and recorded. Soil-water content is proportional to the number of slow neutron reflections counted. Because the neutron source and its detector tube can vary in radiation-flux emissions and detections with time, count ratios are used to normalize the field counts for a given set of measurements. Count ratios are calculated by dividing the field counts by standard counts obtained while the neutron probe is within its shield above the ground.

Access tubes at both the vegetated, native soil profile (VS1, VS2, and VS3; fig. 2) and the devegetated, native soil profile (NV1 and NV2; fig. 3) are large-steel tubes with a 140-mm outside diameter and a 6.4-mm wall thickness. These access tubes were installed at the vegetated, native soil site (July 1984) and the devegetated, native soil site (September 1988) using a pneumatically driven downhole-hammer system (Tyler, 1988). Access tubes at the two simulated waste trenches (ET1, ET2, WT1, and WT2; fig. 3) are small-steel tubes with a 51-mm outside diameter and 3.0-mm wall thickness. These access tubes were installed during trench construction (September 1987) with tubes placed in holes that were hand-augured below the trench floor prior to backfilling (Andraski, 1996). Three access tubes (VS1, VS2, and VS3; fig. 2) were used at the vegetated, native soil profile with the neutron probe reaching a maximum recording depth of 13.75, 29.75, and 13.75 m, respectively. Two access tubes were used at each of the other sites (fig. 3) with a maximum neutron probe depth of about 5.25 m.

Neutron counts were accumulated for 30-second time interval at each depth selected within the individual access tubes. At the vegetated, native soil profile (within the instrument shaft area; fig. 2), single readings were obtained at each depth, and readings were obtained at intervals of 0.25 m to a depth of 10.75 m and then 0.5 m below that depth. At the devegetated, native soil profile and the two trenches (within the simulated trench area; fig. 3), two readings were obtained at each depth, and readings typically were obtained at intervals of 0.25 m.

Using count ratios, calibration equations were developed with coefficients of determination greater than 0.96 (Andraski, 1997, p. 1904). The standard error of estimate for small-diameter tubes ranged from 0.017 $m^3/m^3$ for measurements at the 15 m depth to 0.012 $m^3/m^3$ for measurements at depths greater than 15 m. For large-diameter tubes, the standard error of estimate was less than 0.009 $m^3/m^3$ at all depths.

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## Evapotranspiration Instrumentation

ET instrumentation consists of a CSI eddy covariance system which includes a CSAT3 three-dimensional sonic anemometer, a KH20 krypton hygrometer, and a FW05 fine-wire thermocouple (type E, 0.0005 inch diameter). These instruments measure two main energy budget components: the transfer of water vapor (latent-heat flux) and the transfer of heat (sensible-heat flux) through the atmosphere, using the eddy covariance technique. Additional sensors were added to this instrumentation to document the two other principal energy budget components of net radiation and soil-heat flux. Net radiation is measured by a REBS Q7.1 net radiometer. Soil-heat flux is calculated by measurements obtained from ground sensors consisting of two REBS HFT3.1 heat-flow transducer plates, a TCAV-L (CSI) averaging soil-temperature probe, and a CS616 water content reflectometer. The eddy covariance system uses a HMP45C Vaisala temperature and relative humidity probe to derive other necessary variables for the eddy covariance technique.

The anemometer, hygrometer, and fine-wire thermocouple were mounted on their own tripod with cables running to a second tripod used to mount the net radiometer, Vaisala temperature and relative humidity probe, cellular phone antenna, and enclosure box containing a CSI 23X data logger, storage module, cellular phone and other terminals and controls. The installation geometry of the soil sensors is the same as at the weather station. The net radiometer was mounted 3 m above the ground and 3 m out from the tripod; this sensor placement was selected to provide a representative measurement of the land surface consisting of sparse plant canopy and bare soil. The temperature and humidity probe along with the anemometer, hygrometer, and fine-wire thermocouple were mounted 2 m above the ground surface.

The ET station was operated using a field program (flx232_3.csi, version 2.3, 22 March 2001) obtained from Campbell Scientific, Inc. (Ed Swiatek, Campbell Scientific, Inc., written commun., 2002). The field program was modified to the specific sensors used at the ADRS. The eddy covariance fluxes are computed for a 15-minute covariance period based on a 0.1-second execution or sampling interval. Other sensors generally sample data for a 1-second sampling interval and output data every 15 minutes.

## Selected Micrometeorological Data

Complete micrometeorological data sets are available in appendixes A–F of this report. Appendix A lists daily mean micrometeorological data and daily total precipitation for 2001–05. Hourly mean micrometeorological and hourly precipitation data for 2001–05 are listed in appendixes B–F.

Appendix A lists daily mean values of micrometeorological data computed from instantaneous readings sampled every 10 seconds during the day (8,640 samples). These daily mean values are equivalent to daily mean values computed by averaging hourly mean values (appendixes B-F) computed from (the same) instantaneous readings sampled every 10 seconds during the hour (360 samples). In this report, daily mean values are included only in appendix A. Any reference to daily mean values computed from hourly mean values can be looked up in appendix A. However, daily maximum and minimum values of micrometeorological data computed from instantaneous readings sampled every 10 seconds throughout a day are not equivalent to daily maximum and minimum values computed from hourly mean values of the same data. In this report, discussions of micrometeorological data will focus on the daily mean values (appendix A) with reference to daily maximum and minimum values from hourly mean values (appendixes B–F).

### Solar Radiation

Daily maximum and mean solar radiation computed from hourly averaged values at ADRS are shown in figure 4. Complete daily and hourly solar-radiation data are in appendixes A–F. Solar radiation is the amount of incident radiation from the sun that reaches the surface of the earth at the point of detection. Both daily and hourly mean and maximum solar-radiation data in this report and solar-radiation data presented in the previous report (Johnson and others, 2002) are based on instantaneous readings sampled every 10 seconds. Earlier ADRS publications (Wood and Fischer, 1991, 1992; Wood and others, 1992; Wood and Andraski, 1992, 1995; Wood, 1996) also reported daily mean and maximum solar radiation derived from hourly mean values based on instantaneous readings sampled every 10 seconds.

The daily maximum and mean solar-radiation curves (fig. 4) show the annual solar-energy cycle and the difference between the daily mean and maximum for any given day of the year. The maximum radiation for the year occurs during the summer solstice in late June during clear sky days with maximum daily values generally averaging about 1,020 $W/m^2$ during the 5 years of record. Conversely, during the winter solstice period in late December during clear sky days maximum daily values generally average about 580 $W/m^2$ during the 5 years of record. The downward spikes in figure 4 show days where average daily solar radiation is reduced during extended periods of cloud cover. As indicated in figure 4, the difference between the daily maximum and daily mean time-series values varies from more than 720 $W/m^2$ during the summer to an average of about 410 $W/m^2$ during the winter.

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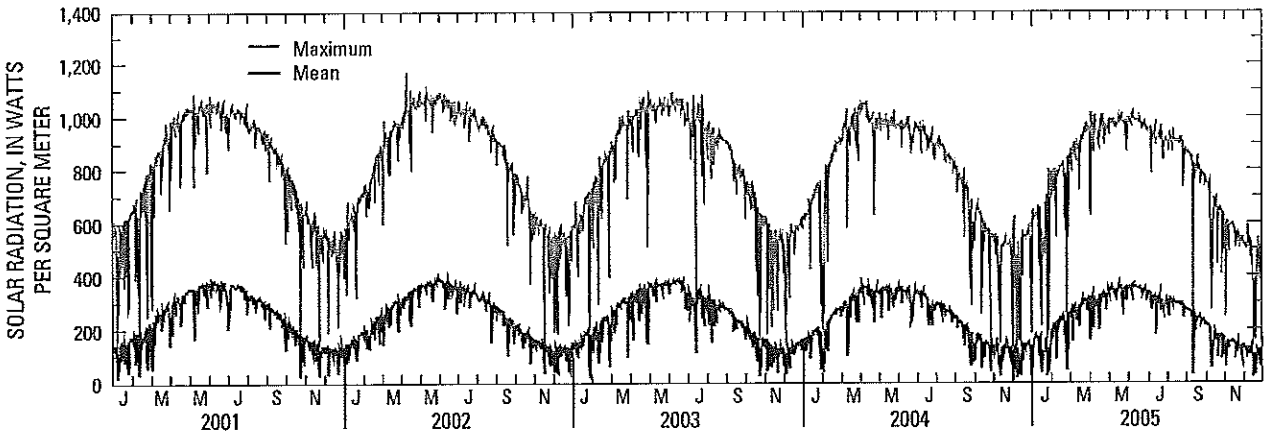


**Figure 4.** Daily maximum and mean solar radiation computed from hourly averaged values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

Figure 4 shows a shift in the data set, which occurred on May 5, 2004, with the replacement of one pyranometer with another. The shift is about 5 percent of the maximum expected absolute error in natural daylight for this kind of sensor. During any given 1-year period an individual sensor can range ±2 percent.

## Net Radiation

Daily maximum and mean net radiation computed from hourly averaged values are shown in figure 5. Complete daily and hourly net-radiation data are in appendixes A–F. Net radiation is the difference between all downward and upward radiation fluxes of both short- and long-wave radiation. Net radiation is a measure of the energy available at the surface of the Earth that can be partitioned into such energy-consuming processes as heating the soil and air, ET, and plant growth. By convention, net radiation is defined as positive when downward components (incoming radiation) exceed upward components (outgoing radiation), and this typically occurs after sunrise and before sunset. Allocation of this net radiative energy varies with seasonal surface conditions. For example, in late spring after a rainstorm, more energy is used to evaporate water from wet soils and for plant transpiration than is used to heat the air and soil. Later in the summer under dry conditions almost all the net radiative energy goes to heat the air and soil.

During 2001–05, the daily mean net radiation generally ranged from about 20 W/m$^2$ in early winter to about 160 W/m$^2$ in early summer (fig. 5; appendix A). The daily maximum generally ranged from a low of about 290 W/m$^2$ in early winter to a high of about 570 W/m$^2$ in early summer. The mean net radiation that occurs from 8 a.m. to 4 p.m. PST also is shown in figure 5 to illustrate that a large part of daily net radiation available to the site occurs during the 4 hours before and after noon. This daily 8 a.m. to 4 p.m. mean radiation often is within 100 W/m$^2$ of the daily maximum radiation.

Variations in measured net radiation values can occur over time as the transparent polyethylene shields on the net radiometer age and become less translucent from the UV radiation component of solar radiation or from the scouring from wind driven particles. Cracks in the shield will cause abrupt changes in net radiation values as shown in figure 5 from August 14, 2004, to October 25, 2004, when the shield was replaced. UV radiation can dry the polyethylene shield to the point where the shield is shattered from heavy rains during summer thunderstorms or from wind driven particles such as sand. Radiation values can increase or decrease when the radiometer is not level, such as when birds damage the shields or tilt the sensor head. An example of an abnormal increase in radiation can be seen from July 3, 2001, to September 5, 2001 (fig. 5). Most sensor problems can be easily fixed by replacing shields and leveling the sensors. The extended periods of poor-quality data reflect the timing of the occurrence of sensor problems with the scheduled field visits limited to quarterly visits.

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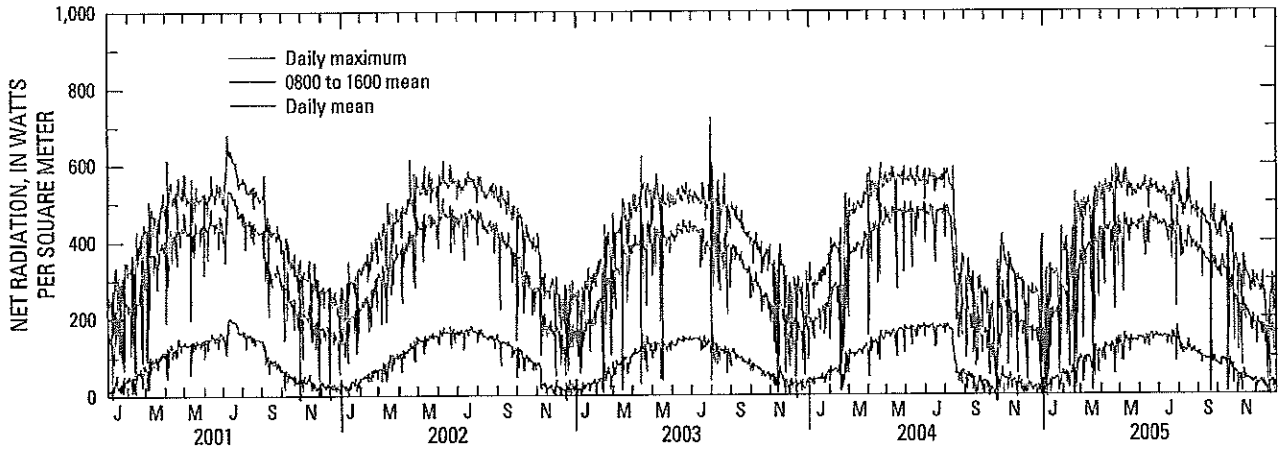


**Figure 5.** Daily maximum and mean net radiation compared to mean from 8 a.m. to 4 p.m. of net radiation computed from hourly averaged values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

## Air Temperature

Monthly maximum, minimum, and mean air temperatures computed from hourly averaged values are listed in table 1. Daily maximum, minimum, and mean air temperatures are shown in figure 6. Complete data for daily and hourly air temperatures are in appendixes A–F. During 2001–05, air temperatures averaged 18.3°C with the warmest month averaging 31.7°C during July and the coldest month averaging 6.4°C during December. From 2001 through 2005, the maximum hourly average temperature recorded was 44.7°C in July 2005 and the minimum temperature recorded was -8.5°C in January 2002.

Daily and seasonal temperature fluctuations are large at the study site. Differences between daily maximum and minimum temperatures commonly exceed 20°C as shown in figure 6. Differences between winter minimum and summer maximum temperatures exceed more than 40°C, and sometimes more than 50°C. The desert environment, with its high percentage of clear skies, has a large heating capacity from incoming solar (short-wave) radiation during the day, and a proportionally large heat discharge by terrestrial (long-wave) radiation during the night. The large gains and losses in energy on a daily basis and their relative variation on a seasonal basis are what regulate the temperatures that occur in this environment.

## Relative Humidity

Daily maximum, minimum, and mean relative-humidity computed from hourly averaged values is shown in figure 7. Complete daily and hourly relative-humidity data are in appendixes A–F. Relative humidity is the ratio of the amount of water vapor in the air at a specific temperature (vapor pressure) to the maximum amount of water vapor that the air can hold at that temperature (saturated vapor pressure), expressed as a percent. Daily mean values ranged from 5 to 95 percent. In contrast, hourly mean values ranged from 1 percent during the drier summer months to 100 percent during winter storms. During mid-day hours in the summer, relative-humidity values of less than 10 percent are common in the Amargosa Desert where prevailing high summer temperatures lower the relative-humidity measurements of available vapor content of the air relative to what saturated levels would be if maximum water vapor were available in the area.

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**Table 1.** Monthly, maximum, minimum, and mean air temperatures computed from hourly averaged values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

[Temperatures are in degrees Celsius. Maximum and minimum based on hourly mean values. Monthly mean obtained by averaging mean daily values]

| Month | Air temperatures in degrees C | | | | |
|---|---|---|---|---|---|
| | Maximum | Day | Minimum | Day | Mean |
| **2001** | | | | | |
| January | 21.4 | 3 | -3.7 | 21 | 5.7 |
| February | 23.6 | 4 | -5.2 | 9 | 6.9 |
| March | 27.6 | 31 | -0.4 | 1 | 14.2 |
| April | 32.3 | 30 | 0.3 | 9 | 15.3 |
| May | 39.0 | 24 | 8.8 | 3 | 25.7 |
| June | 40.8 | 30 | 11.2 | 14 | 28.5 |
| July | 43.4 | 2 | 16.6 | 23 | 29.5 |
| August | 42.1 | 18 | 16.2 | 22 | 30.9 |
| September | 36.6 | 24 | 12.9 | 9 | 26.0 |
| October | 35.7 | 2 | 6.5 | 25 | 19.9 |
| November | 26.5 | 3 | -4.5 | 28 | 11.8 |
| December | 17.4 | 31 | -5.9 | 16 | 5.8 |
| **2002** | | | | | |
| January | 20.3 | 13 | -8.5 | 17 | 5.9 |
| February | 24.6 | 23 | -8.4 | 1 | 9.4 |
| March | 29.6 | 30 | -4.2 | 17 | 11.4 |
| April | 33.5 | 14 | 3.8 | 21 | 18.2 |
| May | 39.0 | 30 | 5.9 | 21 | 22.4 |
| June | 40.9 | 30 | 14.1 | 12 | 29.0 |
| July | 44.7 | 9 | 18.7 | 28 | 32.7 |
| August | 43.2 | 14 | 15.1 | 31 | 29.7 |
| September | 38.6 | 2 | 10.5 | 8 | 25.6 |
| October | 32.5 | 8 | 3.6 | 30 | 17.1 |
| November | 25.4 | 20 | -0.7 | 2 | 12.2 |
| December | 19.0 | 5 | -7.4 | 19 | 6.3 |
| **2003** | | | | | |
| January | 26.0 | 31 | -1.2 | 16 | 10.5 |
| February | 23.4 | 1 | -5.4 | 8 | 8.7 |
| March | 26.7 | 31 | -0.9 | 3 | 13.3 |
| April | 27.7 | 10 | 0.9 | 6 | 14.5 |
| May | 41.3 | 28 | 7.3 | 9 | 22.6 |
| June | 40.6 | 28 | 15.5 | 25 | 29.1 |
| July | 43.8 | 12 | 16.8 | 1 | 32.9 |
| August | 40.6 | 18 | 16.5 | 7 | 29.9 |
| September | 38.9 | 27 | 11.7 | 19 | 26.8 |
| October | 35.0 | 21 | 2.5 | 31 | 21.6 |
| November | 19.2 | 11 | -4.0 | 25 | 8.3 |
| December | 19.9 | 2 | -4.8 | 16 | 5.8 |
| **2004** | | | | | |
| January | 20.4 | 14 | -7.3 | 26 | 6.1 |
| February | 22.3 | 17 | -4.4 | 13 | 7.1 |
| March | 32.1 | 21 | 2.3 | 1 | 16.6 |
| April | 33.1 | 27 | 3.3 | 18 | 17.5 |
| May | 36.3 | 31 | 8.4 | 12 | 23.0 |
| June | 39.9 | 5 | 9.7 | 10 | 28.4 |
| July | 40.6 | 19 | 16.4 | 2 | 31.1 |
| August | 42.4 | 11 | 14.9 | 28 | 29.1 |
| September | 39.2 | 1 | 8.5 | 23 | 24.3 |
| October | 32.0 | 8 | 2.2 | 29 | 16.7 |
| November | 25.3 | 6 | -7.0 | 30 | 9.6 |
| December | 21.2 | 10 | -4.7 | 25 | 7.0 |
| **2005** | | | | | |
| January | 23.2 | 19 | -2.5 | 7 | 8.0 |
| February | 18.4 | 17 | -1.3 | 9 | 8.8 |
| March | 27.4 | 9 | -0.6 | 15 | 12.3 |
| April | 29.1 | 17 | 1.0 | 1 | 15.1 |
| May | 37.4 | 26 | 8.8 | 13 | 22.7 |
| June | 39.4 | 22 | 11.1 | 8 | 26.0 |
| July | 44.7 | 18 | 18.1 | 5 | 32.4 |
| August | 40.7 | 28 | 15.4 | 30 | 29.3 |
| September | 37.0 | 2 | 8.5 | 13 | 22.7 |
| October | 32.3 | 2 | 5.0 | 11 | 17.9 |
| November | 25.2 | 19 | -3.6 | 28 | 12.1 |
| December | 22.7 | 23 | -6.1 | 17 | 6.8 |

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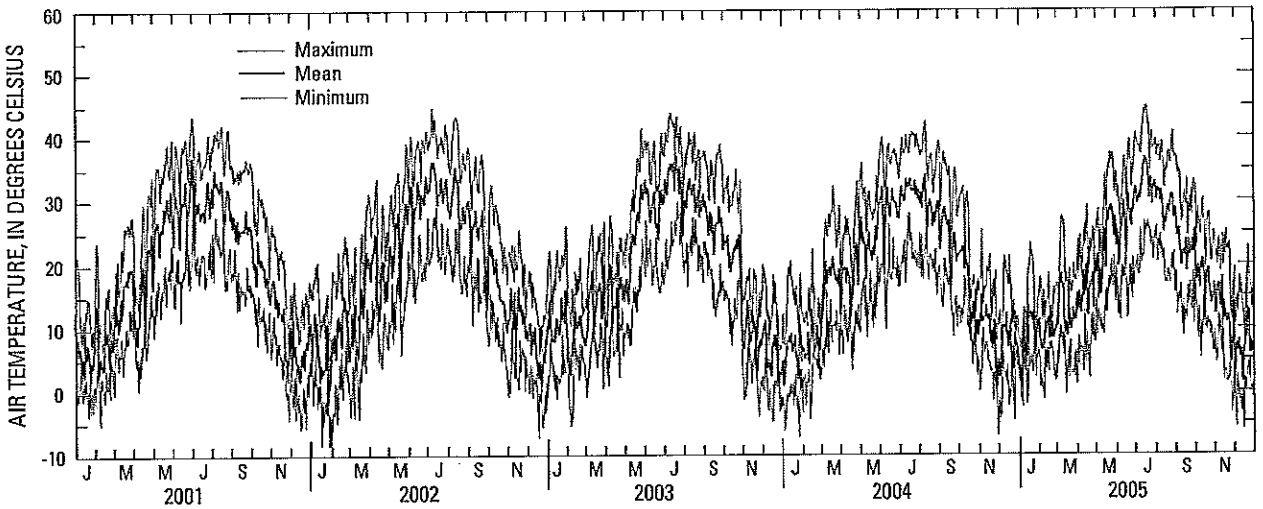


**Figure 6.** Daily maximum, minimum, and mean air temperature computed from hourly averaged values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

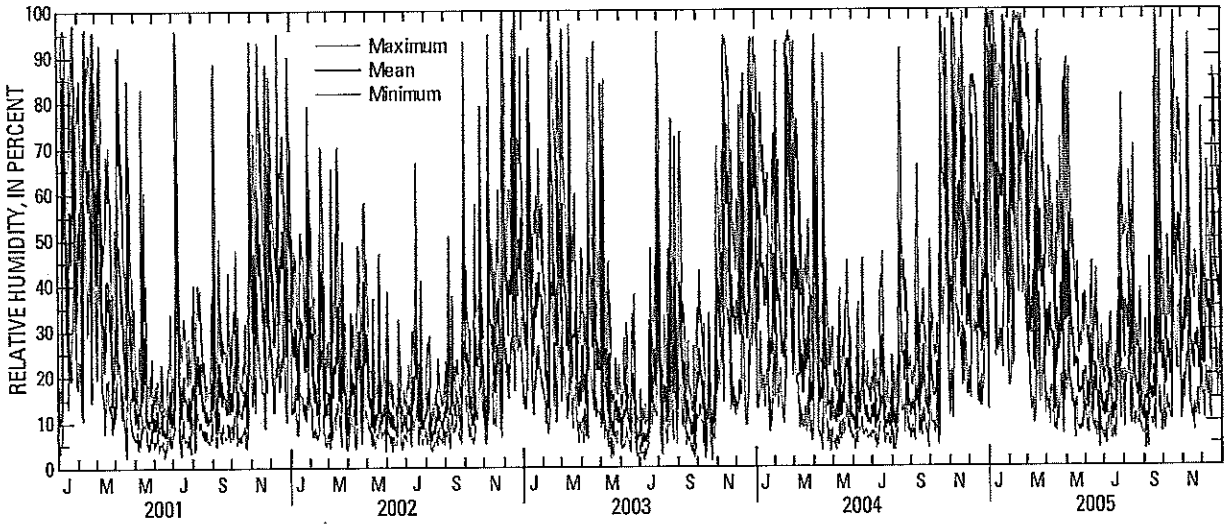


**Figure 7.** Daily maximum, minimum, and mean relative humidity computed from hourly averaged values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

CALCULATION
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## Saturated and Ambient Vapor Pressure

Daily mean vapor pressures computed from hourly averaged values are shown in figure 8. Complete daily and hourly vapor pressure data are in appendixes A–F. Ambient vapor pressure is the partial pressure exerted by water vapor present in the air and indicates the water-vapor content of the air under prevailing atmospheric conditions. The ambient vapor pressure is the product of the saturated vapor pressure and the relative humidity. Saturated vapor pressure is the highest concentration of water vapor that can exist in equilibrium over a free-water surface at that temperature. The data logger calculates the saturated vapor pressure in kilopascals from measured air temperature using an algorithm from Lowe (1977).

The mean saturated vapor pressures are higher during the summer months and lower during winter months (fig. 8) because warm air can potentially hold considerably more water vapor than cold air. For this reason, the summer rain events cause generally somewhat higher ambient vapor pressures than the larger winter precipitation. Figure 8 generally shows these higher ambient vapor pressures predominantly during the summer months. However, the mean ambient vapor pressure during the months of June through August average only about 0.15 kPa more than the mean ambient vapor pressure during the months of December through February, or about 0.60 kPa and 0.45 kPa, respectfully. Daily variations in ambient maximum and minimum vapor pressure from the mean vapor pressure typically are less than 0.15 kPa. During 2001–05, ambient-vapor pressures averaged about 0.5 kPa with daily means ranging from 0.08 to 2.1 kPa, while saturated-vapor pressures averaged 2.6 kPa with daily means ranging from 0.6 to 6.5 kPa. This large difference between saturated and ambient vapor pressure is an indication of the large water deficit that exists in this desert environment.

## Wind Speed and Direction

Daily mean wind speeds are shown in figure 9. Complete daily and hourly wind speed data are in appendixes A–F. Annual mean wind speed computed from daily mean wind speeds for the 5 years of record (2001–05) was 2.8, 2.9, 2.8, 3.0, and 2.7 m/s, respectively. During these 5 years, the mean wind speed was 2.8 m/s, and the maximum daily mean wind speed was 8.8 m/s on February 2, 2003 (fig. 9). The maximum hourly mean wind speed was 13.0 m/s and occurred on February 2, 2003. The distribution of hourly mean wind speed for the 5-year monitoring period is shown in figure 10. For example, 4 percent of the time the wind speed was below 1.0 m/s, and about 80 percent of the time the wind speed was less than 4.0 m/s. Winds of less than the anemometer threshold of 0.28 m/s are set to zero by the field recorder to indicate they are not measurable. Hourly mean wind speeds of less than 0.28 m/s occurred less than 0.6 percent of the time during the 5 years of record, as shown in figure 10. However, most days had at least one 10-second sampling interval with wind speeds below the instrument threshold giving most days a daily minimum based on a 10-second sampling interval of 0.0 m/s.

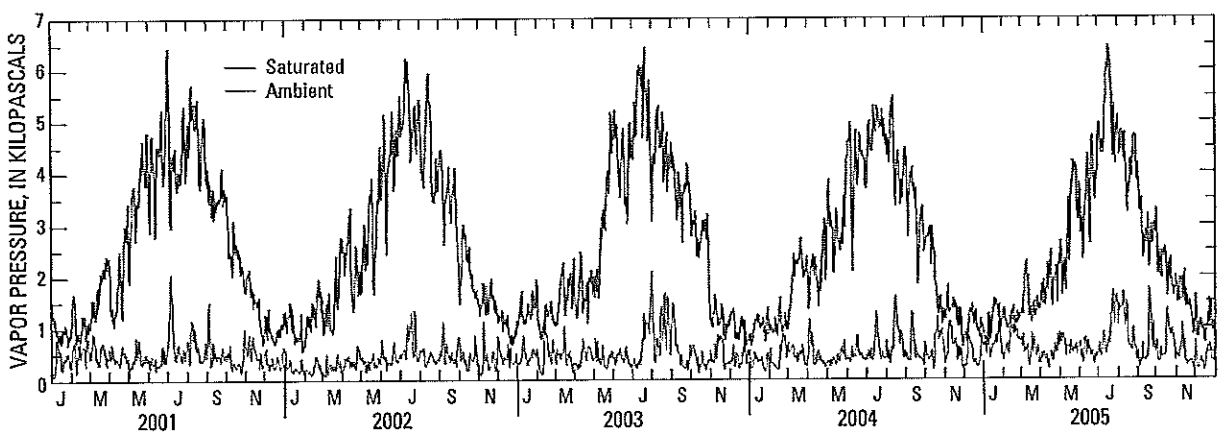


**Figure 8.** Daily mean saturated and ambient vapor pressure from hourly averaged values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

CALCULATION
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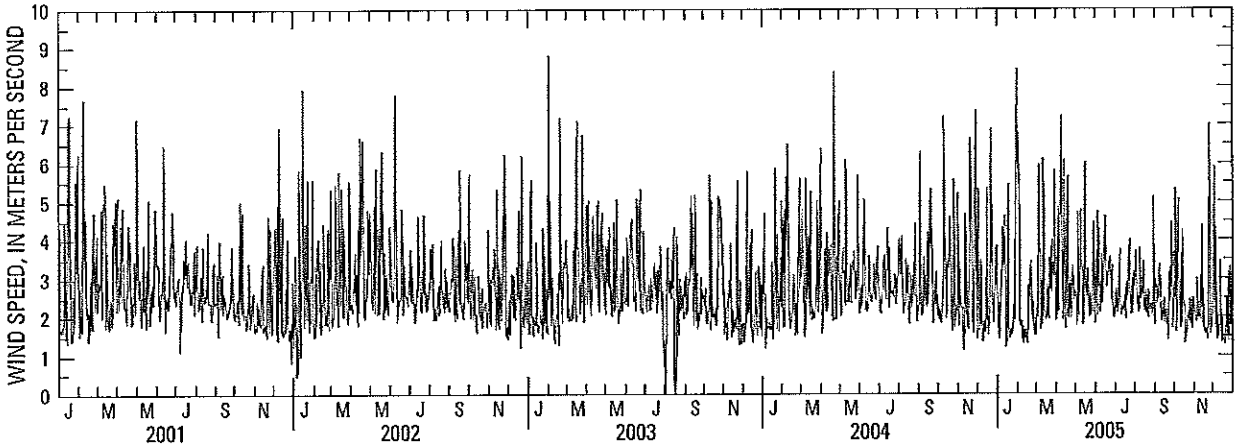


**Figure 9.** Daily mean wind speed computed from hourly averaged values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

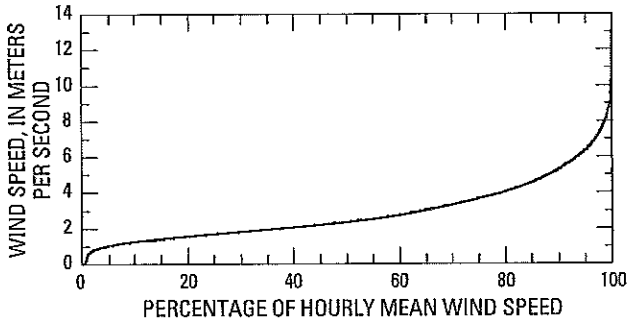


**Figure 10.** Distribution of hourly mean wind speed as a percentage of all hourly mean values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

Daily and hourly mean wind-vector directions in degrees Azimuth of true north with standard deviation are listed in appendixes A–F. Mean horizontal wind-vector direction was calculated by vectorially summing the individual wind vectors consisting of wind magnitude and direction using available data logger commands. The daily mean wind-vector directions are shown in figure 11. Daily wind directions indicate seasonal variability and annual recurrent patterns for 2001–05. Wind at the ADRS predominantly was from the northwest from September through February, and generally associated with regional frontal systems moving in from the west coast during the autumn and winter seasons. Winds from March to September are more evenly distributed from the northwest, southwest, and southeast. The ill-defined summer to autumn winds have at times been observed (D.I. Stannard, U.S. Geological Survey, oral commun., 2006) to be strongly katabatic, blowing up the valley during the day and down the valley at night. Southwest and southeast winds typically are associated with the counter-clockwise rotation of subtropical lows moving inland from the west coast of Mexico or southern California.

## Barometric Pressure

Daily mean barometric pressure and hourly mean barometric pressure data are listed in appendixes A–F. Barometric pressures at the ADRS facility are corrected to sea level using an altitude of 847.2 m. Daily mean barometric-pressure values from hourly averaged values are shown in figure 12. The mean barometric pressure for 2001–05 was about 101.5 kPa. Higher pressures generally occurred during clear winter days and lower pressures occurred during storm periods and summer. An hourly reading of 103.77 kPa occurred on February 10, 2002, and an hourly reading of 99.48 kPa occurred on April 15, 2002.

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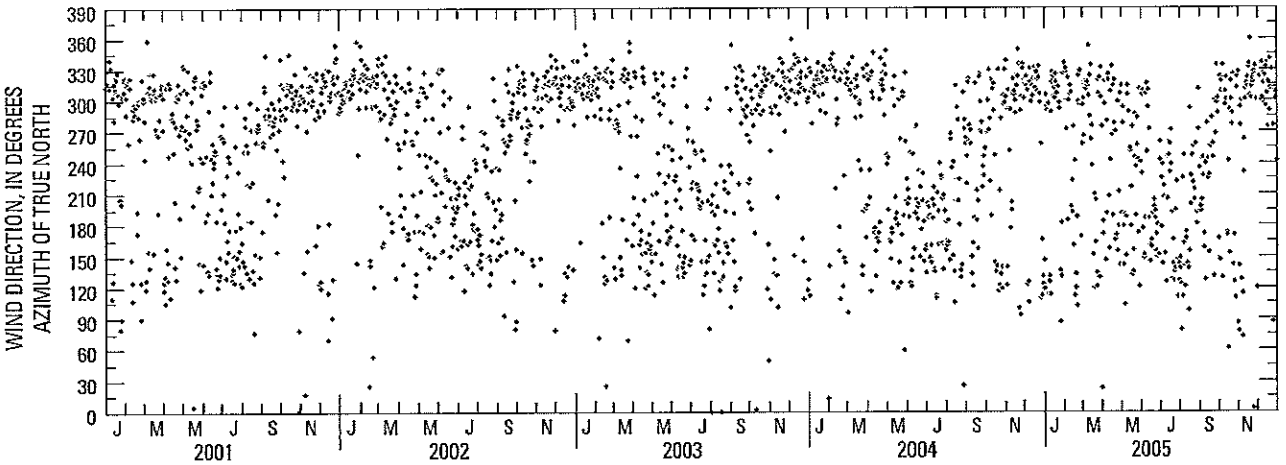


**Figure 11.** Daily mean wind-vector direction in degrees Azimuth of true north at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

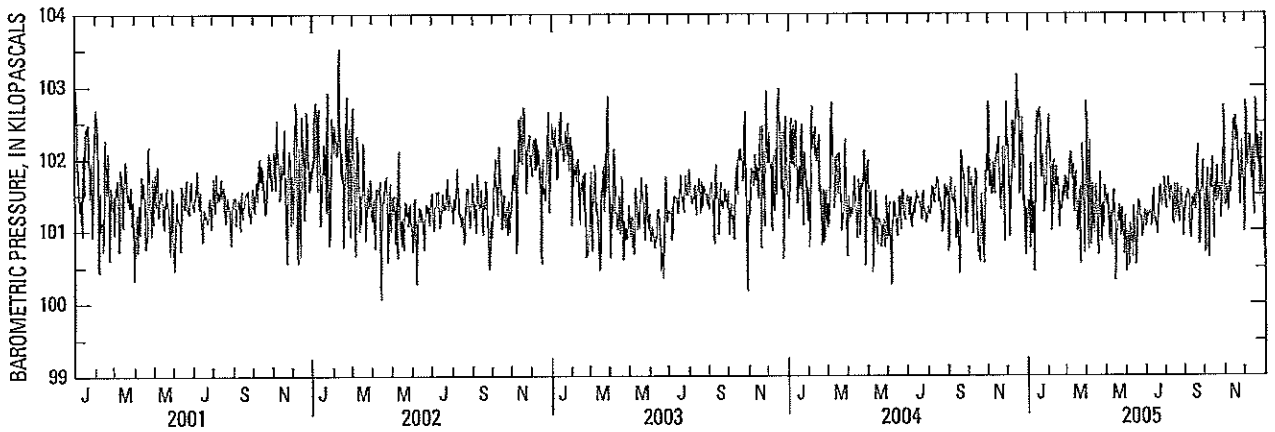


**Figure 12.** Daily mean barometric pressure from hourly averaged values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

## Precipitation

Daily total precipitation is summarized in table 2 (from appendix A), and monthly total precipitation is shown in figure 13. Hourly precipitation is listed in appendixes B–F. During the times that the tipping-bucket precipitation gage malfunctioned, precipitation volumes from the waste-facility precipitation gage adjacent to ADRS were used. These substituted volumes for individual storm events were accurately measured and only the time distribution was estimated for one to several days. The procedure for estimating daily precipitation followed technical guidelines established by the U.S. Geological Survey[1].

Total annual precipitation averaged 130.3 mm for the 5 years of record (2001–05) with measured totals of 164.8 mm in 2001, 3.5 mm in 2002, 131.8 mm in 2003, 173.6 mm in 2004, and 177.7 mm in 2005 (table 2). Based on a combination of waste-facility and ADRS precipitation records for 25 years (1981–2005), the long-term average annual precipitation was 112 mm at ADRS. Annual precipitation for the previous 20 years of record (1981–2000) averaged 108 mm (Johnson and others, 2002). Precipitation during the 5 years of record (2001–05) was about 147, 3, 117, 115, and 158 percent, respectively, of the 25-year long-term average. The low annual precipitation in 2002 was associated with a La Niña event which occurred along the eastern Pacific Ocean during that year. Winter frontal systems typically account for 70 percent of ADRS precipitation (Andraski and Stonestrom, 1999, p. 459), whereas summer storms typically account for 30 percent of precipitation. In the Amargosa Desert, the predominant winter precipitation comes from regional winter frontal systems moving in from the west coast.

[1] Collection, Quality Assurance, and Presentation of Precipitation Data: U.S. Geological Survey, Office of Surface Water Technical Memorandum, No. 2006.01, December 28, 2005, 29 p.

CALCULATION REFERENCE



**Table 2.** Daily total precipitation at Armagosa Desert Research Site near Beatty, Nevada, 2001–05.

[Values are in millimeters. No precipitation was recorded on unlisted dates]

| Date | Julian day | Daily total precipitation |
|---|---|---|
| 2001 | | |
| 01-08 | 8 | 7.62 |
| 01-10 | 10 | 1.38 |
| 01-11 | 11 | 15.13 |
| 01-26 | 26 | 8.33 |
| 01-27 | 27 | 2.08 |
| 02-12 | 43 | 14.00 |
| 02-13 | 44 | 6.32 |
| 02-25 | 56 | 9.12 |
| 02-26 | 57 | 8.15 |
| 03-06 | 65 | 7.87 |
| 04-05 | 95 | 8.57 |
| 04-07 | 97 | 0.57 |
| 04-11 | 101 | 1.27 |
| 04-21 | 111 | 6.60 |
| 05-12 | 132 | 0.25 |
| 07-06 | 187 | 32.90 |
| 07-07 | 188 | 2.66 |
| 09-03 | 246 | 18.03 |
| 10-30 | 303 | 1.02 |
| 11-12 | 316 | 5.16 |
| 11-13 | 317 | 1.19 |
| 11-24 | 328 | 2.29 |
| 12-14 | 348 | 4.32 |
| **Annual total precipitation** | | 164.8 |
| 2002 | | |
| 01-27 | 27 | 0.76 |
| 06-02 | 153 | 0.25 |
| 07-17 | 198 | 0.76 |
| 10-01 | 274 | 1.02 |
| 11-30 | 334 | 0.25 |
| 12-20 | 354 | 0.51 |
| **Annual total precipitation** | | 3.5 |
| 2003 | | |
| 02-12 | 43 | 17.27 |
| 02-24 | 55 | 0.51 |
| 02-27 | 58 | 0.76 |
| 03-15 | 74 | 4.57 |
| 2003—Continued | | |
| 04-14 | 104 | 14.73 |
| 04-22 | 112 | 1.27 |
| 05-07 | 127 | 1.52 |
| 07-28 | 209 | 1.67 |
| 07-30 | 211 | 6.03 |
| 07-31 | 212 | 14.40 |
| 08-19 | 231 | 11.18 |
| 08-21 | 233 | 7.62 |
| 08-26 | 238 | 7.62 |
| 09-02 | 245 | 5.39 |
| 09-05 | 248 | 0.45 |
| 11-12 | 316 | 12.70 |
| 11-15 | 319 | 2.79 |
| 11-16 | 320 | 8.38 |
| 12-11 | 345 | 2.03 |
| 12-25 | 359 | 10.92 |
| **Annual total precipitation** | | 131.8 |
| 2004 | | |
| 02-03 | 34 | 8.26 |
| 02-18 | 49 | 3.81 |
| 02-22 | 53 | 22.44 |
| 02-23 | 54 | 1.18 |
| 02-25 | 56 | 8.98 |
| 02-26 | 57 | 3.36 |
| 02-27 | 58 | 1.12 |
| 03-01 | 61 | 1.42 |
| 03-02 | 62 | 5.69 |
| 04-02 | 93 | 0.39 |
| 04-03 | 94 | 9.27 |
| 04-17 | 108 | 0.51 |
| 08-13 | 226 | 0.42 |
| 08-14 | 227 | 3.39 |
| 10-19 | 293 | 16.81 |
| 10-20 | 294 | 10.87 |
| 10-27 | 301 | 15.49 |
| 11-07 | 312 | 19.91 |
| 11-08 | 313 | 2.95 |
| 11-20 | 325 | 0.25 |
| 12-28 | 363 | 22.02 |
| 12-29 | 364 | 14.05 |
| 12-31 | 366 | 1.01 |
| **Annual total precipitation** | | 173.6 |
| 2005 | | |
| 01-03 | 3 | 20.43 |
| 01-04 | 4 | 4.21 |
| 01-07 | 7 | 4.57 |
| 01-08 | 8 | 1.34 |
| 01-09 | 9 | 3.34 |
| 01-10 | 10 | 1.00 |
| 01-11 | 11 | 0.67 |
| 01-25 | 25 | 1.52 |
| 01-26 | 26 | 13.80 |
| 01-27 | 27 | 2.21 |
| 01-28 | 28 | 2.40 |
| 01-29 | 29 | 0.40 |
| 02-11 | 42 | 9.06 |
| 02-12 | 43 | 0.85 |
| 02-18 | 49 | 7.64 |
| 02-19 | 50 | 2.41 |
| 02-20 | 51 | 0.20 |
| 02-21 | 52 | 13.53 |
| 02-22 | 53 | 11.05 |
| 02-23 | 54 | 11.05 |
| 02-24 | 55 | 0.51 |
| 02-26 | 57 | 1.01 |
| 03-04 | 63 | 2.79 |
| 03-22 | 81 | 1.02 |
| 03-28 | 87 | 0.25 |
| 04-28 | 118 | 2.29 |
| 05-02 | 122 | 1.27 |
| 05-06 | 126 | 0.25 |
| 07-28 | 209 | 5.33 |
| 08-04 | 216 | 3.27 |
| 08-14 | 226 | 0.56 |
| 08-15 | 227 | 1.11 |
| 08-16 | 228 | 6.96 |
| 09-20 | 263 | 31.24 |
| 10-17 | 290 | 3.30 |
| 11-10 | 314 | 4.06 |
| 11-11 | 315 | 0.76 |
| **Annual total precipitation** | | 177.7 |

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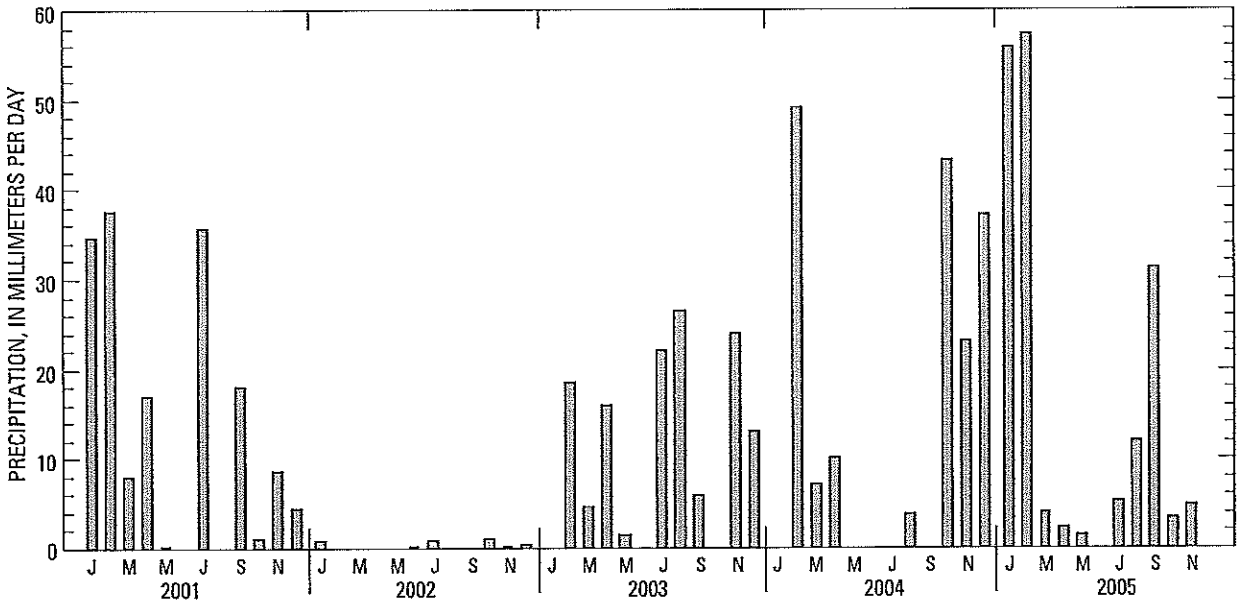


**Figure 13.** Monthly total precipitation computed from accumulated daily totals at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

However, in this desert environment, precipitation is scant and unpredictable because of the rain shadow effect of the Sierra Nevada Mountains, which similarly shadow Death Valley west of the Amargosa Desert. Summer precipitation, mainly from localized convective storms, is even more uncertain within different locations of the Amargosa Desert. Summer storms are dependent on water vapor transported into the area by southwesterly winds, which bring water vapor primarily from subtropical low-pressure systems from off the west coast of either Mexico or Southern California. Previous comparisons between the ADRS weather station and two National Oceanic and Atmospheric Administration (NOAA) sites (Wood and Andraski, 1995, p. 15) indicate monthly values also differ considerably between sites within the Amargosa Desert.

Monthly total precipitation is highly variable from year to year for a given month, and from month to month in a given year as shown in figure 13. For example, significant precipitation fell during January 2001 and 2005, but not during intervening Januarys. Other months also show monthly variability. In 2002, precipitation was minimal for the 12-month period, defining the driest year for the 25-years of record at the ADRS, although the other 4 years were wetter than normal and increased the long-term average annual precipitation.

## Near-Surface Soil Temperature, Soil-Heat Flux, and Soil-Water Content

Daily and hourly mean values of near-surface soil temperature and soil-heat flux are listed in appendixes A–F. Daily mean soil temperatures and soil-heat-flux values are shown in figures 14 and 15, respectively. The averaging soil-thermocouple probe measures the temperature in soil between the soil surface and the 8-cm depth. The soil-heat-flux plates measure thermal energy that enters or leaves the soil. As the thermal energy enters the soil and moves downward, the soil-heat flux is defined as positive, and as the thermal energy leaves the soil the soil-heat flux is defined as negative. The mean soil temperature for 5 years of record (2001–05) was 21.4°C. Daily mean soil temperatures ranged from 42.9°C on July 23, 2003, to -0.4°C on January 4, 2004 (fig. 14). The mean values of soil-heat flux for the 5 years of record were 1.3 W/m$^2$. Daily mean soil-heat flux ranged from 16.0 W/m$^2$ on July 10, 2001, to -19.0 W/m$^2$ on October 21, 2004 (fig. 15).

Daily and hourly mean values of near-surface soil-water content are listed in appendixes A–F. Daily mean values of soil-water content are shown in figure 16. The mean soil-water content for 5 years of record (2001-05) was 0.05 m$^3$/m$^3$ (5 percent). The near-surface soil-water content ranged from a low daily mean of less than 0.016 m$^3$/m$^3$ (1.6 percent) during June, July, and August 2002 to a high of about 0.31 m$^3$/m$^3$ (31 percent) on January 4, 2005 (fig. 16). Spikes in the soil-water content shown in figure 16 are indications of rain events occurring at the research site (fig. 13).

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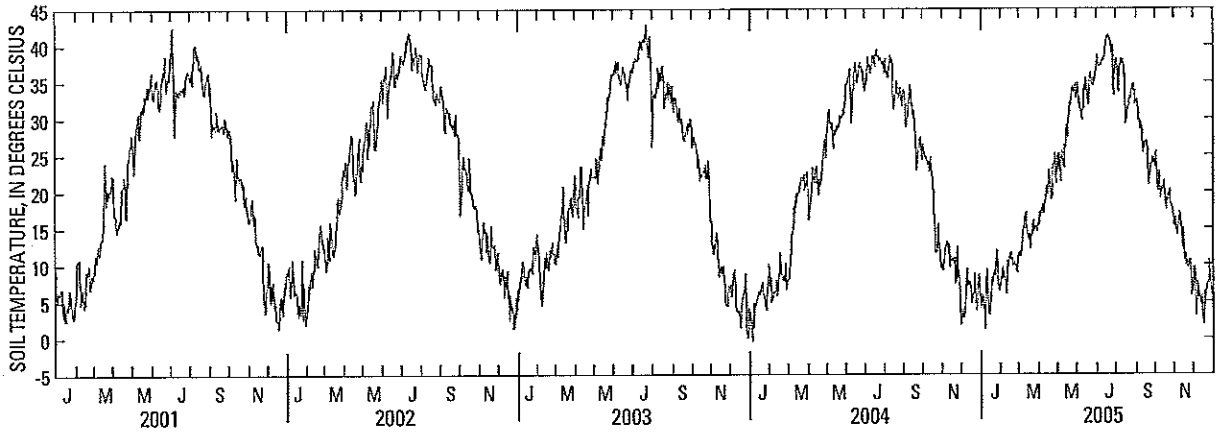


**Figure 14.** Daily mean soil temperature computed from hourly averaged values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

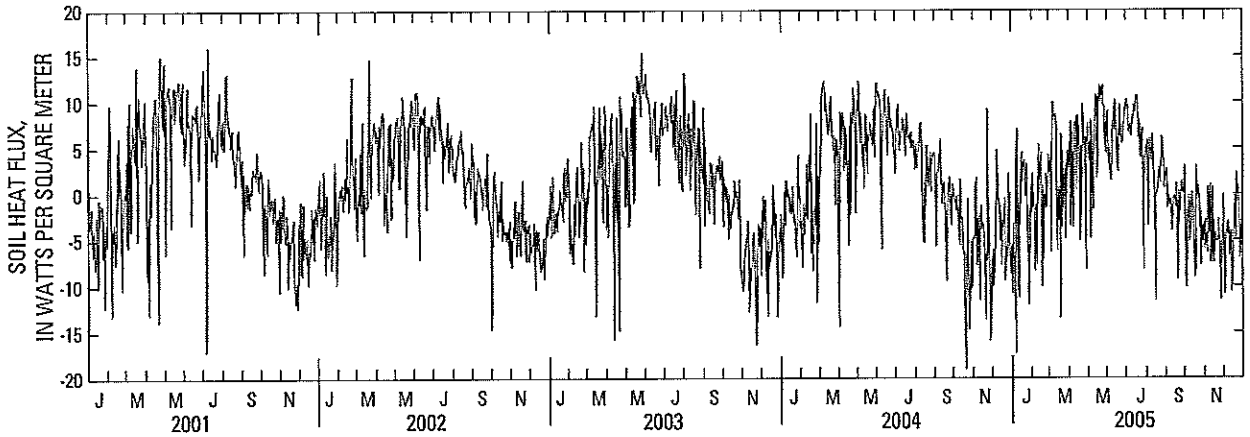


**Figure 15.** Daily mean soil-heat flux computed from hourly averaged values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

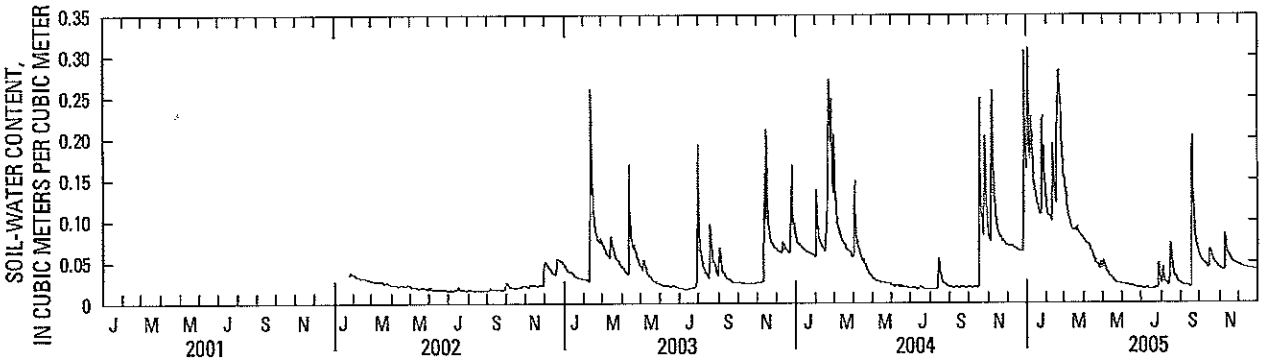


**Figure 16.** Daily mean soil-water content in upper 0.08 meters of soil computed from hourly averaged values at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

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When power availability is low, the soil-moisture probe does not operate and data loss occurs. The soil-moisture probe requires higher levels of power than the other sensors used at the weather station. Hourly averaged soil-water content values were obtained only during daytime when solar energy met power requirements (appendix B and start of appendix C). High resistance wiring and the solar panel were replaced on January 17, 2002. The new equipment enabled the batteries to meet the soil-moisture probe power requirements and continued soil-water content monitoring.

## Selected Soil-Moisture Data At Depth

At depth, soil-water content under natural-site and simulated waste-site conditions was monitored at four experimental sites: one vegetated, native soil profile; one devegetated, native soil profile; and two non-vegetated, simulated waste trenches with disturbed soil used as backfill (figs. 2 and 3). The simulated waste trenches have 208-L soil-filled drums buried at depths from 1.5 to 2.5 m and 3.5 to 4.5 m; soil-water content is not determined for these depths because of the influence of simulated waste on neutron-probe readings. Soil-water content is reported in volumetric units of cubic meter per cubic meter (volumetric water content).

Complete soil-water content data and the associated calibration equations are available in appendixes G–H. Volumetric water-content data by date and depth for each of the four experimental sites are listed in appendix G, and volumetric water-content data by date and depth for each individual neutron-probe access tube located at the experimental sites are listed in appendix H.

### Volumetric Water-Content Profiles

Variations in volumetric water content with depth were measured periodically at ADRS to define moisture levels at the different depths within the sedimentary geology and to identify temporal changes in the profile. The deepest access tube (VS2, fig. 2) at ADRS measures a vegetated native-soil profile to a depth of 29.75 m. Figure 17 shows selected water content profiles obtained during the 5-year data collection period at the vegetated, native soil profile. Within the upper 1 m of the soil profile, water content ranged from a low of about 0.02 $m^3/m^3$ to a high of about 0.12 $m^3/m^3$ as shown by profiles of August 4, 2004, and January 25, 2005, respectively. For the 5-year data set (appendix G), the average volumetric water content within the upper 1 m of soil at the vegetative native-soil profile averaged about 0.05 $m^3/m^3$. The devegetated native-soil profile and the two non-vegetated simulated waste trench sites averaged about 0.07 $m^3/m^3$ within the upper 1 m of soil. The difference in average volumetric water content between the vegetated site and the three sites without

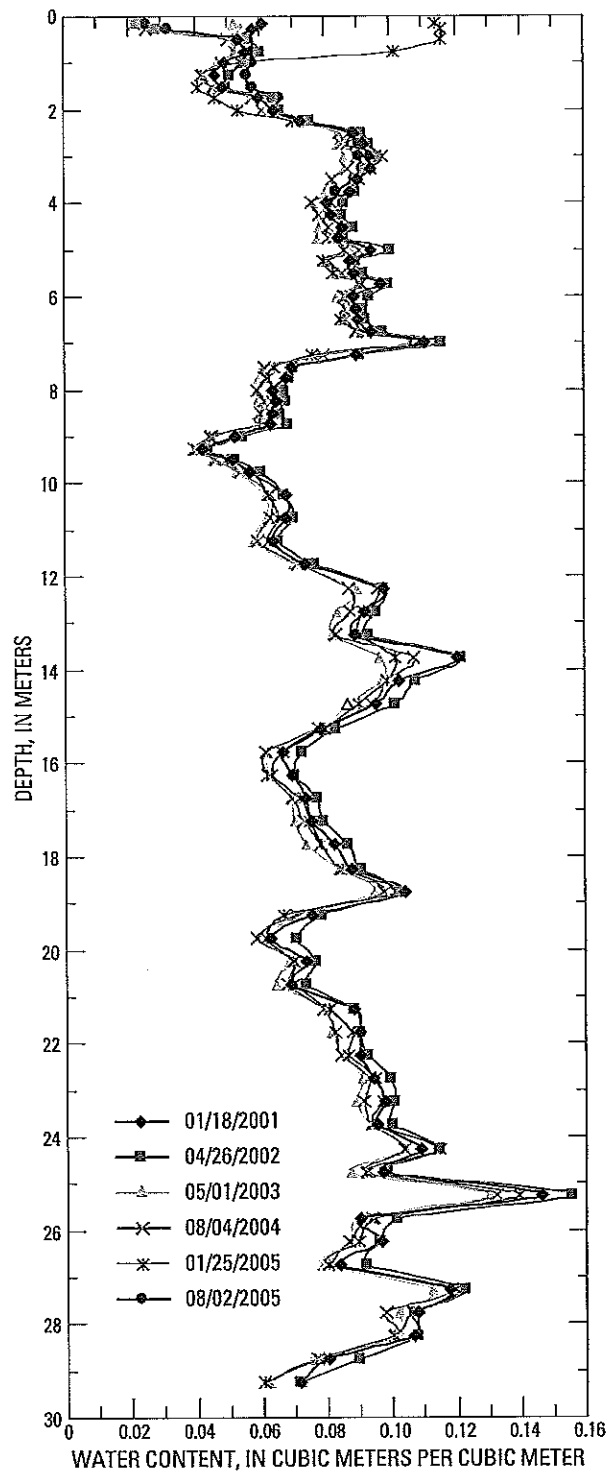


**Figure 17.** Water content variations to 30 meters below land surface for selected dates for the vegetated, native soil profile at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

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vegetation is attributed primarily to loss of root-zone soil-moisture by plant transpiration. The highest water content in the vegetated native-soil profile averaged about 0.14 $m^3/m^3$ at a depth of 25.25 m. At depth, moisture retention appears to be primarily a function of grain size within the varying basin fill. Clay lenses in sediments tend to have higher water content, whereas gravel layers have lower water content.

Figure 17 shows that temporal changes in soil moisture with depth are limited to the upper profile, generally in the upper 1 m, whereas below several meters the variation with depth reflects changes in lithology that does not appreciably change in time. Below several meters the profiles in figure 17 show profile changes of less than 0.02 $m^3/m^3$ at any given depth, and these changes are within the measurement error estimated at 0.017 $m^3/m^3$ based on calibration uncertainties (Andraski, 1997). In the upper 1 m of the soil profile, substantial moisture is derived from local rain events. Variations in soil moisture in the upper 1 m can be accounted for by the downward redistribution of water from precipitation, which infiltrates the soils after a storm event and by increased soil-water discharge by ET.

Figure 18 shows in more detail the temporal variations in soil moisture within the upper 5.5 m for each of the four experimental sites from May 2004 through August 2005. Figure 19 compares the water content between the four experimental sites at selected depths over time (2001–05).

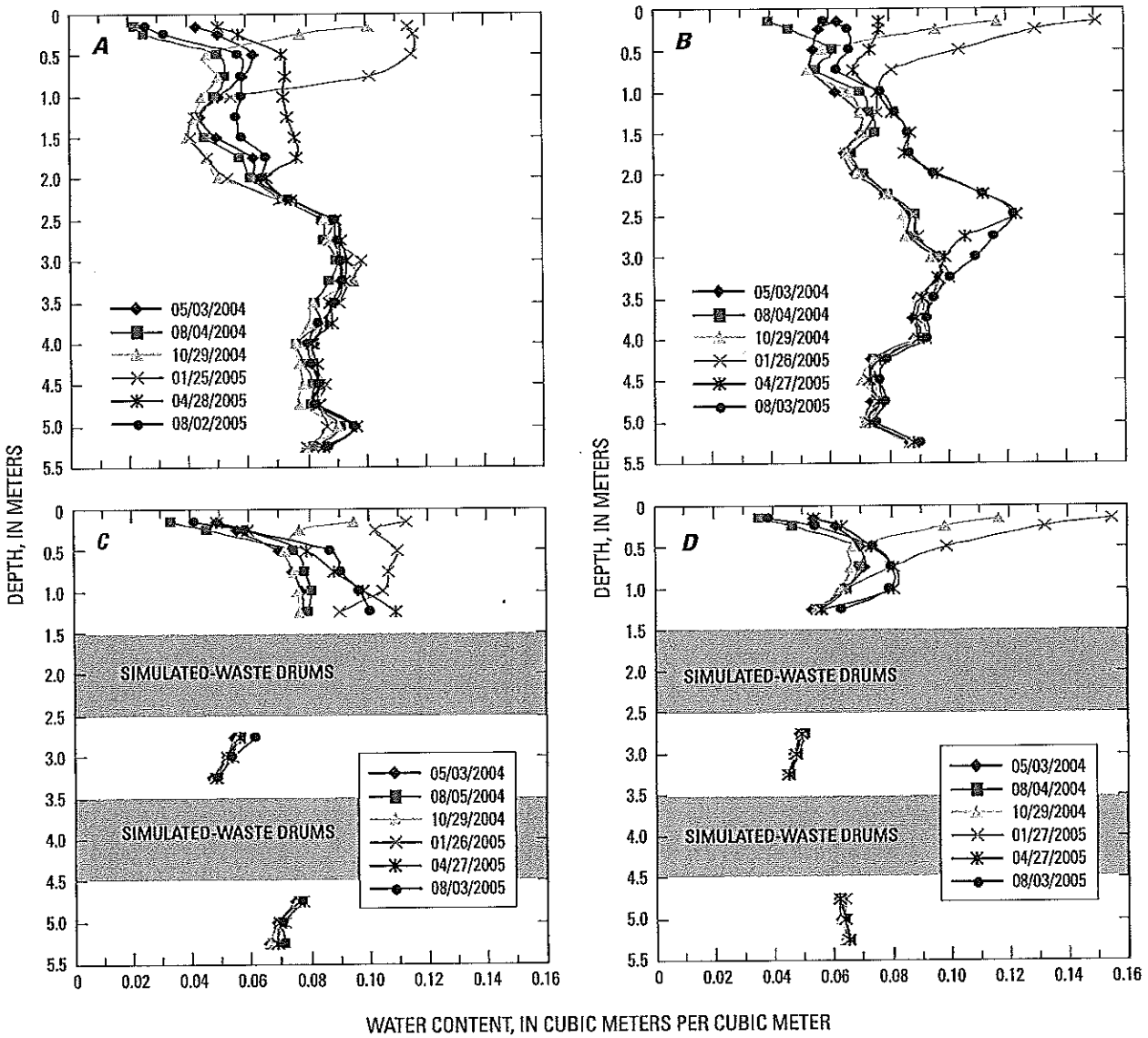


**Figure 18.** Water content variations with depth in upper 5.5 meters of soil for selected dates at four experimental sites: (*A*) vegetated, native soil profile; (*B*) devegetated, native soil profile; (*C*) non-vegetated east trench; and (*D*) non-vegetated west trench at Amargosa Desert Research Site near Beatty, Nevada, May 2004 to August 2005.

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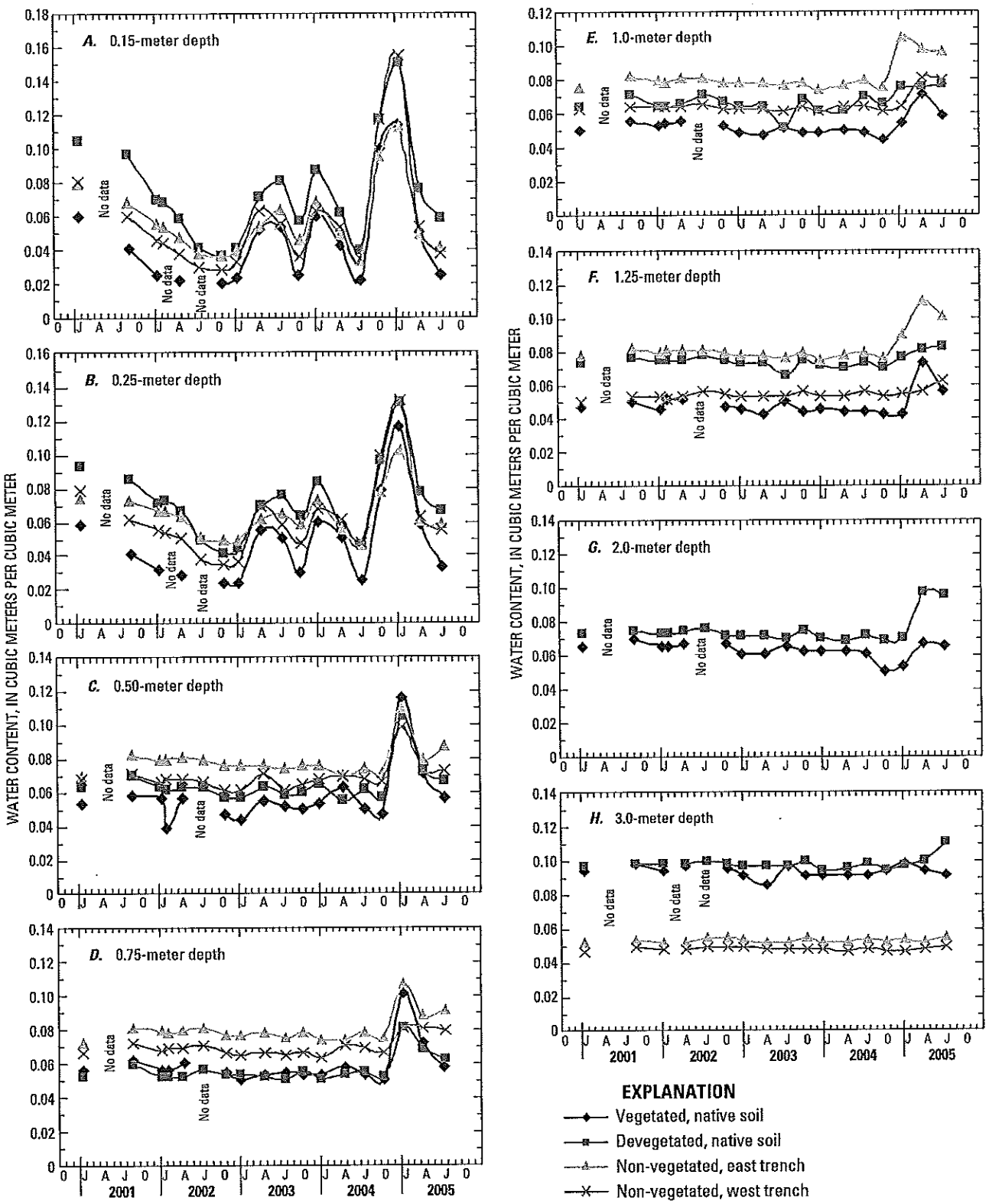


**Figure 19.** Cumulative changes in water content with time for selected depth at four experimental sites: (*A*) 0.15 –meter depth; (*B*) 0.25-meter depth; (*C*) 0.5-meter depth; (*D*) 0.75-meter depth; (*E*) 1.0-meter depth; (*F*) 1.25-meter depth; (*G*) 2.00-meter depth; and (*H*) 3.0-meter depth at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

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Significant rain events occurred during the 5 months from October 2004 through February 2005 that totaled about 217 mm of precipitation (fig. 13). These rain events are first indicated by the October 2004 profile in figure 18. All four experimental sites show measurable temporal variations in soil-water content in response to precipitation recharge in the upper 1.25 m of the soil profile. The August 2005 profile indicates that water from winter precipitation reached a depth of 2.75 m at the devegetated, native soil site (fig. 18*B*), although for the same profile at the vegetated native-soil site (fig. 18*A*), winter precipitation penetrated the soil to a depth of 1.75 m. Below these depths, downward movement of water from precipitation cannot be substantiated given that profile differences are equal to or less than the inherent uncertainty of the soil moisture measurements. The change in water content profiles from August 2004 to August 2005 at the devegetated native-soil site (fig. 18*B*) graphically illustrates the maximum recorded downward redistribution of soil moisture at the four experimental sites. This is the deepest documented temporal variation in soil-water content at the ADRS since soil moisture research began in 1983.

# Selected Evapotranspiration Data

ET data sets are available in appendixes I–M. Daily ET measurements are listed in appendix I. Appendixes J–M list the four principal energy budget components of latent-heat flux, sensible-heat flux, soil-heat flux, and net radiation during 15-minute intervals for 2002–05. Other field data, including air temperature, air-vapor pressure, soil-heat flux at individual flux plates, and soil-temperature and soil-water content above the flux plates, were collected and used to derive variable coefficients used in the calculations (appendixes J-M).

## Daily Evapotranspiration and Energy Fluxes

Daily total ET is summarized in appendix I and is shown graphically in figure 20 for 2002–05. ET data collection started on February 13, 2002. Total recorded ET was 48 mm (based on 321 days) for 2002, 148 mm for 2003, 198 mm for 2004, and 233 mm for 2005 (appendix I). ET totals for each year in this desert environment are highly variable and dependent on available moisture primarily from precipitation and precipitation-derived water stored in the upper soil profile. A much smaller component of ET is supplied by water moving upward through the deep unsaturated zone to the land surface. ET totals also can include the net effect of daily recycling of atmospheric moisture and surface dew. In addition, moisture from localized convective storms can be advectively transported by katabatic winds over the ADRS. Thus, measured ET will include moisture inputs that are not limited to just precipitation measured at the site.

ET in 2002 (fig. 20) is limited throughout the year by a lack of precipitation (fig. 13). In figure 20, daily ET spikes after a rainstorm and gradually decreases until the next rain event. Elevated ET right after a storm is derived from evaporation of surface and near-surface soil moisture that supplements the increased plant transpiration. This high rate of evaporation can last for one to several days depending on the amount of precipitation. Depending on the duration and intensity of the rain event, deeper soil-moisture percolation may occur and maintain the decreasing daily ET curve for longer periods. This more sustained daily ET is attributed primarily to loss of root-zone soil-moisture by plant transpiration.

During 2002, available soil moisture sustained daily ET of less than 0.2 mm/d during summer when there is maximum energy available for ET. In late autumn 2002, with less energy available, daily ET was estimated at less than 0.05 mm/d indicating a lower base discharge, though these values are within the measurement error. In contrast to 2002 (fig. 20), with an average daily ET of 0.15 mm/d for the period of record, ET in 2003–05 (figs. 20) averaged about 0.5 mm/d. During 2003–05, ET increased substantially due to increased precipitation at the site or in the basin near the site that introduced moisture directly or through advection. Because 2002 was an extremely low precipitation year with maximum depletion of the upper several meters of soil moisture, data from 2003 can provide a comparison of measured ET to precipitation from a water budget perspective. Average daily ET for 3 years of record (2003–05) exceeded the available precipitation measured at the site by 0.086 mm/d. On an annual basis, ET during those three years averaged about 193 mm exceeding average precipitation of 161 mm by about 32 mm. ET uncertainty, (conservatively) estimated to be about 0.05 mm/d, or on an annual basis about 18 mm, would not account for all the excess water. This excess water between ET and measured precipitation needs to be attributed to some combination of long-term, upward-moving soil moisture from depth, additional ET from advection of precipitation moisture near the site but not recorded by the precipitation gage, and measurement uncertainties.

Figures 21*A* and *B* show the change in energy budget fluxes before and after a rain event of 22.1 mm, which occurred at the end of July 2003. The results of those changes on the daily ET (fig. 20) are shown for three days before (July 25–27) and the three days after (August 1–3) the rain event of July 28–31. Prior to the rain event, there was a fairly stable but low latent-heat flux with most available energy being used as sensible-heat flux (fig. 21). Latent-heat flux is the energy used to drive the ET process and the sensible-heat flux is the energy used to heat the air. Both the latent-heat flux and the sensible-heat flux partition the total available energy (net radiation at the surface of the earth less energy used to heat the soil).

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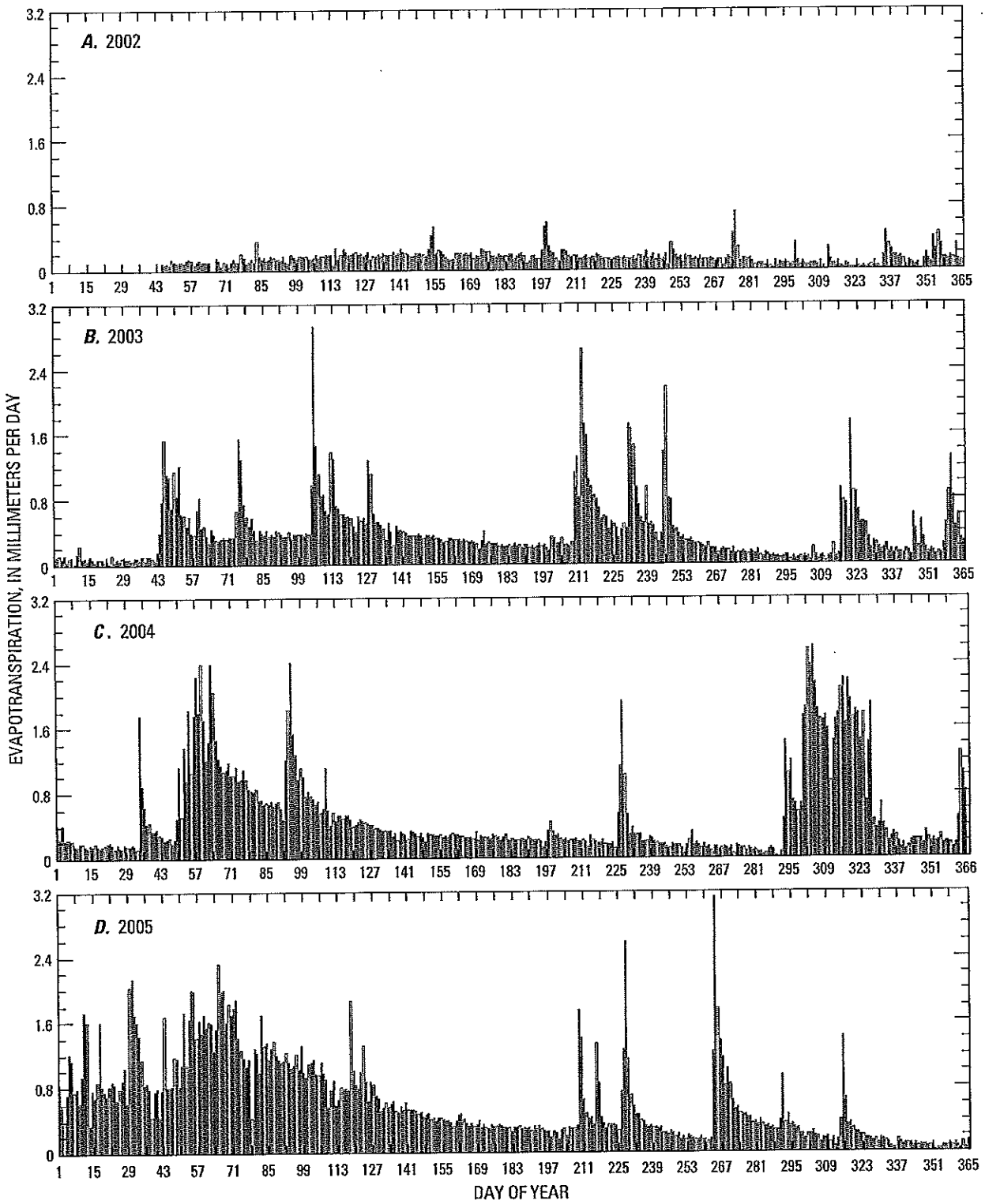


**Figure 20.** Daily evapotranspiration at the Amargosa Desert Research Site near Beatty, Nevada, 2002–05.

CALCULATION REFERENCE



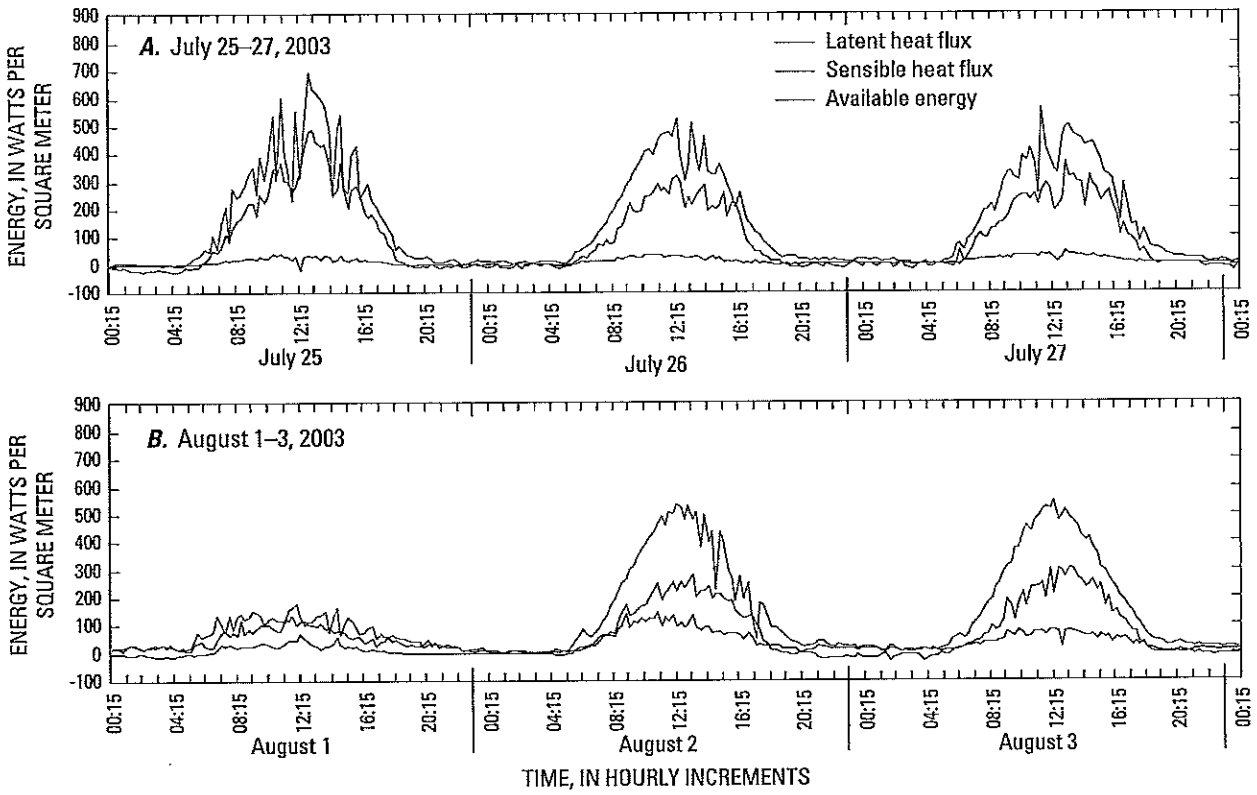


**Figure 21.** Energy fluxes 3 days before and after a rain event during July 28-31, 2003, at Amargosa Desert Research Site near Beatty, Nevada, 2003.

With little soil moisture for plant transpiration or soil evaporation, the energy used for sensible-heat flux would nearly equal the available energy. Conversely, with sufficient moisture the energy used for latent-heat flux would dominate. As shown in figure 21, under dry desert conditions (July 25-27), the latent-heat flux during mid-day is about 20 to 30 W/m$^2$, which is less than one-twelfth the sensible-heat flux, generating about 0.2 mm of daily ET (fig. 20). After the rain event, the latent-heat flux on August 1 dominates the sensible-heat flux on a cloudy day with limited available energy (fig. 21*B*). During the 3 days after the rain event (and for many days after), latent-heat flux levels were above pre-rain levels. During the 3 days, mid-day latent-heat flux decreased from about 130 to 80 W/m$^2$ and daily ET decreased from 1.7 to 1.0 mm as shown in figure 20 (for days 213, 214, and 215). The highest daily ET of about 2.6 mm (fig. 20) occurred during the last day of the rain event ending on calendar day 212 (July 31). During this day, rain ended at 1000 hours followed by clear skies with mid-day latent-heat flux energy exceeding 400 W/m$^2$, sensible-heat flux less than 130 W/m$^2$, and wet surfaces evaporating water and drying.

# Summary

Micrometeorological and soil-moisture data were collected at the Amargosa Desert Research Site facility adjacent to a low-level radioactive and hazardous-chemical waste facility near Beatty, Nevada, 2001–05. Evapotranspiration (ET) data were collected from February 14, 2002, through December 31, 2005. Data were collected in support of ongoing research to improve the understanding of hydrologic and contaminant-transport processes in arid environments.

Micrometeorological data include solar radiation, net radiation, air temperature, relative humidity, saturated and ambient vapor pressure, wind speed and direction, barometric pressure, precipitation, and near-surface soil temperature, soil-heat flux, and soil-water content. All micrometeorological data were collected using a 10-second sampling interval by data loggers that output daily and hourly mean values. Daily maximum and minimum values are based on hourly mean values. Precipitation data output included daily and hourly totals. Selected soil-moisture profiles at depth include periodic

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measurements of soil volumetric water-content measurements at nine neutron-probe access tubes to depths ranging from 5.25 to 29.25 m. ET data include measurements of daily ET and 15-minute fluxes of the four principal energy budget components of latent-heat flux, sensible-heat flux, soil-heat flux, and net radiation. Time-series data are plotted to illustrate temporal variations in micrometeorological, soil-water content, and ET data.

Total annual precipitation for 2001–05 averaged 130.3 mm with measured totals of 164.8 mm in 2001, 3.5 mm in 2002, 131.8 mm in 2003, 173.6 mm in 2004, and 177.7 mm in 2005. The 25-year (1981–2005) long-term average annual precipitation averaged 112 mm at the ADRS. The low annual precipitation in 2002 was associated with a La Niña event along the eastern Pacific Ocean. After significant winter rains that totaled 217 mm from October 2004 through February 2005, changes in soil moisture were recorded in early August 2005 to a depth of at least 2.75 m at the devegetated native-soil site and 1.25 m at the vegetated native-soil site. This is the deepest downward percolation of soil moisture documented at ADRS since investigations began in 1983. Recorded annual ET was 48 mm (based on 321 days) for 2002, 148 mm for 2003, 198 mm for 2004, and 233 mm for 2005.

ET consumes available moisture from plants and soil, and depends on precipitation to replace depleted soil moisture in this desert environment. During drought conditions, with maximum available energy during the summer months of 2002, daily ET typically was less than 0.2 mm/d. With less energy available during drought conditions in late autumn 2002, daily ET was estimated at less than 0.05 mm/d indicating a lower base discharge, although these values are within the measurement error. In contrast to 2002 (fig. 20), with an average daily ET of 0.15 mm/d for the period of record, ET in 2003–05 averaged about 0.5 mm/d. With precipitation to infiltrate soils, daily ET abruptly increased to as much as several millimeters per day and quickly decreased over several days or weeks, but maintained higher base levels of water discharge for extended periods after a storm event. Annual ET during 2003–05 exceeded precipitation measured at the site. ET in excess of precipitation may be attributed to some combination of long-term upward-moving soil moisture from depth, additional moisture inputs from dew formation and advection of unrecorded precipitation-derived moisture near the site, and measurement uncertainties.

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# Appendixes

Data files that contain the complete micrometeorological (appendixes A–F), soil-moisture (appendixes G and H), and ET (appendixes I–M) field data sets are presented in 13 Microsoft© Excel spreadsheets. The appendixes can be accessed and downloaded at URL http://pubs.water.usgs.gov/ds284/.

**Appendix A.** Summary of Daily Mean Micrometeorological Data Collected at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

**Appendix B.** Summary of Hourly Mean Micrometeorological Data Collected at Amargosa Desert Research Site near Beatty, Nevada, 2001.

**Appendix C.** Summary of Hourly Mean Micrometeorological Data Collected at Amargosa Desert Research Site near Beatty, Nevada, 2002.

**Appendix D.** Summary of Hourly Mean Micrometeorological Data Collected at Amargosa Desert Research Site near Beatty, Nevada, 2003.

**Appendix E.** Summary of Hourly Mean Micrometeorological Data Collected at Amargosa Desert Research Site near Beatty, Nevada, 2004.

**Appendix F.** Summary of Hourly Mean Micrometeorological Data Collected at Amargosa Desert Research Site near Beatty, Nevada, 2005.

**Appendix G.** Volumetric Water-Content Data at Depth for Each Experimental Site at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

**Appendix H.** Volumetric Water-Content at Depth for Each Neutron-Probe Access Tube at Amargosa Desert Research Site near Beatty, Nevada, 2001–05.

**Appendix I.** Daily Evapotranspiration Rates at Amargosa Desert Research Site near Beatty, Nevada, 2002–05.

**Appendix J.** 15-minute Evapotranspiration Data—Energy Flux Rates and Other Field Data Parameters at Amargosa Desert Research Site near Beatty, Nevada, 2002.

**Appendix K.** 15-minute Evapotranspiration Data—Energy Flux Rates and Other Field Data Parameters at Amargosa Desert Research Site near Beatty, Nevada, 2003.

**Appendix L.** 15-minute Evapotranspiration Data—Energy Flux Rates and Other Field Data Parameters at Amargosa Desert Research Site near Beatty, Nevada, 2004.

**Appendix M.** 15-minute Evapotranspiration Data—Energy Flux Rates and Other Field Data Parameters at Amargosa Desert Research Site near Beatty, Nevada, 2005.

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Director, Nevada Water Science Center
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2730 N. Deer Run Road
Carson City, Nevada 89701
http://nevada.usgs.gov

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Johnson and Others—**Micrometeorological, Soil-Moisture, and ET Data at Amargosa Desert Research Site, Nye County, Nevada, 2001–05**—Data Series 284

# UNSAT-H

## Model Output

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 20-DEC-**
Time of Run: 19: 5:18
Title: Beatty-36inch-year1

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 9.000E+03 | 0.0527 | 0.00 | 2 | 1.000E-01 | 9.000E+03 | 0.0527 | 0.00 |
| 3 | 3.000E-01 | 9.000E+03 | 0.0527 | 0.00 | 4 | 8.000E-01 | 9.000E+03 | 0.0527 | 0.00 |
| 5 | 1.000E+00 | 9.000E+03 | 0.0527 | 0.00 | 6 | 2.000E+00 | 9.000E+03 | 0.0527 | 0.00 |
| 7 | 5.000E+00 | 9.000E+03 | 0.0527 | 0.00 | 8 | 1.000E+01 | 9.000E+03 | 0.0527 | 0.00 |
| 9 | 2.000E+01 | 9.000E+03 | 0.0527 | 0.00 | 10 | 3.500E+01 | 9.000E+03 | 0.0527 | 0.00 |
| 11 | 5.000E+01 | 9.000E+03 | 0.0527 | 0.00 | 12 | 6.000E+01 | 9.000E+03 | 0.0527 | 0.00 |
| 13 | 7.500E+01 | 9.000E+03 | 0.0527 | 0.00 | 14 | 8.500E+01 | 9.000E+03 | 0.0527 | 0.00 |
| 15 | 9.000E+01 | 9.000E+03 | 0.0527 | 0.00 | 16 | 9.100E+01 | 9.000E+03 | 0.0527 | 0.00 |
| 17 | 9.200E+01 | 9.000E+03 | 0.0527 | 0.00 | | | | | |

Initial Water Storage = 4.8482 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.2049E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8542E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 4.5559E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9256E+00 | [cm] |
| Mass Balance Error | = | -4.5336E-01 | [cm] |
| Total Successful Time Steps | = | 16598981 | |
| Total Attempted Time Steps | = | 16598981 | |
| Total Time Step Reductions (DHMAX) | = | 11598 | |
| Total Changes in Surface Boundary | = | 14622418 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -1.3304E+00 | 0.050 | -1.2041E+00 | 0.200 | -1.1731E+00 |
| 0.550 | -1.1727E+00 | 0.900 | -1.1649E+00 | 1.500 | -1.1507E+00 |
| 3.500 | -1.1039E+00 | 7.500 | -1.0149E+00 | 15.000 | -8.7107E-01 |
| 27.500 | -6.8264E-01 | 42.500 | -4.8638E-01 | 55.000 | -3.3413E-01 |
| 67.500 | -1.9102E-01 | 80.000 | -6.9848E-02 | 87.500 | 2.2052E-03 |
| 90.500 | 3.1056E-02 | 91.500 | 4.0698E-02 | 92.000 | 4.5559E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 20-DEC-**
Time of Run: 19:25:43
Title: Beatty-36inch-year2

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|---|---|---|---|---|---|---|---|---|---|
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| 3 | 3.000E-01 | 1.910E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.684E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.604E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.261E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.816E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.280E+05 | 0.0348 | 0.00 |
| 9 | 2.000E+01 | 4.290E+04 | 0.0399 | 0.00 | 10 | 3.500E+01 | 2.521E+04 | 0.0433 | 0.00 |
| 11 | 5.000E+01 | 1.961E+04 | 0.0453 | 0.00 | 12 | 6.000E+01 | 1.773E+04 | 0.0461 | 0.00 |
| 13 | 7.500E+01 | 1.624E+04 | 0.0468 | 0.00 | 14 | 8.500E+01 | 1.581E+04 | 0.0471 | 0.00 |
| 15 | 9.000E+01 | 1.573E+04 | 0.0471 | 0.00 | 16 | 9.100E+01 | 1.573E+04 | 0.0471 | 0.00 |
| 17 | 9.200E+01 | 1.572E+04 | 0.0471 | 0.00 | | | | | |

Initial Water Storage = 3.9256 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1158E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8544E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.0378E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9159E+00 | [cm] |
| Mass Balance Error | = | -4.6029E-01 | [cm] |
| Total Successful Time Steps | = | 17026932 | |
| Total Attempted Time Steps | = | 17026932 | |
| Total Time Step Reductions (DHMAX) | = | 11611 | |
| Total Changes in Surface Boundary | = | 15067244 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -4.3964E-01 | 0.050 | -3.1416E-01 | 0.200 | -2.8671E-01 |
| 0.550 | -2.9532E-01 | 0.900 | -2.9578E-01 | 1.500 | -2.9580E-01 |
| 3.500 | -2.9576E-01 | 7.500 | -2.9522E-01 | 15.000 | -2.8544E-01 |
| 27.500 | -2.5728E-01 | 42.500 | -2.0424E-01 | 55.000 | -1.4536E-01 |
| 67.500 | -8.2745E-02 | 80.000 | -2.5879E-02 | 87.500 | 8.6992E-03 |
| 90.500 | 2.3010E-02 | 91.500 | 2.7898E-02 | 92.000 | 3.0378E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 20-DEC-**
Time of Run: 23:28:15
Title: 36-inch Year3

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.013E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.688E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.609E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.268E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.919E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.317E+05 | 0.0347 | 0.00 |
| 9 | 2.000E+01 | 4.363E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.559E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.989E+04 | 0.0451 | 0.00 | 12 | 6.000E+01 | 1.798E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.647E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.604E+04 | 0.0469 | 0.00 |
| 15 | 9.000E+01 | 1.596E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.595E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.595E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9159 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9882E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.8336E-08 | [cm] |
| Total Infiltration | = | 1.9562E+01 | [cm] |
| Total Drainage at Base of Profile | = | 1.9734E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9877E+00 | [cm] |
| Mass Balance Error | = | -5.8830E-01 | [cm] |
| Total Successful Time Steps | = | 17383668 | |
| Total Attempted Time Steps | = | 17383669 | |
| Total Time Step Reductions (DHMAX) | = | 11403 | |
| Total Changes in Surface Boundary | = | 14243641 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -3.1916E-01 | 0.050 | -1.0474E-01 | 0.200 | -4.3564E-02 |
| 0.550 | -4.8754E-02 | 0.900 | -4.9262E-02 | 1.500 | -4.9394E-02 |
| 3.500 | -4.9823E-02 | 7.500 | -5.1316E-02 | 15.000 | -5.2072E-02 |
| 27.500 | -3.6995E-02 | 42.500 | -4.3780E-03 | 55.000 | 3.2140E-02 |
| 67.500 | 7.7552E-02 | 80.000 | 1.3332E-01 | 87.500 | 1.7264E-01 |
| 90.500 | 1.8904E-01 | 91.500 | 1.9456E-01 | 92.000 | 1.9734E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 20-DEC-**
Time of Run: 23:51:31
Title: 36-inch Year4

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.473E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.093E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.730E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.056E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.875E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.311E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.802E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.629E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.489E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.449E+04 | 0.0479 | 0.00 |
| 15 | 9.000E+01 | 1.441E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.441E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.441E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9877 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9946E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.8348E-08 | [cm] |
| Total Infiltration | = | 1.9562E+01 | [cm] |
| Total Drainage at Base of Profile | = | 2.0289E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9878E+00 | [cm] |
| Mass Balance Error | = | -5.8737E-01 | [cm] |
| Total Successful Time Steps | = | 17346488 | |
| Total Attempted Time Steps | = | 17346489 | |
| Total Time Step Reductions (DHMAX) | = | 11408 | |
| Total Changes in Surface Boundary | = | 14216369 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -3.8442E-01 | 0.050 | -1.6997E-01 | 0.200 | -1.0878E-01 |
| 0.550 | -1.1389E-01 | 0.900 | -1.1435E-01 | 1.500 | -1.1437E-01 |
| 3.500 | -1.1431E-01 | 7.500 | -1.1402E-01 | 15.000 | -1.0790E-01 |
| 27.500 | -8.4240E-02 | 42.500 | -4.0152E-02 | 55.000 | 6.6463E-03 |
| 67.500 | 6.3227E-02 | 80.000 | 1.2941E-01 | 87.500 | 1.7465E-01 |
| 90.500 | 1.9337E-01 | 91.500 | 1.9972E-01 | 92.000 | 2.0289E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 21-DEC-**
Time of Run: 0:23:38
Title: Beatty-36inch-year5

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.473E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.093E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.729E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.055E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.874E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.311E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.801E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.629E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.489E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.449E+04 | 0.0479 | 0.00 |
| 15 | 9.000E+01 | 1.441E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.441E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.441E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9878 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1222E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8546E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.1857E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9173E+00 | [cm] |
| Mass Balance Error | = | -4.6480E-01 | [cm] |
| Total Successful Time Steps | = | 16988235 | |
| Total Attempted Time Steps | = | 16988235 | |
| Total Time Step Reductions (DHMAX) | = | 11601 | |
| Total Changes in Surface Boundary | = | 15027985 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -5.0345E-01 | 0.050 | -3.7797E-01 | 0.200 | -3.5050E-01 |
| 0.550 | -3.5899E-01 | 0.900 | -3.5939E-01 | 1.500 | -3.5931E-01 |
| 3.500 | -3.5881E-01 | 7.500 | -3.5653E-01 | 15.000 | -3.4094E-01 |
| 27.500 | -3.0530E-01 | 42.500 | -2.4126E-01 | 55.000 | -1.7357E-01 |
| 67.500 | -1.0113E-01 | 80.000 | -3.3666E-02 | 87.500 | 6.7005E-03 |
| 90.500 | 2.3413E-02 | 91.500 | 2.9022E-02 | 92.000 | 3.1857E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 21-DEC-**
Time of Run: 0:47:10
Title: Beatty-36inch-year6

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.012E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.688E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.608E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.267E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.904E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.312E+05 | 0.0347 | 0.00 |
| 9 | 2.000E+01 | 4.352E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.553E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.985E+04 | 0.0452 | 0.00 | 12 | 6.000E+01 | 1.795E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.644E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.600E+04 | 0.0470 | 0.00 |
| 15 | 9.000E+01 | 1.592E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.592E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.591E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9173 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.4406E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.7624E+02 | [cm] |
| Actual Evaporation | = | 1.2463E+00 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 5.9996E-13 | [cm] |
| Total Infiltration | = | 3.5560E-01 | [cm] |
| Total Drainage at Base of Profile | = | 1.7576E-03 | [cm] |
| Total Applied Water | = | 3.5560E-01 | [cm] |
| Actual Rainfall | = | 3.5560E-01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.2825E+00 | [cm] |
| Mass Balance Error | = | -2.5777E-01 | [cm] |
| Total Successful Time Steps | = | 18064949 | |
| Total Attempted Time Steps | = | 18064949 | |
| Total Time Step Reductions (DHMAX) | = | 11212 | |
| Total Changes in Surface Boundary | = | 17451445 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -8.9075E-01 | 0.050 | -8.9079E-01 | 0.200 | -8.9088E-01 |
| 0.550 | -8.9112E-01 | 0.900 | -8.9133E-01 | 1.500 | -8.9167E-01 |
| 3.500 | -8.9251E-01 | 7.500 | -8.9122E-01 | 15.000 | -8.6337E-01 |
| 27.500 | -7.5212E-01 | 42.500 | -5.8328E-01 | 55.000 | -4.3686E-01 |
| 67.500 | -2.9045E-01 | 80.000 | -1.4149E-01 | 87.500 | -5.2078E-02 |
| 90.500 | -1.6200E-02 | 91.500 | -4.2667E-03 | 92.000 | 1.7576E-03 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 21-DEC-**
Time of Run: 7:44:52
Title: 36-inch Year7

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.180E+06 | 0.0294 | 0.00 | 2 | 1.000E-01 | 1.167E+06 | 0.0295 | 0.00 |
| 3 | 3.000E-01 | 1.142E+06 | 0.0295 | 0.00 | 4 | 8.000E-01 | 1.082E+06 | 0.0296 | 0.00 |
| 5 | 1.000E+00 | 1.059E+06 | 0.0296 | 0.00 | 6 | 2.000E+00 | 9.494E+05 | 0.0298 | 0.00 |
| 7 | 5.000E+00 | 6.832E+05 | 0.0303 | 0.00 | 8 | 1.000E+01 | 4.262E+05 | 0.0313 | 0.00 |
| 9 | 2.000E+01 | 2.512E+05 | 0.0326 | 0.00 | 10 | 3.500E+01 | 1.157E+05 | 0.0351 | 0.00 |
| 11 | 5.000E+01 | 7.278E+04 | 0.0371 | 0.00 | 12 | 6.000E+01 | 6.141E+04 | 0.0379 | 0.00 |
| 13 | 7.500E+01 | 5.305E+04 | 0.0387 | 0.00 | 14 | 8.500E+01 | 5.083E+04 | 0.0389 | 0.00 |
| 15 | 9.000E+01 | 5.043E+04 | 0.0389 | 0.00 | 16 | 9.100E+01 | 5.040E+04 | 0.0390 | 0.00 |
| 17 | 9.200E+01 | 5.039E+04 | 0.0390 | 0.00 | | | | | |

Initial Water Storage = 3.2825 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9274E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.3157E-08 | [cm] |
| Total Infiltration | = | 1.9564E+01 | [cm] |
| Total Drainage at Base of Profile | = | 1.4664E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9866E+00 | [cm] |
| Mass Balance Error | = | -5.6030E-01 | [cm] |
| Total Successful Time Steps | = | 17665215 | |
| Total Attempted Time Steps | = | 17665217 | |
| Total Time Step Reductions (DHMAX) | = | 11480 | |
| Total Changes in Surface Boundary | = | 14473058 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | 2.9041E-01 | 0.050 | 5.0492E-01 | 0.200 | 5.6631E-01 |
| 0.550 | 5.6128E-01 | 0.900 | 5.6098E-01 | 1.500 | 5.6119E-01 |
| 3.500 | 5.6166E-01 | 7.500 | 5.5902E-01 | 15.000 | 5.3416E-01 |
| 27.500 | 4.5778E-01 | 42.500 | 3.5707E-01 | 55.000 | 2.8749E-01 |
| 67.500 | 2.2800E-01 | 80.000 | 1.8485E-01 | 87.500 | 1.5958E-01 |
| 90.500 | 1.5081E-01 | 91.500 | 1.4803E-01 | 92.000 | 1.4664E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 21-DEC-**
Time of Run: 8: 7:21
Title: 36-inch Year8

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.474E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.094E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.742E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.059E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.882E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.315E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.804E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.631E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.491E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.451E+04 | 0.0478 | 0.00 |
| 15 | 9.000E+01 | 1.444E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.443E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.443E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9866 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9945E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.8351E-08 | [cm] |
| Total Infiltration | = | 1.9562E+01 | [cm] |
| Total Drainage at Base of Profile | = | 2.0280E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9878E+00 | [cm] |
| Mass Balance Error | = | -5.8734E-01 | [cm] |
| Total Successful Time Steps | = | 17345931 | |
| Total Attempted Time Steps | = | 17345932 | |
| Total Time Step Reductions (DHMAX) | = | 11408 | |
| Total Changes in Surface Boundary | = | 14216430 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -3.8338E-01 | 0.050 | -1.6893E-01 | 0.200 | -1.0774E-01 |
| 0.550 | -1.1286E-01 | 0.900 | -1.1331E-01 | 1.500 | -1.1334E-01 |
| 3.500 | -1.1328E-01 | 7.500 | -1.1300E-01 | 15.000 | -1.0727E-01 |
| 27.500 | -8.3778E-02 | 42.500 | -3.9720E-02 | 55.000 | 6.9123E-03 |
| 67.500 | 6.3642E-02 | 80.000 | 1.2947E-01 | 87.500 | 1.7468E-01 |
| 90.500 | 1.9324E-01 | 91.500 | 1.9965E-01 | 92.000 | 2.0280E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 21-DEC-**
Time of Run: 8:29: 8
Title: Beatty-36inch-year9

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.473E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.093E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.729E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.055E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.874E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.311E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.801E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.629E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.489E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.449E+04 | 0.0479 | 0.00 |
| 15 | 9.000E+01 | 1.441E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.441E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.441E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9878 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1222E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8546E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.1857E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9173E+00 | [cm] |
| Mass Balance Error | = | -4.6480E-01 | [cm] |
| Total Successful Time Steps | = | 16988235 | |
| Total Attempted Time Steps | = | 16988235 | |
| Total Time Step Reductions (DHMAX) | = | 11601 | |
| Total Changes in Surface Boundary | = | 15027985 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -5.0345E-01 | 0.050 | -3.7797E-01 | 0.200 | -3.5050E-01 |
| 0.550 | -3.5899E-01 | 0.900 | -3.5939E-01 | 1.500 | -3.5931E-01 |
| 3.500 | -3.5881E-01 | 7.500 | -3.5653E-01 | 15.000 | -3.4094E-01 |
| 27.500 | -3.0530E-01 | 42.500 | -2.4126E-01 | 55.000 | -1.7357E-01 |
| 67.500 | -1.0113E-01 | 80.000 | -3.3666E-02 | 87.500 | 6.7005E-03 |
| 90.500 | 2.3413E-02 | 91.500 | 2.9022E-02 | 92.000 | 3.1857E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 21-DEC-**
Time of Run: 8:50:26
Title: Beatty-36inch-year10

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.012E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.688E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.608E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.267E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.904E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.312E+05 | 0.0347 | 0.00 |
| 9 | 2.000E+01 | 4.352E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.553E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.985E+04 | 0.0452 | 0.00 | 12 | 6.000E+01 | 1.795E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.644E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.600E+04 | 0.0470 | 0.00 |
| 15 | 9.000E+01 | 1.592E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.592E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.591E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9173 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1150E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8544E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.0160E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9157E+00 | [cm] |
| Mass Balance Error | = | -4.5961E-01 | [cm] |
| Total Successful Time Steps | = | 17038507 | |
| Total Attempted Time Steps | = | 17038507 | |
| Total Time Step Reductions (DHMAX) | = | 11605 | |
| Total Changes in Surface Boundary | = | 15072134 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -4.3105E-01 | 0.050 | -3.0557E-01 | 0.200 | -2.7812E-01 |
| 0.550 | -2.8674E-01 | 0.900 | -2.8719E-01 | 1.500 | -2.8722E-01 |
| 3.500 | -2.8720E-01 | 7.500 | -2.8678E-01 | 15.000 | -2.7765E-01 |
| 27.500 | -2.5064E-01 | 42.500 | -1.9884E-01 | 55.000 | -1.4110E-01 |
| 67.500 | -8.0045E-02 | 80.000 | -2.4358E-02 | 87.500 | 8.9869E-03 |
| 90.500 | 2.2998E-02 | 91.500 | 2.7756E-02 | 92.000 | 3.0160E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 8-JAN-**
Time of Run: 14:49:30
Title: Beatty-36inch-year11

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.013E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.689E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.609E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.268E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.921E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.319E+05 | 0.0346 | 0.00 |
| 9 | 2.000E+01 | 4.365E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.560E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.989E+04 | 0.0451 | 0.00 | 12 | 6.000E+01 | 1.799E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.647E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.604E+04 | 0.0469 | 0.00 |
| 15 | 9.000E+01 | 1.596E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.596E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.596E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9157 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1148E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8541E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.0122E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9157E+00 | [cm] |
| Mass Balance Error | = | -4.5954E-01 | [cm] |
| Total Successful Time Steps | = | 17038430 | |
| Total Attempted Time Steps | = | 17038430 | |
| Total Time Step Reductions (DHMAX) | = | 11607 | |
| Total Changes in Surface Boundary | = | 15075482 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -4.2942E-01 | 0.050 | -3.0393E-01 | 0.200 | -2.7648E-01 |
| 0.550 | -2.8510E-01 | 0.900 | -2.8556E-01 | 1.500 | -2.8559E-01 |
| 3.500 | -2.8557E-01 | 7.500 | -2.8514E-01 | 15.000 | -2.7616E-01 |
| 27.500 | -2.4932E-01 | 42.500 | -1.9767E-01 | 55.000 | -1.4017E-01 |
| 67.500 | -7.9334E-02 | 80.000 | -2.3756E-02 | 87.500 | 9.1755E-03 |
| 90.500 | 2.3103E-02 | 91.500 | 2.7733E-02 | 92.000 | 3.0122E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 8-JAN-**
Time of Run: 15:22:39
Title: Beatty-36inch-year12

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.013E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.689E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.609E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.268E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.921E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.318E+05 | 0.0346 | 0.00 |
| 9 | 2.000E+01 | 4.365E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.560E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.989E+04 | 0.0451 | 0.00 | 12 | 6.000E+01 | 1.799E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.647E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.604E+04 | 0.0469 | 0.00 |
| 15 | 9.000E+01 | 1.596E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.596E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.596E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9157 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1148E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8541E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.0122E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9157E+00 | [cm] |
| Mass Balance Error | = | -4.5954E-01 | [cm] |
| Total Successful Time Steps | = | 17038439 | |
| Total Attempted Time Steps | = | 17038439 | |
| Total Time Step Reductions (DHMAX) | = | 11607 | |
| Total Changes in Surface Boundary | = | 15075483 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -4.2942E-01 | 0.050 | -3.0393E-01 | 0.200 | -2.7648E-01 |
| 0.550 | -2.8510E-01 | 0.900 | -2.8556E-01 | 1.500 | -2.8559E-01 |
| 3.500 | -2.8557E-01 | 7.500 | -2.8514E-01 | 15.000 | -2.7616E-01 |
| 27.500 | -2.4932E-01 | 42.500 | -1.9767E-01 | 55.000 | -1.4017E-01 |
| 67.500 | -7.9335E-02 | 80.000 | -2.3756E-02 | 87.500 | 9.1755E-03 |
| 90.500 | 2.3104E-02 | 91.500 | 2.7734E-02 | 92.000 | 3.0122E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 8-JAN-**
Time of Run: 15:55:32
Title: 36-inch Year13

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.013E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.689E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.609E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.268E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.921E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.318E+05 | 0.0346 | 0.00 |
| 9 | 2.000E+01 | 4.365E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.560E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.989E+04 | 0.0451 | 0.00 | 12 | 6.000E+01 | 1.799E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.647E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.604E+04 | 0.0469 | 0.00 |
| 15 | 9.000E+01 | 1.596E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.596E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.596E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9157 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9882E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.8336E-08 | [cm] |
| Total Infiltration | = | 1.9562E+01 | [cm] |
| Total Drainage at Base of Profile | = | 1.9734E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9877E+00 | [cm] |
| Mass Balance Error | = | -5.8850E-01 | [cm] |
| Total Successful Time Steps | = | 17384855 | |
| Total Attempted Time Steps | = | 17384856 | |
| Total Time Step Reductions (DHMAX) | = | 11403 | |
| Total Changes in Surface Boundary | = | 14244812 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -3.1913E-01 | 0.050 | -1.0471E-01 | 0.200 | -4.3535E-02 |
| 0.550 | -4.8724E-02 | 0.900 | -4.9234E-02 | 1.500 | -4.9364E-02 |
| 3.500 | -4.9792E-02 | 7.500 | -5.1289E-02 | 15.000 | -5.2032E-02 |
| 27.500 | -3.7010E-02 | 42.500 | -4.3973E-03 | 55.000 | 3.2078E-02 |
| 67.500 | 7.7532E-02 | 80.000 | 1.3334E-01 | 87.500 | 1.7265E-01 |
| 90.500 | 1.8904E-01 | 91.500 | 1.9457E-01 | 92.000 | 1.9734E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 9-JAN-**
Time of Run: 8:51:37
Title: 36-inch Year14

| | | Initial Conditions | | | | | Initial Conditions | | |
|---|---|---|---|---|---|---|---|---|---|
| NODE | DEPTH (cm) | HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | HEAD (cm) | THETA (vol.) | TEMP (K) |
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.473E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.093E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.730E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.056E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.875E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.311E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.802E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.629E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.489E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.449E+04 | 0.0479 | 0.00 |
| 15 | 9.000E+01 | 1.441E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.441E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.441E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9877 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9946E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.8348E-08 | [cm] |
| Total Infiltration | = | 1.9562E+01 | [cm] |
| Total Drainage at Base of Profile | = | 2.0289E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9878E+00 | [cm] |
| Mass Balance Error | = | -5.8737E-01 | [cm] |
| Total Successful Time Steps | = | 17346488 | |
| Total Attempted Time Steps | = | 17346489 | |
| Total Time Step Reductions (DHMAX) | = | 11408 | |
| Total Changes in Surface Boundary | = | 14216369 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -3.8442E-01 | 0.050 | -1.6997E-01 | 0.200 | -1.0878E-01 |
| 0.550 | -1.1389E-01 | 0.900 | -1.1435E-01 | 1.500 | -1.1437E-01 |
| 3.500 | -1.1431E-01 | 7.500 | -1.1402E-01 | 15.000 | -1.0790E-01 |
| 27.500 | -8.4240E-02 | 42.500 | -4.0152E-02 | 55.000 | 6.6463E-03 |
| 67.500 | 6.3227E-02 | 80.000 | 1.2941E-01 | 87.500 | 1.7465E-01 |
| 90.500 | 1.9337E-01 | 91.500 | 1.9972E-01 | 92.000 | 2.0289E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 9-JAN-**
Time of Run: 9:30:52
Title: Beatty-36inch-year15

| | | Initial Conditions | | | | | Initial Conditions | | |
|---|---|---|---|---|---|---|---|---|---|
| NODE | DEPTH (cm) | HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | HEAD (cm) | THETA (vol.) | TEMP (K) |
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.473E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.093E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.729E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.055E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.874E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.311E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.801E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.629E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.489E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.449E+04 | 0.0479 | 0.00 |
| 15 | 9.000E+01 | 1.441E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.441E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.441E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9878 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1222E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8546E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.1857E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9173E+00 | [cm] |
| Mass Balance Error | = | -4.6480E-01 | [cm] |
| Total Successful Time Steps | = | 16988235 | |
| Total Attempted Time Steps | = | 16988235 | |
| Total Time Step Reductions (DHMAX) | = | 11601 | |
| Total Changes in Surface Boundary | = | 15027985 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -5.0345E-01 | 0.050 | -3.7797E-01 | 0.200 | -3.5050E-01 |
| 0.550 | -3.5899E-01 | 0.900 | -3.5939E-01 | 1.500 | -3.5931E-01 |
| 3.500 | -3.5881E-01 | 7.500 | -3.5653E-01 | 15.000 | -3.4094E-01 |
| 27.500 | -3.0530E-01 | 42.500 | -2.4126E-01 | 55.000 | -1.7357E-01 |
| 67.500 | -1.0113E-01 | 80.000 | -3.3666E-02 | 87.500 | 6.7005E-03 |
| 90.500 | 2.3413E-02 | 91.500 | 2.9022E-02 | 92.000 | 3.1857E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 9-JAN-**
Time of Run: 10: 2:56
Title: Beatty-36inch-year16

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.012E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.688E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.608E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.267E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.904E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.312E+05 | 0.0347 | 0.00 |
| 9 | 2.000E+01 | 4.352E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.553E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.985E+04 | 0.0452 | 0.00 | 12 | 6.000E+01 | 1.795E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.644E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.600E+04 | 0.0470 | 0.00 |
| 15 | 9.000E+01 | 1.592E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.592E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.591E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9173 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.4406E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.7624E+02 | [cm] |
| Actual Evaporation | = | 1.2463E+00 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 5.9996E-13 | [cm] |
| Total Infiltration | = | 3.5560E-01 | [cm] |
| Total Drainage at Base of Profile | = | 1.7576E-03 | [cm] |
| Total Applied Water | = | 3.5560E-01 | [cm] |
| Actual Rainfall | = | 3.5560E-01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.2825E+00 | [cm] |
| Mass Balance Error | = | -2.5777E-01 | [cm] |
| Total Successful Time Steps | = | 18064949 | |
| Total Attempted Time Steps | = | 18064949 | |
| Total Time Step Reductions (DHMAX) | = | 11212 | |
| Total Changes in Surface Boundary | = | 17451445 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -8.9075E-01 | 0.050 | -8.9079E-01 | 0.200 | -8.9088E-01 |
| 0.550 | -8.9112E-01 | 0.900 | -8.9133E-01 | 1.500 | -8.9167E-01 |
| 3.500 | -8.9251E-01 | 7.500 | -8.9122E-01 | 15.000 | -8.6337E-01 |
| 27.500 | -7.5212E-01 | 42.500 | -5.8328E-01 | 55.000 | -4.3686E-01 |
| 67.500 | -2.9045E-01 | 80.000 | -1.4149E-01 | 87.500 | -5.2078E-02 |
| 90.500 | -1.6200E-02 | 91.500 | -4.2667E-03 | 92.000 | 1.7576E-03 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 9-JAN-**
Time of Run: 10:54:56
Title: 36-inch Year17

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.180E+06 | 0.0294 | 0.00 | 2 | 1.000E-01 | 1.167E+06 | 0.0295 | 0.00 |
| 3 | 3.000E-01 | 1.142E+06 | 0.0295 | 0.00 | 4 | 8.000E-01 | 1.082E+06 | 0.0296 | 0.00 |
| 5 | 1.000E+00 | 1.059E+06 | 0.0296 | 0.00 | 6 | 2.000E+00 | 9.494E+05 | 0.0298 | 0.00 |
| 7 | 5.000E+00 | 6.832E+05 | 0.0303 | 0.00 | 8 | 1.000E+01 | 4.262E+05 | 0.0313 | 0.00 |
| 9 | 2.000E+01 | 2.512E+05 | 0.0326 | 0.00 | 10 | 3.500E+01 | 1.157E+05 | 0.0351 | 0.00 |
| 11 | 5.000E+01 | 7.278E+04 | 0.0371 | 0.00 | 12 | 6.000E+01 | 6.141E+04 | 0.0379 | 0.00 |
| 13 | 7.500E+01 | 5.305E+04 | 0.0387 | 0.00 | 14 | 8.500E+01 | 5.083E+04 | 0.0389 | 0.00 |
| 15 | 9.000E+01 | 5.043E+04 | 0.0389 | 0.00 | 16 | 9.100E+01 | 5.040E+04 | 0.0390 | 0.00 |
| 17 | 9.200E+01 | 5.039E+04 | 0.0390 | 0.00 | | | | | |

Initial Water Storage = 3.2825 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9274E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.3157E-08 | [cm] |
| Total Infiltration | = | 1.9564E+01 | [cm] |
| Total Drainage at Base of Profile | = | 1.4664E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9866E+00 | [cm] |
| Mass Balance Error | = | -5.6030E-01 | [cm] |
| Total Successful Time Steps | = | 17665215 | |
| Total Attempted Time Steps | = | 17665217 | |
| Total Time Step Reductions (DHMAX) | = | 11480 | |
| Total Changes in Surface Boundary | = | 14473058 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | 2.9041E-01 | 0.050 | 5.0492E-01 | 0.200 | 5.6631E-01 |
| 0.550 | 5.6128E-01 | 0.900 | 5.6098E-01 | 1.500 | 5.6119E-01 |
| 3.500 | 5.6166E-01 | 7.500 | 5.5902E-01 | 15.000 | 5.3416E-01 |
| 27.500 | 4.5778E-01 | 42.500 | 3.5707E-01 | 55.000 | 2.8749E-01 |
| 67.500 | 2.2800E-01 | 80.000 | 1.8485E-01 | 87.500 | 1.5958E-01 |
| 90.500 | 1.5081E-01 | 91.500 | 1.4803E-01 | 92.000 | 1.4664E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 9-JAN-**
Time of Run: 11:39:38
Title: 36-inch Year18

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.474E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.094E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.742E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.059E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.882E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.315E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.804E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.631E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.491E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.451E+04 | 0.0478 | 0.00 |
| 15 | 9.000E+01 | 1.444E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.443E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.443E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9866 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9945E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.8351E-08 | [cm] |
| Total Infiltration | = | 1.9562E+01 | [cm] |
| Total Drainage at Base of Profile | = | 2.0280E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9878E+00 | [cm] |
| Mass Balance Error | = | -5.8734E-01 | [cm] |
| Total Successful Time Steps | = | 17345931 | |
| Total Attempted Time Steps | = | 17345932 | |
| Total Time Step Reductions (DHMAX) | = | 11408 | |
| Total Changes in Surface Boundary | = | 14216430 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -3.8338E-01 | 0.050 | -1.6893E-01 | 0.200 | -1.0774E-01 |
| 0.550 | -1.1286E-01 | 0.900 | -1.1331E-01 | 1.500 | -1.1334E-01 |
| 3.500 | -1.1328E-01 | 7.500 | -1.1300E-01 | 15.000 | -1.0727E-01 |
| 27.500 | -8.3778E-02 | 42.500 | -3.9720E-02 | 55.000 | 6.9123E-03 |
| 67.500 | 6.3642E-02 | 80.000 | 1.2947E-01 | 87.500 | 1.7468E-01 |
| 90.500 | 1.9324E-01 | 91.500 | 1.9965E-01 | 92.000 | 2.0280E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 9-JAN-**
Time of Run: 12:37:38
Title: Beatty-36inch-year19

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.473E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.093E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.729E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.055E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.874E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.311E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.801E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.629E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.489E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.449E+04 | 0.0479 | 0.00 |
| 15 | 9.000E+01 | 1.441E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.441E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.441E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9878 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1222E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8546E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.1857E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9173E+00 | [cm] |
| Mass Balance Error | = | -4.6480E-01 | [cm] |
| Total Successful Time Steps | = | 16988235 | |
| Total Attempted Time Steps | = | 16988235 | |
| Total Time Step Reductions (DHMAX) | = | 11601 | |
| Total Changes in Surface Boundary | = | 15027985 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -5.0345E-01 | 0.050 | -3.7797E-01 | 0.200 | -3.5050E-01 |
| 0.550 | -3.5899E-01 | 0.900 | -3.5939E-01 | 1.500 | -3.5931E-01 |
| 3.500 | -3.5881E-01 | 7.500 | -3.5653E-01 | 15.000 | -3.4094E-01 |
| 27.500 | -3.0530E-01 | 42.500 | -2.4126E-01 | 55.000 | -1.7357E-01 |
| 67.500 | -1.0113E-01 | 80.000 | -3.3666E-02 | 87.500 | 6.7005E-03 |
| 90.500 | 2.3413E-02 | 91.500 | 2.9022E-02 | 92.000 | 3.1857E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 9-JAN-**
Time of Run: 13:10:54
Title: Beatty-36inch-year20

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.012E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.688E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.608E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.267E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.904E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.312E+05 | 0.0347 | 0.00 |
| 9 | 2.000E+01 | 4.352E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.553E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.985E+04 | 0.0452 | 0.00 | 12 | 6.000E+01 | 1.795E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.644E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.600E+04 | 0.0470 | 0.00 |
| 15 | 9.000E+01 | 1.592E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.592E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.591E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9173 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1150E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8544E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.0160E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9157E+00 | [cm] |
| Mass Balance Error | = | -4.5961E-01 | [cm] |
| Total Successful Time Steps | = | 17038507 | |
| Total Attempted Time Steps | = | 17038507 | |
| Total Time Step Reductions (DHMAX) | = | 11605 | |
| Total Changes in Surface Boundary | = | 15072134 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -4.3105E-01 | 0.050 | -3.0557E-01 | 0.200 | -2.7812E-01 |
| 0.550 | -2.8674E-01 | 0.900 | -2.8719E-01 | 1.500 | -2.8722E-01 |
| 3.500 | -2.8720E-01 | 7.500 | -2.8678E-01 | 15.000 | -2.7765E-01 |
| 27.500 | -2.5064E-01 | 42.500 | -1.9884E-01 | 55.000 | -1.4110E-01 |
| 67.500 | -8.0045E-02 | 80.000 | -2.4358E-02 | 87.500 | 8.9869E-03 |
| 90.500 | 2.2998E-02 | 91.500 | 2.7756E-02 | 92.000 | 3.0160E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 9-JAN-**
Time of Run: 13:46:14
Title: Beatty-36inch-year21

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.013E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.689E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.609E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.268E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.921E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.319E+05 | 0.0346 | 0.00 |
| 9 | 2.000E+01 | 4.365E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.560E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.989E+04 | 0.0451 | 0.00 | 12 | 6.000E+01 | 1.799E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.647E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.604E+04 | 0.0469 | 0.00 |
| 15 | 9.000E+01 | 1.596E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.596E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.596E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9157 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1148E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8541E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.0122E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9157E+00 | [cm] |
| Mass Balance Error | = | -4.5954E-01 | [cm] |
| Total Successful Time Steps | = | 17038430 | |
| Total Attempted Time Steps | = | 17038430 | |
| Total Time Step Reductions (DHMAX) | = | 11607 | |
| Total Changes in Surface Boundary | = | 15075482 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -4.2942E-01 | 0.050 | -3.0393E-01 | 0.200 | -2.7648E-01 |
| 0.550 | -2.8510E-01 | 0.900 | -2.8556E-01 | 1.500 | -2.8559E-01 |
| 3.500 | -2.8557E-01 | 7.500 | -2.8514E-01 | 15.000 | -2.7616E-01 |
| 27.500 | -2.4932E-01 | 42.500 | -1.9767E-01 | 55.000 | -1.4017E-01 |
| 67.500 | -7.9334E-02 | 80.000 | -2.3756E-02 | 87.500 | 9.1755E-03 |
| 90.500 | 2.3103E-02 | 91.500 | 2.7733E-02 | 92.000 | 3.0122E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 9-JAN-**
Time of Run: 14:22:26
Title: Beatty-36inch-year22

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.013E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.689E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.609E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.268E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.921E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.318E+05 | 0.0346 | 0.00 |
| 9 | 2.000E+01 | 4.365E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.560E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.989E+04 | 0.0451 | 0.00 | 12 | 6.000E+01 | 1.799E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.647E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.604E+04 | 0.0469 | 0.00 |
| 15 | 9.000E+01 | 1.596E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.596E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.596E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9157 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1148E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8541E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.0122E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9157E+00 | [cm] |
| Mass Balance Error | = | -4.5954E-01 | [cm] |
| Total Successful Time Steps | = | 17038439 | |
| Total Attempted Time Steps | = | 17038439 | |
| Total Time Step Reductions (DHMAX) | = | 11607 | |
| Total Changes in Surface Boundary | = | 15075483 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -4.2942E-01 | 0.050 | -3.0393E-01 | 0.200 | -2.7648E-01 |
| 0.550 | -2.8510E-01 | 0.900 | -2.8556E-01 | 1.500 | -2.8559E-01 |
| 3.500 | -2.8557E-01 | 7.500 | -2.8514E-01 | 15.000 | -2.7616E-01 |
| 27.500 | -2.4932E-01 | 42.500 | -1.9767E-01 | 55.000 | -1.4017E-01 |
| 67.500 | -7.9335E-02 | 80.000 | -2.3756E-02 | 87.500 | 9.1755E-03 |
| 90.500 | 2.3104E-02 | 91.500 | 2.7734E-02 | 92.000 | 3.0122E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 9-JAN-**
Time of Run: 15: 4:18
Title: 36-inch Year23

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.013E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.689E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.609E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.268E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.921E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.318E+05 | 0.0346 | 0.00 |
| 9 | 2.000E+01 | 4.365E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.560E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.989E+04 | 0.0451 | 0.00 | 12 | 6.000E+01 | 1.799E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.647E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.604E+04 | 0.0469 | 0.00 |
| 15 | 9.000E+01 | 1.596E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.596E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.596E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9157 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9882E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.8336E-08 | [cm] |
| Total Infiltration | = | 1.9562E+01 | [cm] |
| Total Drainage at Base of Profile | = | 1.9734E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9877E+00 | [cm] |
| Mass Balance Error | = | -5.8850E-01 | [cm] |
| Total Successful Time Steps | = | 17384855 | |
| Total Attempted Time Steps | = | 17384856 | |
| Total Time Step Reductions (DHMAX) | = | 11403 | |
| Total Changes in Surface Boundary | = | 14244812 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -3.1913E-01 | 0.050 | -1.0471E-01 | 0.200 | -4.3535E-02 |
| 0.550 | -4.8724E-02 | 0.900 | -4.9234E-02 | 1.500 | -4.9364E-02 |
| 3.500 | -4.9792E-02 | 7.500 | -5.1289E-02 | 15.000 | -5.2032E-02 |
| 27.500 | -3.7010E-02 | 42.500 | -4.3973E-03 | 55.000 | 3.2078E-02 |
| 67.500 | 7.7532E-02 | 80.000 | 1.3334E-01 | 87.500 | 1.7265E-01 |
| 90.500 | 1.8904E-01 | 91.500 | 1.9457E-01 | 92.000 | 1.9734E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 9-JAN-**
Time of Run: 15:42:37
Title: 36-inch Year24

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.473E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.093E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.730E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.056E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.875E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.311E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.802E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.629E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.489E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.449E+04 | 0.0479 | 0.00 |
| 15 | 9.000E+01 | 1.441E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.441E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.441E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9877 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9946E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.8348E-08 | [cm] |
| Total Infiltration | = | 1.9562E+01 | [cm] |
| Total Drainage at Base of Profile | = | 2.0289E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9878E+00 | [cm] |
| Mass Balance Error | = | -5.8737E-01 | [cm] |
| Total Successful Time Steps | = | 17346488 | |
| Total Attempted Time Steps | = | 17346489 | |
| Total Time Step Reductions (DHMAX) | = | 11408 | |
| Total Changes in Surface Boundary | = | 14216369 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -3.8442E-01 | 0.050 | -1.6997E-01 | 0.200 | -1.0878E-01 |
| 0.550 | -1.1389E-01 | 0.900 | -1.1435E-01 | 1.500 | -1.1437E-01 |
| 3.500 | -1.1431E-01 | 7.500 | -1.1402E-01 | 15.000 | -1.0790E-01 |
| 27.500 | -8.4240E-02 | 42.500 | -4.0152E-02 | 55.000 | 6.6463E-03 |
| 67.500 | 6.3227E-02 | 80.000 | 1.2941E-01 | 87.500 | 1.7465E-01 |
| 90.500 | 1.9337E-01 | 91.500 | 1.9972E-01 | 92.000 | 2.0289E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 10-JAN-**
Time of Run: 9:29:12
Title: Beatty-36inch-year25rev1

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.473E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.093E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.729E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.055E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.874E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.311E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.801E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.629E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.489E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.449E+04 | 0.0479 | 0.00 |
| 15 | 9.000E+01 | 1.441E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.441E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.441E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9878 cm

Transpiration Scheme is: = 0

| | | | |
|---|---|---|---|
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1222E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8546E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.1857E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9173E+00 | [cm] |
| Mass Balance Error | = | -4.6480E-01 | [cm] |
| Total Successful Time Steps | = | 16988235 | |
| Total Attempted Time Steps | = | 16988235 | |
| Total Time Step Reductions (DHMAX) | = | 11601 | |
| Total Changes in Surface Boundary | = | 15027985 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -5.0345E-01 | 0.050 | -3.7797E-01 | 0.200 | -3.5050E-01 |
| 0.550 | -3.5899E-01 | 0.900 | -3.5939E-01 | 1.500 | -3.5931E-01 |
| 3.500 | -3.5881E-01 | 7.500 | -3.5653E-01 | 15.000 | -3.4094E-01 |
| 27.500 | -3.0530E-01 | 42.500 | -2.4126E-01 | 55.000 | -1.7357E-01 |
| 67.500 | -1.0113E-01 | 80.000 | -3.3666E-02 | 87.500 | 6.7005E-03 |
| 90.500 | 2.3413E-02 | 91.500 | 2.9022E-02 | 92.000 | 3.1857E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 11-JAN-**
Time of Run: 16:42:13
Title: Beatty-36inch-year26

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.012E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.688E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.608E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.267E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.904E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.312E+05 | 0.0347 | 0.00 |
| 9 | 2.000E+01 | 4.352E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.553E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.985E+04 | 0.0452 | 0.00 | 12 | 6.000E+01 | 1.795E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.644E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.600E+04 | 0.0470 | 0.00 |
| 15 | 9.000E+01 | 1.592E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.592E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.591E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9173 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.4406E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.7624E+02 | [cm] |
| Actual Evaporation | = | 1.2463E+00 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 5.9996E-13 | [cm] |
| Total Infiltration | = | 3.5560E-01 | [cm] |
| Total Drainage at Base of Profile | = | 1.7576E-03 | [cm] |
| Total Applied Water | = | 3.5560E-01 | [cm] |
| Actual Rainfall | = | 3.5560E-01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.2825E+00 | [cm] |
| Mass Balance Error | = | -2.5777E-01 | [cm] |
| Total Successful Time Steps | = | 18064949 | |
| Total Attempted Time Steps | = | 18064949 | |
| Total Time Step Reductions (DHMAX) | = | 11212 | |
| Total Changes in Surface Boundary | = | 17451445 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -8.9075E-01 | 0.050 | -8.9079E-01 | 0.200 | -8.9088E-01 |
| 0.550 | -8.9112E-01 | 0.900 | -8.9133E-01 | 1.500 | -8.9167E-01 |
| 3.500 | -8.9251E-01 | 7.500 | -8.9122E-01 | 15.000 | -8.6337E-01 |
| 27.500 | -7.5212E-01 | 42.500 | -5.8328E-01 | 55.000 | -4.3686E-01 |
| 67.500 | -2.9045E-01 | 80.000 | -1.4149E-01 | 87.500 | -5.2078E-02 |
| 90.500 | -1.6200E-02 | 91.500 | -4.2667E-03 | 92.000 | 1.7576E-03 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 11-JAN-**
Time of Run: 17:16:53
Title: 36-inch Year27

| | | Initial Conditions | | | | | Initial Conditions | | |
|---|---|---|---|---|---|---|---|---|---|
| NODE | DEPTH (cm) | HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | HEAD (cm) | THETA (vol.) | TEMP (K) |
| 1 | 0.000E+00 | 1.180E+06 | 0.0294 | 0.00 | 2 | 1.000E-01 | 1.167E+06 | 0.0295 | 0.00 |
| 3 | 3.000E-01 | 1.142E+06 | 0.0295 | 0.00 | 4 | 8.000E-01 | 1.082E+06 | 0.0296 | 0.00 |
| 5 | 1.000E+00 | 1.059E+06 | 0.0296 | 0.00 | 6 | 2.000E+00 | 9.494E+05 | 0.0298 | 0.00 |
| 7 | 5.000E+00 | 6.832E+05 | 0.0303 | 0.00 | 8 | 1.000E+01 | 4.262E+05 | 0.0313 | 0.00 |
| 9 | 2.000E+01 | 2.512E+05 | 0.0326 | 0.00 | 10 | 3.500E+01 | 1.157E+05 | 0.0351 | 0.00 |
| 11 | 5.000E+01 | 7.278E+04 | 0.0371 | 0.00 | 12 | 6.000E+01 | 6.141E+04 | 0.0379 | 0.00 |
| 13 | 7.500E+01 | 5.305E+04 | 0.0387 | 0.00 | 14 | 8.500E+01 | 5.083E+04 | 0.0389 | 0.00 |
| 15 | 9.000E+01 | 5.043E+04 | 0.0389 | 0.00 | 16 | 9.100E+01 | 5.040E+04 | 0.0390 | 0.00 |
| 17 | 9.200E+01 | 5.039E+04 | 0.0390 | 0.00 | | | | | |

Initial Water Storage = 3.2825 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9274E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.3157E-08 | [cm] |
| Total Infiltration | = | 1.9564E+01 | [cm] |
| Total Drainage at Base of Profile | = | 1.4664E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9866E+00 | [cm] |
| Mass Balance Error | = | -5.6030E-01 | [cm] |
| Total Successful Time Steps | = | 17665215 | |
| Total Attempted Time Steps | = | 17665217 | |
| Total Time Step Reductions (DHMAX) | = | 11480 | |
| Total Changes in Surface Boundary | = | 14473058 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | 2.9041E-01 | 0.050 | 5.0492E-01 | 0.200 | 5.6631E-01 |
| 0.550 | 5.6128E-01 | 0.900 | 5.6098E-01 | 1.500 | 5.6119E-01 |
| 3.500 | 5.6166E-01 | 7.500 | 5.5902E-01 | 15.000 | 5.3416E-01 |
| 27.500 | 4.5778E-01 | 42.500 | 3.5707E-01 | 55.000 | 2.8749E-01 |
| 67.500 | 2.2800E-01 | 80.000 | 1.8485E-01 | 87.500 | 1.5958E-01 |
| 90.500 | 1.5081E-01 | 91.500 | 1.4803E-01 | 92.000 | 1.4664E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 14-JAN-**
Time of Run: 8:17:36
Title: 36-inch Year28

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.474E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.094E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.742E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.059E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.882E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.315E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.804E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.631E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.491E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.451E+04 | 0.0478 | 0.00 |
| 15 | 9.000E+01 | 1.444E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.443E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.443E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9866 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 1.9632E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 7.8529E+02 | [cm] |
| Actual Evaporation | = | 1.9945E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 9.8351E-08 | [cm] |
| Total Infiltration | = | 1.9562E+01 | [cm] |
| Total Drainage at Base of Profile | = | 2.0280E-01 | [cm] |
| Total Applied Water | = | 1.9558E+01 | [cm] |
| Actual Rainfall | = | 1.9558E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9878E+00 | [cm] |
| Mass Balance Error | = | -5.8734E-01 | [cm] |
| Total Successful Time Steps | = | 17345931 | |
| Total Attempted Time Steps | = | 17345932 | |
| Total Time Step Reductions (DHMAX) | = | 11408 | |
| Total Changes in Surface Boundary | = | 14216430 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -3.8338E-01 | 0.050 | -1.6893E-01 | 0.200 | -1.0774E-01 |
| 0.550 | -1.1286E-01 | 0.900 | -1.1331E-01 | 1.500 | -1.1334E-01 |
| 3.500 | -1.1328E-01 | 7.500 | -1.1300E-01 | 15.000 | -1.0727E-01 |
| 27.500 | -8.3778E-02 | 42.500 | -3.9720E-02 | 55.000 | 6.9123E-03 |
| 67.500 | 6.3642E-02 | 80.000 | 1.2947E-01 | 87.500 | 1.7468E-01 |
| 90.500 | 1.9324E-01 | 91.500 | 1.9965E-01 | 92.000 | 2.0280E-01 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 14-JAN-**
Time of Run: 9:44:55
Title: Beatty-36inch-year29

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 1.806E+06 | 0.0289 | 0.00 | 2 | 1.000E-01 | 1.759E+06 | 0.0289 | 0.00 |
| 3 | 3.000E-01 | 1.671E+06 | 0.0290 | 0.00 | 4 | 8.000E-01 | 1.473E+06 | 0.0291 | 0.00 |
| 5 | 1.000E+00 | 1.402E+06 | 0.0292 | 0.00 | 6 | 2.000E+00 | 1.093E+06 | 0.0296 | 0.00 |
| 7 | 5.000E+00 | 4.729E+05 | 0.0311 | 0.00 | 8 | 1.000E+01 | 1.055E+05 | 0.0355 | 0.00 |
| 9 | 2.000E+01 | 3.874E+04 | 0.0405 | 0.00 | 10 | 3.500E+01 | 2.311E+04 | 0.0440 | 0.00 |
| 11 | 5.000E+01 | 1.801E+04 | 0.0459 | 0.00 | 12 | 6.000E+01 | 1.629E+04 | 0.0468 | 0.00 |
| 13 | 7.500E+01 | 1.489E+04 | 0.0476 | 0.00 | 14 | 8.500E+01 | 1.449E+04 | 0.0479 | 0.00 |
| 15 | 9.000E+01 | 1.441E+04 | 0.0479 | 0.00 | 16 | 9.100E+01 | 1.441E+04 | 0.0479 | 0.00 |
| 17 | 9.200E+01 | 1.441E+04 | 0.0479 | 0.00 | | | | | |

Initial Water Storage = 3.9878 cm

| | | | |
|---|---|---|---|
| Transpiration Scheme is: | = | 0 | |
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1222E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8546E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.1857E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9173E+00 | [cm] |
| Mass Balance Error | = | -4.6480E-01 | [cm] |
| Total Successful Time Steps | = | 16988235 | |
| Total Attempted Time Steps | = | 16988235 | |
| Total Time Step Reductions (DHMAX) | = | 11601 | |
| Total Changes in Surface Boundary | = | 15027985 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -5.0345E-01 | 0.050 | -3.7797E-01 | 0.200 | -3.5050E-01 |
| 0.550 | -3.5899E-01 | 0.900 | -3.5939E-01 | 1.500 | -3.5931E-01 |
| 3.500 | -3.5881E-01 | 7.500 | -3.5653E-01 | 15.000 | -3.4094E-01 |
| 27.500 | -3.0530E-01 | 42.500 | -2.4126E-01 | 55.000 | -1.7357E-01 |
| 67.500 | -1.0113E-01 | 80.000 | -3.3666E-02 | 87.500 | 6.7005E-03 |
| 90.500 | 2.3413E-02 | 91.500 | 2.9022E-02 | 92.000 | 3.1857E-02 |

UNSAT-H Version 2.03

INITIAL CONDITIONS

Input Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.in
Results Filename: C:\Program Files\University of Wisconsin\WinUnsatH\project.re
Date of Run: 14-JAN-**
Time of Run: 10:21:15
Title: Beatty-36inch-year30

| NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) | NODE | DEPTH (cm) | Initial Conditions HEAD (cm) | THETA (vol.) | TEMP (K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000E+00 | 2.066E+06 | 0.0287 | 0.00 | 2 | 1.000E-01 | 2.012E+06 | 0.0288 | 0.00 |
| 3 | 3.000E-01 | 1.912E+06 | 0.0288 | 0.00 | 4 | 8.000E-01 | 1.688E+06 | 0.0290 | 0.00 |
| 5 | 1.000E+00 | 1.608E+06 | 0.0290 | 0.00 | 6 | 2.000E+00 | 1.267E+06 | 0.0293 | 0.00 |
| 7 | 5.000E+00 | 5.904E+05 | 0.0306 | 0.00 | 8 | 1.000E+01 | 1.312E+05 | 0.0347 | 0.00 |
| 9 | 2.000E+01 | 4.352E+04 | 0.0398 | 0.00 | 10 | 3.500E+01 | 2.553E+04 | 0.0432 | 0.00 |
| 11 | 5.000E+01 | 1.985E+04 | 0.0452 | 0.00 | 12 | 6.000E+01 | 1.795E+04 | 0.0460 | 0.00 |
| 13 | 7.500E+01 | 1.644E+04 | 0.0467 | 0.00 | 14 | 8.500E+01 | 1.600E+04 | 0.0470 | 0.00 |
| 15 | 9.000E+01 | 1.592E+04 | 0.0470 | 0.00 | 16 | 9.100E+01 | 1.592E+04 | 0.0470 | 0.00 |
| 17 | 9.200E+01 | 1.591E+04 | 0.0470 | 0.00 | | | | | |

Initial Water Storage = 3.9173 cm

Transpiration Scheme is: = 0

| | | | |
|---|---|---|---|
| Potential Evapotranspiration | = | 2.3296E+02 | [cm] |
| Potential Transpiration | = | 0.0000E+00 | [cm] |
| Actual Transpiration | = | 0.0000E+00 | [cm] |
| Potential Evaporation | = | 9.3185E+02 | [cm] |
| Actual Evaporation | = | 1.1150E+01 | [cm] |
| Evaporation during Growth | = | 0.0000E+00 | [cm] |
| Total Runoff | = | 8.8544E-08 | [cm] |
| Total Infiltration | = | 1.0719E+01 | [cm] |
| Total Drainage at Base of Profile | = | 3.0160E-02 | [cm] |
| Total Applied Water | = | 1.0719E+01 | [cm] |
| Actual Rainfall | = | 1.0719E+01 | [cm] |
| Actual Irrigation | = | 0.0000E+00 | [cm] |
| Total Final Moisture Storage | = | 3.9157E+00 | [cm] |
| Mass Balance Error | = | -4.5961E-01 | [cm] |
| Total Successful Time Steps | = | 17038507 | |
| Total Attempted Time Steps | = | 17038507 | |
| Total Time Step Reductions (DHMAX) | = | 11605 | |
| Total Changes in Surface Boundary | = | 15072134 | |
| Total Time Actually Simulated | = | 3.6500E+02 | [days] |

Total water flow (cm) across different depths at the end of 3.6500E+02 days:

| DEPTH | FLOW | DEPTH | FLOW | DEPTH | FLOW |
|---|---|---|---|---|---|
| 0.000 | -4.3105E-01 | 0.050 | -3.0557E-01 | 0.200 | -2.7812E-01 |
| 0.550 | -2.8674E-01 | 0.900 | -2.8719E-01 | 1.500 | -2.8722E-01 |
| 3.500 | -2.8720E-01 | 7.500 | -2.8678E-01 | 15.000 | -2.7765E-01 |
| 27.500 | -2.5064E-01 | 42.500 | -1.9884E-01 | 55.000 | -1.4110E-01 |
| 67.500 | -8.0045E-02 | 80.000 | -2.4358E-02 | 87.500 | 8.9869E-03 |
| 90.500 | 2.2998E-02 | 91.500 | 2.7756E-02 | 92.000 | 3.0160E-02 |

AquAeTer

*optimizing environmental resources - water; air; earth*

# CALCULATION SUMMARY SHEET



PROJECT NUMBER: 073113

PROJECT NAME: USEN – Trench 12 Design, Supplemental Calculations

DATE: November 8, 2007

CALCULATION NUMBER: _____ Revision: _____

**CALCULATION TITLE: Runoff and Discharge of Storm Water**

**DESCRIPTION OF CALCULATION:**

This calculation determines the runoff and ultimate discharge of storm runoff from Trench 11, 12 and their corresponding site drainage areas.

**REFERENCES USED:** Number of Reference Pages Attached: _____

Previous calc: 1996 calculation by TRW titled "Surface Water Management"

Urban Hydrology for Small Watersheds (TR-55) by USDA NRCS - June 1986

**REVIEW COMMENTS:**

CALCULATION MADE BY: CAB DATE: November 8, 2007

CALCULATION CHECKED BY: APM DATE: November 9, 2007

CALCULATION REVISED BY: CAB DATE: January 24, 2008

CALCULATION REVIEWED BY: SLW DATE: December 6, 2007

# CALCULATION

# PEAK DISCHARGE RATES

## PURPOSE

Calculate peak runoff rates expected from closed (covered) Trench 11 and Trench 12 drainage areas at the US Ecology Beatty Facility under the influence of design rain storms.

## APPROACH

The USDA Natural Resource Conservation Service Technical Release 55 (TR-55) titled Urban Hydrology for Small Watersheds (June 1986) was used to estimate storm runoff volume and peak rate of storm discharge. To estimate runoff from storm rainfall, TR-55 uses the runoff curve number (CN) method. The CN method is based on the soil type of the trench final covers and cover conditions including hydrologic soil group, cover type, treatment, and hydrologic condition. The runoff equations are:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad S = \frac{1000}{(CN)} - 10$$

Where:

Q = runoff (in)
P = rainfall (in)
S = potential maximum retention after runoff begins (in)
$I_a$ = initial abstraction (in) and $I_a = 0.2S$

Rearranging and substituting 0.2S for Ia yields the following.

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

The CN was chosen from options provided in the TR-55 Table 2-2. The following cover conditions were chosen

| | |
|---|---|
| cover type | Open space |
| treatment (vegetation cover) | Poor condition |
| hydrologic soil group | sandy loam |
| curve number | 68 |

Two storm events were assessed in this estimation of storm runoff. The two-year, 24-hour storm for the Beatty, Nevada area is approximately 1.0 inch of precipitation (NOAA Atlas 2, Volume VII). The 25-year, 24-hour storm for the Beatty area is approximately 2.1 inches of precipitation (NOAA Atlas 2, Volume VII). Using the curve number and the two design storm events, runoff is calculated. Substituting into the above equations, resulting in a runoff (Q) of 0.00 inches from the two-year storm and a Q of 0.23 inches from the 25-year storm.

The next step in the TR-55 guidance is calculation of the travel time or the time it takes water to travel from one location to another on the Beatty site. The factors impacting the time of travel include the surface type, the surface roughness (Manning's coefficient), flow length, rainfall, and the land slope. The cover surface is modeled as sheet flow over a planar surface. The Manning's coefficient applicable to the US Ecology site is 0.011, described in Table 3-1 of the TR-55 guidance as a gravel/bare soil surface.

A drawing of the cover configuration was used to determine drainage areas on the Trench 11 and Trench 12 final covers. In addition, drainages contributing to overall flow at US Ecology discharge points were added, including drainage from the adjacent low level radiological waste area. Areas, average slope and an estimated slope length were determined for each drainage area (A1, A2....A15), and are summarized on Table 1. The attached figure depicts the drainage areas.

## ANALYSIS

The analysis yields peak discharge (in cubic feet per second) for both the two-year, 24-hour storm and the 25-year, 24-hour storm. For all of the drainage areas, the two-year, 24-hour storm did not result in runoff. Peak runoff in separate basin areas from the 25-year, 24-hour storm varied from less than 1 cubic feet per second (cfs) to 3 cfs, depending on the area contributing and the time of concentration.

Depending on the storm event modeled, runoff from a storm event leaving the US Ecology site will only include one drainage area. In other cases runoff will include up to four drainage areas. Drainage areas contributing to a drainage basin were summed in order to size drainage channels. Peak runoff expected in drainage basins is summarized in Table 1.

Using an open flow calculator, peak discharge conditions were modeled to size a channel capable of carrying peak discharges. The two scenarios modeled included a total peak discharge of 3 cfs and 8 cfs. Using the same Manning's coefficient as the cover materials described above (0.011), a drainage slope of 0.005 ft/ft, and specifying side slopes, a ditch depth was determined.

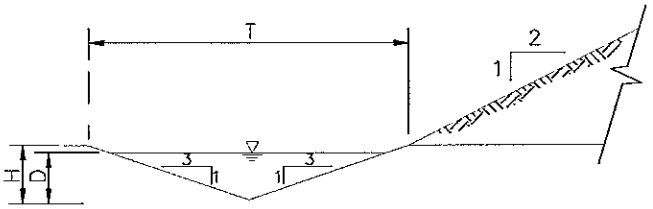
## CONCLUSIONS

Using the TR-55 model, storm runoff volume and peak rate of storm discharge have been estimated for two-year, 24-hour and 25-year, 24-hour rainfall events occurring within drainage areas at the USEN facility. Drainage areas were summed to determine peak discharges from

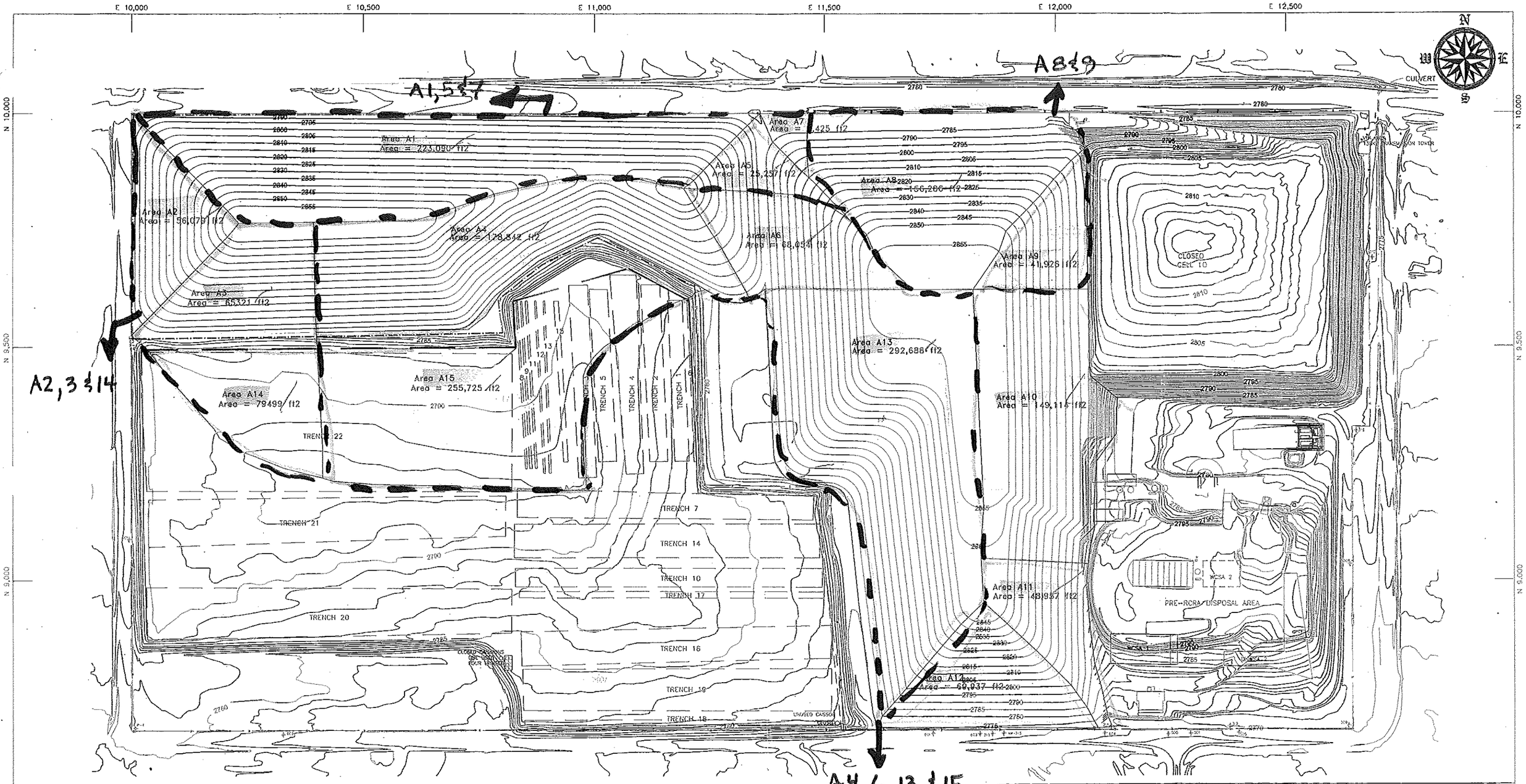
drainage basins at points where storm discharges leave the USEN property. The following peak discharge amounts were calculated for drainage basins.

| Drainage Areas Summed to Create Drainage Basins | Peak Flow 2yr/24hr (cfs) | Peak Flow 25yr/24hr (cfs) |
|---|---|---|
| A1+A5+A7 | 0 | 3 |
| A2+A3+A14 | 0 | 3 |
| A4+A6+A13+A15 | 0 | 8 |
| A8+A9 | 0 | 2 |

Based on the peak flow, USEN channels were sized. The channel sizes are shown below.




| REACH (SEE DRAWING 004) | $Q_{25}$ (cfs) | S (ft/ft) | D (feet) | H (feet) | T (feet) |
|---|---|---|---|---|---|
| 1 | 3 | 0.005 | 0.52 | 0.7 | 4.2 |
| 2 | 8 | 0.005 | 0.75 | 1.0 | 6.0 |




## LEGEND

| | |
|---|---|
| PERMIT LINE | 2790 — 5' CONTOUR INTERVAL, FEET (MSL) |
| FENCE LINE | 1' CONTOUR INTERVAL, FEET (MSL) |
| DRAINAGE DITCH AND SWALE AND DIRECTION OF FLOW | MW-601 MONITOR WELL LOCATION AND NUMBER |
| UNIMPROVED ROAD | |

100 50 0 100
SCALE FEET

DATE OF CELL 11 TOPOGRAPHY: OCTOBER 2006
DATE OF CELL 12 TOPOGRAPHY: APRIL 2007
DATE OF AERIAL TOPOGRAPHY: JUNE 1994

AquAeTer
Project Number 073113
Project Name BEATTY TNRTL Desc
Prepared By CAB Date 11/8/07
Checked By AJM Date 11/7/07
Page 5 of 17

| REV. | DESCRIPTION | DRWN BY | DSGN BY | CHECK BY | APP'D BY | DATE |
|---|---|---|---|---|---|---|

US ECOLOGY INC.

PROJECT NUMBER: 073113 DATE: 5/17/07

BEATTY NEVADA
HAZARDOUS WASTE MANAGEMENT FACILITY

SITE COMPLETION PLAN
DRAINAGE AREAS

| DRWN BY | DATE | DSGN BY | DATE | CHKD BY | DATE | APP'D BY | SCALE | JOB NO. | DRAWING NO. | REV. |
|---|---|---|---|---|---|---|---|---|---|---|
| LAM | 5/17/07 | CAB | 5/17/07 | SLW | 5/17/07 | SLW | | 073113 | | — |

CAD FILE NAME: F:\Data\073113\NDEP Meeting\Excavation Plan.dwg

PLOT DATE: 5/18/07

Table 1
Trench 11 and Trench 12 Cover Drainage Zones
US Ecology
Beatty, Nevada

| ID | Area ($ft^2$) | Area (acres) | Area ($mi^2$) | Slope Length (ft) | Change in Elevation (ft) | Area Slope (ft/ft) | Curve Number | Manning's Coefficient | Time of Concentration (hr) | Peak Flow* 2yr/24hr (cfs) | Peak Flow* 25yr/24hr (cfs) | Runoff* 2yr/24hr (in) | Runoff* 25yr/24hr (in) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 223090 | 5.12 | 0.0080 | 232 | 74 | 0.32 | 68 | 0.011 | 0.02 | 0 | 3 | 0.00 | 0.23 |
| A2 | 56079 | 1.29 | 0.0020 | 232 | 75 | 0.32 | 68 | 0.011 | 0.02 | 0 | 1 | 0.00 | 0.23 |
| A3 | 65321 | 1.50 | 0.0023 | 236 | 75 | 0.32 | 68 | 0.011 | 0.02 | 0 | 1 | 0.00 | 0.23 |
| A4 | 178842 | 4.11 | 0.0064 | 233 | 77 | 0.33 | 68 | 0.011 | 0.02 | 0 | 2 | 0.00 | 0.23 |
| A5 | 25257 | 0.58 | 0.0009 | 170 | 53 | 0.31 | 68 | 0.011 | 0.02 | 0 | 0 | 0.00 | 0.23 |
| A6 | 68054 | 1.56 | 0.0024 | 272 | 80 | 0.29 | 68 | 0.011 | 0.03 | 0 | 1 | 0.00 | 0.23 |
| A7 | 8425 | 0.19 | 0.0003 | 121 | 30 | 0.25 | 68 | 0.011 | 0.02 | 0 | 0 | 0.00 | 0.23 |
| A8 | 156286 | 3.59 | 0.0056 | 300 | 80 | 0.27 | 68 | 0.011 | 0.03 | 0 | 2 | 0.00 | 0.23 |
| A9 | 41926 | 0.96 | 0.0015 | 240 | 60 | 0.25 | 68 | 0.011 | 0.03 | 0 | 0 | 0.00 | 0.23 |
| A10 | 149114 | 3.42 | 0.0053 | 240 | 60 | 0.25 | 68 | 0.011 | 0.03 | 0 | 2 | 0.00 | 0.23 |
| A11 | 48957 | 1.12 | 0.0018 | 228 | 59 | 0.26 | 68 | 0.011 | 0.03 | 0 | 1 | 0.00 | 0.23 |
| A12 | 69937 | 1.61 | 0.0025 | 266 | 72 | 0.27 | 68 | 0.011 | 0.03 | 0 | 1 | 0.00 | 0.23 |
| A13 | 292688 | 6.72 | 0.0105 | 300 | 84 | 0.28 | 68 | 0.011 | 0.03 | 0 | 3 | 0.00 | 0.23 |
| A14 | 79499 | 1.83 | 0.0029 | 300 | 8 | 0.03 | 68 | 0.011 | 0.07 | 0 | 1 | 0.00 | 0.23 |
| A15 | 255725 | 5.87 | 0.0092 | 240 | 10 | 0.04 | 68 | 0.011 | 0.06 | 0 | 2 | 0.00 | 0.23 |

Note:
Precipitation Type II Rainfall Distribution
Slope Length of greater than 300 feet were rounded down to 300 feet

| Drainage Areas Summed to Create Drainage Basins | Peak Flow 25yr/24hr (cfs) |
|---|---|
| A1+A5+A7 | 3 |
| A2+A3+A14 | 3 |
| A4+A6+A13+A15 | 8 |
| A8+A9 | 2 |

AquAeTer
Project Number 073113
Project Name Beatty T11 & T12 Design
Prepared By CAB Date 11/8/07
Checked By APM Date 11/9/07
Page 6 of 7

AquAeTer
optimizing environmental resources - water; air; earth

Project Number: 073113 Sheet No. 7 of 7
Project Name: T11 & T12 Design
Prepared by: CAB Date: 11/8/07
Checked by: ALR Date: 12/7/07
Title: Open Channel Flow

$Q_{25}$ = 3 cfs

Slope = 0.005 ft/ft

Mannings Coefficient = 0.011

Dn = 0.52 ft

Use H = 0.7 ft
T = 4.2 ft

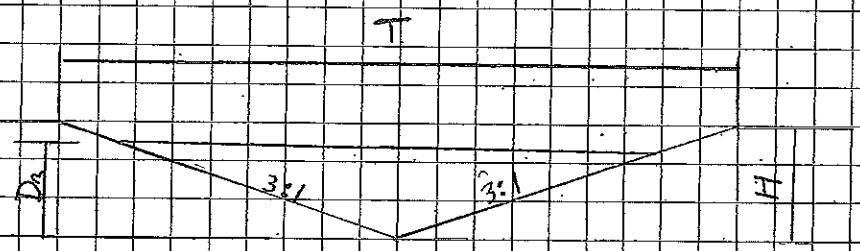
$Q_{25}$ = 8 cfs

Slope = 0.005 ft/ft

Mannings Coefficient = 0.011

Dn = 0.75

Use H = 1.0 ft
T = 6.0 ft



# TR-55

## Model Output

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A1

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A1

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 232 | 0.32 | A | | | | | 0.023 |
| | | | | | | | | Time of Concentration = | 0.02* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated --- Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A1

Data: Drainage Area : 5.12 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.02 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 2.040 | 2.453 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 3 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A2

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A2

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 232 | 0.32 | A | | | | | 0.023 |
| | | | | | | | | Time of Concentration = | 0.02* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated --- Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A2

Data: Drainage Area : 1.29 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.02 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 2.040 | 2.453 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 1 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A3

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A3

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 236 | 0.32 | A | | | | | 0.024 |
| | | | | | | Time of Concentration = | | | 0.02* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated --- Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A3

Data: Drainage Area : 1.5 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.02 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 2.040 | 2.453 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 1 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A4

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A4

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 233 | 0.33 | A | | | | | 0.023 |
| | | | | | | | | Time of Concentration = | 0.02* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated --- Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A4

Data: Drainage Area : 4.11 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.02 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 2.040 | 2.453 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 2 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A5

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A5

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 170 | 0.31 | A | | | | | 0.018 |
| | | | | | | | | Time of Concentration = | 0.02* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated --- Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A5

Data: Drainage Area : .58 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.02 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 2.040 | 2.453 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 0 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A6

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A6

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 272 | 0.29 | A | | | | | 0.028 |
| | | | | | | | | Time of Concentration = | 0.03* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated --- Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A6

Data: Drainage Area : 1.56 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.03 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 1.628 | 2.008 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 1 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A7

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A7

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 121 | 0.25 | A | | | | | 0.015 |
| | | | | | | | | Time of Concentration = | 0.02* |

--- Sheet Flow Surface Codes ---

| | | |
|---|---|---|
| A Smooth Surface | F Grass, Dense | --- Shallow Concentrated --- |
| B Fallow (No Res.) | G Grass, Burmuda | --- Surface Codes --- |
| C Cultivated < 20 % Res. | H Woods, Light | P Paved |
| D Cultivated > 20 % Res. | I Woods, Dense | U Unpaved |
| E Grass-Range, Short | J Range, Natural | |

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A7

Data: Drainage Area : .19 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.02 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 2.040 | 2.453 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 0 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A8

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A8

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 300 | 0.27 | A | | | | | 0.031 |
| | | | | | | | | Time of Concentration = | 0.03* |

--- Sheet Flow Surface Codes ---

| | | |
|---|---|---|
| A Smooth Surface | F Grass, Dense | --- Shallow Concentrated --- |
| B Fallow (No Res.) | G Grass, Burmuda | --- Surface Codes --- |
| C Cultivated < 20 % Res. | H Woods, Light | P Paved |
| D Cultivated > 20 % Res. | I Woods, Dense | U Unpaved |
| E Grass-Range, Short | J Range, Natural | |

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A8

Data: Drainage Area : 3.59 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.03 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 1.628 | 2.008 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 2 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A9

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A9

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 240 | 0.25 | A | | | | | 0.026 |
| | | | | | | | | Time of Concentration = | 0.03* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated --- Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A9

Data: Drainage Area : .96 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.03 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 1.628 | 2.008 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 0 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A10

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A10

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 240 | 0.25 | A | | | | | 0.026 |
| | | | | | | | | Time of Concentration = | 0.03* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated --- Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A10

Data: Drainage Area : 3.42 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.03 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 1.628 | 2.008 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 2 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A11

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A11

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 228 | 0.26 | A | | | | | 0.025 |
| | | | | | | | | Time of Concentration = | 0.03* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: _____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A11

Data: Drainage Area : 1.12 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.03 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 1.628 | 2.008 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 1 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A12

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A12

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 266 | 0.27 | A | | | | | 0.028 |
| | | | | | | | | Time of Concentration = | 0.03* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated --- Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A12

Data: Drainage Area : 1.61 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.03 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 1.628 | 2.008 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 1 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A13

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A13

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 300 | 0.28 | A | | | | | 0.030 |
| | | | | | | | | Time of Concentration = | 0.03* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated --- Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A13

Data: Drainage Area : 6.72 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.03 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 1.628 | 2.008 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 3 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A14

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A14

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 300 | 0.03 | A | | | | | 0.074 |
| | | | | | | | | Time of Concentration = | 0.07* |

--- Sheet Flow Surface Codes ---

A Smooth Surface
B Fallow (No Res.)
C Cultivated < 20 % Res.
D Cultivated > 20 % Res.
E Grass-Range, Short
F Grass, Dense
G Grass, Burmuda
H Woods, Light
I Woods, Dense
J Range, Natural

--- Shallow Concentrated --- Surface Codes ---

P Paved
U Unpaved

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A14

Data: Drainage Area : 1.83 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.07 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 1.022 | 1.308 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 1 |

* - Value(s) provided from TR-55 system routines

RUNOFF CURVE NUMBER COMPUTATION Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A15

Subarea : Cover

| COVER DESCRIPTION | Hydrologic Soil Group A | B | C | D |
|---|---|---|---|---|
| | | Percent (CN) | | |
| FULLY DEVELOPED URBAN AREAS (Veg Estab.) | | | | |
| Open space (Lawns,parks etc.) | | | | |
| Poor condition; grass cover < 50% | 100(68) | - | - | - |
| Total Area (by Hydrologic Soil Group) | 100 | | | |

SUBAREA: Cover TOTAL DRAINAGE AREA: 100 Percent WEIGHTED CURVE NUMBER: 68*

* - Generated for use by GRAPHIC method

TIME OF CONCENTRATION AND TRAVEL TIME Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A15

| Flow Type | 2 year rain | Length (ft) | Slope (ft/ft) | Surface code | n | Area (sq/ft) | Wp (ft) | Velocity (ft/sec) | Time (hr) |
|---|---|---|---|---|---|---|---|---|---|
| Sheet | 1.0 | 240 | 0.04 | A | | | | | 0.055 |
| | | | | | | | | Time of Concentration = | 0.06* |

--- Sheet Flow Surface Codes ---

| | | |
|---|---|---|
| A Smooth Surface | F Grass, Dense | --- Shallow Concentrated --- |
| B Fallow (No Res.) | G Grass, Burmuda | --- Surface Codes --- |
| C Cultivated < 20 % Res. | H Woods, Light | P Paved |
| D Cultivated > 20 % Res. | I Woods, Dense | U Unpaved |
| E Grass-Range, Short | J Range, Natural | |

* - Generated for use by GRAPHIC method

GRAPHICAL PEAK DISCHARGE METHOD Version 2.10

Project : US ECOLOGY BEATTY User: CAB Date: 11-09-2007

County : NYE State: NV Checked: ____ Date: _____

Subtitle: TRENCH 11 AND 12 COVER DESIGN - DRAINAGE AREA A15

Data: Drainage Area : 5.87 Acres
Runoff Curve Number : 68 *
Time of Concentration: 0.06 * Hours
Rainfall Type : II
Pond and Swamp Area : NONE

| Storm Number | 1 | 2 |
|---|---|---|
| Frequency (yrs) | 2 | 25 |
| 24-Hr Rainfall (in) | 1.0 | 2.1 |
| Ia/P Ratio | 0.94 | 0.45 |
| Used | 0.50 | 0.45 |
| Runoff (in) | 0.00 | 0.23 |
| Unit Peak Discharge (cfs/acre/in) | 1.111 | 1.415 |
| Pond and Swamp Factor 0.0% Ponds Used | 1.00 | 1.00 |
| Peak Discharge (cfs) | 0 | 2 |

* - Value(s) provided from TR-55 system routines

# References

United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

**Conservation
Engineering
Division**

Technical
Release 55

June 1986

# Urban Hydrology for Small Watersheds

CALCULATION
REFERENCE

## TR-55

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CALCULATION REFERENCE



**Table 2-2a** Runoff curve numbers for urban areas [1]

| Cover description: Cover type and hydrologic condition | Average percent impervious area [2] | Curve numbers for hydrologic soil group: A | B | C | D |
|---|---|---|---|---|---|
| *Fully developed urban areas (vegetation established)* | | | | | |
| Open space (lawns, parks, golf courses, cemeteries, etc.) [3]: | | | | | |
| Poor condition (grass cover < 50%) | | 68 | 79 | 86 | 89 |
| Fair condition (grass cover 50% to 75%) | | 49 | 69 | 79 | 84 |
| Good condition (grass cover > 75%) | | 39 | 61 | 74 | 80 |
| Impervious areas: | | | | | |
| Paved parking lots, roofs, driveways, etc. (excluding right-of-way) | | 98 | 98 | 98 | 98 |
| Streets and roads: | | | | | |
| Paved; curbs and storm sewers (excluding right-of-way) | | 98 | 98 | 98 | 98 |
| Paved; open ditches (including right-of-way) | | 83 | 89 | 92 | 93 |
| Gravel (including right-of-way) | | 76 | 85 | 89 | 91 |
| Dirt (including right-of-way) | | 72 | 82 | 87 | 89 |
| Western desert urban areas: | | | | | |
| Natural desert landscaping (pervious areas only) [4] | | 63 | 77 | 85 | 88 |
| Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders) | | 96 | 96 | 96 | 96 |
| Urban districts: | | | | | |
| Commercial and business | 85 | 89 | 92 | 94 | 95 |
| Industrial | 72 | 81 | 88 | 91 | 93 |
| Residential districts by average lot size: | | | | | |
| 1/8 acre or less (town houses) | 65 | 77 | 85 | 90 | 92 |
| 1/4 acre | 38 | 61 | 75 | 83 | 87 |
| 1/3 acre | 30 | 57 | 72 | 81 | 86 |
| 1/2 acre | 25 | 54 | 70 | 80 | 85 |
| 1 acre | 20 | 51 | 68 | 79 | 84 |
| 2 acres | 12 | 46 | 65 | 77 | 82 |
| *Developing urban areas* | | | | | |
| Newly graded areas (pervious areas only, no vegetation) [5] | | 77 | 86 | 91 | 94 |
| Idle lands (CN's are determined using cover types similar to those in table 2-2c). | | | | | |

1 Average runoff condition, and $I_a = 0.2S$.
2 The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.
3 CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.
4 Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.
5 Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

CALCULATION REFERENCE



## Sheet flow

Sheet flow is flow over plane surfaces. It usually occurs in the headwater of streams. With sheet flow, the friction value (Manning's n) is an effective roughness coefficient that includes the effect of raindrop impact; drag over the plane surface; obstacles such as litter, crop ridges, and rocks; and erosion and transportation of sediment. These n values are for very shallow flow depths of about 0.1 foot or so. Table 3-1 gives Manning's n values for sheet flow for various surface conditions.

**Table 3-1** Roughness coefficients (Manning's n) for sheet flow

| Surface description | n [1] |
|---|---|
| Smooth surfaces (concrete, asphalt, gravel, or bare soil) | 0.011 |
| Fallow (no residue) | 0.05 |
| Cultivated soils: | |
| Residue cover ≤20% | 0.06 |
| Residue cover >20% | 0.17 |
| Grass: | |
| Short grass prairie | 0.15 |
| Dense grasses [2] | 0.24 |
| Bermudagrass | 0.41 |
| Range (natural) | 0.13 |
| Woods:[3] | |
| Light underbrush | 0.40 |
| Dense underbrush | 0.80 |

[1] The n values are a composite of information compiled by Engman (1986).
[2] Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.
[3] When selecting n, consider cover to a height of about 0.1 ft. This is the only part of the plant cover that will obstruct sheet flow.

For sheet flow of less than 300 feet, use Manning's kinematic solution (Overtop and Meadows 1976) to compute $T_t$:

$$T_t = \frac{0.007(nL)^{0.8}}{(P_2)^{0.5} s^{0.4}} \qquad \text{[eq. 3-3]}$$

where:

$T_t$ = travel time (hr),
n = Manning's roughness coefficient (table 3-1)
L = flow length (ft)
$P_2$ = 2-year, 24-hour rainfall (in)
s = slope of hydraulic grade line (land slope, ft/ft)

This simplified form of the Manning's kinematic solution is based on the following: (1) shallow steady uniform flow, (2) constant intensity of rainfall excess (that part of a rain available for runoff), (3) rainfall duration of 24 hours, and (4) minor effect of infiltration on travel time. Rainfall depth can be obtained from appendix B.

## Shallow concentrated flow

After a maximum of 300 feet, sheet flow usually becomes shallow concentrated flow. The average velocity for this flow can be determined from figure 3-1, in which average velocity is a function of watercourse slope and type of channel. For slopes less than 0.005 ft/ft, use equations given in appendix F for figure 3-1. Tillage can affect the direction of shallow concentrated flow. Flow may not always be directly down the watershed slope if tillage runs across the slope.

After determining average velocity in figure 3-1, use equation 3-1 to estimate travel time for the shallow concentrated flow segment.

## Open channels

Open channels are assumed to begin where surveyed cross section information has been obtained, where channels are visible on aerial photographs, or where blue lines (indicating streams) appear on United States Geological Survey (USGS) quadrangle sheets. Manning's equation or water surface profile information can be used to estimate average flow velocity. Average flow velocity is usually determined for bankfull elevation.

CALCULATION REFERENCE

# Appendix A Hydrologic Soil Groups

Soils are classified into hydrologic soil groups (HSG's) to indicate the minimum rate of infiltration obtained for bare soil after prolonged wetting. The HSG's, which are A, B, C, and D, are one element used in determining runoff curve numbers (see chapter 2). For the convenience of TR-55 users, exhibit A-1 lists the HSG classification of United States soils.

The infiltration rate is the rate at which water enters the soil at the soil surface. It is controlled by surface conditions. HSG also indicates the transmission rate—the rate at which the water moves within the soil. This rate is controlled by the soil profile. Approximate numerical ranges for transmission rates shown in the HSG definitions were first published by Musgrave (USDA 1955). The four groups are defined by SCS soil scientists as follows:

**Group A** soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively drained sand or gravel and have a high rate of water transmission (greater than 0.30 in/hr).

**Group B** soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (0.15-0.30 in/hr).

**Group C** soils have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (0.05-0.15 in/hr).

**Group D** soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0-0.05 in/hr).

In exhibit A-1, some of the listed soils have an added modifier; for example, "Abrazo, gravelly." This refers to a gravelly phase of the Abrazo series that is found in SCS soil map legends.

## Disturbed soil profiles

As a result of urbanization, the soil profile may be considerably altered and the listed group classification may no longer apply. In these circumstances, use the following to determine HSG according to the texture of the new surface soil, provided that significant compaction has not occurred (Brakensiek and Rawls 1983).

| *HSG* | *Soil textures* |
|---|---|
| A | Sand, loamy sand, or sandy loam |
| B | Silt loam or loam |
| C | Sandy clay loam |
| D | Clay loam, silty clay loam, sandy clay, silty clay, or clay |

## Drainage and group D soils

Some soils in the list are in group D because of a high water table that creates a drainage problem. Once these soils are effectively drained, they are placed in a different group. For example, Ackerman soil is classified as A/D. This indicates that the drained Ackerman soil is in group A and the undrained soil is in group D.

CALCULATION
REFERENCE

# Appendix B Synthetic Rainfall Distributions and Rainfall Data Sources

The highest peak discharges from small watersheds in the United States are usually caused by intense, brief rainfalls that may occur as distinct events or as part of a longer storm. These intense rainstorms do not usually extended over a large area and intensities vary greatly. One common practice in rainfall-runoff analysis is to develop a synthetic rainfall distribution to use in lieu of actual storm events. This distribution includes maximum rainfall intensities for the selected design frequency arranged in a sequence that is critical for producing peak runoff.

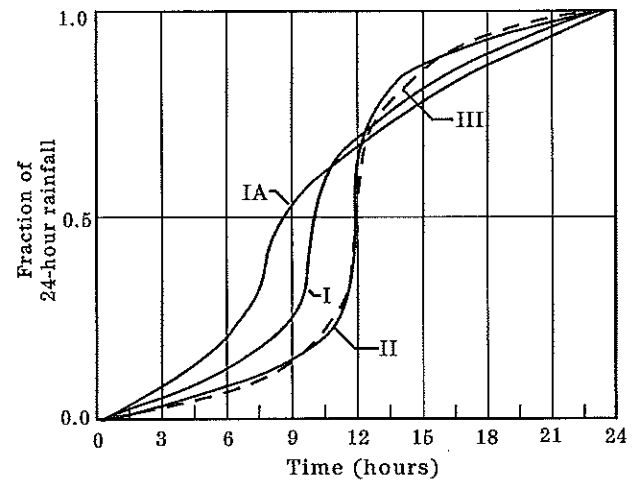
## Synthetic rainfall distributions

The length of the most intense rainfall period contributing to the peak runoff rate is related to the time of concentration ($T_c$) for the watershed. In a hydrograph created with NRCS procedures, the duration of rainfall that directly contributes to the peak is about 170 percent of the $T_c$. For example, the most intense 8.5-minute rainfall period would contribute to the peak discharge for a watershed with a $T_c$ of 5 minutes. The most intense 8.5-hour period would contribute to the peak for a watershed with a 5-hour $T_c$.

Different rainfall distributions can be developed for each of these watersheds to emphasize the critical rainfall duration for the peak discharges. However, to avoid the use of a different set of rainfall intensities for each drainage area size, a set of synthetic rainfall distributions having "nested" rainfall intensities was developed. The set "maximizes" the rainfall intensities by incorporating selected short duration intensities within those needed for longer durations at the same probability level.

For the size of the drainage areas for which NRCS usually provides assistance, a storm period of 24 hours was chosen the synthetic rainfall distributions. The 24-hour storm, while longer than that needed to determine peaks for these drainage areas, is appropriate for determining runoff volumes. Therefore, a single storm duration and associated synthetic rainfall distribution can be used to represent not only the peak discharges but also the runoff volumes for a range of drainage area sizes.

**Figure B-1** SCS 24-hour rainfall distributions

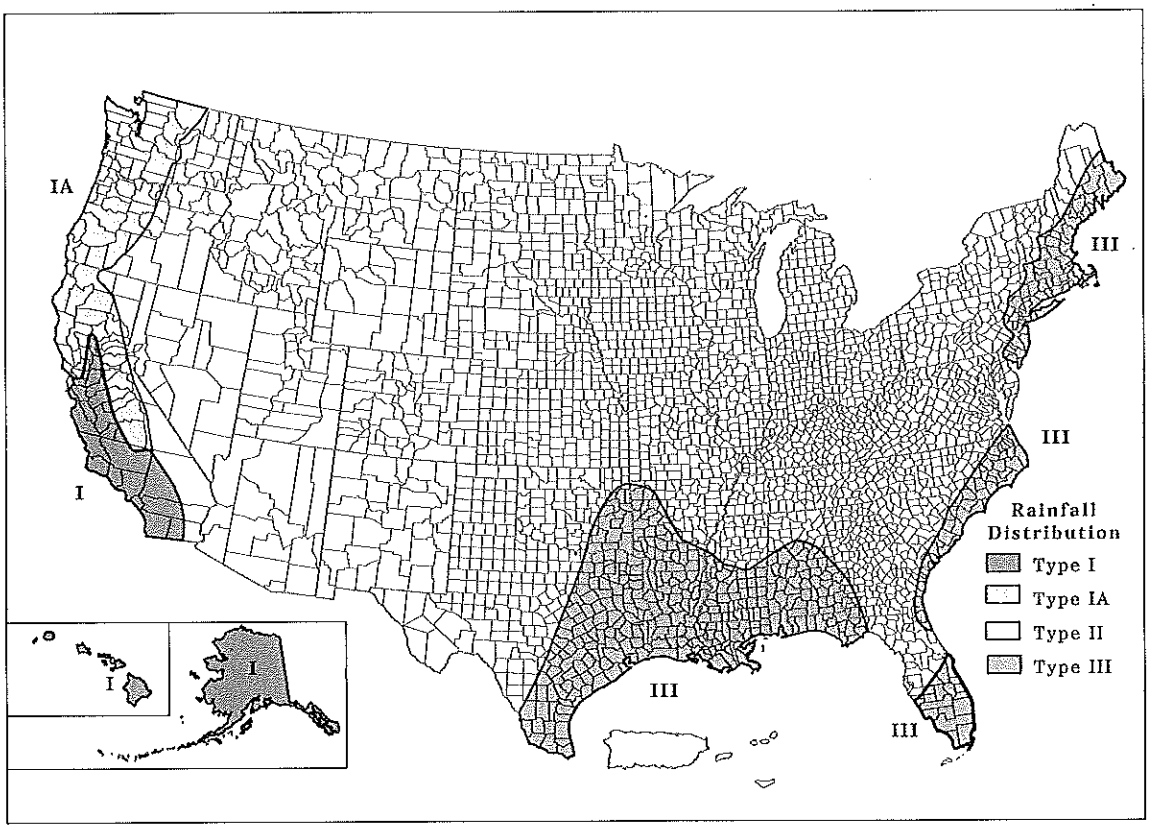



The intensity of rainfall varies considerably during a storm as well as geographic regions. To represent various regions of the United States, NRCS developed four synthetic 24-hour rainfall distributions (I, IA, II, and III) from available National Weather Service (NWS) duration-frequency data (Hershfield 1061; Frederick et al., 1977) or local storm data. Type IA is the least intense and type II the most intense short duration rainfall. The four distributions are shown in figure B-1, and figure B-2 shows their approximate geographic boundaries.

Types I and IA represent the Pacific maritime climate with wet winters and dry summers. Type III represents Gulf of Mexico and Atlantic coastal areas where tropical storms bring large 24-hour rainfall amounts. Type II represents the rest of the country. For more precise distribution boundaries in a state having more than one type, contact the NRCS State Conservation Engineer.

CALCULATION REFERENCE

**Figure B-2** Approximate geographic boundaries for NRCS (SCS) rainfall distributions




## Rainfall data sources

This section lists the most current 24-hour rainfall data published by the National Weather Service (NWS) for various parts of the country. Because NWS Technical Paper 40 (TP-40) is out of print, the 24-hour rainfall maps for areas east of the 105th meridian are included here as figures B-3 through B-8. For the area generally west of the 105th meridian, TP-40 has been superseded by NOAA Atlas 2, the Precipitation-Frequency Atlas of the Western United States, published by the National Ocean and Atmospheric Administration.

### East of 105th meridian

Hershfield, D.M. 1961. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. U.S. Dept. Commerce, Weather Bur. Tech. Pap. No. 40. Washington, DC. 155 p.

### West of 105th meridian

Miller, J.F., R.H. Frederick, and R.J. Tracey. 1973. Precipitation-frequency atlas of the Western United States. Vol. I Montana; Vol. II, Wyoming; Vol III, Colorado; Vol. IV, New Mexico; Vol V, Idaho; Vol. VI, Utah; Vol. VII, Nevada; Vol. VIII, Arizona; Vol. IX, Washington; Vol. X, Oregon; Vol. XI, California. U.S. Dept. of Commerce, National Weather Service, NOAA Atlas 2. Silver Spring, MD.

### Alaska

Miller, John F. 1963. Probable maximum precipitation and rainfall-frequency data for Alaska for areas to 400 square miles, durations to 24 hours and return periods from 1 to 100 years. U.S. Dept. of Commerce, Weather Bur. Tech. Pap. No. 47. Washington, DC. 69 p.

### Hawaii

Weather Bureau. 1962. Rainfall-frequency atlas of the Hawaiian Islands for areas to 200 square miles, durations to 24 hours and return periods from 1 to 100 years. U.S. Dept. Commerce, Weather Bur. Tech. Pap. No. 43. Washington, DC. 60 p.

### Puerto Rico and Virgin Islands

Weather Bureau. 1961. Generalized estimates of probable maximum precipitation and rainfall-frequency data for Puerto Rico and Virgin Islands for areas to 400 square miles, durations to 24 hours, and return periods from 1 to 100 years. U.S. Dept. Commerce, Weather Bur. Tech. Pap. No. 42. Washington, DC. 94 P.

CALCULATION
REFERENCE

**Figure B-3** 2-year, 24-hr rainfall

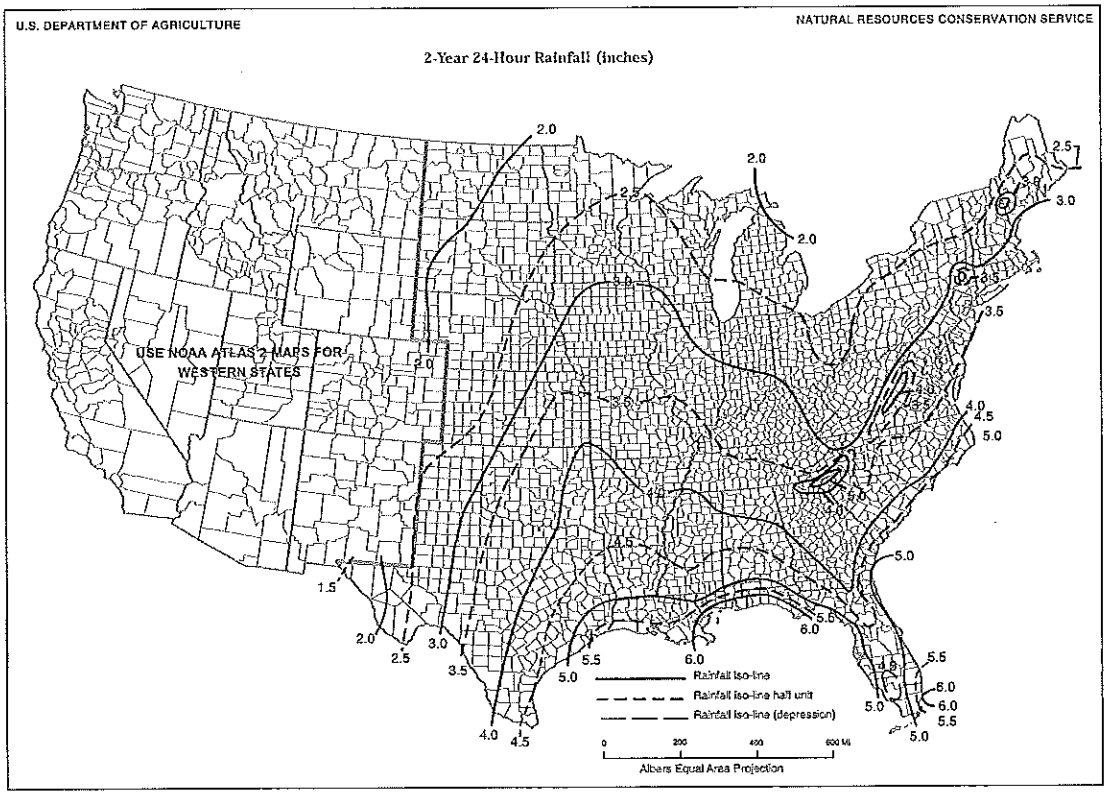
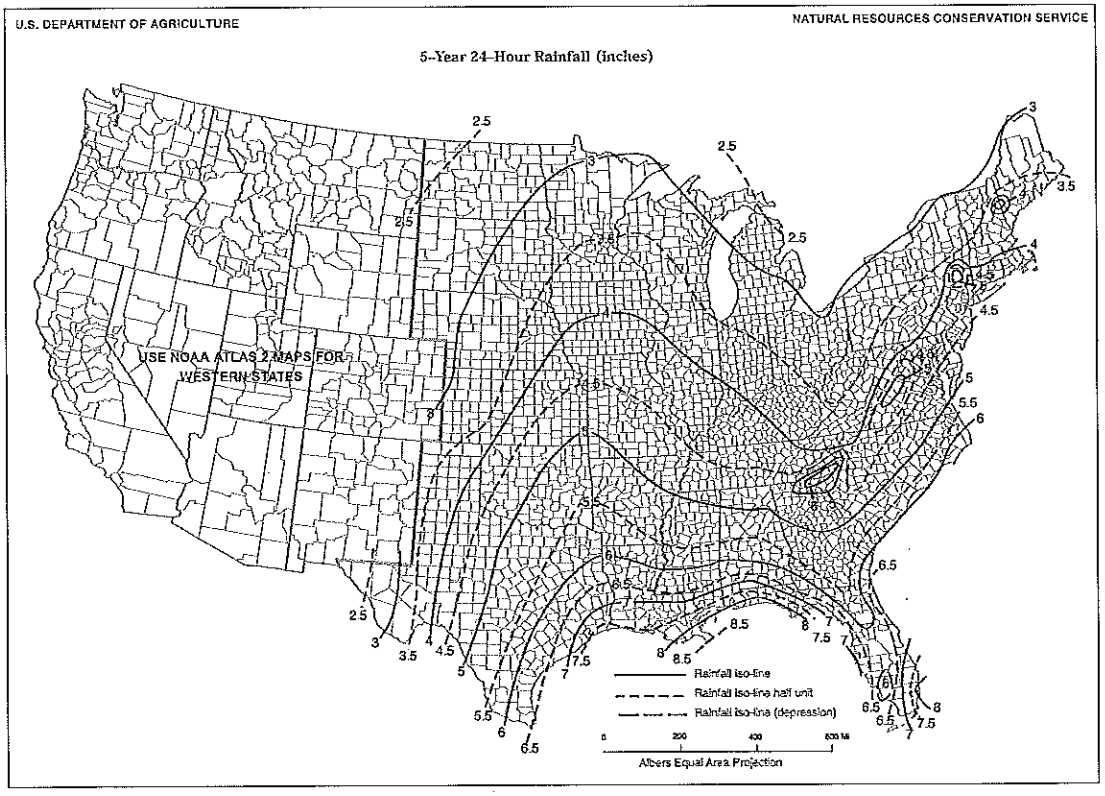



**Figure B-4** 5-year, 24-hour rainfall



CALCULATION REFERENCE

**Figure B-5** 10-year, 24-hour rainfall

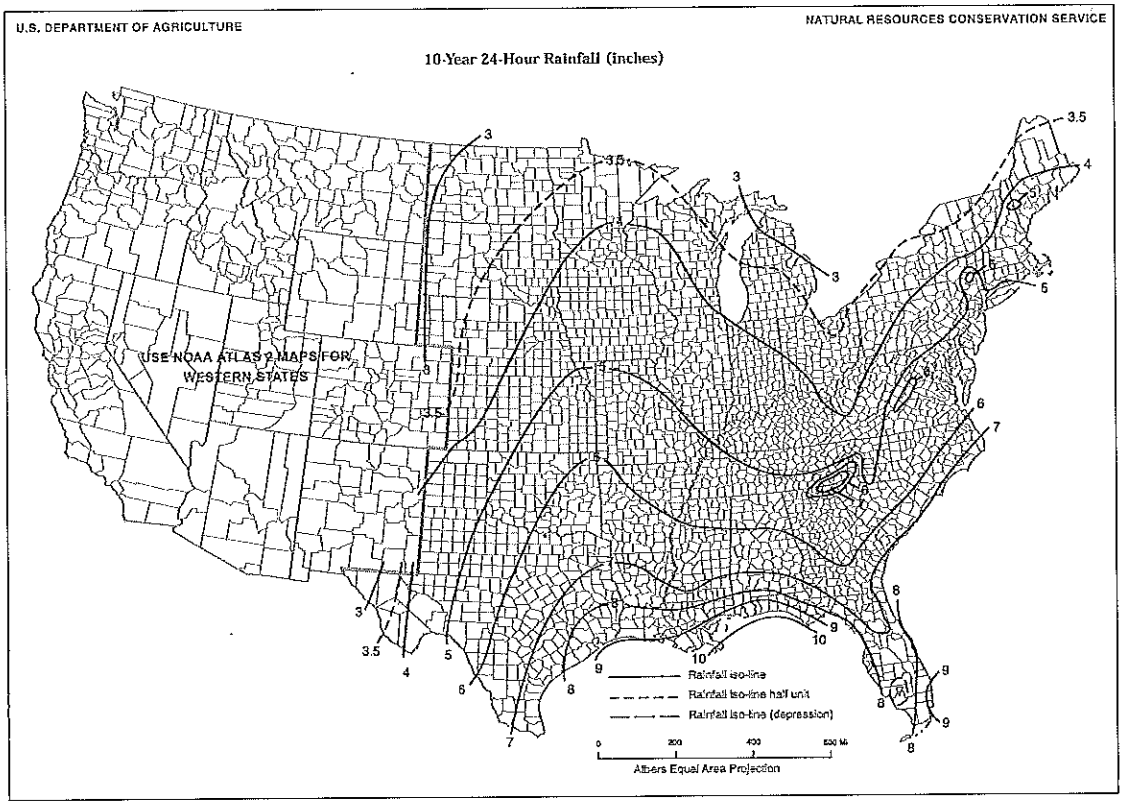
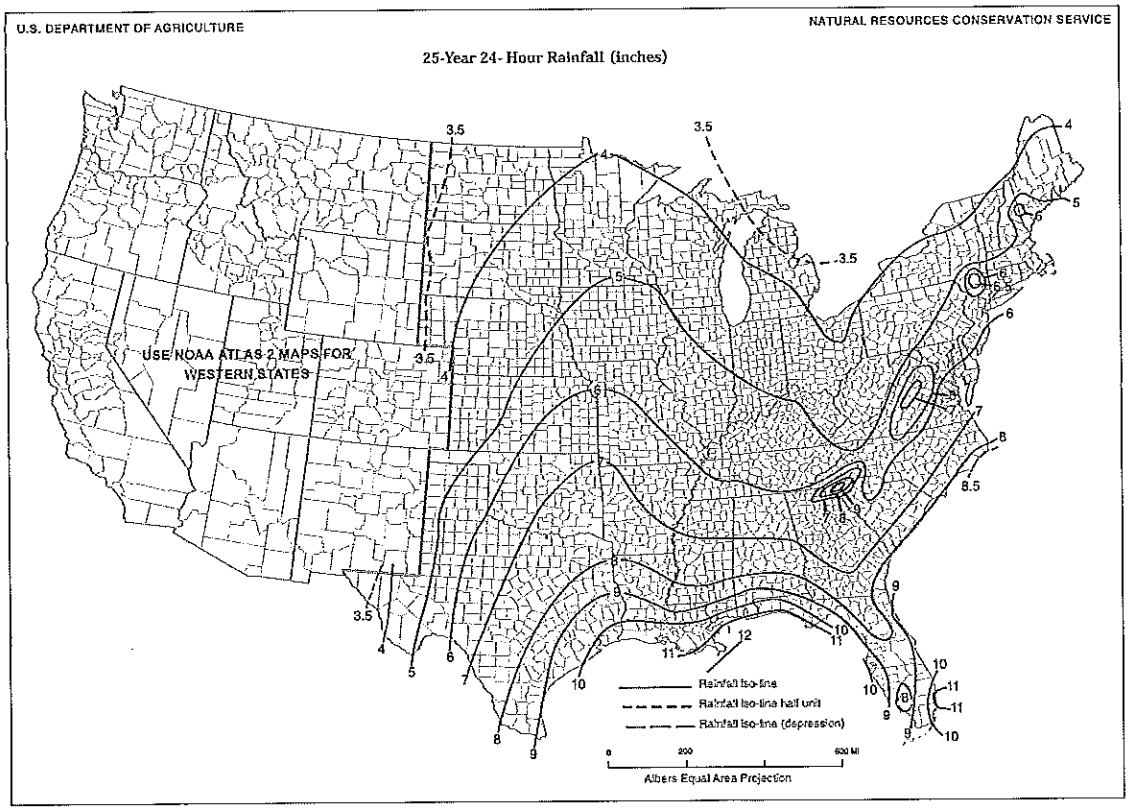



**Figure B-6** 25-year, 24-hour rainfall



CALCULATION
REFERENCE

**Figure B-7** 50-year, 24-hour rainfall

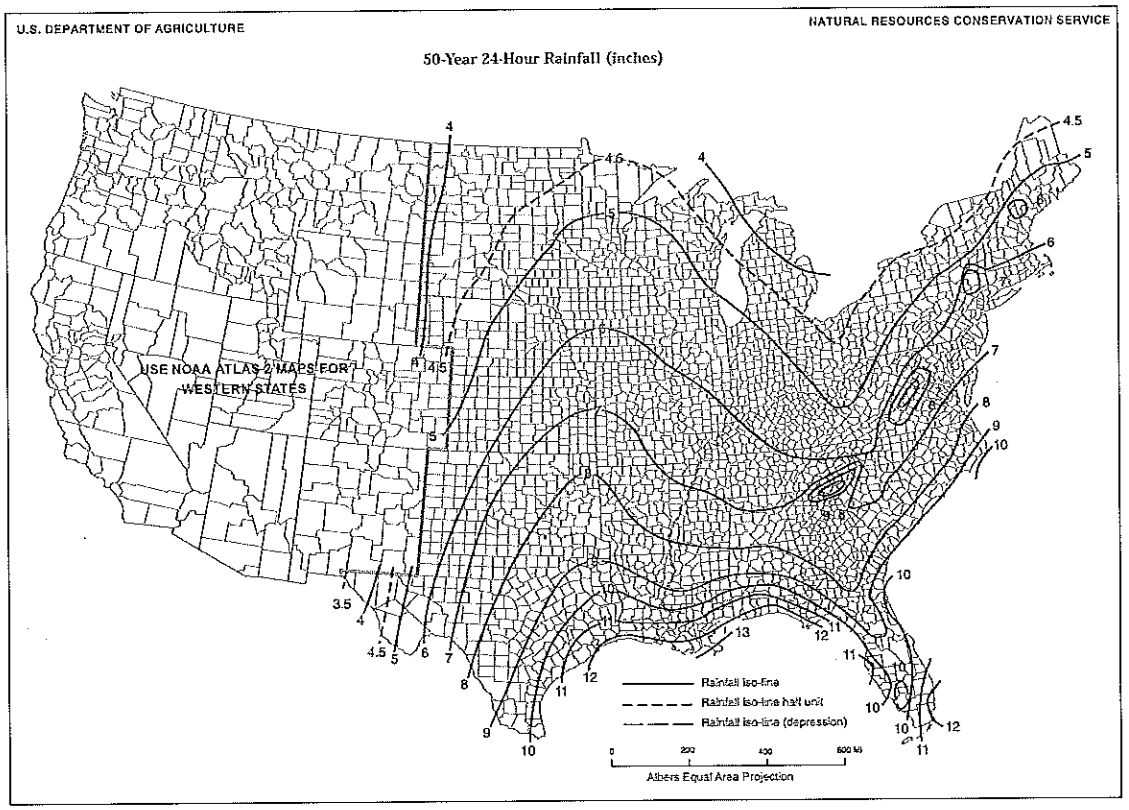
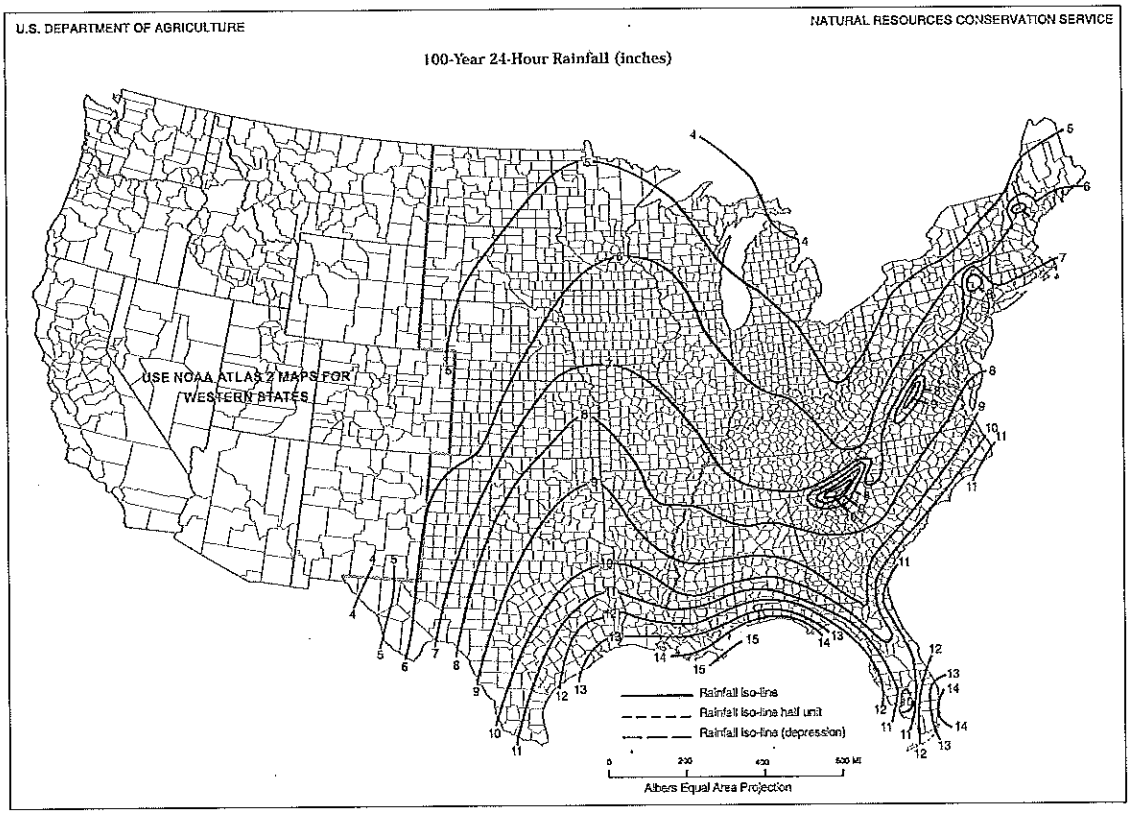



**Figure B-8** 100-year, 24-hour rainfall



CALCULATION REFERENCE

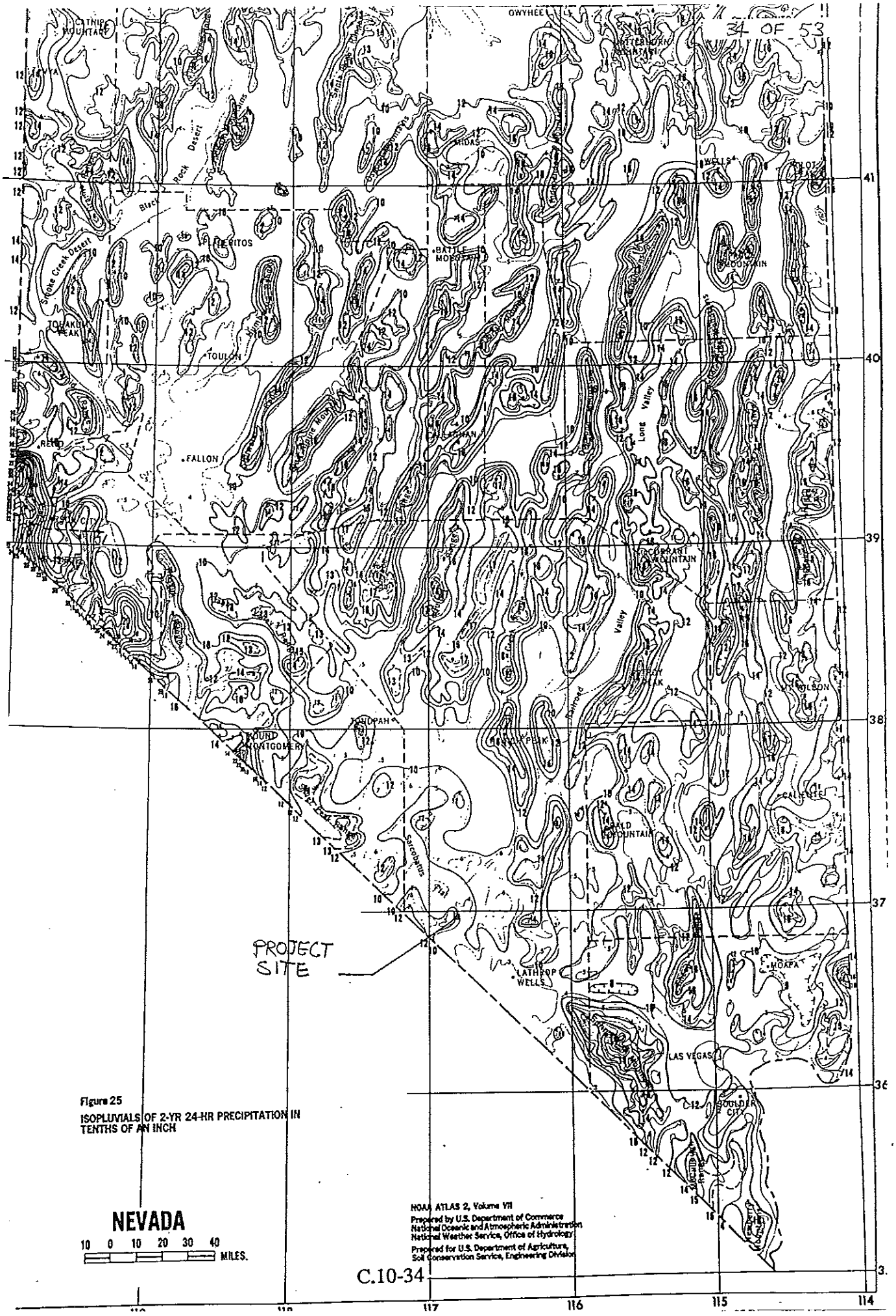



Figure 25

ISOPLUVIALS OF 2-YR 24-HR PRECIPITATION IN TENTHS OF AN INCH

NEVADA

10 0 10 20 30 40 MILES.

NOAA ATLAS 2, Volume VII

Prepared by U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Weather Service, Office of Hydrology

Prepared for U.S. Department of Agriculture,
Soil Conservation Service, Engineering Division

CALCULATION REFERENCE 35 OF 53

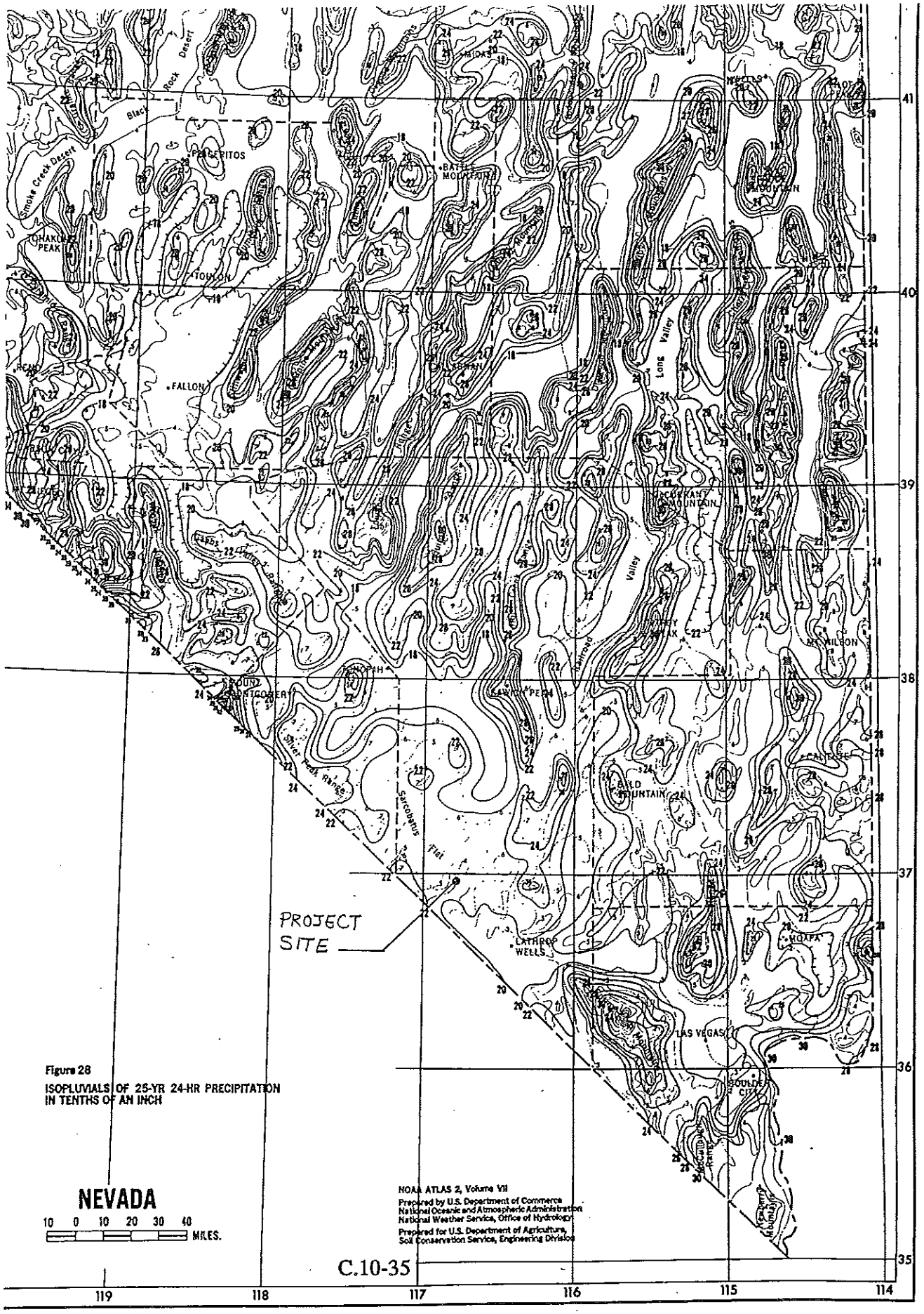



Figure 28

ISOPLUVIALS OF 25-YR 24-HR PRECIPITATION IN TENTHS OF AN INCH

NEVADA

10 0 10 20 30 40 MILES.

NOAA ATLAS 2, Volume VII

Prepared by U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Weather Service, Office of Hydrology

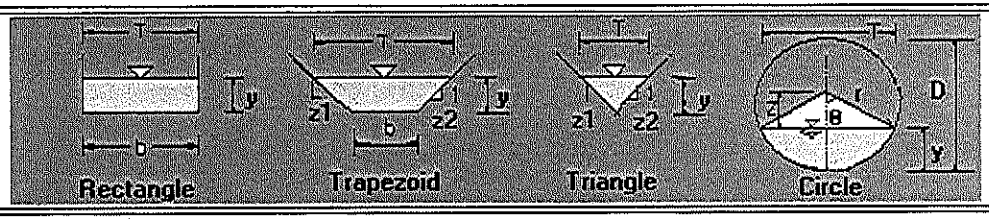
Prepared for U.S. Department of Agriculture,
Soil Conservation Service, Engineering Division

CALCULATION
REFERENCE

# OPEN FLOW CALCULATOR

# The open channel flow calculator

Select Channel Type: Triangle




Depth from Q

Select unit system: Feet(ft)

| | | | | | |
|---|---|---|---|---|---|
| Channel slope: | 0.005 | ft/ft | Water depth(y): 0.52 | ft | Bottom W(b) 0 ft |
| Flow velocity | 3.707 | ft/s | LeftSlope(Z1): 3 | Z1/y | RightSlope(Z2): 3 Z2/y |
| Flow discharge | 3 | ft^3/s | Input n value 0.011 | or select n | |
| Calculate! | | | Status: Calculation finished | | Reset |
| Wetted perimeter | 3.28 | ft | Flow area 0.81 | ft^2 | Top width(T) 3.12 ft |
| Specific energy | 0.73 | ft | Froude number 1.28 | | Flow status Supercritical flow |
| Critical depth | 0.58 | ft | Critical slope 0.0028 | ft/ft | Velocity head 0.21 ft |

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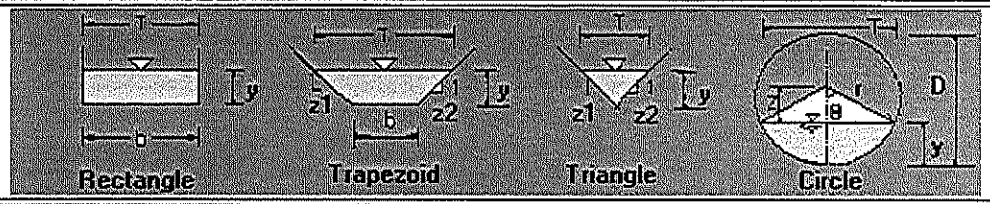
CALCULATION REFERENCE

# The open channel flow calculator

Select Channel Type: Triangle




Depth from Q

Select unit system: Feet(ft)

| | | | | | |
|---|---|---|---|---|---|
| Channel slope: | 0.005 ft/ft | Water depth(y): | 0.75 ft | Bottom W(b) | 0 ft |
| Flow velocity | 4.745 ft/s | LeftSlope(Z1): | 3 Z1/y | RightSlope(Z2): | 3 Z2/y |
| Flow discharge | 8 ft^3/s | Input n value | 0.011 or select n | | |
| Calculate! | | Status: | Calculation finished | Reset | |
| Wetted perimeter | 4.74 ft | Flow area | 1.69 ft^2 | Top width(T) | 4.5 ft |
| Specific energy | 1.1 ft | Froude number | 1.37 | Flow status | Supercritical flow |
| Critical depth | 0.85 ft | Critical slope | 0.0025 ft/ft | Velocity head | 0.35 ft |

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CALCULATION REFERENCE

AquAeTer

*optimizing environmental resources - water; air; earth*

# CALCULATION SUMMARY SHEET



PROJECT NUMBER: 073113

PROJECT NAME: USEN – Trench 12 Design, Supplemental Calculations

DATE: November 8, 2007

CALCULATION NUMBER: _____ Revision: _____

**CALCULATION TITLE: Soil Cover Erosion Using RUSLE2**

**DESCRIPTION OF CALCULATION:**

This calculation determines the rate of soil cover erosion of the Trench 11 and 12 surfaces using the Revised Universal Soil Loss Equation (RUSLE).

**REFERENCES USED:** Number of Reference Pages Attached: _____

Previous calc: 1996 calculation by TRW titled "Erosion Control"

RUSLE2 Version 1.26.6.4 (November 13, 2006)

**REVIEW COMMENTS:**

CALCULATION MADE BY: CAB DATE: November 8, 2007

CALCULATION CHECKED BY: APM DATE: November 9, 2007

CALCULATION REVISED BY: CAB DATE: December 26, 2007

CALCULATION REVIEWED BY: SLW DATE: December 21, 2007

# CALCULATION

## RATE OF SOIL COVER EROSION

### PURPOSE

This calculation calculates the erosion possible from the proposed final cover design of Trenches 11 and 12 at the US Ecology Beatty Facility.

### APPROACH

The Revised Universal Soil Loss Equation (RUSLE) is used for this analysis. RUSLE is used to calculate the expected soil loss based on soil properties, rainfall, slopes and ground cover. Specifically, the NRCS (U.S. Natural Resources Conservation Service) RUSLE2 modeling software was used for the analysis. RUSLE2 software estimates soil loss, sediment yield, and sediment characteristics from rill and inter-rill (sheet and rill) erosion caused by rainfall and its associated overland flow. RUSLE2 uses factors that represent the effects of climatic erosivity (climatic causes of soil erosion), soil erodibility, topography, cover-management and support practices to compute erosion. The RUSLE equation used by the software is:

$$A = RKLSCP$$

Where

A = computed average annual soil loss

R = rainfall runoff erosivity factor

K = soil erodibility factor

LS = length-slope factor

C = cover management factor

P = supporting practices factor

The use of the RUSLE2 computer model allows the user to upload region-specific database information instead of manual determination of the above factors. The following three databases were uploaded from the Revised Universal Soil Loss Equation, Version 2 (RUSLE2), Official NRCS RUSLE2 Program, Official NRCS Database web page[1] for modeling the Beatty site.

1. Climate Data (NV climate120303.zip)
2. Soils Data (Nye SW, 785.gdb and generic soils.gdb)
3. Crop Management Template (CMZ-31.zip)

---

[1] http://www.ars.usda.gov/Research/docs.htm?docid=6010

Using the database values provides the model with appropriate sources for the above factors, R, K, C, and P. Slope angle and length are site-specific inputs added by the user.

The first input for RUSLE2 is climate, which is based on the location input. For the US Ecology Beatty facility, the location "USA\Nevada\Nye County\NV_Nye R3" was chosen. Values for the climate of Nevada Nye R3 were imported into RUSLE2.

The soil survey for Nye County Southwest Part was used to determine the soil type prevalent at the US Ecology Facility. The prevalent soil type and the one used in RUSLE 2 is the Yermo, hot-Yermo-Arizo association. Values for this soil type were imported as a database file in RUSLE2.

The crop management zone is set using the construction site template provided in RUSLE2 for CMZ Zone 31 and assumes contouring with no row grading. The construction site template assumes newly disturbed soil with no vegetation. All other management options were left as default.

For modeling Trenches 11 and 12 at the US Ecology site, three slopes were analyzed. The longest slope length for each slope type (i.e., 5%, 33%, and 50%) was assumed as a worst case scenario. See attached figures for the longest slope length applicable to each slope segment and the corresponding length used in the RUSLE2 model.

| Slope (ft/ft) | Slope Length (Along Slope) | Slope Length (Horizontally) |
|---|---|---|
| 20:1 or 5% | 125 | ~125 |
| 3:1 or 33% | 220 | 207 |
| 2:1 or 50% | 26.8 | 22 |

**ANALYSIS**

Erodibility is calculated using soil type and the soil's hydrologic class. In RUSLE2, these values are not editable and therefore, site-specific values (such as grain size) obtained during on-site soil testing could not be used as inputs. The RUSLE2 model was run using the default values for the Yermo, hot-Yermo-Arizo association and then re-run using the generic soil type, "gravely sand 15 to 60 percent coarse fragments," that most closely approximates the soil type estimated for use in the cover construction.

RUSLE2 allows the user to specify a rock cover. A 100 percent rock cover was modeled to assess the benefit of a rock cover on the cover. Rock is defined by RUSLE2 as non-decomposing surface material and must be sufficiently large not to be moved by raindrop impact or surface runoff. The minimum rock size that is measured is site-specific, but as a guideline, the minimum rock size is 10 millimeter, or 3/8 inch diameter.

The analysis was first run assuming no rock cover and then again using 100 percent rock cover for each slope segment. Analysis also was done for site soils according to the soil survey; however, since soils used to form the Trench 11 and Trench 12 covers will not come only from surface soils present at the facility surface, the generic soil type (i.e., gravelly sand, 15 to 60 percent coarse fragments), more closely matching that sampled at the US Ecology site also was modeled. The results of these analyses are shown on the attached "RUSLE2 Erosion Calculation Record" sheets.

All but one of the calculated erosion rates are less than the 2 tons per acre per year USEPA-recommended maximum rate[2]. The Yermo, soil with 220 feet length along the 3:1 slope, eroded at 2.2 tons per acre per year assuming that there is no rock cover. With 100 percent rock cover, all soil erosion losses are below the USEPA recommended 2 tons per acre per year.

The soil loss tolerance value assigned by NRCS as a standard for protecting soil as natural resource, but not for sediment yield, is 5 tons per acre per year for the Yermo, hot-Yermo-Arizo association. All calculated values are below the NRCS soil loss tolerance value.

## CONCLUSION

Using regional input values believed to be a reasonable representation of site conditions, the calculated estimates of surface erosion by water on the various cover slope sections do not exceed the USEPA recommendations for maximum erosion rate for a landfill cover. This conclusion is applicable to uses of native soil types in the Trench 11 and 12 final covers without special attention to placement of a surficial layer specifically intended to reduce surface erosion. In fact, the native soil type intended for final cover construction will be sufficiently coarse-grained to be considered an "erosion reduction" layer without special treatment (such as, use of a grizzly or screen). Also, no special attention in cover design I s needed to reduce erosion potential by shortening cover slope sections. Thus, no benches or otherwise engineered flattening of slopes is required to reduce erosion potential.

---

[2] Handbook Remedial Action at Waste Disposal Sites (Revised). October 1985. EPA/625/6-85/006

USDA NRCS Natural Resources Conservation Service

Rusle Program Version:
Rusle Science Version:
Data Base:

AquAeTer
Project Number 073113
Project Name Beatty
Prepared By CAB Date 11/8/07
Checked By ARM Date 12/7/07
Page 5 of 6

# RUSLE2 Erosion Calculation Record

**File:** plans\Beatty-Yermo
**Access Group:** R2_NRCS_Fld_Office

**Inputs:**

| *Owner name* | *Location* | *Info* |
|---|---|---|
| **AquAeTer for US Ecology** | **Nevada\Nye County\NV_Nye R 3** | **Trench 12 Cross Section B (Slope from 2860 ft (msl) to base of slope.** |

| *Field name* | *Soil* | *Slope T Value* | *Slope length, ft* | *Slope steepness, %* |
|---|---|---|---|---|
| 5% slope on top of Trench 12 | Nye SW, NV785\2054 YERMO, HOT-YERMO-ARIZO ASSOCIATION\YERMO very gravelly sandy loam 30% | 5.0 | 125 | 5.0 |
| 3:1 slope on Trench 12 | Nye SW, NV785\2054 YERMO, HOT-YERMO-ARIZO ASSOCIATION\YERMO very gravelly sandy loam 30% | 5.0 | 207 | 33 |
| 2:1 slope around bsase of Trench 12 | Nye SW, NV785\2054 YERMO, HOT-YERMO-ARIZO ASSOCIATION\YERMO very gravelly sandy loam 30% | 5.0 | 22.0 | 50 |

**Results:**

| *Field name* | *Description* | *Management* | *Contouring system* | *Support practices* | *Terrace/diversion system* | *Cons. plan. soil loss, t/ac/yr* | *Sed. delivery* | *Fuel cost, US$/ac* |
|---|---|---|---|---|---|---|---|---|
| 5% slope on top of Trench 12 | 0 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 0.17 | 0.17 | 0 |
| 5% slope on top of Trench 12 | 100 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 0.0100 | 0.0100 | 0 |
| 3:1 slope on Trench 12 | 0 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 2.2 | 2.2 | 0 |
| 3:1 slope on Trench 12 | 100 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 0.082 | 0.082 | 0 |
| 2:1 slope around bsase of Trench 12 | 0 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 0.94 | 0.94 | 0 |
| 2:1 slope around bsase of Trench 12 | 100 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 0.033 | 0.033 | 0 |

USDA NRCS Natural Resources Conservation Service

Rusle Program Version:
Rusle Science Version:
Data Base:

AquAeTer
Project Number 073113
Project Name BEATTY
Prepared By CAB Date 11/8/07
Checked By APM Date 12/07/07
Page 6 of 6

# RUSLE2 Erosion Calculation Record

**File:** plans\Beatty-Gravely Sand
**Access Group:** R2_NRCS_Fld_Office

**Inputs:**

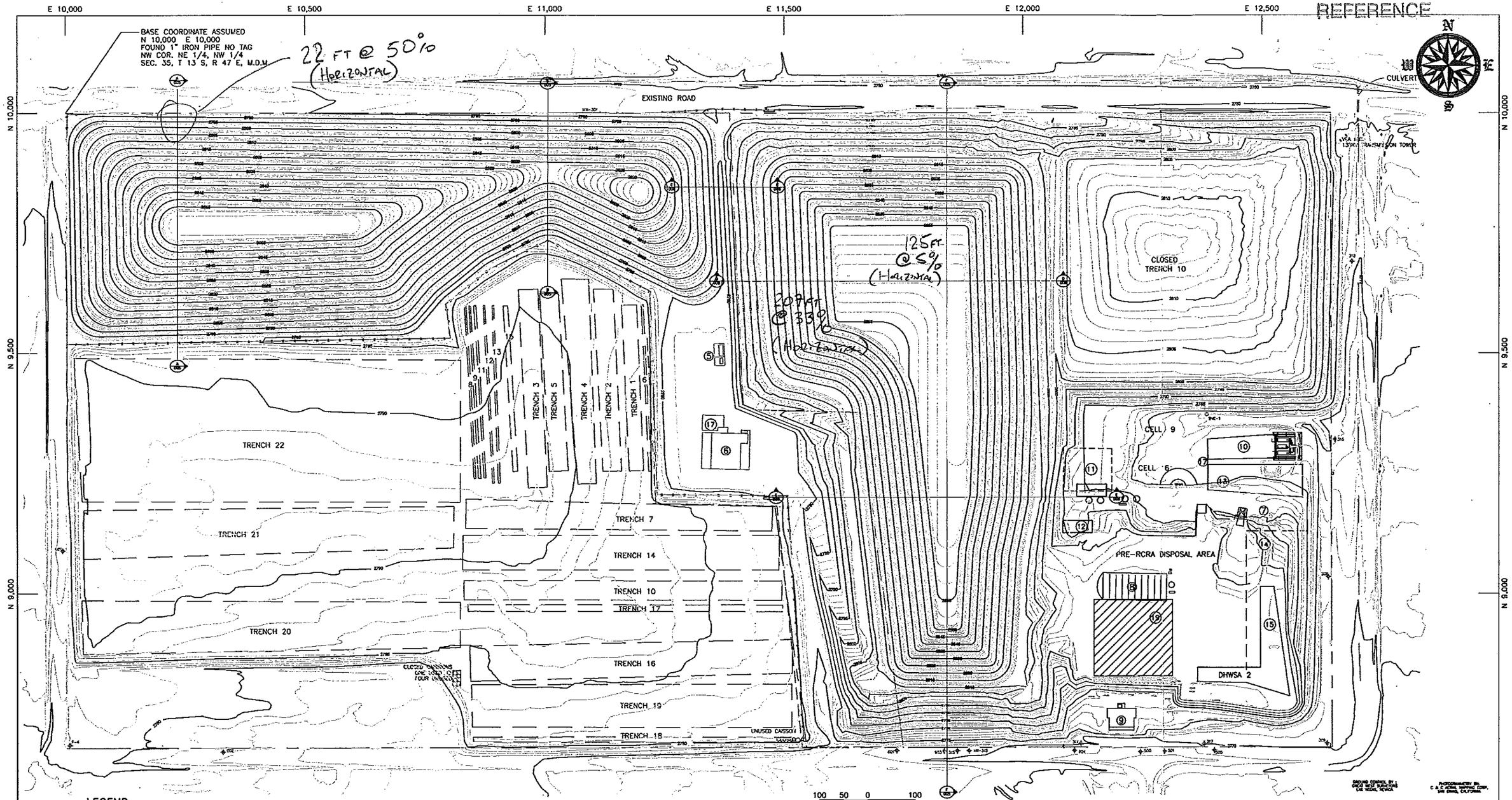
| *Owner name* | *Location* | *Info* |
|---|---|---|
| **AquAeTer for US Ecology** | **Nevada\Nye County\NV_Nye R 3** | **Trench 12 Cross Section B (Slope from 2860 ft (msl) to base of slope.** |

| *Field name* | *Soil* | *Slope T Value* | *Slope length, ft* | *Slope steepness, %* |
|---|---|---|---|---|
| 5% slope on top of Trench 12 | Generic Soils\gravely sand 15 to 60 pct coarse fragments | 3.0 | 125 | 5.0 |
| Trench 11 | Generic Soils\gravely sand 15 to 60 pct coarse fragments | 3.0 | 207 | 33 |
| 2:1 slope around base of Trench 12 | Generic Soils\gravely sand 15 to 60 pct coarse fragments | 3.0 | 22.0 | 50 |

**Results:**

| *Field name* | *Description* | *Management* | *Contouring system* | *Support practices* | *Terrace/diversion system* | *Cons. plan. soil loss, t/ac/yr* | *Sed. delivery* | *Fuel cost, US$/ac* |
|---|---|---|---|---|---|---|---|---|
| 5% slope on top of Trench 12 | 0 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 0.037 | 0.037 | 0 |
| 5% slope on top of Trench 12 | 100 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 0.0020 | 0.0020 | 0 |
| Trench 11 | 0 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 0.48 | 0.48 | 0 |
| Trench 11 | 100 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 0.48 | 0.48 | 0 |
| 2:1 slope around base of Trench 12 | 0 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 0.18 | 0.18 | 0 |
| 2:1 slope around base of Trench 12 | 100 percent rock cover | CMZ 31\d.Construction Site Templates\default | c. perfect contouring no row grade | -- none -- | -- none -- | 0.18 | 0.18 | 0 |

CALCULATION REFERENCE




## LEGEND

- HORIZONTAL CONTROL LINE
- PERMIT LINE
- DRAINAGE DITCH AND DIRECTION OF FLOW
- PROPERTY LINE
- FENCE LINE
- MONITOR WELL LOCATION AND NUMBER
- SOIL VAPOR EXTRACTION WELL
- 1' CONTOUR INTERVAL, FEET (MSL)
- 5' CONTOUR INTERVAL, FEET (MSL)
- TRENCH 1 — LOW LEVEL RADIOLOGICAL WASTE TRENCH

⑤ FUEL STORAGE
⑥ MAINTENANCE SHOP
⑦ LOW TEMPERATURE THERMAL DESORPTION
⑧ TRUCK PARKING
⑨ EVAPORATION TANK
⑩ PCB PROCESSING AREA
⑪ BATCH STABILIZATION TANK AND SILOS
⑫ STABILIZATION TANKS
⑬ THERMAL TREATMENT AREA
⑭ LOW TEMPERATURE THERMAL DESORPTION FUTURE EXPANSION
⑮ DRY HAZARDOUS WASTE STORAGE AREA
⑲ CONTAINER MGNT./STABL. BUILDING

| REV. | DESCRIPTION | DRWN. BY | DSGN. BY | CHECK BY | APP'D BY | DATE |
|---|---|---|---|---|---|---|
| A | ISSUED FOR USE REVIEW | LAM | CAB | | SLW | 12/26/07 |

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PROJECT NUMBER: 073113 DATE: 12/5/07

BEATTY NEVADA
HAZARDOUS WASTE MANAGEMENT FACILITY

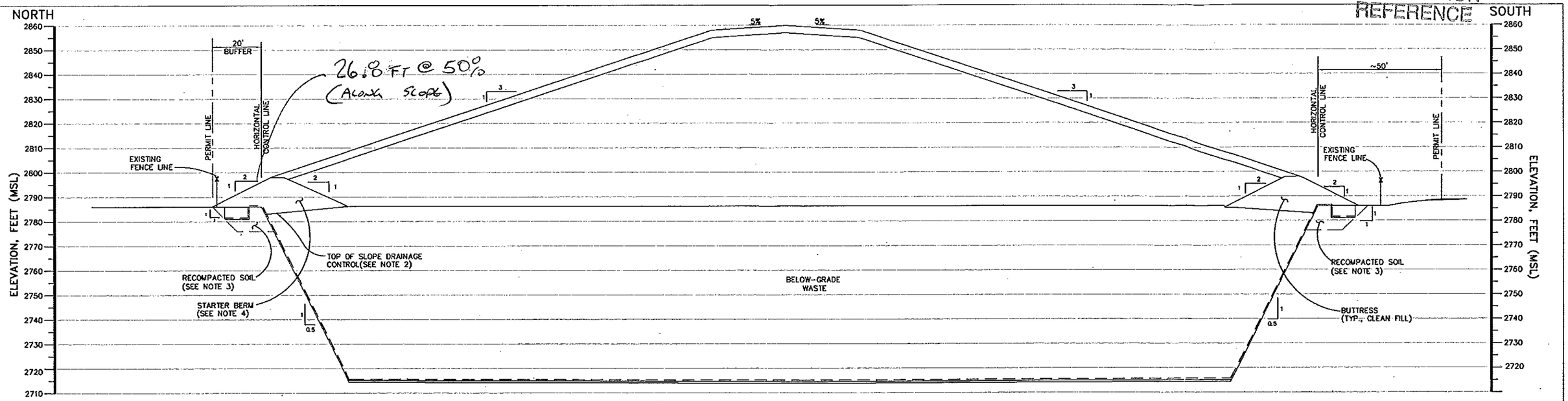
FINAL COVERS
LANDFILL TRENCHES 11 & 12

| DRWN. BY | DATE | DSGN. BY | DATE | CHKD. BY | DATE | APP'D BY | SCALE | JOB NO. | DRAWING NO. | REV. |
|---|---|---|---|---|---|---|---|---|---|---|
| LAM | 12/26/07 | CAB | 12/26/07 | SLW | 12/26/07 | SLW | 1"=100' | 073113 | NV12-07-009 | 0 |

CAD FILE NAME: F:\Data\073113\T12 Design Package\abovegrade design\NV12-07-009.dwg

PLOT DATE: 12/26/07

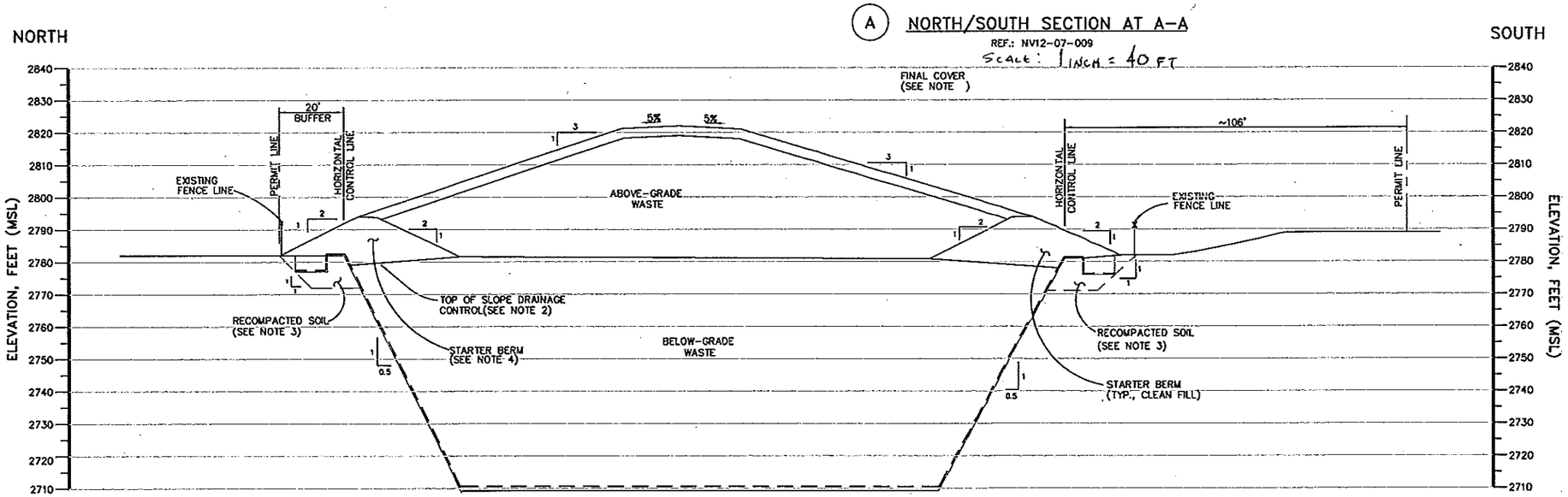
CALCULATION REFERENCE




(A) NORTH/SOUTH SECTION AT A-A

REF.: NV12-07-009

SCALE: 1 INCH = 40 FT




(B) NORTH/SOUTH SECTION AT B-B

REF.: NV12-07-009

SCALE 1 INCH = 40 FEET

SECTION LEGEND

LINER SYSTEM

20 10 0 20
SCALE FEET

NOTES:

1. ANCHOR TRENCHES ARE USED TO SECURE LINER SYSTEMS WHILE EXCAVATIONS ARE BEING FILLED.
2. KEEP WASTE 3' BELOW TOP OF SLOPE UNTIL CONSTRUCTION OF STARTER BERM.
3. RECOMPACTED SURFACE SOIL LIMITS ARE SHOWN NOMINALLY AS 10' BELOW THE TOP OF SLOPE, 10' WIDE (OFFSET TOWARD THE PERMIT LINE). ACTUAL DIMENSIONS WILL BE DETERMINED IN THE FIELD BASED ON ACTUAL DEPTH OF LOOSE SOIL.
4. STARTER BERM IS COMPACTED SOIL. FILL MATERIAL CAN INCLUDE CLEAN, NATIVE SOIL AND SELECT SOIL WASTE. SELECT SOIL WASTE, IF USED, MUST BE PLACED ONLY OVER LINED AREAS AND MUST SATISFY MATERIAL GRADATION AND COMPACTION SPECIFICATIONS.

| REV. | DESCRIPTION | DRWN. BY | DSGN. BY | CHECK BY | APP'D BY | DATE |
|---|---|---|---|---|---|---|
| A | ISSUED FOR US ECOLOGY REVIEW | LAM | CAB | SLW | SLW | 12/26/07 |

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PROJECT NUMBER: 073113 DATE: 12/26/07

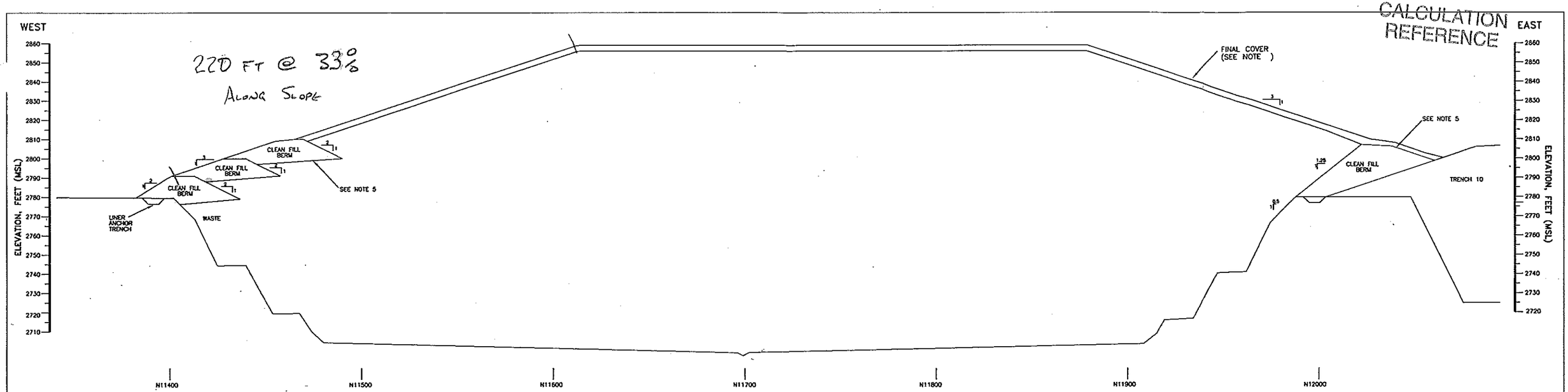
BEATTY NEVADA
HAZARDOUS WASTE MANAGEMENT FACILITY

CROSS SECTIONS A-A AND B-B
TRENCH 12

| DRWN. BY | DATE | DSGN. BY | DATE | CHKD. BY | DATE | APP'D BY | SCALE | JOB NO. | DRAWING NO. | REV. |
|---|---|---|---|---|---|---|---|---|---|---|
| LAM | 12/26/07 | CAB | 12/26/07 | SLW | 12/26/07 | SLW | | 073113 | NV12-07-010 | 0 |

CAD FILE NAME: F:\Data\073113\T12 Design Package\above-grade design\NV12-07-010.dwg PLOT DATE: 12/26/07

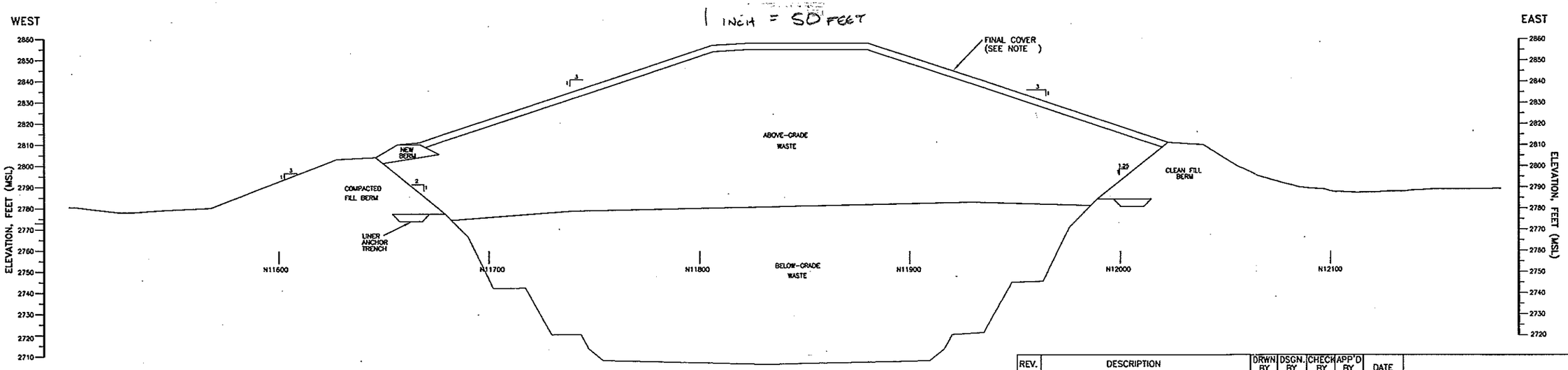
CALCULATION REFERENCE




E NORTH/SOUTH SECTION AT E-E

REF. NV12-02-005

1 INCH = 50 FEET




F NORTH/SOUTH SECTION AT F-F

REF. NV12-02-005

1 INCH = 50 FT

NOTES:

1. ANCHOR TRENCHES ARE USED TO SECURE LINER SHEETS WHILE EXCAVATING THE BERMS FLUSH
2. KEEP A MINIMUM 3' BELOW TOP OF SLOPE UNTIL CONSTRUCTION OF EXTERIOR BERM
3. RECOMPACTED SURFACE SOIL LIFTS ARE SHOWN SCHEMATIC AS 18" BELOW THE TOP OF SLOPE, 18" WIDE (OFFSET TOWARD THE BERM LINE). ACTUAL DIMENSIONS WILL BE DETERMINED IN THE FIELD BASED ON ACTUAL DEPTH OF LOOSE SOIL
4. PREPARATION SUBGRADE THICKNESS BENEATH BERMS IS 18 INCHES
5. TRENCH 11 FEATURES, OTHER THAN FINAL COVER, INCLUDING COMPACTED SOIL BERMS, ALREADY HAVE BEEN CONSTRUCTED

| REV. | DESCRIPTION | DRWN BY | DSGN. BY | CHECK BY | APP'D BY | DATE |
|---|---|---|---|---|---|---|
| A | ISSUED FOR US ECOLOGY REVIEW | LAM | CAB | SLW | SLW | 12/26/07 |

| DRWN. BY | DATE | DSGN. BY | DATE | CHKD. BY | DATE | APP'D BY | SCALE |
|---|---|---|---|---|---|---|---|
| LAM | 12/26/07 | CAB | 12/26/07 | SLW | 12/26/07 | SLW | |

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PROJECT NUMBER: 073113 DATE: 12/26/07

BEATTY NEVADA
HAZARDOUS WASTE MANAGEMENT FACILITY

CROSS SECTIONS D-D, E-E
AND LINER DETAILS, TRENCH 12

| JOB NO. | DRAWING NO. | REV. |
|---|---|---|
| 073113 | NV12-07-012 | 0 |

CAD FILE NAME: F:\Data\073113\T12 Design Package\above-grade design\NV12-07-012.dwg PLOT DATE: 12/26/07

CALCULATION
REFERENCE

EPA/625/6-85/006

# HANDBOOK
# REMEDIAL ACTION AT WASTE DISPOSAL SITES (REVISED)

OCTOBER 1985

HAZARDOUS WASTE ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

OFFICE OF EMERGENCY AND REMEDIAL RESPONSE
OFFICE OF SOLID WASTE AND EMERGENCY RESPONSE
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

CALCULATION
REFERENCE

support the weight of the entire cap and not abrade the liner. If a clay or similarly fine grained soil liner is to be used, the underlying base must be sufficiently fine to preclude piping of the liner. Piping occurs when sections of an overlying fine-grained soil layer erode and fall into an underlying coarser grained soil layer (Matrecon, Inc., 1983). Piping may be prevented by placement of a suitably fine-meshed filter fabric between the two layers.

The drainage layer of the multi-layered cap is placed directly above the low permeability layer. The permeability of the drainage layer should be sufficiently high that it minimizes contact of infiltrating rainwater with the low permeability layer (Lutton, 1982). Current designs generally specify a material with greater than or equal to $10^{-3}$ cm/sec permeability (Cope et al., 1984). This layer can be composed of a sand in the SW or SP range of USCS (less than 5 percent passing through a number 100 sieve) or a coarser material. The thickness of the drainage layer depends on the amount of settling expected and the maximum volume of water that could enter it. The vegetative layer of the multi-layer cap is placed above the drainage layer, usually with a layer of filter fabric in between to prevent piping. The vegetative layer usually exceeds 2 feet in thickness, but may be greater depending on the frost depth, the maximum depth of root penetration, and the rate of anticipated soil loss. The frost depth must not be allowed to reach the low permeability layer because freezing and thawing cycles could greatly increase its permeability. The selection of a vegetative cover should include consideration of root penetration, erosion potential, and competitive advantage over other plant species in the area. These factors can be determined by consulting with local botany professors. Erosion potential of the soil, however can occur even when the vegetative cover has good soil retaining capabilities. Therefore, it is recommended that the soil in the vegetative layer have an erosion rate of less than 2 tons per acre, per year, using the U.S. Department of Agriculture Universal Soil Loss Equation (USLE). This equation is written:

$$A = R \times K \times L \times S \times C \times P$$

Where:

A = average spoil loss in tons/acre for time period used for R

quantitative:

R = rainfall and run-off erosivity index
K = soil erodibility factor
L = slope length factor
S = slope steepness factor

qualitative:

C = cover/management factor
P = supporting practices factor

Directions for determining variables are given in Lutton, Regan, and Jones (1979) pp. 127-133. For information regarding soil sampling and testing, for local data on soils and climate, or for any form of technical assistance regarding selection of cover materials, regional and county Soil Conservation Services (SCS) offices should be consulted.

CALCULATION REFERENCE

The Handbook of Groundwater Engineering - Google Book Search - Microsoft Internet Explorer

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Address http://books.google.com/books?id=qehl6itzdPwC&pg=PT788&lpg=PT788&dq=epa+recommended+erosion+less+than+2+%22tons+acre%22&source=web&ots=obEZfXFCy6&sig=phBtJmkb25

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About this book | Preview this book | The Handbook of Groundwater Engineering By Jacques W. Delleur

In addition to the landfill berms, sedimentation/detention basins may also include perimeter berms. These berms require low permeability in addition to strength.

### 23.5.4 Storm Water Management Systems

Storm water management systems typically consists of two parts. One part controls runoff on the landfill itself to prevent erosion of the final cover; the other part is external to the landfill, and its objective is to prevent runon to the landfill from the surrounding areas. Subtitle D specifies that storm water management systems be designed to collect and control at least the water volume resulting from the 24-hour, 25-year storm. Some state regulations also require verification of the outlet structures of sedimentation/detention basins for the 100-year storm.

The runoff control system on the landfill consists generally of a system of benches/channels located on the final cover. It is difficult to control runoff without benches, although it is possible for flat or short slopes. The vertical distance between the benches/channels is generally selected such that erosion of the final cover, calculated by the U.S. Department of Agriculture Universal Soil Loss Equation, does not exceed 2 tons/acre/year as recommended by the EPA (USEPA, 1982). An additional criterion for selecting the vertical distance between benches/channels is to prevent the surface water flow regime changing from sheet flow to shallow concentrated flow. By preventing this change in the flow regime, the storm water has less energy with which it can mobilize soil. Final cover channels are designed with minimal longitudinal slope, more or less paralleling the final cover contours. Depending on the flow velocity the channels may be lined with grass or rip-rap.

The final cover channels generally discharge into gabion-lined downchutes that convey the flow downslope. A gabion lining is generally used for the downchutes because of their ability to withstand uneven settlements and the relatively high water velocities resulting from steep slopes. Sometimes pipes are also used to convey the flow downslope. The downchutes, in turn, discharge to other channels that convey the flow to sedimentation/detention basins. These other channels typically collect runoff from the final cover and runon from the surrounding areas, and discharge to sedimentation basins which are often converted to detention basins after closure of the facility.

Subtitle D and some state regulations typically require the design of runon and runoff control systems for the 25-year, 24-hour storm event. Methods outlined by the U.S. Department of Agriculture, Soil Conservation Service in the publication entitled, *TR-55: Urban Hydrology for Small Watersheds* (USDA, 1986), are generally used to calculate flow rates for the design of storm water control structures.

### 23.5.5 Leachate Collection and Removal Systems

The leachate collection system (LCS) is a drainage system located on the bottom of the landfill, immediately above the primary liner. The purpose of the LCS is to collect leachate from the waste and to convey it to sumps, where it is removed from the cell. The LCS comprises a high-permeability collection layer, which often contains perforated pipes in swales surrounded by gravel. The collection layer generally consists of gravel, and the perforated pipes are made of HDPE or PVC; crushing resistance of the collection pipes is a critical design factor. Subtitle D requires the LCS be designed to maintain less than one foot of leachate head over the liner. The LCS transfers the leachate to sumps located at the lowest point of each cell, preferably adjacent to the toe of the inside slope of the perimeter berm.

The leachate removal system may consist of either a gravity flow pipe passing through the perimeter berm, a riser pipe which parallels the inside slope of the perimeter berm, or a vertical manhole which daylights out of the final cover (see Figure 23.4). The latter two systems require submersible pumps to remove the leachate. Removal by means of a gravity flow pipe passing through the perimeter berm avoids the need for pumping, but requires a liner penetration that may affect liner performance.

The leachate removed from the cells is generally conveyed by a header pipe to holding tanks or ponds. The header pipe may be gravity or force, depending on the site topography. The holding tanks or ponds

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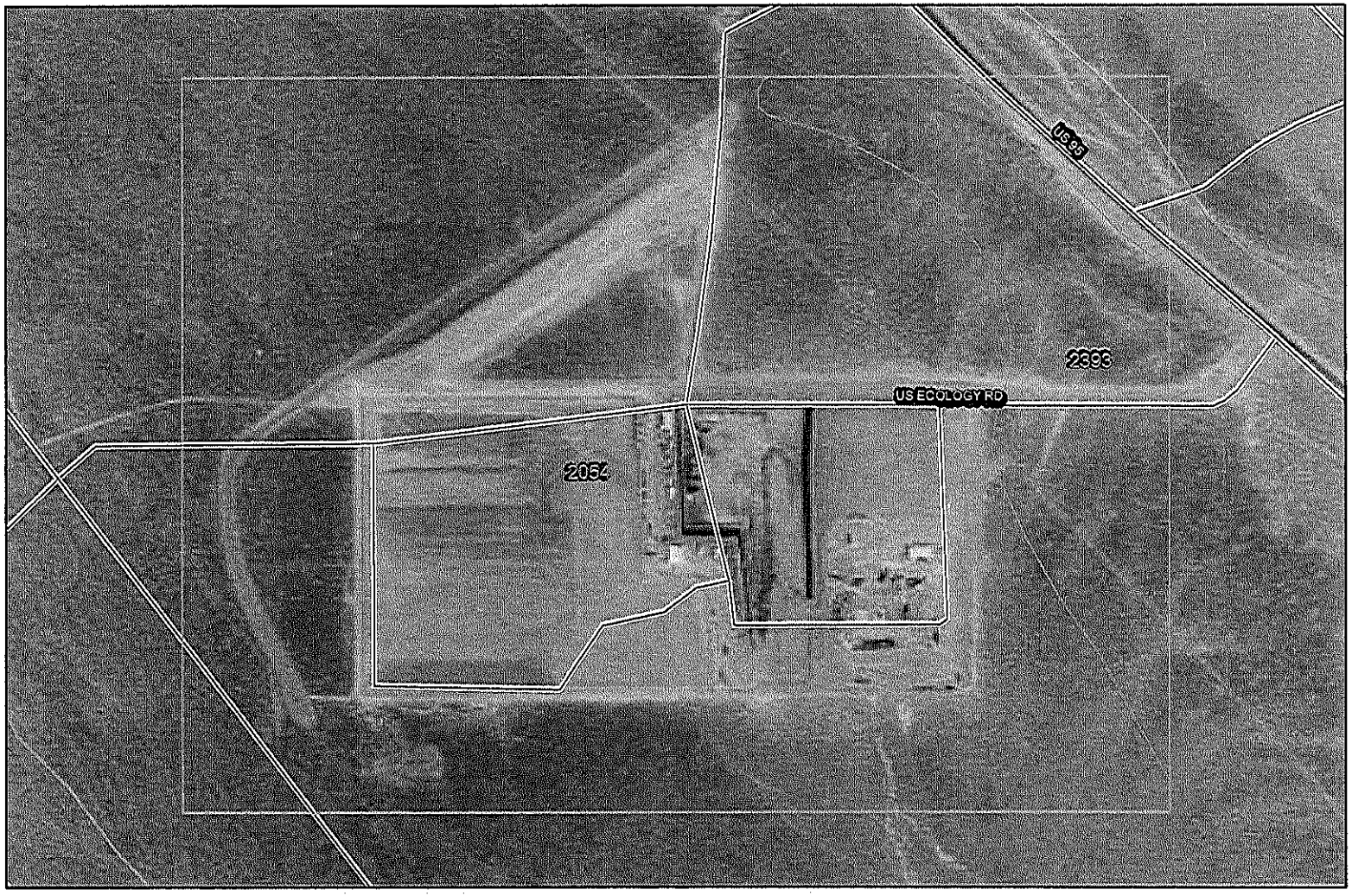
Done

Soil Map–Nye County, Nevada, Southwest Part
(USEN)




N

0 100 200 400 600 Meters

0 500 1,000 2,000 3,000 Feet

USDA Natural Resources Conservation Service

Web Soil Survey 2.0
National Cooperative Soil Survey



CALCULATION REFERENCE

## MAP LEGEND

**Area of Interest (AOI)**
- Area of Interest (AOI)

**Soils**
- Soil Map Units

**Special Point Features**
- Blowout
- Borrow Pit
- Clay Spot
- Closed Depression
- Gravel Pit
- Gravelly Spot
- Landfill
- Lava Flow
- Marsh
- Mine or Quarry
- Miscellaneous Water
- Perennial Water
- Rock Outcrop
- Saline Spot
- Sandy Spot
- Severely Eroded Spot
- Sinkhole
- Slide or Slip
- Sodic Spot
- Spoil Area
- Stony Spot
- Very Stony Spot
- Wet Spot
- Other

**Special Line Features**
- Gully
- Short Steep Slope
- Other

**Political Features**

**Municipalities**
- Cities
- Urban Areas

**Water Features**
- Oceans
- Streams and Canals

**Transportation**
- Rails

**Roads**
- Interstate Highways
- US Routes
- State Highways
- Local Roads
- Other Roads

## MAP INFORMATION

Original soil survey map sheets were prepared at publication scale. Viewing scale and printing scale, however, may vary from the original. Please rely on the bar scale on each map sheet for proper map measurements.

Source of Map: Natural Resources Conservation Service
Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov
Coordinate System: UTM Zone 11N

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: Nye County, Nevada, Southwest Part
Survey Area Data: Version 3, Oct 5, 2006

Date(s) aerial images were photographed: 6/2/1994

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

CALCULATION REFERENCE

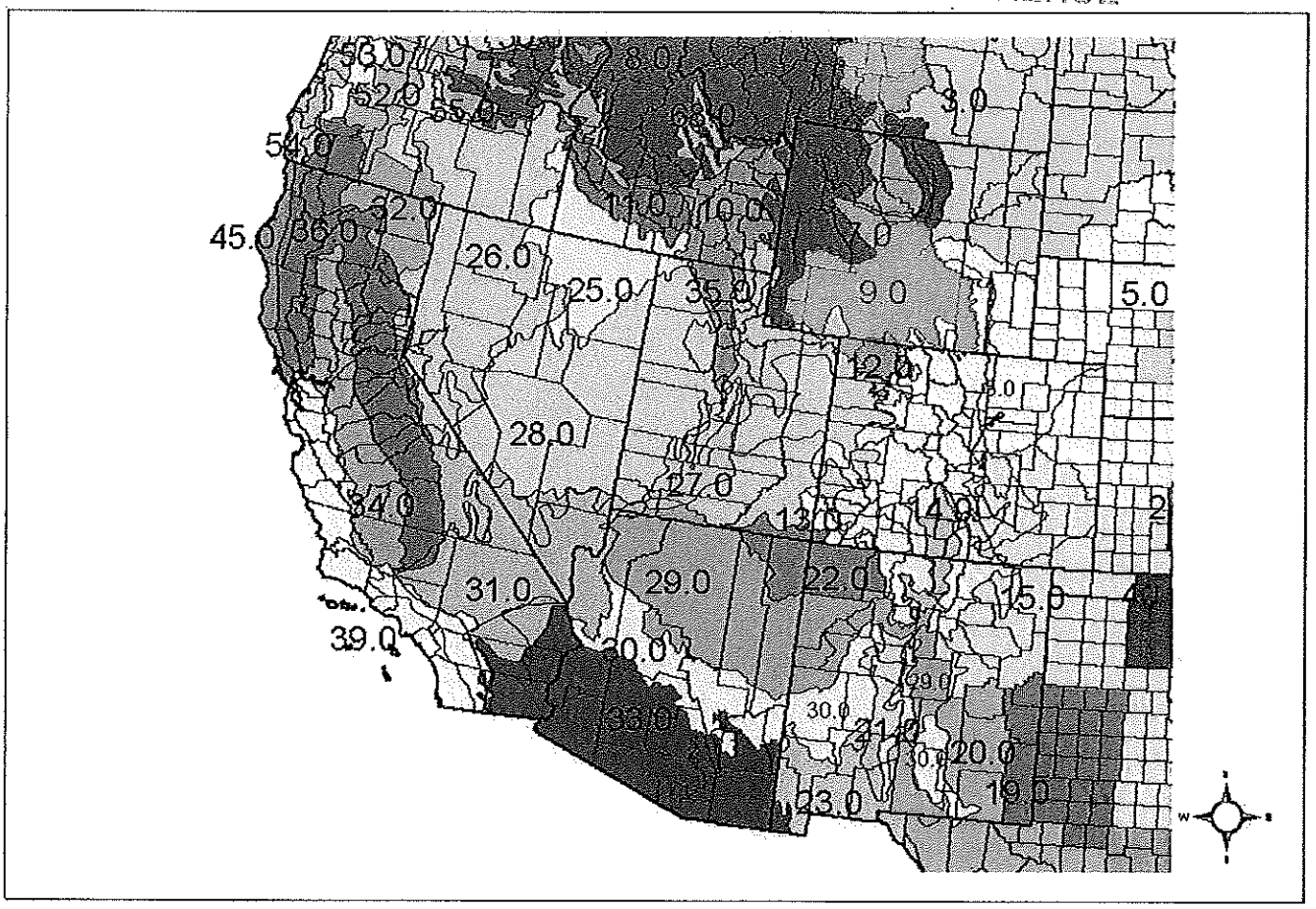
CALCULATION REFERENCE



# Map Unit Legend

| Nye County, Nevada, Southwest Part (NV785) | | | |
|---|---|---|---|
| Map Unit Symbol | Map Unit Name | Acres in AOI | Percent of AOI |
| 2054 | Yermo, hot-Yermo-Arizo association | 285.4 | 86.9% |
| 2393 | Commski-Yermo association | 43.0 | 13.1% |
| Totals for Area of Interest (AOI) | | 328.4 | 100.0% |

CALCULATION REFERENCE



CALCULATION REFERENCE



# RUSLE2 Related Attributes

This report summarizes those soil attributes used by the Revised Universal Soil Loss Equation Version 2 (RUSLE2) for the map units in the selected area. The report includes the map unit symbol, the component name, and the percent of the component in the map unit. Soil property data for each map unit component include the hydrologic soil group, erosion factors Kf for the surface horizon, erosion factor T, and the representative percentage of sand, silt, and clay in the surface horizon.

## Report—RUSLE2 Related Attributes

| RUSLE2 Related Attributes– Nye County, Nevada, Southwest Part | | | | | | | |
|---|---|---|---|---|---|---|---|
| Map symbol and soil name | Pct. of map unit | Hydrologic group | Kf | T factor | Representative value | | |
| | | | | | % Sand | % Silt | % Clay |
| 2054—Yermo, hot-Yermo-Arizo association | | | | | | | |
| Yermo, hot | 40 | B | .24 | 5 | 67.4 | 19.6 | 13.0 |
| Yermo | 30 | B | .24 | 5 | 67.4 | 19.6 | 13.0 |
| Arizo | 15 | A | .32 | 5 | 67.8 | 23.7 | 8.5 |
| 2393—Commski-Yermo association | | | | | | | |
| Commski | 70 | B | .32 | 5 | 66.1 | 19.9 | 14.0 |
| Yermo | 25 | B | .24 | 5 | 67.4 | 19.6 | 13.0 |

## Data Source Information

Soil Survey Area: Nye County, Nevada, Southwest Part
Survey Area Data: Version 3, Oct 5, 2006

# Summary of Soil Testing Results for Trench 12 Samples

| Sample Number | Material | Grain Size (% by weight) | | | Amendment | ASTM D1557 Maximum Dry Density (pcf) (see Note 1) | ASTM D1557 Optimum Moisuture Content (%) | Hydraulic Conductivity Sample Properties | | | | Hydraulic Conductivity (cm/sec) | Direct Shear Test Sample Properties | | | | Cohesion (psf) | Friction Angle (degrees) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Gravel | Sand | Silt/Clay | | | | Dry Density (psf) | % MDD | Moisture Content (%) | Difference from OMC % + or (-) | | Dry Density (psf) | % MDD | Moisture Content (%) | Difference from OMC % + or (-) | | |
| **June-July 2007 Samples: Trench 12 samples for various trench construction objectives (subgrade, sump gravel, surface soil improvement, and final cover)** | | | | | | | | | | | | | | | | | | |
| **Zeolite clay (ZC)** | Imported fines | 24.0 | 23.0 | 53.0 | -- | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | |
| **A1** | Subgrade | 31.0 | 59.7 | 9.3 | -- | 120.5 | 11.0 | 123.4 | 102.4% | 9.3 | (1.7) | 3.90E-07 | -- | -- | -- | -- | -- | -- |
| **A2** | Subgrade | 29.0 | 69.0 | 2.0 | -- | 114.5 | 6.0 | 117.0 | 102.2% | 6.1 | 0.1 | 2.60E-04 | -- | -- | -- | -- | -- | -- |
| **A2** | Subgrade | 47.0 | 48.1 | 4.9 | 5% Pit Run ZC | 106.0 | 7.0 | 106.5 | 100.5% | 6.8 | (0.2) | 5.30E-04 | -- | -- | -- | -- | -- | -- |
| **A3** | Subgrade | 21.0 | 74.8 | 4.2 | -- | 120.0 | 10.0 | 119.3 | 99.4% | 10.4 | 0.4 | 5.55E-04 | -- | -- | -- | -- | -- | -- |
| | | | | | | | | | | | | | | | | | | |
| **B1** | Gravel | 97.0 | 2.6 | 0.4 | -- | -- | -- | 88.3 (wet) | -- | -- | -- | 1.7 | -- | -- | -- | -- | -- | -- |
| **B1** | Gravel | 98.0 | 1.6 | 0.4 | -- | -- | -- | 88.1 (wet) | -- | -- | -- | 2.1 | -- | -- | -- | -- | -- | -- |
| | | | | | | | | | | | | | | | | | | |
| **C1** | Surface soil | 14.0 | 76.7 | 9.3 | -- | 115.0 | 9.5 | -- | -- | -- | -- | -- | 110.9 | 96.5% | 8.7 | (0.8) | 420 | 32.8 |
| **C2** | Surface soil | 20.0 | 70.9 | 9.1 | -- | 119.0 | 10.0 | -- | -- | -- | -- | -- | 114.2 | 95.9% | 8.4 | (1.6) | 320 | 39.9 |
| **C1-C2** | Surface soil | 17.0 | 72.0 | 11.0 | 5% Pit Run ZC | 118.0 | 10.0 | -- | -- | -- | -- | -- | 112.9 | 95.6% | 10.4 | 0.4 | 320 | 41.1 |
| | | | | | | | | | | | | | | | | | | |
| **D1** | Cover soil | 22.0 | 74.7 | 3.3 | -- | 118.5 | 12.0 | -- | -- | -- | -- | -- | 100.8 | 85.1% | 15.1 | 3.1 | 210 | 34.5 |
| **D2** | Cover soil | 26.0 | 68.8 | 5.2 | -- | 122.5 | 10.5 | -- | -- | -- | -- | -- | 101.3 | 82.7% | 12.5 | 2.0 | 130 | 36.7 |
| **D1-D2** | Cover soil | 30.0 | 62.6 | 7.4 | 5% Pit Run ZC | 124.0 | 9.5 | -- | -- | -- | -- | -- | 103.1 | 83.1% | 13.0 | 3.5 | 270 | 36.2 |
| **September-October 2007 Samples: Possible subgrade improvement samples** | | | | | | | | | | | | | | | | | | |
| **Mix 1** | Trench 12 material | 37 | 55 | 8 | 5% IMVite 1016 | 127.5 | 8.0 | 114.5 | 89.8% | 8.1 | 0.1 | 1.15E-05 | | | | | | |
| **Mix 2** | Trench 12 material | 38 | 51 | 11 | 10% IMVite 1016 | 127.5 | 8.5 | 114.9 | 90.1% | 8.5 | 0.0 | 6.32E-06 | | | | | | |
| **Mix 3** | Trench 12 material | 45 | 41 | 14 | 15% IMVite 1016 | 124.5 | 9.0 | 112.7 | 90.5% | 7.5 | (1.5) | 5.54E-06 | | | | | | |
| **Mix 4** | Trench 12 material | 46 | 42 | 12 | 10% SEP/SAP | 124.0 | 9.5 | 113.0 | 91.1% | 9.1 | (0.4) | 6.13E-06 | | | | | | |
| **Mix 5** | Trench 12 material | 45 | 39 | 16 | 15% SEP/SAP | 122.0 | 10.0 | 110.7 | 90.7% | 9.8 | (0.2) | 6.24E-06 | | | | | | |
| **Mix 6** | Trench 12 material | 47 | 45.5 | 7.5 | 5% Portland Cement | 128.0 | 7.5 | 115.5 | 90.2% | 7.3 | (0.2) | 6.68E-07 | | | | | | |
| **Mix 7** | Trench 12 material | 42 | 50.2 | 7.8 | 5% SEP/SAP | 127.0 | 8.0 | 114.5 | 90.2% | 8.0 | 0.0 | 8.34E-06 | | | | | | |

**NOTES** Values are not corrected for the presence of over-size materials

-- Indicates that the test was not run on this sample.

IMVite 1016 and SEP/SAP are clay products of IMV Nevada, Amargosa Valley NV

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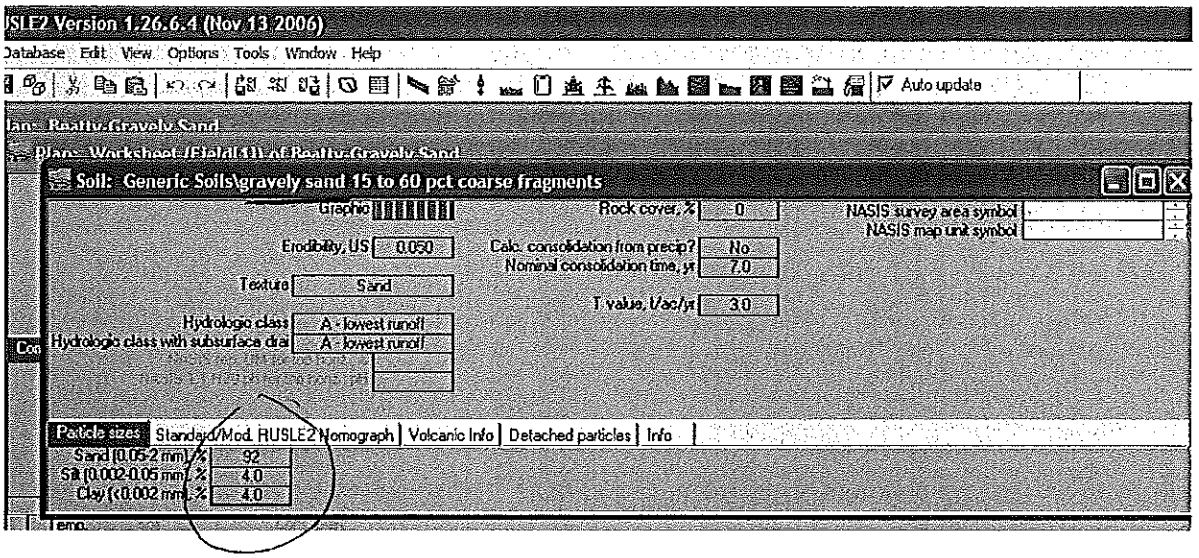

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# CALCULATION SUMMARY SHEET



PROJECT NUMBER: 073113

PROJECT NAME: USEN – Trench 12 Design, Supplemental Calculations

DATE: February 26, 2008

CALCULATION NUMBER: _____ Revision: _____

**CALCULATION TITLE: Soil Cover Erosion Due to Wind Using US NRCS WEPS model**

**DESCRIPTION OF CALCULATION:**

This calculation determines the rate of soil cover erosion of the Trench 11 and 12 surfaces using the Wind Erosion Prediction System (WEPS).

**REFERENCES USED:** Number of Reference Pages Attached: (several)

WEPS Version 1.0 (Release IECA 2008)

**REVIEW COMMENTS:**

CALCULATION MADE BY: CAB DATE: February 26, 2008

CALCULATION CHECKED BY: SLW DATE: February 27, 2008

CALCULATION REVISED BY: _____ DATE: _____

CALCULATION REVIEWED BY: SLW DATE: February 27, 2008

# CALCULATION

## RATE OF SOIL COVER EROSION BY WIND

### PURPOSE

This calculation estimates soil loss by wind erosion from the proposed final covers for Trenches 11 and 12 at the US Ecology Beatty Facility.

### APPROACH

The U.S. Natural Resources Conservation Service (NRCS) Wind Erosion Prediction System (WEPS) model is used for this analysis. WEPS is used to estimate expected soil loss (as soil weight per surface area unit) based on soil properties, wind and climate history for a local weather station, and site geography.

The Wind Erosion Equation (WEQ), upon which WEPS is based, is widely used for estimating soil loss by wind from agricultural fields. The functional form of WEQ is:

$$E = f(I, C, K, L, V)$$

Where, E is the average soil loss (tons/acre/year), I is the soil erodibility, K is the soil ridge roughness, C is the climatic factor, L is the field length along the prevailing wind erosion direction, and V is the vegetative factor.

WEPS is a process-based, daily time-step model that simulates weather, field conditions, and erosion to predict wind erosion. The WEPS model allows the use of uploaded region-specific database information to determine the WEQ soil loss factors. For the Trench 11 and 12 wind erosion estimates, the following three databases were uploaded:

1. Climate Data (Beatty 8N);
2. Soil Data (Nye SW, NV785\2054 Yermo, Hot-Yermo-Arizo Association); and
3. Crop Management Template (CMZ-31)

Climate: The first WEPS input is climate data based on the location input. For the US Ecology Beatty facility, the location "State: Nevada, County: Nye, Longitude: 116.69°W, Latitude: 36.77°N, Elevation: 847 meters" was selected. Natural ground surface is approximately 2780 feet above mean sea level. Based on proximity to the site, the climate factors for the monitoring station "Beatty 8N" and the "Desert Rock" wind monitoring station at Mercury were used.

Soil: The soil survey for Nye County Southwest Part, was used to determine the surface soil type prevalent at the US Ecology Facility. The prevalent soil type and the one used in the WEPS erosion estimate is the Yermo, hot-Yermo-Arizo association. This soil type was considered to be sufficiently similar to the expected final cover materials for use in the soil loss estimate.

Crop Management. The crop management zone was set using the construction template provided in RUSLE2 for CMZ Zone 31. The RUSLE database file for CMZ Zone 31 was converted to a WEPS database file. The construction site template assumes non-vegetated disturbed soil that has been modified using certain combinations of construction or agricultural equipment. In this instance, the soil surface modifications assumed included 1) filling and leveling by bulldozer, 2) heavy disking, and 3) weed growth beginning in the second year after disturbance.

## SOIL LOSS ESTIMATE

The WEPS model simulation used a basic area shape (e.g., rectangle, square, circle, or quarter circle), site-specific dimensions, and an orientation (relative to wind direction) as input for the model run. For Trenches 11 and 12 at the US Ecology site, both areas were modeled as flat-lying rectangles. Trench 11 was modeled as a rectangle with an x-length of 210 meters and a y-length of 396 meters. Trench 12 was modeled as a rectangle with an x-length of 418 meters and a y-length of 145 meters. Both simulations were run with an orientation of 0 degrees (i.e. x-length runs east-west and y-length runs north-south).

| Trench | Area (ha) | Gross Soil Loss (kg/m2) | Gross Soil Loss (tons/acre) |
|---|---|---|---|
| Trench 11 | 8.3 | 0.88 | 3.9 |
| Trench 12 | 6.1 | 0.62 | 2.8 |

Estimates gross loss (by wind erosion) from each trench cover was converted from kilograms per square meter ($kg/m^{2)}$ to tons per acre.

For Trench 11: $$0.88\frac{kg}{m^2} * 4047\frac{m^2}{acre} * 0.0011\frac{ton}{kg} = 3.9\frac{tons}{acre}$$

For Trench 12: $$0.62\frac{kg}{m^2} * 4047\frac{m^2}{acre} * 0.0011\frac{ton}{kg} = 2.8\frac{tons}{acre}$$

## LIMITATIONS

WEPS is intended to estimate erosion from flat-lying agricultural fields that are managed for production of various crop types. The model allows for consideration of certain adjoining topographic features (such as wind breaks) that modify wind direction and velocity, but does not estimate erosion from complex geometric shapes, such as a landfill cover. Also, surface preparation and crop management inputs to the model probably do not accurately reflect the

early history of a closed landfill. As a result, the accuracy of the wind erosion estimate is uncertain.

**CONCLUSION**

The soil loss tolerance value assigned by NRCS as a standard for protecting soil as natural resource, but not for sediment yield, is five tons per acre per year for the Yermo, hot-Yermo-Arizo association in this natural desert setting. Both calculated values are below this NRCS soil loss tolerance value.

Wind erosion is assumed to result in uniform soil removal over a broad area and not in a manner than tends to concentrate soil removal (such as rill erosion by water). Accordingly, consideration of the significance of surface soil removal (or thinning) is pertinent. The soil loss caused by wind erosion was analyzed for the potential of thinning the cover to the point of exposing waste. Using the erosion rate estimated for the orientation of Trench 11, and assuming that cover soil is placed with a density of 100 lbs per square foot or approximately 1.35 tons per cubic yard, the following soil loss is estimated.

For one year: $3.9\frac{tons}{acre} * \frac{1}{1.35}\frac{yd^3}{tons} * \frac{1}{43{,}560}\frac{acre}{ft^2} * \frac{27}{1}\frac{ft^3}{yd^3} = 0.0018\,ft$ of soil loss per year

or 0.022 inches of soil loss per year

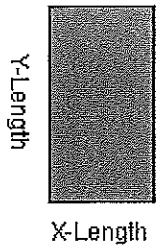
For 30 years: 0.65 inches of soil loss

# WEPS

## Model Runs

# WEPS Run Summary

**Client** USEN
**Farm No** **Tract No** Trench 11 **Field No**
**Run Name** UNEN Run 2_18
**Run Location** USEN Run 2
**Management** Construction site
**Soil** Arizo_2054_15_GRV_SL




**Simulation & Site Information**

**Mode :** NRCS **Soil Loss T:** 5 T/ac/yr
**State :** Nevada **Latitude :** 36.77 °N
**County :** Nye **Longitude :** 116.69 °W

**Field Dimension Information**

**X-Length :** 210 m **Elevation :** 847 m
**Y-Length :** 396 m **Orientation :** 0.0 °
**Area :** 8.32 ha

**Weather Station / Files**

**Cligen Station :** BEATTY 8 N
**Wingen Station :** MERCURY/DESERT ROCK

| Period | Crop | Gross Loss (kg/m^2) | Net Soil Loss From Field (kg/m^2) Total | Creep/Salt. | Suspension | PM10 |
|---|---|---|---|---|---|---|
| Rot. yr: 1 | | 0.80 | 0.80 | 0.439 | 0.360 | 0.0220 |
| Rot. yr: 2 | | 0.96 | 0.96 | 0.568 | 0.394 | 0.0244 |
| Ave. Annual | | 0.88 | 0.88 | 0.504 | 0.377 | 0.0232 |

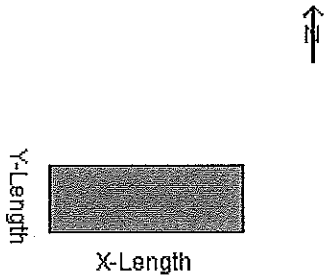
| Date | Operation | Crop |
|---|---|---|
| Mar 15, 01 | Bulldozer, filling-leveling | |
| Mar 30, 01 | Disk, offset, heavy | |
| Mar 15, 02 | Begin weed growth | no crop |

**Run specific information:**

**Date Created:** Feb 26, 2008 10:41

# WEPS Run Summary

**Client** USEN
**Farm No** **Tract No** Trench 12 **Field No**
**Run Name** UNEN Run 2_19
**Run Location** USEN Run 2
**Management** Construction site
**Soil** Arizo_2054_15_GRV_SL




**Simulation & Site Information**

**Mode :** NRCS **Soil Loss T:** 5 T/ac/yr
**State :** Nevada **Latitude :** 36.77 °N
**County :** Nye **Longitude :** 116.69 °W

**Field Dimension Information**

**X-Length :** 418 m **Elevation :** 847 m
**Y-Length :** 145 m **Orientation :** 0.0 °
**Area :** 6.06 ha

**Weather Station / Files**

**Cligen Station :** BEATTY 8 N
**Wingen Station :** MERCURY/DESERT ROCK

| 'eriod | Crop | Gross Loss (kg/m^2) | Net Soil Loss From Field (kg/m^2) Total | Creep/Salt. | Suspension | PM10 |
|---|---|---|---|---|---|---|
| Rot. yr: 1 | | 0.51 | 0.51 | 0.343 | 0.171 | 0.0098 |
| Rot. yr: 2 | | 0.73 | 0.73 | 0.477 | 0.256 | 0.0155 |
| Ave. Annual | | 0.62 | 0.62 | 0.410 | 0.214 | 0.0127 |

| Date | Operation | Crop |
|---|---|---|
| Mar 15, 01 | Bulldozer, filling-leveling | |
| Mar 30, 01 | Disk, offset, heavy | |
| Mar 15, 02 | Begin weed growth | no crop |

**Run specific information:**

**Date Created:** Feb 26, 2008 12:09

# References

CALCULATION REFERENCE

topozone

Create 3D With A Camera - PhotoModeler software for modeling and measuring from photos www.photomodeler.com

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- Large

**View Scale**
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**Coordinate Format**
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**Map Datum**
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## USGS Carrara Canyon (NV) Topo Map

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36.7700°N, 116.6900°W (NAD83/WGS84)

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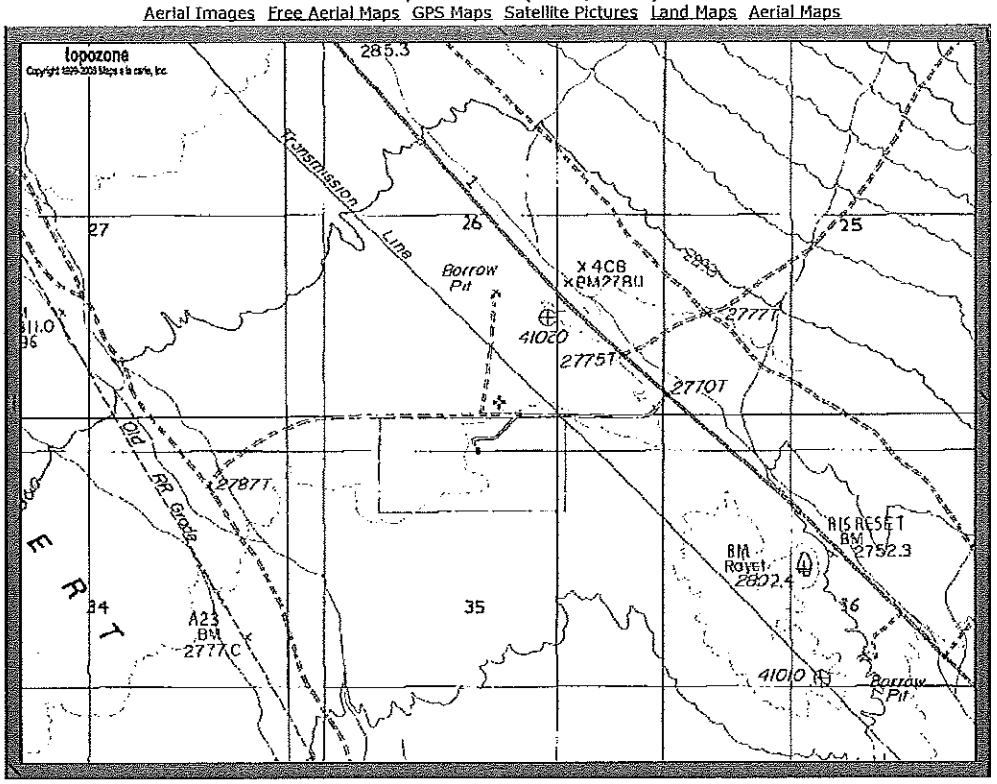


Print Map | Download MapPack | Bookmark Map | Email Map

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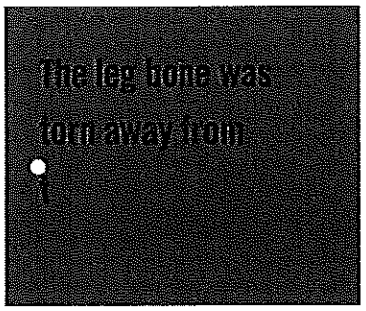
0 0.4 0.8 1.2 1.6 2 mi

M=13.258
G=0.186
What's this?

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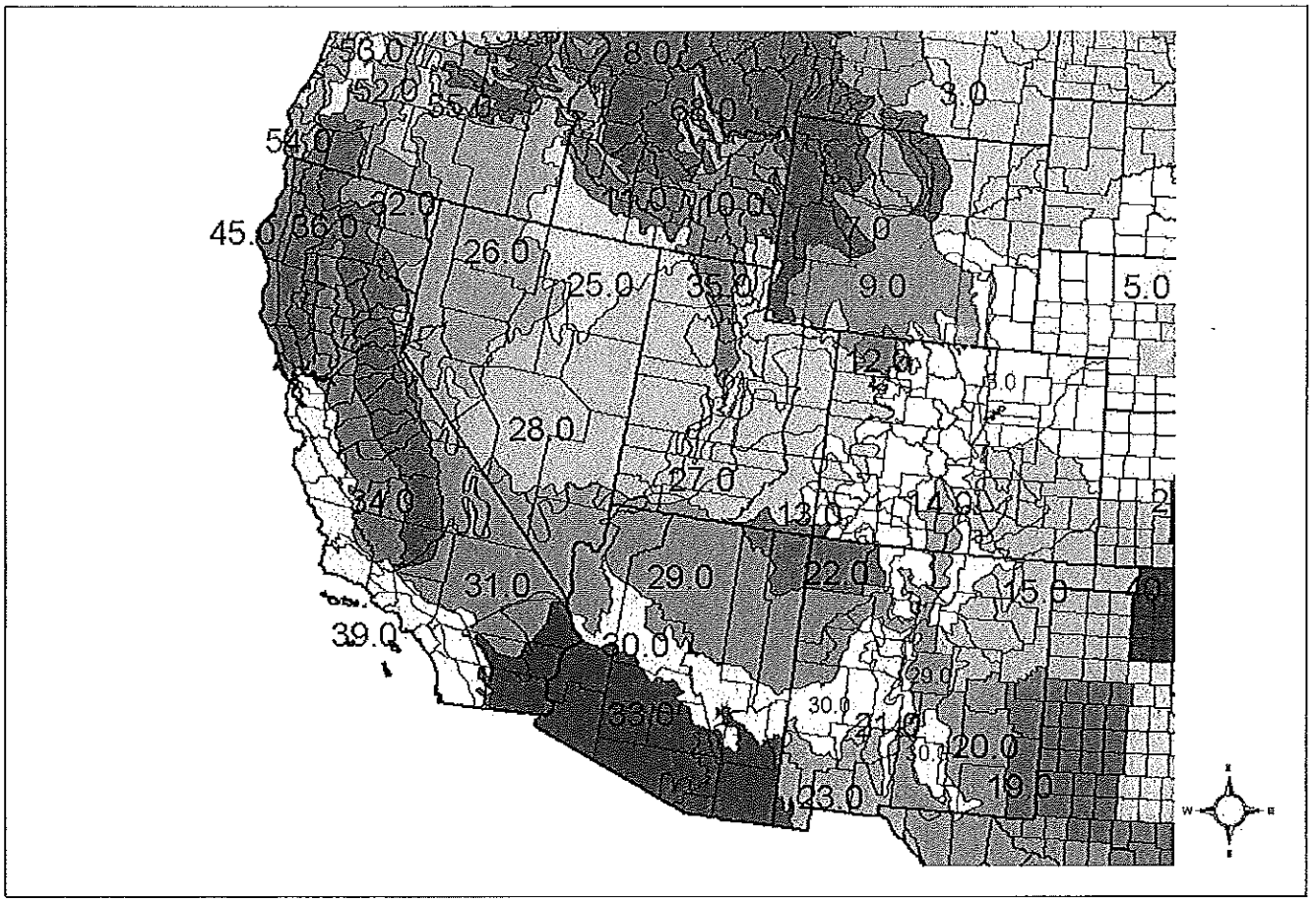

073113 CALCULATION DATA REFERENCE

2

CALCULATION
REFERENCE



## MAP LEGEND

**Area of Interest (AOI)**
- Area of Interest (AOI)

**Soils**
- Soil Map Units

**Special Point Features**
- Blowout
- Borrow Pit
- Clay Spot
- Closed Depression
- Gravel Pit
- Gravelly Spot
- Landfill
- Lava Flow
- Marsh
- Mine or Quarry
- Miscellaneous Water
- Perennial Water
- Rock Outcrop
- Saline Spot
- Sandy Spot
- Severely Eroded Spot
- Sinkhole
- Slide or Slip
- Sodic Spot
- Spoil Area
- Stony Spot
- Very Stony Spot
- Wet Spot
- Other

**Special Line Features**
- Gully
- Short Steep Slope
- Other

**Political Features**

**Municipalities**
- Cities
- Urban Areas

**Water Features**
- Oceans
- Streams and Canals

**Transportation**
- Rails

**Roads**
- Interstate Highways
- US Routes
- State Highways
- Local Roads
- Other Roads

## MAP INFORMATION

Original soil survey map sheets were prepared at publication scale. Viewing scale and printing scale, however, may vary from the original. Please rely on the bar scale on each map sheet for proper map measurements.

Source of Map: Natural Resources Conservation Service
Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov
Coordinate System: UTM Zone 11N

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: Nye County, Nevada, Southwest Part
Survey Area Data: Version 3, Oct 5, 2006

Date(s) aerial images were photographed: 6/2/1994

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

## Map Unit Legend

| Nye County, Nevada, Southwest Part (NV785) | | | |
|---|---|---|---|
| Map Unit Symbol | Map Unit Name | Acres in AOI | Percent of AOI |
| 2053 | Yermo-Greyeagle-Arizo association | 14.9 | 2.8% |
| 2054 | Yermo, hot-Yermo-Arizo association | 458.9 | 86.4% |
| 2393 | Commski-Yermo association | 57.6 | 10.8% |
| Totals for Area of Interest (AOI) | | 531.4 | 100.0% |



CALCULATION REFERENCE

CALCULATION REFERENCE

BASE COORDINATE ASSUMED
N 10,000 E 10,000
FOUND 1" IRON PIPE NO TAG
NW COR. NE 1/4, NW 1/4
SEC. 35, T 13 S, R 47 E, M.D.M.

E 10,000 | E 10,500 | E 11,000 | E 11,500 | E 12,000 | E 12,500

N 10,000 | N 9,500 | N 9,000

1370 FT

696 FT

1300 FT

EXISTING ROAD

CULVERT

CLOSED TRENCH 10

CELL 9

CELL 6

PRE-RCRA DISPOSAL AREA

DHWSA 2

TRENCH 12 X ≅ 418 M

Y ≅ 145 M

TRENCH 22

TRENCH 21

TRENCH 20

TRENCH 1

TRENCH 2

TRENCH 3

TRENCH 4

TRENCH 5

TRENCH 7

TRENCH 14

TRENCH 10

TRENCH 17

TRENCH 16

TRENCH 19

TRENCH 18

UNUSED CASSON

TRENCH 11 X ≅ 210 M

Y ≅ 396 M

SCALE 10 50 0 100 FEET

NOTE:
1. REACHES ARE PERIMETER DITCHES WHICH HAVE A UNIFORM CROSS-SECTION. DITCH CONFIGURATIONS ARE SHOWN IN DETAIL 1 ON DRAWING 013.

## LEGEND

- HORIZONTAL CONTROL LINE
- PERMIT LINE
- DRAINAGE DITCH AND DIRECTION OF FLOW
- PROPERTY LINE
- FENCE LINE
- MONITOR WELL LOCATION AND NUMBER
- SOIL VAPOR EXTRACTION WELL
- 1' CONTOUR INTERVAL, FEET (MSL)
- 5' CONTOUR INTERVAL, FEET (MSL)
- TRENCH 1 — LOW LEVEL RADIOLOGICAL WASTE TRENCH

⑤ FUEL STORAGE
⑥ MAINTENANCE SHOP
⑦ LOW TEMPERATURE THERMAL DESORPTION
⑧ TRUCK PARKING
⑨ EVAPORATION TANK
⑩ PCB PROCESSING AREA
⑪ BATCH STABILIZATION TANK AND SILOS
⑫ STABILIZATION TANKS
⑬ THERMAL TREATMENT AREA
⑭ LOW TEMPERATURE THERMAL DESORPTION FUTURE EXPANSION
⑮ DRY HAZARDOUS WASTE STORAGE AREA
⑱ CONTAINER MGMT./STAB. BUILDING

| REV. | DESCRIPTION | DRWN BY | DSGN BY | CHECK BY | APP'D BY | DATE |
|---|---|---|---|---|---|---|
| A | ISSUED FOR US ECOLOGY REVIEW | LAM | CAB | | SLW | 12/26/07 |

*an American Ecology company*

PROJECT NUMBER: 073113 DATE: 12/26/07

BEATTY NEVADA
HAZARDOUS WASTE MANAGEMENT FACILITY

FINAL COVERS
LANDFILL TRENCHES 11 & 12

| DRWN. BY | DATE | DSGN. BY | DATE | CHKD. BY | DATE | APP'D BY | SCALE | JOB NO. | DRAWING NO. | REV. |
|---|---|---|---|---|---|---|---|---|---|---|
| LAM | 12/26/07 | CAB | 12/26/07 | SLW | 12/26/07 | SLW | 1"=100' | 073113 | NV12-07-009 | 0 |

CAD FILE NAME: F:\Data\073113\T12 Design Package\abovegrade design\NV12-07-009.dwg

PLOT DATE: 12/26/0

CALCULATION REFERENCE

DOC.20061002.0012

QA: QA

ANL-NBS-MD-000009 REV 03

September 2006

BECHTEL SAIC COMPANY LLC

# Soil-Related Input Parameters for the Biosphere Model

Prepared for:
U.S. Department of Energy
Office of Civilian Radioactive Waste Management
Office of Repository Development
1551 Hillshire Drive
Las Vegas, Nevada 89134-6321

Prepared by:
Bechtel SAIC Company, LLC
1180 Town Center Drive
Las Vegas, Nevada 89144

Under Contract Number
DE-AC28-01RW12101

CALCULATION
REFERENCE



Table 6.2-1. Major Types of Agricultural Soils Occurring in Amargosa Valley

| Map Unit | Soil Series | Percent of Map Unit | Soil Series Texture and Description |
|---|---|---|---|
| 2054 Yermo, hot-Yermo-Arizo association | Yermo | 70 | Very gravelly sandy loam; the Yermo series consists of deep, well-drained soils that formed in alluvium from mixed rocks. |
| | Arizo | 15 | Very gravelly sandy loam; the Arizo series consists of very deep, excessively drained soil that form in alluvium derived from mixed rocks. |
| 2070 Shamock | Shamock | 90 | Gravelly fine sandy loam; the Shamock series consists of moderately deep over a duripan well drained soils that formed in alluvium derived from mixed rocks. |
| 2152 Arizo | Arizo | 85 | Very gravelly sandy loam (see description above) |
| 2153 Arizo-Corbilt-Commski association | Arizo | 35 | Very gravelly sandy loam (see description above) |
| | Commski | 25 | Very gravelly fine sandy loam; the Commski series consists of very deep, well-drained soils that formed in alluvium derived from limestone. |
| | Corbilt | 25 | Gravelly fine sandy loam; the Corbilt series consists of very deep, well drained soils that formed in alluvium derived from mixed rocks. |
| 2451 Sanwell-Sanwell, warm-Yermo association | Sanwell | 65 | Gravelly fine sandy loam; the Sanwell series consists of very deep, well-drained soils that form in coarse lacustrine sediments. |
| | Yermo | 20 | Very gravelly sandy loam (see description above) |

Source: USDA 2004 [DIRS 173916], Part I, Detailed Soil Map Units, Classification of the Soils, Taxonomic Units and their Properties; and Maps 40, 41, 46, and 47.

NOTE: Only the major soil series for a given map unit are listed, consistent with the description of soil properties in USDA 2004 [DIRS 173916], Part II.

From inspection of the density values in Table 6.2-2, the lower and upper values of soil density were 1.3 g $cm^{-3}$ and 1.7 g $cm^{-3}$ respectively. For stochastic modeling, it is recommended that the distribution of density be triangular over this range with a mode at the mid-point 1.5 g $cm^{-3}$. If a deterministic value is required, then the moist soil density can be taken as 1.5 g $cm^{-3}$ (the mid-point of the range).

It should be noted that the bulk density ranges for the other minor constituents of soils units occurring in Amargosa Valley (USDA 2004 [DIRS 173916], Part I), not shown in Table 6.2-2, are consistent with the values for the soil series within those units (USDA 2004 [DIRS 173916], Part II, Table 12). This indicates that the moist bulk density ranges for Amargosa Valley soils are consistent among soil series.

Table 6.2-2. Physical Properties of Soils in Amargosa Valley

| Soil Series | Depth, in | | Clay Content Range, % | | Moist Bulk Density Range, g/cm$^3$ | | Available Water Capacity, in/in | | Organic Matter, % | T Factor[a] tons/acre/yr | Wind Erodibility Group |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Lower Limit | Upper Limit | Lower Limit | Upper Limit | Lower Limit | Upper Limit | Lower Limit | Upper Limit | Maximum | | |
| Arizo | 0 | 8 | 5 | 12 | 1.40 | 1.55 | 0.05 | 0.07 | 0.5 | 5 | 5 |
| | 8 | 60 | 0 | 5 | 1.45 | 1.65 | 0.04 | 0.06 | | | |
| Corbilt | 0 | 4 | 5 | 10 | 1.35 | 1.50 | 0.06 | 0.09 | 0.5 | 4 | 5 |
| | 4 | 32 | 5 | 10 | 1.35 | 1.55 | 0.11 | 0.13 | | | |
| Shamock | 0 | 4 | 3 | 8 | 1.50 | 1.70 | 0.10 | 0.12 | 0.8 | 2 | 4 |
| | 4 | 37 | 5 | 10 | 1.55 | 1.70 | 0.09 | 0.11 | | | |
| Yermo | 0 | 6 | 8 | 18 | 1.40 | 1.60 | 0.06 | 0.08 | 0.5 | 5 | 5 |
| | 6 | 60 | 8 | 18 | 1.40 | 1.60 | 0.06 | 0.08 | | | |
| Commski | 0 | 5 | 10 | 18 | 1.40 | 1.60 | 0.06 | 0.08 | 0.5 | 5 | 5 |
| | 5 | 14 | 5 | 15 | 1.40 | 1.60 | 0.04 | 0.06 | | | |
| Sanwell | 0 | 9 | 5 | 10 | 1.40 | 1.60 | 0.10 | 0.13 | 0.5 | 5 | 4 |
| | 9 | 16 | 5 | 10 | 1.30 | 1.50 | 0.08 | 0.12 | | | |

Source: USDA 2004 [DIRS 173916], Part II, Table 12.

[a] T Factor is an estimate of the maximum average annual rate of soil erosion by wind or water that can occur without affecting crop productivity over a sustained period (Troeh et al. 1980 [DIRS 110012], Section 6-1). The rate is in tons per acre per year. This parameter is only applicable to the surface layer that is available for erosion.



CALCULATION REFERENCE