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NUMERICAL EVALUATION OF MONOFIL AND SUBTLE-LAYERED EVAPOTRANSPIRATION (ET) LANDFILL CAPS

prepared by

Glenn V. Wilson, Maren Henley, and Rob Valceschini

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January 1998

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prepared by

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EXECUTIVE SUMMARY

The U.S. Department of Energy/Nevada Operations Office (DOE/NV) has identified the need to design a low-level waste (LLW) closure cap for the arid conditions at the Nevada Test Site (NTS). As a result of concerns for subsidence impacting the cover, DOE/NV redesigned the LLW cover from one containing a “hard” infiltration barrier that would likely fail, to a “soft” (ET) cover that is sufficiently deep to accommodate the hydrologic problems of subsidence. An ET cover is one that does not contain hydrologic barrier layers but relies on soil-water retention and sufficient thickness to store water until evapotranspiration (ET) can remove the moisture. Subtle layering within an ET cap using the native soil could be environmentally beneficial and cost effective.

One of the primary concerns with the monofil ET cover design is the lack of layering to disrupt vertical preferential flowpaths. However, the performance of engineered layers such as capillary barriers is not warranted for the hydrogeologic conditions of the NTS, and the long-term stability of such dramatically contrasting layers is highly questionable. An alternative that was investigated in this report is to incorporate layers with subtle differences in compaction and/or particle size distributions. Screening the borrow source material at the coarse sand (< 2 mm) or fine-gravel (< 5 mm) sizes would not only provide material for constructing a desert armoring surface layer but would result in a thinner cover.

To evaluate this subtle layering design, physical and hydraulic properties of the borrow source material were analyzed and used in unsaturated flow simulations to evaluate various cap designs. The results of the particle size analysis showed that by the USDA soil classification scheme, the Area 3 material is a gravelly loamy sand with about 35% gravel size mass fractions. Compaction tests were run on the < 19 mm, < 5 mm, and < 2 mm size fractions. The respective maximum dry bulk densities were 1.91, 1.84, and 1.84 g cm⁻³ and their associated optimum moisture contents were 11.5, 12.5, and 14.0% by weight, respectively. The saturated hydraulic conductivity, and water retention characteristics were determined on these three size fractions compacted to 83% and 90% maximum dry density, and on the 5 to 2 mm size fraction at the best achievable bulk density. A larger reduction in saturated hydraulic conductivity was achieved by differences in particle size fractions than by compaction. Differences in water retention characteristics were small between compaction and particle size fractions.

These data were incorporated into the computer model, HYDRUS-2D, to simulate infiltration through unsaturated soil for a 100 yr-6 hour storm event for various cover designs. If infiltration moves preferentially through only 5% of the cross-sectional area, the monofil cover would need to be 26% thicker on average to limit infiltration. However, if subtle layering is incorporated into the cover, the thickness could be reduced by 15 to 60% depending upon the number of layers and arrangement. This report recommends that a subtle-layered ET cover should consist of a surface armoring layer from 0 to 15 cm deep, and a loamy sand layer compacted to 90% maximum density at the 45 to 60 cm depth with the intermediate layer and base consisting of the original borrow source material compacted at only 83% maximum density. The thickness of the base layer, essentially the operational cover now in existence, would be determined by the thickness necessary to accommodate subsidence by providing the minimum standard for waste coverage. Simulations based upon this

design for a year consisting of the maximum monthly rainfall recorded over a 30-year period on the NTS, applied as individual storm events at the first of each month, followed by the 100 yr-6 hour event the first day of the second year, showed that infiltration would be limited to less than 75 cm. Subtle layers not only provide redundancy in protection to the thickness, they may also provide a reduction in risk to human health and the environment, and a reduction in overall life-cycle costs by facilitating savings in long-term monitoring requirements.

CONTENTS

EXECUTIVE SUMMARY	ii
LIST OF FIGURES	v
LIST OF TABLES	vi
INTRODUCTION	1
OBJECTIVES	8
NUMERICAL METHODS	8
HYDRUS-2D	10
MATERIALS AND METHODS	10
Particle Size Analysis	10
Modified Proctor Compaction Test	11
Water Retention	11
Constant-Head Hydraulic Conductivity	12
RESULTS	12
Particle Size Analysis	12
Modified Proctor Compaction Test	13
Constant-Head Hydraulic Conductivity	13
Water Retention	14
Cover Design Evaluations Using HYDRUS-2D	16
CONCLUSIONS AND RECOMMENDATIONS	32
REFERENCES	34
Appendix A: Particle Size Analysis Data	
Appendix B: Modified Proctor Compaction Test Data	
Appendix C: Saturated Hydraulic Conductivity Data	
Appendix D: Water Retention Data	

FIGURES

1. Map of the NTS showing the Area 3 and 5 Radioactive Waste Management Sites (reprinted from Johnnejack <i>et al.</i> , 1995)	1
2. Diagram of an ET monofil cover design.	2
3. Diagram of a prescriptive RCRA Title C cover design	3
4. Spatial distribution of cumulative drainage from the bottom of an undisturbed sand block at (a) 4.5 m depth (Kinsall <i>et al.</i> , 1997) and (b) 5.9 m depth (Wilson <i>et al.</i> , 1997)	4
5. Diagram of a Capillary Barrier cover design.	5
6. Illustration of hydrologic impacts of subsidence on covers with barrier layers	6
7. Diagram of a subtle-layered ET cover design	6
8. Mass fractions, expressed as percent by weight, of the particle sizes	13
9. Saturated hydraulic conductivity versus compacted bulk density for the < 19 mm (squares), < 5 mm (circles), < 2 mm (triangles), and 5 to 2 mm (diamonds) size fractions	13
10. Water retention for samples compacted to 83% (triangles) and 90% (circles) maximum dry density for the size fractions: (a) < 19 mm, (b) < 5 mm, (c) < 2 mm and (d) 5 to 2 mm	15
11. Material properties distributions for the six design scenarios indicated by color patterns ..	18
12. Volumetric water content distributions with time (hours) for 5 to 2 mm, over < 5 mm size fraction compacted at 83% maximum density assuming uniform flow	20
13. Volumetric water content distributions with time (hours) for 5 to 2 mm, over < 5 mm size fraction compacted at 83% maximum density assuming preferential flow through 5% CSA	21
14. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 5 mm size fraction compacted at 90%, and 83% maximum density, respectively, assuming uniform flow	23
15. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 5 mm size fraction compacted at 90%, and 83% maximum density, respectively, assuming preferential flow through 5% CSA	24

16. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 19 mm size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming uniform flow	26
17. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 5 mm size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming uniform flow	27
18. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 2 m size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming uniform flow	28
19. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 19 mm size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming preferential flow through 5% CSA	29
20. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 5 mm size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming preferential flow through 5% CSA	30
21. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 2 mm size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming preferential flow through 5% CSA	31
22. Volumetric water content distributions with time (days) for 5 to 2 mm, over layers of < 19 mm size fraction compacted at 83%, < 2 mm size fraction compacted to 90%, and < 19 mm size fraction compacted 83% maximum density, assuming preferential flow through 5% CSA	33

TABLES

1. Estimated Cost for Alternative Cover Designs for Roswell Municipal Landfill (Ankeny <i>et al.</i> , 1997).	7
2. Construction Costs for Alternative Cover Designs (Dwyer, 1997)	7
3. RETC Parameter Results Along with Saturated Hydraulic Conductivity and Bulk Density Values Used in HYDRUS-2D Simulations	16
4. HYDRUS-2D Simulation Results from a Single 100-Year Storm Event for a Cover with Two Layers	19
5. HYDRUS-2D Simulation Results from a Single 100-Year Storm Event for a Cover with Three Layers	22
6. HYDRUS-2D Simulation Results from a Single 100-Year Storm Event for a Cover with Four Layers	25

INTRODUCTION

The DOE/NV Waste Management Program has managed radioactive waste disposal operations since 1961 and provides disposal capability for NTS-generated waste and off-site DOE-approved waste generators. Low-level radioactive, transuranic, mixed, hazardous and classified wastes are disposed in subsidence craters, pits, trenches, landfills and greater confinement boreholes. DOE/NV will eventually close the Area 3 and 5 Radioactive Waste Management Sites (RWMS), Figure 1, for which Bechtel Nevada (Johnejack *et al.*, 1995) developed a proposed closure cap design that included a soil-cement layer as a hydrologic barrier. During performance assessment, concerns developed over the degree and impact of subsidence on the proposed cap and the “hard” soil-cement

Figure 1. Map of the NTS showing the Area 3 and 5 Radioactive Waste Management Sites (reprinted from Johnnejack *et al.*, 1995).

layer. A working group was convened to evaluate the consequences of subsidence at the Area 3 and Area 5 RWMSs. The consequences of subsidence report (COSR) by Arnold *et al.* (1997) concluded that waste disposal practices at Areas 3 and 5 have introduced significant void space which will produce subsidence in the long term that will require excessive measures to accommodate. Subsidence is anticipated to be as much as 3.9 m (12 ft) at Area 3 ax/bl, 14.9 m (49 ft) at Area 3 ah/at, and 5.8 m (19 ft) at Area 5. Concern was expressed that cracks, due to differential subsidence, will provide preferential pathways for infiltration and upward vapor migration, and that depressional areas, due to localized subsidence, will focus runoff into these depressional areas. Both of these subsidence features would likely result in cover failure if not accommodated for in the closure cap design. Gee *et al.* (1992) noted that recharge through covers in arid conditions is “particularly likely under topographic depressions,” such as occurs on covers due to subsidence. The COS working group recommended that a cost-effective “soft” cover that consist of compacted alluvium of sufficient thickness and/or subtle layering could be designed to accommodate subsidence and meet the minimum performance standards established in the COSR. DOE/NV is in the process of designing the “soft” monofil cover, commonly referred to as an ET cover (Figure 2) due to its design and performance being based upon the ability of evapotranspiration to limit infiltration.

Figure 2. Diagram of a ET monofil cover design.

The RCRA cover design (Figure 3) and regulations for shallow burial of waste are appropriate for areas in which high rates of recharge and shallow depth to groundwater are primary concerns. The climate, soil properties, and great depth to groundwater in much of the arid southwest combine to make these designs inappropriate and/or overly costly. In the lower elevations of the NTS, the precipitation is so low that it is generally considered that all the precipitation eventually returns to the atmosphere via evaporation and transpiration (Shott *et al.*, 1995). Indirect measurements by Tyler *et al.* (1996) based upon stable isotope analysis of soil water suggest that the recharge in the alluvial

Figure 3. Diagram of a prescriptive RCRA Title C cover design.

fan areas of the NTS has historically been essentially zero under the current climatic conditions. However, Gee *et al.* (1992) stressed that coarse-textured soil, such as is common in the alluvium of the NTS, and disruptions that limit vegetative growth of deep-rooting plants, such as are common to covers in arid regions for long periods after construction, can induce significant infiltration into the waste even under arid conditions. Even if vegetation is established on the cover to provide water removal by transpiration, the seasonal dynamics of precipitation versus transpiration can result in infiltration into the waste (Gee *et al.*, 1992).

There is additional concern that preferential flow can cause cover failure even for arid conditions (Gee and Ward, 1997; Anderson, 1997). Preferential flow is a generic term applied to situations in which water does not infiltrate uniformly, either in space or velocity, through the soil but instead flows through only a small portion of the soil at higher velocities than would occur if flow were uniform. Preferential flow was originally attributed to flow through large pores, such as biological channels (e.g., worms, roots...) and structural features (e.g., cracks, inter-aggregate voids...). A DOE-funded working group on long-term cover performance (Waugh, 1997) expressed concern over the potential for preferential flowpaths to be established with time as root channels are established. Preferential flowpaths due to root and worm channels typically occupy less than 0.5% of the cross-sectional area (Wilson and Luxmoore, 1988; Edwards *et al.*, 1987), yet they can dominate the flow (Beven and Germann, 1982) by contributing to as much as 85% of the flow (Wilson and Luxmoore, 1988). Recently, preferential flow by processes of fingering, funnel flow, and/or unstable flow have been documented (Kung, 1990) for structureless coarse-grained media such as common to the NTS alluvium. The latest studies have reported that infiltrating water is funneled into these preferential flow fingers and will continue to percolate through these isolated fingers until they contact a contrasting layer to disrupt the flow finger (Kung, 1990; Wilson *et al.*, 1997; Kinsall *et al.*, 1997). An example of such funnel flow can be seen in the findings of Kinsall *et al.* (1997) and Wilson *et al.* (1997), presented in Figure 4. Flow out of two undisturbed soil blocks, during simulated rainfall events that were applied uniformly over the surface, was clearly spatially heterogeneous and these funnel flow areas were stable with time. Wilson *et al.* (1997) concluded that the more physically homogeneous the porous media, the more heterogeneous these flowpaths. They

Figure 4. Spatial distribution of cumulative drainage from the bottom of an undisturbed sand block at (a) 4.5 m depth (Kinsall *et al.*, 1997) and (b) 5.9 m depth (Wilson *et al.*, 1997).

reported 88% of the flow through only 4% of the cross-sectional area for homogeneous, coarse-grained media. This process is likely to occur in monolayer ET covers that do not possess contrasting layers to disrupt the flow fingers. Thus, a thicker cover would be required to prevent infiltration into the waste and increase the long-term risk for failure.

The possibility of this preferential finger-flow occurring suggests that direct measurements of hydrologic performance of monolayer ET covers are needed. Allison *et al.* (1994) stressed the need for direct physical measurement of the movement through covers due to the observations (Gee *et al.*, 1994) of deep recharge even in desert climates where potential ET (PET) exceeds precipitation by an order of magnitude. Direct measures of flux via lysimetry are the most robust estimator of recharge under arid conditions (Fayer *et al.*, 1996; Tyler and Walker, 1994), however, such facilities are not currently available at the NTS and data acquisition would require long-term monitoring (> 5 years) before confidence could be placed in the results. Sully (unpublished data) instrumented two weighing lysimeters at Area 5 filled with native NTS soil in layers that simulate the natural soil but not the monofil ET cover. These lysimeters will provide direct measurements of the potential recharge of the native soil under current rainfall and PET conditions with bare and vegetative surfaces. These data to date indicate that net recharge is indeed zero, however, this is based on two years of data under current natural rainfall conditions and for the native-layered conditions. While this work will provide excellent baseline data, data on performance of monofil ET covers are seriously lacking (Skahn, 1997) and comparison to the native conditions as a natural analog for cover performance is completely lacking.

DOE/NV can express great confidence in asserting that infiltration into the alluvium is limited to the upper couple of meters (Arnold *et al.*, 1997, Shott *et al.*, 1995), however, it must be kept in mind that this natural analog is highly layered. The assertion of the NTS alluvium being highly layered is in opposition to the report by Schmeltzer *et al.* (1994) that claims that the Area 3 alluvium is homogeneous. Schmeltzer *et al.* (1994) referenced the work by Fernald (1974), who compiled data for 42 boreholes, however, the depth increments of these data were approximately 15 m, which

would preclude any characterization of layering. They also referenced the site characterization data of Holmes and Narver (1962), but this analysis was on drill cuttings which will homogenize the material and not on undisturbed cores samples. Shott *et al.* (1995) and Johnjack *et al.* (1994), in reviewing site characterization data for Area 5 by Istok *et al.* (1994) and Ginanni *et al.* (1993), respectively, both conceded that there is obvious layering as a result of depositional variations, but concluded that since the physical properties of the material vary little with depth, it “behaves as a homogeneous mass.” Yet, the hydraulic conductivity shown in the report by Shott *et al.* (1995) varied by 2 to 3 orders of magnitude between depth increments. Additionally, Istok *et al.* (1994) concluded in their refereed paper that the material is homogeneous for bulk density in the horizontal direction but “the alluvium must be considered heterogeneous (layered heterogeneity)” due to significant differences in K_s and particle size distribution between the vertical layers. It is clear that the natural analog that is effective in limiting recharge is a layered system.

One alternative to monofil ET covers that has gained popularity in semi-arid conditions is the Capillary Barrier design (Figure 5). The principle behind this design is that a positive water pressure

Figure 5. Diagram of a Capillary Barrier cover design.

would be required in the capillary barrier layer for outflow into the coarser-grained (gravel) drainage layer below. Since the cover would be predominately unsaturated in semi-arid regions, this capillary barrier layer would serve to hold water in the upper layers for plants to extract. By sloping the capillary barrier layer, excess water could be laterally diverted to minimize downward movement. This unsaturated flow principle is predicated upon there being a dramatic contrast in particle sizes between the capillary barrier layer and the drainage layer. Two major concerns reported by Waugh (1997) with this design are (1) the mixing of these layers with time due to illuviation and biological activity causing the capillary barrier to lose its effectiveness over the long term, and (2) differential subsidence providing preferential flowpaths directly into the waste zone (Figure 6) as a result of the

lateral flow divergence in the capillary barrier layer. The COSR suggested that a subtle-layered design (Figure 7) may be cost effective. This design would be based upon the principles of a monofil ET cover but with the added insurance against preferential flow causing infiltration into the waste zone by incorporating layers with subtle variations in particle size distribution and/or compaction analogous to the native alluvium. The cost benefit would be realized through the reduction in depth of cover necessary to prevent infiltration into the waste. Due to the variations in lifts (layers) being subtle, illuviation would not be a concern.

Figure 6. Illustration of hydrologic impacts of subsidence on covers with barrier layers.

Figure 7. Diagram of a subtle-layered ET cover design.

In addition to performance concerns, a capillary barrier design may be more expensive to construct than an ET cover depending upon the thickness. The cost savings and proficiency in limiting infiltration of an ET cover depends upon the cap depth. Ankeny *et al.* (1997) estimated the cost of various covers for the Roswell municipal landfill in New Mexico (Table 1). Due to less thickness required, the Capillary Barrier cover was slightly less expensive than the monofil ET cover despite the former including a geotextile to prevent mixing of layers. An ET cover that consists of subtle layering such that a geotextile is not required, but with the benefit of less thickness necessary, would further enhance the cost savings. The costs at a DOE facility are substantially higher than for a municipal facility, thus, the cost savings would be more. This is evident by the study by Dwyer

(1997), shown in Table 2, for the actual construction cost of covers at Sandia National Laboratories' test facilities. The Soil Cover design, which was by far the most cost-effective, is analogous to the subtle-layering design we propose to test in that it consists of layers of compacted native soil which reduce the cover thickness required.

In addition to cost savings, monofil and subtle-layered ET covers are expected to better accommodate subsidence since infiltration barriers of the more elaborate designs (e.g., capillary barrier, clay barrier, geosynthetic clay liner (GCL)) are likely to fail under such conditions. However, ET covers would continue to function adequately since the infiltration protection is not based upon a hydrologic barrier layer but upon water retention and thickness which would not be affected. ET covers should self-heal, in that deformation of the monofil layer would, at worst, result in some degree of layering, and deformation of the subtle layers may cause an offset of the layers, but their ability to store water and disrupt unstable flowpaths would not be affected. This self-healing would further save in future maintenance costs. The exception to this hypothesis that ET covers can accommodate subsidence is the problem of preferential flow through fractures that are caused by differential subsidence. This problem could be reduced and possibly eliminated if overland flow into

Table 1. Estimated Cost for Alternative Cover Designs for Roswell Municipal Landfill (Ankeny *et al.*, 1997).

Cover Design	Required Thickness (cm)	Cost/ha (\$)	Total Cost (\$)
Prescriptive Cover (infiltration barrier)	90	185,000	2,400,000
Capillary Barrier	90	83,000	1,100,000
ET (high permeability)	135	87,000	1,100,000
GCL Barrier	103	110,000	1,400,000

Table 2. Construction Costs for Alternative Cover Designs (Dwyer, 1997).

Cover Design	Required Thickness (cm)	Cost/ha (\$)
Subtitle C-Baseline 2 (Compacted clay barrier)	90	929,000
GCL Cover-Alternative 1	90	1,576,000
Capillary Barrier-Alt. 2	140	965,000
ET Cover-Alt. 4	90	727,000
Soil Cover-Baseline 1	60	524,000

these surface cracks is eliminated. Thus, the cover should not only prevent run-on, but should be designed with a surface layer with a high infiltration capacity, e.g. surface armoring layer, such that localized run-off is minimal. Under such conditions, preferential flow through the fractures would be restricted by the drainage rate out of the surface armoring layer.

OBJECTIVES

DOE/NV has elected to redesign the cover for Area 3 to a monofil ET cover design. This report will not review the hydrogeologic conditions or the waste disposal regulations that have led to this decision, as this information can be found in the literature referenced in this report. The objective of this project was to (1) determine the physical and hydraulic properties of the Area 3 borrow source and (2) use these properties in a physically rigorous unsaturated flow code to numerically evaluate various design options. Specifically, the impact of preferential flow on cover thickness will be evaluated, and the concept of a subtle-layered ET cover to disrupt these flowpaths will be demonstrated.

NUMERICAL METHODS

Traditionally, water flow was considered to be uniform through relatively homogeneous layers of the soil profile. Darcy's Law describes steady-state unsaturated flow as:

$$q = Q/At = -K(h)dH/dz \quad (1)$$

where q is the flux density, i.e., volume of flow (Q) per area (A) per time (T), with units of length per time. The hydraulic head, H , is the sum of the gravity, Z , and pressure heads, h , with the latter being positive for saturated conditions and negative for unsaturated conditions. The hydraulic conductivity, K , is considered a constant under saturated conditions ($h \geq 0$) representing the ability of the soil to conduct water. While K has units of length per time, it is not the rate or velocity that water moves through soil. The rate that water is being conducted is the product of the hydraulic conductivity and the hydraulic gradient, dH/dz . The hydraulic gradient is the change in total hydraulic head, H , with distance, z , and is the driving force causing flow. While the flux density, q , has units of velocity, it is only a macroscopically average velocity that water is moving through soils, not the velocity that water is moving through pores. The average pore water velocity, v , is taken as the flux density, q , divided by the ratio of the pore area actually contributing to flow to the total area, i.e., the effective porosity.

Unfortunately, flow through the vadose zone, unsaturated zone from the soil surface to the groundwater table, is rarely if ever steady or one-dimensional under natural conditions. Thus, Darcy's Law must be extended to transient three-dimensional flow conditions by the continuity equation

$$\partial\theta/\partial t = -[\partial q_x/\partial x + \partial q_y/\partial y + \partial q_z/\partial z] = -\nabla \cdot q \quad (2)$$

Since $\partial\theta/\partial t = (\partial\theta/\partial h)(\partial h/\partial t) = C(\theta)\partial h/\partial t$, the three-dimensional transient flow equation, known as Richard's equation for isotropic soil, $K_x = K_y = K_z = K(h)$, is

$$C(\theta)\partial h/\partial t = K(h) [\partial^2 h/\partial x^2 + \partial^2 h/\partial y^2 + \partial^2 h/\partial z^2 + \partial h/\partial z] \quad (3)$$

The specific water capacity, $C(\theta)$, is the slope of the water retention curve, $\theta(h)$. The water retention curve is a fundamental soil property that represents the relationship between the water content, θ , and the soil-water energy status, h , called the pressure head. The water retention function, $\theta(h)$, reflects the physical properties of the soil such as texture and structure, and its shape is dependent upon the pore-size distribution.

Water retention curves are typically determined experimentally because no theory has been developed yet that is accurate enough to derive it analytically based upon the soil's physical characteristics, although many methods are currently being proposed. Fractal theory and capillary bundle theory have tried with limited success. Thus, to obtain the $\theta(h)$ function, one must fit the experimental data with empirical expressions. Van Genuchten (1980) developed the following water retention model:

$$\theta = \theta_r + [\theta_s - \theta_r] / [1 + (\alpha h)^n]^m, \quad (4)$$

where h is the absolute value of the matric head. The θ_r is the residual water content, and α (cm^{-1}) and n are fitted parameters assuming $m = 1 - 1/n$. It has been proposed that the fitted parameters have physical significance in which α is a measure of the air-entry value (pressure head at which air enters the soil) and the product mn is a measure of the pore-size distribution.

Hydraulic conductivity is a macroscopic value that represents an overall average of the microscopic velocities of the different pores and within pores over the total soil volume. For saturated soil, K_s is a constant (with high spatial and experimental variability) that represents the cumulative effects of soil structure (pores: size distribution, connectivity, and tortuosity), soil particles (size distribution and mineralogy), and soil water properties (solute concentration, T , viscosity). For unsaturated soil, the soil water is under negative pressure head, i.e., matric head. Water flow is still in the direction of decreasing energy, from higher soil water pressure to lower soil water pressure, however, the proportionality factor equating the flux to the hydraulic gradient is not a constant value but is dependent upon the water content and matric head. Thus, for unsaturated soil, $K(h, \theta)$ is not a unique value but dependent upon the hydrologic conditions (matric head and water content) with extreme spatial, temporal, and experimental variability.

One of the greatest difficulties in predicting unsaturated water flow is in determining the $K(h)$ properties. Empirical models are simple mathematical equations adjusted by least-squares fitting to match experimental data but have no physical process basis for the mathematical expression. Physical models for $K(h)$ require knowledge of a soil property that is correlated by some physical law or numerical expression to the ability of the soil to conduct water, such as particle-size or pore-size distributions. Since the shape of the water retention curve is a reflection of the pore-size distribution, which is directly related to flow velocity, there is a relationship between the $\theta(h)$ function and $K(h)$ function. One such relationship is the van Genuchten model (1980), where:

$$K_r = K(h)/K_s = \frac{\{1 - (\alpha h)^{n-1} [1 + (\alpha h)^n]^{-m}\}^2}{[1 + (\alpha h)^n]^{m/2}}. \quad (5)$$

Here, α , n , and m are determined from $\theta(h)$ parameterization. Parameter optimization is obtained using the Marquardt nonlinear least-squares fitting procedure.

HYDRUS-2D

The HYDRUS-2D code developed by Simunek *et al.* (1996) uses the van Genuchten expressions (Equations 4 and 5) to solve the two-dimensional Richard's equation (Equation 3) to model unsaturated flow. The flow domain for evaluating various cap design options was 50 cm wide by 300 cm deep. Simulations were made for six hours of rainfall at a rate of 0.66 cm/hr, which was equivalent to the NTS 100 yr-6 hour storm event (Miller *et al.*, 1973), followed by a sufficient period of evapotranspiration for internal drainage to essentially cease. The evaporation rate of 0.005 cm/hr was equivalent to the average ET rate at the NTS during December to January (Shott *et al.*, 1995), assuming that actual ET was 80% of the potential ET.

MATERIALS AND METHODS

The physical and hydraulic properties of the native soil from the Area 3 borrow source were tested. The material underwent a particle-size analysis, modified proctor compaction test, a constant-head hydraulic conductivity for two different bulk densities, and water retention for two different bulk densities. This information was then incorporated into the computer model HYDRUS-2D for simulation of infiltration into prescribed cover designs under extreme (100 yr-6 hr) precipitation events.

Particle-Size Analysis

The particle-size distribution was determined by the sieve and hydrometer mechanical analysis methods (ASTM, 1990). All material that had a diameter greater than 19 mm (3/4 in) was removed, and subsequently passed through 50 mm (2 in), 37.5 mm (1.5 in), 25 mm (1 in), and 19 mm (3/4 in) diameter sieves. The amount of sample retained on each sieve was weighed. A subsample that would be easier to work with was separated out of the original by repeatedly splitting the sample. This smaller sample was weighed and then washed through the No. 200 (0.080 mm) sieve to remove the silt and clay sized particles. The remaining sample was then oven dried and sorted through the 12.7 mm (1/2 in), 9.5 mm (3/8 in), 4.75 mm (No. 4), 2 mm (No. 10), 1.180 mm (No. 16), 0.85 mm (No. 20), 0.25 mm (No. 60), 0.15 mm (No. 100), and 0.080 mm (No. 200) sieves. As before, the weight retained on each sieve was recorded. These data were converted into the percentage of sample by mass of each size fraction.

To determine the grain sizes smaller than the 0.080 mm sieve, the hydrometer method was used (ASTM, 1990). Approximately 40 g was prepared with 100 ml of sodium hexametaphosphate dispersing solution, and soaked for at least three hours. The presoaked sample was put into a blender and mixed thoroughly for five minutes before decanting into a sedimentation cylinder. The dispersed sample was brought up to volume in a 1000 ml sedimentation cylinder. A control blank was set with just distilled water and 100 ml of dispersing solution in another cylinder. The hydrometer was slowly placed into the cylinder and a reading taken at 0.5, 1, 3, 10, 30, 60, 90, 120, and 1440 minutes. After the 24-hour period, the solution in the sedimentation cylinder was washed through

the No. 230 sieve. The sieved portion was oven-dried and then sorted through a stack of 2.36 mm (#8), 1.18 mm (#16), 0.85 mm (#20), 0.50 mm (#35), 0.25 mm (#60), 0.125 mm (#120), and 0.063 mm (#230) sieves by a mechanical shaker for five minutes. The mass retained on each sieve was recorded. This procedure produced a little overlap between the wet-sieving and the post hydrometer dry-sieving due to chemical dispersion of the latter.

Modified Proctor Compaction Test

The Area 3 material was separated into selected size fractions for testing. The size separations selected for testing were < 19 mm ($< 3/4$ inch), < 5 mm ($< \text{No. 4}$ sieve), < 2 mm ($< \text{No. 10}$ sieve), and 5 mm to 2 mm (No. 4 to No. 10 sieve). The original sample was separated into the desired size fractions by dry-sieving using a 60 cm by 60 cm sieve. It was concluded upon inspection of the material that only the < 19 mm, < 5 mm, and < 2 mm samples would be acceptable for the modified compaction test. The samples separated between these classes (19 to 5 mm, and 5 to 2 mm) were too coarse and therefore would not successfully compact. Water was added to these samples to obtain moisture contents of 2%, 4%, 6%, and 8% by weight. Thus, for each size fraction there were four compaction tests, i.e., one for each respective soil moisture content. Next, 2500 g of soil were weighed out for each test and water was added to the sample to obtain the prescribed water content. The 12 different test samples sat in their containers overnight to let the soil-water equilibrate. For these tests, a 10 cm mold was used, with five layers (or lifts) at 25 blows each of a 10 lb hammer dropped from a height of 45 cm (ASTM, 1992). The material and mold were weighed to determine the mass of the wet soil. The soil was then forced out of the mold and a sub-sample of the soil was weighed (at least 700 g). The subsample was reweighed after drying in an oven overnight at 105°C to determine the moisture content and the dry bulk density. The dry bulk density was plotted against gravimetric moisture content such that the peak of the graph represents the maximum dry density and optimum moisture content.

These results provided guidance to the rest of the experiments. For the hydraulic conductivity and water retention test, each sample (except the 5 to 2 mm) was compacted at 90% maximum density and 83% maximum density. The 5 to 2 mm sample was too coarse to determine a maximum dry density, so the sample was compacted as well as could be and the density recorded.

Water Retention

The hanging water column and pressure plate extraction methods were employed to determine water retention (Klute, 1986). The cores for this experiment were 6.05 cm in diameter, and 5.10 cm in length, which gave a cross-sectional area of 28.75 cm^2 and a volume of 146.61 cm^3 . Each sample size fraction and density was analyzed on replicate cores. The only exception was the < 19 mm sample, which was not analyzed due to concerns for the coarse gravel (19 to 5 mm) complicating the compaction in the small water retention cores. Thus, the < 5 mm material had a sufficient mass of fine gravel (2 to 5 mm sample) added to it to mimic the < 19 mm sample. The samples were saturated with distilled water treated with a 0.1% Phenol solution to prevent biological activity. Porous plate (bubbling pressure > 500 cm) buchner funnels (350 ml) were saturated in the same solution. The cores were placed into the funnels and allowed to equilibrate with the negative water pressure exerted on the core bottom for a minimum of 24 hours. The distances between the core

bottom and the outflow air port of the hanging water column equaled the negative water pressure. The samples were subjected to -25, -50, -100, -150, and -200 cm water pressures. Three lower water pressures (-500, -750, and -1000 cm) were achieved by placing the cores on 1-bar ceramic porous plates and applying a pneumatic pressure with a pressure chamber and allowing a minimum of 48 hours for equilibration. Following the lowest pressure, samples were resaturated and the saturated hydraulic conductivity was determined by simply attaching a cylinder to the top of the core and maintaining a constant head while recording the outflow. Cores were subsequently oven-dried for 48 hours to double check the predetermined dry weights. The van Genuchten (1980) model (Equation 4) was fit to the experimental water retention data to determine the $\theta(h)$ function. The θ_r (residual water content) was set to slightly below the water content at 1000 cm water pressure, while α and n were fitted with $m = 1 - 1/n$ using the RETC computer code of van Genuchten (1980).

Constant-Head Hydraulic Conductivity

The saturated hydraulic conductivity was determined on repacked samples by the constant-head method (Klute and Dirksen, 1986). The setup consisted of the core (diameter of 8.27 cm and length of 7.55 cm) with porous fabric on both ends, a bottom influent port through which water entered the core and a top outflow plate. The inflow and outflow pressure heads were maintained constant while the outflow into a graduated cylinder was recorded with time.

The < 19 mm (same fabricated sample used for the water retention) and 5 to 2 mm samples had only two repetitions, whereas the < 5 mm and < 2 mm samples were run in triplicate for each density. To prepare the sample, the amount of soil for the prescribed density was determined and compacted into the core with a hammer. The < 5 mm samples had carbon dioxide pumped through them prior to saturation, whereas all other samples were simply saturated from the bottom up by placing them in a water bath. Once saturated, the samples were hooked up to the constant head setup previously described. Measurements were taken by picking a fixed volume of outflow and recording the time.

RESULTS

Particle-Size Analysis

The results of the particle-size analysis (Figure 8) showed that 96.2% of the Area 3 borrow source material was finer than 19 mm (3/4 in) diameter (Appendix A, Table A-1, A-2.1). According to the USDA classification scheme, this material is a gravelly loamy sand with mass fractions of 7.8% coarse gravel, 26.6% fine gravel, 46.5% sand, 11.5% silt, and 7.6% clay. The sand size mass fractions were 2.8% very coarse, 8.0% coarse, 11.8% medium, 15.5% fine, and 8.4% very fine sand. The resulting curve from the hydrometer test overlaps the wet-sieving analysis for the < 2 mm sample. The mass fractions determined by dry-sieving following the hydrometer test on the < 2 mm portion were higher than the wet-sieving on the original sample. This could be because the dispersing solution was able to break down more aggregates into individual particles than accomplished by the physical dispersion of the original sample. More fine particles would have remained attached to larger particles sieved out by the wet-sieve analysis, thereby resulting in a lower mass fraction for the smaller size classes than for the other method.

Figure 8. Mass fractions, expressed as percent by weight, of the particle sizes.

Modified Proctor Compaction Test

The compaction tests resulted in the < 19 mm sample having a maximum dry density of 1.91 g cm^{-3} at an optimum water content of 11.5% by weight (Appendix B). The < 2 mm sample had a maximum dry density of 1.84 g cm^{-3} and optimum moisture content of 14.0% by weight. The < 5 mm had a maximum dry density of 1.84 g cm^{-3} and optimum moisture content of 12.5% by weight.

Constant-Head Hydraulic Conductivity

The saturated hydraulic conductivity, K_s , values were similar within sample treatments with a clear separation between treatments (Figure 9). The K_s values for the 5 to 2 mm sample following

Figure 9. Saturated hydraulic conductivity versus compacted bulk density for the < 19 mm (squares), < 5 mm (circles), < 2 mm (triangles), and 5 to 2 mm (diamonds) size fractions.

water retention analysis were an order of magnitude lower than determined on the more accurate constant-head setup, and two orders of magnitude lower for the < 5 mm fraction at 90% compaction. The variances are likely due to differences in compaction and saturation methods. As expected, the fine gravel (5 to 2 mm sample) had the highest K_s , on the order of 10^{-3} m s^{-1} . The 83% compaction consistently had a higher K_s than the 90% compaction. The geometric mean K_s for the < 5 mm sample was $8.5 \times 10^{-6} \text{ m s}^{-1}$ at 90% compaction as compared to $3.4 \times 10^{-5} \text{ m s}^{-1}$ at 83% compaction. The < 2 mm fraction showed a larger contrast with a geometric mean K_s of $8.6 \times 10^{-7} \text{ m s}^{-1}$ at 90% as compared to $7.2 \times 10^{-6} \text{ m s}^{-1}$ at 83% compaction. It appears from these data that a slightly larger difference in K_s is obtained from the subtle difference in particle-size distribution than from differences in compaction. However, since the < 5 mm at 90 % maximum density and the < 2 mm at 83% maximum density had similar K_s values, ranging between 10^{-6} m s^{-1} to 10^{-5} m s^{-1} , similar cap performance may be achievable with either treatment. This makes sense because even though the < 2 mm is finer than the < 5 mm, it was compacted to a lower density. The < 5 mm and < 2 mm samples behaved as expected: K_s decreased as density, within each fraction, increased and K_s decreased as particle size decreased. The exception appears to be the < 19 mm sample which had lower K_s than expected from its particle-size distribution. It is possible for K_s to decrease as the particle-size range increases, since coarse gravel (19 to 5 mm) acts as a nonconductive void effectively reducing the conductive volume of the cores. However, these samples did not contain coarse gravel but were reconstructed with a proportionate amount of fine gravel (5 to 2 mm) to mimic the < 19 mm sample. The reduced K_s values for this size fraction are therefore more likely a result of the higher bulk densities. It should be noted that K_s on these samples was only determined after water retention analysis, which also gave low K_s values for the other size fractions. Therefore, the K_s values used in the HYDRUS-2D simulations for the < 19 mm size fraction were assumed an order of magnitude higher than the values measured.

Water Retention

There was very little difference in the water retention curves between compaction densities and minimal to substantial differences between size fractions depending upon the size class (Figure 10). Slight differences between different densities were seen at the lower water pressures, < -100 cm, with the 90% maximum density retaining more water as expected. It also appears that differences in water retention between the < 5 mm (Figure 10b) and < 2 mm (Figure 10c) are negligible. In contrast to these samples, the < 19 mm sample showed a slightly higher saturated water content and larger decrease at the first negative pressure (-25 cm) due to a greater abundance of large pores. It should be kept in mind that this < 19 mm sample does not contain particles > 5 mm but was fabricated by adding the proportionate amount of fine gravel to simulate a < 19 mm sample. Thus, one would expect an even higher saturated water content and bigger decrease in water content at the first negative pressure than was observed for the simulated < 19 mm sample. This can be seen in the water retention curve for the fine gravel (5 to 2 mm) sample which did exhibit a substantial difference in water retention (Figure 10d) when isolated from the finer sand fractions. This size fraction is so coarse that essentially all the water contained under saturated conditions (pressure head=10⁰ in Figure 10d) is present in large pores such that it is removed with the slightest negative water pressure. This size fraction may be used, with the > 5 mm included in it, as the desert armoring

Figure 10. Water retention for samples compacted to 83% (triangles) and 90% (circles) maximum dry density for the size fractions: (a) < 19 mm, (b) < 5 mm, (c) < 2 mm and (d) 5 to 2 mm.

surface layer. This project used the fine gravel (5 to 2 mm) size fraction to represent the desert armoring material, but it should be kept in mind that the actual material would be coarser grained. The result would likely be a slightly higher saturated water content, but the bigger difference would be K_s value orders of magnitude higher than that obtained for the fine gravel alone.

The RETC computer code by van Genuchten (1980) for modeling water retention (Equation 4) was used to obtain best-fit values for the α and N parameters (Table 3). A value slightly lower than the water content at the -1000 cm water pressure was used as the residual water content. Modeling of the water retention data by fitting the residual water content in addition to α and N provided negligible differences in the residual water content value and in goodness of fit (r^2), so the assumed value was used in the flow simulations. Since the α parameter is related to the inverse of the air-entry value, the coarse-grained material should have a higher value, i.e., lower air-entry value. This was seen for the < 19 mm sample only. Failure to observe this for the 5 to 2 mm sample is likely due to the inability of the RETC code to obtain a stable convergence to the best fit values. More water content measurements between saturation and -25 cm water pressure would be needed for this fraction to obtain a stable fit. Failure to obtain a stable fit to the fine gravel fraction should not affect the accuracies of the flow simulations. Given the extremely large K_s values for this fraction, the retention properties, other than total porosity, which is not dependent upon the model fit, would not be important. A lower α value for the 90% than the 83% maximum density was also expected, but this was not observed due to the lack of difference in water retention characteristics at the wet end between compactions.

Table 3. RETC Parameter Results Along with Saturated Hydraulic Conductivity and Bulk Density Values Used in HYDRUS-2D Simulations.

ID	θ_s	θ_r	a cm^{-1}	N	r^2	K_{sat} cm h^{-1}	Bulk Density g cm^{-3}
5 to 2 mm	0.42	0.03	0.0806	2.1322	NA	1724	1.32
5 to 2 mm	0.42	0.03	0.0932	2.0677	NA	1724	1.32
<19 mm 90%	0.40	0.15	0.3025	1.3034	.998	0.21	1.72
<19 mm 90%	0.42	0.15	0.2070	1.3476	.998	0.21	1.72
<19 mm 83%	0.42	0.14	0.1256	1.4576	.997	6.48	1.59
<19 mm 83%	0.42	0.14	0.3034	1.3577	.995	6.48	1.59
< 5 mm 90%	0.34	0.15	0.0962	1.3465	.998	6.23	1.66
< 5 mm 90%	0.34	0.15	0.0457	1.6051	.993	6.23	1.66
< 5 mm 83%	0.34	0.15	0.9206	1.2972	.921	15.2	1.53
< 5 mm 83%	0.34	0.15	0.0474	1.7064	.992	15.2	1.53
< 2mm 90%	0.35	0.15	0.0146	1.5383	.996	0.23	1.66
< 2mm 90%	0.35	0.15	0.0573	1.4889	.997	0.23	1.66
< 2 mm 83%	0.39	0.15	0.0348	1.9211	.999	3.55	1.53
< 2 mm 83%	0.39	0.15	0.0684	1.7121	.998	3.55	1.53

Cover Design Evaluations Using HYDRUS-2D

A total of 30 unsaturated flow simulations were made with the HYDRUS-2D code. It should be noted that these simulations were not made to make a definitive assessment of cover performance, but to scope out various design options. It was assumed that the most likely scenario for cover failure from an infiltration standpoint is an extreme precipitation event during a period of low ET (i.e., late fall through winter). Therefore, all simulations were for the same antecedent moisture conditions (water pressure = -1000 cm), with a single 100 yr-6 hour storm event. Simulations were continued until water redistribution stabilized, i.e., negligible increase in the depth of infiltration, which was found to be 840 hours. The design combinations included two-layered, three-layered and four-layered covers. For each case, the upper layer (0 to 15 cm) consisted of the fine gravel (5 to 2 mm size fraction) to simulate desert armoring. Each case was simulated assuming spatially uniform flow, then simulations repeated assuming that infiltration was preferentially funneled through a 5% cross-sectional area (CSA). For the preferential flow simulations, the lateral extent of each layer was

conceptually divided into 20 vertical sections each consisting of 5% CSA. One 5% CSA section was randomly chosen from each layer, except for the surface layer. The water retention curves were the same for all sections within a layer, however, the K_s for all sections except the one randomly chosen was set to be four orders of magnitude lower than the measured value. Thus, infiltrating water would prefer to move through the 5% CSA with the measured K_s value than the remaining 95% CSA with a hydraulic conductivity that was substantially lower. The material properties distributions for the three-layered cases and the corresponding preferential flow cases can be seen in Figure 11. All simulations had extremely low mass balance errors with > 90% having mass balance errors of < 1% and the highest observed being only 3%.

Due to the extremely high hydraulic conductivity of the surface layer in all simulations, this gravel material allowed all precipitation of a 100 yr-6 hour storm event to infiltrate with zero runoff. This is advantageous, not only from the standpoint of preventing erosion, but if differential subsidence features such as fissures exist, water will have to move laterally through this layer to enter these fissures instead of the more rapid process of overland flow. Due to the large size of the pores, as indicated from the water retention curves, and the high flow rates through this layer, surface sealing should not be expected, as aeolian materials will be readily transported through this layer. Sealing at the layer interfaces may be a concern if the contrast in particle-size distributions is dramatic. However, the native alluvium material is sufficiently coarse that the size separations tested (< 19 mm, < 5 mm, and < 2 mm) should not cause a sealing at the interfaces, particularly for the case of a 83% maximum density being used as the root zone media layer (layer just below the desert armoring).

The two-layer cover design is the monofil ET design which the COSR (Arnold *et al.*, 1997) recommended but with surface armoring. The depth of infiltration and the impact of preferential flow are presented in Table 4. On average, compaction to the 83% maximum dry density resulted in infiltration to the 146 cm depth as compared to the 97 cm depth for the 90% maximum dry density compaction if flow is uniform. While there is a large reduction in depth required by compacting to the 90% level, the depth necessary for meeting the minimum standard for limiting infiltration can be easily achieved without the added construction cost for compaction. The impact of varying the particle size distributions is more difficult to assess due to the complication of higher bulk densities for the < 19 mm size class. If this size class had the same maximum dry density as the other two classes (< 5 mm and < 2 mm), one should expect a similar response as was observed for them. The average depth of infiltration was 164 cm for the < 5 mm as compared to 115 cm for the < 2 mm, which would suggest an average infiltration depth of over 200 cm for the < 19 mm size class if compacted to the same density. It appears for the case of uniform flow through a monofil cover that compaction had an equal impact on reducing the depth of infiltration as the variations in particle size class.

Assuming uniform flow, the maximum depth of infiltration from a single 100-yr maximum storm event averaged 121 cm for the six cases. However, if preferential flow does occur due to funnel flow processes, the maximum depth predicted averaged 153 cm for these six cases. Both worse cases occurred for the < 5 mm material compacted at 83% maximum density, and comparing

Figure 11. Material properties distributions for the six design scenarios indicated by color patterns.

Table 4. HYDRUS-2D Simulation Results from a Single 100-Year Storm Event for a Cover with Two Layers.

Materials Order	Layering Depths (cm)	Max. Infil. Depth (cm), Uniform Flow	Max. Infil. Depth (cm), Preferential Flow	Impact of Preferential Flow % Change
5 to 2 mm over <19 mm - 83%	0 to 15 15 to 300	139	159	14%
5 to 2 mm over <19 mm - 90%	0 to 15 15 to 300	33	33	0%
5 to 2 mm over <5 mm - 83%	0 to 15 15 to 300	180	247	37%
5 to 2 mm over <5 mm - 90%	0 to 15 15 to 300	147	190	29%
5 to 2 mm over <2 mm - 83%	0 to 15 15 to 300	119	170	43%
5 to 2 mm over <2 mm - 90%	0 to 15 15 to 300	111	120	8%

results for the uniform (Figure 12) to the preferential flow case (Figure 13) clearly shows the concern. On average, preferential flow resulted in 26% deeper penetration of the wetting front. Thus, a 3-m-deep monofil as recommended in the COSR would be sufficient to meet the minimum standard of limiting infiltration into the waste zone even with the preferential flow in these simulations. For infiltration to reach the waste zone, either antecedent moisture conditions would need to be wetter than the -1000 cm water pressures used in these simulations, or multiple storm events, as opposed to the single event used in these simulations, would need to occur before the soil water storage capacity is fully restored. Another concern is that plant root channels will develop with time over the 1000-year life of a cover. These can provide preferential flow pathways that occupy an order of magnitude lower CSA, thus, substantially deeper penetration than that simulated for funnel flow through 5% CSA is possible.

The importance of layering by variations in compaction and soil texture can be easily seen in the flow simulations for the three-layer case (Table 5). The most likely scenario is to have the root zone, which was assumed to only be 30 cm thick, to be compacted to the 83% maximum density, however, both 83% and 90% compaction cases were simulated for comparison. The average depth of infiltration for the six cases decreased from 121 cm for the two layer to 109 cm for the three-layer designs. The real benefit of layering, however, is seen in the preferential flow simulations. Instead of increasing the depth of infiltration, as was the case with the two-layer (monofil) design, the depth of infiltration is decreased by 31% on average. This can be seen in the worst case simulation, which was the < 5 mm - 90% over the 83% maximum dry density. If flow is uniform (Figure 14), the root-zone layer compacted at 90% maximum density is not able to restrict the wetting front from

entering the more permeable sublayer. However, since preferential flowpaths at the interface of these two layers do not vertically line up, the preferential flowpath is restricted until the lateral flow over the interface reaches the preferential flowpath for the sublayer (Figure 15). The preferential flowpath through the sublayer will become hydrologically active but the delay provides time for enhanced ET losses and results in shallower depth of penetration even during this low ET period.

Figure 12. Volumetric water content distributions with time (hours) for 5 to 2 mm, over < 5 mm size fraction compacted at 83% maximum density assuming uniform flow.

Figure 13. Volumetric water content distributions with time (hours) for 5 to 2 mm, over < 5 mm size fraction compacted at 83% maximum density assuming preferential flow through 5% CSA.

Table 5. HYDRUS-2D Simulation Results from a Single 100-Year Storm Event for a Cover with Three Layers.

Materials Order	Layering Depths (cm)	Max. Infil. Depth (cm), Uniform Flow	Max. Infil. Depth (cm), Preferential Flow	Impact of Preferential Flow % Change
5 to 2 mm over <19 mm - 90% over <19 mm - 83%	0 to 15 15 to 45 45 to 300	47	33	-29.8%
5 to 2 mm over <19 mm - 83% over <19 mm - 90%	0 to 15 15 to 45 45 to 300	60	52	-13.3%
5 to 2 mm over <5 mm - 90% over <5 mm - 83%	0 to 15 15 to 45 45 to 300	167	103	-38.3%
5 to 2 mm over <5 mm - 83% over <5 mm - 90%	0 to 15 15 to 45 45 to 300	152	118	-22.4%
5 to 2 mm over <2 mm - 90% over <2 mm - 83%	0 to 15 15 to 45 45 to 300	103	60	-38.8%
5 to 2 mm over <2 mm - 83% over <2 mm - 90%	0 to 15 15 to 45 45 to 300	122	70	-42.6%

The two-layer simulations, i.e., monofil cover, suggest that a 2-m cover thickness compacted to 83% maximum density is adequate if flow is uniform. The main justification for layering is the disruption of preferential flowpaths both from a plant-root intrusion and unstable-funnel flowpath. According to the three-layer simulations, this can be accomplished without large contrasts in compaction or soil texture but with layers of subtle contrast. This scenario was tested for each treatment with the root-zone and sub-base material being compacted at the 83% maximum density with a single lift (15 cm) of the same texture compacted at the 90% maximum density in between. This combination provided the most promising results (Table 6) with a 47% reduction in infiltration depth for the preferential flow scenarios. Assuming that flow is uniform, the depth of infiltration is not reduced by this 15-cm layer compacted at 90% maximum density when compared to the three-layer case in which this layer extends to 300 cm (Figures 16, 17 and 18). The benefit, however, of disrupting preferential flowpaths is obvious (Figures 19, 20 and 21). It is also apparent in the preferential flow simulations that the lateral flow due to this disruption in a finger flowpath is not significant enough to be concerned with movement into differential subsidence fissures. Such a fissure would have to be in close proximity to the flow finger for any appreciable quantity of infiltration to be diverted into it.

Figure 14. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 5 mm size fraction compacted at 90%, and 83% maximum density, respectively, assuming uniform flow.

Figure 15. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 5 mm size fraction compacted at 90%, and 83% maximum density, respectively, assuming preferential flow through 5% CSA.

Table 6. HYDRUS-2D Simulation Results from a Single 100-Year Storm Event for a Cover with Four Layers.

Materials Order	Layering Depths (cm)	Max. Infil. Depth (cm), Uniform Flow	Max. Infil. Depth (cm), Preferential Flow	Impact of Preferential Flow % Change
5 to 2 mm over <19 mm - 83% over <19 mm - 90% over <19 mm - 83%	0 to 15 15 to 45 45 to 60 60 to 300	83	52	-37.3%
5 to 2 mm over <5 mm - 83% over <5 mm - 90% over <5 mm - 83%	0 to 15 15 to 45 45 to 60 60 to 300	174	66	-62.1%
5 to 2 mm over <2 mm - 83% over <2 mm - 90% over <2 mm - 83%	0 to 15 15 to 45 45 to 60 60 to 300	112	65	-42.0%

(text continues on page 32)

Figure 16. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 19 mm size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming uniform flow.

Figure 17. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 5 mm size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming uniform flow.

Figure 18. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 2 m size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming uniform flow.

Figure 19. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 19 mm size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming preferential flow through 5% CSA.

Figure 20. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 5 mm size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming preferential flow through 5% CSA.

Figure 21. Volumetric water content distributions with time (hours) for 5 to 2 mm, over layers of < 2 mm size fraction compacted at 83%, 90%, and 83% maximum density, respectively, assuming preferential flow through 5% CSA.

Figure 22. Volumetric water content distributions with time (days) for 5 to 2 mm, over layers of < 19 mm size fraction compacted at 83%, < 2 mm size fraction compacted to 90%, and < 19 mm size fraction compacted 83% maximum density, assuming preferential flow through 5% CSA.

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Appendix A

Particle Size Analysis Data

Table A-1. Particle Size Analysis

NTS Area 3 - Particle Size Analysis -> Wet Sieve Method (> 0.080 mm)

Date: 6/26/97 By: Maren Henley

Dry Wt. of total sample: 207.6 lb (94,184 g)

Dry Wt. of sample used in sieving: 1493.6 g

Sieve Size	Ind. Weight Retained (g)	Weight Retained Cumulative (g)	Cumulative % Finer -3/4 Portion	Normalized Cumulative % Finer
3 in. (76.2 mm)	0			100.0
2-1/2 in. (63.5 mm)	0			100.0
2 in. (50.8 mm)	472	472		99.5
1-1/2 in. (38.1 mm)	400	872		99.1
1 in. (25.4 mm)	1191	2063		97.8
3/4 in. (19.1 mm)	1502	3565		96.2
1/2 in. (12.7 mm)		61.53	95.9	92.2
3/8 in. (9.53 mm)		128.62	91.4	87.9
sieve #4 (5.0 mm)		271.30	81.8	78.7
sieve #10 (2.0 mm)		474.33	68.2	65.6
sieve #16 (1.18 mm)		645.89	56.8	54.6
sieve #20 (.850 mm)		810.68	45.7	44.0
sieve #60 (.250 mm)		958.20	35.8	34.5
sieve #100 (.150 mm)		1095.69	26.6	25.6
sieve #200 (.080 mm)		1226.36	17.9	17.2

Table A-2.1. Hydrometer Analysis: Trial 1

Particle Size Analysis -> Sieve Analysis of Hydrometer Method: > No. 230 Sieve
Trial 1 By: Maren Henley

Sample Name: NTS Area 3 < No. 10 Standard U.S. Sieve

Mass of Transfer Beaker: 10 g

Mass of Wet Soil and Beaker: 50 g

Mass of Wet Soil: 40 g

Adjusted Dry Mass of Soil: 38.11 g

Time (min)	Blank Hydrometer Reading	Blank Solution Temperature °C	Soil Hydrometer Reading	Soil Solution Temperature °C
0.5	6.0	20.2	17.0	20.2
1	6.0	20.2	16.0	20.2
3	6.0	20.3	14.5	20.3
10	6.0	20.4	13.5	20.4
30	6.0	20.7	12.0	20.7
60	6.0	21.0	11.5	21.0
90	6.0	21.3	11.0	21.3
120	5.5	21.5	10.9	21.5
1440	6.0	21.8	9.0	21.8

Mass of Transfer Beaker: 12.42 g

Mass of Beaker and Sand: 37.52 g

Mass of Sand: 25.1 g

Mass of Clay and Silt: 13.01 g

Sieve Size (micrometer)	Sieve Mass (g)	Sieve and Soil Mass (g)	Soil Fraction Mass (g)	% of Sample	% Sample Adjusted for Sample Loss	% Total
2360 (#8 sieve)	488.38	488.38	0.00	0.00	0.00	100.00
1180 (#16 sieve)	463.01	463.70	0.69	1.81	1.84	98.16
850 (#20 sieve)	430.11	431.66	1.55	4.07	4.14	94.02
500 (#35 sieve)	404.20	407.73	3.53	9.26	9.43	84.58
250 (#60 sieve)	363.96	370.62	6.66	17.48	17.79	66.79
125 (#120 sieve)	310.04	317.08	7.04	18.47	18.81	47.98
63 (#230 sieve)	306.75	311.70	4.95	12.99	13.22	34.76
<63			13.01	34.14	34.76	34.76
Sample Lost			0.68	1.78		
Total				98.22	100.00	

Table A-2.2. Hydrometer Analysis: Trial 2

Particle Size Analysis -> Sieve Analysis of Hydrometer Method: > No. 230 Sieve
Trial 2 By: Maren Henley

Sample Name: NTS Area 3 < No. 10 Standard U.S. Sieve

Mass of Transfer Beaker: 10 g

Mass of Wet Soil and Beaker: 50 g

Mass of Wet Soil: 40 g

Adjusted Dry Mass of Soil: 38.11 g

Time (min)	Blank Hydrometer Reading	Blank Solution Temperature °C	Soil Hydrometer Reading	Soil Solution Temperature °C
0.5	5.0	20.5	15.0	20.5
1	5.0	20.5	14.5	20.5
3	5.0	20.5	13.5	20.5
10	5.5	20.5	12.5	20.5
30	6.0	20.9	12.0	20.9
60	5.0	21.2	11.0	21.2
90	5.0	21.5	10.9	21.5
120	4.5	21.6	10.8	21.6
1440	5.0	21.9	8.8	21.9

Mass of Transfer Beaker: 12.25 g

Mass of Beaker and Sand: 37.79 g

Mass of Sand: 25.54 g

Mass of Clay and Silt: 12.57 g

Sieve Size (micrometer)	Sieve Mass (g)	Sieve and Soil Mass (g)	Soil Fraction Mass (g)	% of Sample	% Sample Adjusted for Sample Loss	% Total
2360 (#8 sieve)	488.38	488.38	0.00	0.00	0.00	100.00
1180 (#16 sieve)	462.96	464.10	1.14	2.99	3.03	96.97
850 (#20 sieve)	430.03	432.00	1.97	5.17	5.24	91.72
500 (#35 sieve)	404.07	408.05	3.98	10.44	10.59	81.13
250 (#60 sieve)	363.92	370.51	6.59	17.29	17.54	63.60
125 (#120 sieve)	310.08	316.84	6.76	17.74	17.99	45.61
63 (#230 sieve)	306.71	311.28	4.57	11.99	12.16	33.45
<63			12.57	32.98	33.45	33.45
Sample Lost			0.53	1.39		
Total				98.61	100.00	

Table A-2.3. Hydrometer Analysis: Trial 3

Particle Size Analysis -> Sieve Analysis of Hydrometer Method: > No. 230 Sieve
Trial 3 By: Maren Henley

Sample Name: NTS Area 3 < No. 10 Standard U.S. Sieve

Mass of Transfer Beaker: 10 g

Mass of Wet Soil and Beaker: 50 g

Mass of Wet Soil: 40 g

Adjusted Dry Mass of Soil: 38.11 g

Time (min)	Blank Hydrometer Reading	Blank Solution Temperature °C	Soil Hydrometer Reading	Soil Solution Temperature °C
0.5	5.8	18.8	18.0	18.8
1	6.0	18.9	18.0	18.9
3	6.0	19.1	16.2	19.1
10	5.5	19.5	13.8	19.5
30	5.0	19.7	13.0	19.7
60	6.0	20.1	13.0	20.1
90	5.5	20.4	12.0	20.4
120	5.8	20.7	11.2	20.7
1440	4.8	24.3	8.0	24.3

Mass of Transfer Beaker: 12.46 g

Mass of Beaker and Sand: 37.37 g

Mass of Sand: 24.91 g

Mass of Clay and Silt: 13.2 g

Sieve Size (micrometer)	Sieve Mass (g)	Sieve and Soil Mass (g)	Soil Fraction Mass (g)	% of Sample	% Sample Adjusted for Sample Loss	% Total
2360 (#8 sieve)	488.28	488.28	0.00	0.00	0.00	100.00
1180 (#16 sieve)	462.90	463.52	0.62	1.63	1.66	98.34
850 (#20 sieve)	430.36	431.59	1.23	3.23	3.30	95.03
500 (#35 sieve)	404.08	407.85	3.77	9.89	10.12	84.91
250 (#60 sieve)	363.77	370.65	6.88	18.05	18.47	66.44
125 (#120 sieve)	309.95	316.82	6.87	18.03	18.44	48.00
63 (#230 sieve)	306.07	310.75	4.68	12.28	12.56	35.44
<63			13.20	34.64	35.44	35.44
Sample Lost			0.86	2.26		
Total				97.74	100.00	

Table A-3.1. Hydrometer Analysis for < 0.063 mm: Trial 1

Particle Size Analysis -> Hydrometer Method: < 0.063 mm Sieve
Trial 1 By: Maren Henley

Spec. Grav.: 2.48
Dry Weight: 38.11 g

Time (min)	Blank Hydrometer Reading	Blank Solution Temperature °C	Soil Hydrometer Reading	Constant for Temperature	Effective Depth	Difference in Hydrometer Readings	Percentage Finer for Sample	Diameter of Particle (mm)	Cumulative % Finer
0.5	6.0	20.2	17.0	0.01431	13.5	11.0	29.73	7.44E-02	19.50
1	6.0	20.2	16.0	0.01431	13.7	10.0	27.03	5.30E-02	17.73
3	6.0	20.3	14.5	0.01431	13.9	8.5	22.97	3.08E-02	15.07
10	6.0	20.4	13.5	0.01431	14.1	7.5	20.27	1.70E-02	13.30
30	6.0	20.7	12.0	0.01414	14.3	6.0	16.22	9.76E-03	10.64
60	6.0	21.0	11.5	0.01414	14.4	5.5	14.86	6.93E-03	9.75
90	6.0	21.3	11.0	0.01414	14.5	5.0	13.51	5.68E-03	8.86
120	5.5	21.5	10.9	0.01437	14.5	5.4	14.59	5.00E-03	9.57
1440	6.0	21.8	9.0	0.01437	14.8	3.0	8.11	1.46E-03	5.32

Table A-3.2. Hydrometer Analysis for < 0.063 mm: Trial 2

Particle Size Analysis -> Hydrometer Method: < 0.063 mm Sieve
Trial 2 By: Maren Henley

Spec. Grav.: 2.48
Dry Weight: 38.11 g

Time (min)	Blank Hydrometer Reading	Blank Solution Temperature °C	Soil Hydrometer Reading	Constant for Temperature	Effective Depth	Difference in Hydrometer Readings	Percentage Finer for Sample	Diameter of Particle (mm)	Cumulative % Finer
0.5	5.0	20.5	15.0	0.01414	13.8	10.0	27.03	7.43E-02	17.73
1	5.0	20.5	14.5	0.01414	13.9	9.5	25.68	5.27E-02	16.84
3	5.0	20.5	13.5	0.01414	14.1	8.5	22.97	3.07E-02	15.07
10	5.5	20.5	12.5	0.01414	14.2	7.0	18.92	1.68E-02	12.41
30	6.0	20.9	12.0	0.01414	14.3	6.0	16.22	9.76E-03	10.64
60	5.0	21.2	11.0	0.01414	14.5	6.0	16.22	6.95E-03	10.64
90	5.0	21.5	10.9	0.01397	14.5	5.9	15.95	5.61E-03	10.46
120	4.5	21.6	10.8	0.01397	14.5	6.3	17.03	4.86E-03	11.17
1440	5.0	21.9	8.8	0.01397	14.8	3.8	10.27	1.42E-03	6.74

Table A-3.3. Hydrometer Analysis for < 0.063 mm: Trial 3

Particle Size Analysis -> Hydrometer Method: < 0.063 mm Sieve
Trial 3 By: Maren Henley

Spec. Grav.: 2.48

Dry Weight: 38.11 g

Time (min)	Blank Hydrometer Reading	Blank Solution Temperature °C	Soil Hydrometer Reading	Constant for Temperature	Effective Depth	Difference in Hydrometer Readings	Percentage Finer for Sample	Diameter of Particle (mm)	Cumulative % Finer
0.5	5.8	18.8	18.0	0.01449	13.3	12.2	32.97	7.47E-02	21.63
1	6.0	18.9	18.0	0.01449	13.3	12.0	32.43	5.28E-02	21.28
3	6.0	19.1	16.2	0.01449	13.7	10.2	27.57	3.10E-02	18.08
10	5.5	19.5	13.8	0.01431	14.0	8.3	22.43	1.69E-02	14.72
30	5.0	19.7	13.0	0.01431	14.2	8.0	21.62	9.85E-03	14.18
60	6.0	20.1	13.0	0.01431	14.2	7.0	18.92	6.96E-03	12.41
90	5.5	20.4	12.0	0.01431	14.3	6.5	17.57	5.70E-03	11.52
120	5.8	20.7	11.2	0.01414	14.5	5.4	14.59	4.92E-03	9.57
1440	4.8	24.3	8.0	0.01365	15.0	3.2	8.65	1.39E-03	5.67

Table A-4. Normalized Cumulative % Finer for 0.063 mm - 2.36 mm Sieve

Particle Size Analysis -> Hydrometer > No. 230 Sieve Results
By: Maren Henley

Sieve Size (micrometer)	% Finer Trial 1	% Finer Trial 2	% Finer Trial 3	% Finer Average	Cumulative % Finer
2360 (#8 sieve)	100.00	100.00	100.00	100.00	65.60
1180 (#16 sieve)	98.16	96.97	98.34	97.82	64.17
850 (#20 sieve)	94.02	91.72	95.03	93.59	61.40
500 (#35 sieve)	84.59	81.13	84.91	83.54	54.80
250 (#60 sieve)	66.79	63.60	66.44	65.61	43.04
125 (#120 sieve)	47.98	45.61	48.00	47.20	30.96
63 (#230 sieve)	34.76	33.45	35.44	34.55	22.66
<63	34.76	33.45	35.44	34.55	22.66

Table A-5. Normalized Cumulative % Finer for < 0.063 mm

Particle Size Analysis -> Hydrometer > No. 230 Sieve Results
By: Maren Henley

Diameter of Particle (mm)	% Finer Trial 1	% Finer Trial 2	% Finer Trial 3	% Finer Average	Cumulative % Finer
7.45E-02	29.73	27.03	32.97	29.91	19.62
5.28E-02	27.03	25.68	32.43	28.38	18.62
3.08E-02	22.97	22.97	27.57	24.50	16.07
1.69E-02	20.27	18.92	22.43	20.54	13.47
9.79E-03	16.22	16.22	21.62	18.02	11.82
6.95E-03	14.86	16.22	18.92	16.67	10.93
5.66E-03	13.51	15.95	17.57	15.68	10.28
4.92E-03	14.59	17.03	14.59	15.41	10.11
1.42E-03	8.11	10.27	8.65	9.01	5.91

Appendix B

Modified Proctor Compaction Test Data

Table B-1. Modified Proctor Compaction Test: < 2 mm Sieve

Modified Proctor Compaction Test (layering) NTS Area 3 minus - 2 mm
Date: 6/25/97 By: Maren Henley

Treatment	1	2	3	4
Moisture content to be added (g/g * 100)	2%	4%	6%	8%
Mold + wet soil (g)	3805	3907	3981	3927
Mold (g)	2004	2004	2004	2004
Wet soil (g)	1801	1903	1977	1923
Factor *	0.0662	0.0662	0.0662	0.0662
Wet density (g/cm ³)	1.91	2.02	2.10	2.04
Pan + wet soil (g)	724	790	806	759
Pan + dry soil (g)	680	727	733	682
Moisture loss (g)	44	63	73	77
Pan (g)	201	203	203	201
Dry soil (g)	479	524	530	481
Final moisture content (g/g * 100)	9.2%	12.0%	13.8%	16.0%
Dry density (g/cm ³)	1.75	1.80	1.84	1.76

Table B-2. Modified Proctor Compaction Test: < 5 mm Sieve

Modified Proctor Compaction Test (layering) NTS Area 3 minus - 5 mm
Date: 6/25/97 By: Maren Henley

Treatment	1	2	3	4
Moisture content to be added (g/g * 100)	2%	4%	6%	8%
Mold + wet soil (g)	3841	3936	3968	3929
Mold (g)	2004	2009	2004	2004
Wet soil (g)	1837	1927	1964	1925
Factor *	0.0662	0.0662	0.0662	0.0662
Wet density (g/cm ³)	1.95	2.04	2.08	2.04
Pan + wet soil (g)	773	790	732	842
Pan + dry soil (g)	723	728	669	754
Moisture loss (g)	50	62	63	88
Pan (g)	207	205	204	207
Dry soil (g)	516	523	465	547
Final moisture content (g/g * 100)	9.7%	11.9%	13.5%	16.1%
Dry density (g/cm ³)	1.77	1.83	1.83	1.76

Appendix C

Saturated Hydraulic Conductivity Data

Table C-1. Saturated Hydraulic Conductivities

NTS Area 3 Saturated Hydraulic Conductivities
Date: 6/27/97 By: Maren Henley

Size Fraction- Compaction	Diameter (m)	Length (m)	Head - Initial (m)	Head - Final (m)	Flow Volume (m ³)	T ₁ (sec)	T ₂ (sec)	T ₃ (sec)	T ₄ (sec)	T ₅ (sec)	K _{sat} (m/s)
5 to 2 mm - NA	8.31E-02	7.55E-02	0.674	0.678	1.00E-04	67	67	67	65	68	5.21E-03
5 to 2 mm - NA	8.28E-02	7.54E-02	0.696	0.698	1.00E-04	156	156	164	167	158	4.37E-03
< 5 mm - 90%	8.28E-02	7.51E-02	0.590	0.712	2.50E-05	530	515	503	509	514	5.56E-06
< 5 mm - 90%	8.27E-02	7.53E-02	0.727	0.758	2.50E-05	489	512	512	506	496	2.25E-05
< 5 mm - 90%	8.27E-02	7.53E-02	0.632	0.758	2.50E-05	136	140	137	137	139	2.02E-05
< 5 mm - 90%	8.29E-02	7.55E-02	0.480	0.660	2.00E-05	697	751	732	763	760	2.10E-06
< 5 mm - 83%	8.25E-02	7.54E-02	0.679	0.690	2.00E-05	312	332	329	331	320	7.90E-05
< 5 mm - 83%	8.24E-02	7.56E-02	0.651	0.740	2.50E-05	199	204	199	201	200	1.99E-05
< 5 mm - 83%	8.24E-02	7.56E-02	0.650	0.665	2.00E-05	692	705	707	686	656	2.74E-05
< 2 mm - 90%	8.27E-02	7.55E-02	0.077	0.681	1.00E-05	525	544	579	643	675	3.92E-07
< 2 mm - 90%	8.25E-02	7.53E-02	0.120	0.665	1.50E-05	409	421	428	442	453	9.00E-07
< 2 mm - 83%	8.27E-02	7.55E-02	0.619	0.728	2.50E-05	353	377	358	361	361	8.91E-06
< 2 mm - 83%	8.27E-02	7.55E-02	0.680	0.728	1.00E-05	284	283	298	298	292	1.01E-05
< 2 mm - 83%	8.27E-02	7.55E-02	0.674	0.750	2.50E-05	430	447	443	437	429	1.06E-05

Appendix D

Water Retention Data

Table D-1. Water Retention Data

Water Retention Data from Maren Henley - Area 3

Size Fraction- Compaction	Cell + Dry Soil Wt. (g)	Cell Wt. (g)	Air- Dry Wt. (g)	WT-0*	WC-0**	WT-25	WC-25	WT-50	WC-50	WT-100	WC-100
< 5mm-90%	377.89	133.08	244.81	428.18	0.343042	420.98	0.293929	416.39	0.262619	410.48	0.222306
< 5mm-90%	376.90	132.09	244.81	428.63	0.352865	419.55	0.290928	415.38	0.262483	411.36	0.235061
< 5mm-83%	358.56	132.32	226.24	408.70	0.342019	400.72	0.287585	393.95	0.241405	388.70	0.205593
< 5mm-83%	358.99	132.75	226.24	414.90	0.381378	404.78	0.312347	397.31	0.261392	390.70	0.216303
< 2mm-90%	377.99	133.18	244.81	428.82	0.346726	421.42	0.296248	418.45	0.275989	412.93	0.238336
< 2mm-90%	374.09	132.98	241.11	432.72	0.399932	424.14	0.341405	419.48	0.309618	414.14	0.273192
< 2mm-83%	359.14	132.90	226.24	416.95	0.394338	407.93	0.332810	400.31	0.280832	391.80	0.222783
< 2mm-83%	358.87	132.63	226.24	412.66	0.366917	400.60	0.284652	393.64	0.237176	388.34	0.201023
5 to 2mm-NA	324.33	132.27	192.06	383.34	0.402524	339.90	0.106207	338.94	0.099659	337.83	0.092087
5 to 2mm-NA	329.49	133.03	196.46	390.60	0.416849	344.46	0.102115	343.27	0.093997	342.19	0.086630
< 19mm-90%	381.71	132.45	249.26	440.27	0.399454	423.52	0.285198	419.24	0.256003	416.81	0.239427
< 19mm-90%	384.09	133.73	250.36	446.19	0.423602	427.73	0.297681	423.75	0.270532	419.72	0.243042
< 19mm-83%	362.15	132.37	229.78	423.18	0.416303	406.56	0.302933	399.98	0.258049	394.59	0.221282
< 19mm-83%	362.49	134.20	228.29	423.30	0.414802	402.86	0.275375	398.45	0.245293	394.66	0.219441

* WT = weight (g) at designated tension (cm)

** WC = water content by volume (%)

Table D-1. Water Retention Data (Continued)

Water Retention Data from Maren Henley - Area 3 (Continued)

D-3

Size Fraction- Compaction	WT-150	WC-150	WT-200	WC-200	WT-500	WC-500	WT-750	WC-750	WT-1000	WC-1000
< 5mm-90%	408.12	0.206207	406.22	0.193247	404.85	0.183902	404.00	0.178104	403.31	0.173397
< 5mm-90%	410.02	0.225921	408.82	0.217735	406.87	0.204434	405.72	0.196589	405.13	0.192565
< 5mm-83%	386.92	0.193452	386.10	0.187858	384.40	0.176262	383.51	0.170191	382.63	0.164188
< 5mm-83%	389.13	0.205593	387.90	0.197203	385.61	0.181583	384.35	0.172988	383.79	0.169168
< 2mm-90%	409.85	0.217326	408.62	0.208936	405.99	0.190996	405.07	0.184720	404.12	0.178240
< 2mm-90%	410.74	0.250000	409.73	0.243111	407.11	0.225239	405.52	0.214393	404.10	0.204707
< 2mm-83%	388.49	0.200205	387.23	0.191610	384.33	0.171828	383.32	0.164939	382.48	0.159209
< 2mm-83%	387.03	0.192087	386.22	0.186562	384.24	0.173056	383.03	0.164802	382.42	0.160641
5 to 2mm-NA	337.48	0.089700	337.18	0.087653	337.04	0.086698	336.21	0.081037	335.78	0.078104
5 to 2mm-NA	341.19	0.079809	340.83	0.077353	340.61	0.075853	340.01	0.071760	339.58	0.068827
< 19mm-90%	414.98	0.226944	414.07	0.220737	412.55	0.210368	411.28	0.201705	410.14	0.193929
< 19mm-90%	417.75	0.229604	416.62	0.221896	414.86	0.209891	413.46	0.200341	412.42	0.193247
< 19mm-83%	392.51	0.207094	391.75	0.201910	389.60	0.187244	388.34	0.178649	387.48	0.172783
< 19mm-83%	393.01	0.208186	392.32	0.203479	392.23	0.202865	388.87	0.179945	387.87	0.173124

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