FIELD MEASUREMENT OF THE SOIL-WATER STORAGE CAPACITY OF EVAPOTRANSPIRATION COVERS USING LYSIMETERS

by

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ABSTRACT

Three soils were tested as possible substrates for an evapotranspiration cover for a Uranium mill tailings disposal site in Moab, Utah. Small weighing field lysimeters were used to determine the field capacity of soils with the effect of a coarse-grained capillary barrier placed beneath the soil to increase water retention. Water was ponded on each lysimeter and then covered with plastic to prevent evaporation. Lysimeters were drained and weighed periodically throughout the experiment. Field capacity was determined by the weight of the lysimeter when drainage stopped. Results were compared to a mathematical model for estimating water storage of capillary barriers. Results from particle size analyses were also compared to water storage results and we found that both sand and clay were significant factors ($p < 0.05$) in explaining water storage. After determining the water-holding capacity of the soils, recommendations on the most suitable soil for the Moab evapotranspiration cap will be made.

CHAPTER 1

INTRODUCTION

1.1 Background

Throughout the United States, mine wastes pose a serious threat to human health and the environment. Former uranium mill sites are a particular problem in the southwestern United States because they release chemical as well as radiological hazards into the environment. One such site is located in Moab, Utah where a 130-acre mill tailings pile is located near the entrances to Arches National Park, Canyonlands National Park, and the Colorado River. The ore-processing facility operated from 1956 until 1984. When processing ceased, approximately 11.9 million tons of uranium-contaminated tailings and soil were moved to the location of the current pile. The owners of the facility, Atlas Minerals Corporation, then placed an interim cover over the tailings, drafted a reclamation plan, and an Environmental Impact Statement (EIS) was drafted by the regulatory agency, the U.S. Nuclear Regulatory Commission (NRC). However, Atlas declared bankruptcy in 1998, and ownership of the site was eventually passed to the U.S. Department of Energy (DOE) by the passing of the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001. The DOE Grand Junction Office in Colorado was assigned primary responsibility for the remediation and stewardship of the site (http://gj.em.doe.gov/moab/).

1.2 Disposal Cell Designs

The remedial action proposed by Atlas Minerals Corporation consisted of a landfill cover design that complied with Resource Conservation and Recover Act (RCRA) Subtitle C for hazardous waste disposal, and the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978. RCRA technology guidance recommends the cover have four layers: a topsoil layer with rocks or vegetation to control erosion, a drainage layer, a geomemebrane, and a thick compacted clay layer (CCL) to limit infiltration into the underlying waste (EPA 1989). The UMTRCA design also consists of a CCL, with a maximum hydraulic conductivity of 1×10^{-7} cm s^{-1} designed to impede radon release into the atmosphere, a drainage layer, and usually a rock surface barrier. UMTRCA also requires that the cover be designed to prevent contaminant release for a minimum of 200 years, or 1000 years whenever achievable (EPA 1983). Throughout the United States, however, designs similar to the one proposed in Moab have failed, often due to increased hydraulic conductivity (Benson et al. 1999; Suter et al. 1993). Causes of failure due to damage of the CCL include freeze/thaw cracking (McBrayer et al. 1997; Suter et al. 1993), desiccation (McBrayer et al 1997; Philip et al. 2002), root intrusion (Bowerman and Redente 1998; Reynolds 1990), burrowing animal intrusion (Bowerman and Redente 1998; Hakonson 1999), and erosion (Hillel 1998; Suter et al. 1993).

1.3 Evapotransiration Cover Design

When DOE gained ownership of the Moab site in 2001, another Environmental Impact Statement (EIS) was drafted. In this EIS, however, alternative disposal options for the tailings are being considered, including an Evapotranspiration (ET) Cover design (http://gj.em.doe.gov/moab/). ET covers are a practical alternative in semiarid and arid climates where seasonal potential evaporation and transpiration by plants can exceed yearly precipitation. ET covers are designed for long-term performance by working with the forces of nature rather than attempting to control them (Hauser et al. 2001). However, it is important when designing ET covers to insure that 1) a sustainable plant community can be established that will seasonally remove water from the soil profile, and 2) the soil profile has an adequate water storage capacity in case of extreme or unusual climatological events (e.g. fire, above-average precipitation, etc.) (Hauser et al. 2001). One method of maximizing the water storage of the soil is to place a capillary barrier below the top layer of soil (Stormont 1997). Placement of a coarse-grained soil below a fine-grained soil creates a difference in hydraulic conductivity between the two layers, causing the fine-grained layer to hold a higher amount of water. Fine-grained soils have smaller pores, and water is held under high tensions, while the larger pores of coarser-grained soils tend to be nearly empty at similar tensions. With an initially unsaturated soil, the hydraulic conductivity of the fine-grained soil is high, but in the coarse-grained soil, it is immeasurably small, preventing breakthrough into the coarse-grained soil below (Stormont 1997). As the fine-grained soil approaches saturation, however, tensions in the soil decrease until breakthrough occurs as the conductivity of the coarser layer increases (Porro 2001).

1.4 Water Balance

Thickness and soil texture of the fine-textured soil layer used in a capillary barrier cover design will have a great influence on the water stored in the soil (Khire et al 2000; Stormont and Morris 1998). Additional storage due to presence of a capillary barrier is largely dependent on the texture and uniformity of the coarse-textured layer (Stormont 1997; Stormont and Anderson 1999). It is therefore important to determine the amount of water that each type of soil being considered for the ET cover is capable of holding, and how much of that is available to plants. Coarse-grained soils have large pores, and will store relatively small amounts of water, while fine-grained soils, with higher clay content, will hold more water (Stormont 1997). The ultimate goal of this project is to determine the amount of water that a soil will hold that is available for plant use, the water storage capacity. Water storage capacity is defined as the difference between the "drained upper limit," or field capacity, of the soil, and the "lower limit of extraction," or the permanent wilting point (Ritchie 1981). Therefore, it is important to determine the field capacity of soils, which was the objective for the current study, in which we determined the field capacity of three different soil types over a sand capillary barrier. A future study will be done in which the permanent wilting point will be determined by planting the lysimeters with native vegetation and allowing them to remove all available water in the soil profile. At this point, the water storage capacity of the soils can be determined. This information will be used to determine the soil type best suited for an ET cover in Moab.

In this study, the objective was to determine field capacity of three soil types overlying a layer of sand using an array of small-weighing lysimeters. Lysimeters were filled with a 10-cm bottom layer of pea gravel, a 15-cm layer of washed sand, followed by ten 15-cm lifts of fine-grained soil. Water was ponded on top of each lysimeter at the beginning of the experiment, and lysimeters were covered with plastic to prevent evaporation. Lysimeters were then drained and weighed periodically throughout the experiment. Field capacity was determined by the weight of the lysimeter when drainage stopped. Our second objective was to compare our results of water storage from the lysimeters to an engineering-based estimation that is commonly used instead of field data when designing a barrier cover. Stormont and Morris (1998) published a paper presenting a method to estimate water storage in fine-textured soil with a coarser textured capillary barrier beneath. We also compared the results of the soil texture analyses to the field capacity of each of the three soils selected.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Throughout the United States, mine wastes pose a serious threat to human health and the environment. Former uranium mill sites are a particular problem in the southwestern United States because they release chemical as well as radiological hazards into the environment.

Moab, Utah is the location of a 400-acre former uranium ore-processing facility, and the site of a 130-acre uranium mill tailings pile. The site is located approximately 3 miles northwest of the city of Moab, less than one mile from the entrance to Arches National Park, and is situated along the west bank of the Colorado River near the confluence with Moab Wash. The pile is an environmental and health hazard, as high levels of ammonia from the pile are leaching into the Colorado River, causing concern for endangered fish habitat (http://gj.em.doe.gov/moab/).

In 2001, Congress passed the Floyd D. Spence National Defense Authorization Act, which authorized the U.S. Department of Energy (DOE) to manage and reclaim the Moab facility under Title 1 of the Uranium Mill Tailings Radiation Control Act (UMTRCA). Prior to this act, the facility was regulated by the U.S. Nuclear Regulatory Commission (NRC) under Title II of UMTRCA. The DOE office in Grand Junction, Colorado is assigned the remediation and stewardship of the Moab site (http://gj.em.doe.gov/moab/).

Moab is a semi-arid high desert located on the Colorado Plateau, at an elevation of 1227m. July is usually the hottest month, with an average high temperature of 37.9°C, and the lowest average temperature in January of -6.9°C. Average annual precipitation is around 38cm, with the maximum rainfall of 2.9cm falling in October, and maximum snowfall, an average of 9.7cm, falling in January.

The DOE is currently in the process of writing an Environmental Impact Statement (EIS), in which alternatives for either on-site stabilization or hauling to an off-site disposal cell will be presented (US DOE 2004). The final EIS is expected to be released in Fall 2004.

2.2 Disposal Cell Designs

To satisfy the Resource Conservation and Recovery Act (RCRA) requirements, all hazardous waste locations, including the mill tailings in Moab, must be contained in order to minimize potential impacts to human health and the environment. Engineered covers are the accepted remedial action for disposal of radioactive waste (US DOE 1989). Landfill covers for all types of wastes have three primary requirements (Hauser et al. 2001):

- Minimize infiltration into the underlying waste and percolation of waste into groundwater.
- Control movement of waste by wind or water by isolation.
- Control landfill gas.

Under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA), landfill covers for radioactive waste must also be designed to control radon attenuation and to be effective for a minimum of 200 years, and for 1000 years whenever possible (40 CFR 192.32). Additionally, in semi-arid climates like Moab, the cover must also be designed to withstand other environmental processes such as desiccation, frost penetration, plant root intrusion, and burrowing animal intrusion.

2.2.1 Compacted Clay Barriers

In the past, landfill covers have been designed to minimize infiltration and radon flux by construction of a radon barrier, known as a compacted soil layer (CSL) with a maximum saturated hydraulic conductivity of (K) $\leq 1 \times 10^{-7}$ cm s^{-1}. This type of landfill cover, also called a barrier layer, complies with Subtitle C of RCRA (40 CFR, Part 258.60). This design often consists of a surface layer of rock riprap to prevent the CSL from erosion, with a fine (30-cm) layer of sand bedding between the rock and the CSL to divert water (Richardson 1997). In 1999, the NRC proposed a barrier layer cover design for the Moab site remediation (Figure 2.1).

Problems associated with the performance of barrier-type covers, however, have been addressed in a growing amount of literature. A study by Benson et al (1999) found that 22 of 85 (26%) CSL sites failed to have (K) $\leq 1 \times 10^{-7}$ cm s^{-1}. The main causes of failure in compacted soil barrier systems are due to freeze/thaw cracking, desiccation, root intrusion, burrowing animal intrusion, and erosion.

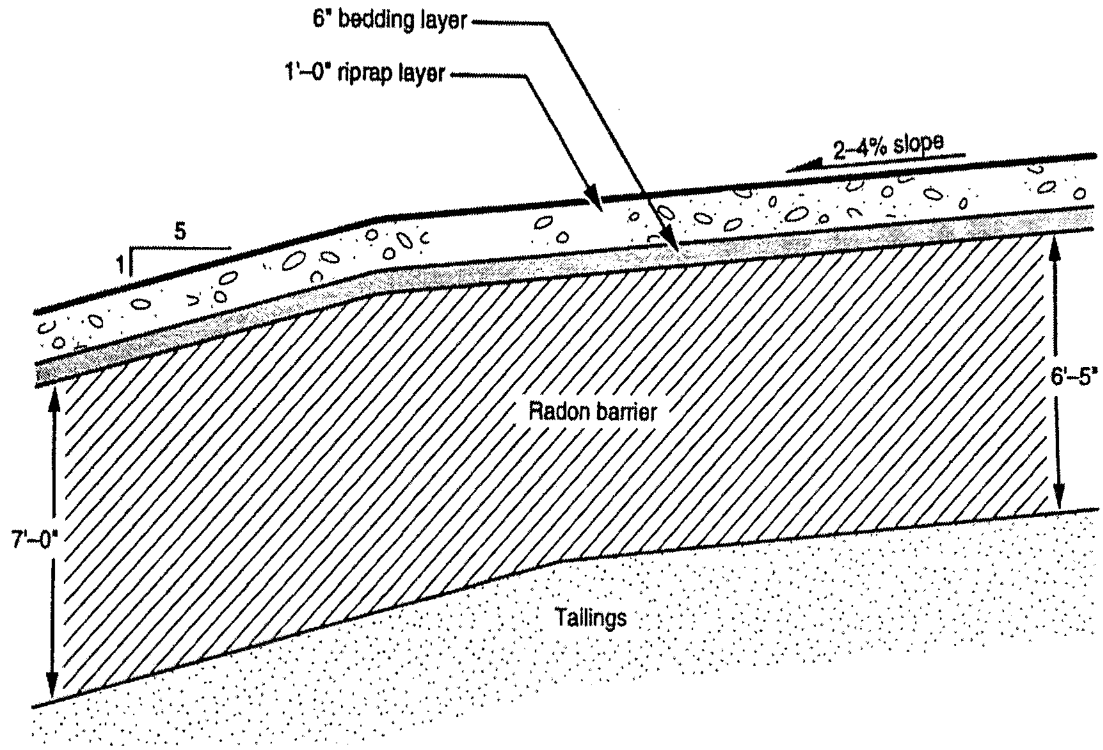

Figure 2.1. Cross-section of UMTRCA rock armored cover design.

2.2.1.1 Freeze/thaw cracking and desiccation

The shrink/swell properties of fine-textured soils make them vulnerable to cracking due to freeze/thaw processes and desiccation. Freezing and thawing of soils can lead to a change in soil texture, due to the formation of shrinkage cracks, and/or reduction of the volume of fine-textured particles in the pores of the coarse fraction (Chamberlain and Gow 1979). Desiccation cracking occurs when moisture is lost from the soil, and the discontinuities that occur naturally throughout the profile are enlarged (Philip et al. 2002). All of these processes lead to increased permeability of the CSL. A laboratory study found that cracks formed during these processes appear to heal, but can still contribute to water flow, and also reopen during subsequent freeze/thaw or desiccation cycles (McBrayer et al. 1997). Preferential flow due to cracking can cause the saturated hydraulic conductivity to increase by several orders of magnitude.

2.2.1.2 Plant root intrusion

Plant root intrusion is a problem at many hazardous waste disposal sites around the United States. The rock riprap layer provides habitat for many plant species, and may actually favor unwanted plant growth (Waugh et al. 1994). Negative impacts of plant root intrusion include transport and dispersion of waste into the environment and physical damage to the barrier (Bowerman and Redente 1998). Plant roots create macropores within the soil profile, which can significantly increase the conductivity of soil (Hillel 1998). Several CSL sites around the country have documented plant root intrusion. The impact of plant roots on the cover depend on the thickness of the rock riprap, sand bedding, and compacted clay layers, as well as the type of plant (Bowerman and Redente 1998). In a study at Los Alamos National Laboratory, root intrusion still occurred even with a maximum CSL thickness of 1.5m (Bowerman and Redente 1998). Reynolds (1990) found that a clay barrier had the highest root penetration and root abundance of the three equally thick biobarriers tested.

2.2.1.3 Burrowing animal intrusion

Burrowing animals, both invertebrates and mammals, also have the potential to threaten the integrity of a barrier system. Burrowing animals can directly or indirectly transport contaminants to the surface, as well as alter the water balance and increase erosion of the barrier (Suter et al. 1993; Bowerman and Redente 1998). Harvester ants (*Pogonomymrex spp.*) have been found to tunnel to depths ranging from 1.7 to 2.7 m, and move an estimated 151 kg yr^{-1} of soil, depending on soil material (Bowerman and Redente 1998). Several cases found that harvester ants had penetrated into the radioactive waste, bringing small fragments to the surface (Bowerman and Redente 1998).

Burrowing mammal species of concern in arid and semiarid climates include species of pocket mice, kangaroo rats, pocket gophers, ground squirrels, prairie dogs, and badgers. Smaller mammals like pocket mice (*Perognathus parvus*) and kangaroo rats (*Dipodomys ordii*) have been documented to burrow into tailings buried beneath 2.4m cover depths (Bowerman and Redente 1998). However, an animal intrusion barrier consisting of a layer of gravel (3.8 – 7.6cm in diameter) deterred burrowing beneath the layer (Bowerman and Redente 1998). In addition, a study conducted at DOE's Hanford site in Washington found that despite lack of vegetation and/or higher-than-normal precipitation, burrowing by small mammals did not significantly increase water storage in test lysimeters without animal intrusion layers (Gee and Ward 1997). Larger mammals may have more of an effect on the integrity of a landfill cover. Pocket gophers (*Thomomys bottae*), prairie dogs (*Cynomyous leucurus*), and ground squirrels (*Spermophilus spp.*) all burrowed through various types of animal intrusion barriers

(Bowerman and Redente 1998). But Gee and Ward (1997) suggest that even large burrows dug by badgers appear to be of minor impact to barriers in the long term.

2.2.1.4 Erosion

Soil erosion is a process that can occur due to wind or water, occurs mainly on sideslopes, and can be enhanced by lack of vegetative cover. It is a three-step process, in which (1) soil particles are detached from the surface, followed by (2) downslope movement of the particles, and finally (3) deposition of the particles, which is known as sedimentation (Hillel 1998). Once water erosion has begun, the soil surface can form rills, gullies, and rivulets. The amount of soil that is eroded due to rainfall depends on the intensity, duration, and energy of a rainfall, as well as the erodibility of the soil, which is related to qualities of the soil such as texture, organic matter content, and structure (Hillel 1998). Wind erosion, also called deflation, can redistribute fine soil particles around the world (Hillel 1998). Different-sized soil particles behave differently when transported by the wind. Larger particles (diameter of 0.5mm or more) are transported by surface creep, and are generally moved only a few centimeters. Finer sand particles (0.1 – 0.5mm diameter) are moved by saltation, which is a hop-skip motion in a repeated sequence, and usually takes place within a half meter of the soil surface (Hillel 1998). Suspension occurs when fine particles (0.02 – 0.1mm) are lifted above the soil surface and remain suspended for longer periods of time, and often are transported by air currents (Hillel 1998). Often, a rock barrier is placed on a cover to decrease erosion, but vegetation has been shown to be the most effective deterrent of erosional processes (Hakonson 1999; Waugh et al. 1994).

2.2.2 Evapotranspiration (ET) Covers

In recent years, several studies have been done to test the applicability of evapotranspiration (ET) covers in semi-arid climates instead of the standard RCRA Subtitle C covers. ET covers are designed to work with the processes of nature instead of controlling these forces. An ET cover differs from the more traditional "vegetative cover" in that the plant-available water-holding capacity is critical to the performance of the cover (Hauser et al. 2001). On an ET cover, the soil must hold all precipitation while plants are dormant or dead, and then the plants must be able to extract most of the stored water during the growing season. In addition to the requirements for all landfill covers (minimize infiltration, isolate wastes, control landfill gas, control erosion, and remain effective for a minimum of 100 years), an ET cover must also be able to support a full vegetative community with rapid growth on all part of the cover, and the soil must have the capability to hold enough water to minimize water movement during periods of abnormal precipitation (Hauser et al. 2001). An ET cover has been proposed as an alternative to the RCRA Subtitle C design for Moab's uranium mill tailings (Figure 2.2) (US DOE 2004).

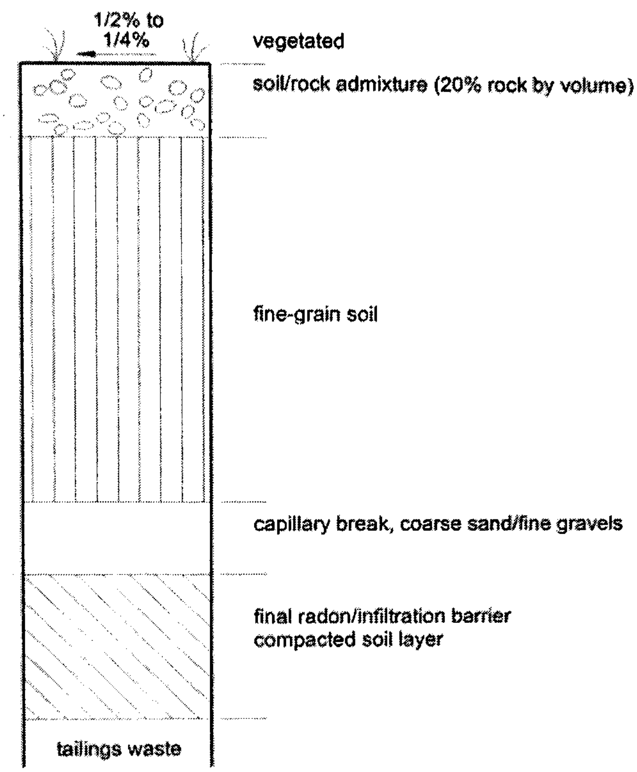

Figure 2.2. Proposed design for Moab ET Cover.

2.2.2.1 *Water balance and infiltration*

The amount of water held in a soil must equal the amount leaving plus the amount stored in the soil. This can be expressed in a simple formula:

$$P + R_i = ET + R_o + G + \Delta S$$

Where P is the amount of precipitation, R_i and R_o are surface runon and runoff, respectively, ET is evapotranspiration, G is the amount of water that reaches the groundwater, and ΔS is the water stored in the soil which changes due to varying amounts of inputs and outputs into the system (Anderson 1997). In semi-arid climates, the amount of precipitation is far exceeded by the potential amount of water lost to evapotranspiration. Normally, R_i and R_o will be minimized, and the cover and profile chosen in order to eliminate G. Therefore, it is important to choose a soil that is thick enough to support a full native vegetative community to maximize ET, but not so thick that the water stored in the soil becomes unavailable to the plants.

When determining the depth of an ET cover, both the maximum amount of water the soil is capable of holding, and the maximum potential amount of water the soil may have to store should be determined (Anderson 1997). Water storage capacity is the maximum amount of water a soil will hold, and can be determined by the difference between the "drained upper limit," or field capacity, of the soil, and the "lower limit of extraction," often referred to as the permanent wilting point (Ritchie 1981). The permanent wilting point is the driest point in which plants can extract water from the soil (Veihmeyer and Hendrickson 1949). This value can of course vary depending on plant species, although drought-tolerant perennial species tend to have little variation (Anderson 1997). The field capacity of a soil is "the amount of water held in a soil after excess water has drained away" (Veihmeyer and Hendrickson 1949). Although it is not an intrinsic property of soils independent of the way it is measured (Hillel 1998), it is an important characteristic in determining the water storage capacity of soils being considered for an ET cover.

Another important factor in determining the depth of an ET cover is the maximum amount of water that the soil cover may be required to store. This can be determined by first examining the historic climatic patterns and conditions of the site (Anderson 1997; Khire et al. 2000). The maximum amount of precipitation, as well as when the majority of yearly precipitation occurs will have an effect on how much and where the water is stored within the soil profile. The time of year in which the majority of a site's yearly precipitation falls plays a factor in determining how much the soil may need to store. In semiarid climates, precipitation during the growing season will typically be quickly evaporated or transpired by plants. Precipitation during the dormant season, however, may accumulate in the soil and infiltrate to depths greater than the roots of plants (Anderson 1997; Khire et al. 2000). It is important, then, to plant a diverse mix of native vegetation; including deep-rooted shrubs, which usually have a competitive advantage with deeper soil water, while perennial grasses remove more water during late spring/early summer precipitation (Anderson 1997). Climate change and worst-case scenario storm events should be considered when choosing cover thickness and vegetation species (Anderson 1997; Waugh 1997). Anderson (1997) and Khire (2000) both recommend methods to estimate layer thickness when the water storage capacity and climate data are known. Ideal layer thicknesses varied from 15-30cm in Denver, Colorado, to >90 cm in Wenatchee, Washington (Khire et al. 2000). Anderson (1997) determined that a layer thickness of 2m was conservative at the Idaho National Engineering and Environmental Laboratory (INEEL).

2.2.2.2 Capillary barrier

A feature that has recently been used on many types of landfill covers, including ET covers, is a capillary barrier. A capillary barrier can increase the amount of water the fine-grained soil can hold, or it can be used to decrease the soil thickness needed to hold a maximum amount of water. It is well known in soil physics that a fine-grained soil will hold more water when an underlying coarse-grained soil acts as a capillary barrier (e.g. Khire et al. 2000; Stormont and Anderson 1999, etc.). This is due to the difference in tensions, or suction head, between the unsaturated soil layers. Fine-grained soils have smaller pores, and water is held under high tensions, while the larger pores of coarser-grained soils have lower tensions with which to hold water. As the fine-grained soil approaches saturation, tensions in the soil decrease until breakthrough occurs when the tension of both soils are equal (Porro 2001). In a study comparing a capillary barrier system to a thick soil design, Porro (2001) initially wetted both systems until breakthrough occurred. He then monitored amounts and rates of drainage, as well as recovery and drainage amounts under natural conditions the following year. He found that drainage from the capillary barrier slowed more quickly than the thick soil system. Also, drainage from the capillary barrier continued longer, but yielded less total drainage. The following year, the capillary barrier produced no drainage, but the thick soil system did. Because capillary barrier systems are capable of storing more water, there is a higher potential for water to be returned to the atmosphere due to evaporation and transpiration. This means that overall, less water is stored in the soil, which allows more room for high precipitation events, such as snow thaw and/or flooding (Nyhan et al. 1990; Porro 2001; Stormont 1997). Similar cycles of breakthrough and restoration of capillary barriers has been shown by Stormont and Anderson (1999). Other studies have been done to determine the effects of different types of soils used for the fine-grained layer and as the coarse layer. The soil texture of the fine-grained layer greatly affects the water storage capacity of a capillary barrier. Silty sand will store a considerable amount more than coarser concrete sand when both are placed over a pea gravel capillary barrier (Stormont 1997). The additional amount of water a soil will hold depends upon the water entry suction of the coarse-grained layer. Since water enters the smallest pores of a network first, a coarse-grained capillary barrier like pea gravel will have a higher resistance for breakthrough than a less coarse capillary barrier like concrete sand (Stormont 1997). Since breakthrough occurs when the suction head of the fine-grained layer decreases to that of the coarse layer, it goes to reason that the coarse-grained layer controls the breakthrough point (Stormont and Anderson 1999). Additionally, water storage can be further increased when a lateral drainage can occur between the fine-grained soil and the capillary barrier, such as on the sloping sides of landfill covers (Heilig et al. 2003; Stormont 1997). Use of a capillary barrier with an ET cover will insure minimal water infiltration into underlying wastes in semiarid climates such as that in Moab, Utah.

2.2.2.3 Radon attenuation

To comply with UMTRCA requirements, all uranium mill tailings disposal sites must have a layer that limits surface flux of ^{226}Rn to less than 20 pCi m^{-2} s^{-1} (US EPA 1983). This is typically achieved with a fine textured soil layer with a maximum saturated conductivity of 1 x 10^{-7} cm s^{-1}. At an UMTRCA site in Monticello, Utah, an ET cover was built with a 60cm thick clay radon barrier below the capillary break (Waugh 1997). The thickness of the radon barrier in Moab will be calculated using physical and hydrological properties of the overlying soil layers, and radiological properties of the tailings (US DOE 2004)

2.2.2.4 Biointrusion control

An ET cover consisting of a native vegetation community will likely provide an ideal habitat for burrowing animals, which in turn may disrupt the water balance of the cover, or potentially bring radioactive waste to the surface. Plant roots extending below the capillary barrier may also threaten the integrity of the cover (Anderson 1997; Waugh 1997). However, the combination of deep soil and a coarse-grained capillary barrier doubling as a biointrusion layer has been shown to deter burrowing of vertebrates and ants (Anderson 1997; Bowerman and Redente 1998). Furthermore, a study by Anderson (1997) showed that plants are unable to extract water from a biointrusion layer of less than 25% volumetric water content, a value not seen on any ambient plots.

2.2.2.5 Erosion Control

Several studies have shown relationships between erosion and vegetative cover. Vegetation reduces raindrop energy and prevents soil compaction while binding soil particles in the root system (Hakonson 1997), but a vegetative cover alone may not provide adequate erosion control, particularly in the first few years after the cover is built before vegetation has fully established. A surface layer of gravel is also commonly used to control erosion on a landfill cover, but Waugh et al. (1994) suggest that mixing a moderate amount of gravel into the topsoil is the best method to control erosion with little effect on plant habitat or the soil-water balance. They found that after five years, plots with and without gravel admixtures showed equivalent changes in plant species, though water content just below the admixture layer was sometimes higher when plants were not present. Sackschewsky et al. (1995) also found that gravel admixture surfaces had no significant effect on the soil water balance, but gravel or sand surface alone reduced evapotranspiration. Additionally, a gravel admixture has also been shown to lead to the formation of conditions similar to that of desert pavement, which further stabilizes the soil and protects it from wind and water erosion (Waugh 1997). A gravel admixture is also the most stable erosion protection during periods when the cover may not have adequate vegetative cover (e.g. fire, drought, etc.) (Gee and Ward 1997; Sackschewsky et al. 1995).

In conclusion, the proposed ET cover for the Moab uranium mill tailings pile is a sensible alternative to the earlier design. Given the semiarid climate of the site, plants would be able to remove water from the cover annually, producing little or no infiltration through the cover into the tailings. Furthermore, the use of a capillary barrier would increase the water storage of the surface soil, providing assurance that in cases of extreme drought, higher than average precipitation, or other climatological changes, the cap would still produce minimal drainage. A capillary barrier would also serve as a biointrusion layer, preventing animals from burrowing, and limiting plant root growth. A gravel admixture on the surface would provide erosion protection and suitable habitat for vegetation.

2.3 Lysimetry

2.3.1 History

Lysimeters are devices for measuring the percolation of water through soil and sampling the drainage for chemical analysis. Lysimetry has been used for various purposes and in many different forms for over three hundred years (Howell et al. 1991). Designs of lysimeters vary from large rectangular to small circular (Howell et al. 1991; Phillips et al. 1991). Though they usually are surrounded by and filled with soil, the methods to fill them also vary. When percolate collection is of primary interest, the "Ebermeyer method" can be used in which the soil is left *in situ* with no walls defining the sides of the lysimeter, and a funnel collecting percolate under the soil (Grebet and Cuenca 1991). Monolithic lysimeters are another method of filling lysimeters, in which an undisturbed soil profile is surrounded by the vertical walls of the lysimeter (Grebet and Cuenca 1991). Another method is the fill-in method, in which soil is taken from a location, sometimes screened and mixed to make it uniform, and placed inside a lysimeter with vertical walls. The fill-in method is most common because of the relative ease and cost (Grebet and Cuenca 1991). Often, lysimeters are used to determine the water balance of a particular soil or soil profile. In this case, weighing lysimeters can directly measure this by the mass balance of the water, or indirectly by non-weighing lysimeters which measure volume balance (Howell et al. 1991). Mechanisms for weighing lysimeters include mechanical, floating, hydraulic, or electronic transducers (Howell et al. 1991).

In the past, lysimeters have mainly been used for agricultural purposes. Evapotranspiration of crops can be determined, which has important implications for irrigation operations. More recently, however, lysimeters have been used intensively for environmental applications. For example, lysimeters have been used to measure leaching of pesticides (Klocke et al. 1991), radionuclide transport (Phillips et al. 1991), and more recently, water balance on landfill covers.

2.3.2 Application to landfill cover designs

Various lysimeters have been designed to test the hydrologic performance of landfill covers. Sackschewsky et al. (1995) compared the effects that erosion control had on infiltration with two weighing lysimeter experiments. Fifteen small-weighing lysimeters were installed in Monticello, Utah, and the effects of varying soil types and soil thicknesses on soil-water balance were examined (Waugh 2002). A later study at the same location evaluated the performance of an ET cover built at the site using two large drainage lysimeters (Waugh 2002, 2004). The ET cover in Monticello also contains a large 3-ha drainage lysimeter that monitors the performance of the cover. Evapotranspiration of the cover can be calculated with the data from the drainage (Waugh 2002).

Many of the lysimeters used in the past have been large and expensive to build and difficult to monitor. Small-weighing lysimeters have been tested and shown to accurately represent water storage in a soil profile. Waugh et al. (1991) tested small-weighing lysimeters (169cm long x 30.4cm i.d.) against large continuous-weighing lysimeters (approximately 1.7m x 3.4m x 2.0m) at the Hanford site in Washington. They found that mean monthly water storage changes were comparable, though there was a small amount of seasonal differences. After installation of insulation collars around the small-weighing lysimeters, soil temperatures paralleled nearby control soil profiles. To test the effects of small-weighing lysimeters on plant water relations, Waugh (2002) performed a study in which small-weighing monolith lysimeters were installed in Monticello, Utah. Leaf water potential, stomatal conductance and leaf area of Western wheatgrass (*Pascopyrum smithii*) were measured and compared to nearby undisturbed plants. Results indicated that plants in the lysimeters were more water-stressed than control plants, and overall would slightly underestimate evapotranspiration. Small-weighing lysimeters are an accurate, less expensive way to monitor soil water balance, as well as a way to represent better statistical replication.

CHAPTER 3

MATERIALS AND METHODS

3.1 Study Area

Lysimeters were installed at a pre-existing Small Lysimeter Array in Monticello, Utah, approximately 50 miles south of Moab. The array was built beginning in 1993 (see Waugh 2002) and consists of a 2.2m deep trench into which thirty permanent lysimeter sleeves were placed. Sleeves consisted of PVC pipes (38 cm diameter, 230 cm long) which were placed and backfilled in the trench, leaving the top 2.5 cm of each sleeve above ground. Nine of the sleeves were used for the outer wall of the lifting lysimeters in this study. A 450 kg capacity gantry on a track was used to lift the lysimeters out of the sleeves. A load cell with a 250 kg capacity, and a resolution equivalent to approximately 1.4mm of water, was used to weigh the lysimeters.

3.2 Lysimeter Assembly

Lysimeters were assembled from sections of 30.4-cm (12-inch) interior diameter schedule-40 PVC pipe, 170 cm (67 in) in length (Figure 3.1). Modified end caps were heat-welded onto the bottom of each lysimeter. The end-caps had an interior PVC ring welded to a plastic plate that sloped into two drainage ports. One of the drainage ports was located inside the interior ring, and the other was between the ring and the outer wall. The purpose of the two drainage ports was to differentiate between preferential flow along the wall of the lysimeter from the soil mass. Each drainage port had a clear, flexible, polymer tube attached, which was kept closed during most of the experiment with a plastic clip. Two lifting ears were attached to either side of the top portion of each lysimeter, and an 8-inch piece of straight-line chain was attached to each lifting ear. After construction, 14-inch thorn-proof bicycle tubes were placed around each lysimeter and then inflated to seal the annulus between the outer sleeve and the lifting lysimeter.

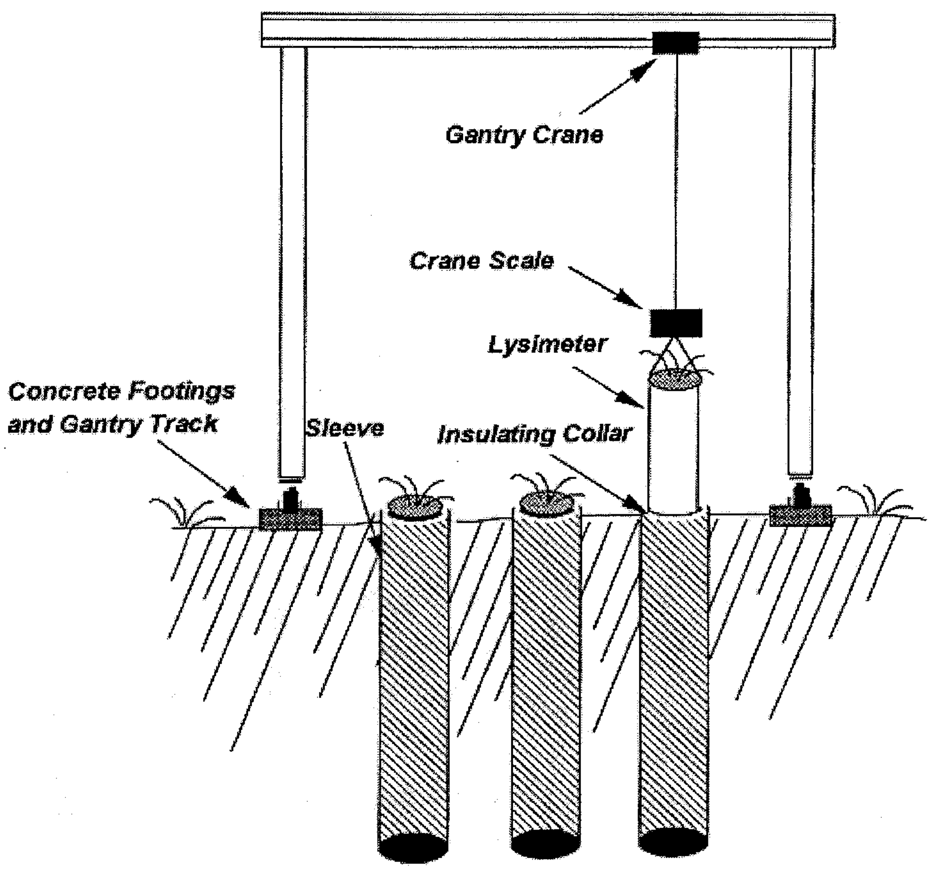

Figure 3.1. Schematic of one row in lysimeter array (adapted from Waugh 1991, Fig. 1).

3.3 Soil Selection

Three types of soils were selected for this study, with DOE and EPA concurrence, and installed in lysimeters, in three replications each. Soil selection was based on Moab Project engineering design criteria, as well as proximity to the Moab Project Site. Soil types represented a range of soil textures that were considered to have adequate water storage for an ET cover in the arid environment of Moab. Soils were also located on public land in large, accessible volumes that would be available for DOE use. Chemical and hydraulic properties, as well as soil ecology and revegetation capabilities were also considered. Classification of soil units was based on "Soil Survey of Grand County, Utah: Central Part" published by the Soil Conservation Service in 1981. See Table 3.1 for further soil properties of the three soil types. Soil units selected for this task were:

3.3.1 Toddler-Ravola-Glenton (map unit 75) (TRG)

This group of closely-associated families occurs on the floodplains of major drainages and on valley flats near marine shale slopes to the north of the Moab site. Soils of all three families are very deep and well drained. The soil families grade one into another across the landscape and vary primarily in the origin of the alluvium within which they formed. TRG family soils formed in alluvium derived from a mixture of marine shale and sandstone and are moderately to strongly saline. Runoff is slow and the erosion hazard is moderate. The potential vegetation is mainly Gardner and mat saltbush (*Atriplex* spp.).

Toddler family soils formed in alluvium derived from a mixture of marine shale and sandstone. They are moderately to strongly saline. Runoff is slow and the erosion hazard is moderate. The potential vegetation, mainly Gardner and mat saltbush, is similar to Chipeta fine sandy loam but with a higher grass composition and greater potential productivity.

The Ravola family soils formed in alluvium derived dominantly from marine shale and, thus, are moderately to strongly saline and alkaline. The hazard of water erosion is moderate; however, the soils are subject to gully formation and piping where runoff is concentrated. Black greasewood (*Sarcobatus vermiculatus*), an obligate phreatophyte, dominates the plant community and accounts for the relatively high productivity. Occasional saltcedars (*Tamarix ramosissima*) occur in the drainages.

The Glenton soils, formed in alluvium derived mainly from sandstone, are very deep, well drained, and with fairly rapid permeability. Runoff is moderate to slow and the hazard of erosion is relatively low; however, deep gullies have formed in areas where runoff is concentrated. The potential vegetation composition and productivity is similar to the TRG soils.

3.3.2 Nakai fine sandy loam (map unit 40)

The Nakai fine sandy loam soil unit is a soil series, rather than a set of families like the TRG soils. This series is less widespread than TRG throughout Utah, but because it is a deep, well-drained soil, it was of interest for this study. The Nakai series soils are commonly found on canyon floors and were formed in eolian, residual, and alluvial material derived predominantly from sandstone. Typically, the A horizon, from 0 – 3 inches, is more sandy than the underlying layers. It can range from very fine sandy loam to loamy fine sand. The B and C horizons are usually made up of fine sandy loam. Sandstone bedrock ranges from depths of 40 to 60 inches. As with most soils found in this area, the Nakai soils tend to be moderately to strongly alkaline. Important plants in the potential community are Indian ricegrass (*Achnatherum hymenoides*), fourwing saltbush (*Atriplex canescens*), and shadscale (*Atriplex confertifolia*). Galleta (*Pleuraphis jamesii*), sand dropseed (*Sporobolus cryptandrus*), and ephedra (*Ephedra viridis*) are also commonly found on this soil type.

3.3.3 Mack loam (map unit 28)

Mack loam is another soil series found near Moab. These soils formed similarly to TRG soils, from alluvial derived from sandstone and shale from the bookcliff mountains to the north of Moab. They are also very deep and well drained soils. They have a slight, rather than moderate, water erosion hazard. However, these soils are composed of more loam-textured soils and, therefore, support a different plant community. The present vegetative community is shadscale, spiny hopsage (*Grayia spinosa*), galleta, and Indian ricegrass.

Table 3.1. Selected soil types and properties for lysimeter testing. (Soil Conservation Service 1981)

Soil Name	*Taxonomy*	*Depth (in)*	*pH*	*Salinity (mmhos/cm)*	*Permeability (in/hr)*	*Available Water (%)*	*Textural Class*	*Clay (%)*	*Erodibility Factors**
Ravola	Fine-silty, mixed (calcareous), mesic Typic Torrifluvents	> 60	7.9 - 9.0	4 - 16	0.2 - 6.0	10 - 18	Silt loam	15 - 35	K = 0.43 T = 5 Wind = 4
Toddler	Fine-silty, mixed (calcareous), mesic Typic Torrifluvents	> 60	7.9 - 9.0	2 - 8	0.6 - 2.0	10 - 18	Silt loam to fine sandy loam	18 - 35	K = 0.32 T = 5 Wind = 4
Glenton	Coarse-loamy, mixed (calcareous), mesic Typic Torrifluvents	> 60	7.9 - 8.4	< 8	2.0 - 6.0	8 - 18	Silt loam to fine sandy loam	5 - 18	K = 0.24 T = 5 Wind = 3
Nakai	Coarse-loamy, mixed, mesic Typic Calciorthids	40 – 60	7.4 – 8.4	<2	2.0 – 6.0	0.10 – 0.16	Fine sandy loam	5 – 18	K= 0.28 T= 3 Wind= 3
Mack loam	Fine-loamy, mixed, mesic typic Haplargids	>60	7.4 – 9.0	<2 – 4	0.2 – 6.0	12 – 19	Silt loam to fine sandy loam	5 – 19	K = 0.32 T = 5 Wind = 4L

*Erodibility factors:

- K, used in the Universal Soil Loss Equation (USLE), is an indicator of the susceptibility of a soil to sheet and rill erosion by water. Values range from 0.02 to 0.69; the higher the value, the more susceptible the soil is to sheet and rill erosion.
- T is an estimate of the maximum average annual rate of water or wind erosion in tons/acre/year.
- Wind erosion factors range from 1 to 8; the lower the value, the more susceptible the soil is to wind erosion.

3.4 Filling of Lysimeters

The first six lysimeters, containing Nakai and TRG soils were installed on June 26, 2002. The final three lysimeters containing the Mack loam soils were installed on August 29, 2002. Each lysimeter was filled manually with a crane scale, buckets, tampers, measuring tapes, and a portable cement mixer. Empty lysimeters were placed into their sleeves and filled. Two pieces of geotextile fabric were placed over the drainage ports to prevent clogging, followed by approximately 10-cm of washed pea gravel, a 15-cm layer of washed sand, and a piece of construction-grade geofabric cut to fit the interior of the lysimeter to prevent fine-textured soils from mixing into the capillary barrier. The fine-textured soil was added in approximately 15-cm lifts to a thickness of 150-cm, consistent with the conceptual cover design for Moab (US DOE 2004). Each lift was uniformly mixed in a cement mixer with enough water to obtain approximately 10% volumetric water content, and then weighed on a crane scale to approximate the native bulk density of about 1.5 g cm^{-3}. Each lift of soil was then individually tamped to a prespecified height to achieve the target bulk density. Each lysimeter was weighed with a crane scale while empty for the initial tare weight, and again when filled with soil

3.5 Soil Analyses

Soil samples were collected in soil cans for each soil lift during installation. After the initial weight was recorded for each lift, further soil analyses were performed at the Environmental Sciences Laboratory in Grand Junction, Colorado. Soil samples were oven-dried, and gravimetric water content, bulk density, and volumetric water content (Grossman and Reinsch 2002; Topp and Ferre 2002) were determined and used in calculating water storage of the lysimeters. Soil texture analyses were also performed for each soil type using the hydrometer method described in Gee and Or (2002). For the first six lysimeters, soil samples from each of the lifts were combined into a composite sample, and texture analyses were done for each lysimeter. For the final three lysimeters, however, soil texture analysis was performed on a single sample that was collected in the field prior to installation of the lysimeters.

3.6 Determination of Field Capacity

After filling the lysimeters with soil, we ponded water on top of each lysimeter, and capped them with plastic lids to prevent moisture loss through evaporation. We continued to add water weekly until we collected drainage from the bottom of the lysimeter, at which point we assumed that the soil was saturated. After that point, we kept the lysimeters capped, and weighed and drained them weekly or bi-weekly. Field capacity was determined from the weight of the lysimeter by calculating the soil water storage at the point at which drainage stopped. Change in water storage (ΔS) was calculated as:

$$\Delta S = (M_t - M_i)/A$$

Where M_t is the lysimeter mass (grams) at the time of weighing, M_i is the initial lysimeter mass (grams), and A is the cross-sectional area (square centimeters) of the lysimeter.

Initial water storage (S_i, centimeters) for the total lysimeter soil profile thickness (H, centimeters) was calculated from volumetric moisture (θ_i) samples of each lift (L_i) taken during the installation of the lysimeters, using the equation

$$S_i = \sum_{i=1}^{n} \theta_i (L_i / H)$$

3.7 Water Storage at Field Capacity Estimation

Stormont and Morris (1998) presented an engineering approach to estimating field capacity from the relationship between suction head and water content, in which water content of the soil profile is integrated over the height of the soil layer. Because we lacked water characteristics for the soils used in this study, we used the function of van Genuchten (1980) to determine water content. The van Genuchten parameters were obtained from the Rosetta (Schaap 2000) program using bulk density, and percent clay, silt, and sand based upon measurements from analyses done during lysimeter installation. Rosetta implements pedotransfer functions based on artificial neural networks. The model formula we used for comparison with our results is:

$$\text{Field capacity} = \theta_r b + (\theta_s - \theta_r) \int_0^b (\{1 + [\alpha (z + h^*_w)]^n\}^{1-1/n})\, dz$$

Where

θ_r = residual volumetric water content
θ_s = saturated volumetric water content
b = thickness of soil layer (cm)
α = van Genuchten function parameter (cm^{-1})
z = distance above bottom of soil layer (cm)
h^*_w = water entry suction head,
n = van Genuchten function parameter (cm)

The value for h^*_w was obtained from Stormont (1997), in which he tested the suction at the interface for two coarse layer types. For a pea gravel capillary barrier, he found the water entry suction head to be 20mm (2cm), and for a concrete sand capillary barrier like the one in this study, the suction was at 200mm (20cm) at breakthrough. Stormont and Morris (1998) used these values to calculate water storage using the formula above, and compared them to gravity-drained soil. The parameters used are listed in Table 3.2. Because only one texture analysis was performed for Mack loam soil, parameters were combined for lysimeters 9a-c.

Table 3.2. Parameters used for water storage estimation (Θ_r, Θ_s, α, and n are from Schaap 2000).

Soil Type	Lysimeter	Θr	b (cm)	Θs	α (cm^{-1})	h*w (cm)	n (cm)
Nakai	7a	0.075	152.4	0.414	0.0161	20	1.363
	7b	0.071	152.4	0.410	0.0219	20	1.319
	7c	0.070	152.4	0.404	0.1720	20	1.363
Toddler-Ravola-Glenton	8a	0.048	152.4	0.391	0.0332	20	1.548
	8b	0.047	152.4	0.400	0.0321	20	1.520
	8c	0.048	152.4	0.400	0.0303	20	1.491
Mack Loam	9a - c	0.059	152.4	0.400	0.0179	20	1.422

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Soil Texture

Soil texture was determined for each soil type used in this study. The results of the soil texture analyses are listed in Table 4.1. The Mack loam soil, as mentioned previously, had only one soil texture analysis performed on it. This one sample lies on the border of the Sandy clay loam classification and the Sandy loam classification on the USDA textural triangle. It was therefore impossible to distinguish this soil as one soil classification.

Table 4.1. Soil Texture Analysis Results

Soil Type	Lysimeter	% Sand	% Silt	% Clay	USDA Soil Classification
Nakai	Lysimeter 7A	44	25	31	Clay Loam
	Lysimeter 7B	57	14	29	Sandy Clay Loam
	Lysimeter 7C	48	24	28	Sandy Clay Loam
Toddler-Ravola-Glenton	Lysimeter 8A	74	15	11	Sandy Loam
	Lysimeter 8B	72	17	11	Sandy Loam
	Lysimeter 8C	70	18	12	Sandy Loam
Mack loam	Lysimeters 9A-9C	54	26	20	Sandy Clay Loam/ Sandy Loam

4.2 Lysimeter Water Storage at Field Capacity

Water storage for each soil type throughout the study is shown in Figure 4.1. Error bars represent one standard error of the mean (SEM). Day 177 is (Julian day) June 26, 2002, and days increase numerically until day 555, which was July 09, 2003. Lysimeters initially gained weight, and therefore water storage, as water was added for the first few weeks of the study. All lysimeters were probably close to field capacity in November 2002, but we were unable to continue weighing the lysimeters because of snow on the ground. When we returned to weigh the lysimeters the following spring, we found that they had increased in weight; this was probably due to some amount of snow infiltrating through the lids on the lysimeters. Therefore, we continued the study until either the lysimeters had stopped draining, or until the study ended in July 2003. The last data point for the TRG soils in Figure 4.1 indicates that one of the three lysimeters was draining; therefore, no SEM was calculated. Overall, TRG soils held significantly less ($p < 0.05$) water throughout the study, while Nakai and Mack Loam soils held similar amounts of water.

Field capacity in this study was defined to be the point at which the lysimeters stopped draining, shown on Table 4.2. One of the Nakai soil lysimeters (7C) stopped draining in September 2002, but the remaining lysimeters stopped in the spring of 2003. Two of the Mack Loam lysimeters were still draining small amounts of water when the study was ended, but they were close to field capacity. A one-way ANOVA showed that the TRG soils held significantly less water than the Nakai and the Mack Loam soils ($P <$

0.005, F-ratio = 36.197). The difference in water storage between Nakai and Mack Loam was insignificant.

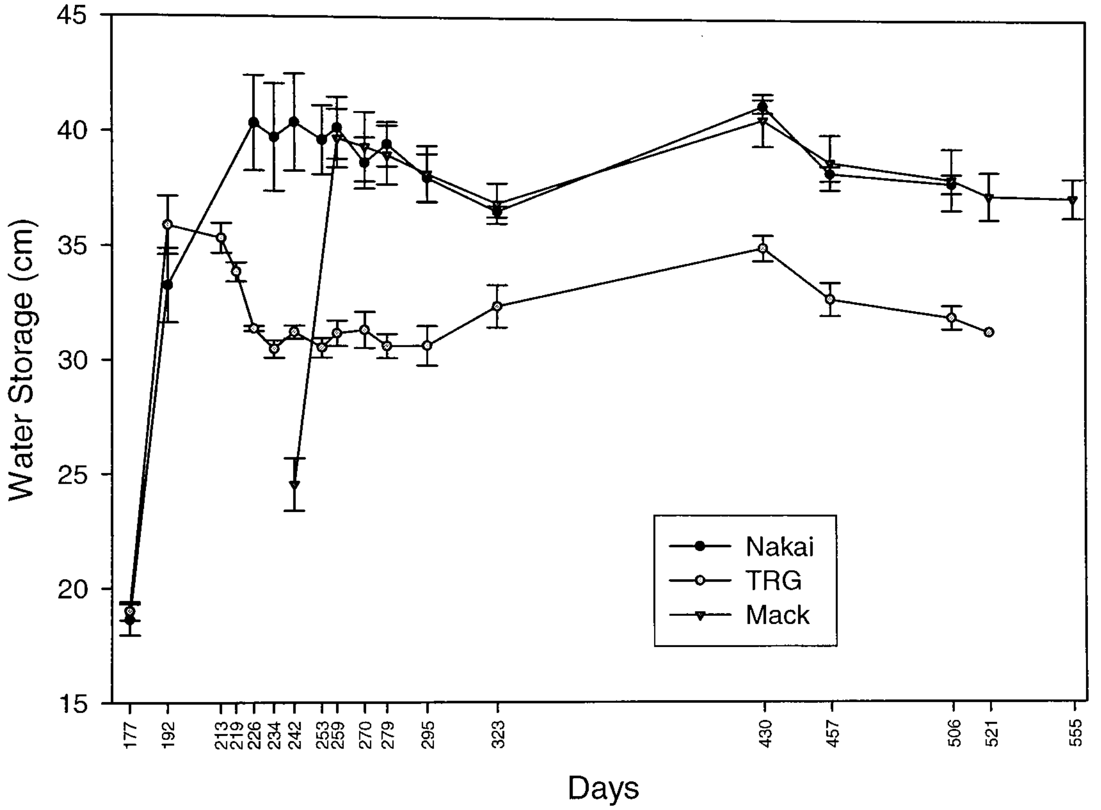

Figure 4.1. Water storage of lysimeters throughout study.

Table 4.2. Water storage at last drainage event

Soil Type	Lysimeter	Water Storage (cm)	Average (cm)	St. Error
Nakai	7a	38.5	37.8	0.4
	7b	37.1		
	7c	37.7		
TRG	8a	30.9	31.6	0.5
	8b	31.3		
	8c	32.5		
Mack Loam	9a	35.6	36.6	0.7
	9b	36.3		
	9c	38.0		

The variation in these results can be explained by texture differences in the soils. A correlation matrix (Table 4.3) showed that percent sand and percent clay, but not percent silt were significantly correlated with water storage of the lysimeters. A multiple regression analysis showed that both sand and clay were significant factors ($p<0.05$) in explaining water storage, where:

Water storage = (0.202 x %Clay) – (0.114 x %Sand) + 37.55

(standard error of estimation = 0.407cm, $r^2 = 0.984$)

Table 4.3. Correlation matrix

	Storage	Sand	Silt	Clay
Storage	1.00			
Sand	***	1.00		
Silt	n/s	n/s	1.00	
Clay	***	**	n/s	1.00

P

>0.05 = n/s
<0.05 = *
<0.01 = **
<0.001 = ***

4.3 Estimation Results

The results of the estimation in comparison to the results obtained from the lysimeters are shown in Table 4.4. These results are comparable to those reported by Stormont and Morris (1998). They estimated that water storage at breakthrough into the underlying coarse layer was 25.3 cm in a 0.66 m layer of silty soil overlying a gravel coarse layer, which translates to a volumetric water content (given by θ = water storage (cm) / depth of soil profile (cm)) of 0.383. The volumetric water content of the soils in this study ranged from 0.215 to 0.322 for the estimation, and 0.203 – 0.258 for the lysimeter results. This method overestimated the Nakai soils by about 21%, the TRG soils by only about 8%, and the Mack loam soils by about 17%.

The overestimation of the formula given by Stormont and Morris (1998) is partly due to lack of consideration for hysteresis of the soils. Water retention data is usually obtained from drying curves rather than wetting curves, which can cause an overestimation of water storage of more than double (Gee et al. 1999). It is important to realize that the estimation method presented by Stormont and Morris (1998) is used as a first-order estimation of water holding capacity of capillary barriers.

Table 4.4. Comparison of water storage results.

Soil Type	Lysimeter	Lysimeter Results (water storage)		Estimation Results	
		cm	θ	cm	θ
Nakai	7a	38.5	0.253	49.0	0.322
	7b	37.1	0.244	47.7	0.314
	7c	37.7	0.248	47.2	0.311
TRG	8a	30.9	0.203	32.6	0.215
	8b	31.3	0.206	34.5	0.227
	8c	32.5	0.214	36.2	0.238
Mack Loam	9a	35.6	0.234	44.0	0.290
	9b	36.3	0.239		
	9c	38.0	0.250		

Results of the estimation may have been closer to that seen in the lysimeters if water retention characteristics had been determined prior to and during the study. Determination of the soil water characteristic curve for each soil would have provided a better water-entry suction parameter (h^*_w) than the one provided by Stormont and Morris (1998). Installation of tensiometers at intervals along the length of each lysimeter would have also provided useful suction data.

However, some error may have also been introduced with the lysimeters, which may have underestimated the true field capacity of the soils. Waugh (2002) performed a similar study at the same lysimeter facility, and determined the field capacity of clay loam soils in a 150-cm lysimeter to be 44.9 cm. Though all lysimeters were covered throughout the study, the covers may not have sealed to the top of the lysimeter, allowing some evaporation. A final determination of water content throughout the lysimeters after the study was concluded would have shown whether evaporation was a factor. One of the lysimeters, 7C, had the cover left off or knocked off in between measuring times (about 2 weeks); however, this did not seem to have a significant impact on the results. It is also possible that not all lysimeters were installed similarly. We noted throughout the study that some of the lysimeters drained faster than others of the same soil type. We postulated that the small piece of fabric placed above the drainage port may have been moved when the gravel was poured into the lysimeter, thus causing the drainage port to become plugged. Though we attempted to thoroughly mix the soil stockpile while assembling the lysimeters, it is possible that fine-textured particles settled to the bottom of the pile, which could cause variation among similar lysimeters.

CHAPTER 5

CONCLUSION

This study showed the field capacity of three soil types. Nakai and Mack loam soils, which were classified mostly as Sandy clay loam, held approximately 37 cm of water, or about 0.25 volumetric water content. TRG soils, classified as Sandy loam, held significantly less water, with an average field capacity of 32 cm, or 0.20 volumetric water content. The method for estimating field capacity based on soil texture overestimated the results of the lysimeters by between 8 and 21 percent. A follow-up study will gather data from retention curves for each of the lysimeters in order to provide more accurate parameters for the estimation method. However, a field study may provide more accurate data for determining field capacity in the designing of caps. In the future, prediction of field capacity of fine-textured soils overlying a coarse-textured layer may be done by determination of percent clay and percent sand alone. We showed a strong correlation between the field capacity of the lysimeters and the soil texture of each of these soils. More field studies should be done to verify this relationship, however.

The next step in the process of choosing the best soil for an evapotranspiration (ET) cover will be to plant the lysimeters with native vegetation and monitor water storage as the plants grow. The permanent wilting point will be determined by the lowest water storage at which the plants can still remove water from the soil. After this is determined, the water storage capacity of the soil can be determined from the difference between the field capacity and the permanent wilting point. At that point, the soil that has the highest water storage capacity should be chosen as the most appropriate soil type for an ET cover.

In the semi-arid southwestern U.S., without proper evaluation of soil textures, and thicknesses, even a cover planted with vegetation may fail (Anderson 1997; Hauser et al 2001). It is therefore important to determine the field capacity, and then the storage capacity of a variety of soils and thicknesses when designing an ET cover. More field studies are needed to determine whether percent clay and percent sand are consistently accurate predictors of field capacity.

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