Assessing the Performance of Evapotranspiration Covers for Municipal Solid Waste Landfills in Northwestern Ohio

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Abstract: Evapotranspiration (ET) covers have gained considerable interest as an alternative to conventional covers for the final closure of municipal solid waste (MSW) landfills, but often produce higher rates of percolation in regions that receive more than 32 cm year^{-1} of precipitation. The goal of this project is to design ET covers for MSW landfills in northwestern Ohio (long-term annual rate of precipitation of 83 cm year^{-1}) that produce rates of percolation $< 32\ \text{cm year}^{-1}$, the rate considered acceptable by the Ohio Environmental Protection Agency (OEPA), and promote habitat restoration. To attain this goal, an adequate soil water-storage capacity was provided using dredged sediment amended with organic material. Two plant mixtures were tested to evaluate the performance of ET covers immediately following construction (immature plants seeded onto the soil) and in the future (mature plants transplanted from a restored tall-grass prairie that is more than 10 years old). ET covers were constructed in drainage lysimeters (1.52-m diameter, 1.52-m depth) and watered at a rate of 91.12 to 95.72 cm year^{-1}, which included simulated 100-year rain events (11.7 cm over 24 h) in July and October. During the 1-year monitoring period, the ET covers using the mature plant mixture produced considerably less percolation (0.12 to 11.44 cm year^{-1}) than the covers with the immature plant mixture (6.71 to 24.16 cm year^{-1}). Thus far, all ET covers have produced rates of percolation less than the maximum standard by the OEPA, and they will continue to be monitored. **DOI:** **10.1061/(ASCE)EE.1943-7870.0000326.**

CE Database subject headings: Dredging; Sediment; Evapotranspiration; Ohio; Water balance; Municipal wastes; Landfills; Solid wastes.

Author keywords: Dredged sediment; Evapotranspiration cover; Municipal solid waste landfill; Northwestern Ohio; Percolation; Water balance.

Introduction

Municipal solid waste (MSW) landfills represent a significant threat to human health and the environment because of their potential to form leachate that may contaminant groundwater and the surrounding areas. The current approach to limit the percolation of precipitation into the deposited waste utilizes a final cover that employs a resistive barrier layer that may consist of fine-grained soil or a geosynthetic materials (e.g., high density polyethylene) underlain by compacted fine-grained soil (USEPA 1993) and functions to promote lateral flow over it. Final covers that use resistive barriers include conventional and composite covers. While regulators and landfill owners generally prefer these types of final covers, they have high costs associated with construction and the covers utilizing compacted clay have been shown to deteriorate with time (Albrecht and Benson 2001; Albright et al. 2006a, b). As a result, alternative cover designs that are less costly to construct and that may improve in performance with time need to be evaluated.

In the United States, the Resource Conservation and Recovery Act (RCRA) and comparable state regulations permit the use of alternative covers when they demonstrate equivalent performance to covers that use resistive barriers (USEPA 1993). The evapotranspiration (ET) cover has gained considerable interest (USEPA 2003) as an alternative cover because (1) it is less costly to construct than conventional and composite covers (Dwyer 2000; Hauser et al. 2001), (2) the overall performance is expected to increase with time (Albright et al. 2004; Hauser 2008), and (3) it may be used to promote habitat restoration, but this is yet to be evaluated. ET covers consist of soil and plants and function to prevent the formation of leachate using water storage principles, which include soil water storage during periods of inactive plant growth and the combination of evaporation from the soil surface and plant transpiration, i.e., evapotranspiration, during the growing season (Hauser 2008). Fine-grained soils are mostly used (Gurdal et al. 2003) because they have a greater water storage capacity than coarse-grained soils (Hausenbuiller 1978), and native plants are used since they are adapted to the regional climate (Rock 2003).

ET covers have been tested in many regions of the United States (Albright and Benson 2002; Albright et al. 2004; Nyhan 2005; Scanlon et al. 2005), with lower rates of percolation being produced by the covers in regions that receive less than 32 cm year^{-1} of precipitation. In these drier areas (e.g., Apple Valley, California; Boardman, Oregon; Helena, Montana), the annual precipitation is less than the annual evapotranspiration, which is favorable for ET covers because water may be lost from the soil rather than accumulated in it, which occurs when precipitation is greater than the evapotranspiration. In the wetter areas (e.g., Albany, Georgia; Cedar Rapids, Iowa; Omaha, Nebraska), ET covers likely produced higher rates of percolation because the soil water storage capacity

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Note. This manuscript was submitted on February 1, 2010; approved on November 8, 2010; published online on November 11, 2010. Discussion period open until September 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Environmental Engineering***, Vol. 137, No. 4, April 1, 2011. ©ASCE, ISSN 0733-9372/2011/4-301–305/$25.00.

was exceeded, plant transpiration capacity was insufficient, or a combination of both. It has been suggested that the rates of percolation produced by the ET covers in these wetter areas will decrease with time as the plants mature and increase their transpiration potential and/or if the soil water storage capacity is increased (Albright et al. 2004).

There has been indication that an ET cover can produce less percolation than a conventional cover in a wet climate. Abichou et al. (2005) compared the performance of an ET cover to a conventional cover that used compacted clay for the resistive barrier in Albany, Georgia, that receives 130 cm year^{-1} of precipitation. In their study, the covers were constructed in drainage lysimeters (10 m by 20 m) located side-by-side and they observed that the ET cover produced a lower rate of percolation (40.1 cm over a 32-month period) than the conventional cover (69.8 cm during the same time period), even when the ET cover received a greater amount of precipitation (additional water was applied to aid the establishment of vegetation). This study demonstrates that ET covers may be effective in wetter areas when constructed accordingly for the climate. For example, the soil water-storage capacity was increased using organic material (peanut compost), and plant transpiration was extended throughout the growing season by using a mixture of grasses and trees.

The overall goal of this research is to design ET covers for MSW landfills in northwestern Ohio (average annual precipitation of 83 cm) that produce acceptable rates of percolation. The rate of percolation produced by the ET covers must be less than 32 cm year^{-1}, which is the maximum allowable rate of percolation for landfill covers in Ohio (OEPA 2003). To attain this goal, the ET covers will need to be constructed with a soil that is able to store the amounts of precipitation received during periods when transpiration rates are low and a plant mixture consisting of cool and warm-season species to extend plant transpiration throughout the growing season. It is worth noting that ET covers represent a cost-effective strategy to address two issues of environmental concern in northwestern Ohio. The first issue is dredged sediment management; recently the Toledo Harbor Project has become one of the largest projects in the Great Lakes by the U.S. Army Corps of Engineers, requiring approximately one million cubic yards of sediment to be dredged from the harbor each year. The second issue is habitat restoration; only a small proportion of the region's natural habitat remains (Green Ribbon Initiative 2004). Thus, constructing the ET covers with dredged sediment and native plants may be an effective method to beneficially use significant volumes of sediment and promote habitat restoration on landfills.

This technical note assesses the performance of ET covers in northwestern Ohio. The ET covers were constructed in drainage lysimeters (1.52-m diameter, 1.52-m depth) with a conical bottom (0.30-m depth) with dredged sediment and either seeded with native plants that consist of species commonly found in tall-grass prairies (referred to as immature plants) or had plants transferred from a tall-grass prairie that has been restored for more than 10 years (referred to as mature plants). Plants in different stages of development were evaluated to determine whether ET covers could be effective immediately following construction, or if several years may be required. It was expected that ET covers with both plant mixtures would produce rates of percolation less than 32 cm year^{-1}, but the covers with mature plants would produce lower rates. The data are reported for the first year (June 11, 2009, through June 10, 2010) of the study that will continue for several years.

Materials and Methods

Plant Species

Ten plant species were evaluated in this study. The immature plant mixture (seeds) included warm-season species—*Andropogon gerardii* (big bluestem), *Eupatorium altissimum* (tall thoroughwort), *Panicum virgatum* (switch grass), *Schizachyrium scoparium* (little bluestem), and *Sorghastrum nutans* (Indian grass); and cool-season species—*Achillia millefolium* (yarrow), *Danthonia spicata* (poverty grass), *Elymus virginicus* (Virginia wildrye), and *Rudbeckia hirta* (black-eyed susan). The mature plant mixture (sod excavated from a nearby tall-grass prairie that is more than 10 years old) included two warm-season species—*A. gerardii* and *Solidago candensis* (Canada goldenrod). The plants in the immature mixture represent potential species that would be used to restore tall-grass prairies in northwestern Ohio, and the plants in the mature mixture are in fact the species that remain dominant in a restored tall-grass prairie after 10 years of succession.

Soil

The soil used for this study consisted of sediment dredged from the Toledo Harbor (85% dry weight), sewage sludge (12% dry weight), and lime sludge (3% dry weight) that was obtained from the Toledo Port Authority Facility 3—Corps of Engineers Dredged Disposal Containment Area (41° 42′ 12″ N, 83° 26′ 01″ W). This soil is referred to as "Nu-soil" (NS) and has been used for landscaping and daily cover at the city of Toledo's active municipal solid waste landfill (Stanley Perry, personal communication, August 2007). Selected chemical and physical properties of NS are listed in Table 1. The NS was amended with peat moss (NSPM) at a rate of 6.5% fresh weight to increase organic matter and soil water-storage capacity (Barnswell 2010).

Drainage Lysimeters

Six drainage lysimeters were used in this study (Fig. 1). In each drainage lysimeter, coarse sand and a deep percolation collection system were first installed in the conical bottom. Nu-soil was placed to a thickness of 60 cm at 10-cm layers and compacted to a bulk density of 1.0 g cm^3. Similarly, NSPM was then placed to a thickness of 60 cm and compacted to a bulk density of 0.85 g cm^{-3}. The remaining 32 cm of each lysimeter was then filled with 20 cm of topsoil (bulk density of 1.20 g cm^{-3}) for

Table 1. Properties of "Nu-Soil" and the "Nu-Soil" Amended with Peat Moss

Property	NS	NSPM
pH	7.7 (0)	7.5 (0.1)
Organic matter (%)	7.4 (0.2)	10.4 (0.3)
CEC (meq 100 g^{-1})	34.5 (0.8)	35.0 (0.1)
P_2O_5 (ppm)	162 (7)	179 (7)
Ca^{2+} (ppm)	16167 (582)	15526 (238)
Mg^{2+} (ppm)	2624 (104)	2682 (11)
K_2O (ppm)	132 (24)	127 (0)
Sand (%)	45.3 (6)	45.3 (6)
Silt (%)	40.0 (1)	40.0 (1)
Clay (%)	14.3 (5)	14.3 (5)
Wilting point ($\text{cm}^3\ \text{cm}^{-3}$)	14.0 (2)	16.0 (2)
Field capacity ($\text{cm}^3\ \text{cm}^{-3}$)	31.0 (3)	35.3 (2)

Note: Values are the mean of three individual replicates with the standard deviation in parenthesis.

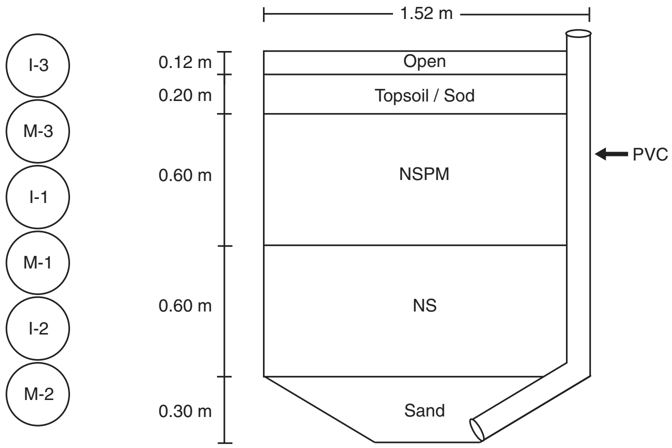

Fig. 1. Drainage lysimeters: (left) plan view of the six drainage lysimeters with the experimental treatments (M = mature plant mixture, I = immature plant mixture); (right) details of the in-ground drainage lysimeter, the conical bottom contained coarse sand to facilitate leachate collection in the system, which consisted of PVC (5.0-cm inside diameter) that extended downward along the sidewall to the base of the conical bottom; the PVC enclosed rubber tubing (0.6-cm inside diameter) that attached to a peristaltic pump (E/S Portable Sampler, Cole-Parmer Instrument Company, Vernon Hills, IL) for leachate removal

the ET covers using the immature plant mixture or 20 cm of sod (bulk density of 1.30 $\mathrm{g\,cm^{-3}}$) from the tall-grass prairie for the ET covers using the mature plant mixture; 12 cm remained unfilled in each lysimeter to prevent the runoff of any surface water. The layering of the soils in the lysimeters resulted in the ET covers using the immature plant mixture to have a water storage capacity of 51.82 cm and the ET covers using the mature plant mixture to have a water storage capacity of 50.22 cm. The water storage capacity for the ET covers was calculated from the field capacity of the soil type (e.g., sand, NSPM, NS, sod, or topsoil) on the basis of Gupta and Larson (1979) and the thickness of the soil type.

Moisture sensors (ECH$_2$O EC-5, Decagon Devices, Inc. Pullman, Washington) were used to measure the spatial distribution of soil water in the lysimeters. They were positioned at two depths from the soil surface (0.30 m and 1.12 m) in a triangular array and connected to data loggers (Em5b, Decagon Devices, Inc. Pullman, Washington) programmed to record at 1-h intervals. The moisture sensors were calibrated in the soils in which they were placed using the method of Campbell (2002).

Application of Water

The drainage lysimeters were watered at rates similar to the wettest year on record (but not identical), which was 2006 that received 116 cm of precipitation (www.ncdc.noaa.gov). The purpose for simulating the wettest year on record was to add water at an annual rate that was much greater than the long-term average of 83 cm. During the summer, fall, and spring months, groundwater was applied three times weekly to attain the rates—June 9.93 cm, July 23.34 cm, August 8.20 cm, September 5.97 cm, October 10.90 cm, November 7.70 cm, April 3.43 cm, and May 16.76 cm. During the winter months, when snow had accumulated on the areas surrounding the translucent roof and drainage lysimeters, a known volume of snow was measured and placed on the drainage lysimeters. Large precipitation events (100-year rain events, 11.7 cm per 24 h) were simulated on July 21 for the mature plant mixture M-2 and the immature plant mixture I-2 (Fig. 2), and on October 4 for the mature plant mixture M-3 and the immature plant mixture I-3. The total water applied to the drainage lysimeters during the one-year study ranged from 91.12 cm to 95.72 cm.

Monitoring

The volumetric water content was downloaded weekly from the data loggers. A peristaltic pump was operated daily to every other day to collect that had percolated to the bottom of each drainage lysimeter. Evapotranspiration was estimated using the water balance equation from Hauser et al. (2005). Plant species not originally included in the plant mixtures were eliminated.

Results and Discussion

Water balance data for the ET covers are summarized in Fig. 2. The mature plant mixture M-1 was compared with the immature plant mixture I-1, the mature plant mixture M-2 was compared with the immature plant mixture I-2, and the mature plant mixture M-3 was compared with the immature plant mixture I-3. This allowed for comparisons between the performance of ET covers with mature and immature plant mixtures that received a similar amount of water, and for evaluation of the effects of extreme precipitation events during the middle and late stages of the growing season.

The dredged sediment was suitable for constructing ET covers in northwestern Ohio as all six of the ET covers produced rates of percolation less than 32 $\mathrm{cm\,year^{-1}}$, the maximum allowable rate for landfill covers in Ohio (OEPA 2003). Percolation from the ET covers was related to the status of the soil water storage (Fig. 2); percolation was produced by most of the covers after the water storage capacity of the cover was exceeded. The 100-year rain events significantly increased the soil water storage of the covers, indicated by the steep rise in the soil water storage for the covers M-2, M-3, I-2, and I-3, and this resulted in the production of a considerable amount of percolation, except for cover M-3. In the M-3 cover, the soil water storage decreased during the growing season, indicating that water was being removed from the soil by evapotranspiration at a rate greater than applied water. This proved to be favorable for the cover because it allowed all of the water from the 100-year rain event on October 4 to be stored in the soil without exceeding the water storage capacity.

Both plant mixtures (mature and immature) removed the stored water from the soil layer, but the mature plant mixture removed greater amounts of water. This is demonstrated in Fig. 2 in which the soil water storage is decreased to lower values by the ET covers with mature plant mixtures. This result was expected because transpiration is influenced by biomass production (Hanks 1974), root depth and density (Ehlers et al. 1991), and leaf area (Vertessy et al. 1995), which increase in time with plant development. The mature plant mixtures attained rates of ET similar to the rates of water application; this was especially apparent for covers M-1 and M-3 (Fig. 2), for which the soil water storage was decreased or at least maintained. In contrast, the rates of evapotranspiration for the immature plant mixtures were considerably less than the rates of water application and the soil water storage gradually increased following the watering events. During the winter months when the plant mixtures were dormant, the soil water storage increased in all of the covers and exceeded the water storage capacity in four of the six covers, which resulted in percolation being produced (Fig. 2).

Overall, the ET covers with a mature plant mixture produced considerably less percolation than covers with an immature plant mixture. The average total percolation for the mature plant mixtures was 4.44% of the applied water and the percolation of the immature

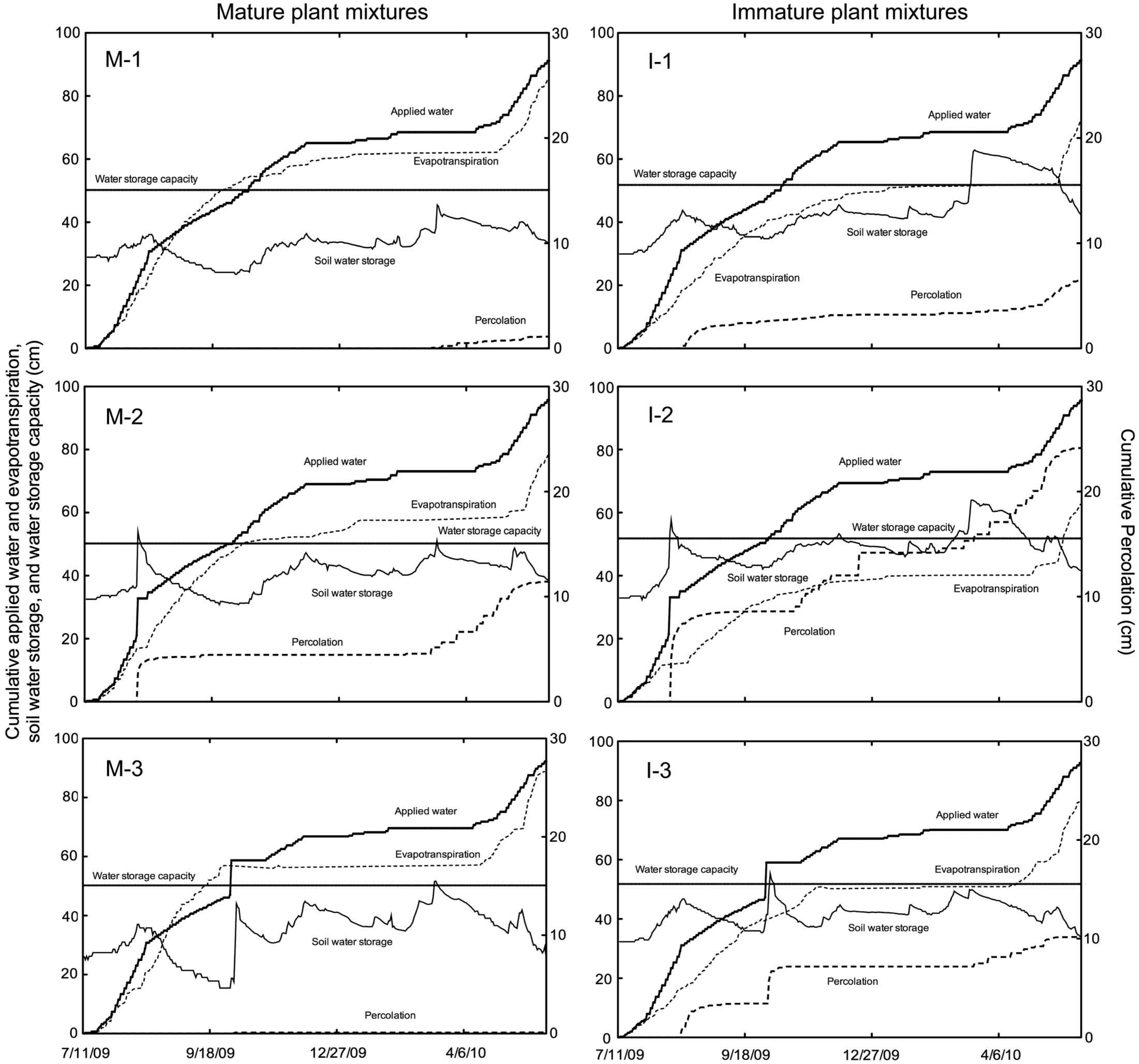

Fig. 2. Water balance data for ET covers; mature plant mixtures (M-1, M-2, M-3) are in the left column and immature plant mixtures (I-1, I-2, I-3) are in the right column

plant mixtures was 14.54% of the applied water. Rates of percolation for the mature plant mixtures ranged from 0.12 to 11.44 cm year^{-1}, with the greatest rate being produced by the M-2 cover that received the 100-year rain event in July. During this time, the species (*A. gerardii* and *S. canadensis*) in the plant mixture had not yet reached their maximum growth for the season, which occurs in August. Rates of percolation for the immature plant mixtures ranged from 6.71 to 24.16 cm year^{-1}, and the I-2 cover that received the 100-year rain event in July also produced the greatest rate; this was likely attributable to the species in the plant mixture being in early stages of development (six weeks from the time seeds were sown into the soil). The percolation that resulted from the 100-year rain event in October was much lower than the percolation that resulted from the rain event in July (Fig. 2). There was no percolation produced from the M-3 cover, and the I-3 cover produced half as much as the I-2 cover that received the rain event in July. This suggests that the time period within the growing season is an important factor that may affect the production of percolation from extreme rain events, and it appears that rain events that occur during the later stages of the growing season will have less of a detrimental impact on ET covers than the rain events that occur during the early or mid stages.

Conclusions

Most of the field studies of ET covers indicate they are not suitable for regions that receive more than 32 cm year^{-1} of precipitation. However, the preliminary results of this study suggest that ET covers may be effective in wetter regions, such as northwestern Ohio. During the one-year monitoring period, all of the ET covers produced percolation rates that meet the standards for landfill covers in Ohio (32 cm year^{-1}; OEPA 2003). As expected, the ET covers with the mature plant mixture had lower rates of percolation than the covers with the immature plant mixture (Fig. 2). The dredged sediment provided sufficient water storage and supported plant growth, which demonstrates that ET covers are a potential long-term management strategy for dredged sediment. However, the months during the non-growing season remain a concern as there was no mechanism to remove the water stored in the soil layer, and during this time the soil water storage continued to increase from inputs of precipitation. To address this issue, the ET covers will continue to be monitored for several years during which large precipitation events will be simulated in different periods of the year, including winter and spring. The data collected from this small-scale study will be used to design ET covers for a large-scale study located at an inactive MSW landfill in the region.

Acknowledgments

The writers acknowledge the U.S. Department of Agriculture Cooperative State Research, Education, and Extension Service (Grant No. 2006-38894-03732); the National Science Foundation GK-12 Program to the University of Toledo's Lake Erie Center; and the Graduate Fellows in High School STEM Education: An Environmental Science Learning Community at the Land-Lake Ecosystem Interface," grant #DGE-0742395 for funding; Deanna Bobak for figures; Jordan Rofkar and Lisa (Delp) Taylor for constructive comments; and Ryan Gorr, Paul Lenos, and Rajiv McCoy for field assistance. This is contribution #2010-10 from the Lake Erie Research Center.

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