Vadose Zone Monitoring at the Radioactive Waste Management Sites at the Nevada National Security Site – 15294

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ABSTRACT

Two lysimeter facilities continuously monitor the vadose zone at the radioactive waste disposal sites at the Nevada National Security Site. The time-series data collected at these facilities support the performance assessments of the radioactive waste disposal sites, the closure cover designs, and the long-term monitoring decisions for these sites. The Weighing Lysimeter Facility at the Area 5 Radioactive Waste Management Site (RWMS) consists of a bare-soil weighing lysimeter and a vegetated weighing lysimeter. The upper surfaces of both weighing lysimeters are exposed to precipitation. The Drainage Lysimeter Facility at the Area 3 RWMS includes bare-soil lysimeters that receive precipitation or precipitation supplemented with irrigation equal to double precipitaton and vegetated lysimeters that have the same upper boundary conditions as the bare-soil lysimeters. Lysimeter sensors are connected to dataloggers that are accessed remotely for data acquisition. Lysimeter water balance measurements show the arid climate and native vegetation at the NNSS provide a natural sustainable system to effectively prevent transport of contaminants from the RWMSs through the vadose zone to groundwater. Transport by infiltration and percolation of present day precipitation at the RWMSs is prevented. The native desert vegetation is adapted to extract moisture from very dry soils and maintains negative matric potentials at the base of the root zone effectively buffering the deep vadose zone from episodic precipitation events at the surface. The very negative matric potential at the base of the root zone effectively intercepts all infiltration from precipitation and draws moisture upward from the vadose zone below the root zone. This system is sustainable because it does not rely on engineered features and mimics the stable landscapes and no groundwater recharge of the current condition surrounding the RWMSs. The system depends on establishing native vegetation in the covers above the waste cells and a stable climate.

INTRODUCTION

Two Radioactive Waste Management Sites (RWMSs) at the Nevada National Security Site (NNSS) are operated for the disposal of radioactive low-level waste (LLW) and mixed low-level waste (MLLW). The NNSS is an approximately 3,536 square kilometers (1,360 square miles) restricted-access federal facility located approximately 105 kilometers (65 miles) northwest of Las Vegas, NV. The Area 5 RWMS covers approximately 300 hectares (741 acres) with approximately 100 hectares (247 acres) used for waste disposal operations. The Area 5 RWMS has been primarily used to dispose of defense-generated LLW and MLLW from cleanup activities at the NNSS and other DOE sites. Currently the waste is received in sealed waste containers. Approximately 37 hectares (90 acres) is in the process of being permanently closed with a vegetated, mono-layer cover. The Area 3 RWMS covers approximately 51 hectares (126 acres) and was primarily used to dispose of bulk low-level waste and potentially some mixed low-level waste. Waste forms at the Area 3 RWMS include contaminated soil and scrap metal, construction debris, and containerized waste. No waste has been received at the Area 3 RWMS since 2006. Approximately 3 hectares (7.4 acres) of the Area 3 RWMS is permanently closed as a hazardous waste landfill with a vegetated, monolayer cover.

Predictive conceptual site models and Performance Assessment (PA) models rely on natural physical and environmental conditions at the NNSS to assure prevention of transport of contaminants from the waste through the vadose zone to groundwater below the RWMSs. Climate and vegetation strongly control the water movement in the upper few meters of alluvium at both the RWMSs. The magnitude and direction of both liquid and vapor fluxes in the upper few meters vary seasonally and often daily. The native desert vegetation established in the southwestern United States during the last 10 to 15 thousand years is adapted to extract moisture from very dry soils and maintains negative matric potentials at the base of the root zone, effectively buffering the deep vadose zone from most episodic precipitation events at the surface. Except for periods following precipitation events, water content values in the near-surface are quite low. The very negative matric potential at the base of the root zone effectively intercepts all infiltration from precipitation and draws moisture upward from the vadose zone below the root zone [1].

Below the dynamic near-surface is a region where relatively steady upward water movement is occurring. In this region of slow upward flow, stable isotope compositions of soil water confirm that evaporation is the dominant process [2]. The upward flow region extends to depths from approximately 3 to 50 m in Area 3 RWMS, and from approximately 3 to 40 m at the Area 5 RWMS. Below the upward flow region, water potential measurements indicate the existence of a static region where the hydraulic gradient is zero. The static region is between approximately 50 and 120 m deep in Area 3, and between approximately 40 and 90 m deep in Area 5 [3, 4].

In the static region, essentially no vertical liquid flow is currently occurring. Below the static region, flow is steady and downward due to gravity. Stable isotope compositions of soil water from these depths indicate that infiltration into this zone occurred under cooler wetter past climatic conditions [2]. If water were to migrate below the current static zones, movement to the groundwater would be extremely slow due to the low water content of the alluvium. Estimates of travel time to the groundwater (assuming zero upward flux), based on hydraulic characteristics of the alluvium, and assuming that current conditions would still apply, are in excess of 500,000 years in Area 3 [5] and 50,000 years in Area 5 [4].

The arid environment, with native vegetation adapted to survive and extract available moisture from very dry soils, the thick dry vadose zone with the capacity to store moisture near the ground surface in the plant root zone, and a deep aquifer with very little flow are important to the effective performance of the RWMS. The measured average annual precipitation at the Area 3 RWMS is 15.0 cm, and the measured average annual precipitation at the Area 5 RWMS is 12.4 cm [6]. Estimates of annual potential evapotranspiration are 10 to 15 times greater than precipitation due to abundant sunshine and low precipitation.

Two types of environmental monitoring are done at the two waste disposal sites at the NNSS: compliance monitoring and function monitoring [7]. Compliance monitoring is the most common monitoring strategy at waste management sites and is used to confirm that defined compliance levels are met at specific monitoring locations, to meet regulatory requirements. At the NNSS waste disposal sites, compliance monitoring includes monitoring of direct radiation exposure, tritium activity in atmospheric moisture, air particulates for specific radionuclides, radon flux from waste pit covers, groundwater elevations, and concentrations of specific indicators of contamination in groundwater and leachate samples.

Compliance monitoring and compliance levels are often dictated by regulation with monitoring locations, timing, analysis, and compliance levels defined. Compliance monitoring may not detect waste isolation deficiencies until long after the inception of the problem because it may take a considerable amount of time for contaminants to reach a monitoring location or exceed compliance limits. Compliance monitoring also does not necessarily identify the cause or mechanism for the deficiency or identify possible remedies for the problem.

Function monitoring is used to confirm the natural and designed systems are performing as expected and are consistent with the assumptions used for site performance assessment. Function monitoring at NNSS waste sites includes measurements of meteorology, lysimeter water balance, and water distribution and movement within the vadose zone. It is done at suitable locations and intervals using appropriate techniques to understand the processes and waste isolation performance of the waste disposal sites. Understanding and monitoring these processes provides data to evaluate, calibrate, and improve predictive conceptual site and PA models. Evolutions of these models improve understanding of the system as a whole and improve monitoring design and interpretation. Because functional monitoring does not rely on point measurements for compliance, it does not typically meet regulatory requirements, but it does improve integration of monitoring information with remedy management and long-term site management [8].

The focus of this paper is the water balance measurements using lysimeters at both the Area 5 and Area 3 RWMSs. These measurements are used to evaluate the hydrologic model of moisture movement in the vadose zone. Specifically, the lysimeters are designed to measure moisture fluxes in the vadose zone, if any, and serve as analogs of closure covers evaluated in the PA models.

METHODS

The effects of vegetation and precipitation on vadose moisture fluxes below the root zone are investigated by monitoring the water balance at the land surface using data from the Area 5 and Area 3 RWMS lysimeter facilities. At the Area 5 RWMS weighing lysimeter facility, water balance data are measured with a vegetated lysimeter and a bare-soil lysimeter. Precipitation is the only source of moisture for these two lysimeters. At the Area 3 RWMS drainage lysimeter facility, water balance data are measured at a bare-soil lysimeter receiving only precipitation, a bare-soil lysimeter receiving precipitation and irrigated at double the precipitation rate, a lysimeter with native vegetation receiving only precipitation, and a lysimeter with native vegetation and irrigated at double the precipitation rate. The total amount of water received by the irrigated lysimeters is three times the annual precipitation.

Lysimeter data represent a simplified water balance:

$$\Delta S = P - E(T) - D$$

where ΔS is the change in water storage in the lysimeter, P is precipitation and irrigation, E is evaporation from a bare-soil lysimeter, ET is evapotranspiration from a vegetated lysimeter, and D is drainage. This simplified water balance equation equates the change in lysimeter water storage to the precipitation and applied irrigation minus E (on bare lysimeters) or ET (on vegetated lysimeters) minus the drainage from the lysimeter. The drainage from the lysimeter bottom is the moisture flux below the root zone. The lysimeters are hydrologically isolated from the surrounding soil with a 2.5 cm (1 in.) lip around the edge of the lysimeters, thus preventing run-on and runoff.

Area 5 Weighing Lysimeter Facility

Two precision weighing lysimeters are located about 400 m southwest of the Area 5 RWMS. Each lysimeter is an open-top steel box, measuring 2 m wide by 4 m long by 2 m deep (6.6 ft wide by 13 ft long by 6.6 ft deep). The lysimeters are filled with native soil packed to a bulk density of 1600 kg m^{-3} (99.9 lb/ft^{-3}), similar to the soil at the Area 5 RWMS. Porous stainless steel suction candles are installed in the bottom of each lysimeter to remove any drainage water that might accumulate at the bottom of the lysimeter. By applying vacuum to the suction candles, drainage water can be removed and quantified without having to saturate the soil at the bottom of the lysimeter. Each lysimeter is mounted on a sensitive scale. Lysimeter weight changes are continuously monitored using an electronic load cell that can measure water storage changes of approximately 0.1 mm (0.004 in.). Depth profiles of time-domain reflectometry (TDR) probes are installed in each lysimeter to measure volumetric water content. The TDR probes are installed at depths of 15, 30, 45, 60, 75, 110, 140, and 170 cm. Precipitation is measured with a tipping bucket rain gauge. These data are collected and stored on dataloggers linked to radio and a LAN connection for remote data acquisition.

One lysimeter is vegetated with the native plant species *Larrea tridentata* (creosote bush), *Lycium andersonii* (Anderson's wolfberry), and *Schismus arabicus* (Arabian schismus) at the approximate density of the surrounding desert. The other lysimeter is kept bare. These lysimeters have provided surface water balance data at the Area 5 RWMS since March 1994.

Area 3 Drainage Lysimeter Facility

The Area 3 Drainage Lysimeter Facility is immediately north of the Area 3 RWMS. There are eight lysimeters at this facility but only results from four lysimeters are presented in this paper. Each lysimeter is constructed from a 3.1 m (10 ft) diameter by 2.4 m (8 ft) long corrugated steel tube inserted vertically in an excavated pit with the bottom of each tube sealed to a concrete base designed with a drain in the middle. The drains are connected to an access vault so that saturated gravity drainage from each lysimeter can be collected and quantified. The top of each lysimeter extends approximately 2.5 cm (1.0 in.) above the soil surface after the pit around the lysimeters was backfilled. Each lysimeter was filled with packed native soil. Eight TDR probes were installed in each lysimeter to measure moisture content depth profiles. The TDR probes are at depths of 7, 15, 30, 60, 90, 120, 180, and 240 cm deep. Drainage from these lysimeters only occurs when the bottom boundary of the lysimeter becomes saturated. The lysimeter data are collected and stored on dataloggers linked to radio and a telephone modem for remote data acquisition.

Non-irrigated lysimeters receive moisture from precipitation. These are identified as 1x or 1 times precipitation lysimeters. Irrigated lysimeters receive moisture from precipitation and are irrigated equal to 2 times precipitation. These lysimeters are identified as 3x or 3 times precipitation lysimeters. The native vegetation species on the vegetated lysimeters are primarily *Atriplex confertifolia* [shadscale saltbush], *Krascheninnikovia lanata* [winterfat], *Ephedra nevadensis* [Nevada jointfir], *Achnatherum hymenoides* [Indian ricegrass], and *Elymus elymoides* [squirreltail grass]).

Results are reported below for a bare-soil 1x precipitation lysimeter, a bare soil 3x precipitation lysimeter, a vegetated 1x precipitation lysimeter, and a vegetated 3x precipitation lysimeter.

RESULTS

Area 5 Weighing Lysimeter Facility

Total soil water storage in the weighing lysimeter from March 1994 through 2014 is presented in Fig. 1. During 1994 and 1995 some irrigation was applied to the vegetated lysimeter to help establish the newly transplanted plants so the vegetated and bare-soil lysimeter have similar water contents in the beginning. Typically the vegetated lysimeter has about 12.5% plant cover, varying between years depending on the amount of precipitation. When precipitation occurs, there is more stored water available for plant growth which results in more ET from increased plant growth. There has been no drainage from either lysimeter.

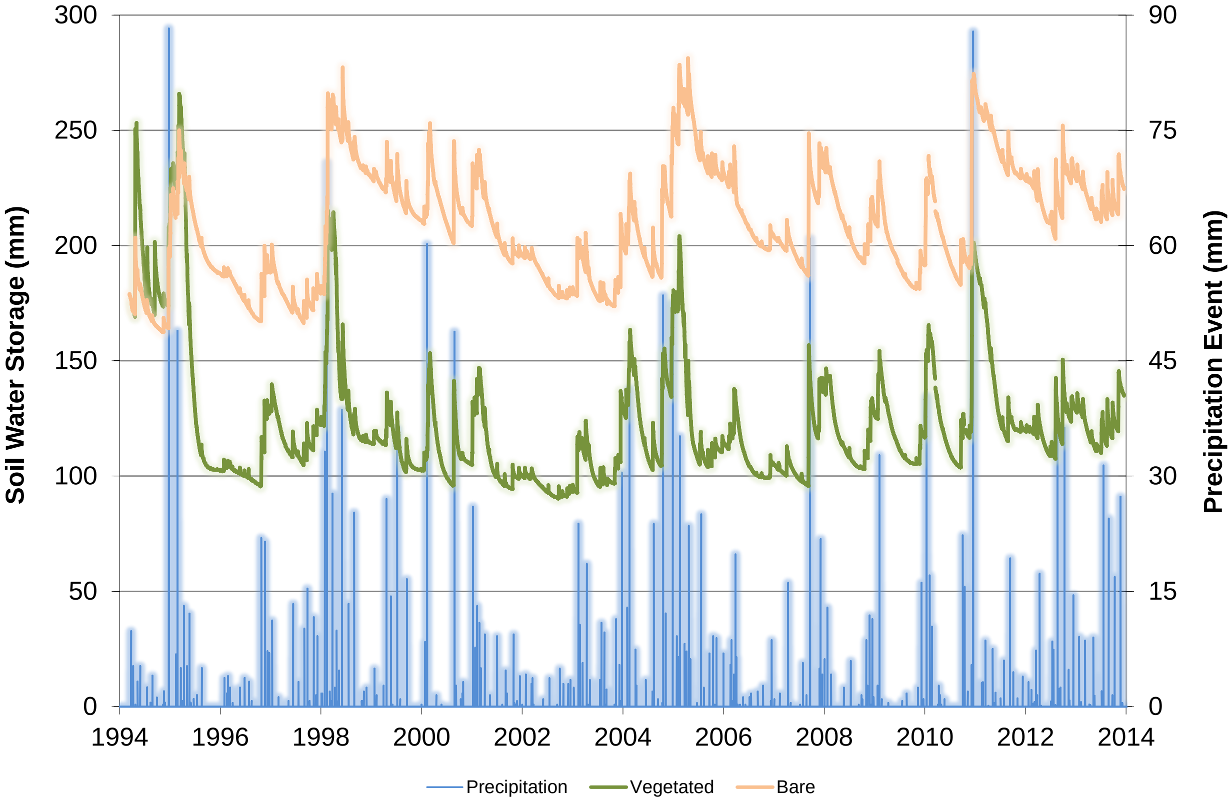

Fig. 1. Weighing Lysimeter Data from March 1994 to December 2013

The average soil water storage depth in the vegetated lysimeter from January 1, 1996, through December 31, 2013, is 118 mm (4.6 in.). This is equivalent to an average volumetric water content (VWC) of 5.9%. For the same period, the average soil water storage depth in the bare lysimeter is 211 mm (8.3 in.), which is equivalent to an average VWC of 10.6%.

Following rainfall in the winter, soil water storage decreases in the vegetated lysimeter due to ET from rapid plant growth in the spring. As the vegetated lysimeter dries out, plant growth and ET slow. Eventually E from the bare lysimeter exceeds ET from the vegetated lysimeter in the summer due to the higher water content in the bare lysimeter. Average monthly precipitation, E from the bare soil lysimeter, and ET from the vegetated lysimeter are provided in Fig. 2. E is calculated as the change in bare lysimeter weight between consecutive days and ET is calculated as the change in vegetated lysimeter weight between consecutive days. E and ET are positive when the lysimeter weight decreases (i.e. water is removed from the lysimeter). These averages are calculated from 2003 through 2013. During this period the average annual precipitation is 134.8 mm, the average annual E is 130.5 mm, and the average annual ET is 130.9 mm. These three values are nearly equal, indicating very little change in the lysimeter stored water during this whole period.

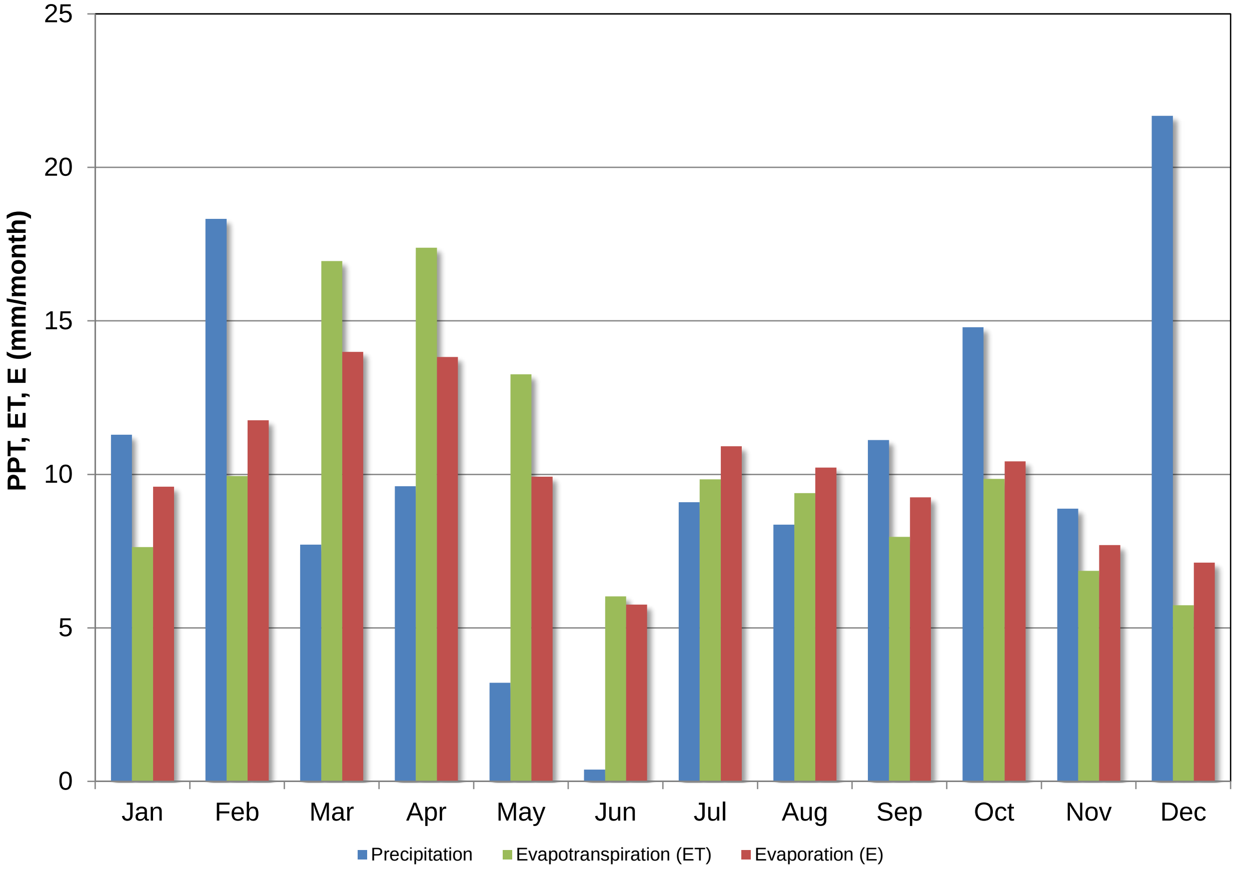

Fig. 2. Monthly average PPT, ET, and E (2003 through 2013)

No water has ever accumulated at the bottom of the vegetated lysimeter. Heavy precipitation during the late fall and winter combined with low E rates and higher initial water contents may result in water accumulation at the bottom of the bare lysimeter. A suction of −8.0 kPa (−1.2 psi) was applied to the porous suction candles on the bottom of the bare lysimeter from May 5–June 19, 2008; March 2–May 12, 2009; and February 3–April 27, 2010. No water effluent was collected from the suction candles during these periods. Long-term numerical simulations (30 years) using a unit gradient bottom boundary estimate the amount of drainage that would have occurred if water could drain from the lysimeters. These simulations indicate an average of 1.0 cm (0.4 in.) per year of water reaches the bottom of the bare lysimeter, and essentially no water reaches the bottom of the vegetated lysimeter [9].

TDR volumetric water content data and precipitation for the bare-soil and the vegetated lysimeter are provided in Fig. 3 and Fig. 4. The TDR water content for the two lysimeters is presented as water content contours plotted by depth and time in Fig. 5 and Fig. 6. These plots were generated using R, which is freely available software for graphics and computing. The bare-soil contour plot shows the bare-soil lysimeter only dries out to about 60 cm and after heavy rain moisture percolates to the bottom of the lysimeter. The vegetated lysimeter is drier then, and even after a heavy rain, the moisture only percolates to approximately 1.25 m before it is removed from the lysimeter by ET.

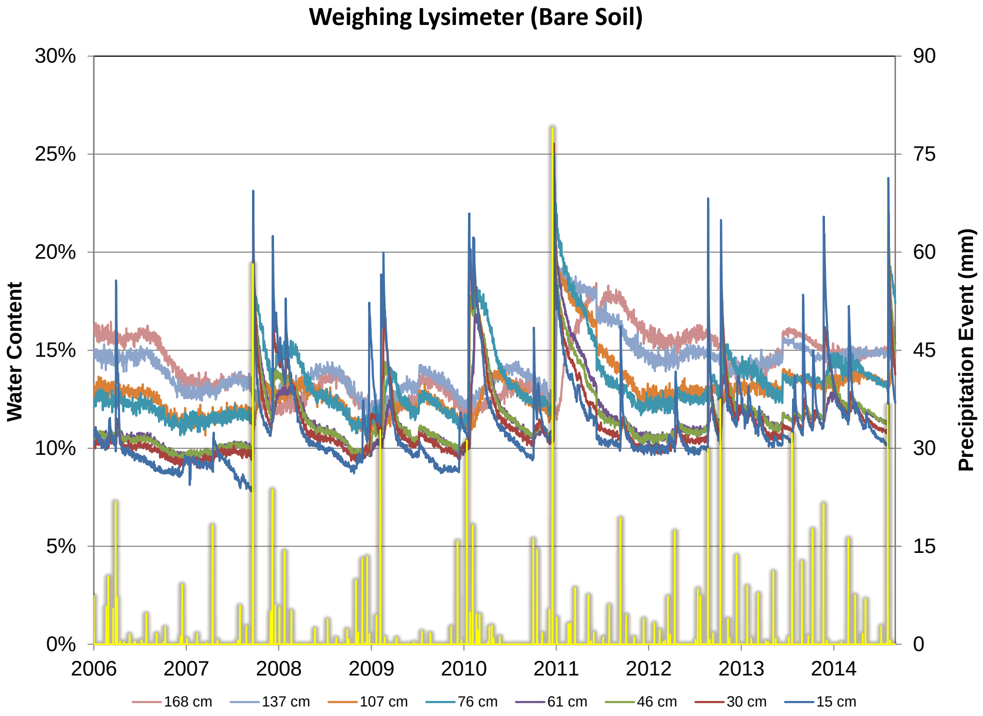

Fig. 3. TDR VWC Data and PPT for Bare Soil Lysimeter 2006 through 2013

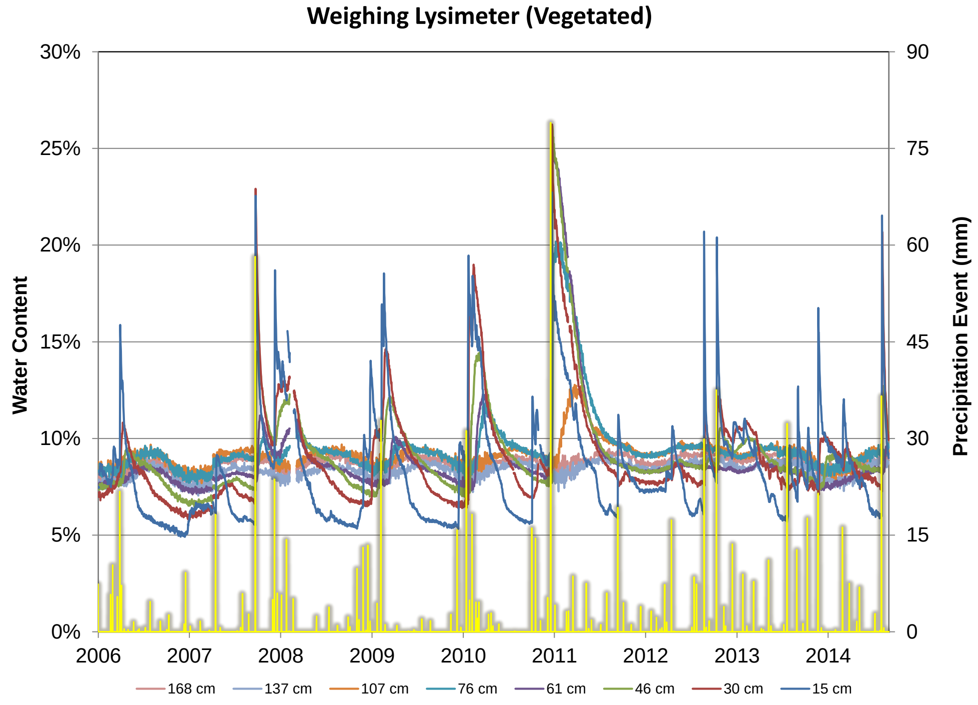

Fig. 4. TDR VWC Data and PPT for Vegetated Lysimeter 2006 through 2013

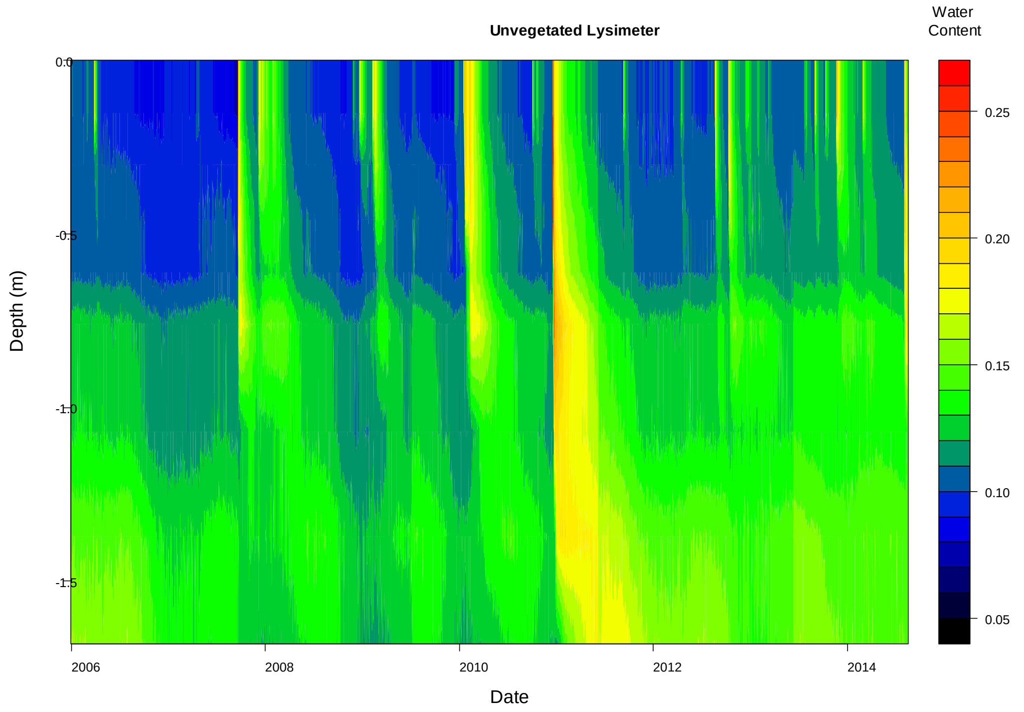

Fig. 5. TDR VWC Contour Data for Bare Soil Lysimeter 2006 through June 2014

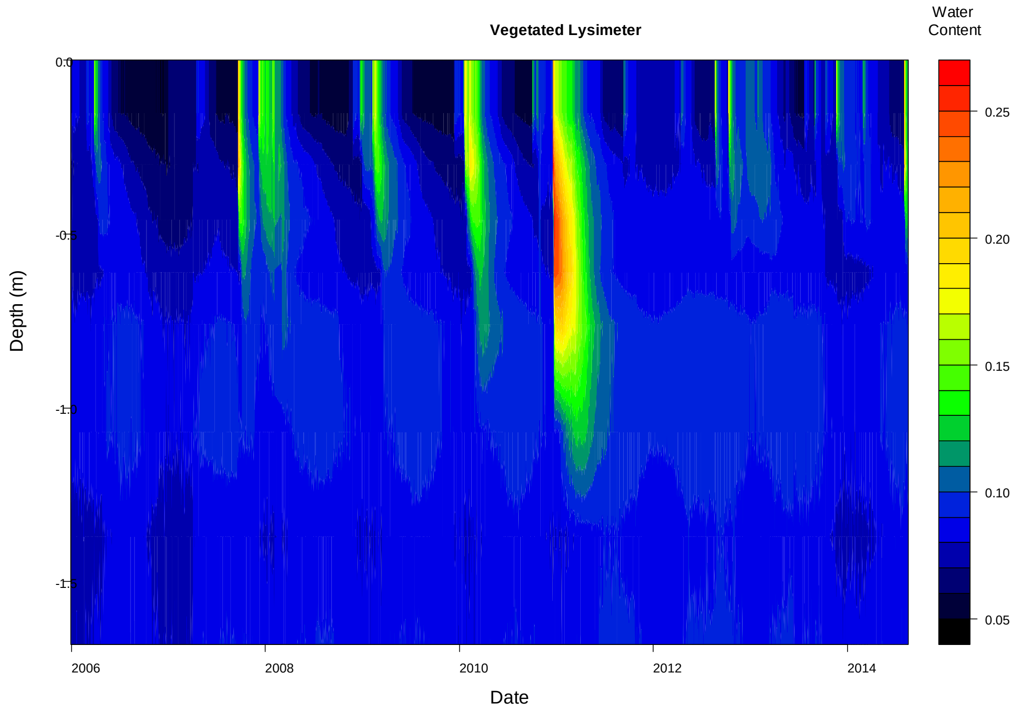

Fig. 6. TDR VWC Contour Data for Vegetated Lysimeter 2006 through June 2014

Area 3 Drainage Lysimeter Facility

To have drainage from the bottom of a drainage lysimeter, the lower boundary must become saturated with moisture that has percolated through the length of the lysimeter. If the lower boundary is not saturated, the negative water potential at the boundary will prevent drainage. There has been no drainage from the bare-soil or vegetated drainage lysimeter with only precipitation (1x lysimeters). There was only drainage from the vegetated 3x lysimeter during 2005 before the vegetation was well established. Drainage has occurred every year from the bare-soil 3x lysimeter. From 2005 through 2014, 44% of the precipitation and irrigation applied to this lysimeter had drained from the lysimeter (Fig. 7).

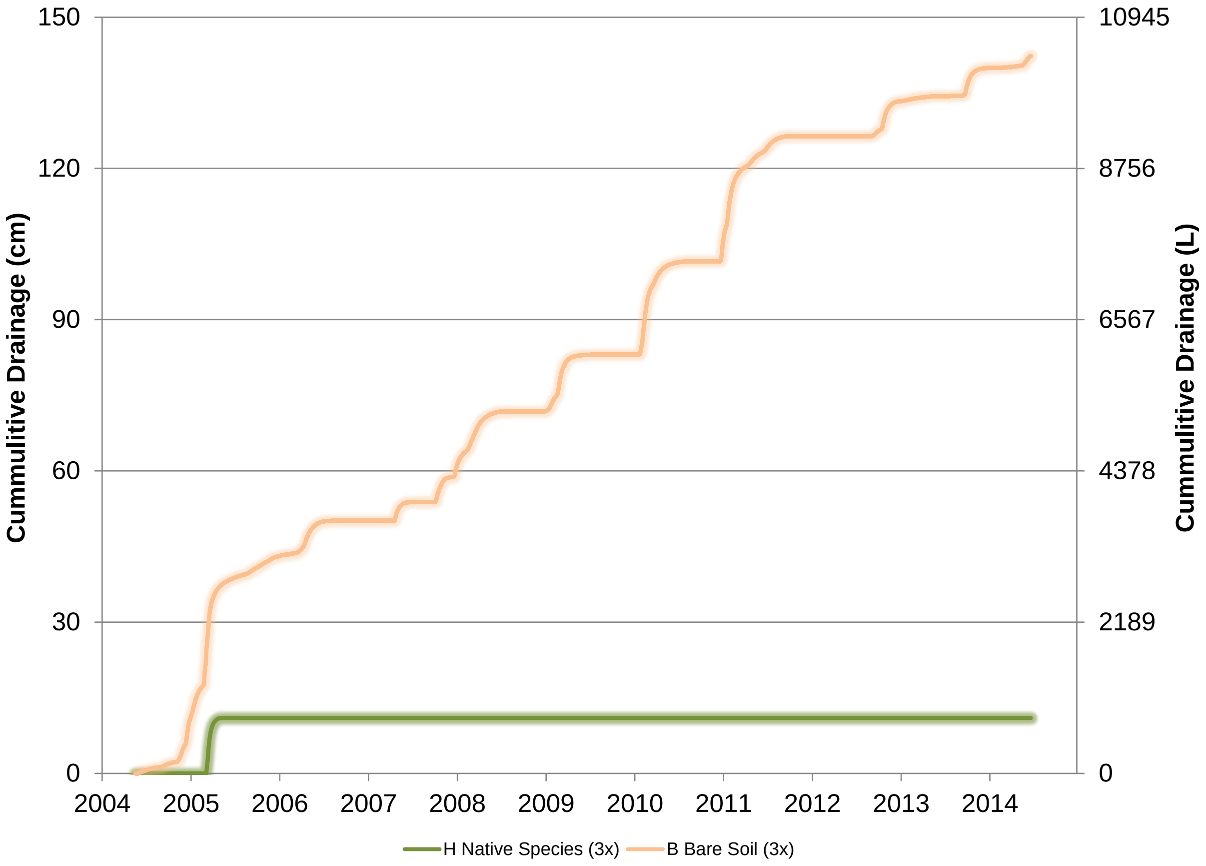

Fig. 7. Drainage for the Irrigated Lysimeters

Water storage in the drainage lysimeters are provided in Fig. 8. As expected, the bare-soil lysimeters store more water than the vegetated lysimeter. The vegetated 3x lysimeter stores more water after precipitation and irrigation than the vegetated 1x lysimeter because more water is applied to this lysimeter. However, the vegetation responds to this increased available water with increased growth and ET. As additional water is removed by ET, the vegetated 1x lysimeter and the vegetated 3x lysimeter store similar amounts of water.

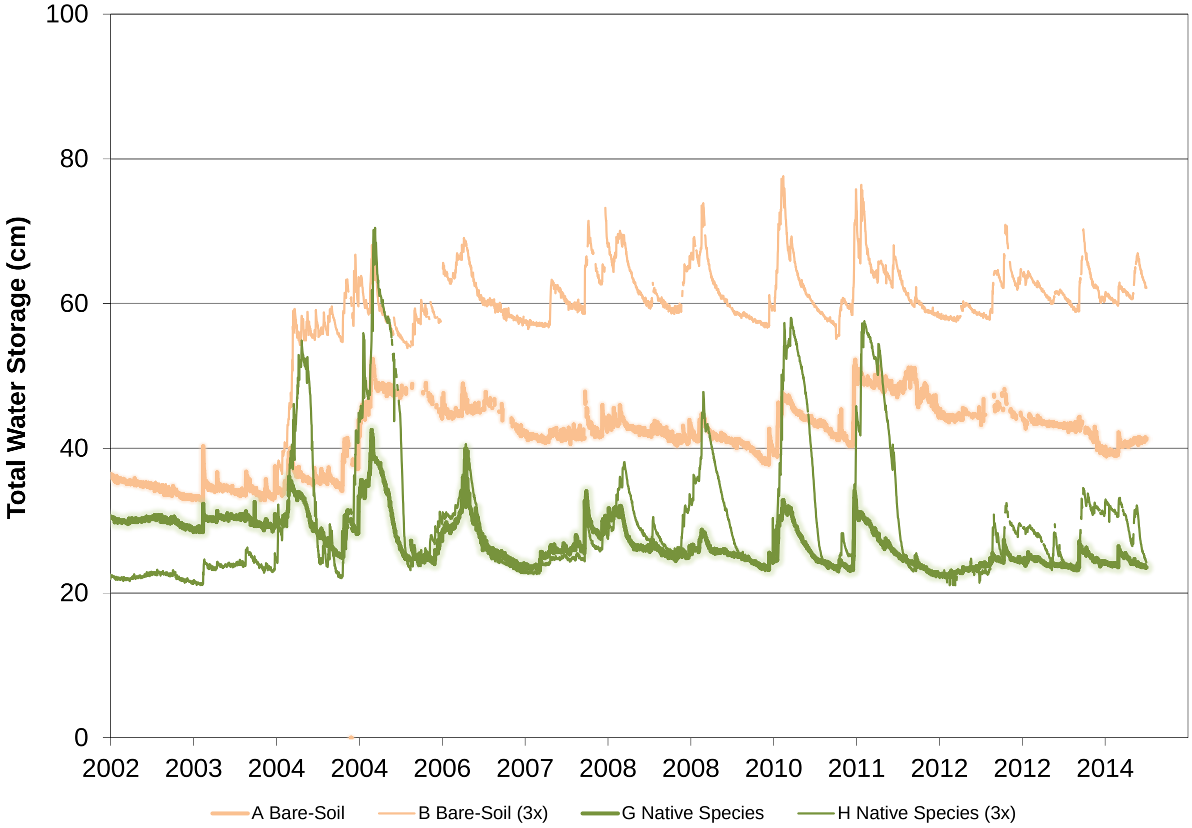

Fig. 8. Water Storage in the Bare-Soil and Vegetated drainage lysimeters with and without supplemental irrigation

TDR water content contours for the bare-soil 1x lysimeter and the bare-soil 3x lysimeter are provided in Fig. 9 and Fig. 10. Fig. 9 shows that water accumulates at the bottom of the bare-soil 1x lysimeter but only percolates to the bottom of the lysimeter after large precipitation events. During years with less precipitation, E slowly removes most of the moisture from the top 1.5 to 2 m of the lysimeter. Moisture from smaller precipitation events can be stored in the drier soil near the top of the lysimeter where it is slowly removed by E. Fig. 10 shows that water accumulates at the bottom of the bare-soil 3x lysimeter. Drainage occurs from this lysimeter, saturating the lower boundary. Water percolates to the lower boundary from smaller precipitation events because the soil is wetter and cannot store as much water near the surface.

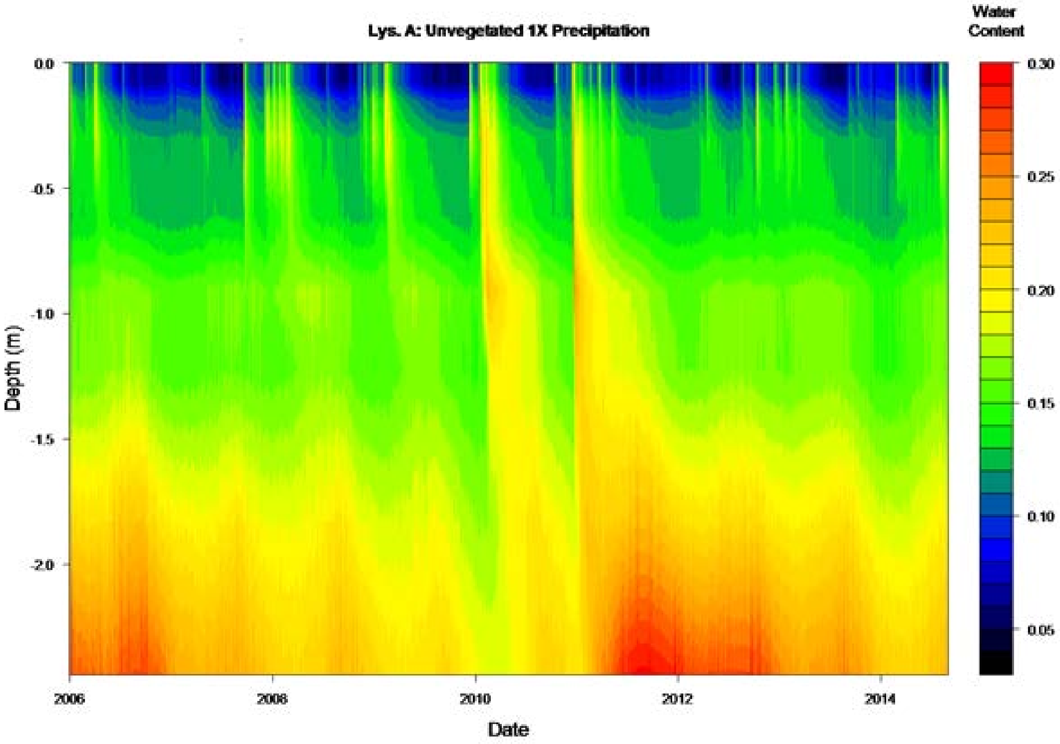

Fig. 9. Bare-Soil 1x precipitation

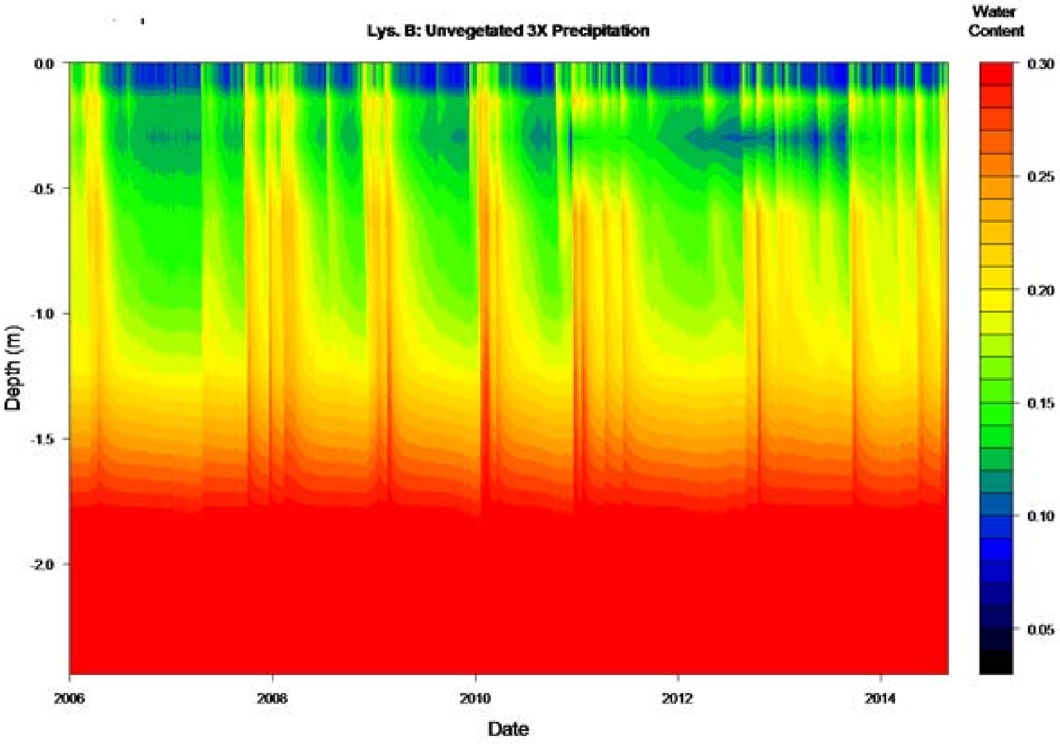

Fig. 10. Bare Soil 3x Precipitation

TDR water content contours for the vegetated 1x lysimeter and the vegetated 3x lysimeter are provided in Fig. 11 and Fig. 12. Most plants on these two lysimeters died during 2005, so during 2006 and 2007 these two lysimeters were replanted and irrigated to establish new plants. By the middle of 2008, plants were reestablished on both lysimeters. Smaller plants with reduced ET and irrigation on the vegetated 3x lysimeter result in moisture percolating to approximately 1.5 m deep during 2006 and early 2008. December 2009–January 2010 precipitation was 8.3 cm, and December 2010–January 2011 precipitation was 10.2 cm. These precipitation events resulted in moisture percolating to approximately 1 m deep in the vegetated 1x lysimeter during the spring following the precipitation event. ET removed this moisture from the lysimeter by mid-summer (Fig. 11). The same precipitation events with irrigation at 2 times the precipitation amount resulted in moisture percolating to the bottom of the vegetated 3x lysimeter. There was no drainage from this lysimeter, but water accumulated at the bottom boundary of the lysimeter. ET removed this moisture by mid-summer (Fig. 12). In subsequent years without large, concentrated precipitation events, moisture did not percolate below 0.5 m in the vegetated 1x lysimeter and did not percolate below 1.5 m in the vegetated 3x lysimeter.

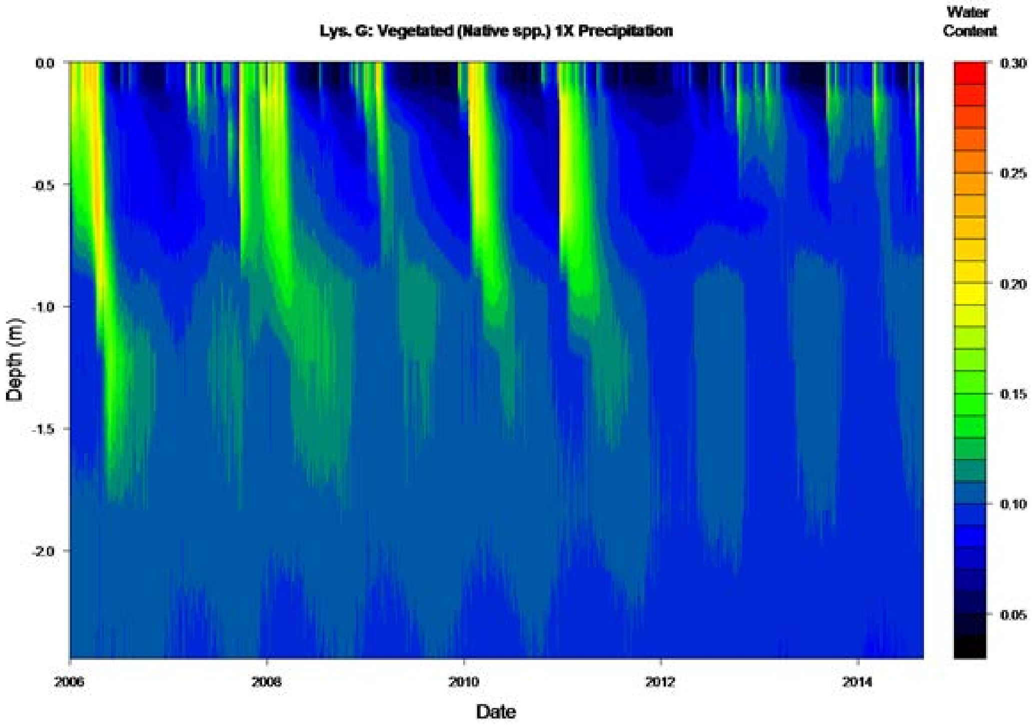

Fig. 11. Vegetation 1x Precipitation

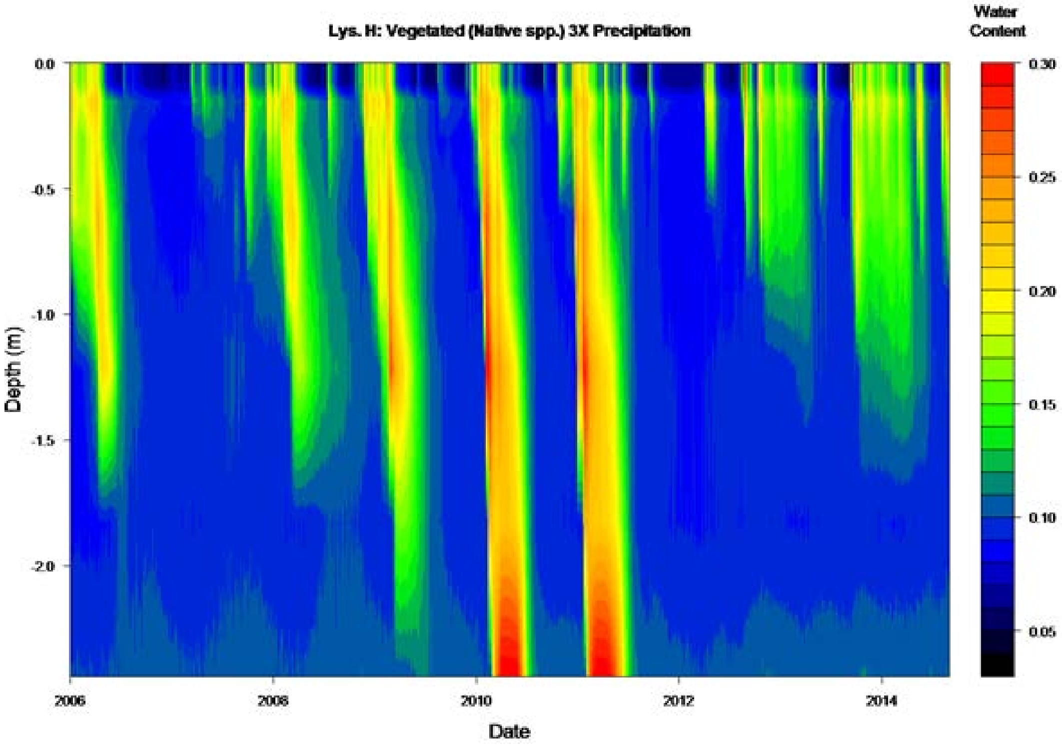

Fig. 12. Vegetation with 3x Precipitation

DISCUSSION

Results from lysimeter water balance measurements demonstrate that climate and vegetation strongly control moisture movement in the upper few meters of the vadose zone below the two RWMSs at the NNSS. The upper few meters of the vadose zone is the root zone for vegetation growing at the RWMSs. The arid climate at the NNSS has abundant sunshine and low precipitation. The measured average annual precipitation at the Area 3 RWMS is 15.0 cm, and the measured average annual precipitation at the Area 5 RWMS is 12.4 cm [6]. Estimates of annual potential ETare 10 to 15 times greater than precipitation.

After influences from initial conditions are gone and lysimeter hydrologic conditions are controlled by physical properties and boundary condition, bare-soil lysimeters store more water (i.e., have higher water contents) than vegetated lysimeters. There is less vadose zone water storage in a given depth of soil due to these higher water contents resulting in moisture percolating to greater depths in bare-soil lysimeters. When there is no drainage, moisture is removed from bare-soil lysimeters by E and moisture is removed from vegetated lysimeters by ET. E removes water from the lysimeter only at the surface, but ET removes moisture from the entire root zone.

Increasing surface infiltration by supplementing precipitation with irrigation at 2 times precipitation causes saturated drainage from a bare-soil lysimeter. E rates are not sufficient to prevent drainage from the bare-soil 3x lysimeter. Water accumulates at the bottom of the vegetated 3x lysimeter during years with high episodic precipitation events. ET removes this accumulated water in a few months and prevents drainage.

CONCLUSIONS

Lysimeter water balance measurements show that the arid climate and native vegetation at the NNSS provide a natural sustainable system to effectively prevent transport of contaminants from the RWMSs through the vadose zone to groundwater. Transport by infiltration and percolation of present day precipitation at the RWMSs is prevented. The natural system is sustainable because it does not rely on engineered features and mimics the current natural system with stable landscapes and no groundwater recharge. The system depends on establishing native vegetation in the covers above the waste cells and a stable climate.

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