Pacific Northwest NATIONAL LABORATORY

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Prototype Hanford Barrier Performance Monitoring Report

Fiscal Year 2024

June 2025

Jonathan Thomle
Dorothy Linneman

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Summary

This report provides an annual update on performance monitoring of the Prototype Hanford Barrier (PHB) at the Hanford Site. The PHB is part of a long-term study that serves as the scientific basis for many of the evapotranspiration-capillary barrier designs currently used globally and for future engineered barrier designs planned for remedial actions over waste and demolition sites at the Hanford Site. The PHB allows us to identify potential future issues and develop better monitoring techniques before these engineered barriers are constructed. Surface barriers like the PHB are essential for preventing water infiltration and curbing the spread of contaminants to groundwater. Effective monitoring of soil moisture levels above and below these barriers is crucial given that performance metrics could span up to 1,000 years.

From July 2023 to June 2024, the water flux (as measured by tipping buckets) through the 2-m-thick silt loam layer of the PHB – a fine silty material that stores water under high capillary tension – remained well below the 0.5-mm-per-year performance threshold, demonstrating its effectiveness in preventing water penetration. In 2024, degraded tipping bucket gauges were replaced to ensure the accuracy of future data. Additionally, neutron probes revealed that the wetting front from the rainy season only penetrated to a maximum depth of 1.2 m into the silt loam. This further demonstrated the barrier's efficiency, as the wetting front did not fully penetrate the 2-m-thick capillary barrier.

The western gravel slope of the PHB, composed of Hanford Site pit gravel of varying sizes, demonstrated low flux rates. In contrast, the eastern riprap slope exhibited higher flux rates. Zhang (2017)[1] found that the riprap side slope of the PHB had the highest drainage rates in January and the lowest in late summer or early fall, indicating significant summer evaporation. Drainage rates increased significantly under enhanced precipitation conditions, far exceeding the design criterion, which could lead to water infiltration into the waste zone. The study introduced the "edge effect," where elevated drainage rates from the riprap may migrate laterally beneath the barrier, compromising its ability to isolate waste, and recommended expanding the barrier and conducting further research to mitigate this issue. This report provides a review on surface barrier edge effects and their potential impact to subsurface contaminant migration.

[1] Zhang, Z. F. 2017. "Long-term drainage from the riprap side slope of a surface barrier." *Water (Basel)*, 8.

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Acronyms and Abbreviations

DOE	U.S. Department of Energy
EMI	electromagnetic induction
ETC	evapotranspiration-capillary
GPR	ground-penetrating radar
NQAP	Nuclear Quality Assurance Program
PHB	Prototype Hanford Barrier
PVC	polyvinyl chloride

Contents

Figures

1.0 Introduction

This report presents an annual update on performance monitoring of the Prototype Hanford Barrier (PHB) at the Hanford Site. The PHB is part of a long-term study that serves as the scientific basis for many of the evapotranspiration-capillary (ETC) barrier designs currently used globally and for future engineered barriers planned for remedial actions over waste and demolition sites at the Hanford Site. The PHB allows us to identify potential future issues and develop better monitoring techniques before these engineered barriers are constructed.

Objectives for this reporting period (July 2023 to June 2024) include continuity of barrier performance monitoring data, system inspection and maintenance, and a literature review on surface barrier edge effects that might impact contaminant migration in the subsurface. The sections are organized as follows:

- **Section 1.1, PHB Background Information:** Describes the layout of the PHB to provide a better understanding of the design and construction.
- **Sections 2.0 to 2.2, Data Collection Activities and Analysis:** Present comprehensive details on precipitation, temperature, drainage, and neutron probe data and provide an overview of the methodologies used and the results obtained from these field data collection activities.
- **Section 2.3, Riprap Edge Effects in ETC Barriers:** Provides a brief literature review on barrier edge effects, summarizing key findings and theories from existing research, providing context and background.
- **Section 3.0, Discussions and Conclusions:** Presents a synthesis of the findings from the entire report. It discusses the implications of the results, evaluates the effectiveness of the methods used, and offers conclusions based on the analysis.

1.1 PHB Background Information

Surface ETC barriers are a common engineering control in environmental site remediation projects and provide a potential long-term remedy for immobilizing vadose zone contaminants (DOE-RL 1992). The U.S. Department of Energy (DOE) has identified surface barriers as one of several alternatives that could be applied broadly to mitigate contaminant flux within the vadose zone at waste sites throughout the Hanford Central Plateau (DOE-RL 1992). The PHB was completed in 1994 and covers the 216-B-57 crib in the 200 East Area (Figure 1). The PHB is an ETC barrier that stores precipitation water in a fine-textured soil layer and later releases it into the atmosphere via evapotranspiration (Zhang 2016). The fine-textured soil is present in the central region of the barrier directly over the 216-B-57 waste crib (6W, 6E, 3W, and 3E in Figure 2), with two separate slope designs on the east and west sides. The east side is constructed of a 50% grade riprap slope (4E and 1E in Figure 2). The west side is constructed of 10% grade pit-run gravel slope (4W and 1W in Figure 2). Between the slopes on both sides there is a transitional zone (2E, 5E, 2W, and 5W in Figure 2). Figure 3 shows an overview of the PHB stratigraphy and construction.

The PHB design criterion for average drainage through the ETC barrier is 0.5 mm per year, excluding the transitions and side slopes. Currently, this criterion is evaluated using data from neutron probe measurements collected from access ports and flux data from tipping bucket rain gauges. Thus, proper operation of the drainage system is essential for accurate validation.

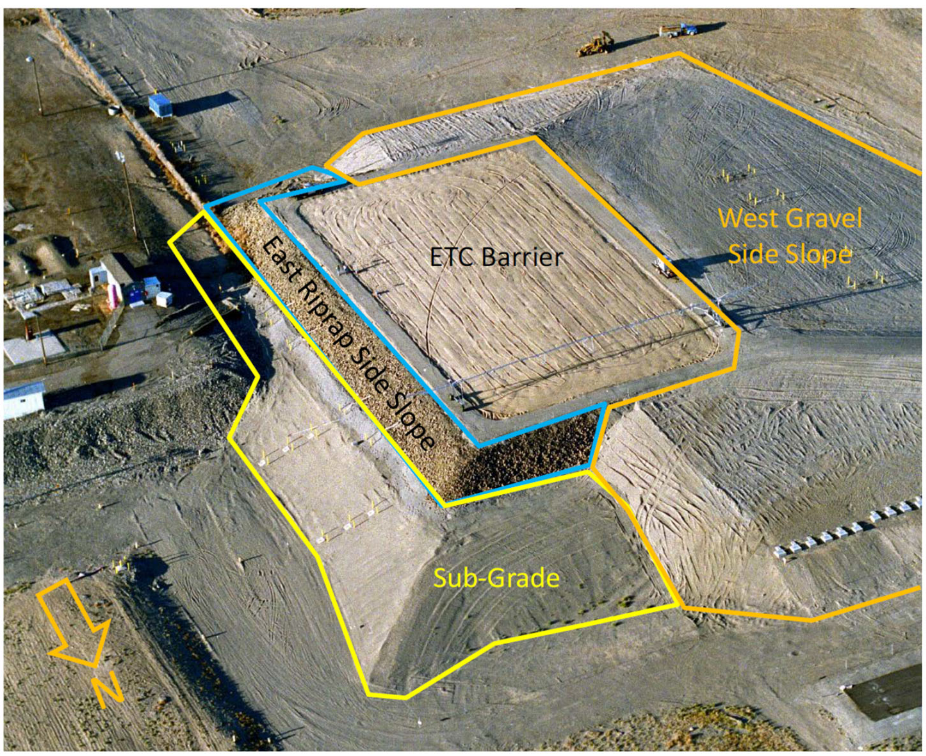

Figure 1. View of the Prototype Hanford Barrier after completion (August 9, 1994) (modified from DOE-RL 2016).

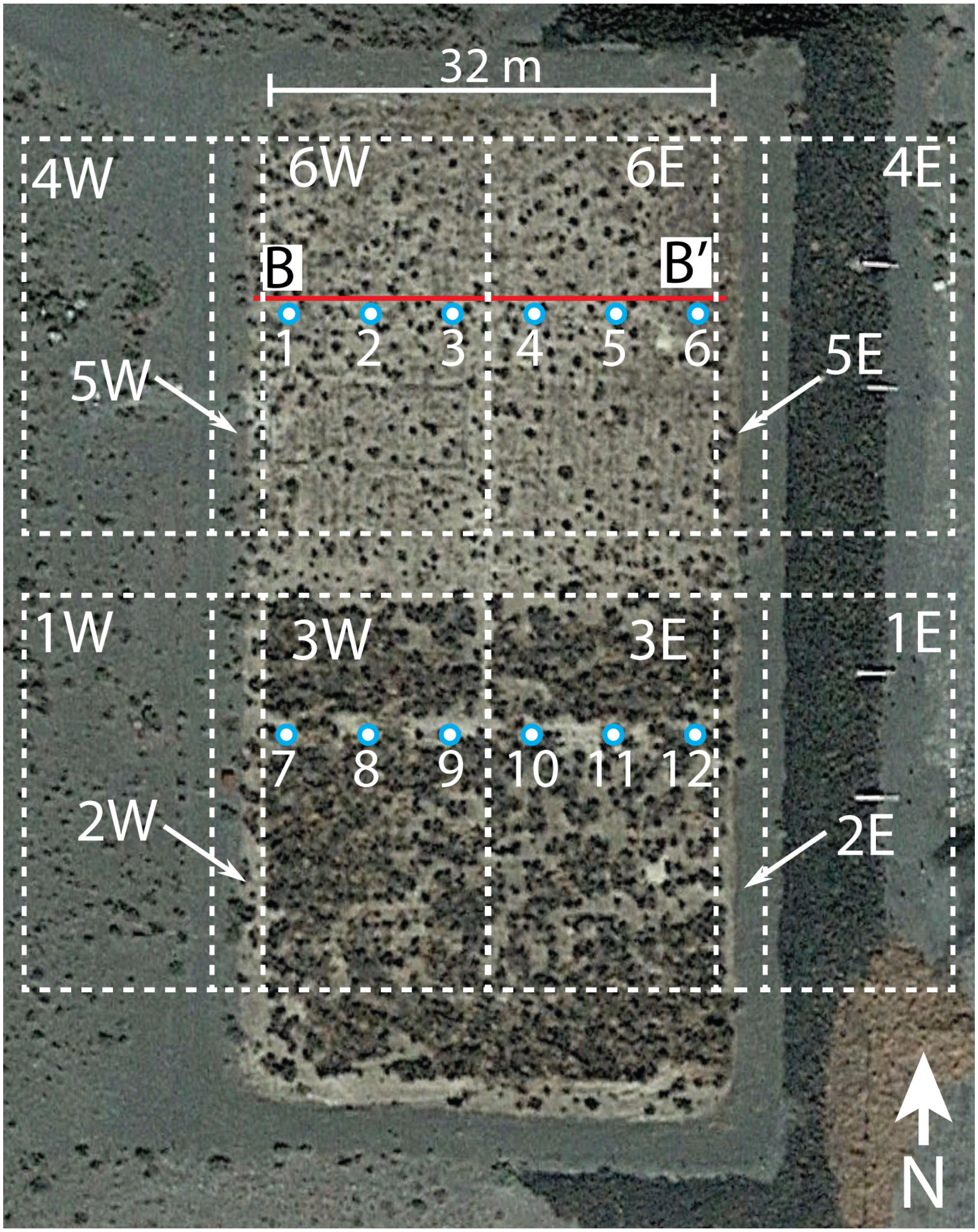

Figure 2. A plan view map of drainage areas (dashed white lines) and borehole locations (blue and white circles) at the PHB (modified from DOE-RL 2016 and Mangel et al. 2022). The dashed white lines represent curbs on the asphalt concrete layer. Boreholes 1-12 are roughly 2 m deep and are lined with aluminum for logging soil moisture with the neutron probe. The red line indicates the B-B' transect where time-lapse ground-penetrating radar data were collected previously for Mangel et al. (2022). All locations are approximate.

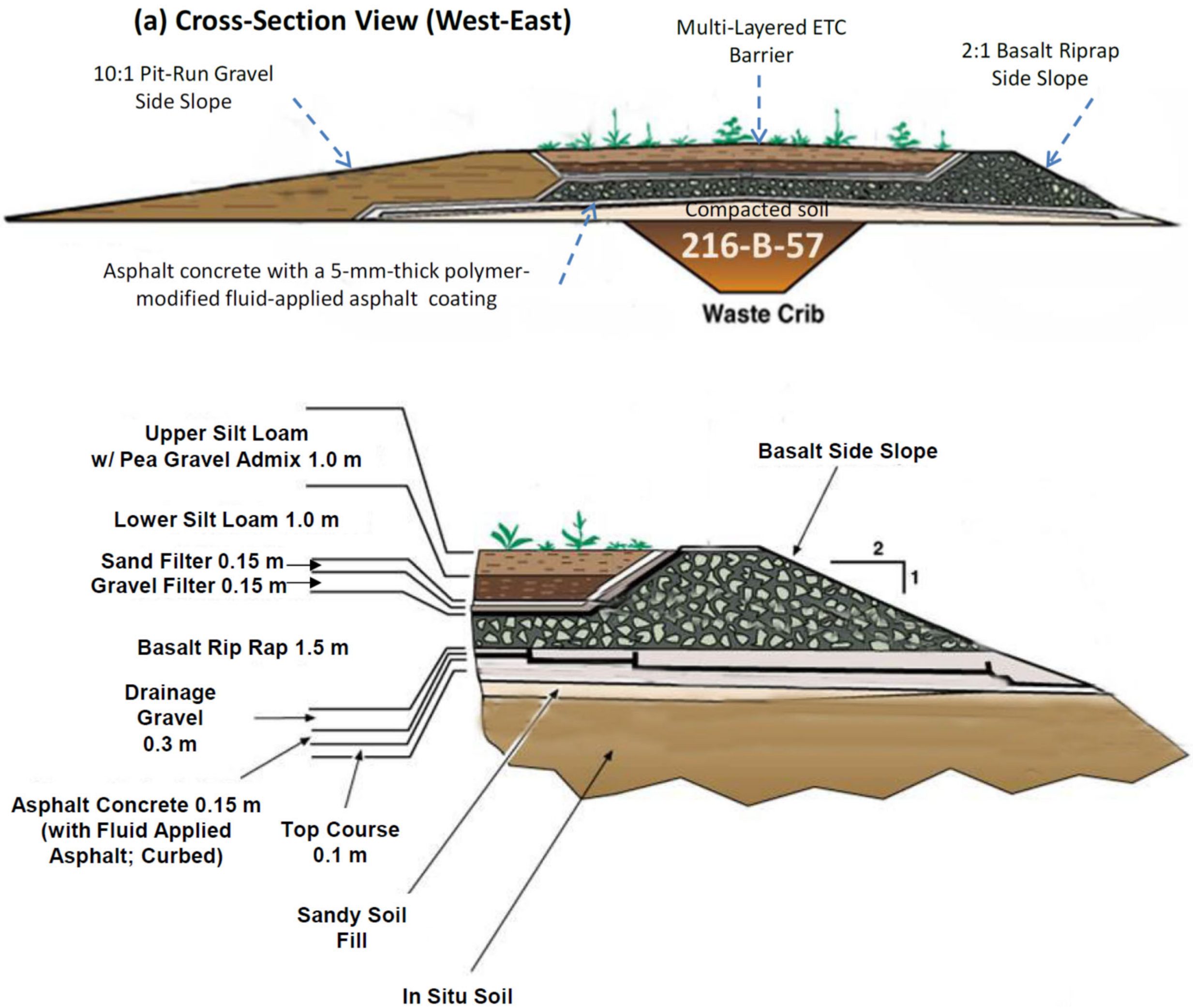

Figure 3. Stratigraphic cross sections of the PHB from DOE-RL 2016 showing the multiple layers and slope construction materials. Infiltrating water is captured at the asphalt concrete layer, which drains to the tipping bucket rain gauges.

2.0 Field Data Collection Activities and Analysis

The PHB is an engineered structure designed to mitigate the downward movement of infiltrating water to reduce contaminant flux from the vadose zone to the groundwater table. Drainage data captured on top of an asphalt layer below the barrier and neutron moisture depth logging data were collected during characteristically wet and dry periods to observe a range of hydrologic states of the barrier soil. Additional information on the design, construction, operation, and monitoring of the PHB can be found in DOE-RL 2016. All data analysis was performed in MATLAB.

Future barrier designs are likely to exclude robust drainage monitoring systems, unlike those in the PHB, due to the prohibitive maintenance and additional installation costs. As a result, alternative non-invasive geophysical tools, such as ground-penetrating radar (GPR) and electromagnetic induction (EMI), have been evaluated at the PHB for estimating moisture flux rates (Mangel et al. 2023). These tools offer an alternative approach for monitoring without the need for direct, intrusive interaction with the barrier, but also have the following limitations:

- GPR generally needs to be near the soil to estimate moisture, but on a barrier these soils are vegetated and may not allow close enough proximity.
- GPR has limited vertical resolution of soil moisture.
- EMI is generally sensitive to adjacent infrastructure.
- Most commercial EMI systems may not be sensitive enough to measure ETC moisture changes.

2.1 Precipitation, Temperature, and Tipping Bucket Data

The tipping bucket rain gauges are in vaults on the north slope of the barrier; water drains from the curbed impermeable asphalt through underground piping to the drainage monitoring system shown in Figure 4. The drainage plot areas shown in Figure 2 are defined by the curbing on the asphalt layer shown in Figure 3.

Data from tipping bucket rain gauges[1] that log at a 10-minute interval using a Campbell Scientific data logger (CR-6 Model) were used to calculate flux through the PHB. A tip is recorded when the buckets fill to a known volume. By counting the number of cumulative tips over a given period, the total volume and flux of water over a given drainage plot can be calculated. Two sizes of tipping buckets are connected in series so water draining from the barrier flows through both gauges. Small tipping bucket data volume is on the order of 5 mL whereas large tipping bucket volume is on the order of 40 mL.

[1] Tipping bucket-style rain gauges are ubiquitously used for measuring rainfall rates (volume through time). However, at the PHB, they are used to effectively monitor subsurface moisture flux and drainage within the barrier. Thus, they are referred to herein as tipping bucket gauges (excluding the rain designation) to avoid confusion about what they are measuring.

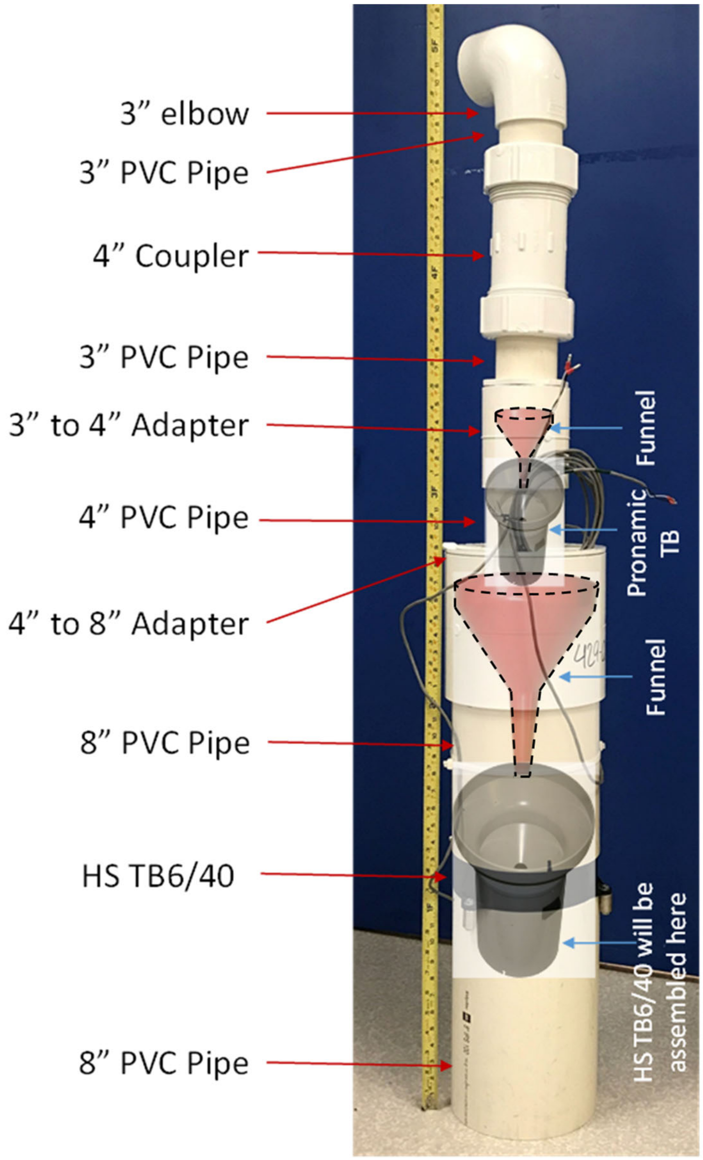

Figure 4. The assembled double-tipping-bucket system. The red arrows point to the polyvinyl chloride (PVC) pipes or adapters. The blue arrows point to the items inside the pipes. The images of the funnels and tipping buckets are not the actual items used in the drainage tipping bucket system and are not to scale (modified from Zhang et al. 2017).

Data from the tipping bucket gauges were downloaded at several times during this monitoring period. Each gauge monitors moisture flux within a specific drainage area in the PHB (i.e., 6W in Figure 2). Local precipitation and temperature data were obtained from the Hanford Meteorological Station and are presented in Figure 5 along with the summed value of drainage as cumulative flux through drainage areas 3W, 3E, 6W, and 6E. This value is referred to as the “central flux” of the PHB and is calculated as an area-weighted average. The most significant rainfall event since monitoring began occurred in early November 2021 and consisted of a 2.2-cm total daily rainfall. The largest observed drainage event, which was about 6 orders of magnitude smaller than the observed rainfall, occurred in late November 2021. Annual temperatures ranged from -18 °C in mid-December 2021 to 48 °C in late June 2021.

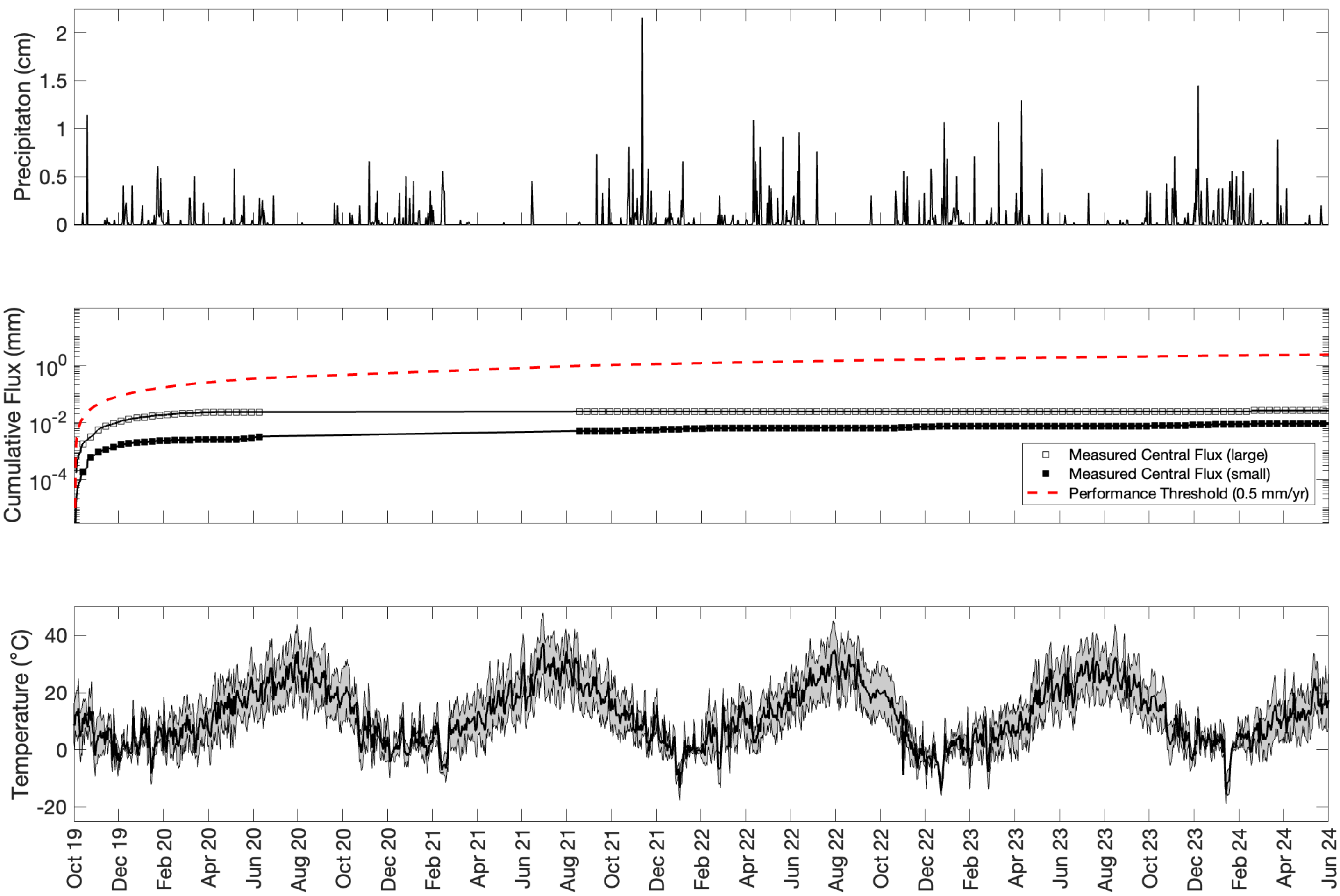

Figure 5. *Top panel*: Daily precipitation data from the Hanford Meteorology Station roughly 3 miles west of the PHB site. *Central panel*: Cumulative drainage flux from the small and large tipping buckets beneath the silt loam areas ("central" areas) of the PHB and the performance threshold. *Lower panel*: Daily temperature from the Hanford Meteorology Station; the shaded area indicates high and low daily temperatures and the black line indicates the daily average temperature.

Figure 6 presents flux data on an area-by-area basis. Analyzing individual contributions, the 4E and 1E plots are clear outliers, with flux data from other plots demonstrating a cumulative flux that is several orders of magnitude lower. Notably, the northern 6E and 6W plots show no flux events after June 2020, while the heavily vegetated southern 3E and 3W plots repeatedly exhibit small flux events. Given that vegetation increases moisture removal through transpiration, this discrepancy was thought to indicate malfunctioning tipping bucket gauges. No data exist for 4W because the tipping bucket malfunctioned during the entire time span shown.

Cumulative flux through the silt loam sections of the barrier (6E, 6W, 3E, and 3W) does not exceed the operational performance threshold of 0.5 mm per year. However, excessive drainage on the eastern riprap slope raises concerns about potential edge effects, as precipitation has a direct path to the drainage monitoring system with minimal evaporation losses.

In 2024, a test of the entire drainage system was initiated due to several tipping buckets showing flatline responses. This system was tested by adding a liter of water to the drainage piping just above the buckets to force them to tip (no water was applied to the soil). If no tips were recorded on the datalogger, the tipping bucket was considered to have failed the test. Seven of the 24 tipping buckets failed: four small buckets (4W, 1E, 5E, and 6E) and three large buckets (1W, 1E, and 4E). On June 20, 2024, these seven tipping buckets were replaced. The failure of bucket 6E explains why no flux events from this bucket had been observed since June 2020. However, it does not account for the absence of tips from 6W. The only explanation is that minimal flux occurred in that area. The large tipping bucket in 4W worked, but the number of tips was too large for the datalogger to store, so an error occurred. In the future, the number of tips should be reset every year to prevent this error.

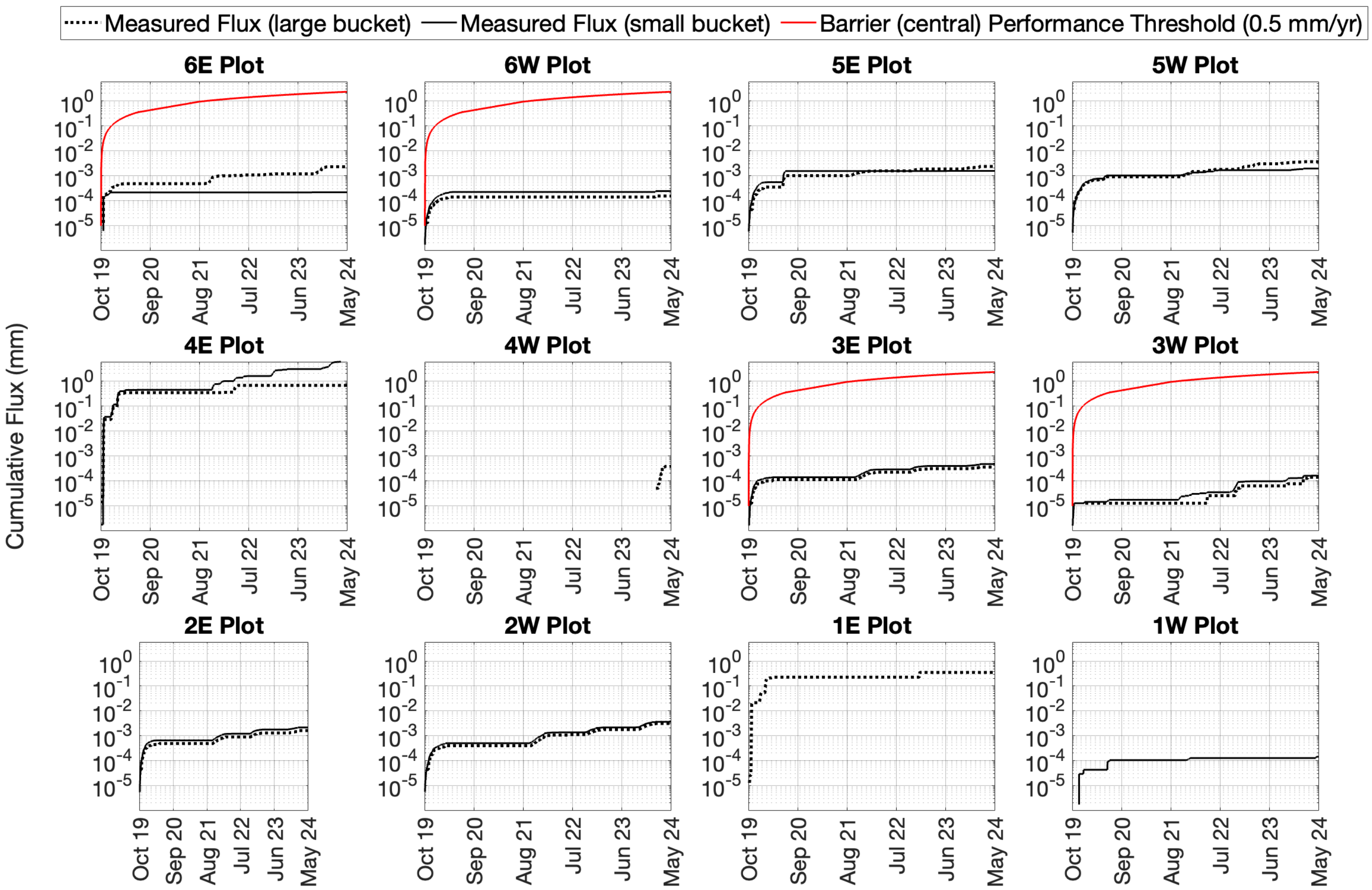

Figure 6. Flux rates throughout the investigation were calculated from small and large tipping bucket data. Plot numbers correspond to annotations on Figure 1. The performance threshold of 0.5 mm/yr shown in red only applies to the silt loam sections (6E, 6W, 3E, and 3W) of the PHB.

2.2 Neutron Probe Data

Neutron probe data were collected using a CPN 503TDR hydroprobe, which uses a radioactive source of americium-241:beryllium to emit neutron radiation into the soil matrix from the access tubes installed in the barrier soil layer. Neutron probe data have been collected since 2019, and additional data were collected in December 2023, March 2024, and June 2024. Before and after data collection, a successful standard count was performed according to the manufacturer's instructions to ensure the instrument functioned properly. The neutron probe was used to measure the vertical distribution of moisture content within the upper 2-m-thick silt loam layer at 12 water balance stations (1-12 on Figure 2). Neutron probe measurements were taken in 16-second counts at 12 depths between 0.15 and 1.80 m at each station. Neutron probe data were converted into moisture contents using the following equation:

$$\emptyset = -0.0481 + 3.1117x10^{-5}(16\,\text{second counts}) \quad (1)$$

Eq. (1) was derived empirically from calibration testing on 2-inch access tubes specific to the PHB site. Figure 7 through Figure 9 illustrate depth profiles of volumetric water content from neutron probe data collected at the PHB. Peaks in volumetric moisture content consistently occur in the spring months at depths of ~0.30 m across the entire network of boreholes. Notably, the peak moisture observed in March 2024 coincides with a rainy winter and spring. The water pulse from this event, coupled with additional precipitation during a notably wet spring in 2024, has led to a relative increase in soil moisture within the upper 1.1 m of soil compared to the very dry conditions generally observed at that depth. Recently, soil moisture conditions have been trending back toward very dry, with volumetric moisture levels in the upper 1.8 m of the PHB estimated to be around 0.05 in June 2024. Neutron probe data were not collected at the south boreholes in May and June 2023 due to lack of available staff.

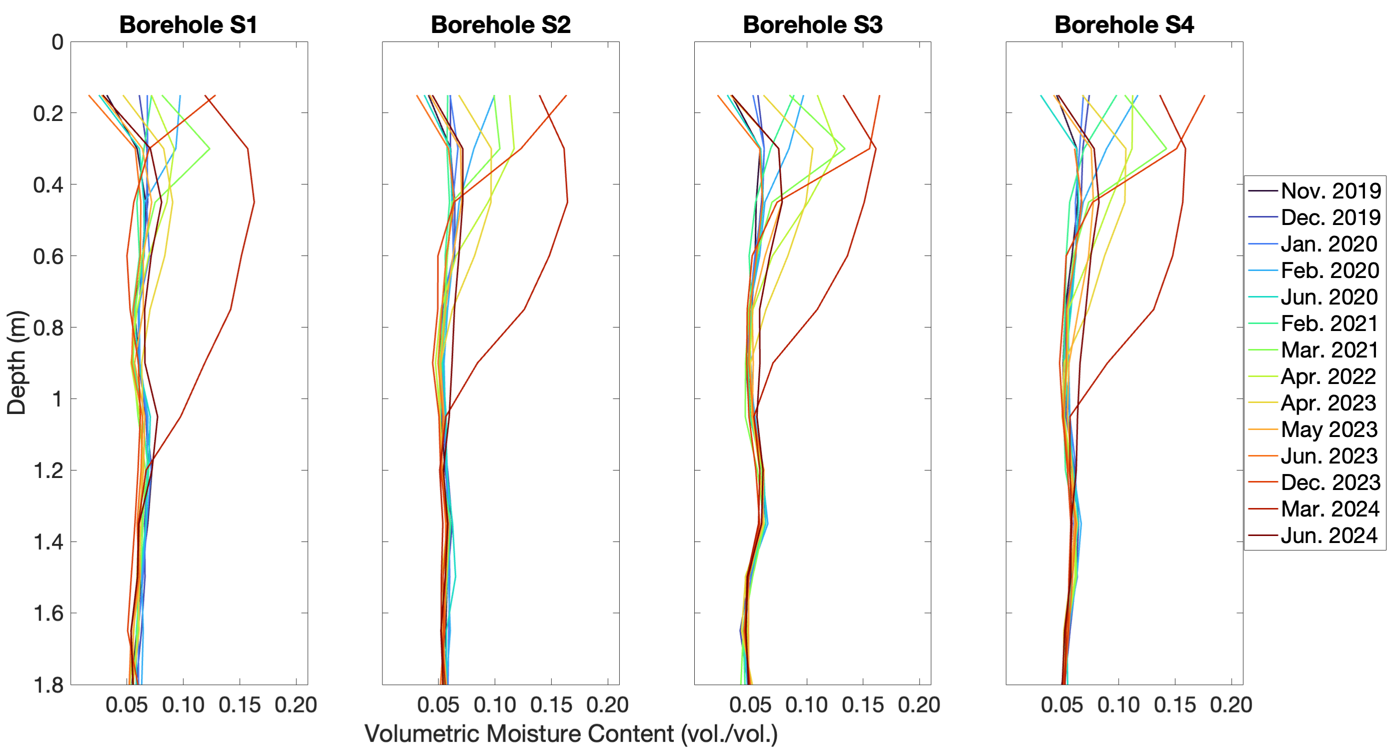

Figure 7. Volumetric moisture profiles over time for boreholes 1-4 in Figure 2 derived from neutron probe data.

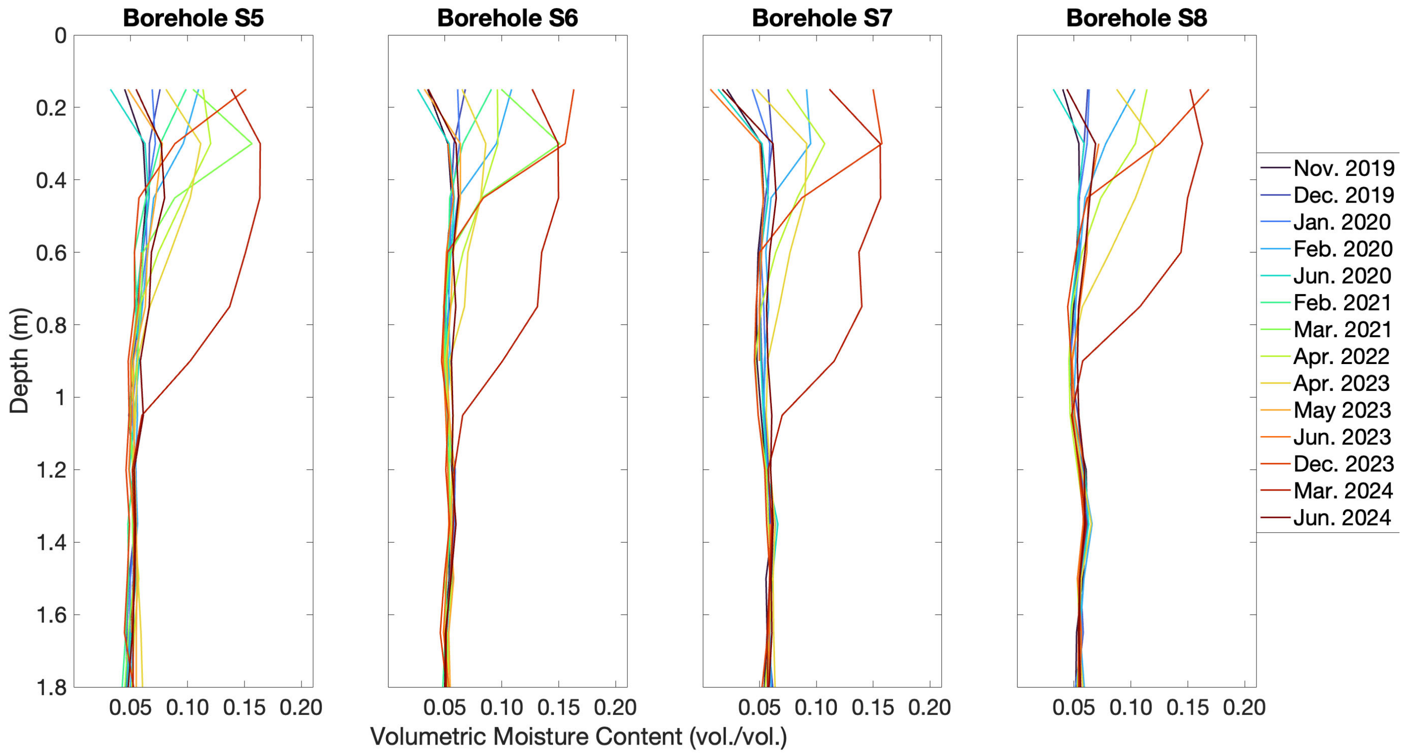

Figure 8. Volumetric moisture profiles over time for boreholes 5-8 in Figure 2 derived from neutron probe data.

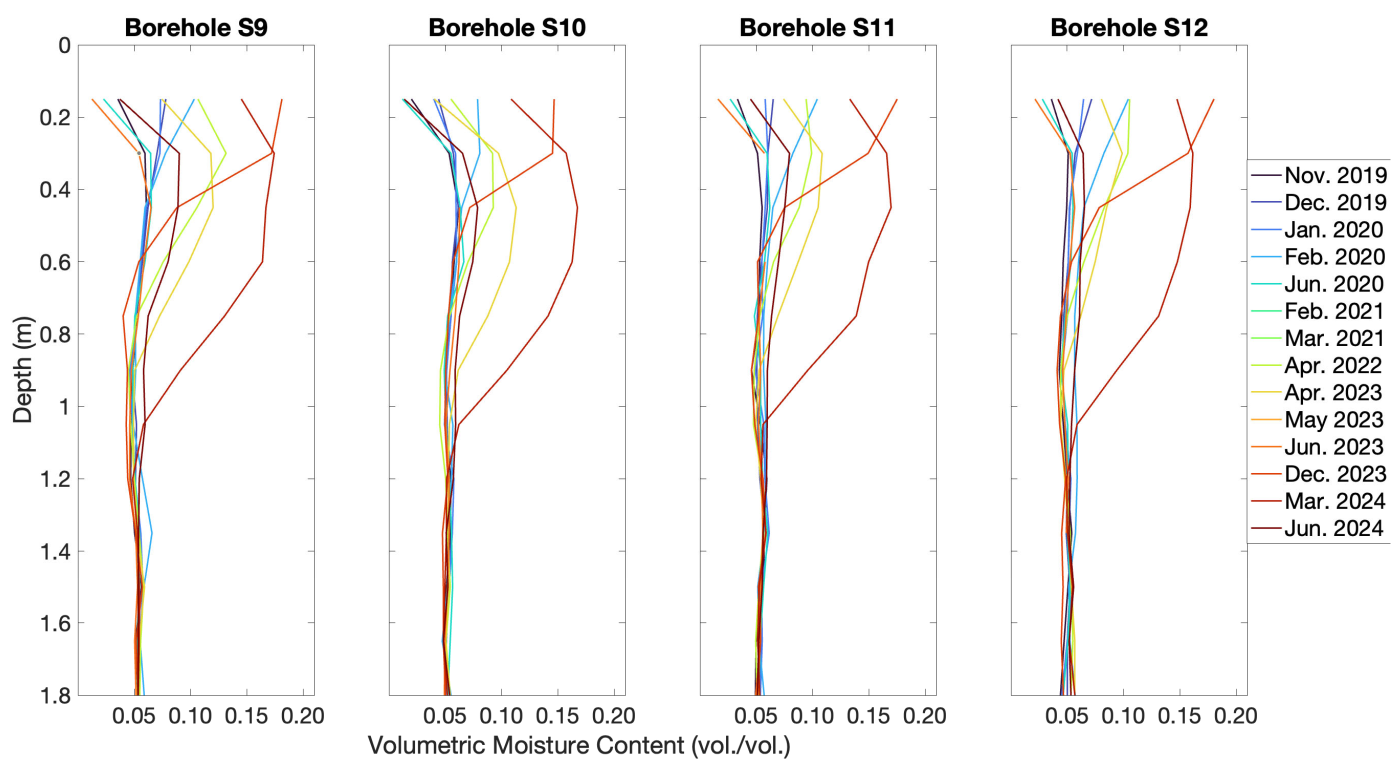

Figure 9. Volumetric moisture profiles over time for boreholes 9-12 in Figure 2 derived from neutron probe data.

2.3 Riprap Edge Effects in ETC Barriers

Through analysis of the drainage monitoring results of the PHB, Zhang (2017) showed that from 1994 to 2013, the riprap side slope of the PHB had the highest drainage rates in January and the lowest in late summer or early fall, indicating significant summer evaporation. On average, 12.9% of annual precipitation drained under natural conditions, increasing to 40.5% under enhanced conditions. With precipitation below 200 mm, only about 6% became drainage, while with precipitation above 200 mm, around 60% of the excess drained through the riprap, highlighting the crucial role of internal evaporation. However, the drainage rate far exceeds the design criterion of 0.5 mm per year at the edge of the barrier, necessitating effective management to prevent water infiltration into the waste zone below.

Literature on ETC edge effects was reviewed to identify studies on enhanced recharge at the edges of barriers. Several studies show that ETC barriers use fine-grained soil materials over a capillary break to absorb and store water during the rainy season and evaporate stored water during the dry season (Zhang 2016; Trpkošová and Mls 2010; Zhan et al. 2020; Lacroix Vachon et al. 2015). Studies have also determined that fine-grained soils can be susceptible to water erosion if they are not engineered properly (Zhang et al. 2019; Waugh and Link 1988; Toy et al. 2002). Water erosion was mitigated on the PHB by supporting the fine-grained soil with gravel or rip-rap. However, these coarse-edge materials increase water infiltration (Qiu et al. 2014; Smith and Benson 2016; Gee et al. 1996; Wing 1993; Waugh and Link 1988), and if not properly constructed, enhanced infiltration from these materials can potentially allow lateral flow under the barrier or to adjacent waste sites (Hunt and Skinner 2010). Wing and Gee (1994) determined that lateral flow can be mitigated by adding a clay or asphalt toe around the edge of the barrier to catch or control water. At the PHB, the asphalt beneath the barrier is designed to capture infiltrated water and redirect it to the drainage system.

It is important to note that few studies have examined the effects of enhanced recharge at the barrier edge. With plans for future barrier construction at the Hanford Site, a modeling study simulating these edge effects would provide a better understanding of how barrier construction might impact the underlying waste, nearby waste sites, and the lateral movement of water. The findings could provide insights into potential waste disturbances caused by lateral movement near the barrier edges.

3.0 Discussion and Conclusion

In Mangel et al. (2023), the tipping buckets, used to measure drainage, were called into question but replaced in the early summer of 2024. Based on the functional tipping buckets before these repairs and the neutron probe data, the drainage flux of the PHB appears to be performing within the drainage design criteria of 0.5 mm yr^{-1}. The highest amount of drainage observed was from the riprap slope, where precipitation is more easily transported to the drainage system, with some losses from evaporation. Moisture contents from the neutron probe show that the PHB is storing most of the water within the top 0.75 m of silt loam topsoil and preventing any change in storage in deeper soil layers. One exception occurred in March 2024, when water penetrated down to about 1.1 m, but by June 2024 that excess of water had dried up to residual moisture content. Changes in moisture content are generally observed over the first 0.3 m of soil, but the remainder of the profile maintains a soil moisture of roughly 5%.

It was also determined in 2024 that more research is needed to better understand the riprap edge effects, as described by Zhang (2017) and summarized in this report, which highlights the increased drainage from coarse-edge materials like riprap during high-precipitation events. This elevated drainage can lead to significant lateral migration of water, potentially undermining surface barrier effectiveness in isolating contaminants. A modeling study is needed to better understand how riprap can potentially enhance recharge at the edge of a barrier and how this affects the PHB specifically. This would have implications for the performance of engineered barriers at Hanford and effects on adjacent waste sites.

4.0 Quality Assurance

This work was performed by the Pacific Northwest National Laboratory Nuclear Quality Assurance Program (NQAP). The NQAP complies with DOE Order 414.1D, *Quality Assurance*. The NQAP uses NQA-1-2012, *Quality Assurance Requirements for Nuclear Facility Application,* as its consensus standard and NQA-1-2012, Subpart 4.2.1, as the basis for its graded approach to quality.

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