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Monitoring the Prototype Hanford Barrier – Fiscal Year 2017 Report

March 2018

ZF Zhang
JN Thomle
RE Clayton

U.S. DEPARTMENT OF ENERGY

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

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Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

After a decade of development activities from 1983 to 1993, the 2.5-ha (6.2-acre) Prototype Hanford Barrier (PHB) was constructed between late 1993 and 1994 over the 216-B-57 Crib in the 200 East Area (46°34'01.23"N, 119°32'28.43"W) at the Hanford Site in southeastern Washington State. The PHB construction was part of a *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA) treatability test of barrier performance for the 200-BP-1 Operable Unit. The CERCLA treatability test was an enhanced precipitation stress test during water year 1995 (WY95) to WY97 to determine barrier response to extreme precipitation events. A controlled fire test was conducted in 2008 to examine the recovery of vegetation under the natural condition and the performance of the barrier with limited vegetation.

The barrier was monitored extensively between November 1994 and September 1998 to evaluate surface-barrier constructability, construction costs, and hydrologic and structural performance at the field scale. From fiscal year 1998 (FY98) to FY13, monitoring focused on a more limited set of water balance, stability, and biotic parameters to evaluate the barrier's hydrologic, structural, and ecological performance. The design, test, and performance of the PHB until 2013 are summarized in DOE-RL (2016). There were no monitoring activities from FY14 to FY16.

In 2016, the U.S. Department of Energy requested that monitoring of the PHB be resumed to lengthen the record of performance, continue to follow the vegetation recovery following the controlled burn in 2008, and collect data specific to extreme events that have a greater chance of occurring during a longer monitoring period.

The hydrological monitoring at the PHB was resumed in FY17. The current strategy is to monitor water balance approximately quarterly. The structural and ecological monitoring was scheduled for a future time and at a less frequent rate (approximately once every several years) because the barrier structure and ecological state are not expected to change quickly during this time frame. The primary activities included (1) restarting water balance monitoring using a newer neutron probe, (2) designing a double-tipping-bucket drainage monitoring system, and (3) removing the unused instruments and supporting accessories from the site.

In WY17, the total precipitation was 195.3 mm, of which 128.0 mm fell in the winter season and 67.3 mm in the summer season. Precipitation during both periods was categorized as "near normal". The snowfall of 711 mm was nearly double the average snowfall of 361 mm. The maximum snowfall for the past 62 years (1946-2017) with records received in one winter was 1424.9 mm, which fell in the winter of 1992-1993.

From November 10, 2017, to March 29, 2018, precipitation was 126.2 mm, of which an average of 117.6 mm (93%) was stored in the evapotranspiration-capillary (ETC) barrier and 8.6 mm was lost to evapotranspiration (ET). For this estimate, zero runoff was assumed because observations supported this assumption, but no measurements are available to confirm it. In late March of 2017, the wetting front depth ranged between about 0.8 and 1.6 m among the 12 monitoring stations, indicating that the infiltration water did not reach the bottom of the ETC barrier. Up to about half of the available storage capacity was used in winter season of WY17.

From March 29 to September 12, 2017, the soil at the ETC barrier lost an average of 198.4 mm water to the atmosphere via ET. This amount is comparable to the total precipitation of 195.3 mm in WY17. Near the end of the summer season, the average ETC water storage in the middle of September was as low as 95 mm, which is lower than the estimated residual water storage of 116 mm.

The soil water content near the bottom of the silt loam layer, about 2 m inside from the side boundary, averaged 0.054 m^3m^{-3} and ranged between 0.046 and 0.067 m^3m^{-3} throughout the year. This average is even slightly less than the minimum water content of 0.058 m^3m^{-3} observed in the past, indicating that there was near zero available water for plant use and near zero mobile water content. However, during the winter season, precipitation or snowmelt infiltrated to the bottom of the silt loam layer at some locations near the edges of the ETC barrier. This water was removed from the soil by the end of the summer. This phenomenon was observed during the enhanced precipitation test from WY95 to WY97. However, it was not observed under natural precipitation conditions during the period from late WY98 to WY13, making the WY17 winter unusual.

In summary, the length of the water-storage monitoring period has now been extended to 23 years. The WY17 weather was normal but there was higher-than-normal snowfall. The barrier response in the form of water storage was normal. Although drainage was not measured directly in FY17, the water storage observations provide no indication of drainage from the ETC barrier.

Reference

DOE-RL. 2016. *Prototype Hanford Barrier 1994 to 2015*, DOE/RL-2016-37, Rev. 0, U.S. Department of Energy, Richland Operations Office. Richland, Washington. Available at http://www.hanford.gov/c.cfm/sgrp/DOE-RL-2016-37/DOE-RL-2016-37_R0.pdf and http://www.hanford.gov/c.cfm/sgrp/DOE-RL-2016-37/Appendices.pdf (Accessed on September 12, 2017).

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Acronyms and Abbreviations

AC	asphalt concrete
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act of 1980*
DOE	U.S. Department of Energy
DTB	double-tipping-bucket
ET	evapotranspiration
ETC	evapotranspiration-capillary
ETR	combined evapotranspiration and runoff/run-on
FGB	fiberglass block
FY	fiscal year
HDU	heat dissipation unit
HMS	Hanford Meteorological Station
NQAP	Nuclear Quality Assurance Program
PHB	Prototype Hanford Barrier
PVC	polyvinyl chloride
SPI	standardized precipitation index
TB	tipping bucket
TDR	time domain reflectometry
WY	water year

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1.0 Introduction

1.1 Background

After a decade of development activities from 1983 to 1993, the 2.5-ha (6.2-acre) Prototype Hanford Barrier (PHB, Figure 1.1) was constructed between late 1993 and 1994 over the 216-B-57 Crib in the 200 East Area (46°34'01.23"N, 119°32'28.43"W) at the Hanford Site in southeastern Washington State as part of a *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA) treatability test of barrier performance for the 200-BP-1 Operable Unit (DOE-RL 2016). The CERCLA treatability test included an enhanced precipitation stress test during water year 1995 (WY95) to WY97 to determine barrier response to extreme precipitation events and a controlled fire test in 2008 to examine the recovery of vegetation under the natural condition and the performance of the barrier with limited vegetation. The barrier was monitored extensively between November 1994 and September 1998 to evaluate surface-barrier constructability, construction costs, and hydrologic and structural performance at the field scale. From fiscal year 1998 (FY98) to FY13, monitoring focused on a more limited set of water balance, stability, and biotic parameters to evaluate the barrier's hydrologic, structural, and ecological performance.

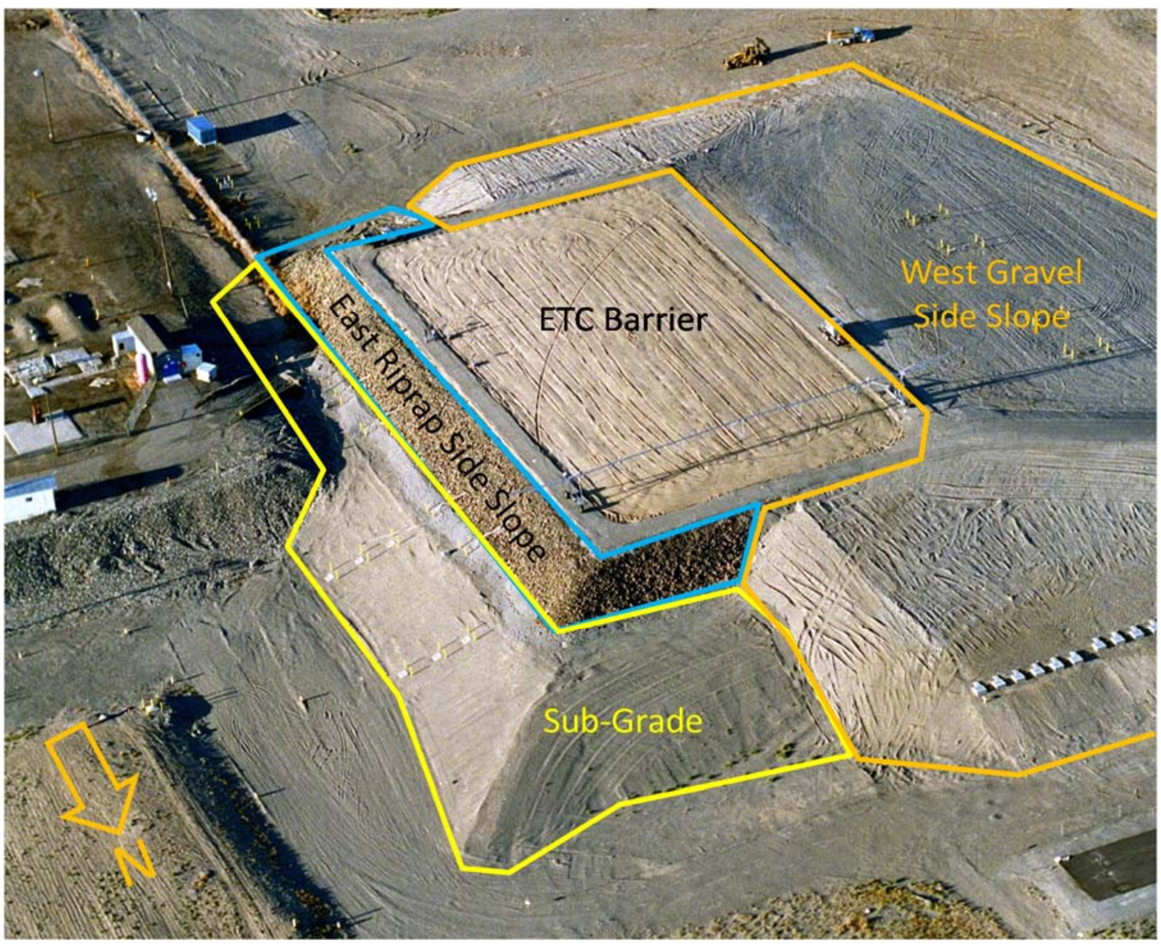


Figure 1.1. Plan view of the Prototype Hanford Barrier after completion of construction. (Photo taken on August 9, 1994. The lines show the approximate boundaries of the main barrier components.)

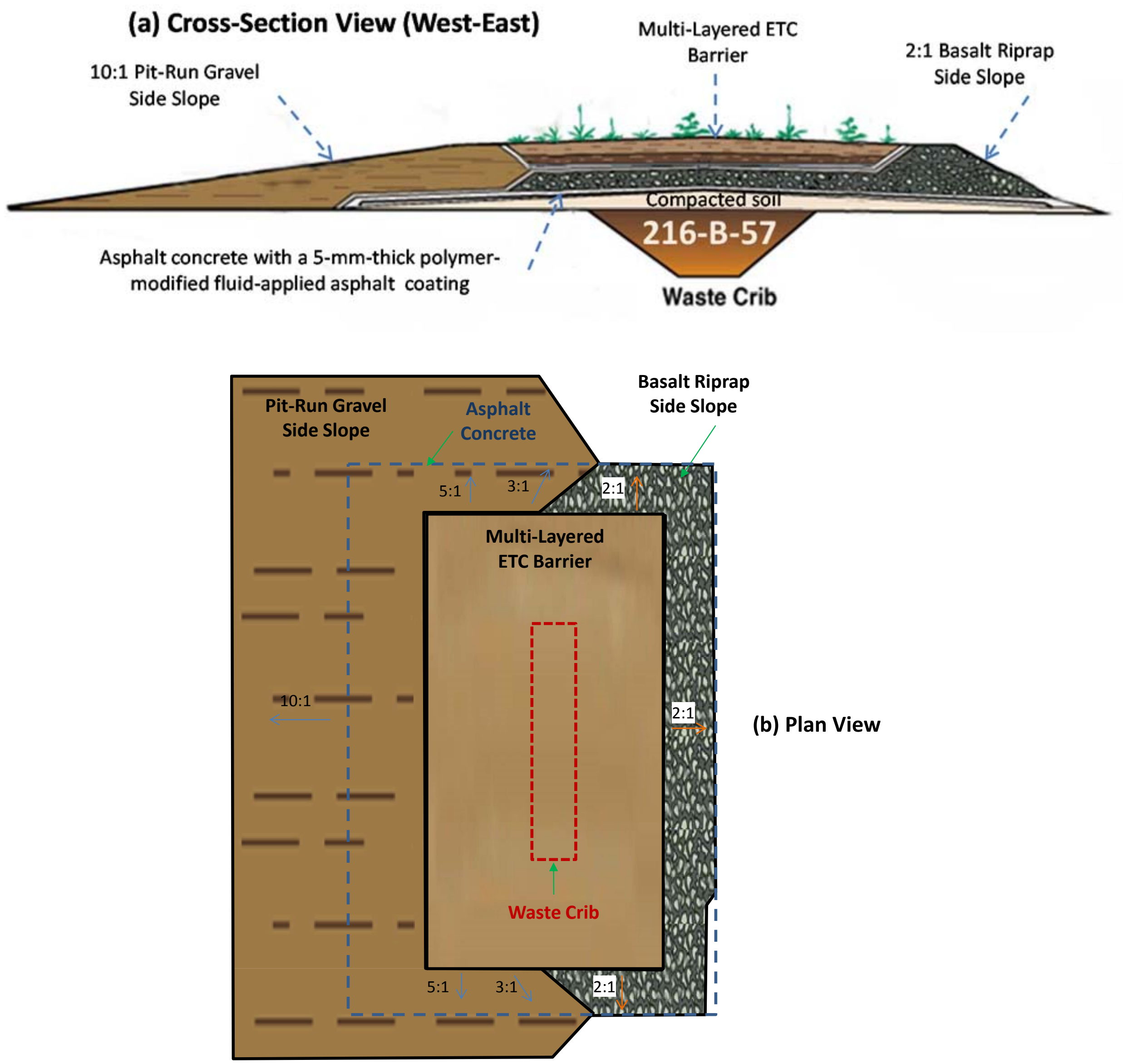


Figure 1.2. Schematic of the PHB: (a) cross-section view (west-east) and (b) plan view (approximate scale).

The PHB consists of four main components (Figure 1.2): (1) An evapotranspiration-capillary (ETC) barrier that consists of a silt loam evapotranspiration (ET) layer and an underlying capillary break (CB) consisting of gravels grading into large basalt, which is intended to prevent intrusion; (2) an asphalt concrete (AC) barrier with a polymer-modified fluid applied asphalt coating and a compacted soil layer beneath it; (3) a gentle pit-run gravel side slope in the west (10:1); and (4) a steep basalt riprap side slope in the east (2:1). The ETC barrier is the portion of the PHB that sits directly above but is larger than the waste zone. The role of the ETC barrier is to store precipitation and release the stored water into the atmosphere and to deter intrusion from the barrier surface by plants, animals, and humans. The AC barrier diverts drainage and hinders intrusion, and thus acts as a backup to the ETC barrier should the functionality of the latter be compromised. The two side slopes maintain barrier stability so that the ETC barrier remains intact and retains its functionality.

1.2 PHB Performance from 1994 to 2015

The design, test, and performance of the PHB until 2015 are summarized in DOE-RL (2016) based on a comprehensive review and analysis of the data collected at the site. The information in DOE-RL (2016) has also been published in several peer-reviewed journal papers. Zhang (2015) analyzed the field water retention of the silt loam layer at four depths and 12 water balance stations using in situ measurements of water content and pressure from 1995 to 2003. In Zhang (2017a), the drainage from the riprap side slope is evaluated with respect to the influence of the side slopes on the effectiveness of a long-term barrier. Additionally, Zhang (2017b) evaluated the performance of the neutron probe used in monitoring the soil water content at the PHB, and Zhang et al. (2017) discussed the surface-barrier design and performance of the PHB under conditions of enhanced and natural precipitation and no vegetation. The main findings with respect to the performance of the barrier components are as follows:

- The ETC barrier of the PHB performed much better than the drainage design goal of 0.5 mm yr^{-1}.
  - During each winter season, the silt loam layer was recharged by precipitation. The CB considerably enhanced the barrier's storage capacity.
  - During each summer season, all of the summer precipitation and nearly all of the stored water from the winter season was returned to the atmosphere by ET. These seasonal observations were consistent year to year and thus explained why average drainage (0.005 mm yr^{-1}) was so much lower than the design goal.
  - After the controlled fire test on the northern half of the PHB in September 2008, significantly less vegetation re-established in the burned section of the PHB than in the unburned section. The re-established grasses still removed nearly all the stored water in the burned section, but at a slower rate than in the unburned section, which had fully grown shrubs. Initially after the fire, the soil showed decreased wettability, but gradually returned to normal in the years that followed.
  - No detectable settlement or compression of the ETC barrier occurred.
  - The number and sizes of animal holes on the barrier surface were small and did not discernibly affect barrier function.
- Both side slopes remained stable and well-drained.
- The AC barrier remained stable and allowed negligible water percolation.

In summary, from 1994 to 2013—during which time the barrier experienced 3 years of enhanced precipitation, three 1000-year return, 24-hour simulated rainstorms, and a controlled fire—the monitoring data demonstrate that the barrier satisfied nearly all objectives in the past two decades. The PHB far exceeded the *Resource Conservation and Recovery Act* criteria, functioned in Hanford's semiarid climate, limited drainage to well below the 0.5 mm yr^{-1} performance criterion, limited runoff, and minimized erosion and bio-intrusion.

1.3 Long-Term Barrier Monitoring Strategy

One of the challenges facing deployment of surface barriers is convincing stakeholders that the technology will be effective and long-lasting. A longer period of performance monitoring will help to address this challenge. Hence, DOE-RL (2016) recommended the continuation of the barrier monitoring for several reasons:

- The two-decade monitoring period accounts for only 2% of the 1000-year design life. Extrapolation of past performance into the future is subject to significant uncertainty, including the possible effects of climate change.
- Extreme events happen very infrequently, perhaps on time scales of decades or longer. Extending the monitoring period increases the likelihood that extreme events will occur and barrier performance will be observed.
- The vegetation on the north section of the PHB was still dominated by the shallow-rooted grasses 4 years after the controlled burn. Precipitation levels during this period were normal and were never high enough to stress the barrier. Extending the monitoring period allows for more-complete observation of vegetation recovery and PHB performance.

Per the recommendation in DOE-RL (2016), the hydrological monitoring of the PHB performance was planned to resume in FY16. However, radioactive rabbit droppings were found at the site during the monitoring gap between FY13 and FY16. This finding required that necessary procedures be established prior to accessing the PHB. Some of the hydrological monitoring activities commenced in FY17. Over the next 1 to 2 years, we will complete the calibration of primary instruments and test procedures and refurbish the runoff plot.

DOE-RL (2016) recommended structural and ecological monitoring commence as soon as possible because the last structural monitoring was in FY12 and the last ecological monitoring was in 2011. In the future, the frequency of both activities will be approximately once every five years. This frequency is less than in the past because, based on past behavior, the barrier structure and ecological state are not expected to change substantially in 1 or 2 years.

The monitoring activities conducted in the past, those conducted in FY17, and those planned for the future are listed in Table 1.1.

1.4 Scope of the Report

Section 2 describes the monitoring system, including monitoring plots and stations, monitoring methods, and instrument calibration. Section 3 presents the activities in FY17. Section 4 summarizes the monitoring results in FY17, and Section 5 describes the quality assurance program. The main findings are summarized in Section 6.

Table 1.1. Past, FY17, and Future Monitoring Components at the Prototype Hanford Barrier

Monitoring Purpose	Monitoring Components	Methods	FY95 to FY13	FY17	Future[(a)]
Hydrology – Primary	Precipitation	Mini-lysimeters	x		
	Surface runoff and erosion	Runoff flume	x		x
	Water content profile	Neutron probe	x	x	x
	Drainage off the asphalt concrete	Drainage vaults	x		x
Hydrology – Secondary	Water content at the bottom of the silt loam and beneath the asphalt layer	Neutron probe	x	x	x
	Soil water pressure and temperature	Heat dissipation units	x		
	Soil water pressure	Fiberglass blocks	x		
Structural Stability	Barrier settlement	Settlement markers	x		x
	Barrier elevation	Elevation markers	x		x
	Riprap side slope stability	Creep gauges	x		x
	Wind erosion	Wind stations	x		
	Overall barrier conditions	Aerial photos	x		x
Ecological Monitoring	Vegetation characteristics (i.e., floristics composition, plant cover and spatial distribution, plant height, and canopy characteristics)	Field survey	x		x
	Gas exchange rate, roots, shrub survivorship, reproduction, and xylem pressure potential	A variety of methods	x		
	Animal activities	Surface inspection, measurement of the counts and dimension of animal burrows, and direct observation using traps	x		x

(a) The future monitoring items are subject to change.

2.0 Monitoring System and Calibration

This section describes the monitoring system and the results of instrument calibration.

2.1 Monitoring System

2.1.1 Monitoring Plots and Stations

The PHB was divided into 12 monitoring plots to address the spatial variability of water balance and hydrologic processes when the PHB was constructed in 1994. Figure 2.1 shows the plots, which are denoted as 1W through 6W for those located in the west half and 1E through 6E in the east half. The 12 plots represent three main types of barrier structure:

1. Silt loam plots: 3W, 3E, 6W, and 6E
2. Side slope plots:
    a. 1W and 4W for the west gravel side slope
    b. 1E and 4E for the east riprap side slope
3. Transitional or silt loam boundary plots: 2W, 2E, 5W, and 5E

Not all of the components were monitored in all of the plots, depending on the primary hydrological processes and the function of the components. Each of the 12 curbed zones collected water beneath the plot, which was discharged to a concrete vault. Each collection zone with a vault is equivalent to a drainage lysimeter. The vaults were installed to the north and downgradient from the AC to allow the movement of water by gravity.

For water balance, the focus was on the silt loam, which serves as the media for water storage and vegetation growth. The riprap side slope has very little water storage capacity and the gravel side slope has some level of water storage. Fourteen monitoring stations, denoted as S1 through S14 (Figure 2.1), were established. Twelve of the fourteen monitoring stations were installed in the four silt loam plots (Figure 2.1)—three stations each in 6W and 6E in the north section and 3W and 3E in the south section—to allow the water processes and balance of these plots to be thoroughly evaluated. Two stations were installed in the two gravel plots, i.e., 1W and 4W, respectively, at the west side slope. There was no water balance monitoring of the east riprap side slope or the four small transition plots because the riprap has little water-holding capacity and the transition plots are less important than others.

Water content of the soil 0.15 m above the bottom of the silt loam storage zone was monitored with eight horizontally oriented neutron probe access tubes (AA1 through AA8 in Figure 2.2) to examine how the side boundaries and the CB at the bottom affected water movement. Water content beneath the AC was monitored with six horizontally oriented neutron probe access tubes (BA1 through BA6 in Figure 2.2) installed at the depths of 1, 2, and 3 m below the AC.

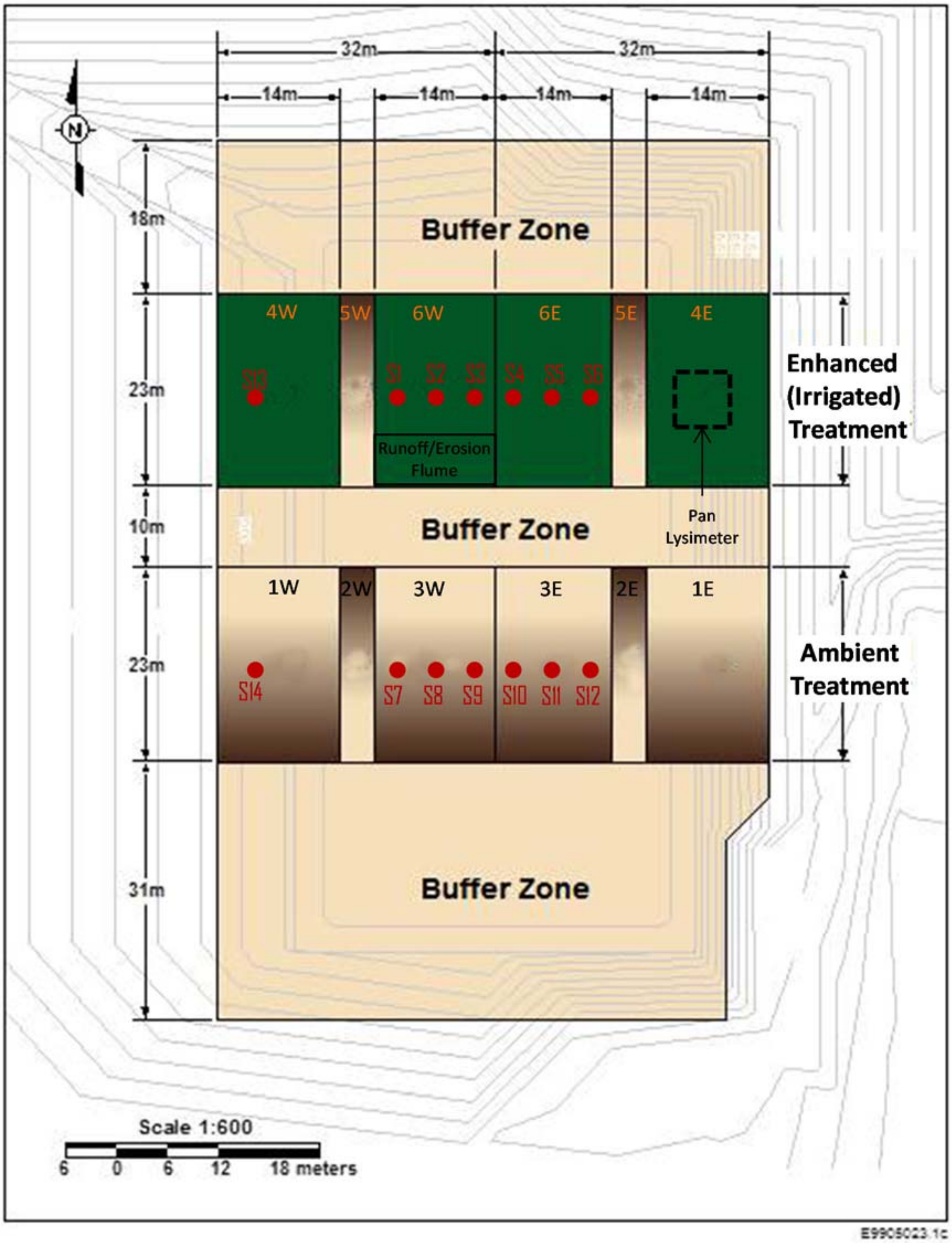


Figure 2.1. Plan view of the Prototype Hanford Barrier showing the 14 water balance monitoring stations (marked as S1 through S14), 12 plots for drainage monitoring (marked as 1W through 6W and 1E through 6E), and the runoff/erosion flume.

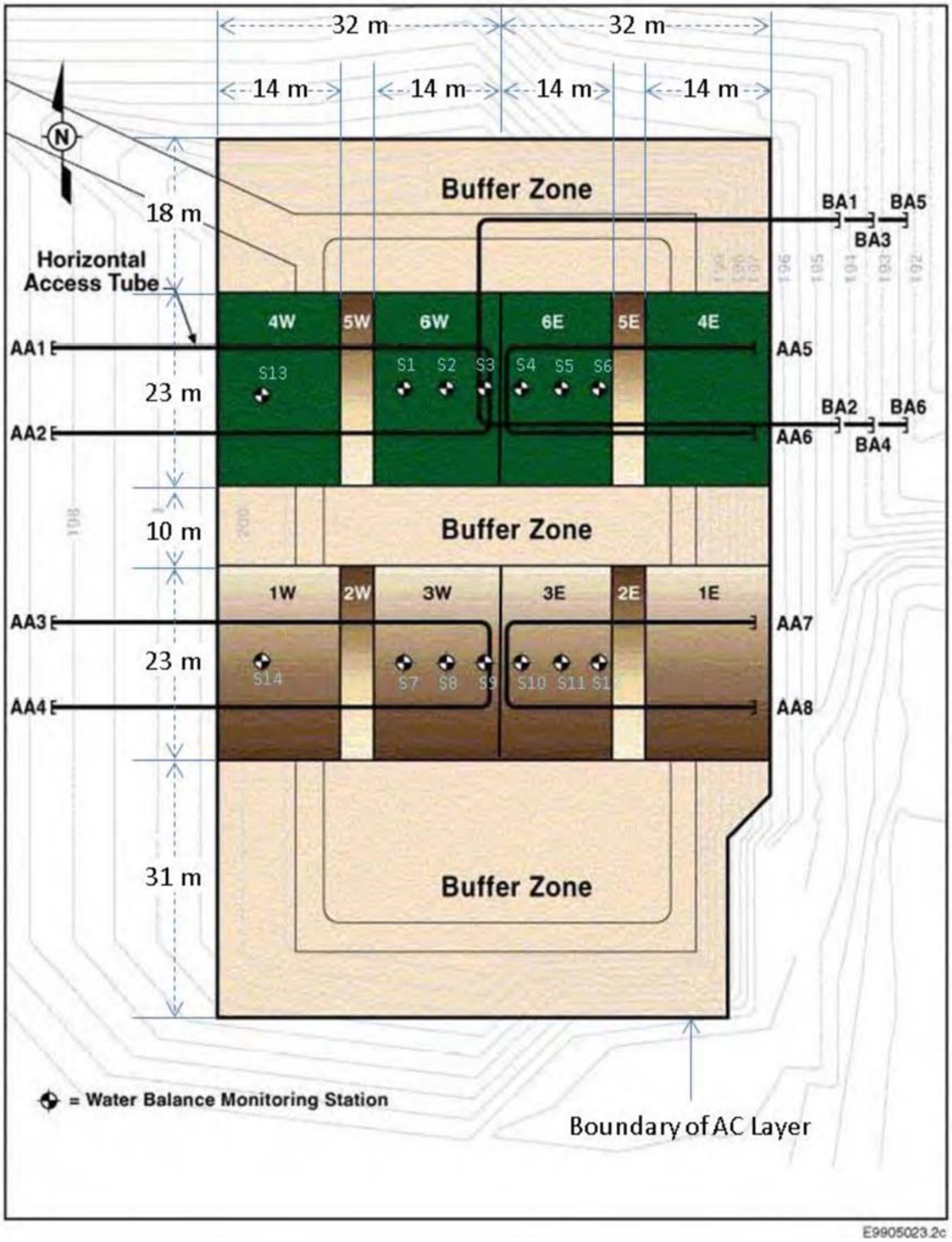


Figure 2.2. The horizontal neutron probe access tubes shown by the U-shaped lines. Tubes AA1 through AA8 are located near the bottom of the silt loam, slightly above the silt-sand interface. Tubes BA1 and BA2 are 1 m below the asphalt concrete, BA3 and BA4 are 2 m below, and BA5 and BA6 are 3 m below.

2.1.2 Drainage Monitoring

Within each of the 12 drainage vaults, the old drainage measurement system [which included a tipping bucket (TB), a pressure transducer, and a dosing siphon] was removed in FY17 (except the bottom portion of the dosing siphon that was partially buried in concrete). This system will be replaced with a double-tipping-bucket (DTB) measuring system (Figure 2.3). The DTB system is composed of one small Pronamic Rain-O-Matic Small PCB 9602 TB (Pronamic APS, Ringkobin, Denmark) sitting above a large HS TB6/40 (Hyquest Solutions P/L, Liverpool, NSW, Australia) TB. Drainage from each monitored plot flows first through the small TB and then the large TB and hence is measured twice. The drainage water then flows out of the vault through a hole on the existing pipe of the old siphon system.

The DTB system is used for two reasons. First, the flow rates are highly variable both seasonally and between plots and they range over several orders of magnitude. The maximum flow rate ever recorded at the PHB was 4.4 L min^{-1}, which occurred from the riprap side slope plot 4E on March 28, 1997, after 69.7 mm of water were applied over an 8-hour period 1 day earlier. The maximum flow rate recorded at the PHB during the period without irrigation (FY99-FY13) was 0.5 L min^{-1}, which occurred from the riprap side slope plot 1E on January 30, 2004. Hence, it is expected that the upper bound of flow rate should be close to 0.5 L min^{-1} under the natural precipitation condition. The lower and upper bounds of the flow rates measurable with the small TB are roughly one order of magnitude less than those of the large TB. The maximum flow rate of the small TB is approximately 0.5[a] L min^{-1} (0.09 mm hr^{-1} for the full plots; 0.33 mm hr^{-1} for the transitional plots) and that for the large TB is 3[b] L min^{-1} (0.56 mm hr^{-1} for the full plots; 1.96 mm hr^{-1} for the full plots). Second, both TBs should function normally under natural precipitation conditions. Data from the two TBs in the same drainage vault can serve as a check of the functionality and accuracy of each other. Another advantage of the DTB system is that it can be removed from the vault for testing, repair, or replacement if it should fail. Currently, no irrigation is planned for this test. If irrigation is applied in the future, the DTB will need to be redesigned if the expected drainage rates exceed 3 L/min.

The 12 assembled DTB systems will be installed in the 12 existing drainage vaults, respectively (Figure 2.4). The total height of the assembled DTB system is about 5 feet (1.5 m). This height can be adjusted as needed.

[a] According the datasheet of the Rain-O-Matic Small Rain Gauge, it takes about 255 ms to open and 295 ms to close. This translates to a maximum of 109 tips/min. Because each tip is about 5 ml, the maximum flow rate is estimated to be 545 ml/min.
[b] Per the datasheet of the Tipping Bucket Flow Gauge Model TB6/40.

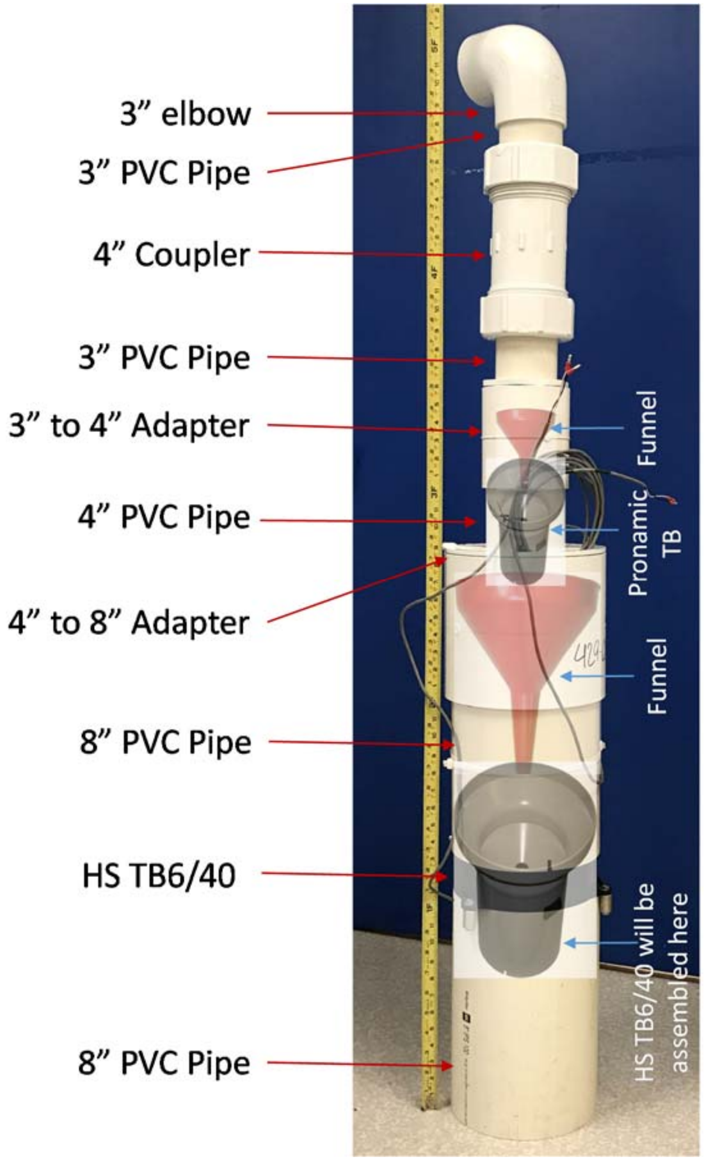


Figure 2.3. The assembled DTB system. The red arrows point to the PVC pipes or adapters. The blue arrows point to the items inside the pipes. The images of the funnels and tipping buckets are not those of the actual items used in the DTB system and are not to scale.

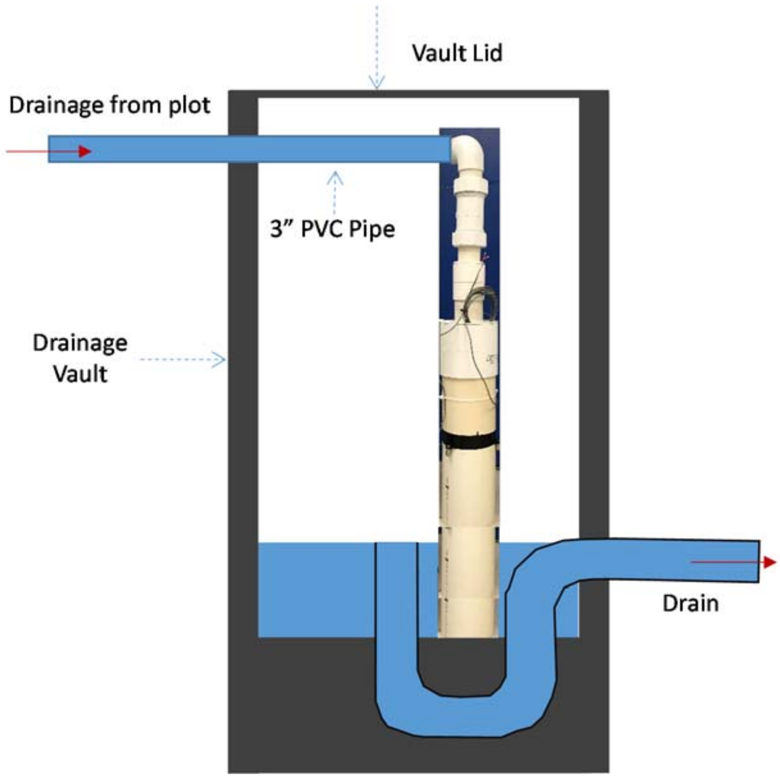


Figure 2.4. Schematic showing the installation of a DTB system in a drainage vault (not to scale).

2.1.3 Runoff and Precipitation

Only one runoff plot (Figure 2.1) was established for runoff monitoring because runoff was not expected to be a major component of the water balance, as reported in DOE-RL (2016). If runoff occurred within that plot, it was assumed that the rate would be applicable to the remaining barrier surface. Any short-distance runoff within the ETC barrier can become run-on in a different location within the ETC. This within-the-barrier runoff cannot be detected by the runoff flume.

Precipitation is not measured on site. The measurement at the nearby Hanford Meteorological Station (HMS) is used in the analysis. The HMS is located near the center of the Hanford Site between the 200 West and 200 East Areas and is about 3 miles west of the PHB.

2.2 Instrument Calibration

This section describes the processes used to calibrate the instruments and calibration results for this study. The term "calibration" here means the determination of the relationship between the two correlated variables.

2.2.1 Neutron Probe

The neutron probe (CPN 503DR Hydroprobe, S/N H33115140; Probe 5140) used from FY95 to FY13 exceeded its design life and was retired. A newer neutron probe (CPN 503DR Hydroprobe, S/N 50200; Probe 50200) was used in FY17 and will be used in the future.

Neutron probe 50200 was calibrated in the silt loam for the 2- and 3-inch aluminum access tubes during the period between February and September 2017. Each calibration was based on the data from three containers located near the PHB, which represented the low, intermediate, and high water content conditions, respectively. The vessel for the low water content soil was a 4-foot-diameter, 5-foot-tall stainless steel container packed with well-mixed silt loam from a soil pile near the PHB and was covered to prevent any gain or loss of water. The container for the intermediate water content soil was a 4-foot-diameter, 5-foot-deep lysimeter, which was filled with silt loam years earlier and was open to the air. A 2-inch access tube and a 3-inch access tube, about 1 foot apart, were installed vertically near the center of each of these containers. The high water content was achieved in two 200-gallon drums, one of which contained a vertically installed 2-inch aluminum tube and the other a 3-inch tube. The drums initially were filled with saturated silt loam two decades ago at the time the PHB was constructed and were covered. Some water was lost from these drums, but the water content was still high.

At the time of neutron probe calibration, after neutron loggings were taken, soil samples were taken from multiple depths from three boreholes around the access tubes for water content and bulk density measurements. A sleeve was used to keep the probe assembly in the middle during the calibration in the 3-inch tube. Due to the lack of an appropriate test facility, the neutron probe was not calibrated in a 3-inch aluminum tube in sand.

Neutron probe 50200 was calibrated in the silt loam with the 2-inch and 3-inch aluminum access tubes following the American Society for Testing and Materials procedures for neutron probe calibration (ASTM 2016) during the period between February and September 2017 based on the data of only three points. A sleeve was used to keep the probe assembly in the middle during calibration in the 3-inch tube. The regression relationship between the 16-sec neutron count (N_{16}) and the volumetric water content (θ) is:

2-inch Tube $$\theta = -0.0481 + 3.1117 \times 10^{-5} N_{16} \qquad r^2 = 0.9921 \tag{2.1}$$

3-inch Tube $$\theta = -0.0467 + 3.3992 \times 10^{-5} N_{16} \qquad r^2 = 0.9892 \tag{2.2}$$

Due to the lack of an appropriate test facility, the neutron probe has not been calibrated in a 3-inch aluminum tube in sand. However, the lack of the calibration relationship did not affect the neutron logging in the access tube in the sand below the AC of the PHB, but the logging reported in neutron counts cannot be converted into water content. Hence, these loggings are not reported at this time.

To convert and compare the logged neutron counts from different neutron probes, a cross calibration between the two probes was conducted in 11 vertical, 2-inch aluminum tubes and 1 PVC access tube at the Hanford Site in 2011 using neutron probes 5140 and 50200. The neutron counts (N) were reported as 16-sec counts. There were 386 data pairs. The relationship of the neutron counts can be described by:

$$N_{5140} = 1.4806 N_{50200} \quad or \quad N_{50200} = 0.67540 N_{5140} \quad r^2 = 0.9928 \tag{2.3}$$

where N_{5140} and N_{50200} are the 16-sec count from probes 5140 and 50200, respectively.

2.2.2 Tipping Buckets

The volume per tip for each TB was determined following procedure TI-DVZ-AFRI-0022 (*Procedures to determine the volume of a tipping bucket*). The results are summarized in Table 2.1.

Table 2.1. Volume per Tip (V) for the Tipping Buckets

Pronamic		HS	
ID	V (ml)	ID	V (ml)
101	5.0	16-01	39.9
102	5.0	16-02	39.9
103	5.2	16-03	39.3
104	5.5	16-04	40.0
105	5.2	16-05	39.4
106	4.8	16-06	40.0
107	5.4	16-07	40.5
108	5.0	16-08	40.1
109	5.3	16-09	40.1
110	4.8	16-10	40.5
111	5.3	16-11	40.0
112	5.1	16-12	40.2

3.0 Field Activities

This section describes the field activities in FY17.

3.1 Neutron Logging

In FY17, neutron probe logging was conducted approximately quarterly in the silt loam and semi-annually in the sand below the PHB. The functionality of the neutron probe was verified on each logging day before and after the logging.

The logging scheme was essentially the same as used in the past except that (1) the logging was repeated four times on each logging day instead of just once as in the past (from FY95 to FY13), and (2) the horizontal neutron loggings were extended to the side slopes so that the edge effect could be revealed more clearly. The logging scheme with four repetitions provides an opportunity to exclude an outlier from the repetitions. A value off by about 400 (0.012-0.014 m^3m^{-3}) or more for Probe 50200 may be considered as an outlier. Repetitions also provide reassurance when unexpected field processes occur (e.g., very wet or dry condition at just one location).

3.2 Removal of Unused Instruments

The surface and near-surface units of the unused instruments at the 14 monitoring stations were removed in FY17. These instruments included mini-lysimeters, heat dissipation units (HDUs), fiberglass blocks (FGBs), time domain reflectometry (TDR) probes, and capacitance probe access tubes. The holes created by instrument removal were filled with the same silt/pea gravel admix from the soil pile outside of the PHB. To protect the integrity of the surface barrier and minimize the disturbance of the barrier, the wires for HDUs, FGBs, and the TDR probes were cut off approximately 5 cm below ground surface, while the sensors with the rest of the buried wire were left in the soil. For the segmented TDR probes, only the top-most probe of the three-probe profile was removed in each monitoring station; the intermediate and deepest TDR probes (0.6-m-long Type K probe of Environmental Sensors, Inc.) were left in the soil. The instruments left for current or potential future monitoring at each of the 12 monitoring stations (i.e., S1 through S12) in the ETC barrier are a neutron access tube and a root observation tube.

Off the barrier surface, the surface units for the pan lysimeter (Figure 2.1; installed below the AC before barrier construction) were removed, while the buried wires, pipes, and pan lysimeter were left in place. The old TBs, pressure transducers, and top portion of the siphon systems installed in the 12 drainage vaults were removed.

3.3 Runoff Monitoring System Checkup

The runoff monitoring system was found to be nonfunctional in FY17 because the battery was dead. Additionally, the pipe that guides the runoff to the monitoring station was broken. The system will be repaired in FY18 as planned.

4.0 Monitoring Results

This section presents the climate conditions and the hydrological monitoring results.

4.1 Climate Conditions

Precipitation was categorized with the standardized precipitation index (SPI) developed by McKee et al. (1993). The SPI is a probability index defined as the standard normal random variable (with mean $\mu = 0$ and standard deviation $\sigma = 1$) obtained from the cumulative probability. The nature of the SPI allows the quantification of an anomalously dry or wet event at a particular time (t) scale. According to the SPI values, McKee et al. (1995) categorized the precipitation of a given period into seven classes:

1. extreme wet (SPI > 2)
2. severe wet (1.5 < SPI ≤ 2)
3. moderate wet (1 < SPI ≤ 1.5)
4. near normal (-1 < SPI ≤ 1)
5. moderate dry (-1.5 < SPI ≤ -1)
6. severe dry (-1 < SPI ≤ -1.5) and
7. extreme dry (SPI ≤ -2)

The Hanford Site has a steppe (semi-arid) climate with typical dry hot summers and cool wet winters (Hoitink et al. 2005). Under the Hanford climate, the most likely season for recharge is between November and March (termed the winter season), when ET is low (Gee et al. 1992; Gee et al. 2005). In addition to winter rains, snowmelt can be an important contributor to recharge. To be consistent with the precipitation pattern, a water year (WY) is defined as the 12-month period from November of previous year to October of current year. As such, a WY consists of a 5-month winter season and a 7-month summer season.

The WY meteoric precipitation at the Hanford Site has an average, P^{avg}, of 171.9 mm (WY48 to WY17) and varies from 101.3 to 293.6 mm. On average, 58.8% (101.2 mm) of the precipitation falls in the winter season and 41.2% (70.8 mm) falls in the summer season. The average snowfall for the past 62 years (1946-2017) with records is 361 mm. The maximum ever recorded in one winter was 1424.9 mm, which fell in the winter of 1992-1993.

Because some of the precipitation stored during WY16 could still reside in the soil by the end of WY16, the precipitation for both WY16 and WY17 is described here. The monthly precipitation for WY16 and WY 17 and the multi-year (WY48-WY17) average are shown in Figure 4.1.

Based on the monitoring data from WY95 to WY13 (DOE-RL 2016), winter-season precipitation has the greatest potential to increase ETC barrier water storage, which could potentially lead to drainage if the soil water storage is above the storage capacity. In WY17, the total precipitation was 195.3 mm, of which

128.0 mm fell in the winter season and 67.3 mm in the summer season. These precipitation amounts corresponded to SPIs of 0.587, 0.807, and 0.015, respectively, and all were categorized as "near normal". It is noted that the precipitation of 65.8 mm in October 2016 is 4.8 times the average precipitation of the month (13.8, mm, Figure 4.1).

In WY17, the first snowfall was on December 4, 2016, and the last was on February 26, 2017, for a period of 85 days. During this period, the total snowfall was 711 mm, which is equivalent to 54.4 mm of precipitation and is nearly double the average snowfall of 361 mm.

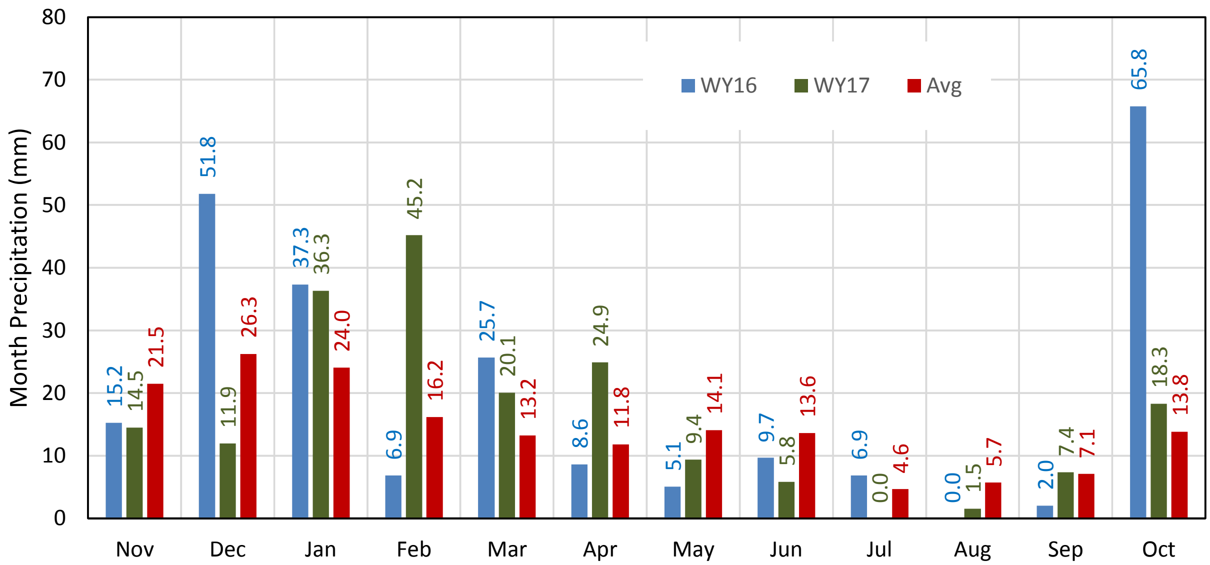


Figure 4.1. Monthly precipitation of WY16, WY17 and multi-year (WY48-WY17) average.

4.2 Soil Water Process in the Silt Loam Storage Layer

Figure 4.2 shows the neutron-probe-measured soil moisture profiles for the 12 monitoring stations in the ETC barrier. Figure 4.3 shows the soil moisture contour of the north (S1 through S6) and south (S7 through S12) cross-sections in the ETC barrier. In November 2016 (Figure 4.2a, Figure 4.3a), the soil profile approximately below 0.6-m depth had very low water content (<0.07 m^3m^{-3}). This was because the stored water had been consumed by the vegetation or evaporation in the previous summer. The soil above 0.6-m depth was wetter because of the unusually high rainfall (Figure 4.1) not long before the November logging.

The precipitation during the winter season of WY17 recharged the ETC barrier (Figure 4.2b, Figure 4.3b). In late March of 2017, the wetting front depth ranged from about 0.8 m (at S3) to about 1.6 m (at S12) among the 12 monitoring stations. Three of the stations (S7, S10, and S12), all in the south section (Figure 2.1), showed much larger depth (about 1.4 to 1.6 m) of wetting front than the rest (about 0.8 to 1.2 m), indicating that the infiltration water did not reach the bottom of the ETC barrier. The main difference between the north and south sections is that the vegetation in the north is dominated by grasses while that in the south is dominated by shrubs (DOE-RL 2016). Some roots of the shrubs in the south section might have created preferential flow channels. Another possibility for the observation is that a shrub community may not have as laterally extensive a root system as a grass community. To date, we have observed neither preferential channels nor the uneven distribution of the roots. However, at any of the monitoring stations, infiltration water had not reached the bottom of the ETC barrier.

By June 2017 (Figure 4.2c, Figure 4.3c), the majority of the stored water in the soil had been released back to the atmosphere by ET. The only exception is S7, in which there was still some plant-available water in the soil of approximately 1.2 to 1.7 m depth. The reason for this exception is not clear. It could be that the vegetation at this location might not grow well.

By September 2017 (Figure 4.2d, Figure 4.3d), nearly all of the mobile water and even some immobile water in the shallow (approximately 0 to 0.3 m) soil had been released to the atmosphere by ET. The soil water content was no more than 0.07 m^3m^{-3} for all the stations. The soil water content at 0.15-m depth was between 0 and 0.02 m^3m^{-3}, indicating that some immobile water was removed from surface soil, probably by evaporation during the hot summer.

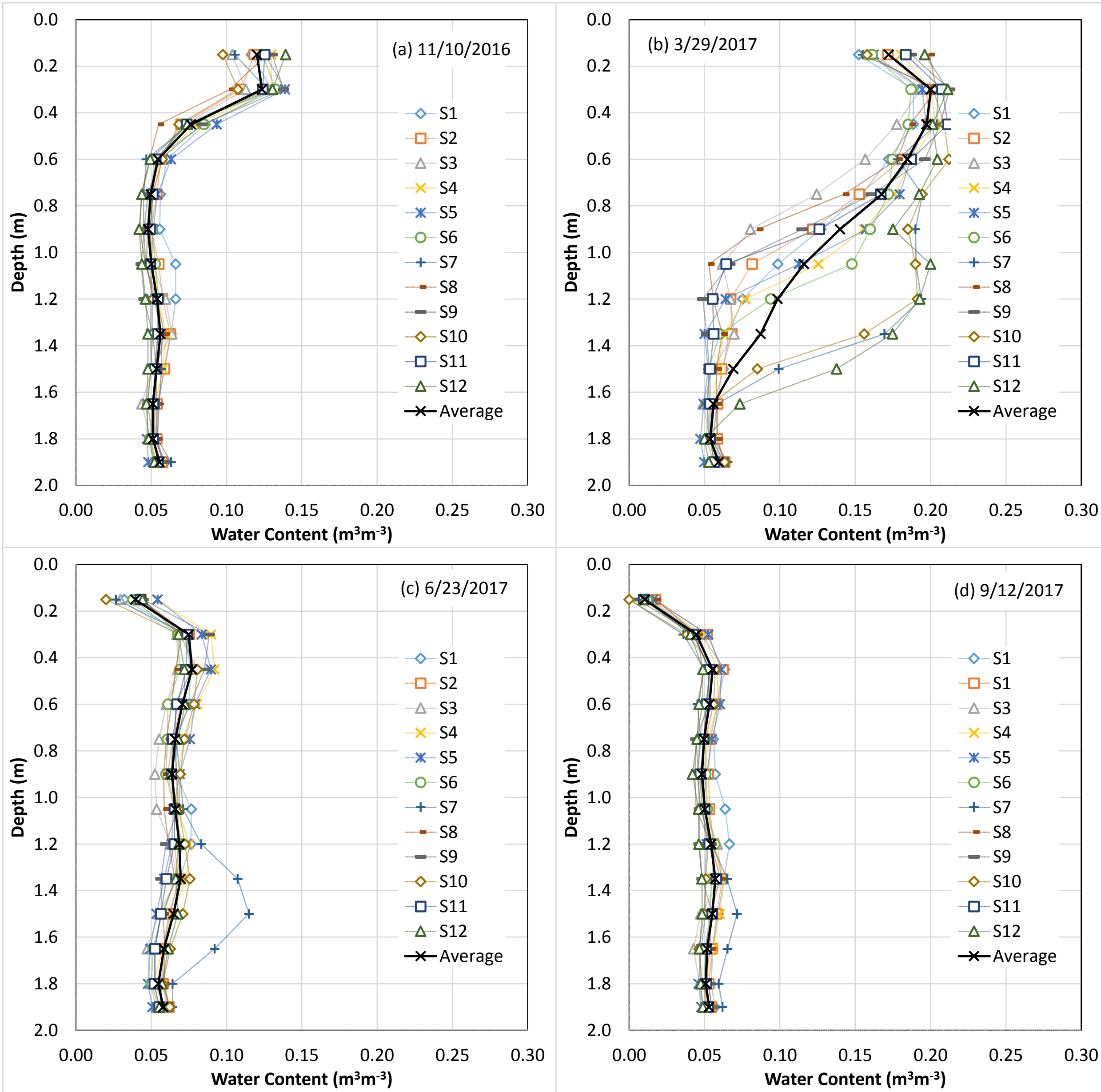
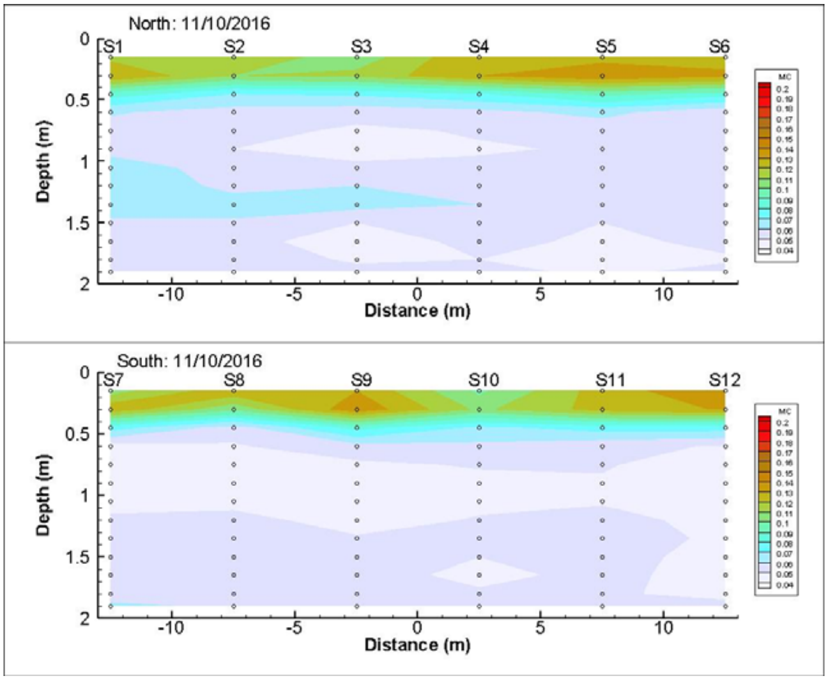
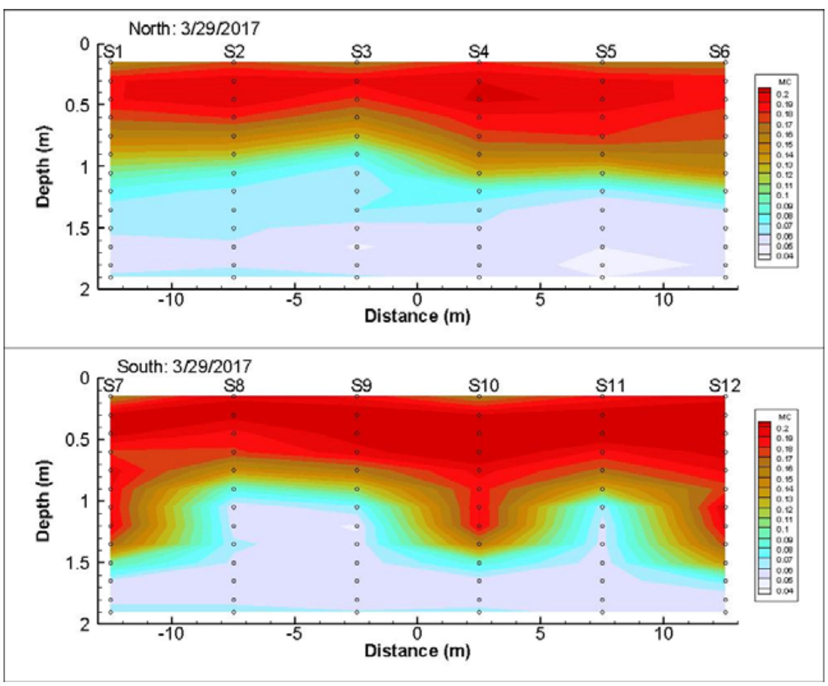


Figure 4.2. Water content profiles in the silt loam of the ETC barrier.

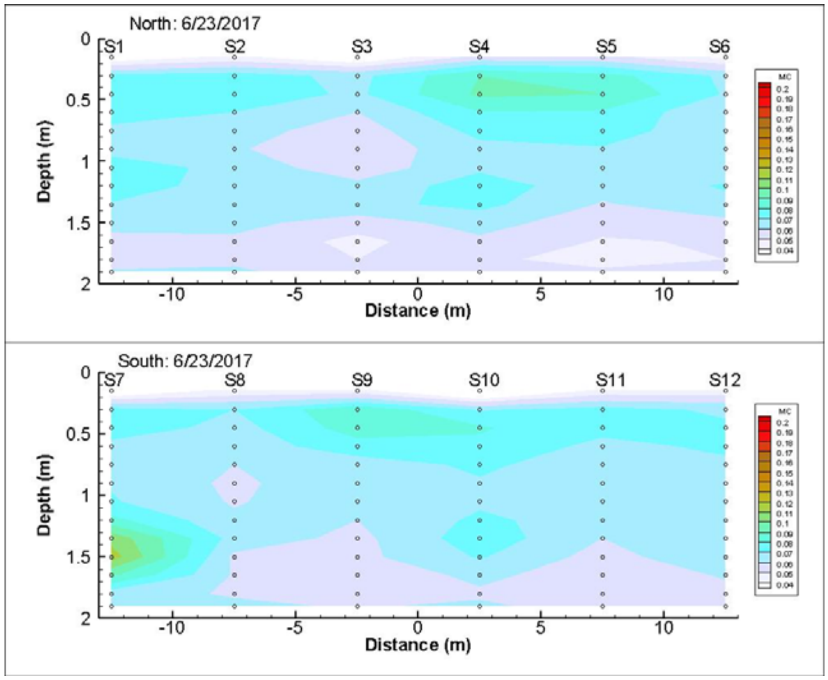


(a)

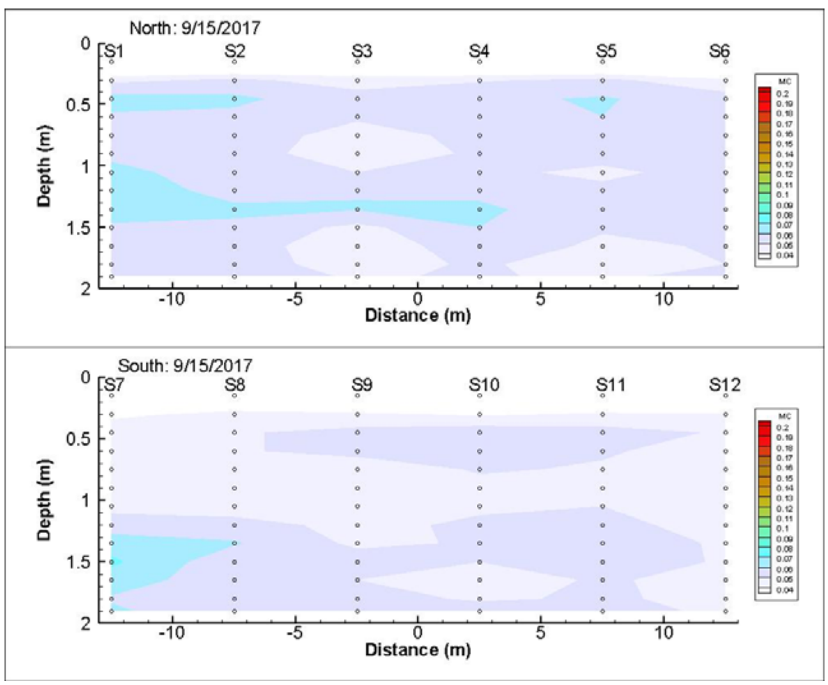


(b)

Figure 4.3. Soil moisture contour of the north and south cross-sections in the silt loam of the ETC barrier at different times.



(c)



(d)

Figure 4.3. Soil moisture contour of the north and south cross-sections in the silt loam of the ETC barrier at different times (cont.)

4.3 Water Balance

Four vertical neutron logging campaigns were conducted in FY17. Hence, water balance was calculated for three periods based on these loggings. Assuming water flow in the barrier soil is vertical only, ET can be estimated based on the mass balance equation:

$$ET = P - R - D - \Delta W \quad (4.1)$$

where P is precipitation, R is runoff (when positive) or run-on (when negative), D is drainage, and ΔW is change in water storage at each monitoring station.

In FY17, the old drainage monitoring system was being replaced by the new DTB system and hence no drainage data were obtained. The soil water dynamics described in the previous section indicated that there was very little chance for drainage to occur from the ETC barrier. Hence, D = 0 was assumed in water balance calculation. Based on the runoff data from 1994 to 2013 (DOE-RL 2016; Zhang 2016), runoff on the PHB is usually negligible but could happen when melted snow flows on frozen soil. Some of the snowmelt might flow from one location to another within the ETC barrier before it infiltrates to the subsoil. Calculated ET using Eq. (4.1) would be overestimated when within-the-barrier runoff happened and underestimated when within-the-barrier run-on happened.

At the PHB, R is not monitored for each of the monitoring stations but for only one separate flume (Figure 2.1). Rearranging terms in Eq. (4.1) and assuming D = 0 yields:

$$ETR = ET + R = P - \Delta W \quad (4.2)$$

where ETR is the combined ET and runoff/run. ET can only take non-negative values, but R can be positive (for runoff) and negative (for run-on). Theoretically, when ETR is negative, R must be negative because ET is always non-negative, suggesting that within-the-barrier run-on has happened. However, when ETR is positive, the results cannot tell if runoff or run-on has happened. In reality, measurement error in water storage could also lead to a negative ETR.

The Winter Season

From November 10, 2016, to March 29, 2017, precipitation was 126.2 mm, of which an average of 117.6 mm was stored in the ETC barrier and 8.6 mm was lost via ET or runoff (Table 4.1).

However, the water storage gain varied between 79.4 and 191.8 mm. In three stations (S7, S10, and S12), the water storage gains (173.1, 180.4, and 191.8 mm, respectively) were considerably more than the precipitation of 126.2 mm during this period. Hence, the ETR is negative [-46.9 mm in S7, -54.2 mm in S10, and -65.6 mm in S12 (Table 4.1), with an average of -55.6 mm]. These results suggest that within-the-barrier runoff and run-on on frozen soil covered with snow with the ETC barrier could have occurred during the winter season of WY17. Alternatively, the measurement of precipitation and water storage could have been imprecise.

The Summer Season

From March 29 to September 12, the soil at all the stations was losing water via ET. The ETC barrier lost an average of 157.3 (= 125.5 + 31.8) mm of stored water and 41.1 (= 39.6 + 1.5) mm of precipitation during this period (Table 4.1). The total amount of water lost to the atmosphere via ET was 198.4 (165.1 + 33.3) mm on average (assuming no runoff/run-on occurring during this period). This amount is comparable to the total precipitation of 195.3 mm in FY17.

Water storage in the 2-m-thick ETC barrier is shown in Figure 4.4 for the 12 monitoring stations located on the ETC barrier. The largest observed storage was 323 mm (on March 29, 2017, in S12); that is, about 51% of the available storage capacity (402 mm) was filled. Taking an average over all 12 monitoring stations, the water storage in late March was 252 mm; in other words, 34% of the available storage capacity was filled. These results show that only up to about half of the available storage capacity was used in the winter season of FY17, indicating very little chance for drainage to occur from the ETC barrier.

When treating the ETC barrier as a whole based on the average values, assuming that there was no water flow out of the ETC barrier, according to Eq. (4.2), the ET for each period can be calculated as the difference between P and ΔW, i.e., ET = P-ΔW. On average, the ET was 8.6 mm between November 10 and March 29, very low during this cold period of over 4 months; the ET was 165.1 mm from March 29 to June 23, and nearly all the available water in the ETC barrier was released during this period; and the ET was 39.3 mm from June 23 to September 12 (Table 4.1). Because of the hot and dry summer in 2017, the 2-m water storage in the middle of September was low at an average of 95 mm (ranging between 84 and 106 mm), which is lower than the residual water storage of 116 mm (Zhang 2015).

Table 4.1. Water Balance at the Monitoring Stations

	11/10 to 3/29			3/29 to 6/23			6/23 to 9/12		
Station	P	ΔW	ETR = P - ΔW	P	ΔW	ETR = P - ΔW	P	ΔW	ETR = P - ΔW
S1	126.2	82.7	43.5	39.6	-100.7	140.3	1.5	-21.8	23.3
S2	126.2	97.8	28.4	39.6	-107.5	147.1	1.5	-23.1	24.6
S3	126.2	79.4	46.8	39.6	-98.2	137.8	1.5	-17.5	19.0
S4	126.2	111.3	14.9	39.6	-113.4	153.0	1.5	-37.3	38.8
S5	126.2	97.9	28.3	39.6	-107.7	147.3	1.5	-32.8	34.3
S6	126.2	106.2	20.0	39.6	-126.6	166.2	1.5	-23.0	24.5
S7	126.2	173.1	-46.9	39.6	-157.4	197.0	1.5	-50.8	52.3
S8	126.2	96.3	29.9	39.6	-104.4	144.0	1.5	-27.2	28.7
S9	126.2	95.3	30.9	39.6	-105.7	145.3	1.5	-37.7	39.2
S10	126.2	180.4	-54.2	39.6	-174.9	214.5	1.5	-40.3	41.8
S11	126.2	99.1	27.1	39.6	-113.3	152.9	1.5	-27.5	29.0
S12	126.2	191.8	-65.6	39.6	-196.2	235.8	1.5	-42.3	43.8
Avg	**126.2**	**117.6**	**8.6**	**39.6**	**-125.5**	**165.1**	**1.5**	**-31.8**	**33.3**

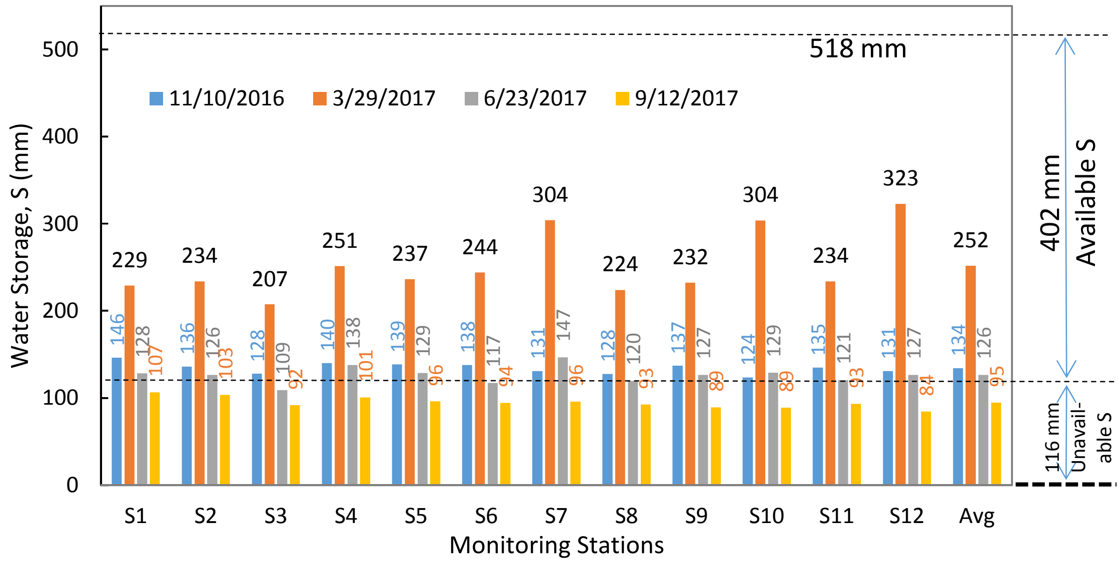


Figure 4.4. The 2-m soil water storage at the 12 monitoring stations in the ETC barrier. The two dashed lines show the storage capacity (518 mm, Section 3.1.2 of DOE-RL 2016) and the residual water storage (116 mm, Zhang 2015) of the silt loam barrier. The labels above the bars are the measured water storage at each station. S: 2-m soil water storage.

4.4 Water Content near the Bottom of the Silt Loam Layer

Figure 4.5 shows the observed soil water content along four horizontal lines near the bottom the silt loam layer within the ETC barrier and across the ETC barrier edges (i.e., AA1-AA5 and AA2-AA6 in the north section; AA3-AA7 and AA4-AA8 in the south section; Figure 2.2). The water content at the side slopes stayed low (approximately between 0.01 and 0.02 m^3m^{-3}) all year round because of the coarse property of the materials.

Near the bottom of the silt loam layer, between x = -15 and x = 14 m (Figure 4.5), the water content all year round ranged between 0.046 and 0.067 m^3m^{-3} with an average of 0.054 m^3m^{-3}. This average is slightly less than the minimum water content of 0.058 m^3m^{-3} observed in the past (Zhang 2015), indicating that there was near zero available water for plant use and near zero mobile water content.

In March (Figure 4.5b) and June (Figure 4.5c) 2017, the water content near the bottom of the silt loam layer stayed low, with a few exceptions near the edges of the ETC barrier. Near the west edge of the ETC barrier (at x = -16 and -17 m), the water content in AA1was as high as 0.263 m^3m^{-3} in March and was slightly lower (0.191 m^3m^{-3}) in June. Near the east edge of the ETC barrier (at x = 15 m), water content in AA6 also increased, to 0.134 m^3m^{-3} in March and 0.151 m^3m^{-3} in June. By the end of the summer season, this water had been removed from the soil by ET (Figure 4.5d). These results indicate that, during the winter season, precipitation or snowmelt infiltrated to the bottom of the silt loam layer at some locations near the edges of the ETC barrier. This deep infiltration appeared only at a couple (i.e., AA1 and AA6) of the access tubes. Recall that the wetting front did not reach the bottom of the ETC barrier at any of the monitoring locations (S1 through S12). These differences could be due to the combined effects of surface flow from the pavement around the ETC barrier and the multi-dimensional flow near the slanted silt loam-sand interface at the side boundaries of the ETC barrier. (The ETC barrier has shape of an inverted isosceles trapezoid, Figure 1.2a.) Hence, the infiltration above the side boundary would converge and hence could reach a larger depth. This phenomenon was observed during the enhanced precipitation test from WY95 to WY97 (DOE-RL 2016). However, it was not observed under natural precipitation conditions during the period from the late WY98 to WY13.

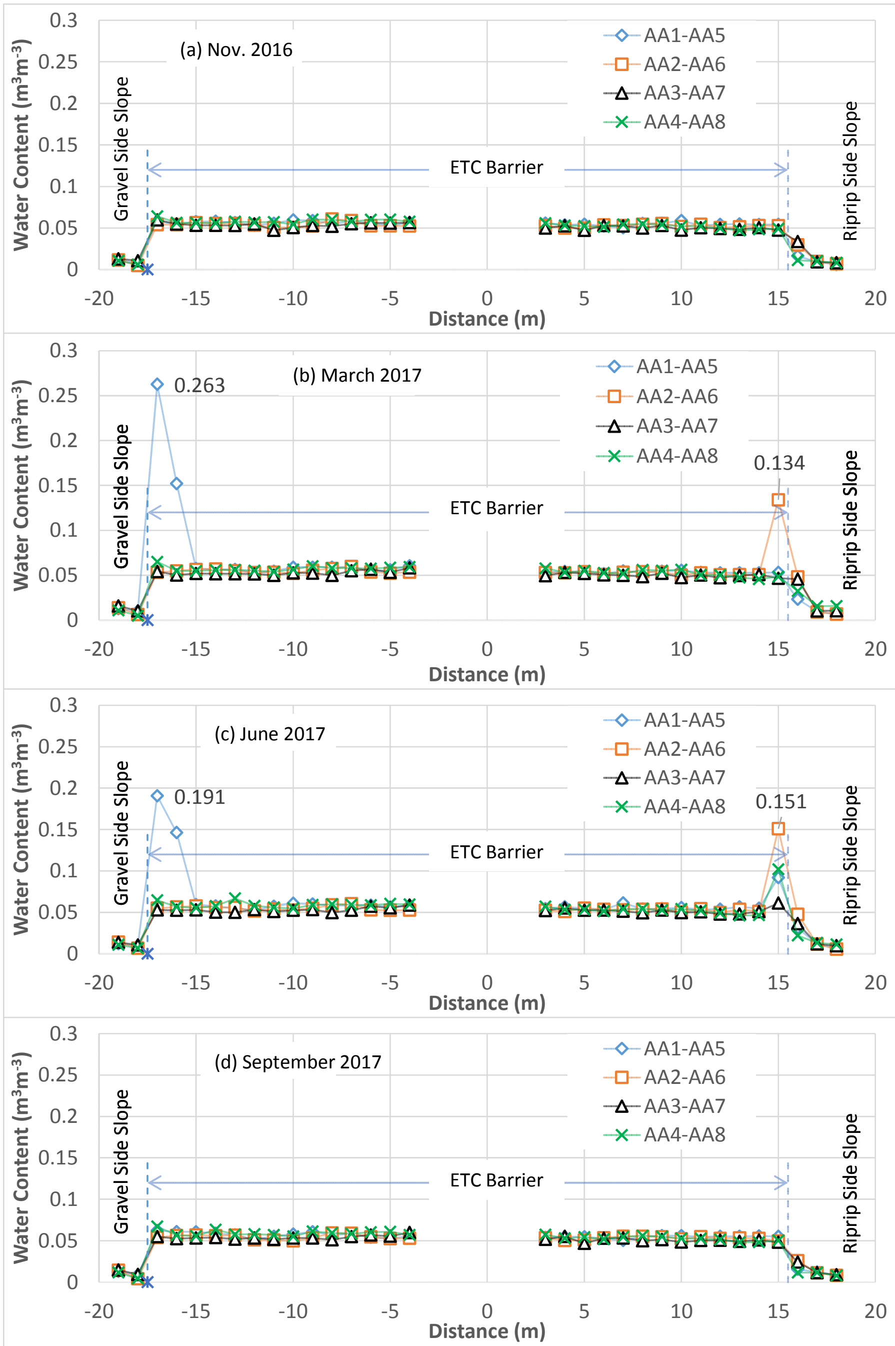


Figure 4.5. Soil water content along four horizontal lines 1.85 m below ground surface (0.15 m above the silt loam/sand capillary break). The approximate locations of the west and east edges of the ETC barrier are marked by vertical dashed lines.

5.0 Quality Assurance

The results presented in this report originate from work governed by the Pacific Northwest National Laboratory Nuclear Quality Assurance Program (NQAP). The NQAP implements the requirements of U.S. Department of Energy Order 414.1D, *Quality Assurance*, and 10 CFR 830 Subpart A*, Quality Assurance Requirements*. The NQAP uses ASME NQA-1-2012, *Quality Assurance Requirements for Nuclear Facility Applications*, as its consensus standard and NQA-1-2012 Subpart 4.2.1 as the basis for its graded approach to quality.

Two quality grading levels are defined by the NQAP:

Basic Research - The required degree of formality and level of work control is limited. However, sufficient documentation is retained to allow the research to be performed again without recourse to the original researcher(s). The documentation is also reviewed by a technically competent individual other than the originator.

Not Basic Research - The level of work control is greater than basic research. Approved plans and procedures govern the research, software is qualified, calculations are documented and reviewed, externally sourced data is evaluated, and measuring instrumentation is calibrated. Sufficient documentation is retained to allow the research to be performed again without recourse to the original researcher(s). The documentation is also reviewed by a technically competent individual other than the originator.

The work supporting the results presented in this report was performed in accordance with the *Not Basic Research* grading level controls.

6.0 Summary

In WY17, the total precipitation was 195.3 mm, of which 128.0 mm fell in the winter season and 67.3 mm in the summer season. These precipitation levels correspond to SPIs of 0.587, 0.807, and 0.015, respectively, and all were categorized as "near normal". The snowfall of 711 mm was nearly double the average snowfall of 361 mm.

From November 10, 2016, to March 29, 2017, there was a precipitation of 126.2 mm, of which an average of 117.6 mm (93%) was stored in the ETC barrier and 8.6 mm was lost either via ET or runoff. In late March of 2017, the wetting front depth ranged between about 0.8 m (at S3) to 1.6 m (at S12) among the 12 monitoring stations, indicating that the infiltration water did not reach the bottom of the ETC barrier. Only up to about half of the available storage capacity was used in winter season of WY17.

From March 29 to September 12, the soil at the ETC barrier was losing water via ET. The total amount of water lost to the atmosphere via ET was 198.4 mm on average. This amount is comparable to the total precipitation of 195.3 mm in WY17. Near the end of the summer season, the 2-m water storage in the middle of September was low at an average of 95 mm, which is lower than the residual water storage of 116 mm.

Near the bottom of the silt loam layer, about 2 m inside from the side boundary, the water content all year round ranged between 0.046 and 0.067 m^3m^{-3}, with an average of 0.054 m^3m^{-3}, which is slightly less than the minimum water content of 0.058 m^3m^{-3} observed in the past, indicating that there was a near zero available water for plant use and a near zero mobile water content. However, during the winter season, precipitation or snowmelt infiltrated to the bottom of the silt loam layer at some locations near the edges of the ETC barrier. This water was removed from the soil after the summer.

The monitoring period extended to 23 years by FY17. The WY17 weather was normal, but there was higher-than-usual snowfall. The barrier response was normal and there was no indication of drainage from the ETC barrier.

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