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Soil Water Balance and Recharge Monitoring at the Hanford Site – FY09 Status Report

ML Rockhold
DL Saunders
CE Strickland
SR Waichler
RE Clayton

September 2009

Pacific Northwest NATIONAL LABORATORY

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Richland, Washington 99352

Abstract

Recharge provides the primary driving force for transporting contaminants from the vadose zone to underlying aquifer systems. Quantification of recharge rates is important for assessing contaminant transport and fate and for evaluating remediation alternatives. This report describes the status of soil water balance and recharge monitoring performed by Pacific Northwest National Laboratory at the Hanford Site for Fiscal Year 2009. Previously reported data for Fiscal Years 2004 - 2008 are updated with data collected in Fiscal Year 2009 and summarized.

Summary

Recharge provides a driving force for transporting contaminants from the vadose zone to underlying aquifer systems. Quantification of recharge rates is therefore important to support calculations of contaminant transport and fate and for design and evaluation of remedial action alternatives. Recharge rates depend on three main factors - soil, vegetation, and climatic conditions – that are highly variable in both space and time. This report reviews the methods that are used for estimating recharge rates and summarizes field soil water balance and recharge data collection efforts for Fiscal Year 2009 at the U.S. Department of Energy's Hanford Site in southeast Washington State. Data for Fiscal Years 2004 through 2009 for various soil and surface covers found and planned in the 200 West and 200 East Areas of the Hanford Site are also presented. In addition, the report provides a summary of weather data collected from the Hanford Meteorological Station from 1957 through 2008. Recharge rates at Hanford are shown to vary from near zero for finer-textured soils (e.g. silt loam) and deeper rooted vegetation (e.g., sagebrush) up to greater than 86 mm yr^{-1} for coarse-textured and unvegetated sediments (e.g., gravel-covered surfaces at tank farms). Continued and uninterrupted monitoring is needed to provide long-term continuity of recharge records to assess the variability and uncertainty of recharge rates.

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Acronyms and Abbreviations

bgs	below ground surface
CHPRC	CH2M-Hill Plateau Remediation Company
DOE	U.S. Department of Energy
FHI	Fluor Hanford, Inc.
FFTF	Fast Flux Test Facility
FLTF	Field Lysimeter Test Facility
FY	Fiscal Year (October 1 to September 30)
HMS	Hanford Meteorological Station
IDF	Integrated Disposal Facility
PNNL	Pacific Northwest National Laboratory
RACS	Remediation And Closure Science (Project)
RDS	Remediation Decision Support (Project)
SWL	solid waste landfill
WFM	water flux meter

Contents

Abstract iii
Summary v
Acknowledgments vii
Acronyms and Abbreviations ix
1.0 Introduction 1.1
2.0 Recharge Estimation 2.1
2.1 Definition 2.1
2.2 Importance 2.1
2.3 Influencing Factors 2.1
2.4 Estimation Methods 2.2
2.4.1 Physical 2.2
2.4.2 Tracers 2.3
2.4.3 Numerical Modeling 2.6
3.0 Brief History of Recharge Investigations at Hanford 3.1
4.0 Hanford Climate Summary 4.1
4.1 Climate and Meteorology 4.1
4.1.1 Precipitation 4.1
4.1.2 Air Temperature 4.2
4.1.3 Humidity 4.2
4.1.4 Solar Radiation 4.3
4.1.5 Wind 4.3
4.2 Long-Term Weather and Climate at HMS 4.3
4.2.1 Data Processing 4.4
4.2.2 Results 4.5
5.0 Recharge Data Collected in FY 2004-2009 ..... 5.1
5.1 Grass Site 5.2
5.2 300N Lysimeter 5.4
5.3 Solid Waste Landfill (SWL) 5.10
5.3.1 Vegetation Characterization 5.13
5.4 Integrated Disposal Facility (IDF) 5.14
5.5 Field Lysimeter Test Facility (FLTF) 5.15
5.6 Field Lysimeter Test Facility (FLTF) Pit 5.29
5.7 Tank Farms 5.32
5.8 200 East Lysimeter 5.32
6.0 Conclusions 6.1
7.0 References 7.1

Figures

2.1 Schematic of Installed Vadose Zone Water Fluxmeter With Diversion Control 2.4
4.1 Annual Timeseries of HMS Weather Variables and Local Regression Lines 4.6
4.2 HMS Weather Data Averaged Over Three-Year Periods 4.7
4.3 Windrose Plots Showing Prevalence of Wind Direction at HMS, Based on Counts of Wind Direction in 22.5-Degree Sectors 4.8
4.4 Windrose Plots Based on Means of Wind Speed in Each 22.5-Degree Sector for HMS Data ... 4.9
4.5 Monthly Mean Temperature by Year Measured at the HMS, with Loess Lines 4.10
4.6 Seasonal Loess Applied to Mean Monthly Temperature at the HMS 4.11
4.7 Seasonal Loess Applied to Precipitation Measured at the HMS 4.12
5.1 Location of Recharge Monitoring Stations at the Hanford Site 5.1
5.2 Surface Conditions on the Water Flux Meters at the Grass Site in Autumn 2006 ..... 5.3
5.3 Volumetric Water Content Measured at 30 and 60 cm Below Ground Surface at the Grass Site. 5.3
5.4 Cumulative Drainage Measured at the Grass Site Using Water Flux Meters. 5.4
5.5 Surface Conditions of 300N Lysimeter Site on September 13, 2007 ..... 5.6
5.6 Cumulative Drainage Measured Since 1981 from the South Caisson at the 300N Lysimeter Site 5.7
5.7 300N Lysimeter Water Contents Measured at 0.3, 0.6, and 0.9 m Below Ground Surface 5.7
5.8 300N Lysimeter Matric Potentials Measured at Six Depths. 5.8
5.9 300N Lysimeter Cone Penetrometer Tensiometer Matric Potentials Measured Outside of the South Caisson at 7.5 m Below Ground Surface. 5.9
5.10 WFM Material at the Hanford SWL 5.10
5.11 SWL Basin Lysimeter 5.11
5.12 Volumetric Water Contents Measured at the SWL Site at 30, 60, and 90 cm Below Ground Surface 5.12
5.13 Cumulative Drainage Measured at the SWL Using Water Flux Meters Since December 21, 2004. ..... 5.13
5.14 Cumulative Drainage Measured at the SWL from the Basin Lysimeter Since July 1, 1996. ..... 5.14
5.15 Artist's Rendering of the FLTF at the Hanford Site. 5.16
5.16 FLTF-Precipitation Plus Irrigation Water Year 2004 ..... 5.19
5.17 FLTF Precipitation Plus Irrigation Water Year 2005 ..... 5.19
5.18 FLTF Precipitation Plus Irrigation Water Year 2006 ..... 5.20
5.19 FLTF Precipitation Plus Irrigation Water Year 2007 ..... 5.20
5.20 FLTF Precipitation Plus Irrigation Water Year 2008 ..... 5.21
5.21 FLTF Irrigation Plus Precipitation Water Year 2009 ..... 5.21
5.22 FLTF Cumulative Drainage for FLTF Treatments D5 and D12 Representing a Hanford Barrier Dune Sand Deposition Test. R is the mean annual drainage rate. 5.22

5.23 Cumulative Drainage for FLTF Treatments D6 and D8 Representing a Sand Dune Migration Test. R is mean annual drainage rate. 5.23
5.24 Cumulative Drainage for FLTF Treatments D2 and D4 Representing a Barrier Side Slope Test. R is the mean annual drainage rate. 5.23
5.25 Cumulative Drainage for FLTF Treatment D13 Representing an Eroded Prototype Hanford Barrier Test. R is the mean annual drainage rate. 5.24
5.26 Cumulative Drainage for FLTF Treatments C1, C2, C4, and C5. ..... 5.24
5.27 Changes in water storage for weighing lysimeters W1 and W3 at the FLTF. 5.26
5.28 FLTF Matric Potentials for Hanford Barrier Erosion/Dune Sand Deposition Test at 100 cm Depth. 5.27
5.29 FLTF Matric Potentials for Hanford Barrier Erosion/Dune Sand Deposition Test at 150 cm Depth. 5.28
5.30 FLTF Matric Potentials for Sand Dune Migration Test. 5.28
5.31 Cumulative Drainage Measured at the FLTF Pit Using Water Flux Meters for Silt Loam, Sand, and Gravel Treatments. 5.31
5.32 Cumulative Drainage Measured at the FLTF Pit Using Water Flux Meters for Road Base/Silt Loam, Sand/Silt Loam, and Road Base Treatments. 5.31

Tables

4.1 Monthly Precipitation Variations Between 1947 and 2008 at the Hanford Meteorological Station 4.2
4.2 Monthly Air Temperature Variations Between 1945 and 2008 at the Hanford Meteorological Station 4.3
5.1 Monitoring Sites, Activities, and Periods 5.2
5.2 Summary of FLTF Treatments and Monitoring Period 5.17
5.3 FLTF Treatment Descriptions 5.18
5.4 Summary of FLTF Drainage Rates Though August 20th, 2009 ..... 5.25
5.5 Chloride Concentrations Measured in FLTF Lysimeter Drainage Waters. 5.29
5.6 FLTF Pit WFM Treatments, Monitoring Periods, and Average Drainage Rates. All WFM surfaces in the FLTF pit are unvegetated. 5.30

1.0 Introduction

Recharge rates are used as boundary conditions for vadose zone and groundwater flow and transport models used to assess the risk associated with subsurface contamination and the potential effectiveness of remediation alternatives. Recharge is therefore an important quantity to characterize for studies, simulations, and evaluations of waste disposal practices at the Hanford Site. The basis for estimating recharge includes substantial fieldwork and data collection from monitoring sites at Hanford.

Pacific Northwest National Laboratory (PNNL) assembled this report for CH2M-Hill Plateau Remediation Company (CHPRC) as part of the Remediation and Closure Science Project (RACS). The RACS project provides scientific and technical support for waste management and cleanup efforts at the U.S. Department of Energy's (DOE) Hanford Site. The purpose of this report is to update field soil water balance and recharge data, previously reported for monitoring activities in Fiscal Years (FY) 2004 through 2008, with data collected in FY2009.

The most robust estimates of Hanford recharge rates are those that are derived from water balance measurements under Hanford Site soil and climatic conditions. Water balance measurements include direct measurements of drainage and measurements of related variables such as soil water content and soil matric potential. Previously published recharge data packages provide reasonable estimates of site-wide recharge for some soil conditions, but continued monitoring of drainage over a wider range of climate variables (i.e., more extremes in precipitation and temperatures), soil/surface barrier conditions, and over longer time periods serves to refine and improve the defensibility of recharge estimates. For low-drainage conditions, such as those typical of Hanford conditions, these measurements may be required over time scales of decades, or longer, in order to obtain reliable measurements. Significant interruptions in data continuity or site maintenance in these conditions adversely impacts data integrity and thereby reduces the defensibility of recharge estimates derived from those data. This report is produced specifically to document additional data collected in recent years in a citable form, and to use those data to refine recharge estimates.

The scope of this report is limited in the following respects:

- Emphasis is on the 200 East and 200 West Areas of the Hanford Site
- Presents recharge data collected in FY 2004 through FY 2009

This report includes an overview of the parameterization of recharge (Section 2), identification of previously published recharge data (Section 3), presentation of previously published data and new data from FY09 (Section 4), discussion of knowledge gaps (Section 5), and conclusions (Section 6). Portions of this report were taken from Nichols et al. (2008) and updated where appropriate.

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2.0 Recharge Estimation

2.1 Definition

Recharge is defined as the flux of water transmitted across the water table from the vadose zone to the saturated zone. Direct measurement of recharge at the water table is usually impractical due to the inaccessibility, especially at Hanford where the water table is commonly located at depths below ground surface (bgs) of 80 meters or more. The influence of aquifer-influencing operations, such as artificial discharges or remediation pump and treat systems, would further complicate efforts at making a direct measurement for a deep water table. Instead, measurements and analyses in the unsaturated zone at shallow depths are used to characterize deep drainage, that is, the water flux leaving the depth below which the processes of evaporation and transpiration can return water from the unsaturated soil to the atmosphere. This deep drainage, with sufficient time, will be manifest as the recharge flux. The time required will depend on the thickness and hydraulic properties of the vadose zone and the deep drainage rate itself. Changes in the deep drainage rate, such as would result from changes in surface vegetative conditions that increase or decrease the evapotranspiration rate, can take many years to be reflected in the recharge rate for a thick vadose zone in arid conditions such as at the Hanford Site and can be an important consideration in characterizing recharge as well (Nichols et al. 2007).

2.2 Importance

Recharge is the primary mechanism for transporting contaminants from the vadose zone to groundwater. Bacon and McGrail (2002) demonstrated this by showing the sensitivity of buried immobilized low-activity waste (ILAW) glass release and transport to recharge. Their evaluation of the release of technetium-99 from the ILAW glass for five recharge rates revealed that the technetium-99 flux beneath the ILAW disposal zone is more sensitive to the recharge rate than to any other parameter for recharge rates below 10 mm/yr. Recharge rates in this range are common for natural vegetation and soil conditions at Hanford. Such a high sensitivity of waste disposal performance to recharge rate underscores the need to characterize this parameter as accurately as possible.

2.3 Influencing Factors

Important physical properties and processes that influence recharge include climate, soil hydraulic properties and stratigraphy, vegetative cover, land use, and topography. Climate determines the driving forces for recharge, namely the quantity of precipitation available for the land surface water balance, and the energy fluxes that determine the partitioning of precipitation into evaporation, transpiration, and recharge. Soil hydraulic properties and stratigraphy determine the rate at which water is transmitted through the vadose zone, and hence it's resident time for processes of evaporation and transpiration. Vegetative cover determines the strength of the transpiration portion of the land surface water balance. Land use will change other influencing factors by altering the surface soils and hence the hydraulic properties and soil stratigraphy of a site, and the vegetative cover and hence transpiration rates.

Topography influences the portion of precipitation that is subject to overland flow, either "run-on" or "run-off", for a given site. Knowledge of all of these influences is important to the estimation of recharge at a given location.

2.4 Estimation Methods

Recharge rates at the Hanford Site can range from near zero to more than 100 mm/yr (Gee et al. 1992). Measuring a parameter that varies over such a large range requires use of complementary methods. An excellent overview of recharge estimation techniques is provided in Scanlon et al. (2002). The methods in use at the Hanford Site include physical techniques (water balance, lysimetry), tracer techniques (chloride, isotopes), and numerical techniques (computer simulation). These are other methods are discussed at length relative to arid climates such as that at Hanford in the January-February 1994 issue of the *Soil Science Society of American Journal*, which contains a series of papers that were presented at a symposium titled "Recharge in Arid and Semiarid Regions." A brief overview of each technique in use at the Hanford Site is provided here for reference purposes.

2.4.1 Physical

Physical methods attempt to calculate recharge as a residual after measuring other terms (precipitation, evaporation, transpiration, runoff, storage) in the land surface water budget (water balance technique) or directly measure recharge in using an apparatus (lysimeter, water flux meters).

2.4.1.1 Water balance

Water balance methods rely on measurement of several terms in the land surface water balance equation to derive recharge as a residual:

$$D = P - ET - R + \Delta S \tag{2.1}$$

where D is drainage (taken to represent recharge) calculated as total precipitation (P) less water returned to the atmosphere through evapotranspiration (ET), less water that runs on or off the control surface (R), plus the net change in storage of water in the soil zone to the depth that evapotranspiration processes affect (ΔS). Precipitation is easily and directly measured. Runoff is often not a parameter of importance for the soils of concern at Hanford, except perhaps along the western edge of the Hanford Site near Rattlesnake Mountain. Soil moisture must be measured over the depth range that is affected by evapotranspiration and at frequent time intervals to complete the calculation of recharge (drainage) as a residual.

2.4.1.2 Lysimetry

A lysimeter is an in situ recharge measurement system that can be used to collect water that has flowed through and below the reach of the evaporation process and plant roots to become deep drainage, and eventually, recharge. The objective of lysimetry is to collect both performance data and model testing data for specific combinations of soil, vegetation, and precipitation. Lysimetry is one of only two methods available (the other being drainage flux meters) to directly measure deep drainage and thereby recharge. A lysimeters primary strength is that it can provide a control volume in which a number of water balance components can be integrated and measured directly. This control volume provides the data necessary to calibrate numerical models, that can in turn be used to predict recharge.

While lysimeters provide a direct measure of recharge, they possess some disadvantages. Lysimeters are usually fixed in space, limiting their ability to quantify the effects of spatial variability. The soil filling the lysimeter may not represent the natural stratification or layering that may be present. The length of a lysimeter record is usually much shorter than time periods of interest, although the longer the lysimeter is operated the more this drawback is alleviated. The lysimeter walls and base alter the natural gradients of temperature, air flow, and vapor flow that could be of importance in measuring recharge rates less than 1 mm/yr. Lysimeter walls restrict lateral root growth and artificially promote downward growth. When an irrigation treatment is used, lysimeter tests are subject to an "oasis effect," a scale effect where heat from un-irrigated surroundings increases the evapotranspiration rate above what it would have been if the entire area surrounding the lysimeter been irrigated. Finally, it is critical to verify that no leaks of drainage water occur in the lysimeter before the data collected are used.

Lysimeters have long been used at the Hanford Site for several purposes (Hsieh et al. 1973, Gee and Jones 1985, Freeman and Gee 1989, Wittreich and Wilson 1991, Gee et al. 1993, Ward et al. 1997). Lysimeters used to provide data reported in this compendium include containers that isolate the soil from its surroundings and field-scale pads that collect drainage but do not isolate the soil.

2.4.1.3 Water Flux Meters (WFMs)

The function and design of a vadose zone water flux meter (WFM) for direct, in situ measurement of recharge is described in Gee et al. (2002). The design, illustrated in Gee et al. (2002) and shown here as Figure 2.1, concentrates flow into a narrow sensing region filled with a fiberglass wick. The wick applies suction, proportional to its length, and passively drains the meter. Such a meter can be installed in an augured borehole at almost any depth below the root zone. Water flux through the meter is measured with a self-calibrating tipping bucket. Further enhancement to this design are discussed in Gee et al. (2003b).

2.4.2 Tracers

Tracer methods estimate past recharge by means of measuring the vertical distribution of a tracer in soil and sediments of the vadose zone. Several tracers are available that enable estimates of recharge rates: the ones used at Hanford have included chloride and chlorine-36 (Fayer et al. 1999, Fayer and Szecsody 2004) and the stable isotopes deuterium and oxygen-18 (DePaolo et al. 2004, Fayer and Szecsody 2004, Singleton et al. 2006).

2.4.2.1 Chloride and Chloride-36

Chloride originates from seawater, is deposited naturally, and can provide recharge estimates spanning hundreds to thousands of years. In contrast, the isotope chlorine-36 originates from two sources: cosmic irradiation of atmospheric chloride and surface and atmospheric nuclear weapons testing. The quantities of chlorine-36 created through nuclear weapons testing far exceeds natural production rates from cosmic irradiation and therefore furnishes a distinctive marker in the subsurface environment, particularly for arid regions with low recharge rates where this "bomb pulse" is still in transit through the vadose zone. Chlorine-36 data is used to estimate the average recharge rate over the last 50 years for such environments.

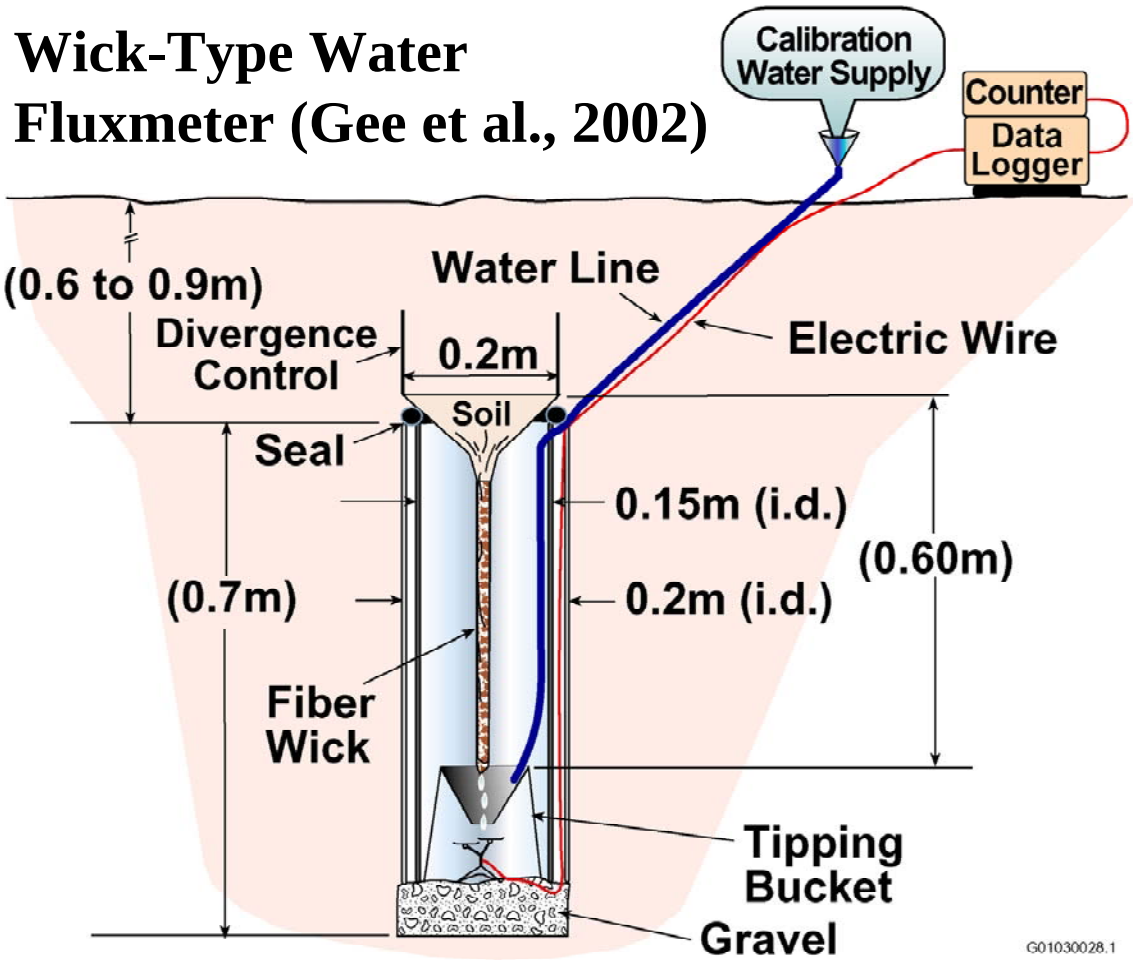

Figure 2.1. Schematic of Installed Vadose Zone Water Fluxmeter With Diversion Control (Gee et al. 2002)

Both chloride and chlorine-36 are conservative, nonvolatile, and almost completely retained in the soil when water evaporates or is transpired by plants (Phillips 1994). Some chloride is subject to plant uptake; examples of this shown in Rickard and Vaughn (1988) and in Sheppard et al. (1998). Over hundreds to thousands of years, plant cycling is expected to have a minimal impact on the evolution of the chloride distribution in the soil profile beneath plants. Recharge rates determined using chloride as a tracer reflect conditions that existed hundreds to thousands of years ago and are sometimes called paleorecharge or paleofluxes. When using such paleofluxes to represent current or future conditions, the assumption is that the climate, soil, and vegetation conditions remain similar. In contrast, bomb-pulse chlorine-36 has been present in the environment for only about 50 years. In soils with high pH and high adsorption of other anions, anion exclusion can result in faster movement of chloride. Previous studies strongly suggest a relationship between soil surface area, which is primarily determined by clay content, and anion exclusion, for example Thomas and Swoboda (1970). Most of the sandy soil found at the Hanford Site has a relatively low percentage of clay, so the effects of anion exclusion in this soil would be relatively minor. Two other issues that affect chloride-based estimates of recharge are mineral dissolution and the chloride dilution that is part of the measurement technique. Both issues can be significant when recharge rates exceed a few millimeters per year (Tyler et al. 1999).

Phillips (1994) suggested that systematic uncertainties in estimated chloride deposition rates can be as great as 20% if the chloride mass balance technique is extended to estimate recharge rates prior to the Holocene epoch (approximately 10,000 years ago). Scanlon (2000) suggested the uncertainty was as high as 38%. Because the Hanford Site was flooded by glacial melt water about 13,000 years ago, the interpretation is not extended beyond that time. Therefore, the uncertainty in chloride deposition rates at the Hanford Site is expected to be less than 38%.

There is some uncertainty about the local influence that Hanford Site operations may have had on the time-dependent concentrations of both chloride and chlorine-36 deposited at Hanford (Fayer et al. 1999). Murphy et al. (1991) examined the issue relative to chlorine-36 and concluded there was no nearby source that would confuse the chlorine-36 signal in the sediment.

2.4.2.2 Deuterium and Oxygen-18

Deuterium and oxygen-18 are inert isotopes of hydrogen and oxygen, respectively, that are naturally occurring. Their concentration increases as the lighter components evaporate disproportionately. The increased concentration can be used to delineate seasonal variations in water flux, identify the depth of evaporative enrichment, and roughly estimate recharge.

The recharge rate is determined largely by the magnitude of transpiration and evaporation relative to precipitation and overland flow that has infiltrated the soil. Because water consists of several isotopes of hydrogen and oxygen, each with slightly different atomic weights, evaporation tends to remove the lighter isotopes preferentially. The net result is that the residual water contains a higher proportion of the heavier isotopes. There is a progressive decrease in the proportion of heavy stable isotopes with soil depth because evaporation decreases with depth and because of mixing with infiltrating water. At some depth, the isotopic profile becomes somewhat uniform; this depth represents the vertical extent of significant water vapor flux. The amount of enrichment (relative to the isotopic signature in precipitation) is indicative of the recharge rate.

Oxygen-18 and deuterium are the two isotopes that constitute useful tracers because they are stable (and benign) and occur in measurable quantities. The oxygen-18 and deuterium ratios ($R = {}^{18}O/{}^{16}O$; $R = {}^{2}H/{}^{1}H$) are used to express isotopic composition in delta (δ) units relative to a standard material as follows:

$$\delta = \left[\frac{R_{sample}}{R_{standard}} - 1 \right] \times 1000 \qquad (2.2)$$

where δ is reported in permil units (‰; a δ value of 10‰ is equivalent to 1%). Typical values for winter precipitation (the primary source of recharge water for the climate at the Hanford Site) are -19 to -16‰ for δ ^{18}O and -142 to -120‰ for δ ^{2}H (Singleton et al. 2006). The actual depth of enrichment will depend on factors that include recharge rate, soil properties, meteorological conditions, and average annual temperature. Murphy et al. (1991) described how deuterium and oxygen-18 could be used to understand recharge rates at the Hanford Site.

2.4.3 Numerical Modeling

Numerical modeling of unsaturated flow in the vadose zone can be used to estimate recharge rates, but because this method introduces the highest uncertainty it is usually reserved for situations where there are little or no data, or to leverage limited short-term data to estimate long-term recharge.

Simulations of recharge at Hanford have been successful at highlighting the important factors that affect recharge and predicting recharge rates for specific cases. Modeling is the primary tool for forecasting recharge rates for future climate and land use scenarios. The simulations also allow the results of the lysimetry and tracer methods to be merged on a consistent basis.

3.0 Brief History of Recharge Investigations at Hanford

Recharge at the Hanford Site has been studied for decades because of its importance to evaluation of waste transport in the vadose zone and unconfined aquifer. Examples of early attention to natural recharge included the studies of the 200 East Area deep well by Enfield and Hsieh (1971) and Enfield et al. (1973).

With the transition of the Hanford Site's mission from nuclear materials production to environmental cleanup, more resources and effort were brought to bear on measuring and estimating natural recharge at the site. A lysimeter facility was constructed, maintained, and monitored to measure recharge rates for several soil and vegetation covers (Gee 1987, Gee et al. 1989). The 200 East Lysimeter was also constructed and data collection began there (Routson et al. 1988, Gee et al. 1994) and later a lysimeter was installed north of the 300 Area (Gee et al. 2005).

In the mid-1990s a site-wide map of natural groundwater recharge was constructed by using numerical simulation along with soil and vegetation cover maps to extrapolate available point measurements (Fayer and Walters 1995). Site-specific recharge measurements for areas of special interest were undertaken such as at the prototype Hanford Barrier to measure the effectiveness of proposed infiltration barriers (Ward et al. 2005). Data packages were prepared to support compliance assessments including the Solid Waste Landfill (SWL) (Gee et al. 2005), the Integrated Disposal Facility (IDF) (Rockhold et al. 1995, Fayer et al. 1999, Fayer and Szecsody 2004) and the recharge data package for the RCRA Facility Investigation (Fayer and Keller 2007).

By the late 1990s tracer-based methods began to be employed in addition to water balance measurement based methods to estimate recharge (Murphy et al. 1996, Prych 1998, Fayer et al. 1999, Maher et al. 2003, DePaolo et al. 2004, Fayer and Szecsody 2004, Gee et al. 2005, Maher et al. 2006, Singleton et al. 2006, Keller et al. 2007).

Monitoring of field soil water balance and recharge measurement sites has continued at a low level for the past several years. In the following sections a summary of the climate at Hanford is given, followed by a presentation of water balance and recharge data collected at various field sites from 2004-2009.

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4.0 Hanford Climate Summary

4.1 Climate and Meteorology

The Cascade Mountains, 100 km to the west, exert a strong rain-shadow effect on the climate of the Hanford area. This mountain range also serves as a source of cold air drainage, which has a considerable effect on the wind regime on the Hanford Site. Climatological data have been collected at the Hanford Meteorological Station (HMS) since 1945 (Hoitink et al. 2005). HMS is the primary weather station on the Hanford Site and is sited between the 200 East and 200 West Areas at 733 ft (223 m) elevation, latitude 46.563, longitude 119.599. The data are representative of the general climatic conditions for the region and describe the specific climate of the Central Plateau.

Most of the statistics presented in sections 4.1.1-4.1.5 (through "Wind") are gleaned from tables provided on the HMS website. These tables are updated versions (through 2008) of those presented in the last available annual summary report, for the year 2004 (Hoitink et al. 2005). Other statistics in these sections come directly from Hoitink et al. (2005) and are cited as such; these have not been updated but are believed to still be valid.

4.1.1 Precipitation

Between 1947 and 2008, annual precipitation at the HMS averaged 172 mm and varied between 76 and 313 mm. Table 4.1 shows how monthly averages have varied in that time. The wettest season on record was the winter period from December 1996 to February 1997, with 138 mm of precipitation; the driest season was the summer of 1973 (June-August) when only 0.8 mm of precipitation was measured.

On average, half of the annual precipitation occurs during the four months from November through February. A rainfall intensity of 20 mm/hr persisting for 1 hour is expected only once every 1,000 years (Hoitink et al 2005). A day with 18 mm precipitation is expected to occur about once every 2 years, while a day with 54 mm precipitation is expected only once every 1,000 years. Hanford nearly experienced such a 1,000-yr event when it received 48.5 mm in a 24-hr period in October 1957.

Snowfall accounts for about 42% of all precipitation from November through February. Monthly average snowfall is greatest in December (126 mm) and January (132 mm). The record monthly snowfall of 594 mm occurred in January 1950. The seasonal record snowfall of 1,425 mm occurred during the winter of 1992-1993. This amount has a return period of almost 500 years. On average, the first measurable snow appears on November 29 and the last on February 16. Since 1946, snow has been measured as early as October 22 and as late as May 24.

Total precipitation measured at the HMS from September 2008 through August 2009 was 133.9 mm. For September 2007 through August 2008 the total precipitation measured at HMS was 151.9 mm, and for September 2006 through August 2007 it was 164.2 mm. Therefore the total precipitation in FY09 and in the preceding two years was somewhat lower than the long-term average of 172.3 mm (Table. 4.1).

Table 4.1. Monthly Precipitation (mm) Variations Between 1947 and 2008 at the Hanford Meteorological Station

Month	Maximum	Mean	Minimum
January	62.7	23.9	2
February	53.3	16.1	0
March	47.2	12.5	0.5
April	56.6	12	0
May	51.6	13.1	0
June	74.2	13.5	0
July	44.7	5.1	0
August	34.5	6.2	0
September	34	7.7	0
October	69.1	13.3	0
November	67.8	22.4	0
December	93.7	26.5	1.8
Annual	312.7	172.3	75.9

4.1.2 Air Temperature

Table 4.2 shows the range of monthly temperatures since 1945. The highest winter monthly average temperature was 7.0°C in February 1958 and 1991, while the lowest average temperature was -11.1°C in January 1950. The highest summer monthly average temperature was 27.9°C in July 1985, while the lowest average temperature was 17.2°C in June 1953.

During 1955-2008, there were, on average, 49 days during the months of April through September with maximum temperatures ≥ 32°C and 12 days with maxima ≥38°C.

During the months of October through March, an average of 84 days had temperature minimums below 0°C; an average of 2 days had minimum temperatures that were ≤18°C.

During 1945-2008, the record maximum temperature is 45°C; the record minimum temperature is -31°C. The potential for plant activity can be represented by the number of growing days, which is the number of days between the last freezing temperature in spring and the first freezing temperature in autumn. During 1945-2004, the number of growing days averaged 181 days per year, with annual values ranging from 142 (in 1974) and 216 days (in 1994) (Hoitink et al. 2005).

4.1.3 Humidity

Since 1955, the average annual relative humidity at the HMS has been 55%; annual values ranged from 49 to 59%. December had the highest monthly average humidity (81%), with values that ranged from 70 to 90%. July had the lowest monthly average humidity (33%), with values that ranged from 22 to 46%.

Table 4.2. Monthly Air Temperature (C) Variations Between 1945 and 2008 at the Hanford Meteorological Station

Month	Maximum	Mean	Minimum
January	5.8	-0.5	-11.1
February	7	3.2	-3.6
March	10.8	7.5	4.1
April	14.6	11.6	8.6
May	20.4	16.6	13.3
June	24.9	20.8	17.2
July	27.9	24.9	21.4
August	27.5	24	21
September	22.5	19	14.9
October	15.3	11.7	8.8
November	8.1	4.5	-4
December	3.6	0.1	-6.1
Annual	13.6	11.9	9.8

4.1.4 Solar Radiation

Since 1955, the average annual daily solar radiation at the HMS has been 351 langleys. Average daily values were lowest in December (81 langleys) and highest in July (627 langleys). Five dates have no recorded solar radiation; the lowest non-zero observed daily value was 6 langleys on December 11, 2002; the highest observed daily value was 861 langleys on June 8, 1977.

4.1.5 Wind

Prevailing wind directions on the Central Plateau were either from the west-northwest or northwest in all months of the year. At a height of 15.2 m (50 ft), average annual (1945-2004) wind speed was 12.2 km/hr (Hoitink et al. 2005). Monthly average wind speeds were lowest during the winter months (9.7 km/h in December) and highest during the summer (14.6 km/hr in June). Peak wind gusts in every month originated from the west-southwest, southwest, and south-southwest; monthly peak gusts varied from 105 to 129 km/hr.

4.2 Long-Term Weather and Climate at HMS

The amount and timing of natural recharge depends on the interaction of weather, vegetation, and soil. Climate change is potentially significant for recharge, so for this year's report, weather data at the Hanford Meteorological Station (HMS) were analyzed for long-term trends. Hourly data from 1/1/1955 to 12/31/2008 (54 years; 473,376 hourly records) were provided by Ken Burk/PNNL. The weather variables most relevant for hydrology and used for this analysis were: air temperature, dew point temperature, precipitation, snow fall, snow water equivalent, wind speed, wind direction, sky cover, and solar radiation.

HMS staff used to publish annual summary reports on weather and climate at Hanford, ending with year 2004 (Hoitink et al. 2005). These reports emphasized statistics of normal and extreme weather and compared the current year to a 30-year period. Hoitink et al. did not attempt to characterize long-term trends.

4.2.1 Data Processing

First, the raw data text files were joined together into a single, 32 MB file. A text editor was used to change obvious "not available" values in the entirely numeric file, e.g. 999 for air temperature, to "NA". Next, the revised file was read into the R software environment (version 2.9.1, R Team, 2009), where all subsequent processing and graphing took place, using a multi-part script. Erroneous (out-of-order) date and time values were fixed, and records having hour=24 (midnight) were changed to hour=0 on the next day. For each variable, complete information about missing values was generated, including the number of time gaps and the beginning and ending time of each gap. Most variables had very few missing values, ranging from 0 to 0.93% of the total record. The two major exceptions to this were wind direction, missing 6% of records, primarily during 1971-1973; and sky cover, missing 6%, primarily during 1972-1973 and weekend nights after April 1995. Sky cover requires a human observer and staffing was reduced in 1995.

Since trends in climate rather than short-term weather variations were of interest, the hourly values were aggregated to daily, monthly, and annual timeseries, and saved to plain text files. Aggregation consisted of taking the mean of the hourly data for the respective time period, except as noted in the additional comments about individual variables below.

Daily mean, minimum, and maximum temperatures were generated from the hourly data. Monthly and annual values are means of the daily values. Units are degrees F.

Dew point temperature is a measure of absolute humidity, a factor in evapotranspiration from the land surface. Units are degrees F.

Rainfall and snow water equivalent were recorded in number of hundredths of inches (0.01"), with 50 = Trace. Rain is the liquid component of hourly precipitation, and snow water equivalent (SWE) is the liquid equivalent of frozen hourly precipitation. Rain and SWE were added together to obtain total hourly precipitation. Aggregation to daily, monthly, and annual timesteps was done by summing the hourly values with Trace amounts assigned a value of zero. Precipitation was converted to mm, and snow fall was converted to cm.

Snow fall was recorded in number of tenths of inches (0.1”), respectively, with 50 = Trace. Snow fall is the depth of frozen precipitation that falls during the hour.

Wind speed was recorded in miles per hour. Wind direction was recorded as one of 16 compass sectors before 1986, with 1 = NNE (center value 22.5 deg), 2 = NE (center value 45 deg), 16 = north (center value 0 deg), etc. From 1986 on, the values range from 1 to 36 and are the compass direction divided by 10. For all times, 0 = calm. Wind direction values not falling in these ranges were assigned NA. All valid data were converted to compass direction (0 to 360 deg).

Sky cover is the fraction of the celestial dome that is obscured by clouds or fog, recorded in tenths. All values greater than 10 were assigned NA, and the valid data was converted to percent.

Solar radiation was recorded in langleys per minute (1 gm-cal/cm2/min). Negative solar data were assigned NA. Daily solar radiation was computed by multiplying the hourly values by 60 and summing them. Monthly and annual values were means of the daily values.

4.2.2 Results

The simplest way to consider long-term trends is to look at a plot of annual timeseries (Figure 4.3). The data are plotted with robust, locally-weighted polynomial regression ("loess") lines that represent the trend. The three air temperature variables have similar patterns, with the average trend varying up to 2.5 degrees over the period of record. Hanford has been in an overall cooling trend since the early 1990s. Precipitation is highly variable in the steppe climate, with a coefficient of variation (CV) = 29%, but a significant long-term trend is not apparent. Annual snow fall and snow water equivalent are even more variable (CV~72%), and again no significant long-term trends are evident. Average annual wind speed has fluctuated up to a couple miles per hour in a similar pattern to air temperature. Average sky cover has declined from 58% to 51% over the last 30 years, but solar radiation has not changed appreciably over the same time period.

Since year-to-year variability in weather variables can be large, it is also instructive to consider averages over discrete multi-year time periods. Figure 4.4 shows climate averaged over three-year periods. There is considerable variation between three-year periods, indicating that recharge would also be highly variable even at this multi-year timescale. For example, average annual precipitation was 258 mm during 1994-96, but only 165 mm during the most recent period. Since the 1994-96 period there seems to be a clearer inverse relationship between sky cover and solar radiation than was indicated in the loess smoothing of the annual timeseries. Figures 4.5 and 4.6 show windrose counts and means, respectively, for six-year periods. The same pattern of wind has held over time—winds are predominantly from the west to northwest, but many of the strongest winds come from the southwest.

Variability from year to year for a given month is also large, as shown in Figure 4.6, which shows mean temperature by month across years. Loess lines are again shown in an attempt to characterize trends. Some are intriguing, such as the rise in March over the first 30 years of record, but the scatter of the data is such that the apparent trends are relatively uncertain.

Finally, another way to evaluate long-term trend is to formally separate a timeseries into seasonal, trend, and remainder components using an iterative loess procedure (Cleveland et al. 1990). The decomposition for mean temperature is shown in Figure 4.7. The procedure is as follows. The seasonal (monthly) component is found by taking the mean for each month across all years. Then the monthly component is removed from the data, and the remainder is smoothed with loess to find the long-term component, which includes trends and oscillations whose periods are longer than monthly. Then that long-term component is subtracted from the data, and a new seasonal component is smoothed to the remainder. Then the new seasonal component is again subtracted from the data and a new long-term component is fit to the remainder, and so on. The final result is an additive model: Data = Monthly + Trend + Remainder. The remainder term is the residual from the combined monthly and trend terms. The monthly term can also be fit by loess instead of taking the means, but the mean approach was used here to emphasize variability in the long-term component.

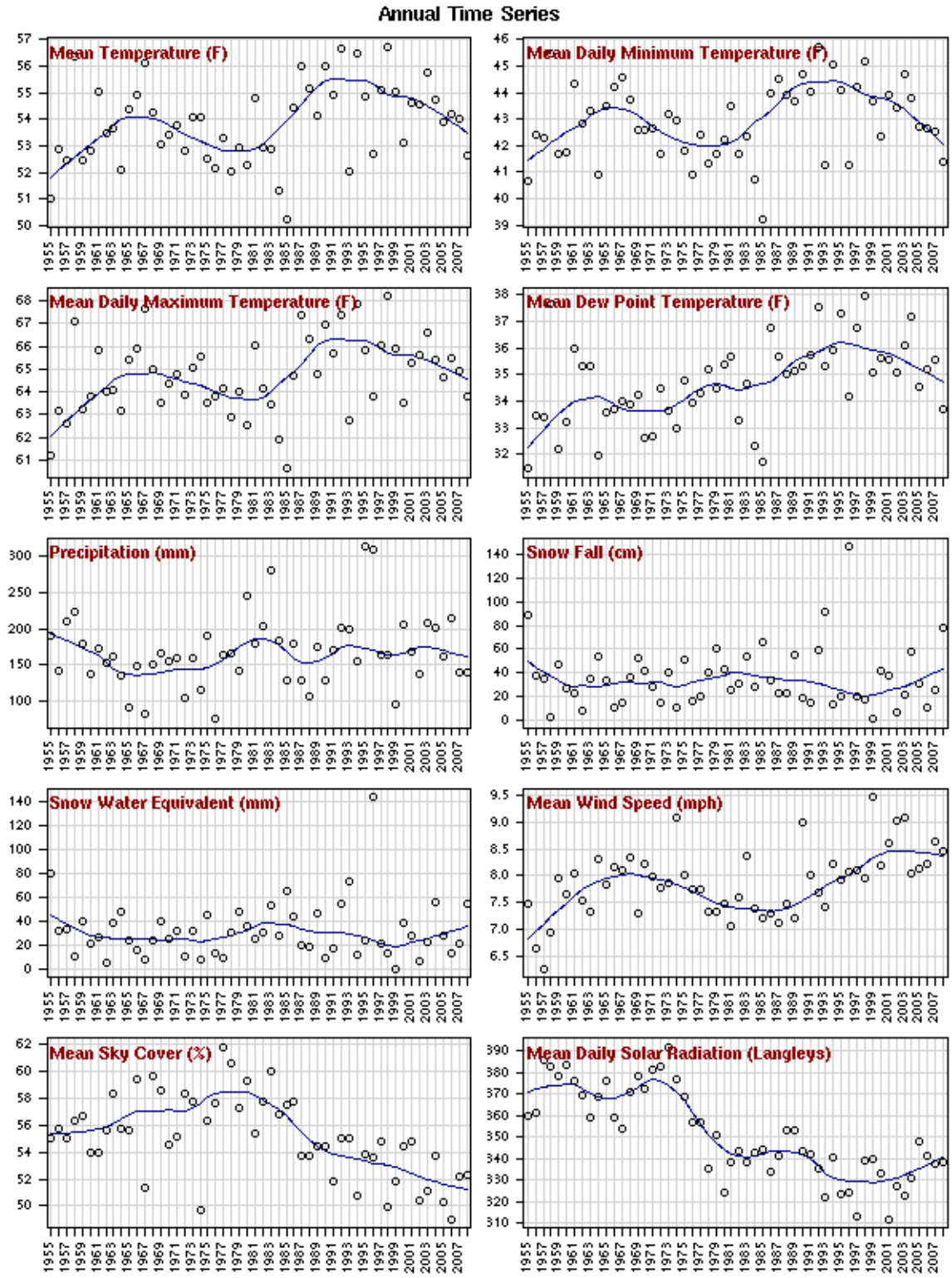

Figure 4.1. Annual Timeseries of HMS Weather Variables and Local Regression (Loess) Lines

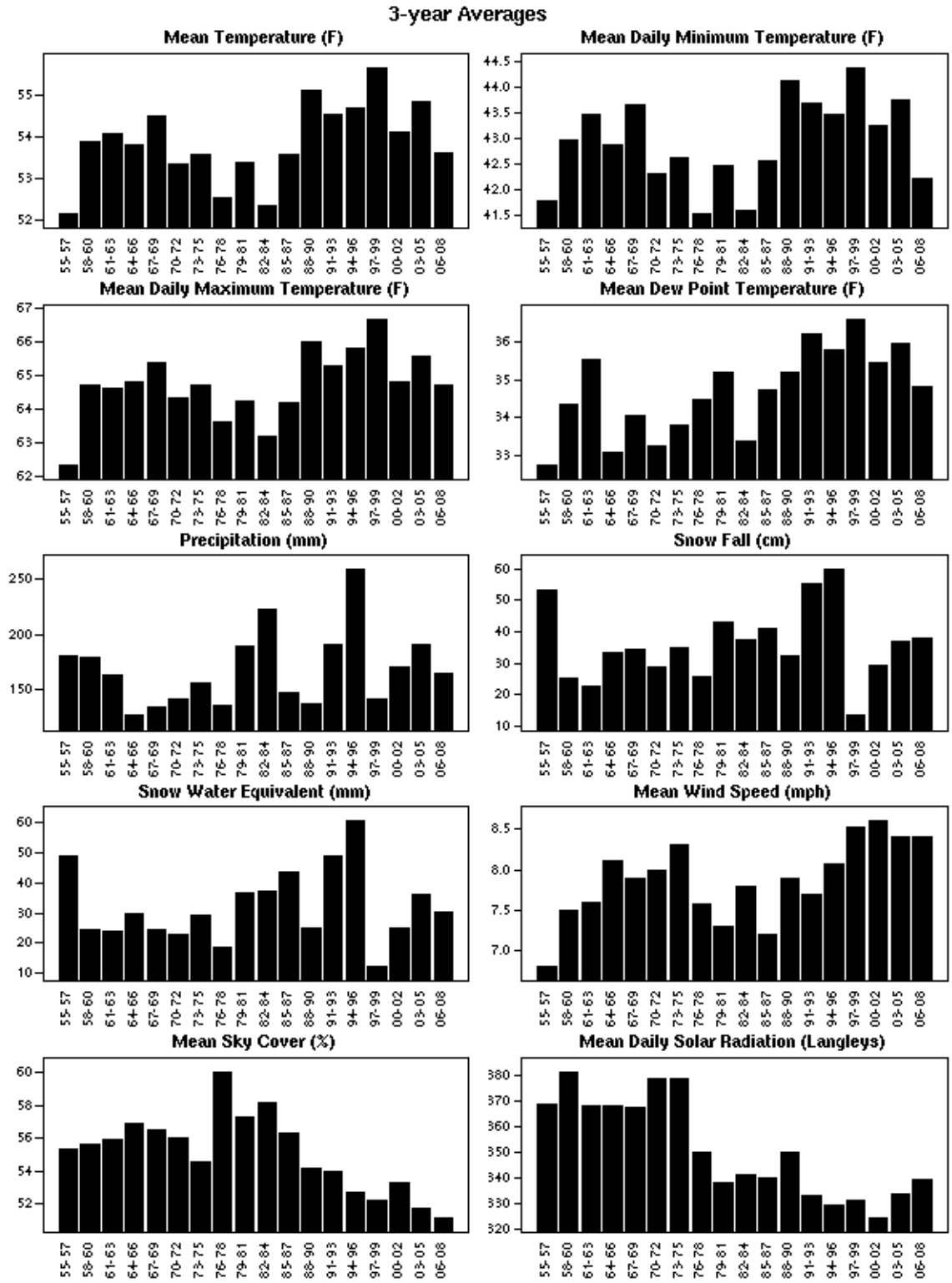

Figure 4.2. HMS Weather Data Averaged Over Three-Year Periods

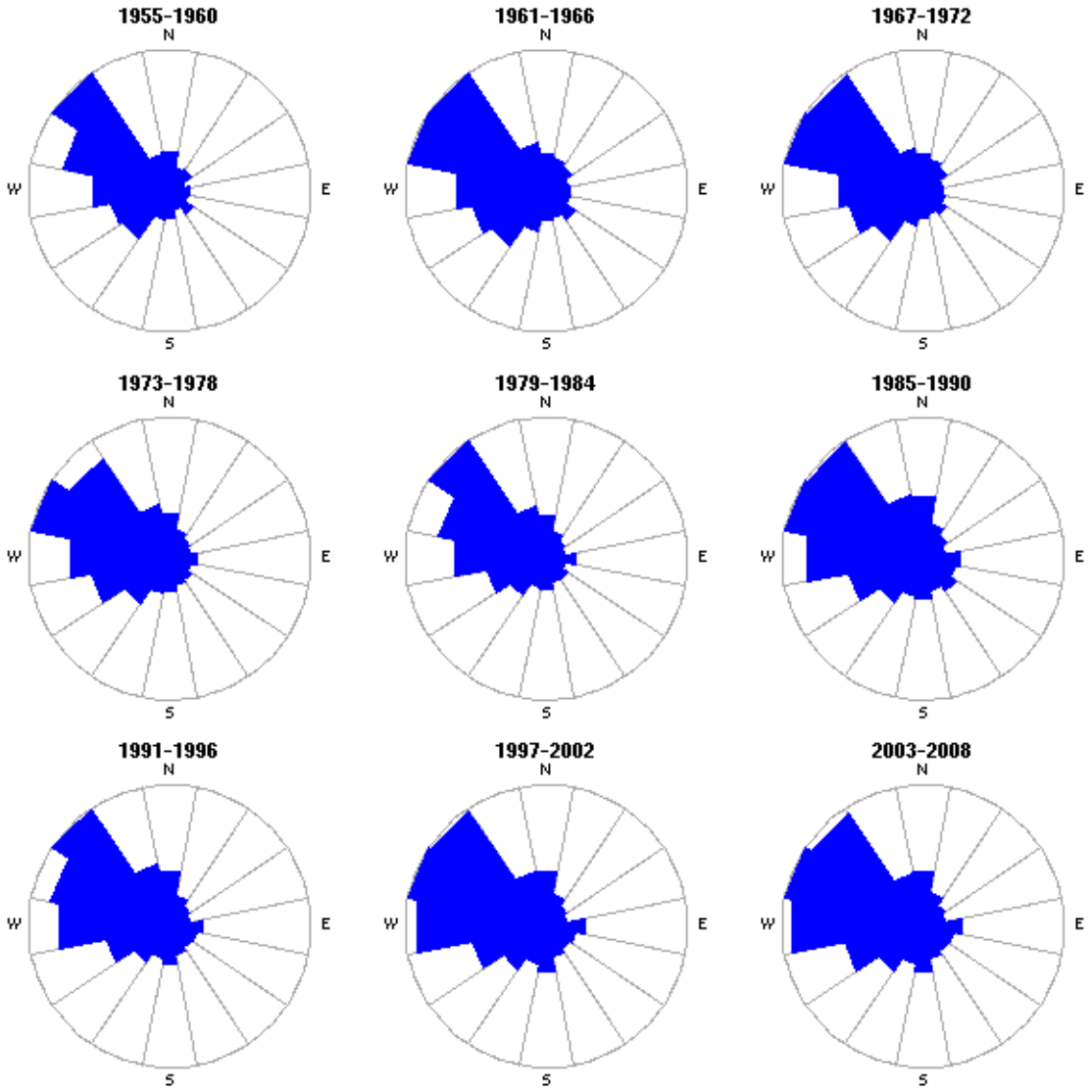

Figure 4.3. Windrose Plots Showing Prevalence of Wind Direction at HMS, Based on Counts of Wind Direction in 22.5-Degree Sectors. The predominant wind direction is from W-NW.

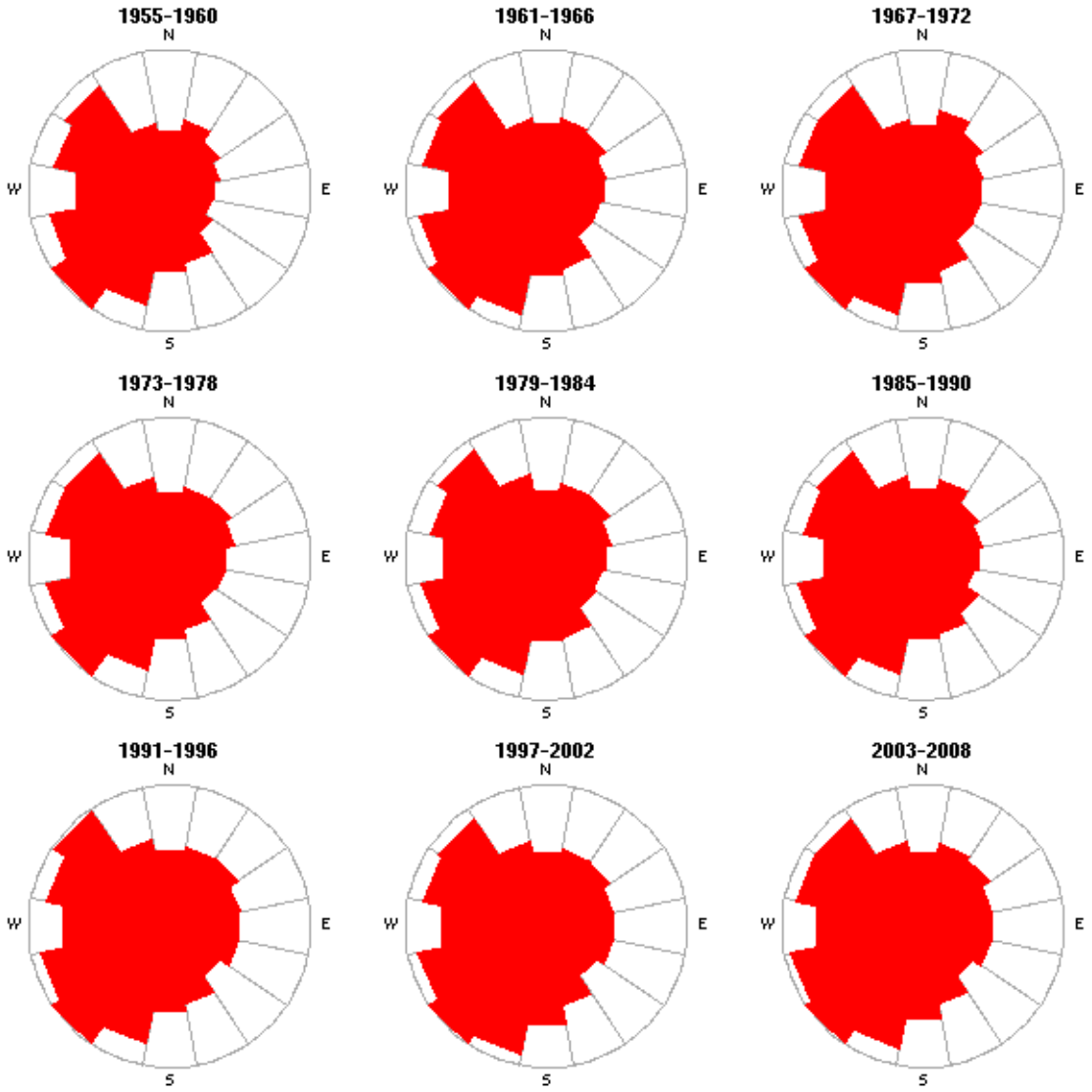

Figure 4.4. Windrose Plots Based on Means of Wind Speed in Each 22.5-Degree Sector for HMS Data. The peak gusts are usually from the SW.

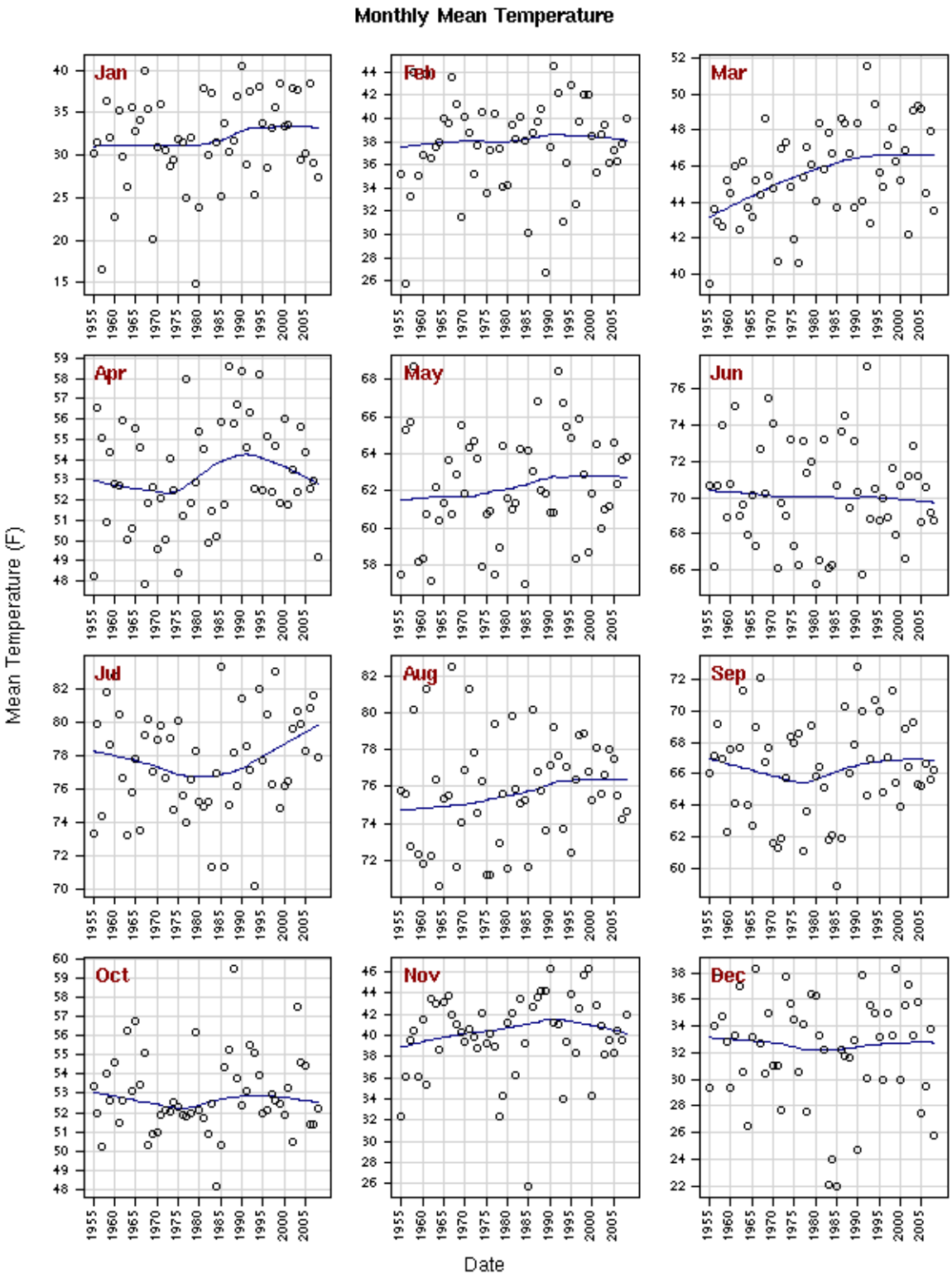

Figure 4.5. Monthly Mean Temperature by Year Measured at the HMS, with Loess Lines

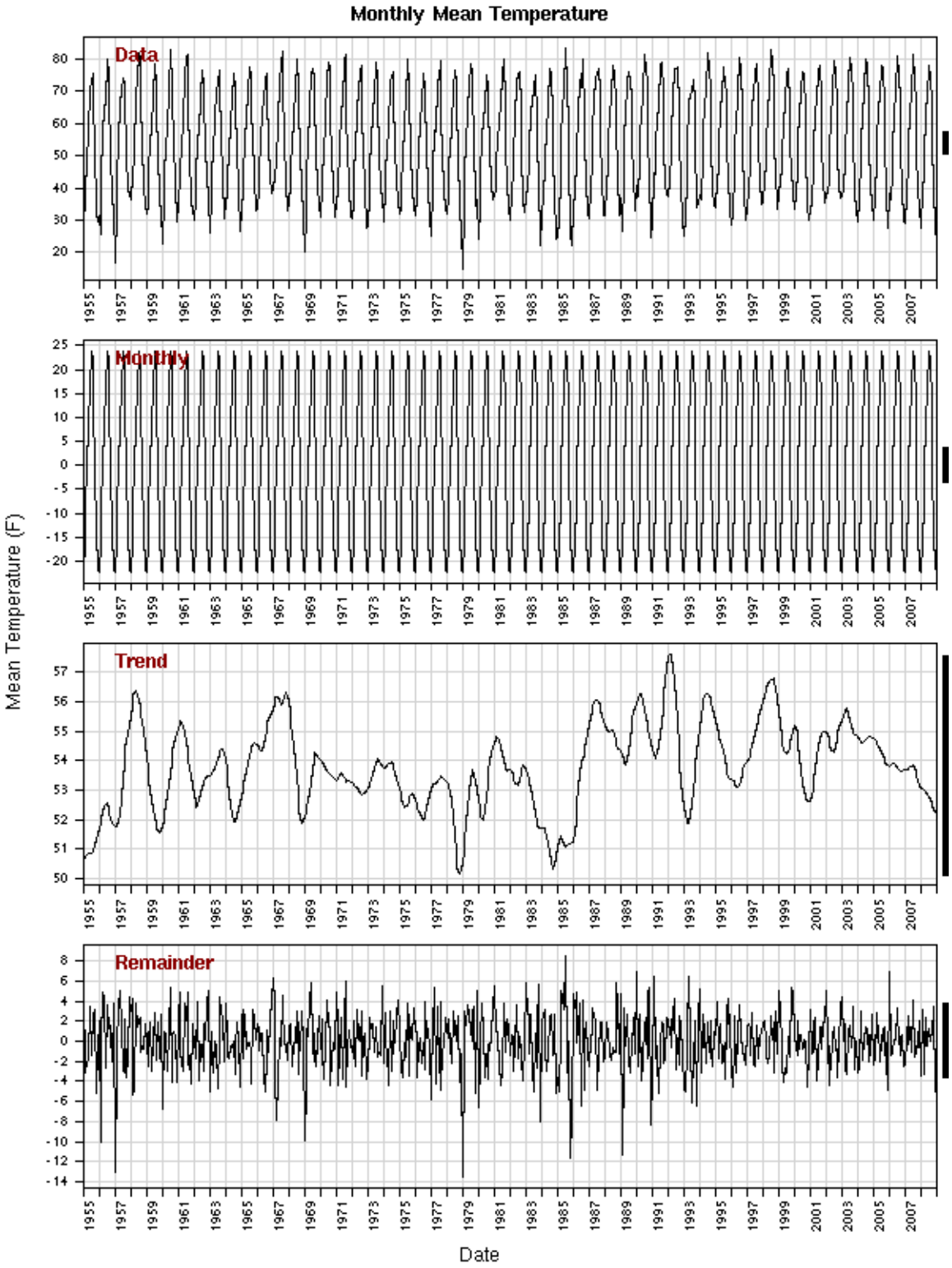

Figure 4.6. Seasonal Loess Applied to Mean Monthly Temperature at the HMS. Data = Monthly + Trend + Remainder.

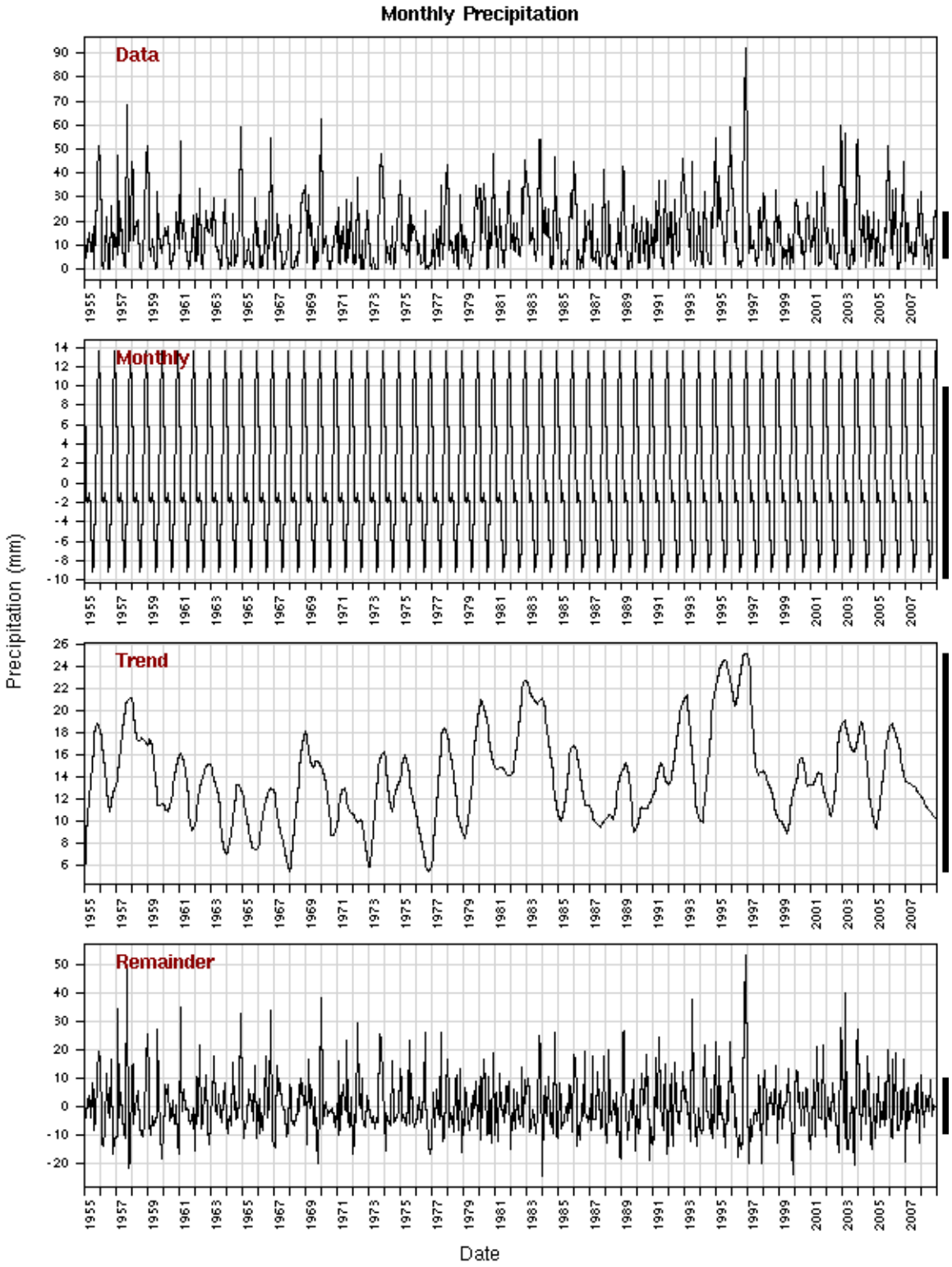

Figure 4.7. Seasonal Loess Applied to Precipitation Measured at the HMS

The relative sizes of the components can be judged by referring to the black bars to the right of the graphs, which show the same absolute distance in units on each, different vertical axis. A component with a relatively short bar contains a relatively large proportion of the total variation in the data, as compared to a component with a relatively long bar. For example, the monthly component of mean temperature is the largest one, and the remainder term is the second largest. These indicate that seasonal and random variations comprise most of the variability in temperature. The trend component, though smaller, does show frequent changes on the order of 3 degrees over cycles of 1 to 3 years.

The remainder term is the dominant one for precipitation (Figure 4.7) and the snow variables, indicating again how important random variation is in determining these variables.

Overall, there do not appear to be any persistent long-term trends that would significantly impact natural recharge. However, there is significant inter-annual variability in addition to the more familiar seasonal variability. It is to be expected that recharge will vary significantly not only from year-to-year, but even in the averages of different multi-year periods.

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5.0 Recharge Data Collected in FY 2004-2009

Monitoring of water flux and related properties (e.g. water content, matric potential) has been performed at various locations for different periods at the Hanford Site. Several monitoring locations, both active and inactive, are shown on the site map in Figure 5.1. The monitoring sites, activities, and periods for each site are listed in Table 5.1. Monitoring data for active sites are presented and examined in this section on a site-by-site basis.

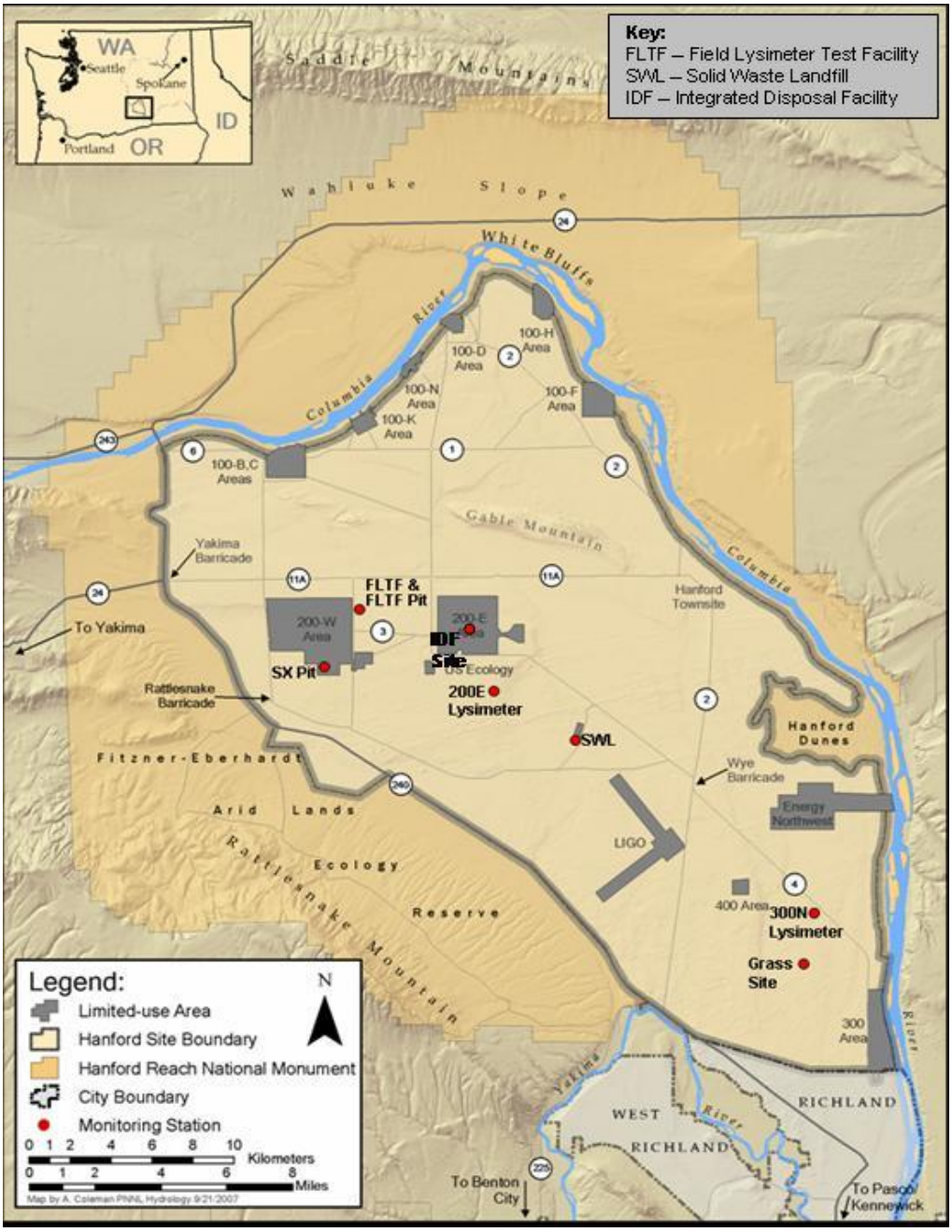

Figure 5.1. Location of Recharge Monitoring Stations at the Hanford Site

Table 5.1. Monitoring Sites, Activities, and Periods

Monitoring Site	Monitoring Activities	Monitoring Periods
Grass Site	Water flux, water content	1-Feb-2005 to present
300N Lysimeter	Water flux, water content, matric potential	1981 – December 2006 (Wind damage outage) February 2007 - present
Solid Waste Landfill[(a)]	Water flux, water content	December 2004 to present
Integrated Disposal Facility (IDF)	Environmental tracer methods, water content	2000-2008
200 East Lysimeter	Water content	1991 to 2007
Field Lysimeter Test Facility (FLTF)	Water flux, water content, matric potential	1987 to present
Field Lysimeter Test Facility (FLTF) Pit	Water flux	2001 to present
Tank Farms	B: Water flux, water content SX: Water flux, water content TX: matric potential	B: From 2001 to ~2003 SX: From January 2003 to Sept. 2007 TX: October 2002 to September 2007

(a) Leachate data from the SWL has been collected since 1996.

5.1 Grass Site

The Grass Site is located approximately 4.5 km northwest of the 300 Area in a location dominated by stabilized sand dunes. Layered soil conditions exist at the site with a sandy loam to loamy sand soil present from the surface to a depth of approximately 40 cm followed by a sandy soil. Vegetation at the Grass Site is predominately annual and perennial grass. In 2005 a recharge monitoring station consisting of duplicate WFMs and two water content sensors was installed at this location. WFMs were installed keeping the layered soil column intact. Additional information about the Grass Site and the installation of monitoring equipment can be found in Keller and Gee (2005)[1]. Figure 5.2 shows photographs of the grass-covered surface of the two WFMs at this site in the autumn of 2006. Note that the exposed tops of these WFMs are both 20-cm in diameter.

The water content and cumulative drainage since instrument installation are presented in Figures 5.3 and 5.4, respectively. Changes in water content are consistent with seasonal precipitation trends (i.e. wet winters and dry summers). Increased water content is observed in the sand layer (60 cm bgs sensor) underlying the sandy loam layer. This signifies that the soil profile wets up enough to overcome the capillary break formed by this layering.

[1] Keller JM and GW Gee. 2005. "Remediation Decision Support / Characterization of Systems Fiscal Year 2005 Recharge Task Status Report". Letter Report to George Last, PNNL, September 10, 2005.

Figure 5.2. Surface Conditions on the Water Flux Meters at the Grass Site in Autumn 2006. The Exposed Tops of these Water Flux Meters are 20-cm in Diameter.

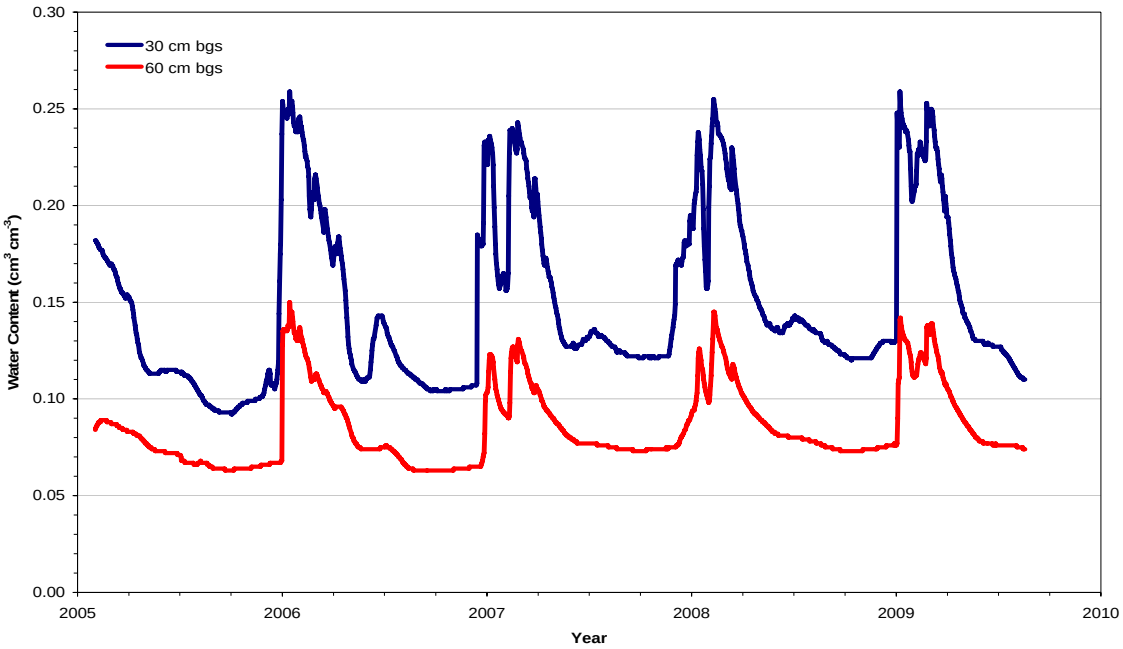

Figure 5.3. Volumetric Water Content Measured at 30 and 60 cm Below Ground Surface at the Grass Site.

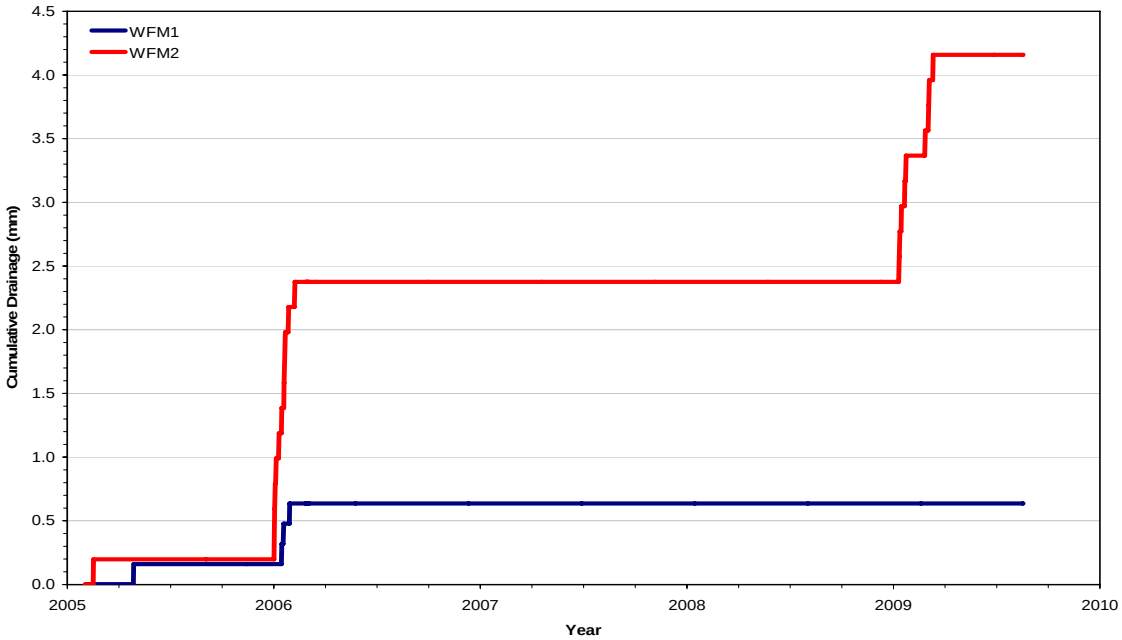

Figure 5.4. Cumulative Drainage Measured at the Grass Site Using Water Flux Meters.

The water content sensors at the Grass Site have performed remarkably well over the past 4.5 years. However, drainage amounts to date are markedly different between both flux meters (4.16 mm vs. 0.64 mm), possibly reflecting the variability in soil properties. This may be natural variation or a result of differences brought about during installation of the WFMs. The latter is probably more likely. The WFMs did not measure drainage in 2007 or 2008, but 1.76 mm of drainage was recorded for WFM2 in 2009.

5.2 300N Lysimeter

The 300-N Lysimeter site is located about 10 km north of Richland, Washington, just south of the Fast Flux Test Facility (FFTF), and within 300 m of the 300 Area Burial Grounds (618-10). A series of lysimeters designed for water-balance studies and to simulate waste-burial-grounds with bare, coarse-grained surfaces was constructed at this site in 1978. Detailed descriptions of the site are provided by Gee and Jones (1985), Gee et al. (1992), and Sisson et al. (2002). Other instrumentation includes a Pronamic rain gage installed at the drainage outlet in the bottom of the lysimeter in August 2000. This rain gage was connected electronically to a data logger to measure drainage on a continuous basis. In April 2002, two WFMs were also installed in the south lysimeter and connected to the datalogger.

Presently the 300-N Lysimeter site consists of two 2.7 m diameter, 7.6 m deep caissons, and four 0.6 m diameter, 7.6 m deep caissons. Monitoring of natural recharge (deep drainage) at this site is restricted to one of these, the south caisson. The south caisson lysimeter is filled with Hanford formation sediment screened to contain less than one percent gravel (material > 2 mm). The lysimeter has remained essentially void of vegetation over its lifetime.

Automated measurement of drainage from the bottom of the lysimeter is accomplished using a tipping spoon gauge. In addition to this water flux measurement, two WFMs are installed within the lysimeter near the soil surface. Water content and matric potential profiles within the south caisson

lysimeter are also monitored, as is matric potential outside the lysimeter at the 7.5 m depth. Additional information about the 300N Lysimeter Site and instrumentation can be found in Phillips et al. (1979) and Sisson et al. (2002).

In December 2006 a windstorm produced a peak gust of 74 mph (a record for the month of December) at the Hanford Meteorological Station (HMS). This windstorm blew over the 300N Lysimeter tripod that housed the datalogger and other measurement control devices. The resulting damage to the datalogger and power supply as well as to the associated wiring was substantial. Soon after the damage at the site was identified, efforts were made to repair and reconnect wiring as well as to better secure the tripod at this location. By February of 2007 the site was again operational, except for the datalogger switch ports controlling the WFMs. In the process of reconstructing the site it was recognized that many undocumented and unused instruments were at the site and that the datalogger program was outdated. An evaluation of instrumentation and the datalogger was performed and a decision made to overhaul the site. This effort included removing unnecessary code from the datalogger program, removing unused sensors from the site, checking functionality of equipment, and encasing all wiring. Because the datalogger switch ports no longer functioned and with consideration given to the age of the dataloggers and the fact that technical support for this model was being phased out by the manufacturer, a new datalogger was purchased for this site. In August of 2007 the new datalogger was installed. By the end of August 2007 the overhaul of the 300N Lysimeter Site was complete. This effort significantly streamlined operation of the site and extended the operation of this critical facility. Figure 5.5 shows the surface of the 300N Lysimeter Site after completion of the overhaul.

The key measurement at this site is drainage from the bottom of the south caisson lysimeter. Figure 5.6 depicts cumulative drainage from this lysimeter for the period ending August 18, 2009. From the onset of drainage in 1981 to August 18, 2009 the drainage rate has averaged 62.6 mm/yr. During the time that the monitoring system was down in December 2006 and January 2007 due to the wind damage outage, drainage from the base of the lysimeter was not measured. Given the length of the drainage record at this site, the absence of this data does not significantly affect the reported average drainage rate.

Measured water contents and matric potentials at this site for FY 2007-2009 are shown in Figures 5.7 and Figure 5.8, respectively. The water content data displays increases in water content in response to the onset of winter precipitation and drying of the profile into the drier spring and summer months in each year. The datalogger at the 300N lysimeter site started to record periodic NAN (“not a number”) values from the water content sensors in February 2008. Later in the year periodic NAN values also started to appear for some of the matric potential sensors. Inspection of the wiring and datalogger connections at the field site did not reveal any obvious problems. The periodic NAN values generally occurred between the hours of 8PM and 4AM, during periods in which the air temperature was dropping, which suggested that this problem could possibly be a result of condensation on the datalogger/sensor leads inside the datalogger enclosure.

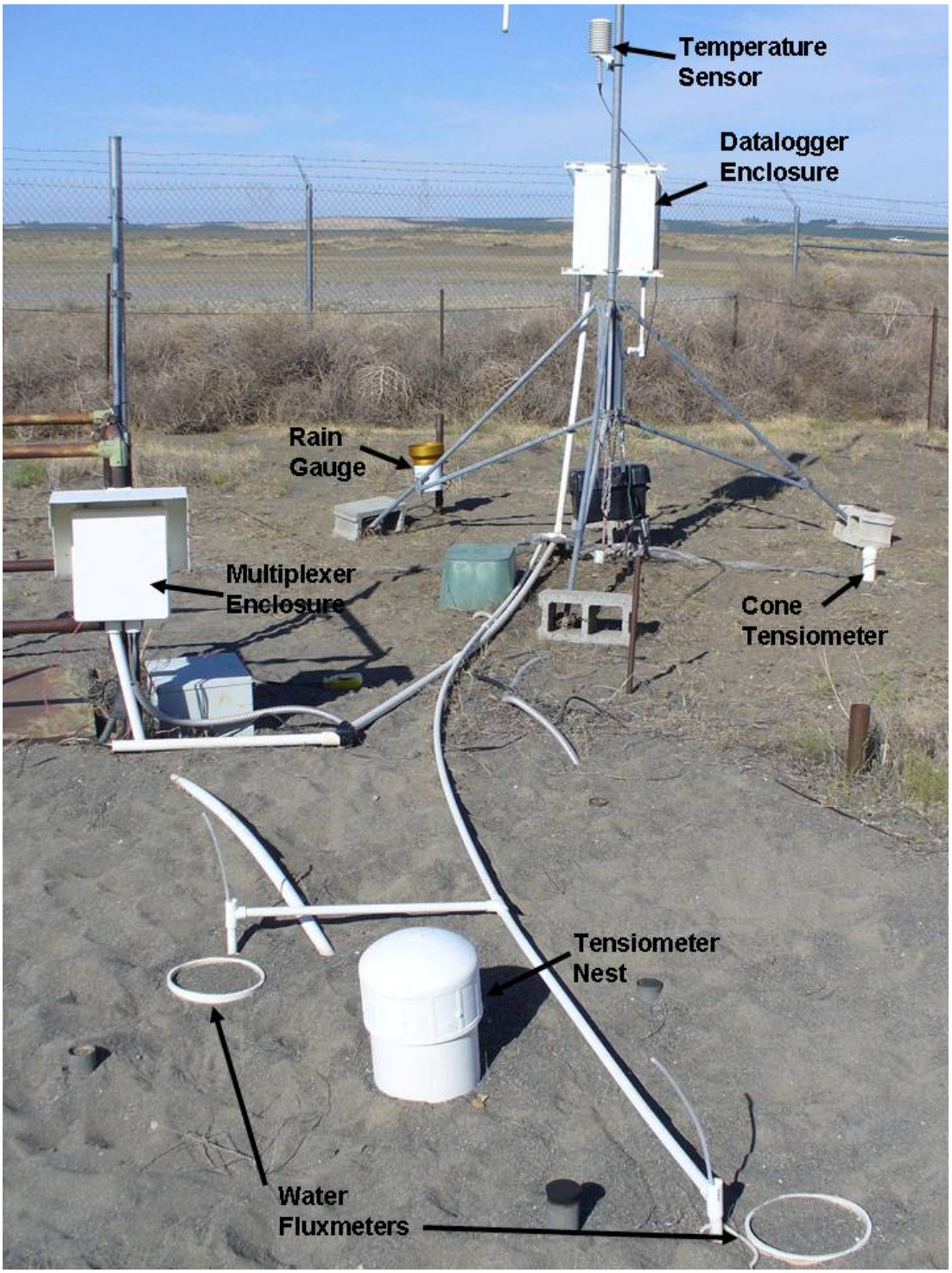

Figure 5.5. Surface Conditions of 300N Lysimeter Site on September 13, 2007. The coarse textured sand in the foreground is the approximate location of the south caisson.

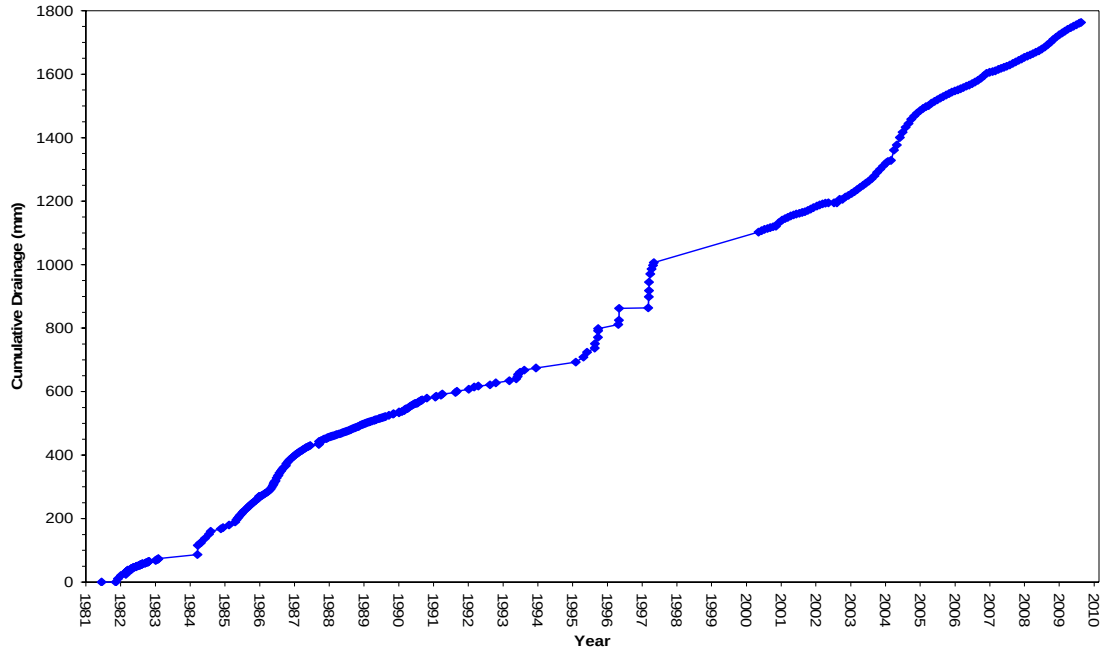

Figure 5.6. Cumulative Drainage Measured Since 1981 from the South Caisson at the 300N Lysimeter Site

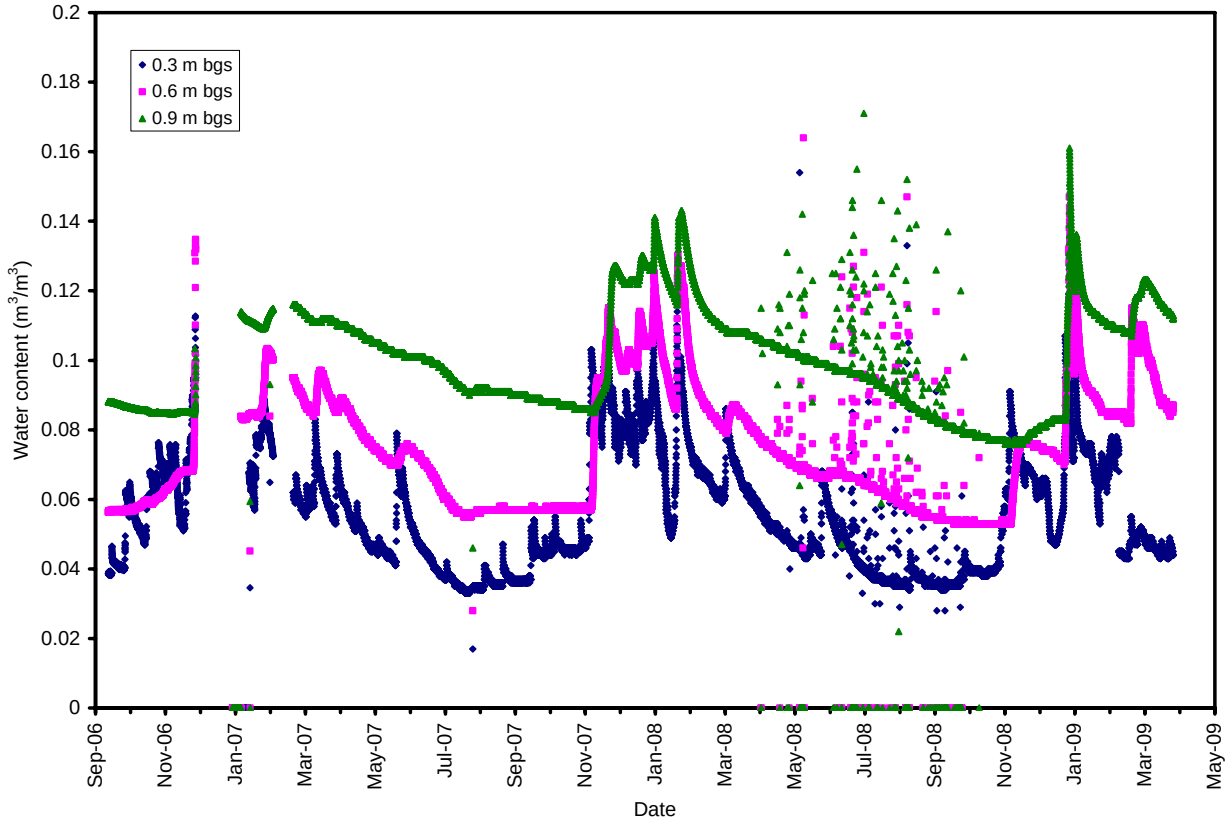

Figure 5.7. 300N Lysimeter Water Contents Measured at 0.3, 0.6, and 0.9 m Below Ground Surface

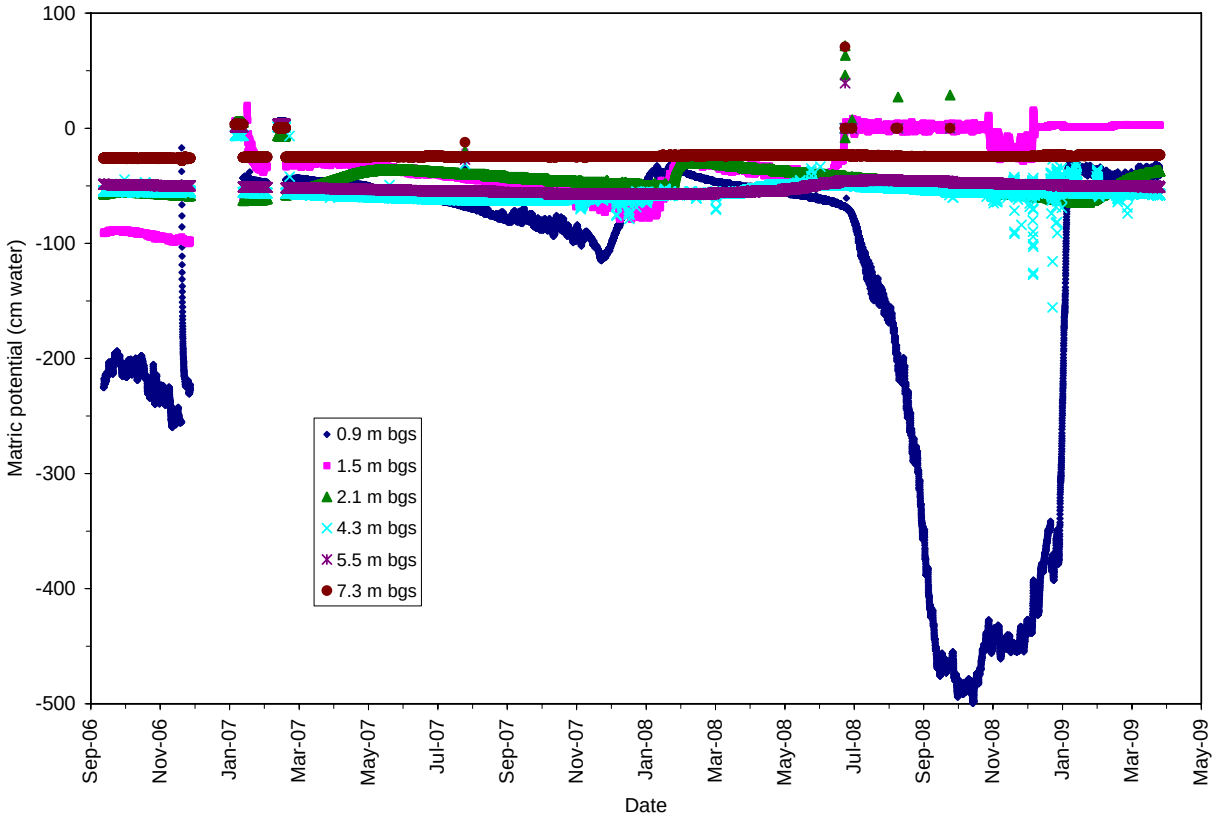

Figure 5.8. 300N Lysimeter Matric Potentials Measured at Six Depths.

Desiccant was added to datalogger enclosure in September 2008 and this seemed to resolve the problem, until March 2009. In FY09 a new project was started at the 300N lysimeter site to study the possible role of colloids in radionuclide transport. This project, whose principal investigator is Dr. Markus Flury of Washington State University, is supported by the DOE, Office of Science, Environmental Remediation Sciences Program (ERSP). The PNNL lead for this project was originally Dr. Glendon Gee who is now retired. The current PNNL lead for the project is Dr. Fred Zhang.

All six of the caissons at the 300N lysimeter facility are being used for this ERSP project. Field work for this project began in March 2009. On March 11, 2009, 3 mm of water containing a colloid with a stable Europium isotope was added to the south caisson and to three of the small caissons (Personal communication with Fred Zhang, March 24, 2009). The water application to the south caisson was a one-time addition, since this caisson is being monitored for long-term drainage rates. The water added to one of the small caissons also contained a KBr tracer. On March 24, 2009, 3 mm of water containing a colloid with stable Europium isotope was added to the north caisson and 6 mm of water with colloid was applied to the fourth small caisson. Water is being added periodically to all of the other caissons, except for the south caisson, to increase the rate of transport of the colloids and tracer.

The water content sensors appeared to be performing well from October 2008 through early-March 2009 at which point the datalogger again started recording spurious “NaN” values and significantly lower apparent water content values for all three water content sensors. Initial efforts to identify the problem

were unsuccessful. A recent site visit and more thorough investigation revealed that the water content probes had been nearly pulled out of the ground, apparently during preparation of the ground surface prior to water and colloid additions for the ERSP project described above. The probes were still partially covered with sand so this problem was not immediately obvious in the field. The probes were reinstalled to their correct depths in early September 2009 and fresh dessicant was also added to the datalogger enclosure. The water content probes now appear to be functioning properly again.

The matric potential data measured by tensiometers within the lysimeter are shown in Figure 5.8. The data are relatively predictable for some time periods with the near surface sensors exhibiting a drying profile into the spring and summer. The 0.9 m depth sensor prior to the December 2006 wind damage recorded uncharacteristic matric potential data, as did the 1.5 m depth sensor just after the system was repaired in early February 2007.

Figure 5.9 shows matric potential data from a cone penetrometer tensiometer located outside of the lysimeter at the 7.5 m depth. Although there is considerable scatter in the data from this sensor, the trend of the matric potential data fluctuates between about 24 and 34 cm over the three-year period that is shown. This range is consistent with the data from the tensiometer located at the 7.3-m-depth within the lysimeter (Figure 5.8) that indicates a relatively constant value of ~25 cm.

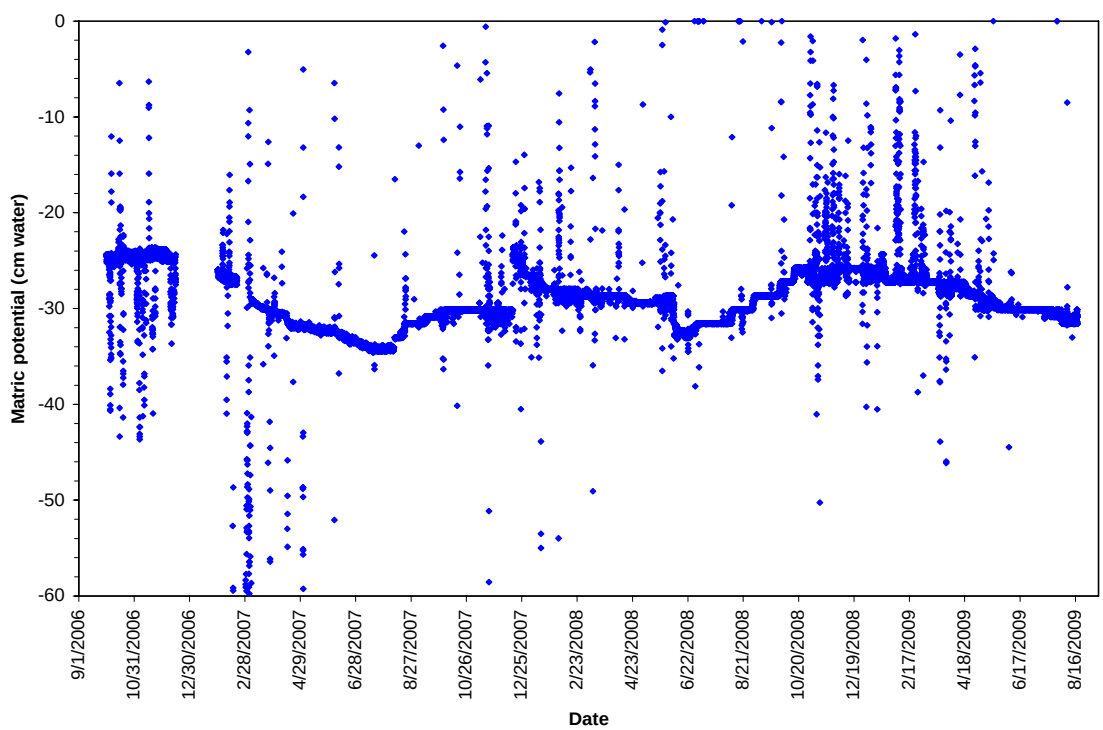

Figure 5.9. 300N Lysimeter Cone Penetrometer Tensiometer Matric Potentials Measured Outside of the South Caisson at 7.5 m Below Ground Surface (unfiltered data).

5.3 Solid Waste Landfill (SWL)

The Hanford SWL is located in the 600 Area approximately 6.5 km northwest of the Wye Barricade. At this location are two duplicate WFMs and three water content sensors. The WFMs are filled with gravelly sand material that includes large cobbles (Figure 5.10). The surfaces of the WFMs are void of vegetation. The water content sensors are placed in similar soil adjacent to the WFMs. Additional information about the instruments can be found in Keller and Gee (2005)[1]. Also at this site is a large (capture area of 85 m^2) basin lysimeter placed at the bottom of the landfill trench and filled with nonorganic waste thoroughly mixed with Hanford formation sediments (Wittreich and Wilson 1991). The surface material above the basin lysimeter is not as cobbly as the WFMs but is still very coarse. In addition, the basin lysimeter surface is vegetated with a sparse population of Indian Ricegrass (Figure 5.11). Measurement of the basin lysimeter drainage is carried out by a separate project, but the RACS project does maintain the data record for the basin lysimeter.

Figure 5.10. WFM Material at the Hanford SWL

[1] Keller JM and GW Gee. 2005. "Remediation Decision Support / Characterization of Systems Fiscal Year 2005 Recharge Task Status Report". Letter Report to George Last, PNNL, September 10, 2005.

Figure 5.11. SWL Basin Lysimeter (orange dots represent approximate corners of the basin lysimeter)

Figure 5.12 shows the sensor-measured water content from December 2004 through August 2009. As expected, the water content at all depths display seasonal variation in accordance with the wet winter months and dry summer months. The SWL dataset has a gap (missing data) from May 14, 2008 through March 26, 2009. The SWL is a remote site that does not have a phone line or a telemetry system. The data logging equipment runs on batteries that are recharged by solar panels. Data are uploaded manually during periodic site visits. The datalogger has the capacity to store data for in excess of 6 months with hourly measurement frequency before it overwrites memory. However, if equipment problems occur between site visits, we have no knowledge of them until after the data are uploaded during the next site visit.

During FY08, the last site visit prior to writing of the year-end recharge summary report (Nichols et al. 2008) was on May 14, 2008. Funding for recharge field site monitoring was temporarily discontinued in August, 2008 and was not resumed again until late-January, 2009 after a change in the Hanford Site contractors (from Fluor-Hanford to CHPRC) that are supporting the recharge monitoring efforts. When the SWL site was revisited in early February 2009, the data logger was found to be without power and battery was dead. All data that had been recorded after May 14, 2008 were lost.

Initial efforts to restore the site by recharging the battery were unsuccessful. After replacing a voltage regulator and battery, it was determined that one of the water content sensors had a short and was drawing excessive power that could not be maintained by the battery and solar panel.

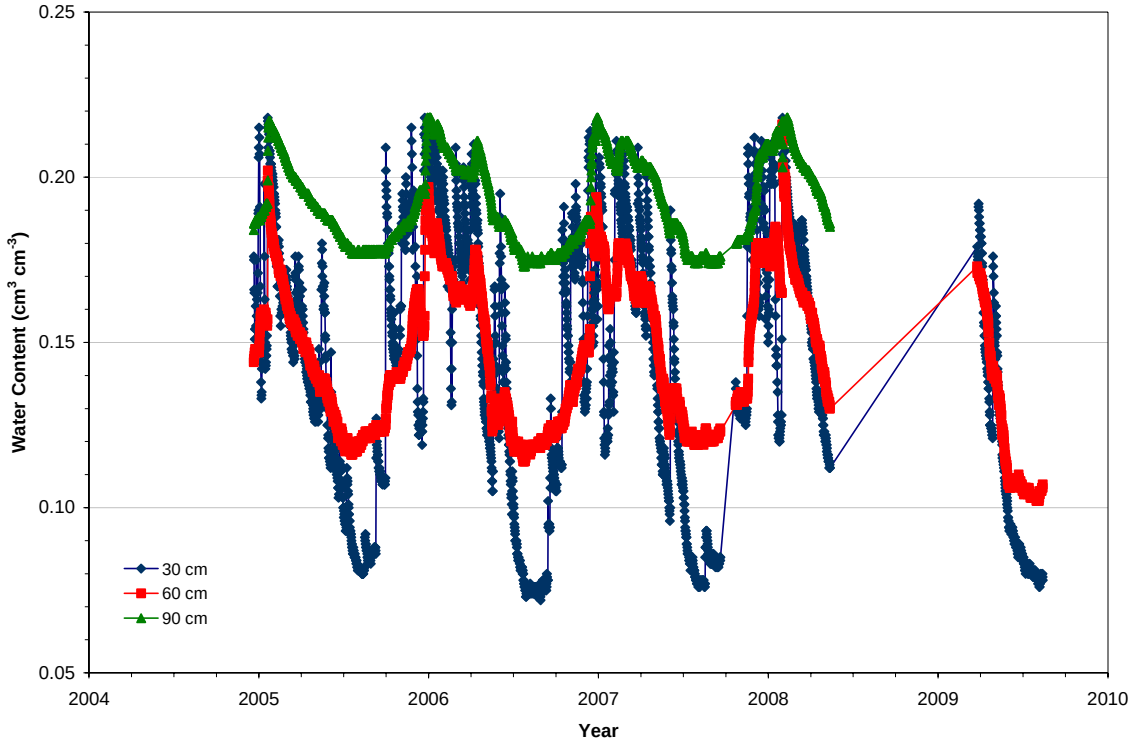

Figure 5.12. Volumetric Water Contents Measured at the SWL Site at 30, 60, and 90 cm Below Ground Surface

This water content sensor was disconnected from the datalogger and logging of the other sensors at the SWL site resumed on March 26, 2009. The faulty water content sensor at the SWL has not yet been replaced, but this is recommended.

Figure 5.13 shows the WFM measured drainage at this location. Beginning in March of 2007 the second WFM (WFM 2) measured significantly less drainage than the first WFM (WFM 1). A site visit determined that a plant had established itself next to the WFM 2, but outside of the divergence control tube, and the plant canopy was intercepting precipitation. As a result, in FY 2007 WFM 2 measured nearly 75 mm less drainage than did WFM 1. This affirms the significance of plant canopies in limiting recharge by capturing precipitation before it reaches the ground surface. The plant near WFM 2 was removed at that time, and any other plants in the vicinity of the WFMs are removed whenever they are noticed during site visits.

The data collected for January 31, 2008 and Feb 1, 2008 showed an excessive number of "tips" were recorded for WFM-2 in particular, but also for WFM-1. Although this could possibly be attributed, in part, to snowmelt and runon, it is also possible that a “spill event” may have occurred. A similar event was noted on January 19, 2005. The data shown in Figure 5.13 include corrections for these events. Although the evidence for spills is not conclusive, such spills could occur when the carboy located in an instrument caisson at this site used to store leachate is hauled to the surface to take away for emptying. If this carboy is accidentally tipped during transfer, the WFMs, which are installed very near the top of the caisson, could detect the additional water.

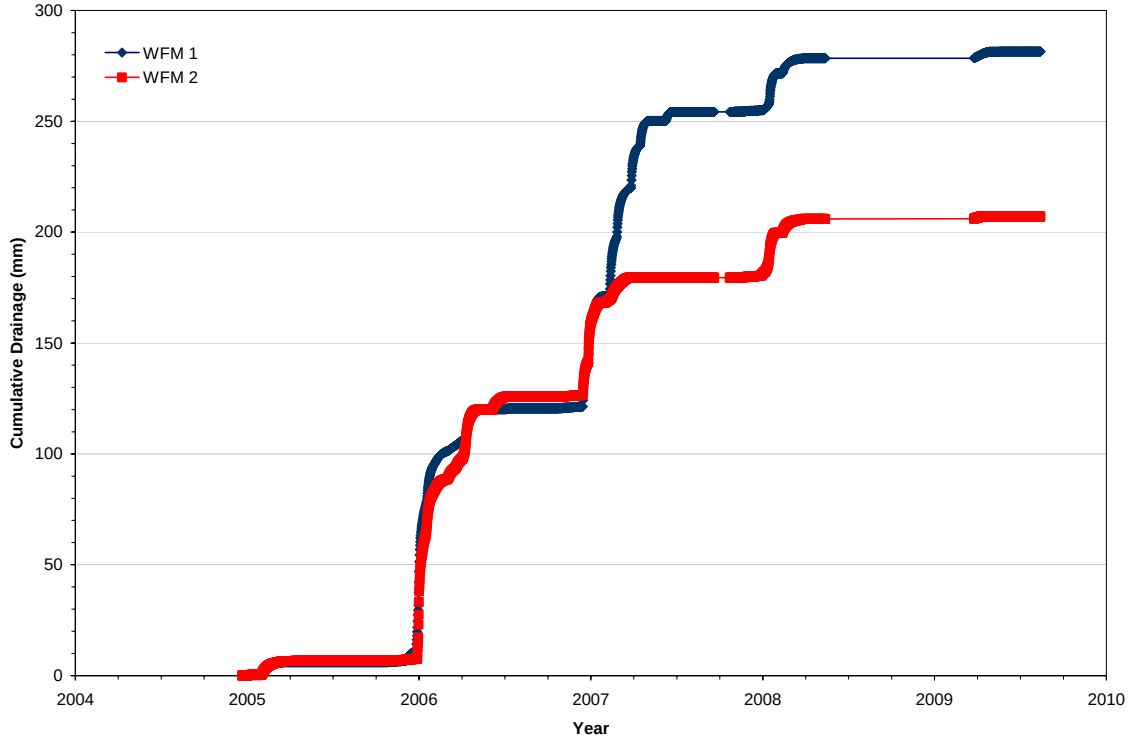

Figure 5.13. Cumulative Drainage Measured at the SWL Using Water Flux Meters Since December 21, 2004.

These spill events are speculative. Nevertheless, considering these possible spill events and other factors, such as the ability of plants to quickly establish themselves on the WFMs, and the infrequent site visits that can result in data losses if equipment failures occur, we consider the drainage measured from the basin lysimeter to be much more reliable than the WFMs for estimating long-term recharge rates at this site.

A plot of the drainage intercepted by the basin lysimeter is depicted in Figure 5.14. From July 1, 1996 to August 20, 2009, the average recharge calculated based on the basin lysimeter data was 50.3 mm/yr. This represents ~29% of the total precipitation that was recorded at the HMS during that time period. The rate of drainage appears to be greater in FY09 relative to FY08, but similar to the rates seen in FY03 and FY04.

5.3.1 Vegetation Characterization

Nichols et al. (2008) describe the results of a vegetation survey that was performed at the SWL site in August 2008. The surface of the SWL is dominated by bare ground with an average live plant cover of about 24%. This plant cover is mainly large bunchgrasses (Indian Ricegrass) with a minor component of cheatgrass scattered between bunchgrass clumps. Interested readers are referred to Nichols et al. (2008) for further details regarding this vegetation survey.

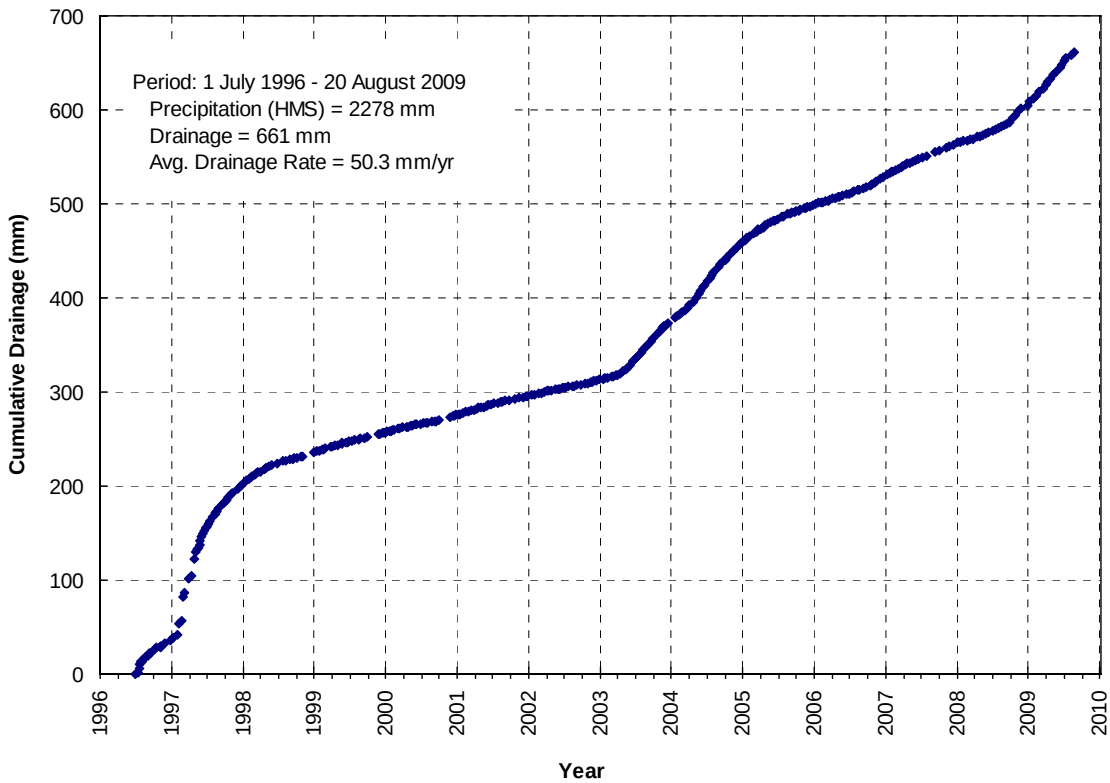

Figure 5.14. Cumulative Drainage Measured at the SWL from the Basin Lysimeter Since July 1, 1996.

It is interesting to note that the average drainage rate of 50.3 mm/yr determined from the 13-year record of data for the sparsely vegetated SWL basin lysimeter is almost as great as the average rate of 62.6 mm/yr determined from the 29-year record of data for the unvegetated south caisson at the 300N lysimeter facility. The sediments at the SWL site are somewhat coarser than those filling the south caisson at the 300N lysimeter facility and the SWL is sparsely vegetated, but the long-term average drainage rates are nevertheless similar.

5.4 Integrated Disposal Facility (IDF)

The IDF site is located on the south side of the Cold Creek bar, a depositional bar left in the lee of the Umtanum Ridge during Pleistocene cataclysmic flooding. This bar is dominated by gravel on the north side (closest to the main flood channels) grading to fine sand on the south side. A long, stabilized dune occupies the southern end of the IDF site. The presence of the dune at the IDF site indicates a history of sand dune activity in this area following the last cataclysmic flood (~13,000 years ago). The dune represents the northern fringe of a large dune field that exists below and south of the Central Plateau. The dune is stabilized by a very healthy stand of shrub-steppe vegetation and is not actively growing or migrating (the dune will eventually be removed during construction of the IDF). The nearest active dune to the IDF site is approximately 3 km south of this area (Gaylord and Stetler 1994).

Recharge for the IDF site has been estimated using environmental tracers. For the immobilized low-activity waste (ILAW) 2001 Performance Assessment, Fayer et al. (1999) used the chloride and chlorine-36 tracer techniques to estimate recharge rates. For the 2005 IDF PA, two tracer techniques were used:

chloride mass balance (CMB) and deuterium and oxygen-18 (Fayer and Szecsody 2004). A description of these two techniques can be found in Appendix B of Fayer and Szecsody (2004).

Neutron probe measurements of soil moisture were collected at this site from a series of 16 access tubes located in different vegetation regimes from 2000 through 2008. No measurements were made at the IDF site in 2009 because precipitation levels were normal, suggesting that the frequency of neutron probe measurements could be reduced. Neutron probe monitoring of soil moisture at this site is expected to resume in FY10.

5.5 Field Lysimeter Test Facility (FLTF)

The Field Lysimeter Test Facility (FLTF) was originally constructed from November 1986 through June 1987 (Gee et al. 1989, Campbell et al. 1990) and is located adjacent to the HMS. There are three different lysimeters types at the FLTF: fourteen 3-m-deep by 2-m-diameter drainage lysimeters; six 3-m-deep by 0.3-m-diameter small-tube lysimeters; and four 1.5-m by 1.5-m by 1.7-m-deep weighing lysimeters.

Figure 5.15 depicts an artist's rendering of the FLTF at the Hanford Site (Fayer and Gee 2006) showing the layout of the facility. Additional information about the facility and data collection prior to 2004 can be found in Fayer and Szecsody (2004). Under the Recharge Measurement task, drainage is measured from twelve of the drainage lysimeters, four of the small-tube lysimeters, and one of the weighing lysimeters. Automated hourly measurements of mass are made on all four weighing lysimeters. Additionally, tensions are measured in seven lysimeters at various depths. Temperatures within the lysimeters are also measured at over 50 locations, but those data are not summarized here. Of the 21 lysimeters being monitored, nine of them are regularly irrigated to mimic precipitation conditions that are three times greater than the long-term average ambient precipitation. Table 5.2 Summary of FLTF Treatments and Monitoring Periods - summarizes the test treatments for the monitored lysimeters. A brief description of each test is provided in Table 2.

The enhanced precipitation treatment is attained through irrigation that is applied to attain a target precipitation plus irrigation rate. Figures 5.16 through 5.21 illustrate the cumulative application rate and cumulative target rate for the FLTF water years[1] 2004-2009. The enhanced precipitation treatment does not necessarily represent climatic conditions three times wetter than current climatic conditions. This is because a larger fraction of the enhanced precipitation is applied during spring and summer months when the atmosphere is relatively dry and warm than would be expected for a wetter climate. Consequently, the portion of the enhanced precipitation that is lost to evapotranspiration is likely greater than would be expected with an actual wetter climate with greater precipitation occurring in cooler months.

[1] A *water year* is a twelve-month period, usually selected to begin and end during a relative dry season, used as a basis for processing stream flow and other hydrologic data. The period from October 1 to September 30 is widely used in the United States, but other periods are also used depending on local climate conditions. The FLTF water year is designated to begin November 1 and end October 31; this period was selected based on considerations of local soil moisture and climatic patterns encountered at this facility.

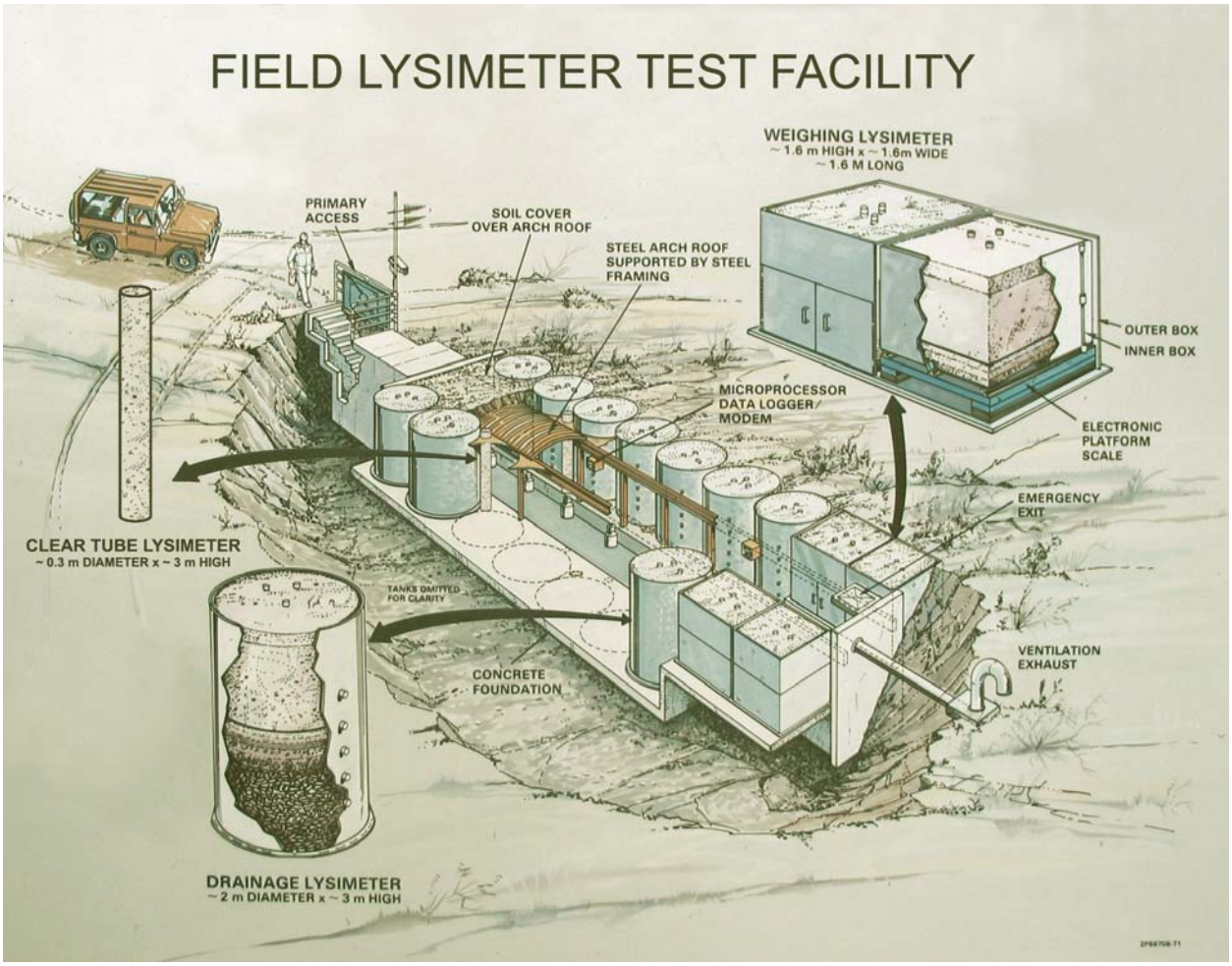

Figure 5.15. Artist's Rendering of the FLTF at the Hanford Site (Fayer and Gee 2006).

Table 5.2. Summary of FLTF Treatments and Monitoring Period

Test Description	ID Treatment	Precipitation		Vegetation[a]			ID Lysimeter	Monitoring Period	
		Ambient	Enhanced	NV	SRV	DRV		Start	End
Hanford Barrier	1	✓				✓	W1	4 Nov 87	present
		✓				✓	C3	9 Nov 88	present
	2	✓		✓			D1	4 Nov 87	present
	3		✓			✓	W3	4 Nov 87	present
			✓			✓	C6	9 Nov 87	present
Eroded Hanford Barrier	6	✓				✓	D3	4 Nov 87	present
	18		✓			✓	D13	27 May 98	present
Gravel Mulch	8	✓		✓			C1	17 Nov 89	present
	10		✓	✓			C4	17 Nov 89	present
Pitrun Sand	9	✓				✓	C2	17 Nov 89	present
	11		✓			✓	C5	17 Nov 89	present
Basalt Side Slope	12	✓		✓			D2	1 Nov 94	present
Sandy Gravel Side Slope	14	✓		✓			D4	1 Nov 94	present
Hanford Barrier Erosion / Dune Sand Deposition	19	✓			✓		D5	17 Nov 97	present
		✓			✓		W2	17 Nov 97	present
	20		✓		✓		D12	17 Nov 97	present
			✓		✓		W4	17 Nov 97	present
Sand Dune Migration	21	✓			✓		D6	22 Jul 98	present
	22		✓		✓		D8	22 Jul 98	present
Modified RCRA Subtitle C Barrier	23	✓				✓	D7	23 Feb 99	present
	24		✓			✓	D9	23 Feb 99	Present

(a) Vegetation Symbols: NV = no vegetation, SRV = shallow rooted vegetation and DRV = Deep rooted vegetation.

Table 5.3. FLTF Treatment Descriptions

Treatment Name	Treatment Description	Lysimeter ID
Hanford Barrier	1.5 m of silt loam that rests on a sequence of materials grading from sand to gravel filter layers and finally to basalt riprap.	W1, C3, D1, W3, C6
Eroded Hanford Barrier	Similar to the Hanford Barrier test, with the exception that the silt loam layer thickness is reduced from 1.5 to 1.0 m.	D3, D13
Gravel Mulch	0.15 m of coarse gravel above 1.35 m of screened (to remove gravel) Pitrun sand, on top of unscreened Pitrun sand.	C1, C4
Pitrun Sand	1.5 m of screened (to remove gravel) Pitrun sand on top of unscreened Pitrun sand.	C2, C5
Basalt Side Slope	1.5 m of unscreened basalt riprap. Beneath the basalt layer is a 0.15-m thick asphaltic concrete layer underlain by gravel and more basalt riprap. Resting on top of the asphaltic concrete is about 2 to 3 cm of silt loam.	D2
Sandy Gravel Side Slope	1.5 m of sandy gravel resting on an asphaltic concrete layer in a manner similar to the basalt side slope test.	D4
Hanford Barrier Erosion / Dune Sand Deposition	Similar to the Hanford Barrier test, with the exception that the top 20 cm of silt loam is removed and replaced with dune sand.	D5, W2, D12, W4
Sand Dune Migration	3 m of dune sand.	D6, D8
Modified RCRA Subtitle C Barrier	A barrier design with only 1 m of silt loam. In addition, the silt layer has two modifications: 1) the upper 0.5 m of silt loam is amended with pea gravel at the rate of 15% by weight, and 2) the lower 0.5 m of silt is compacted to create a low-conductivity layer.	D7, D9

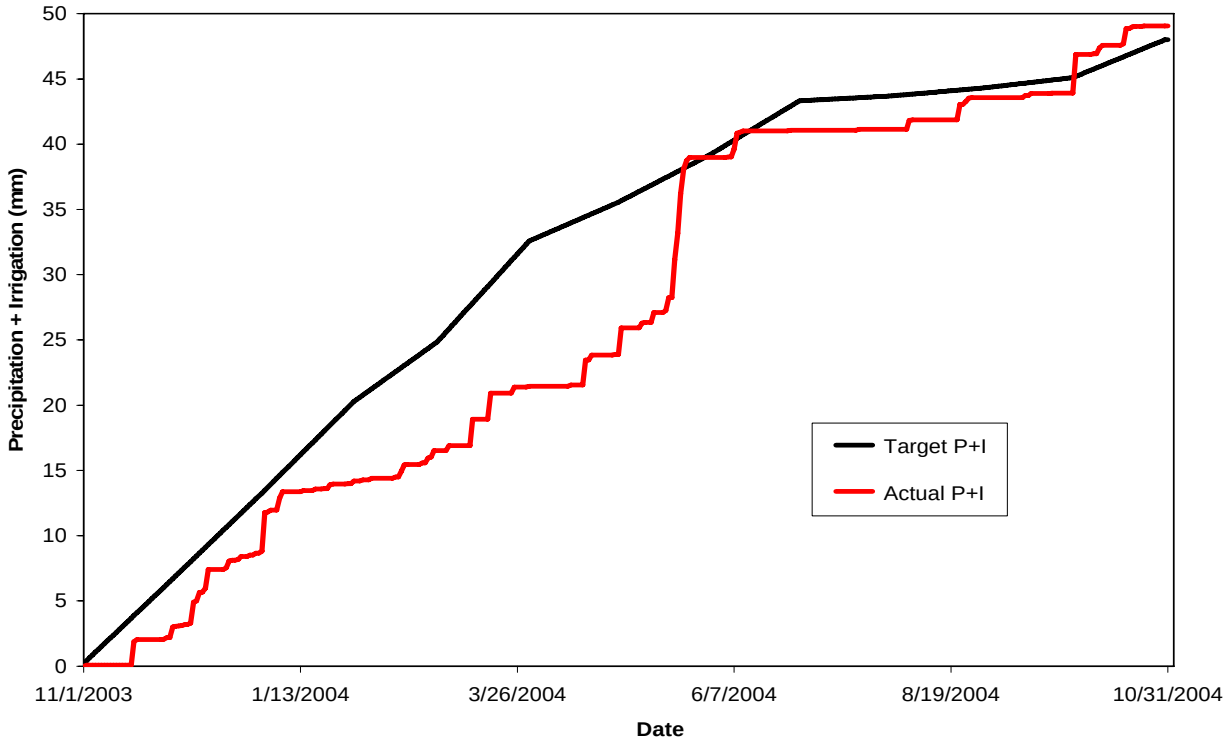

Figure 5.16. FLTF-Precipitation Plus Irrigation Water Year 2004 (11/01/03-10/31/04)

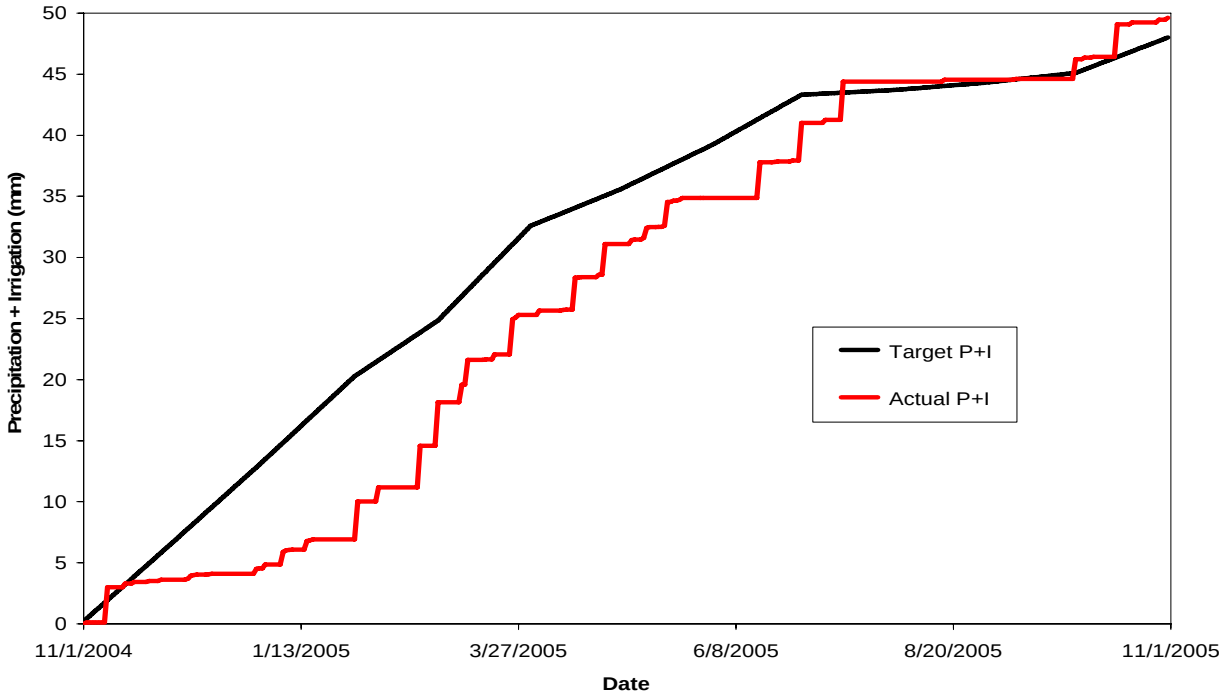

Figure 5.17. FLTF Precipitation Plus Irrigation Water Year 2005 (11/01/04-10/31/05)

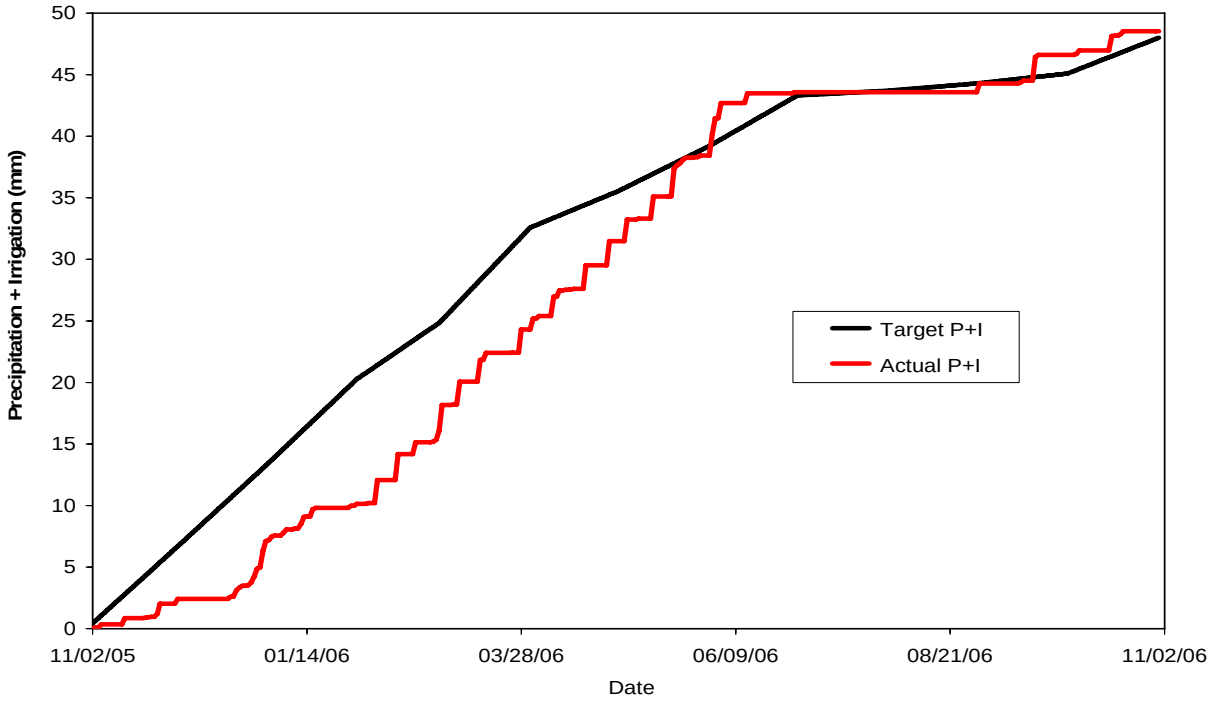

Figure 5.18. FLTF Precipitation Plus Irrigation Water Year 2006 (11/01/05-10/31/06)

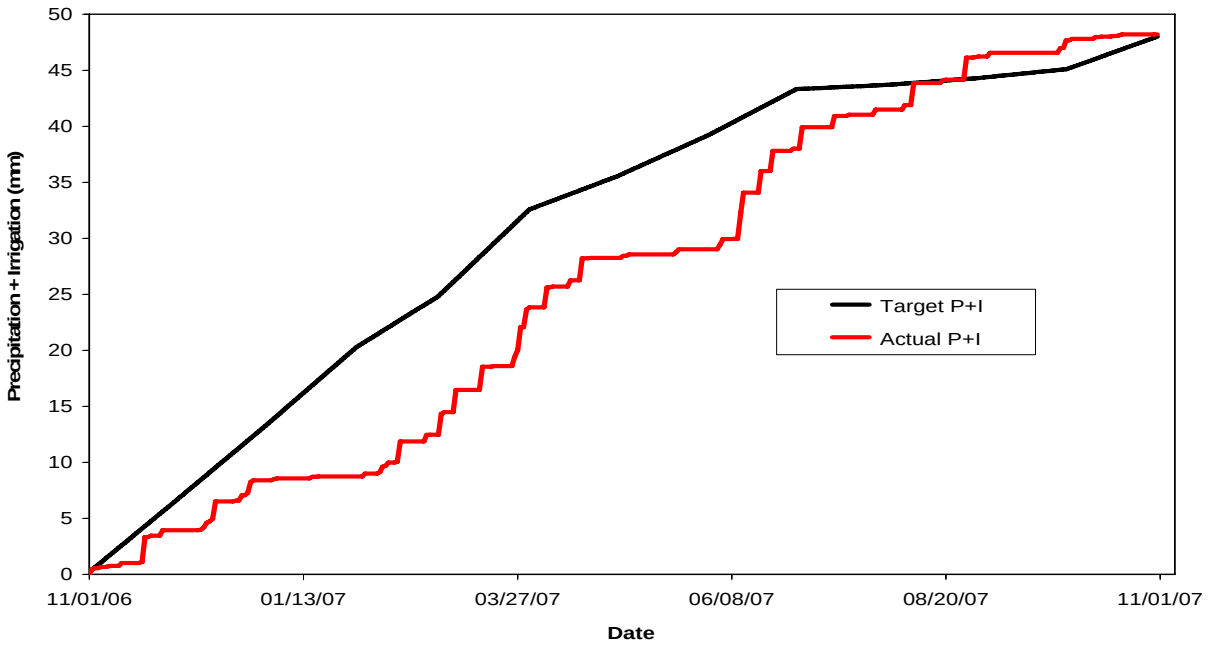

Figure 5.19. FLTF Precipitation Plus Irrigation Water Year 2007 (11/01/06-10/31/07)

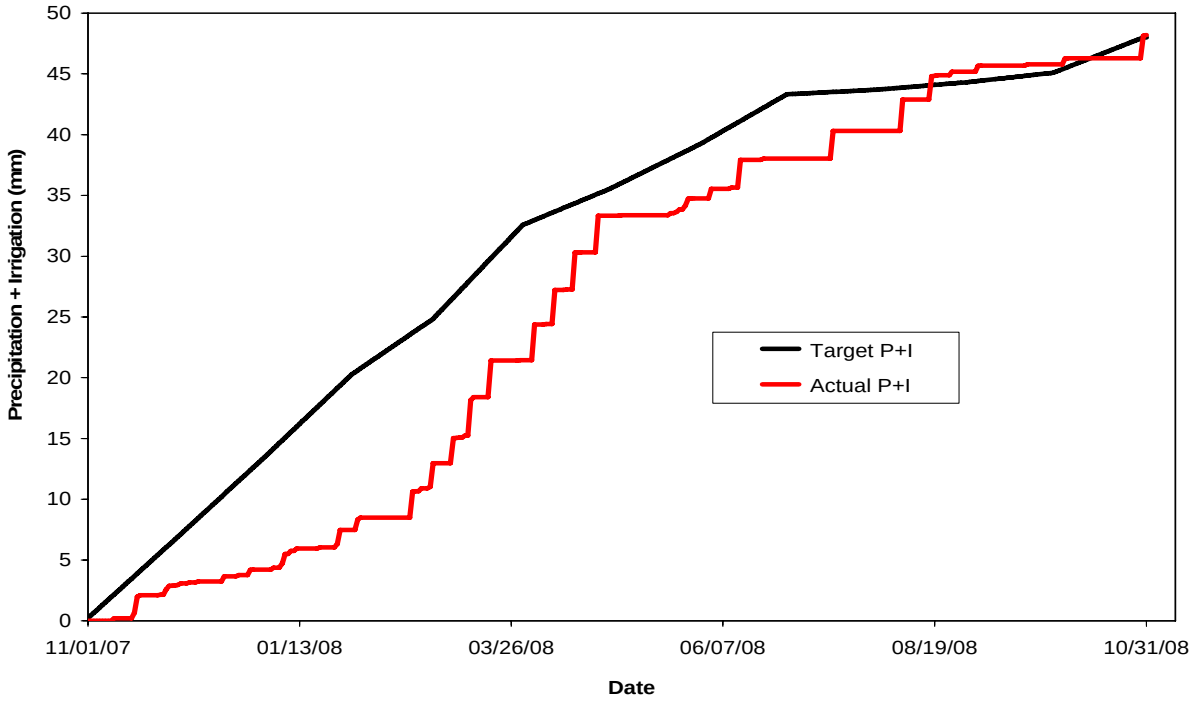

Figure 5.20. FLTF Precipitation Plus Irrigation Water Year 2008 (11/01/07-10/31/08).

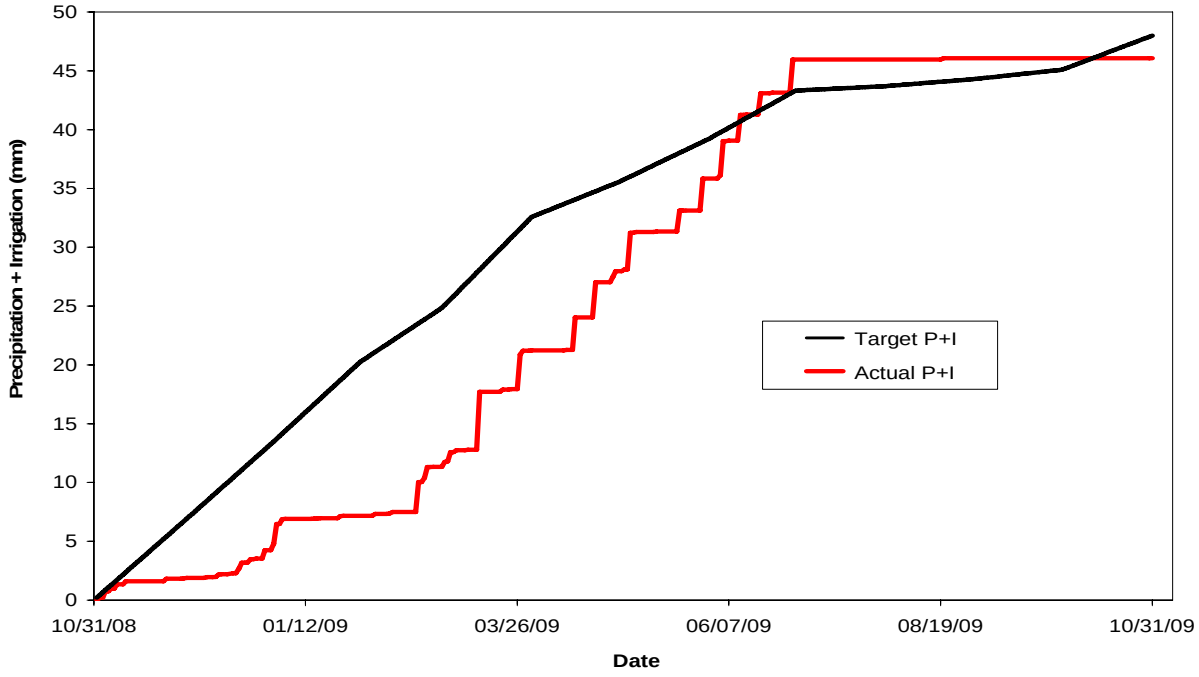

Figure 5.21. FLTF Irrigation Plus Precipitation Water Year 2009 (11/01/08-10/31/09)

Figure 5.22 shows the cumulative drainage from the Hanford Barrier Erosion/Dune Sand Deposition treatment. Drainage is measured at a rate of 151.6 mm/yr under the 3X precipitation conditions for D12. The same treatment under ambient precipitation conditions (D5) began draining in 2002 and has drained a total of 2.7 mm for an average drainage rate of 0.2 mm/yr calculated since installation (0.4 mm/yr if calculated since drainage onset). Figure 5.23 shows the cumulative drainage from the sand dune migration test. Under enhanced precipitation this treatment produces significant drainage, with a measured drainage rate of 198.2 mm/yr. The D6 lysimeter (ambient precipitation) did not begin draining until 2004, but has drained steadily since that time for an average drainage rate of 21.9 mm/yr calculated since installation (38.2 mm/yr if calculated since drainage onset). Figure 5.24 shows the cumulative drainage for the sandy gravel (D4) and basalt side slope (D2) treatments under ambient precipitation conditions. Both lysimeters have consistently drained at significant rates since monitoring of these treatments began, with drainage rates of 41.0 mm/yr for the basalt treatment and 94.6 mm/yr for the sand gravel treatment. Figure 5.25 shows the cumulative drainage for the eroded Hanford Barrier treatment. Drainage from this lysimeter didn't begin until 2003, but has continually drained since, although at decreasing rates every year. Figure 5.26 shows cumulative drainage from the gravel mulch and pit run sand treatments under ambient and enhanced precipitation. Both treatments continued to have significant drainage in 2009. A summary of average drainage rates for each treatment as of September 14, 2007 is presented in Table 3.

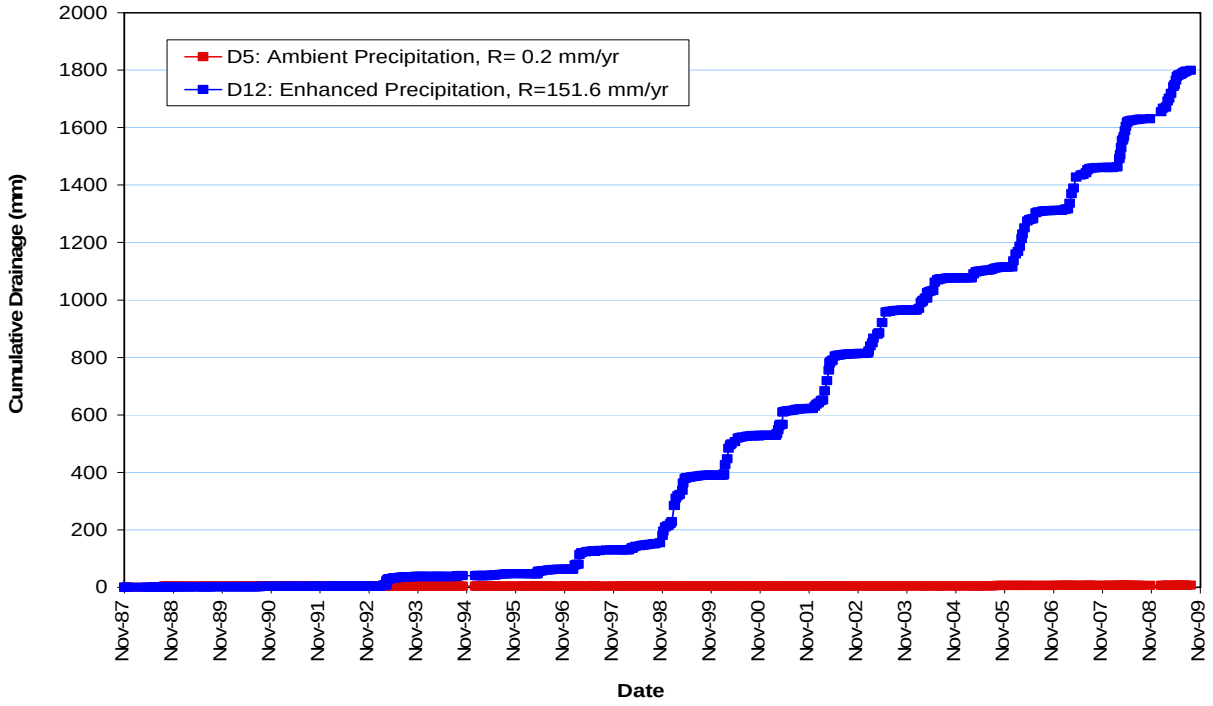

Figure 5.22. FLTF Cumulative Drainage for FLTF Treatments D5 and D12 Representing a Hanford Barrier Dune Sand Deposition Test (Shallow Rooted Vegetation). R is the mean annual drainage rate.

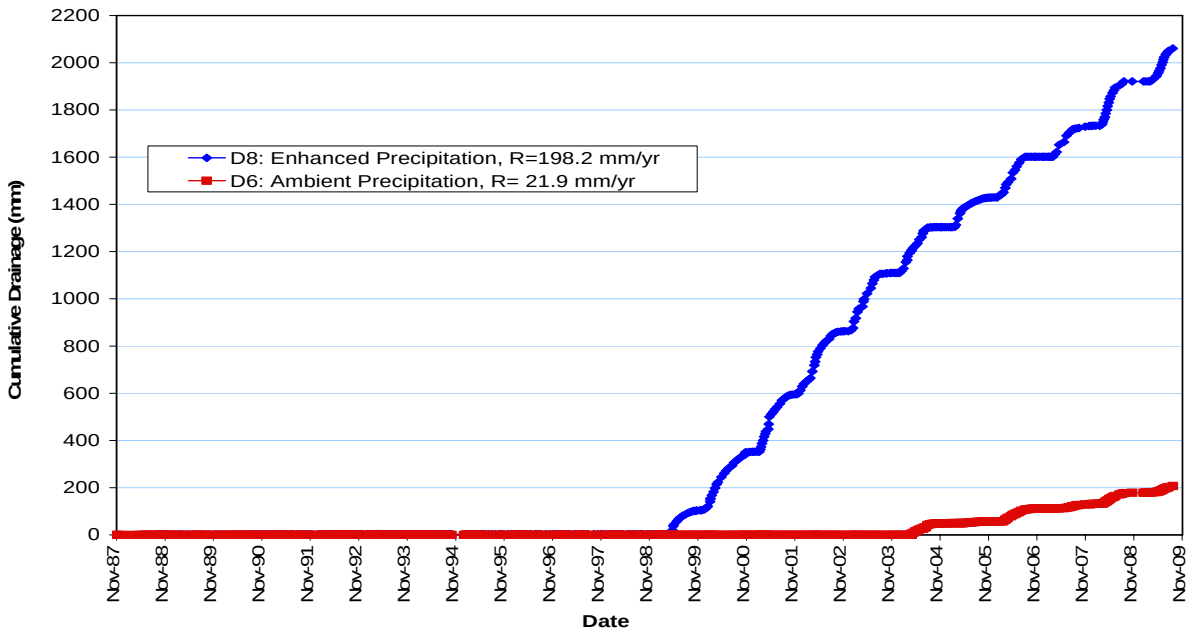

Figure 5.23. Cumulative Drainage for FLTF Treatments D6 and D8 Representing a Sand Dune Migration Test (Shallow Rooted Vegetation). R is mean annual drainage rate.

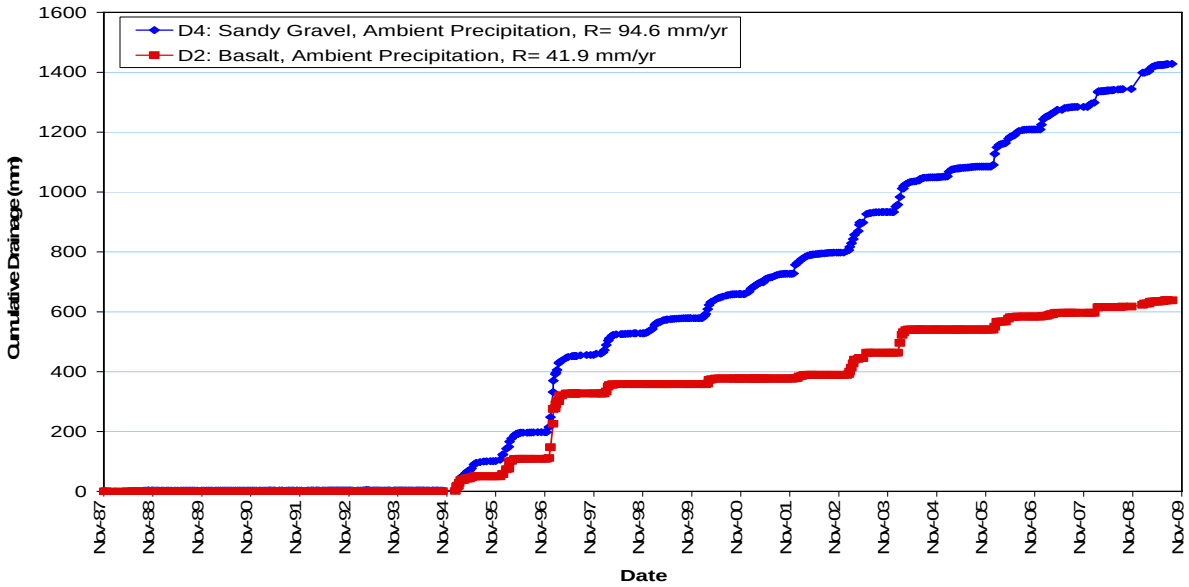

Figure 5.24. Cumulative Drainage for FLTF Treatments D2 and D4 Representing a Barrier Side Slope Test. R is the mean annual drainage rate.

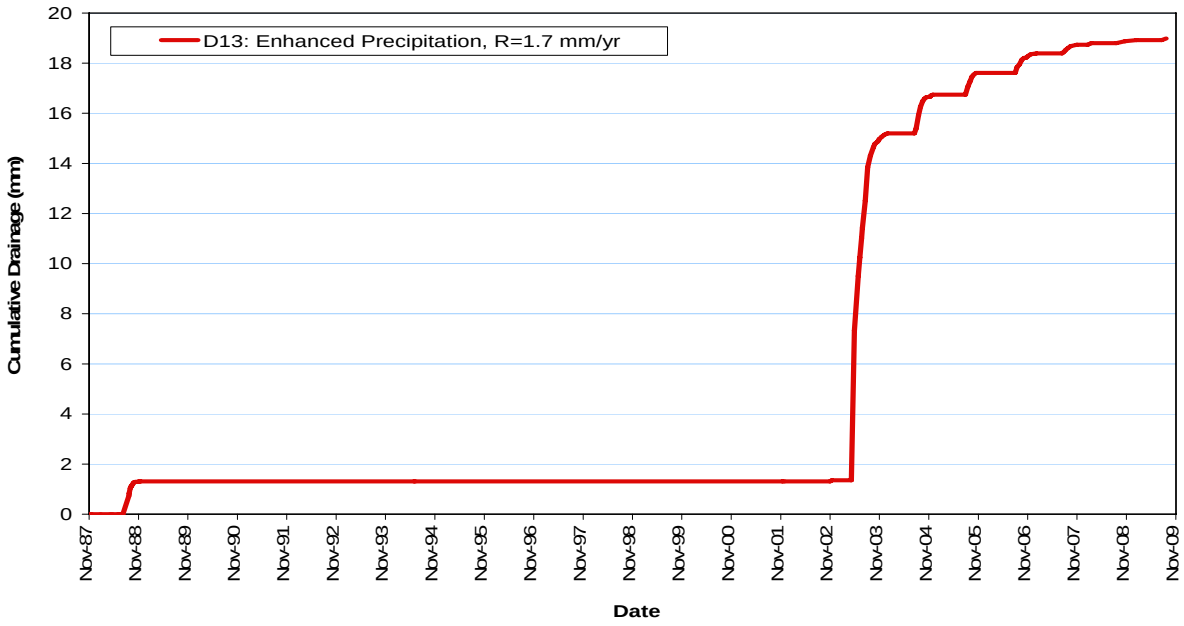

Figure 5.25. Cumulative Drainage for FLTF Treatment D13 Representing an Eroded Prototype Hanford Barrier Test. R is the mean annual drainage rate.

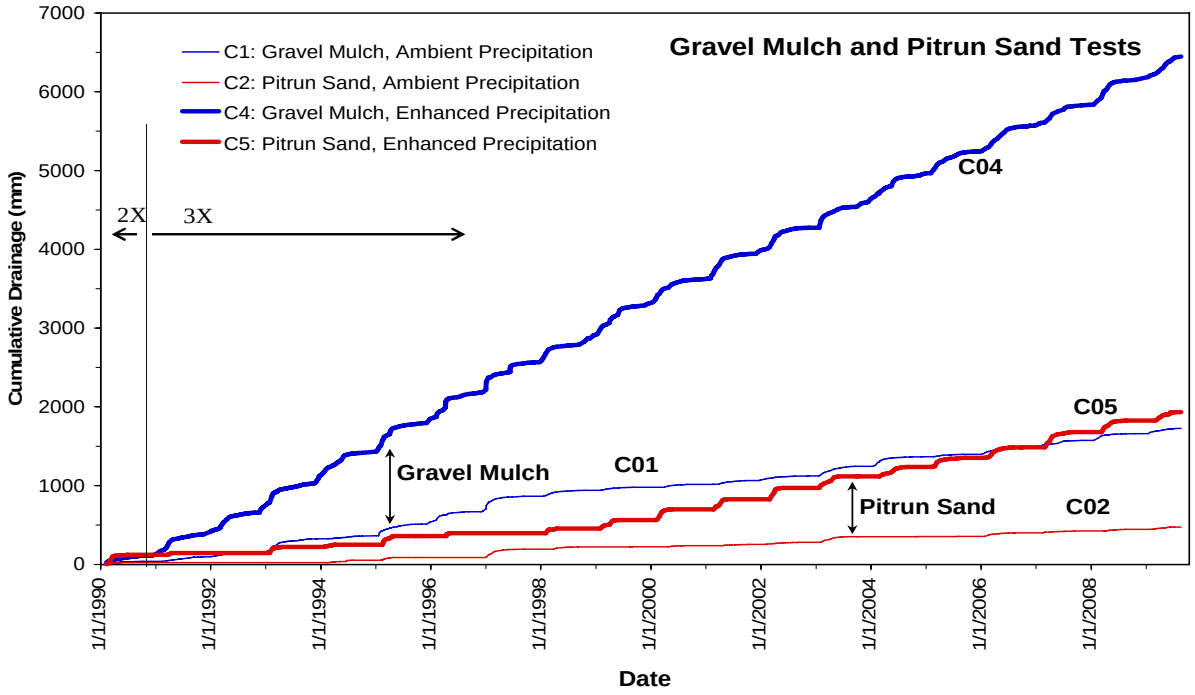

Figure 5.26. Cumulative Drainage for FLTF Treatments C1, C2, C4, and C5.

Table 5.4. Summary of FLTF Drainage Rates Though August 20th, 2009

Test Description	Lysimeter ID	Precipitation Treatment	Monitoring Period Start	Drainage Rate (mm/yr)[a]	
				Installation Basis	Drainage Onset Basis
Hanford Barrier	D1	Ambient	4-Nov-1987	0.00	NA
Eroded Hanford Barrier	D3	Ambient	4-Nov-1987	0.00	NA
	D13	Ambient	27-May-1998	1.70	2.6
Gravel Mulch	C1	Ambient	17-Nov-1989	86.9	87.6
	C4	Enhanced	17-Nov-1989	324.8	58.5
Pitrun Sand	C2	Ambient	17-Nov-1989	23.5	4.2
	C5	Enhanced	17-Nov-1989	97.8	17.6
Basalt Side Slope	D2	Ambient	1-Nov-1994	41.9	41.9
Sandy Gravel Side Slope	D4	Ambient	1-Nov-1994	94.6	94.6
Hanford Barrier Erosion / Dune Sand Deposition	D5	Ambient	17-Nov-1997	0.20	0.20
	D12	Enhanced	17-Nov-1997	151.6	151.6
	W4	Enhanced	17-Nov-1997	66.7	66.7
Sand Dune Migration	D6	Ambient	22-Jul-1998	21.9	38.2
	D8	Enhanced	22-Jul-1998	198.2	198.2
Modified RCRA SubtitleC Barrier	D7	Ambient	23-Feb-1999	0.00	
	D9	Enhanced	23-Feb-1999	0.00	

(a) All drainage rates reported to three significant figures.

The drainage rate is calculated for two bases: first calculating the average annual drainage rate on the basis of time since installation, and second calculating the average annual drainage rate on the basis of time since drainage onset. A newly installed lysimeter requires some time to stabilize and begin to drain at a long-term average rate, so including the time required to reach a long-term moisture profile may not provide the best basis for estimating an annual average drainage rate; hence the reason for the second basis. A lysimeter experiencing higher precipitation (such as for the enhanced precipitation treatments) will stabilize faster, so in those cases the drainage rates calculated under both bases do not differ much or at all. For ambient conditions in less conductive soils, stabilization of the moisture profile takes longer and the difference can be substantial.

Figure 5.27 shows the change in water storage since October 1, 2004 for W1 and W3, as calculated from the weighing lysimeter measurements of mass. As to be expected, water storage increases during the winter and decreases to a minimum in late summer, with a greater change in water storage under enhanced precipitation conditions.

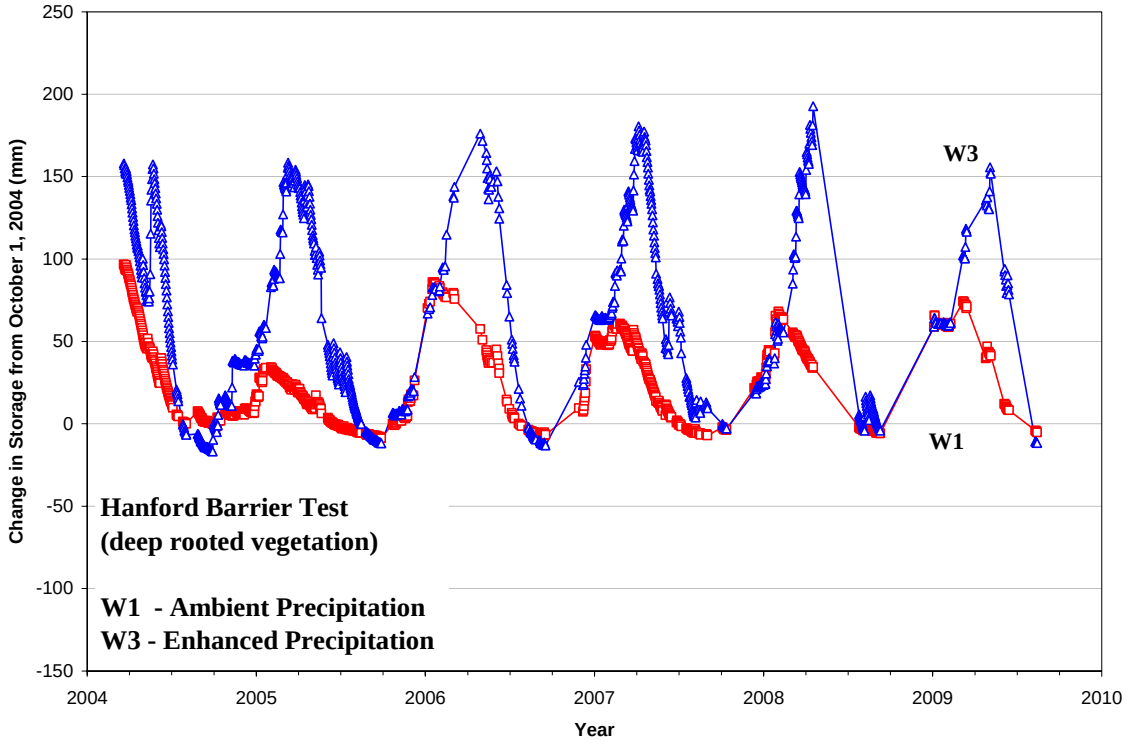

Figure 5.27. Changes in water storage (in equivalent water depth, mm) for weighing lysimeters W1 and W3 at the FLTF.

The scale for W4 was replaced in late 2006. During FY 2007 weighing lysimeters W2 and W4 both responded uncharacteristically. Just after it was installed and calibrated (mid-January 2007), W4 appeared to experience a bind that went unnoticed until late in 2007. Intervention in the form of prying on the scale between the sediment-filled lysimeter box and its enclosure appeared to alleviate the problem at least temporarily.

The CR7 datalogger that records measurements from the weighing lysimeters has been working intermittently for the past 3-4 years resulting in numerous periods without data. This datalogger was slated for replacement in FY 2008 but several issues were identified with using the replacement datalogger, a CR1000 model: the CR7 was determined to be better suited for use with the scales at FLTF. The CR1000 would appear to require voltage amplifiers be built in order to achieve the same precision as the CR7. The lack of wiring diagrams for this old system that includes numerous thermocouples connected to the CR7 datalogger has also hindered such an upgrade. Before commencing such an upgrade, the use and value of the data collected from the weighing lysimeters and thermocouples needs to be reviewed. During FY08 the control module of the CR7 datalogger at FLTF was replaced with one from another CR7 datalogger that was no longer in use. These changes do not appear to have corrected the problems.

During FY2008 lysimeters W2 and W4 continued to respond uncharacteristically. The weighing lysimeter scales were calibrated again in September 2008. The scale readings for W4 in particular were hysteretic, which lead the technician who calibrated the scales to speculate that the scale for W4 has a bad

load cell. Lysimeters W2 and W4 continue to exhibit uncharacteristic behavior so the data from these lysimeters is not shown here.

At some point a decision should be made about what to do with these two weighing lysimeters (W2 and W4) and the datalogger at FLTF. Drainage from the bottom of the various lysimeters at the FLTF is the key variable of interest, so measuring the changes in water storage recorded by the weighing lysimeters is not considered to be absolutely critical. Nevertheless, changes in water storage represent one component of the soil water balance equation so if these data were reliable they would be very useful for relative comparison, and for validation of numerical models that include the processes of evapotranspiration and root-water update.

Matric potential data for the D12 and W4 lysimeters at 100 cm and 150 cm depths are shown in Figures 5.28 and 5.29, respectively. These data exhibit typical seasonal variation, with drying in the summer (more negative matric potentials) and wetting in the winter (less negative matric potentials). At times the matric potential measurements in the W4 lysimeter is positive, likely because saturated conditions in the lysimeter occurred between drainage measurements. Matric potentials within the sand dune migration treatment lysimeters also display typical season variation (Figure 5.30). Measured water potentials for the ambient D6 lysimeter and enhanced precipitation D8 lysimeter are generally comparable.

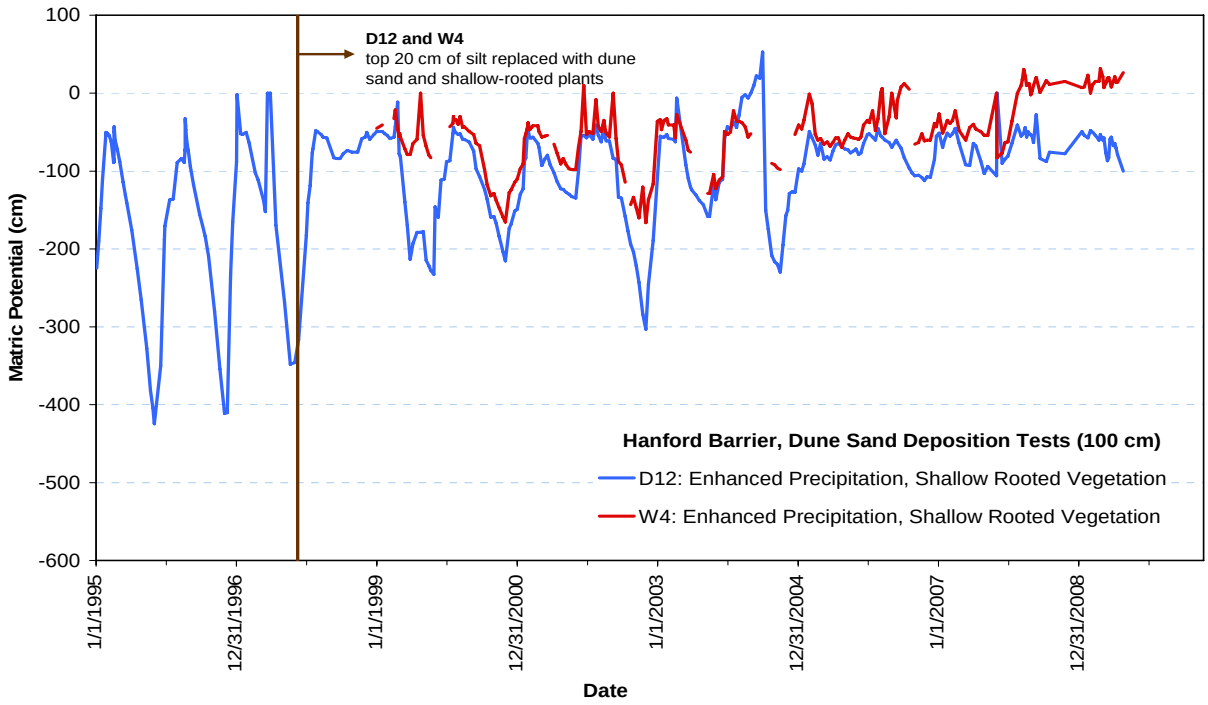

Figure 5.28. FLTF Matric Potentials for Hanford Barrier Erosion/Dune Sand Deposition Test at 100 cm Depth.

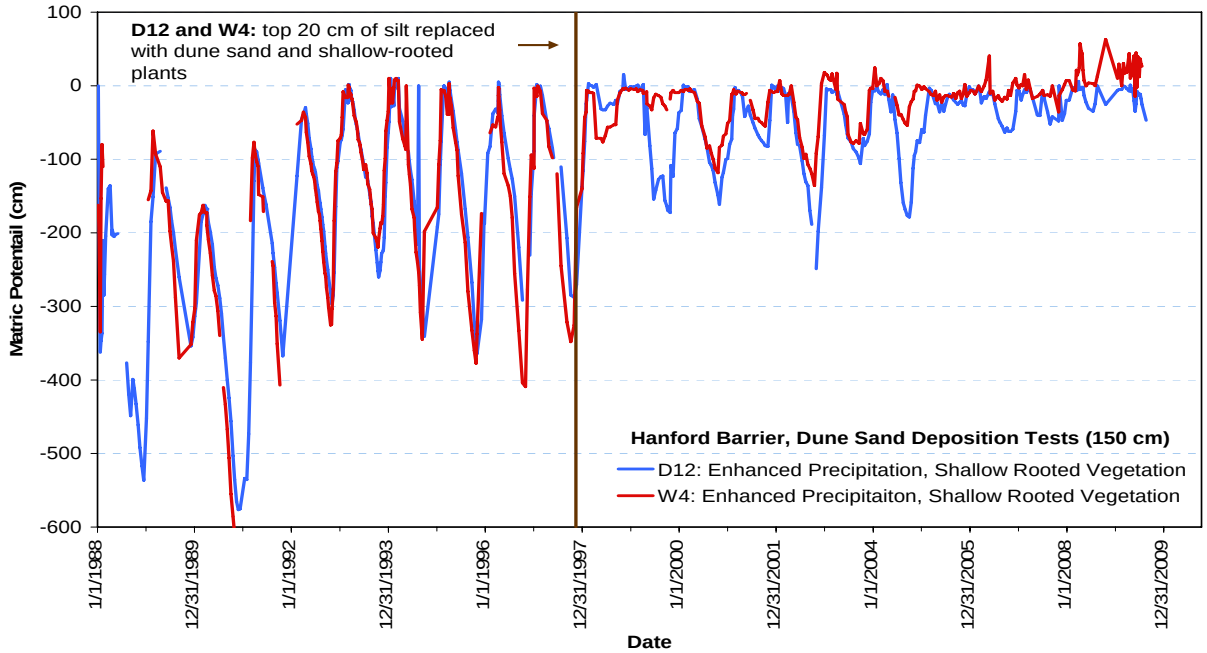

Figure 5.29. FLTF Matric Potentials for Hanford Barrier Erosion/Dune Sand Deposition Test at 150 cm Depth.

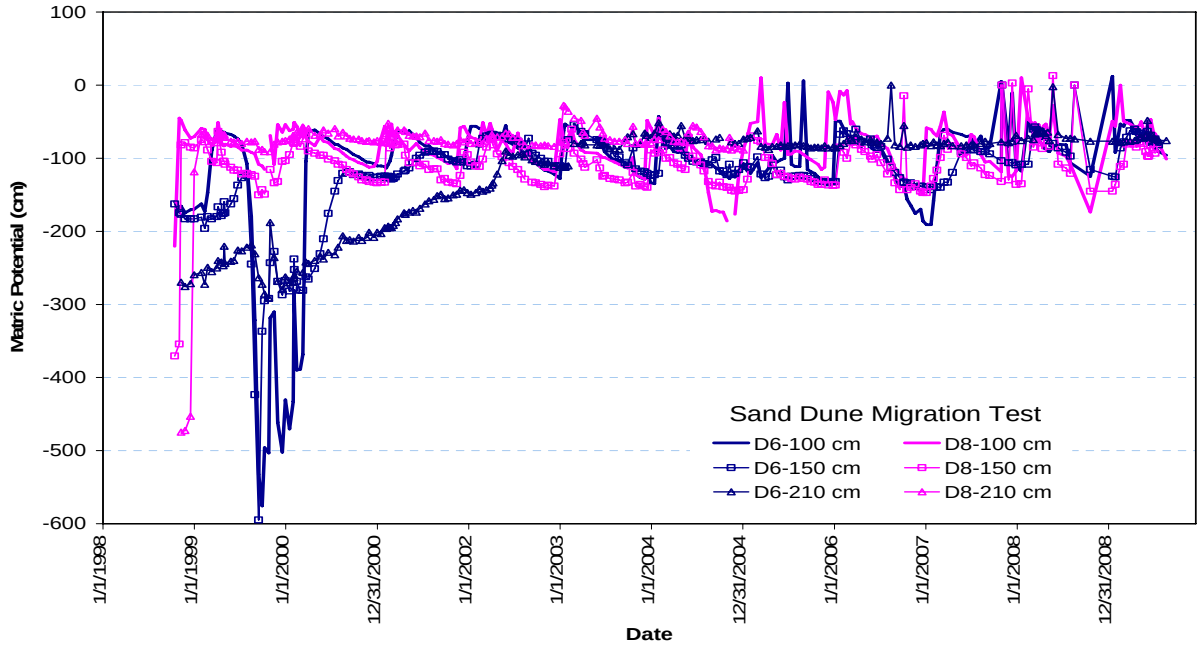

Figure 5.30. FLTF Matric Potentials for Sand Dune Migration Test (100, 150, and 210 cm Depths).

Efforts were begun in FY 2007 to use chloride concentrations in drainage water from FLTF lysimeters to capture the modern atmospheric chloride deposition rate. The atmospheric chloride deposition rate is important because it is a critical parameter in the calculation of recharge using the chloride mass balance method. The first round of measurements was made in September 2007 and

measurements have since been taken in September of 2008 and June of 2009. Drainage water was collected from each Lysimeter in high-density polyethylene bottles and taken to the Applied Geology and Geochemistry lab for analysis using ion chromatography. Table 5.5 presents the chloride concentration results. Drainage samples were collected in late June this year, and during September in previous years. Therefore more of the lysimeters were actively draining this year and hence more samples were analyzed for chloride. Of the three lysimeters that were sampled in all three years (C1, D4, and D6), C1 and D4 show relatively low (1.23-2.87 mg L^{-1}) and stable concentrations, while D6 shows high, but declining concentrations (254, 88.9, 67.7 mg L^{-1}). D2 also showed a relatively high concentration (48.2 mg L^{-1}), but all of the other lysimeters had concentrations <4 mg L^{-1}. The reasons why D2 and D6 have higher concentrations are currently unknown but may be related to the source materials. Both of these lysimeters have ambient precipitation (no irrigation).

Previous studies using $^{36}Cl/Cl$ ratios measurements in the soil (Murphy et al. 1996, Prych 1998, Fayer et al. 1999) have estimated Hanford chloride deposition rates ranging from 33 to 40 mg/m^2/yr. One possible explanation for the discrepancy is that geochemical conditions within the lysimeters may not be in equilibrium (as assumed). In particular, the high chloride from D6 may reflect residual chloride being flushed from the sediment. Interestingly, at the 300N Lysimeter Site (Gee et al. 2005) also measured drainage water chloride concentrations that were greater than expected given the documented drainage rate of the lysimeter. In that instance, a 22 percent increase in q_{cl} was required in order for the CMB estimated drainage to match the lysimeter drainage record. The analysis of chloride in drainage water from the FLTF is preliminary and thus inconclusive. Additional drainage water samples will be collected and analyzed for chloride concentrations in the coming years to help resolve this issue of apparent chloride deposition rate variability and uncertainty.

Table 5.5. Chloride Concentrations Measured in FLTF Lysimeter Drainage Waters.

Lysimeter ID	Chloride Concentation (mg L^{-1})		
	Sept. 14, 2007	Sept. 2, 2008	June 29, 2009
C1	2.87	2.43	2.20
C2	5.39	7.82	---
C4	---	---	2.00
C5	---	---	3.92
D2	---	---	48.20
D4	1.23	1.36	1.35
D6	254.06	88.90	67.70
D8	---	---	1.87
D12	---	---	1.70
W4	---	---	2.88

5.6 Field Lysimeter Test Facility (FLTF) Pit

The FLTF Pit site is a collection of four cement caissons containing WFMs packed with different soil types adjacent to the FLTF. The FLTF Pit flux meters, their treatments, monitoring periods, and average drainage rates are presented in Table 5.6. The gravel soil is similar to the gravel material in the FLTF D4 lysimeter (Sandy Gravel Side Slope Test). The silt loam soil is from the same source as that used in the FLTF Hanford Barrier treatments. The sand soil is similar to the FLTF Dune Sand Migration test (D6 and D8 lysimeters) soil. The 5/8-inch minus material is similar to the commercial road base material existing on the surfaces of many Hanford tank farms. All WFMs have the divergence columns at the soil

surface, with the exception of one silt loam WFM that has the divergence column at 1 m below the soil surface.

A plot of WFM measured drainage for the sand and sandy gravel material and silt loam at two depths is shown in Figure 5.31. Both silt loam WFMs continue to experience no measurable drainage since 2003. The sand and sandy gravel WFMs readily drain, although the sandy gravel filled WFM has stopped functioning, as displayed by its lack of drainage response when the sand WFM is draining. Only a trace of drainage was measured from the sand WFM in 2009. The road base WFMs and sand/silt loam WFM drainage data are depicted in Figure 5.32. Data from the first quarter of 2005 are a bit suspect, with greater drainage expected from the road base only material relative to the sand/silt loam material. Trouble encountered with data collection and functionality of these three WFMs upon installation and into the first quarter of 2005 may have led to this discrepancy. From January of 2006 to present all three of these WFMs appear to be working properly, with measurable drainage in 2006 and 2007. Note that that average drainage rates reported in Table 5.6 are calculated using data from January 2006 through August 2009. As expected, based on material properties, the road base material WFM has the greatest drainage of WFMs 5, 6, and 6. Addition of silt loam to both the sand and road base material results in an increase in the storage capacity of the soil and reduced drainage.

A general comment about the water flux meters is warranted. In some cases, the WFMs appear to provide reliable data but overall their track record at the Hanford field water balance monitoring sites has not been good. Most of the time, poor performance has been attributed to problems with installation and disturbance of the soil profile such that capillary breaks are created. Therefore we recommend that the WFM data be used with caution. Long-term drainage rates measured from the lysimeter facilities are considered to be much more reliable.

Table 5.6. FLTF Pit WFM Treatments, Monitoring Periods, and Average Drainage Rates (Jan 2006 – present). All WFM surfaces in the FLTF pit are unvegetated.

Water Flux Meter ID	Soil Description	Monitoring Period	Average Drainage Rate (mm yr^{-1})
1	Sandy Gravel	Nov 2001 – present	49.3
2	Silt Loam	Nov 2001 – present	0
3	Silt Loam (1 m)	Nov 2001 – present	0
4	Sand	Nov 2001 – present	34.3
5	80% Sand, 20% Silt Loam (wt %)	Jun 2004 – present	10.9
6	5/8-in minus material	Jun 2004 – present	21.9
7	80% 5/8-inch minus material 20% Silt Loam (wt%)	Jun 2004 – present	11

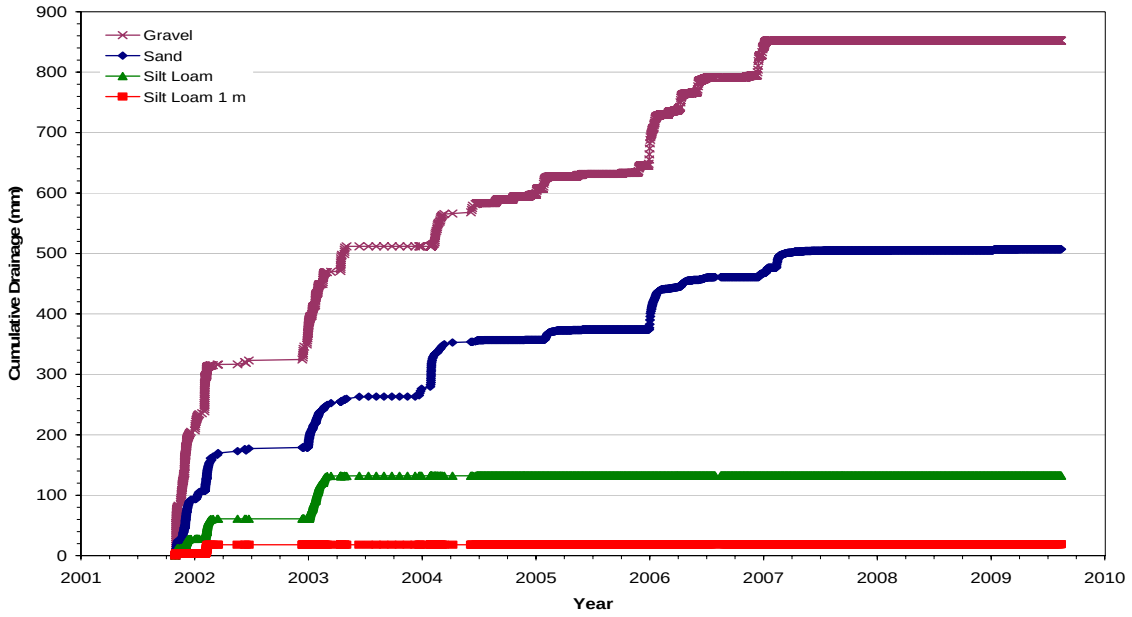

Figure 5.31. Cumulative Drainage Measured at the FLTF Pit Using Water Flux Meters for Silt Loam, Sand, and Gravel Treatments.

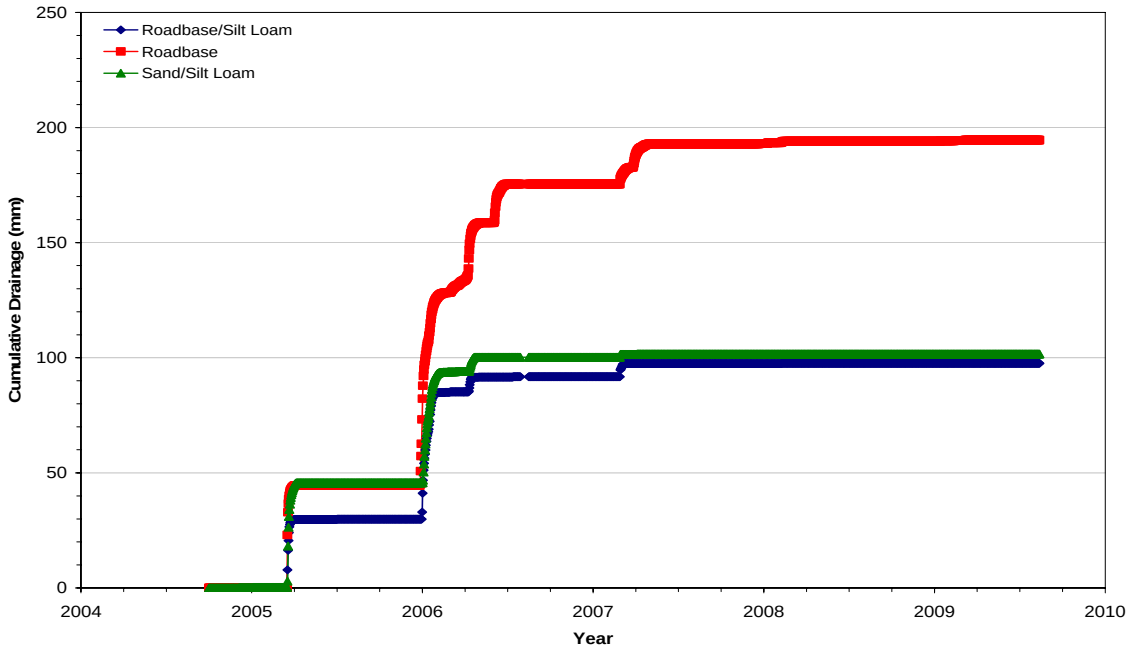

Figure 5.32. Cumulative Drainage Measured at the FLTF Pit Using Water Flux Meters for Road Base/Silt Loam, Sand/Silt Loam, and Road Base Treatments.

5.7 Tank Farms

Single- and double-shell tanks used for radioactive waste storage pose special concerns at the Hanford Site. Characterization of recharge for the surface conditions of these sites has been a subject of great interest. All available evidence suggests that past tank farm management practices of maintaining gravel-covered surface devoid of vegetation maximizes recharge rates and hence increases the rates of transport of leaked contaminants to the groundwater. Several monitoring sites were active in the past at locations adjacent to the B, SX, and TX tank farms (Nichols et al. 2008). These monitoring sites have since been decommissioned owing to inadequate funding for long-term support of these efforts.

PNNL is currently providing recharge monitoring support for an interim cover at the T farm (Zhang et al. 2009). The interim cover is a polymer that was sprayed over the ground surface. Water that accumulates on the cover is diverted to an adjacent evaporation pond. There are currently four monitoring stations: two under the middle of the cover, one at the edge of the cover, and another located ~100m away from the edge of the cover that acts as a control. Water contents are being measured at each of these monitoring stations using capacitance and neutron probes. Water potentials are being monitored using heat-dissipation units (HDUs). Water flux meters are also installed at these stations, but they have never functioned properly.

5.8 200 East Lysimeter

As noted by Nichols et al. (2008), a large hole developed adjacent to the 300 East Lysimeter Site in March 2005, presumably because of poor compaction after the site was initially installed. This hole compromised the value of the neutron logging data that were collected within the lysimeter. Nearby neutron probe access tubes in grass and sagebrush areas still had potential value, but access to this general area has become increasingly restrictive due to its designation as a surface contamination area. Therefore the 200 East Lysimeter Site is no longer being monitored.

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6.0 Conclusions

The importance of recharge and available measurement techniques were presented. Data collected at several recharge measurement sites in FY 2004 through 2009 are presented and discussed. These data are available for use in refining and improving recharge rate estimates for soils of the Hanford Site, with emphasis on the soils of the Central Plateau. Critical gaps in the knowledge of recharge at the Hanford Site were presented. These listed gaps serve as a guide to assist in prioritizing future Hanford recharge work towards developing more defensible recharge estimates.

The field soil water balance and recharge measurement sites have been monitored over the past several years with a very low level of effort that relies heavily on automated acquisition and uploading of data and periodic review of the data streams. Disruption of funding in FY09 due to the change in site contractors prevented any site visits or data reviews until early February. This funding disruption and a sensor failure at one site that does not have automated data uploading resulted in the loss of several months worth of data from that site (SWL). Problems also occurred at several other sites. Water content sensors at the 300N lysimeter were disturbed when a new project was started at that site, but this problem went unnoticed for several months. Two of the weighing lysimeters and the datalogger for these lysimeters at the FLTF have continued to exhibit anomalous behavior and it is speculated that one of the load cells on one of the weighing lysimeters is bad. Although no lysimeter drainage (or recharge) data were compromised, the problems that have occurred this year suggest that a longer-term strategic plan for the FLTF and other water balance and recharge monitoring sites is probably warranted to ensure that high-quality, long-term records of recharge and related water balance data continue to be generated.

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