3.3 Vadose Zone Studies

D. G. Horton

This section summarizes the activities and results of several technical studies done at the Hanford Site in fiscal year 2003 to better understand the vadose zone sediments, vadose zone hydrology, and vadose zone contamination. These studies are designed to result in new, innovative methods for cleanup and monitoring at the Hanford Site. These studies include the application of geochemical tools to study the interactions between vadose zone porewater and contaminants, infiltration studies at a monitored prototype surface barrier site, the development of new tools to measure the influx of water into the subsurface, and the use of computer modeling to estimate the future behavior of surface barriers. A review of the many tests to determine the effects of soil type, plant populations, and precipitation rates on infiltration of soil moisture is also included in this section.

Vadose zone studies are designed to result in new, innovative methods for cleanup and monitoring.

3.3.1 Field Lysimeter Test Facility

M. J. Fayer

During 2003, a summary of 15 years of testing at the Field Lysimeter Test Facility became available. A lysimeter is a structure used to measure quantities of water used by plants, evaporated from soil, and lost by deep percolation. In 1987, the Protective Barrier Program constructed the Field Lysimeter Test Facility to test the performance of capillary barrier covers (PNL-6810; Wing and Gee 1994) and operated the facility until 1994. Between the end of 1994 and 2003, the Integrated Disposal Facility project (formerly the Immobilized Low-Activity Waste Project) sponsored the tests. During this period, some of the original test treatments were ended and replaced with new tests designed to answer questions about new barrier designs (e.g., modified *Resource Conservation and Recovery Act* [RCRA] Subtitle C) and barrier degradation mechanisms such as erosion and dune sand migration. Now, Pacific Northwest National Laboratory (PNNL) operates the Field Lysimeter Test Facility, which is located ~400 meters west of the Hanford Meteorological Station (between 200 East and 200 West Areas; Figure 3.3-1).

DOE published the results of 15 years of testing at the Field Lysimeter Test Facility in fiscal year 2003.

Figure 3.3-2 shows that the Field Lysimeter Test Facility contains a total of 24 lysimeters of three types: 14 drainage, 4 weighing, and 6 small-tube lysimeters. The drainage lysimeters are vertical cylinders that are 3 meters deep and 2 meters in diameter (surface area is 3.1 square meters) and comprise the walls of the Field Lysimeter Test Facility. The weighing lysimeters are boxes with length and width dimensions of 1.5 meters and a depth of 1.7 meters (surface area is 2.3 square meters). The boxes rest on platform scales to enable hourly weight measurements of water gain and loss. The small-tube lysimeters are vertical cylinders that are 3 meters deep and 0.3 meter in diameter (surface area is 0.07 square meter). Unlike the others, the small-tube lysimeters are clear Plexiglas to allow root and soil observations. These lysimeters are located along the inner walls of the Field Lysimeter Test Facility. All lysimeters contain ports for measuring drainage. The drainage and weighing lysimeters contain sensors to measure soil water contents and storage, matric potentials, and temperature.

Since 1987, 12 tests and 26 treatments have been set up in the Field Lysimeter Test Facility to reflect various combinations of soil type and layering and vegetation under ambient and enhanced precipitation. The enhanced precipitation treatment was intended to examine the impact of potentially higher precipitation rates in the future that could result from climate change. The lysimeters were irrigated each month so that ambient precipitation plus irrigation equaled either 2 or 3 times the long-term average monthly precipitation. From November 1987 to October 1990, the enhanced rate was 2 times;

since November 1990, the enhanced rate has been 3 times. The test configurations are described below along with some of the results.

Hanford Barrier. The objective of this test (and the original objective of the Field Lysimeter Test Facility) is to document the performance of a Hanford barrier, which consists of a 1.5-meter-thick top layer of silt loam resting on top of a sequence of sand to gravel filter layers that rest on basalt riprap. Test results show that with plants, the Hanford barrier continues to limit drainage to well below the design specification of 0.5 millimeter per year. Without plants, the Hanford barrier continues to function under ambient conditions, even under 2 times precipitation during a 3-year test. Only under 3 times precipitation, with no plants, has the Hanford barrier allowed drainage to occur.

Hanford Barrier with Gravel Admix. The objective of this test is to document the impact of a gravel admix on the performance of a Hanford barrier. The admix was created by amending the top 0.2 meter of silt loam with pea gravel (15% by weight) to increase resistance to erosion. This test (shrub-steppe vegetation and ambient precipitation only) continues to show no drainage.

Lysimeters measure drainage of liquids such as precipitation through soil.

Eroded Hanford Barrier. The objective of this test is to document the performance of an eroded Hanford barrier. To mimic erosion, the thickness of the silt loam layer was reduced from 1.5 to 1.0 meter. In many respects, this design is similar to that of the modified RCRA Subtitle C Cover (see discussion under Modified RCRA Subtitle C Cover). This test (shrub-steppe vegetation only) continues to show no drainage, even for the enhanced precipitation regime.

Gravel Mulch. The objective of this test is to document the performance of a gravel mulch layer above Hanford formation sand. The configuration was 0.15 meter of coarse gravel above 1.35 meters of screened pitrun sand (gravel removed), on top of unscreened pitrun sand. This test was conducted only in the clear-tube lysimeters and did not include vegetation. Although not its primary purpose, this test may be useful to characterize deep drainage rates at the high-level waste tank farms at the Hanford Site. This test continues to show significant drainage (average = 89.1 millimeters of water per year under ambient precipitation and 332 millimeters of water per year under enhanced precipitation).

Pitrun Sand. The objective of this test is to document the performance of a coarse gravelly sand taken from a nearby borrow pit (hence "pitrun" sand). The configuration is 1.5 meters of screened pitrun sand (to remove the gravel) resting on top of unscreened pitrun sand. This vegetated test continues to generate a significant amount of drainage (average = 21.8 millimeters of water per year under ambient precipitation and 63.5 millimeters of water per year under enhanced precipitation).

Basalt Side Slope. The objective of this test is to document the performance of basalt riprap that could be used to construct side slopes for surface covers. The configuration is 1.5 meters of unscreened basalt riprap. This material is being tested for side slope use on a larger scale at the prototype surface barrier in the 200-BP-1 Operable Unit (PNNL-11789). This unvegetated test continues to generate a significant amount of drainage, even though it receives only ambient precipitation (average = 53.9 millimeters per year).

Sandy Gravel Side Slope. The objective of this test is to document the performance of unprocessed local sandy gravel that could be used to construct side slopes for surface covers. The configuration is 1.5 meters of sandy gravel resting on an asphaltic concrete layer in a manner similar to the basalt side-slope test. The sandy gravel material was tested for side slope use on a larger scale at the prototype surface barrier, where it is called clean-fill gravel (PNNL-11789). Although not its primary purpose, this test may be useful to characterize deep drainage rates at the high-level waste tank farms at the Hanford Site that have similar textures. This unvegetated test continues to generate a significant amount of drainage (average = 109 millimeters of water per year under ambient precipitation and 365 millimeters of water per year under enhanced precipitation).

Hanford Prototype Barrier. The objective of this test is to document the performance of the Hanford Prototype Barrier design. The configuration is 1 meter of silt loam amended with pea gravel (15% by weight) resting on top of 1 meter of silt loam to give a combined silt loam thickness of 2 meters. Beneath the silt layer are sand and gravel filter layers that rest on top of the asphaltic concrete layer. This design mirrors that of the full-scale prototype surface barrier (PNNL-11789). This vegetated test continues to show no drainage, even under 3 times precipitation.

Hanford Barrier Erosion/Dune Sand Deposition. The objective of this test is to document the performance of the Hanford barrier after erosion of some of the silt loam layer and subsequent deposition of dune sand. The top 20 centimeters of silt loam of the Hanford barrier design was removed and replaced with dune sand obtained from the dune that is aligned along the southern edge of the Integrated Disposal Facility Site (PNNL-11957). This test is being conducted with shallow-rooted vegetation, primarily cheatgrass. The presence of dune sand on the Hanford barrier continues to generate a significant amount of drainage under 3 times precipitation. To date, we have observed increased matric potentials under the ambient precipitation treatment but minimal drainage.

Lysimeters have been used to evaluate the performance of the Hanford barrier, which will limit infiltration through waste sites.

Sand Dune Migration. The objective of this test is to document the impact of a sand dune that might migrate onto a surface cover. Two lysimeters were completely filled with dune sand to provide data on the impact of a dune forming on a barrier, as well as provide data on the behavior of dunes that might form around a barrier and elsewhere at the Hanford Site. The dune sand was obtained from the dune that is aligned along the southern edge of the Integrated Disposal Facility Site. This test is being conducted with shallow-rooted vegetation, primarily cheatgrass. Since starting in July 1998, this test has shown clearly that drainage is significant under the 3 times precipitation treatment. In contrast, we have observed no drainage under the ambient precipitation treatment. Matric potentials in the ambient treatment have been rising, so it may be just a matter of time before drainage occurs.

Modified RCRA Subtitle C Cover. The objective of this test is to document the performance of a modified RCRA Subtitle C barrier that was proposed in DOE/RL-93-33. This barrier design meets the requirements for a RCRA Subtitle C barrier but uses a thinner silt loam soil than the Hanford Prototype Barrier (1 rather than 2 meters). In addition, the silt layer has two modifications. The first is that the upper 0.5 meter of silt loam is amended with pea gravel (15% by weight). The second feature is that the lower 0.5 meter of silt is compacted. The rationale for the compacted layer was to create a low-conductivity layer to impede downward drainage (DOE/RL-93-33). Construction of this test required slight design modifications to the sand filter layer, the gravel drainage layer, and the density of the compacted silt layer (PNNL-13033). Although the testing period is short (3.5 years), this vegetated test continues to show no drainage, even under the 3 times precipitation treatment.

Glass. The objective of this test is to determine the performance of glass waste forms in a field setting that receives enhanced precipitation to accelerate the glass dissolution rate. The lysimeters are packed with vadose zone sediments (predominantly gravelly sand) from the Integrated Disposal Facility Site. The glass waste forms are in the shape of cylinders (20 centimeters diameter; 46 centimeters tall). The glass cylinders are placed in two layers in each lysimeter, three cylinders per layer, for a total of six cylinders per lysimeter. One lysimeter is scheduled to be excavated and the glass cylinders tested in fiscal year 2006 before emplacement of actual glass in the first Integrated Disposal Facility trench. The remaining two lysimeters will continue to be monitored to provide a long-term data record of glass behavior.

3.3.2 Vadose Zone Water Fluxmeter Improvements and Tests

G. W. Gee, Z. F. Zhang, and A. L. Ward

DOE modified a lysimeter to provide a better way to measure water flux.

A wick lysimeter was modified so it could provide nearly instantaneous water-flux measurements and serve as a water fluxmeter. The water fluxmeter consists of a soil-filled tube with a fiberglass wick at the bottom, which has the capability of providing continuous and reliable monitoring of unsaturated water fluxes ranging from <1 millimeter per year to >1,000 millimeters per year. The water fluxmeter is placed in the ground, below the root zone. The wick applies suction, proportional to its length, and passively drains the soil. Water flows by gravity from the wick through a funnel to an isolated tipping spoon (or similar counting device) where drainage volumes are recorded. In the latest design of the water fluxmeter, water drained from the tipping spoon is routed down to a collection vial where it can be sampled for chemistry (Gee et al. 2003). Data became available from a test of the water fluxmeter at the Hanford Site during fiscal year 2003. Figure 3.3-3 shows a water fluxmeter with solution-collection capability.

To illustrate the performance of the water fluxmeter for drainage monitoring, an example from the Hanford Site is discussed. However, water fluxmeters have now been installed throughout the United States, Germany, Sri Lanka, the Tongan Islands in the Pacific, and several other locations throughout the world.

The Field Lysimeter Test Facility pit is a test site for monitoring drainage from selected surface cover materials. It is located on the Hanford Site, just east of the 200 West Area and adjacent to the Hanford Meteorological Station. The Field Lysimeter Test Facility pit consists of four instrumented caissons, 2.3 meters in diameter and 1.5 meters deep, filled with native soil and sediment being tested as landfill cover materials. The cover materials include (1) a coarse gravel, (2) a dune sand, (3) a 0.1-meter-thick silt loam, and (4) a 1-meter-thick silt loam. A water fluxmeter is located in the center of each caisson. Instruments were installed in the caissons during the fall of 2001. Irrigation was applied to each of the caissons after construction and periodically through February of 2002, after which the cover materials were subject only to natural precipitation. Figure 3.3-4 shows the drainage from the four cover treatments at the Field Lysimeter Test Facility pit.

The data in Figure 3.3-4 illustrate that under the same climatic regime, there can be large differences in drainage as a result of the surface soil materials and their water-holding capacity (soil-water storage). Water-storage capacity in gravel materials is typically <30 millmeters per meter whereas for silt loam, it can be as much as 300 millimeters per meter. For landfill covers at arid sites, gravel side slopes can be a source of subsurface water that may contact existing contaminant plumes and move them to the underlying water table. Documentation of subsurface drainage is critical to any analysis of risk resulting from leaving waste in the ground at the Hanford Site or similar arid waste sites.

Similar results have been found at other test locations at the Hanford Site. Drainage occurs at non- or sparsely vegetated waste sites that have coarse sand or gravel surfaces. Examples include sites containing leaking high-level waste tanks and covered trenches found in solid-waste burial grounds where surfaces are kept vegetation-free to minimize plant and animal intrusion (Gee et al. 1992). As much as 40% or more of the annual precipitation is lost to drainage at barren sites with coarse sands and gravels. Documentation of the actual drainage is required to support the performance assessment of waste sites left in a barren state for more than a few decades because water can accumulate and provide transport for contaminants to underlying water tables. Water-flux measurements at such sites will provide operators with information on the extent of the problem and can also be used to evaluate the effectiveness of remediation strategies that include surface-cover placement over waste sites that are vulnerable to leaching.

The ability to measure continuous water and solute flux simultaneously with the same instrument provides a capability that previously was either not available or required multiple sets of instrumentation. The direct measure and simplicity of the new fluxmeters makes them an attractive alternative to other vadose-zone monitoring methods, such as water-content sensors, water-potential sensors, pore-water samplers, and other schemes used in the past to obtain drainage water quantity and quality.

3.3.3 Mineralogical and Bulk-Rock Geochemical Signatures of Ringold and Hanford Formation Sediment

Y. Xie, G. V. Last, C. J. Murray, and R. Mackley

PNNL explored the possibility of applying statistical methods to classify sediment samples belonging to the Hanford and Ringold Formations using mineralogy and geochemical data. A database was constructed consisting of existing mineral chemistry obtained from electron microprobe analyses, bulk-rock analyses obtained by x-ray fluorescence analyses, and petrography. Principal component analysis was used to examine the multivariate structure of the data. In addition, several classification methods were employed to identify classification functions that could be used to distinguish between the two formations.

Statistical methods provide valuable tools for quantifying mineral and chemical variables.

The results of this study indicate that principal component analysis, discriminant function analysis, and machine learning methods are valuable tools for quantifying mineral and chemical variables and determining which variables are the most effective in distinguishing between Ringold and Hanford Formation sediment. Electron microscopy and petrography data for the Hanford and Ringold Formations from 200 West Area showed significant differences; however, significant spatial variability of electron microscopy data between 200 West and 200 East Areas caused inconsistent variable differences. X-ray fluorescence analyses from 200 West Area also distinguished between the two formations and, when applied to pooled data from 200 East Area, the two formations could still be distinguished. Principal component analyses supported the use of mineralogy and geochemical data for classifying samples from the two formations as well; the petrography data was particularly valuable. Classification routines such as discriminant function analysis and machine learning tools including C4.5 and One R, provided useful and consistent classification of samples. Complete results were published in 2003 (PNNL-14202).

3.3.4 Isotopic Investigation of Vadose Zone Pore Water

M. J. Singleton, P. E. Dresel, and G. V. Last

Investigators from the Lawrence Berkeley National Laboratory and PNNL used natural isotopes of strontium, carbon, and oxygen as tracers to infer the depositional environment and diagenetic history of buried carbonate layers and to provide constraints on groundwater recharge, flow, and vadose zone/groundwater interaction (Singleton et al. 2002, 2003).

Clastic sediments of the Hanford formation, the Cold Creek Unit, and the Ringold Formation contain laterally extensive carbonate layers beneath the 200 West Area. The carbonate layers, known as caliche, are associated with high moisture and high ion concentrations in vadose zone pore water. The layers likely impede infiltrating fluids due to their low permeability relative to surrounding sand and gravel and may interact with contaminants migrating through the unsaturated zone. The carbonates have been attributed to soil forming processes during depositional hiatuses with later modification by groundwater (BHI-01203).

The Cold Creek Unit carbonate-cemented sediment forms a zone at a depth of ~45 meters beneath the Hanford Site 200 West Area. The carbonate zone ranges from about 0.9 to 4 meters in thickness. Within this zone, carbonate occurs as thin laminae (caliche layers) separated by silty or sandy zones with disseminated carbonate. Whole rock samples of the caliche layers have $\delta\,^{13}C$ PDB (Peedee Formation belemnite) values of -8.7 to -4.4 per mil and $\delta\,^{18}O$ SMOW (standard mean ocean water) values of 15.2 to 18.6 per mil. Carbon isotope compositions of these samples show a generally positive, linear correlation with oxygen isotope compositions. Disseminated carbonates, on the other hand, have higher $\delta\,^{13}C$ PDB values, and lower $\delta\,^{18}O$ SMOW values than the caliche layers. Unsaturated zone pore waters at the Hanford Site have $\delta\,^{18}O$ SMOW values up to -7.5 per mil near the surface and -17 to -14 per mil at depth, whereas groundwater values are generally -18 to -16 per mil. The caliche layers at the Hanford Site retain an isotopic signature consistent with deposition from strongly evaporated, near surface waters; whereas disseminated carbonates are generally near isotopic equilibrium with less evaporated pore waters suggesting that the disseminated carbonates may be forming today. Preliminary strontium isotope results suggest little modern interaction between the carbonate layers and pore water.

The strontium isotope composition of groundwater samples provides a way to evaluate groundwater recharge, vadose zone drainage, and the effects from industrial activity.

Strontium isotope compositions of samples from more than 270 wells in the unconfined aquifer provide a way to evaluate groundwater recharge, vadose zone drainage, and the effects from Hanford Site operations. Natural recharge to the unconfined aquifer primarily comes from exposed basalt on Yakima Ridge and the Rattlesnake Hills at the west margin of the Hanford Site, and thus groundwater in this area has lower strontium-87/strontium-86 ratios than either Columbia River water or water that has equilibrated with Hanford formation sediment. Artificial recharge of the unconfined aquifer from discharged Columbia River water has resulted in groundwater with high strontium-87/strontium-86 ratios downgradient from infiltration ponds. Transient, high strontium-87 and strontium-86 flushed out of the vadose zone by infiltrating disposal water at the 200 Areas dominates over the shift of strontium isotopes caused by reaction of aquifer sediments with groundwater. Low strontium-87/strontium-86 ratios south of Gable Mountain are evidence for upwelling from the upper confined aquifer, which may affect the shape and concentrations of contaminant plumes in this area.

Groundwater strontium-87/strontium-86 ratios increase systematically from 0.707 to 0.712 along aquifer flow paths, generally running west to east across the Hanford Site. The addition of strontium from interactions with the aquifer sediment and infiltration through the vadose zone causes this variation in strontium isotope composition. The degree to which groundwater strontium-87/strontium-86 composition approaches the composition of dissolving or infiltrating strontium is governed by the groundwater velocity, vadose zone drainage flux, aquifer thickness, and by reaction rates with the aquifer sediment. Vadose zone pore waters are approximately an order of magnitude higher in total strontium concentration than the groundwater; therefore, recharge through the vadose zone has a strong effect on the strontium isotope composition of groundwater. Combining measurements of hydraulic head and aquifer thickness with measurements of groundwater strontium-87/strontium-86 and total strontium concentration allows for estimates of vadose zone drainage flux. The strontium-87/strontium-86 increase along a background profile across the Hanford Site is consistent with an average vadose zone flux of 3 to 15 millimeters per year, based on a steady-state model of strontium reactive transport and infiltration.

3.3.5 Hydrologic Performance of a Prototype 1,000-Year Hanford Barrier

A. L. Ward, G. W. Gee, and C. D. Wittreich

Surface barriers form an integral part of the U.S. Department of Energy's (DOE's) waste management strategy. At the Hanford Site alone, an estimated 200 barriers with design lives of 500 to 1,000 years are planned for an area of ~404.7 hectares. Proven designs, as well as reliable, accurate, and cost-effective monitoring techniques, are needed to ensure post-closure compliance. In an effort to evaluate the long-term performance of field-scale barriers, a prototype Hanford barrier was constructed over the 216-B-57 crib. The barrier was routinely monitored between November 1994 and September 1998 as part of a *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA) treatability test of barrier performance for the 200-BP-1 Operable Unit. The results of this test have been documented in DOE/RL-99-11. Since fiscal year 1998, monitoring has focused on barrier stability and the key components of water balance. The results have been summarized in previous Hanford Site groundwater monitoring reports (e.g., PNNL-14187). This section provides a summary of observations made through fiscal year 2003.

Surface barriers form an integral part of DOE's waste management strategy.

As in previous years, the fiscal year 2003 hydrologic performance monitoring focused on water balance evaluation. The barrier is equipped with 14 automated stations to monitor the components of the water balance.

Precipitation. Precipitation in fiscal 2003 (October 1, 2002 through September 30, 2003) totaled 215.90 millimeters. Of this amount, 128 millimeters occurred during the winter (December 2002 through February 2003). Although this is almost twice the long-term average for a Hanford Site winter, it is still slightly less than that observed in fiscal year 1997, which had the maximum winter precipitation recorded at the Meteorological Station since 1946 (PNNL-14242). Fiscal year 2003 also saw a shift in the seasonal distribution relative to the previous year with an almost 50% decline in summer precipitation, a 150% increase in the winter precipitation, and a four-fold increase in spring precipitation. These differences translated into large increases in the amount of water stored in the fine-soil profile and increased drainage amounts from the side slopes compared to fiscal year 2002. The cumulative amount of water received by the barrier from November 1, 1994, through the end of September 2003, was 2,340.63 millimeters on the north half (formerly irrigated) and 1,667.76 millimeters on the south half.

Water Storage. Measured soil water contents were used to calculate the amount of water stored in the fine-textured layer as a function of time (Figure 3.3-5). No storage data were collected in fiscal year 1999, hence the break in the record. These data show a well-defined annual cycle in water storage during the 3 years of the treatability test (November 1994 through October 1997). Although plants in both precipitation treatments were able to recycle most of the water intercepted by the barrier, the data show a divergence in the storage values at the end of each summer. On the south side, which was never irrigated, plants removed water to essentially the same minimum each year.

Even though the plants on the irrigated north side were able to remove essentially all of the water received, the lower limit of storage is larger than the non-irrigated side and remained so until at least 2 years after the irrigation had ceased. This may indicate a reduced ability of the irrigated plants to recycle water. Nevertheless, the system had shown a dramatic recovery by mid-2000; by this time differences in the lower limit of storage, between the formerly irrigated and non-irrigated portions, had essentially disappeared, and the water storage values returned to values similar to those observed on the south side of the barrier.

Drainage. Perhaps the most important observation is the extremely low amounts of drainage from the soil-covered plots. During fiscal year 2003, the soil-covered plots generated an average of 3.6 x 10^{-5} millimeters (or ~12 milliliters) drainage for the entire year or an average cumulative drainage of only 0.08 millimeters over the entire life of the barrier. Thus in 9 years, the soil-covered plots have generated just over 15% of the drainage amount allowed for a year. Even then, none of this water would have entered the waste zone because of the presence of the asphalt layer. These results clearly show the effectiveness of the soil-covered section in eliminating recharge. In contrast, the side slopes have generated significant amounts of drainage (Figure 3.3-6). In general, the gravel slopes accounted for the most drainage, with the irrigated gravel draining about 23% of the total precipitation and non-irrigated gravel draining about 21%. In contrast, the non-irrigated rip rap drained only 15% of precipitation whereas the irrigated rip rap drained 23%. This discrepancy has been attributed to water loss from wind action on the rock surfaces which acts to reduce drainage from the rock slopes. The non-irrigated part of the Hanford barrier is toward the south, and the primary wind direction at the Hanford Site is from the southwest.

Synopsis. Not all waste sites will require the degree of protection offered by the Hanford barrier. However, the results of the CERCLA treatability test and long-term monitoring program are valuable in guiding the design of more modest covers, especially those sharing similar design concepts. A graded approach to barrier deployment that matches the level of protection to a specific waste site with specific waste stream characteristics will result in tremendous cost savings.

Results of testing illustrate the importance of water storage capacity, vegetation, and drainage when designing surface barriers.

The analysis of seasonal variations in precipitation, especially in winter amounts, is of particular importance for evaluating cover performance and the design of future covers to be used at the Hanford Site. Results thus far illustrate the importance of water storage capacity even in the design of more modest covers. All designs should be capable of storing the expected winter precipitation until it can be recycled by plants in the spring and summer months. The prototype Hanford barrier is designed with a 2-meter silt-loam layer capable of storing ~600 millimeters of water, which is more than three times the long-term average precipitation (160 millimeters per year) for the Hanford Site. This capacity has never been exceeded by the barrier, even during treatability tests when the prototype barrier was irrigated. Results also emphasize the importance of choosing the right vegetation to enhance the function of capillary barriers. Native species are particularly resilient and appear capable of recovering from short-term stresses, such as those imposed by elevated precipitation. The design of final barriers, therefore, will require close attention to the choice of plant species, realizing that some maintenance may be required to ensure that the right mix of plant species remain active. With respect to drainage, the data suggest that in arid or semiarid climates, side-slope design will affect the amount of drainage through the edge of the barrier into the subsurface. Thus, design optimization will require an analysis of side-slope configurations and their hydrologic performance to minimize the amount of peripheral recharge.

3.3.6 STOMP-Based Tool to Optimize Surface Barrier Design

A. L. Ward, M. D. White, and E. J. Freeman

Surface barriers are expected to play a critical role in the closure of the Hanford Site's 200 Area, with an estimated 200 barriers to be constructed. Optimizing barrier designs for the proposed graded-barrier approach can minimize performance uncertainty and reduce costs that could result from under- or over-engineering. In designing barriers, the environmental interactions that govern barrier performance must be carefully considered (Figure 3.3-7). Successful hydrologic performance depends on a complex interaction of physical, environmental, and biotic processes in which precipitation can be stored in the upper soil layers until it can be recycled to the atmosphere by the plants, routed from the surface by runoff, or moved through the profile to be diverted laterally from the waste. Predicting the hydrologic performance of field-scale surface barriers, therefore, requires an ability to simulate the multidimensional cycling of water, air, and energy. These simulations must include the influences of the local climate to accurately predict the net fluxes at the soil-atmosphere boundary. Most of the tools available for modeling these processes are one-dimensional, which limits their ability to predict the performance of multidimensional field-scale covers.

Pacific Northwest National Laboratory modified a computer model in fiscal year 2003 to evaluate barrier performance.

PNNL developed a computer model, Subsurface Transport Over Multiple Phases (STOMP) to provide scientists and engineers from varied disciplines with multi-dimensional analysis capabilities for modeling subsurface flow and transport phenomena (PNNL-12034). In fiscal year 2002, the STOMP model was upgraded to include a plant-soil-atmosphere module to support the simulation of barrier performance (PNNL-14388). The necessary modifications were completed in fiscal year 2003 and the model was calibrated using water balance data from the prototype Hanford barrier (Section 3.3.6). The 2003 modifications were made to the part of the model used for solving the equations for coupled water flow, heat transport, and solute transport in variably saturated soil.

The processes of coupled water flow and thermal energy transport in variably saturated soil are described by a set of coupled conservation (mass and energy) equations, associated constitutive laws (Darcy-Buckingham, Fick, Fourier), and equilibrium thermodynamic relations. Quantifying the exchange of matter, energy, and momentum between the soil and atmosphere required a detailed understanding of the interactions between vegetation and the local microclimate. The vertical structure of the mixed vegetation canopy typical of vegetated barriers affects the microclimate by intercepting radiation, extracting momentum from the air flow, and acting as a source or sink for mass and energy. The microclimate surrounding the vegetation also directly impacts the physiological and biophysical processes controlling the exchange of heat and water vapor across the soil-atmosphere continuum. These effects are incorporated into the model using nodal sink terms, based on root distributions, coupled with a surface energy balance that depends on the vegetative canopy. The Shuttleworth-Wallace (1985) model for sparse canopies was used to separate transpiration and soil evaporation on hourly or daily time steps. The model considers most of the important hydrologic processes and uses a recently developed method for describing lateral transfer of water due to saturation dependent anisotropy. Whereas modeling tools currently available make a number of simplifying assumptions to solve these equations, the 2003 modifications to the STOMP code solve the full set of equations.

Although the primary use of the STOMP model is to evaluate barrier performance, the model is equally applicable to other problems in waste remediation, such as phytoremediation or estimation of recharge rates.

Although the primary use of the model is to evaluate barrier performance, the model is equally applicable to other problems in waste remediation, such as phytoremediation, estimation of recharge rates, or problems of practical interest in agriculture and forestry. Input parameters for the model include physical characteristics of the vegetation such as canopy characteristics, root distributions, soil hydraulic and thermal properties, and climate data including daily precipitation, maximum and minimum temperatures, solar radiation, atmospheric vapor pressure, and wind speed, all of which are easily obtained from the Hanford Meteorological Station.

Model verification is currently in progress using the same set of test problems used in the verification of PNNL's UNSAT-H model (PNNL-13249). The simulated layered soil has a configuration critical to the performance of capillary barriers. The top

30 centimeters of the soil profile is a well characterized soil (the composite soil of PNL-5604) with 15% pea gravel admix. The 30- to 150-centimeter zone is the composite soil only and a coarser drainage gravel is below the depth of 150 centimeters. Figure 3.3-8 shows the saturation profiles from a STOMP simulation using 1962 weather conditions following PNNL-13249. The effect of the capillary break is quite clear. The soil configuration causes water to be retained within the fine textured, composite soil layer (between ~390 and 510 centimeters elevation on Figure 3.3-8) making it available for recycling by plants. This soil configuration, which increases the water storage capacity of the fine soil layer, is an integral part of the barrier designs being considered.

Results of the fiscal year 2003 model verification show that the model adequately captures diurnal and seasonal variations in components of the water balance.

The layered soil simulation was repeated with the addition of heat flow (Problem 7.6 of PNNL-13249). Figure 3.3-9 shows a plot of the STOMP simulated air and soil surface temperature for days 143 through 146. Peak soil surface temperatures typically occurred between 1200 hours (noon), when the net solar radiation reached a maximum, and 1500 hours when the air temperature reached its maximum. In general, soil temperature remained above the air temperature except for occasions when condensation of moisture on the surface caused a reduction in latent heat and a decline in soil temperature. This phenomenon is one that is typically ignored in current models but plays an important role in the water balance.

The preliminary results of the fiscal year 2003 model verification show that the model adequately captures diurnal and seasonal variations in components of the water balance: soil water storage, evapotranspiration, and drainage. Unlike previous modeling tools that make several simplifying assumptions to solve coupled water and heat flow equations, the STOMP code solves the full set of equations. The resulting model will have applications in the evaluation of Hanford Site barrier performance as well as other practical problems of waste remediation.

3.3.7 Impact of Clastic Dikes on Vadose Zone Flow

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Clastic dikes have been observed in all sedimentary units in the Pasco Basin and on the Hanford Site. Studies have been ongoing to explore the role of these heterogeneous sub-vertical structures on water flow in the vadose zone (PNNL-13788, Section 3.3; PNNL-13404, Section 3.1). High-resolution multi-parameter data sets from a dike exposure were used to develop a two-dimensional numerical model of unsaturated flow. Flow simulations were performed with the STOMP computer code to investigate the subsurface hydraulic structure and its dependence on recharge rate and saturation.

Information on clastic dikes helps improve conceptual models to guide the design of remedial systems and closure activities for waste management areas.

The presence of clastic dikes leads to the development of complex, complementary flow networks that sometimes mask the underlying structure of heterogeneity and whose structure depends on recharge rate. The major finding of this investigation is that at the low fluxes typical of vegetated areas on the Hanford Site, the fine-textured region of the dikes dominate flow; at intermediate fluxes both the coarse sand host matrix and the fine textured regions contribute to flow; and at high input fluxes the coarse-textured host sediments dominate flow. The phenomenon of complementary flow networks is a reflection of a fundamental characteristic of flow in variably saturated heterogeneous systems and cannot be replicated with simplified one-dimensional models or models in which a clastic dike is represented as an effective homogeneous medium with field-averaged hydraulic properties. Results of this investigation provide insight into the processes controlling flow in the vadose zone and the conditions under which they are active. This information is being used to improve conceptual models that are needed to guide the design of remedial systems and closure activities for waste management areas.

Figure 3.3-1. View of the Field Lysimeter Test Facility Looking Southwest Toward Rattlesnake Mountain

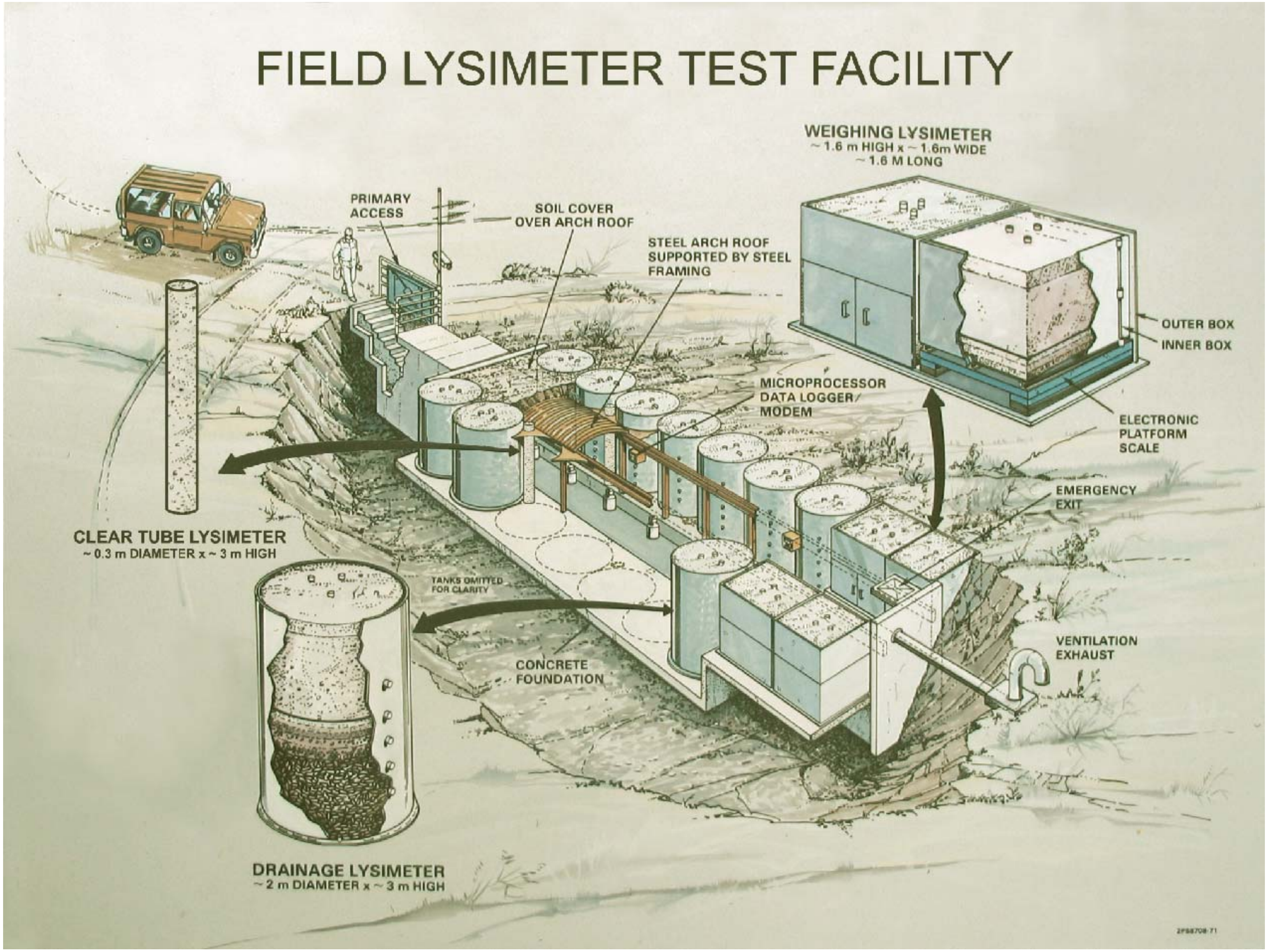

Figure 3.3-2. Drawing of the Field Lysimeter Test Facility

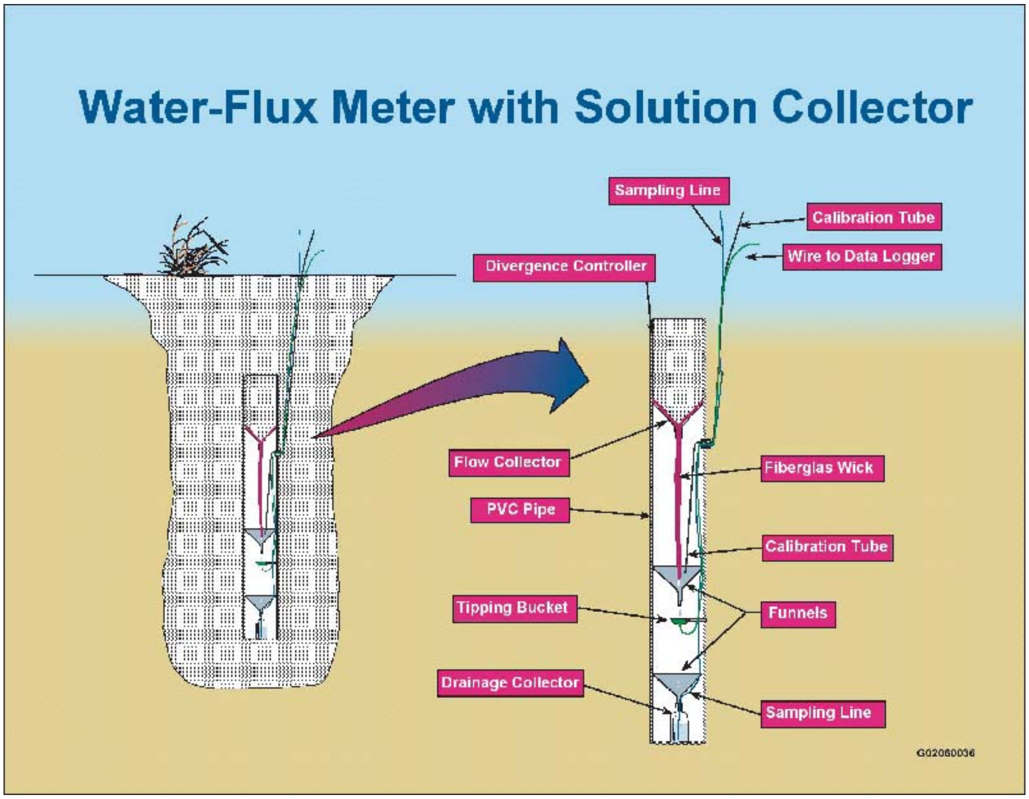

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Figure 3.3-3. Water Fluxmeter with Solution Collection Capability (after Gee et al. 2003)

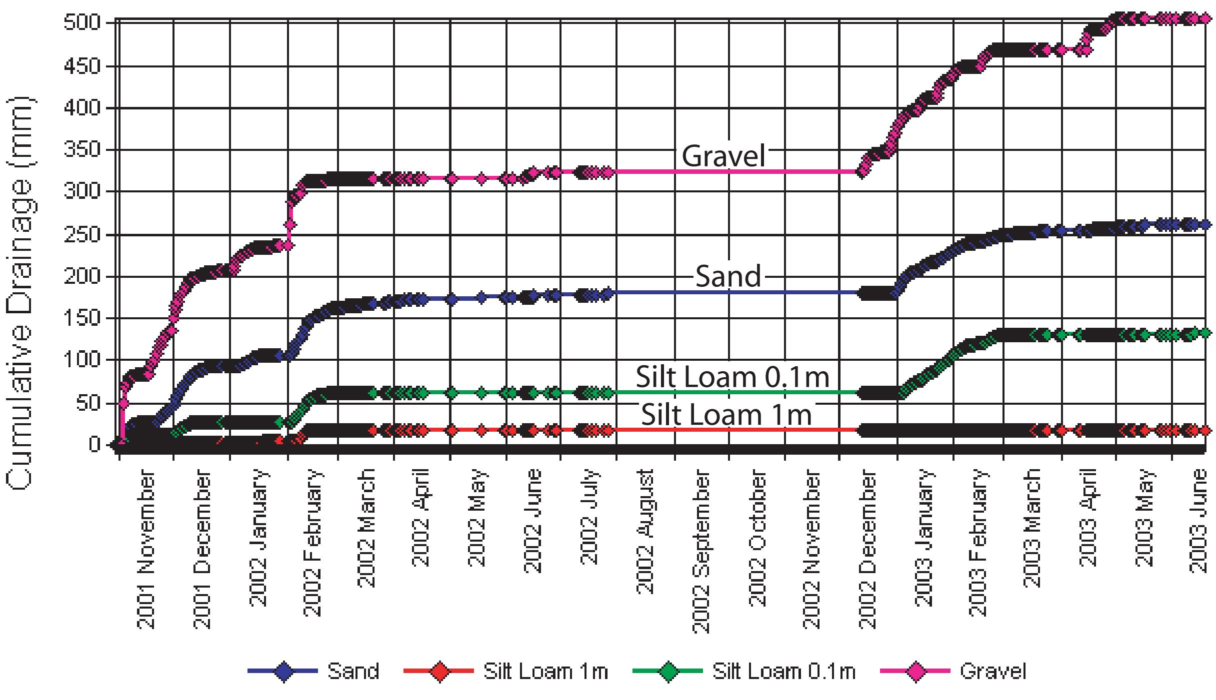

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Figure 3.3-4. Water Fluxmeter Data Showing Drainage from Soil Materials Tested at the Hanford Site. After February 2002, all soil materials were subject only to natural precipitation.

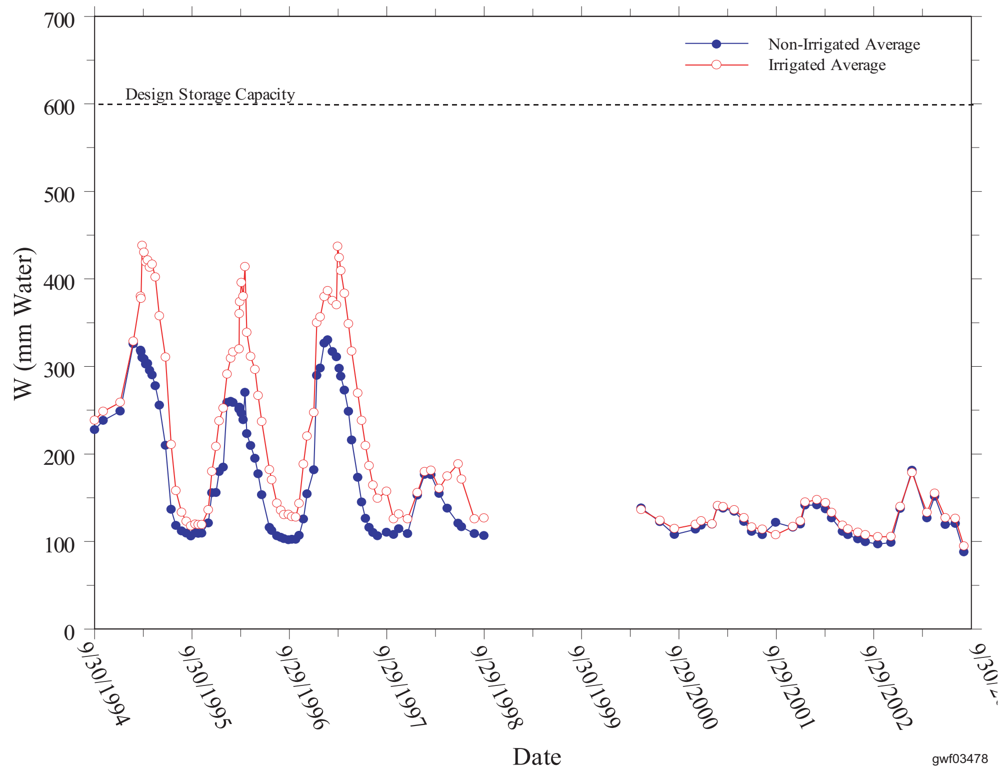

Figure 3.3-5. Temporal Variation in Mean Soil Water Storage on the North (irrigated) and South (non-irrigated) Plots at the Prototype Hanford Barrier, November 1994 through September 2003 (design water storage capacity is 600 millimeters)

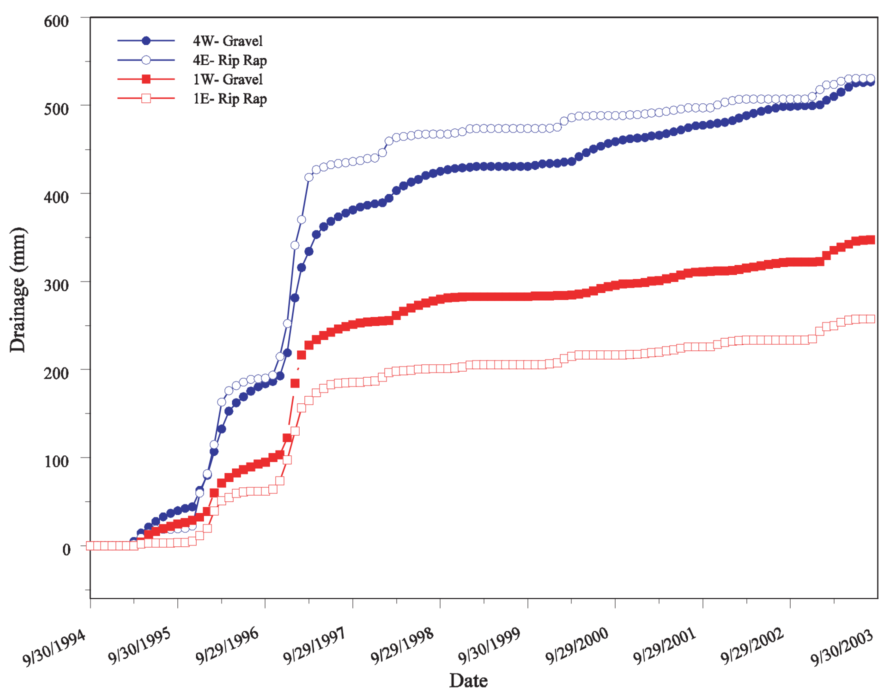

Figure 3.3-6. Cumulative Amounts of Water Diverted by the Asphalt Pad (drainage) from the Side-Slope Plots at the Prototype Hanford Barrier in September 1994 through September 2003. Data in red are from the south side of the barrier; data in blue are from the north side of the barrier.

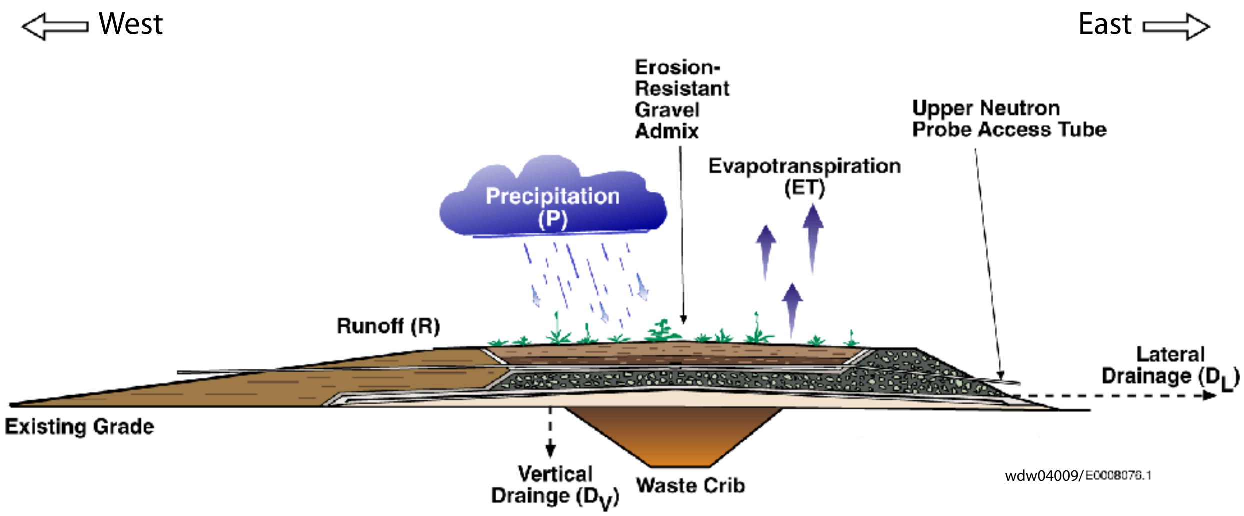

Figure 3.3-7. Primary Environmental Interactions Governing Functional Performance of a Typical 1,000-Year Capillary Barrier

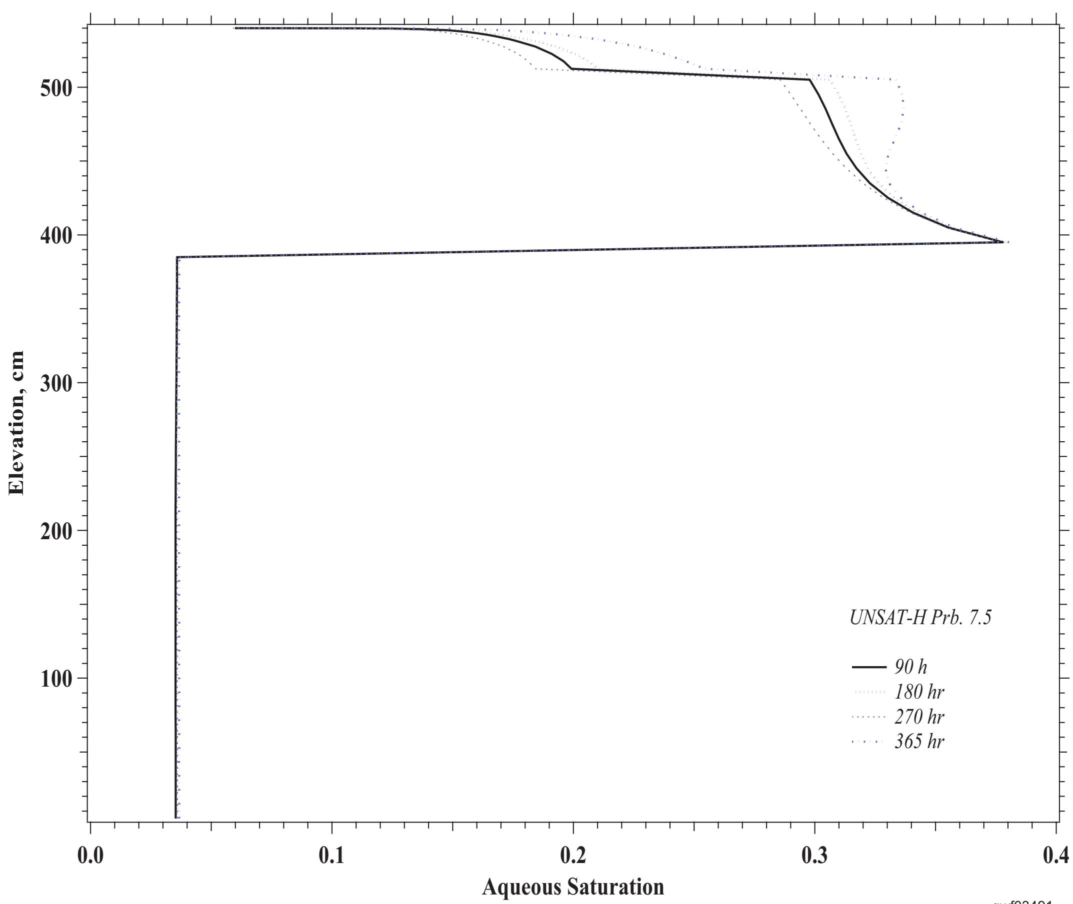

Figure 3.3-8. Simulated Aqueous Saturation as a Function of Depth within a Layered Soil. This configuration causes water to be retained within the fine textured layer making it available for recycling by plants. This configuration, which increases the water storage capacity of the fine soil layer, is an integral part of barrier designs being considered.

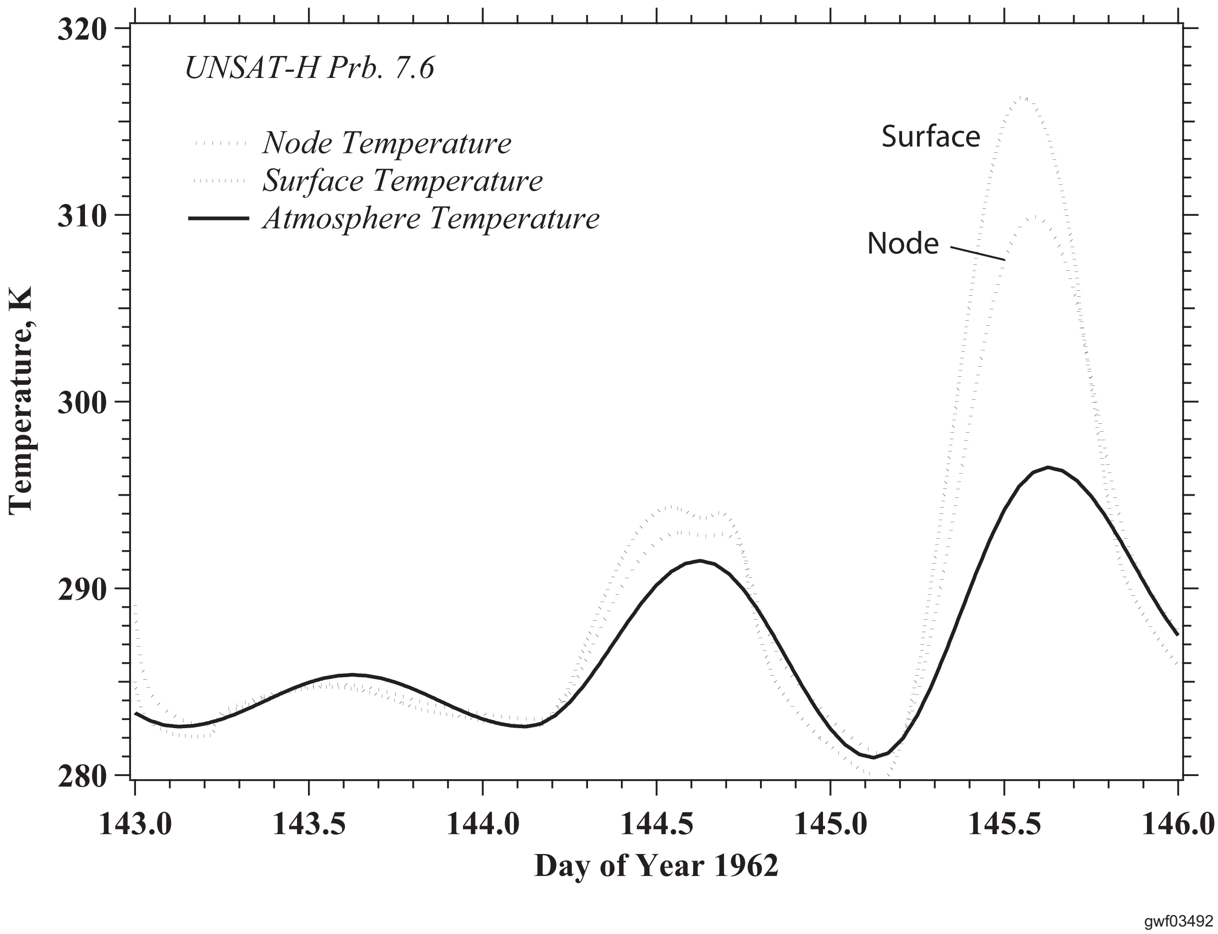

Figure 3.3-9. STOMP Simulated Air and Soil Surface Temperature for Water and Heat Flow in a Layered Soil System Typical of a Capillary Barrier