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**MODEL ASSESSMENT OF PROTECTIVE
BARRIERS: PART IV, STATUS OF
FY 1992 WORK**

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March 1992

**Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

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PREFACE

Protective barriers are being considered for use at the Hanford Site to enhance the isolation of radioactive wastes from water, plant, and animal intrusion. This study is part of an ongoing effort to assess the effectiveness of protective barriers for isolation of wastes from water. Part I of this study was the original modeling assessment by Pacific Northwest Laboratory of various protective barrier designs (e.g., soil type, vegetation). In Part II of this study, additional barrier designs were reviewed and several barrier modeling assumptions were tested. A test plan was then produced that detailed the requirement for hydrologic modeling of protective barriers. Part III of this study summarized the status of work in FY 1990 dealing with two-dimensional flow beneath the barrier and with validation testing using lysimeter data. This report (Part IV) addresses the application of a calibrated model to a much longer data set, the application of the calibrated model to a lysimeter that received a different treatment, and the effect of hysteresis on the behavior of water in the protective barrier.

SUMMARY

In Fiscal Year (FY) 1992, Pacific Northwest Laboratory (PNL) conducted work under the Barrier Simulation task of the Protective Barriers program, which is managed jointly by PNL and Westinghouse Hanford Company. Simulations of several of the lysimeters at the Field Lysimeter Test Facility were conducted using the water balance model UNSAT-H. Weighing lysimeter WL-4 (non-vegetated, 2x and 3x average precipitation) was simulated using the calibrated parameters discussed in the previous status report; the simulation period was from November 1987 to April 1992. Simulated storage (i.e., the depth of water stored) in WL-4 followed the trend of the measured values during the first 2 years (the years of calibration). After the second year, summer values of storage were always within 10 to 15 mm of the measured storage. In contrast, winter values did not match as well. In the winter of 1990-1991, the simulated storage was 40 mm less than measured. In the winter of 1991-1992 (during the 3x precipitation treatment), the simulated value was at least 50 mm less than the value measured. This result demonstrates the difficulty of extrapolating models from a short calibration base period to a much longer prediction period.

Weighing lysimeter WL-2 (non-vegetated, ambient precipitation) was also simulated for the period from November 1987 to April 1992. The calibration parameters derived from the WL-4 comparisons in the previous status report were used. Simulated storage in WL-2 followed the trend of the measured values during the first 2 years and were always within 10 to 20 mm of the measured storage. After December 1989, however, simulated values tended to diverge from the measured values. By April 1992, the simulated storage was 50 mm less than measured. Over the four summers, the difference between the measured and simulated minimum storage increased from 9 to 24 mm. This divergence did not occur for lysimeter WL-4, suggesting that calibrations derived from lysimeters under one treatment are not necessarily applicable to lysimeters under different treatments; i.e., each treatment may require a separate calibration.

Hysteresis was added to the UNSAT-H model. Verification tests were successfully simulated. The UNSAT-H model was then used to simulate water movement in drainage lysimeter D9. Hysteresis reduced evaporation slightly and promoted drainage. Water contents at several depths were not matched well with or without hysteresis. In the case of storage, the effect of hysteresis was of the same order of magnitude as the effect of changing parameters such as saturated hydraulic conductivity. Lack of fit to water content data remains unresolved.

This work is funded by the Office of Technology Development (via the Underground Storage Tank Integrated Demonstration) and the Office of Environmental Restoration for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

ACKNOWLEDGMENTS

The author is grateful to the support staff who collected the field data (rain or shine), Anita Phillips for processing the field data, Bob Lenhard for providing the hysteresis subroutines, Sharon Williamson for linking the hysteresis routines with the UNSAT-H computer code, and Glendon Gee for providing comments on an early draft of the report.

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1.0 INTRODUCTION

Radioactive and chemical wastes have been stored in or disposed to the sediments in a variety of locations at the U.S. Department of Energy's (DOE) Hanford Site in southcentral Washington State. To protect human health and the environment, multilayer protective barriers (i.e., covers) have been proposed as a means of limiting the flow of water through these waste sites (DOE 1987). A multiyear research program [managed jointly by Pacific Northwest Laboratory (PNL)^(a) and Westinghouse Hanford Company for the DOE] is aimed at assessing the performance of these barriers (Adams and Wing 1986). One aspect of this program involves the use of computer models to predict barrier performance. The simulation work reported here was conducted by PNL and extends the work described in Fayer et al. (1992a,b). The field data were collected from lysimeters at the Field Lysimeter Test Facility (FLTF) (Gee et al. 1989).

The purpose of this report is to test hypotheses related to modeling of water movement within and through protective barriers using the UNSAT-H model (Fayer and Jones 1990). The goal is to demonstrate that such water movement can be successfully simulated, thus giving the model user confidence that the model can be used to improve barrier design and assess long-term hydrologic behavior.

Two topics were studied: the application of a calibrated model to a time outside the calibration period and to a lysimeter receiving a different treatment, and the importance of hysteresis effects on the movement of water in a protective barrier. The first topic, the application of a calibrated model, involved the use of the UNSAT-H model to simulate weighing lysimeter WL-4 (non-vegetated, 2x and 3x average precipitation) for a 3-year period outside the calibration period. The objective was to determine whether such extrapolation would be successful with the given calibration. The calibrated model was also used to simulate weighing lysimeter WL-2 (non-vegetated, ambient precipitation) for the same 3-year period. The objective was to determine whether the calibrated model could be applied to a lysimeter that received a treatment different from that of the lysimeter used in the calibration process.

The second topic involved the study of hysteresis. A hysteresis model was incorporated into the UNSAT-H model, verification tests were conducted, and lysimeter D9 (non-vegetated, irrigated till drainage occurred) was simulated. The objective was to demonstrate whether hysteresis significantly affected simulations of water movement and, if so, whether hysteresis should be included in all future simulations of protective barriers.

Section 2.0 describes the simulations of lysimeters WL-2 and WL-4 with the calibrated model. Section 3.0 describes the inclusion of hysteresis in the UNSAT-H model, the verification tests, and the application of the hysteresis model to lysimeter D9. Conclusions and recommendations are given in Section 4.0.

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute.

2.0 SIMULATIONS OF MULTIYEAR STORAGE CHANGES

One of the objectives of using models is to predict what might happen in the future. The scenario might involve changes to barrier materials, changes to the climate, or just the desire to predict the multiyear performance of the final barrier. One of the concerns about using models to predict performance many years in the future is whether the models can be calibrated using data from a short duration and then extrapolated to a much longer duration. Another concern is whether calibration parameters determined for one treatment can be applied to another treatment. In this section, these two concerns are explored. The calibration parameters determined for a 1.5-year period for lysimeter WL-4 (non-vegetated, 2x and 3x average precipitation) were applied to the following 3-year period for the same lysimeter. The same parameters were then applied to lysimeter WL-2 (non-vegetated, ambient precipitation) for the same 3-year period.

2.1 PROBLEM DESCRIPTION

A complete description of the simulation inputs can be found in Fayer et al. (1992a,b). Changes to that description are reported below.

Subsequent to the work of Fayer et al. (1992b), the data from the FLTF were reviewed and adjusted. These adjustments were to the weighing lysimeter storage values, neutron probe calibration equation, initial conditions, cloud data, and wind data. Briefly, the new weighing lysimeter storage values are about 0.5 cm higher for WL-2 and 1.0 cm higher for WL-4 compared to the storage values reported in Fayer et al. (1992b). The new calibration equation for the neutron probe yields water contents that are equal to the old equation for water contents around $0.0695 \text{ cm}^3/\text{cm}^3$. At a water content of $0.4 \text{ cm}^3/\text{cm}^3$ using the new equation, the old equation yielded a water content of $0.37 \text{ cm}^3/\text{cm}^3$. This change to the probe equation resulted in new initial conditions for the simulations.

Cloudiness data were used to calculate potential evaporation (PE). The cloudiness data used in the previous report represented the daily averages. The description in the computer code FAOPET (Doorenbos and Pruitt 1977) calls for the average cloudiness during daylight hours rather than for the whole day. A repeat of the simulation of lysimeter WL-4 in the previous report but using the daylight cloudiness average yielded a difference of less than 2 mm for the duration of the 1.5-year simulation. While the effect was minimal, all simulations will henceforth use the average daylight cloudiness.

Wind data were used to calculate PE. The wind data used in the past were from the 15.24-m (50-ft) height. A routine in FAOPET scaled this value to the representative value at the 2-m level. Subsequently, wind data from the 2.13-m (7-ft) height were obtained and also scaled to the 2-m level. A comparison of the predicted 2-m wind speeds showed that those derived from the measurement at 15.24 m were 0.5 mph higher in 1987 than those derived from the measurement at 2 m. For 1989, the predicted wind speed was

0.8 mph higher using the 15.24-m measurement relative to the measurement at 2.13 m. Because the relationship in FAOPET to scale wind speeds between various sensor heights was not developed at the Hanford Site, it may be sensitive to wind speed height. The farther the measurement height is from the 2-m ideal, the less likely the scaling relationship will hold. A repeat of the simulation of lysimeter WL-4 in the previous report but using the 2.13-m-derived wind speed values yielded 10 mm more storage during the 1988-1989 winter. This change improved the simulation of WL-4 relative to the measured storage values. All simulations will henceforth use the wind speed measured at the 2.13-m height.

Two corrections were made to the irrigation data used in the simulations reported by Fayer et al. (1992b) for lysimeter WL-4. On 25 January 1988, the irrigation amount should have been 1.18 rather than 1.2002 cm. On 13 June 1988, the record indicates that 0.41 cm of water was added to the lysimeters but was not included in the previous simulations. Both corrections did not affect the results or conclusions in Fayer et al. (1992b); both corrections were made for the simulation reported here.

The irrigation amounts were determined from hourly lysimeter weight changes as was done in the previous status report. Comparing the cumulative irrigation amount determined using rain gauges versus using the lysimeter weight changes revealed the lysimeter showed about 6% less water addition. Because evaporation occurred during each irrigation, the hourly lysimeter weight change underestimated the amount added. Review of 10-min weight changes for selected irrigation events revealed that the problem of evaporation was most noticeable in the summer (up to 10%) and hardly detectable in the winter. Because there were times when the irrigation amounts differed significantly from the rain gauges, the weighing lysimeter weight changes were used as the measure of irrigation. This choice allowed for the correct irrigation amount during the winter when evaporation during irrigation was not significant. A similar review of precipitation events was less conclusive because of the complicating factors of snow and the indeterminate start and finish of each precipitation event. The lysimeter appeared to register about 5% more water than the rain gauge. Because of the uncertainties, however, this difference was not factored into the simulations.

The simulations of the two lysimeters, WL-4 and WL-2, cover the period from 4 November 1987 through 30 April 1992. For each lysimeter, two simulation results are reported: one using the standard parameters, the other using the calibrated parameters as determined in the previous report. Those parameters include a saturated conductivity value increased by a factor of 1.43, pore interaction term reduced from 0.5 to 0.0, PE reduced by a factor of 0.7, and extended snow cover mimicked by reducing PE to zero during the time of the snow cover. These calibrated parameters were determined on lysimeter WL-4 for the period from 4 November 1987 through 30 April 1989. The simulations reported below include this period plus an additional 3 years of data. During the extra 3 years, only one period of extended snow cover occurred (19 December 1991 to 12 January 1992). This period was represented in the following simulations in the same manner as for the previous snow cover periods.

2.2 SIMULATION OF LYSIMETER WL-4

The results in Figure 2.1 show that the simulation using standard parameters did not match the measured values of high storage in winter and low storage in summer. This result is consistent with the earlier work. The simulation does not appear to diverge from the measured values. The observation that high values of storage in the winter are not reproduced by the simulation is important because it is during winter months that drainage through the barrier is most likely to occur.

The simulation with the calibrated parameters significantly improved the match to the measured values (Figure 2.1). Summer values were always within 10 to 15 mm of the measured storage. In contrast, winter values did not match as well. In winter 1990-1991, the simulated storage was 40 mm less than measured. In winter 1991-1992, the value was more than 50 mm less than measured. The inability to predict the high values of storage in the winter months must be addressed if the model is to be used to predict drainage.

2.2 SIMULATION OF LYSIMETER WL-2

The results in Figure 2.2 show that the simulation using standard parameters did not match the measured values of high storage in winter and low storage in summer. This result is consistent with the earlier work and with the simulation results for WL-4. The observation that high values of storage in the winter are not reproduced by the simulation is important because it is during these times that drainage through the barrier is most likely to occur. For WL-2, however, the storage is so low that it is unlikely that any improvement in matching winter storage would yield any answer other than zero drainage.

The simulation with the calibrated parameters followed the trend of the measured values during the first 2 years. During that time, simulated storage values were always within 10 to 20 mm of the measured storage. After December 1989, however, the simulated values tended to diverge from the measured values. By April 1992, the simulated storage was 50 mm less than measured.

Figure 2.2 shows that, when measured storage was at a summer minimum, the difference between measured and simulated storage increased. The differences were 9, 9, 15, and 24 mm for the 4 years. This result differs from the lysimeter WL-4 simulation, where the difference varied between 5 and 9 mm and that did not diverge over the 4 years. The implication is that the calibration on lysimeter WL-4, which received the 2x and 3x average precipitation treatment, was not entirely applicable to WL-2, which received the ambient precipitation treatment.

2.4 DISCUSSION

An explanation for why the simulation of WL-2 diverged could be that the calibration on data from WL-4 may be treatment specific. This result is perplexing because if the physics were captured adequately in the conceptual model, only a single calibration should be necessary. But, when all processes are

FIGURE 2.1. Measured and Simulated Storage in Lysimeter WL-4

FIGURE 2.2. Measured and Simulated Storage in Lysimeter WL-2

considered, it becomes clear that a single calibration using one data set could easily produce an incomplete result. For example, WL-2 experiences much more drying. Processes that operate in the dry range would dominate the behavior of water in this lysimeter. In WL-4, which is a wetter lysimeter, dry processes may be less important and therefore show little response to a calibration. Conversely, because it was wetter, lysimeter WL-4 may have been more susceptible to an inadequate characterization of evaporation.

Other factors certainly affect the transferability of the calibration. For example, in a desert environment, irrigated lysimeters may receive energy from surrounding dry areas. The extra energy is termed advective energy and can increase evaporation well above the calculated value of PE. This increased level of evaporation due to advective energy is called the clothesline effect (Rosenberg et al. 1983). Given the relatively small area of the irrigated lysimeter in comparison to the non-irrigated surroundings, the clothesline effect could be very significant. Any attempt to transfer a calibration from the irrigated lysimeters to the non-irrigated lysimeter would meet with difficulty, as already discussed in Section 2.3.

Another area of concern is the calculation of PE. Fayer et al. (1992b) noted the winter evaporation rates often approached the PE rates whereas summer rates did not. Therefore, any uncertainty in PE directly affected simulated winter evaporation rates. Table 2.1 shows how measured and simulated water balance parameters varied during the period March 6-8, 1989. On March 7, measured and simulated evaporation matched well; both also essentially matched the calibrated PE value. Simulated evaporation on March 8, however, was about 40% higher than measured. The simulated rates were equivalent to the calibrated PE value, showing that such a calibration may not be applicable on a day-to-day basis. March 6 was treated as a snow day in the calibration and thus PE was set equal to zero. As the lysimeter data indicate, however, 0.8 mm of water was removed during March 6. Were the simulation to allow evaporation on that date, the calibrated PE value of 1.5 mm would have exceeded the measured evaporation rate by 88% (assuming evaporation was not limited by the soil). The comparisons presented in Table 2.1 do not represent the entire record. Of the data reviewed, many of the snow dates have evaporation rates that are nearly zero or at least far below calculated PE rates.

Model calibration requires care and caution. Because many parameters are adjustable, the model can be made to fit one data set only to find that it doesn't reproduce another data set. This process can be complicated by attempts to calibrate on the data set that received 2x and 3x average precipitation and apply that calibration to another data set, in this case the data set that received the ambient precipitation treatment. Recognition of this problem in calibration may seem frustrating, but it offers a unique opportunity. The Protective Barriers program has lysimeter data for both dry and wet conditions. This wealth of data means that eventually a unique calibration can be obtained that is operable over all expected wetness states of the barrier, thus making predictions of performance that much more defensible.

TABLE 2.1. Water Balance Parameters (mm) During March 6-8, 1989. Precipitation and drainage were zero. Measured evaporation was determined as the change in storage. The simulations used the calibrated parameters.

<u>Lysimeter WL-2</u>	<u>March 1989</u>			<u>Total</u>
	<u>6</u>	<u>7</u>	<u>8</u>	
Measured Evaporation	0.8	1.4	1.5	3.7
Simulated Evaporation	0.0	1.3	2.1	3.4
<u>Lysimeter WL-4</u>				
Measured Evaporation	0.8	1.3	1.5	3.6
Simulated Evaporation	0.0	1.3	2.1	3.4
Potential Evaporation	2.2	1.9	3.0	7.1
0.7*PE (calibrated PE)	1.5	1.3	2.1	4.9

3.0 HYSTERESIS

For sediments, hysteresis is the phenomenon whereby the relationship between water content and water potential is not unique, i.e., the relationship depends on the history of wetting and drying of the sediment. Hysteresis in sediments has been demonstrated in laboratory studies (Topp and Miller 1966; Stauffer and Dracos 1984; Lenhard et al. 1991), field studies (Royer and Vachaud 1975; Watson et al. 1975), and numerical simulations (Dane and Wierenga 1975; Hopmans and Dane 1986; Lenhard et al. 1991).

Fayer et al. (1992b) observed that hysteresis was an important phenomenon in the movement of water within lysimeter D9 at the FLTF. If important in D9, hysteresis might also be important in the other lysimeters as well as in the protective barrier itself. Their conclusion was that if simulations of drainage through protective barriers were to be accurate, hysteresis would have to be included or addressed in the conceptual model. In this section, the hysteresis model that was added to the UNSAT-H computer code is described, the modified UNSAT-H code is verified, and the modified code is applied to lysimeter D9. The objective was to determine whether the inclusion of hysteresis allows the UNSAT-H model to more accurately reproduce the field measurements of water content and drainage.

3.1 MODEL DESCRIPTION

The hysteresis model described by Lenhard et al. (1991) was chosen for inclusion in the UNSAT-H model because only two additional parameters were required and because the computer subroutines were available. The first parameter was iS_{nr} , the maximum amount of air that becomes entrapped when the soil is wetted from an air dry condition to saturation, a condition whereby the sediment has a matric potential of zero but is not necessarily completely saturated. The other parameter was α_i (subscript i refers to imbibition), one of the parameters used to describe the primary sorption curve. The parameter α_i is set equal to twice the value of α_d , a similar parameter but associated with the primary desorption curve. The parameter α_d has the same value used in the simulations in Section 2.0.

The basis for the hysteresis model is that the internal scanning curves can be scaled from either the primary desorption curve or the primary imbibition curve. The scanning curves and the primary sorption curve are further scaled according to the amount of entrapped air. Figure 3.1 illustrates the effect on water retention.

3.2 VERIFICATION TEST

The verification test was described by Lenhard et al. (1991). Briefly, a sand-filled column was subjected to lowering and raising of a water table while water contents and matric potentials were monitored. Values of water saturation at several elevations were recorded; only the values at the 70-cm

FIGURE 3.1. Hysteresis Effect on Water Retention in Silt Loam

elevation above the base of the column were used for this verification test. Lenhard et al. (1991) also simulated the experiment with a code that incorporated their hysteresis model. Both their measured and simulated values of saturation are in the Appendix.

Figure 3.2 shows that the comparison between the UNSAT-H code and the Lenhard et al. code was very good for the case with a) no hysteresis or air entrapment, b) air entrapment, and c) hysteresis and air entrapment. With hysteresis and air entrapment, both codes reasonably matched the experimental data. The modified UNSAT-H code was considered ready for application to a field situation.

3.3 APPLICATION TO LYSIMETER D9

To simulate the protective barrier, values for iS_{nr} were determined for the silt loam and the sand. Based on laboratory measurements, the iS_{nr} value for silt loam was 0.206 (i.e., θ_{air}/θ_s , the volumetric air content divided by the porosity). Based on the field data, the silt loam value was 0.127. For this calculation, the initial field water content was $0.222 \text{ cm}^3/\text{cm}^3$ in lysimeter D9 at the 135-cm depth and the average maximum water content was $0.439 \text{ cm}^3/\text{cm}^3$, which was achieved at the 135-cm depth during five consecutive measurements once the lysimeter started to drain. Simulations were conducted using both values to demonstrate the sensitivity. For the sand, a value of 0.05 was chosen based on laboratory measurements. The calibrated parameters discussed in Section 2.0 were used for these simulations. The use of calibrated parameters did not appreciably change the results from those reported in Fayer et al. (1992b).

Figure 3.3 shows that, with $iS_{nr} = 0.206$, the hysteresis model resulted in cumulative drainage that was comparable to that measured. With $iS_{nr} = 0.127$, the wetting front penetrated to within 50 cm of the base of the lysimeter but did not result in drainage (although if continued several more days, simulated drainage would have occurred). In contrast, use of the standard desorption curve yielded no water movement into the gravel and thus no drainage (same result as in Fayer et al. 1992b). Further examination of the results revealed, however, that the comparison of water contents at several depths was less than adequate. Figure 3.4 shows that, at the 15-cm depth, the simulations underpredicted water content by 0.05 to $0.06 \text{ cm}^3/\text{cm}^3$ between days 20 and 40. After day 80, the simulations had much larger amplitudes in water content than occurred in the field data. During this period, the neutron probe measurements were conducted 1 or 2 days following an irrigation. To detect such a large amplitude in water content, the measurements could be conducted just before the irrigation event in addition to 1 day later. By day 182, the simulated water contents were lower than measured by as much as 0.05 to $0.06 \text{ cm}^3/\text{cm}^3$. Figure 3.5 shows that, at the 60-cm depth, the comparison of water contents is quite reasonable, although between days 20 and 80 the simulations showed a steady decline while the measured data indicated some sort of peak around day 50. Figure 3.6 shows that, at the 135-cm depth, the simulated water contents lagged the measured increase around day 100. The simulated water contents by day 160 were 0.05 to $0.08 \text{ cm}^3/\text{cm}^3$.

FIGURE 3.2. Verification Test of the UNSAT-H Code with Hysteresis

FIGURE 3.3. Measured and Simulated Drainage from Lysimeter D9

FIGURE 3.4. Measured and Simulated Water Contents at a Depth of 15 cm in Lysimeter D9

FIGURE 3.5. Measured and Simulated Water Contents at a Depth of 60 cm in Lysimeter D9

FIGURE 3.6. Measured and Simulated Water Contents at a Depth of 135 cm in Lysimeter D9

less than the measured values. Clearly, while hysteresis may have allowed drainage to occur, it did not significantly improve the match to measured water contents within the profile.

Another way to judge the measure of the simulations is to look at storage in the silt loam layer in 1988. Figure 3.7 shows that the simulations did not reproduce the measured storage peak around day 35. Even more puzzling is that the simulations did not store as much water as the measured values indicate, despite the cover being in place. Theoretically, whatever water was added through irrigation should have been detected with the neutron probe. For the period between days 75 and 125, the simulations showed less storage gain (about 60 mm) than the measurements, indicating the possibility that more irrigation was added than was recorded.

Figure 3.7 shows that, after day 125, the hysteresis simulation yielded a decrease in storage following each irrigation. This decrease reflected the drainage of water from the silt loam into the sand and subsequently into the gravel. In Figure 3.7, the onset of drainage into the sand occurred when storage was around 500 mm, and was well under way once storage reached its maximum value of 550 mm around day 155. The implication is that drainage may occur before the highest storage value is attained. Thus, while it is a good indicator of likely drainage, the value of storage does not precisely indicate drainage conditions.

Based on these results, the question that arises is whether matching the simulation to the drainage data is conclusive evidence that the model adequately represents the movement of water within the lysimeter. For the silt loam, the measured and simulated storage changes differed by at least 60 mm. The simulated storage change in the sand was 24 mm; the simulated storage change in the gravel was 23 mm. Storage was not measured in either material. Compared to these amounts, drainage was a mere 15 mm. An experiment of this type might be more useful if continued until such time that the change in storage in the sand and gravel was nearly zero and drainage was as large or larger than the change in storage in the silt loam.

Can lysimeter D9 be used for hysteresis testing? Partly. The simulation results demonstrated that hysteresis reduced evaporation by 20% over the period 4 November 1987 to 14 March 1988. This reduction is consistent with the finding of Hillel (1977), who demonstrated that hysteresis reduced cumulative evaporation. In the case of the barrier, the reduction occurred during the winter. If the simulation were continued into the summer, the extra stored water would be subject to evaporation. Thus, the net annual result might be minimal from a storage perspective, but certainly of concern during the winter when the possibility of drainage is greatest.

The simulation results with and without hysteresis showed similar water content and storage values, yet only the hysteresis simulations yielded drainage into the gravel layer. The hysteresis simulation with a iS_{nr} value of 0.206 produced drainage; the other hysteresis simulation (with $iS_{nr} = 0.127$) had a drainage pulse within 50 cm of the gravel base. Figure 3.8 shows that during 1988, matric potential values measured at the silt-sand interface increased to about -10 cm. In the simulation without hysteresis, potentials at

FIGURE 3.7. Measured and Simulated Storage in Lysimeter D9

FIGURE 3.8. Measured and Simulated Matric Potentials at a Depth of 150 cm in Lysimeter D9

the interface did not exceed -75 cm. At this value, water was able to enter the sand but not enough water entered to increase the potential at the sand-gravel interface to allow significant drainage (i.e., greater than 0.05 cm/yr). In the simulations with hysteresis, matric potentials at the silt-sand interface increased to -14 cm. This allowed potentials at the sand-gravel interface to increase to -4 cm. At this potential, water easily entered the gravel (a significant flux of water started to enter the gravel when potentials exceed -30 cm). These results demonstrate that drainage into the sand and gravel layers was sensitive to hysteresis, which allowed the potentials to become sufficiently high at the interfaces to allow water to enter the sand and gravel.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The simulations described in this report illustrate three issues related to modeling of protective barriers: extrapolation beyond a calibration period, transferability of a calibrated model between treatments, and the effect of hysteresis on the simulation of water movement in a protective barrier.

Extrapolation of the calibrated model to the 3-year period following the calibration period showed that the model did not maintain the same degree of fit to the measurements as observed during the calibration period. The primary reason appeared to be an inadequacy to represent winter evaporation. This inadequacy might be addressed by further calibration, or it may reflect an incomplete conceptual model that is sensitive to winter evaporation.

Application of the calibrated model to another lysimeter, one that received a different precipitation treatment, resulted in a marked and growing divergence from the measurements. This result suggested that calibrations derived from lysimeters under one treatment were not necessarily transferrable to lysimeters under different treatments, i.e., each treatment may require its own calibration. More generally, this result indicates that different processes may be dominant in each treatment. Thus, calibration for one treatment may not apply to another. Given that the largest identified concern is the exposure of the irrigated lysimeters, resulting in the clothesline effect, the preferred option is to calibrate the model to the lysimeter receiving ambient precipitation, for which the clothesline effect should be minimal.

The simulation results demonstrated that hysteresis allowed matric potentials at the sand-gravel interface to increase above -30 cm, resulting in drainage through the underlying layer of gravel. In contrast, the simulation without hysteresis did not allow potentials to exceed -65 cm and thus significant amounts of water did not enter the gravel (in contradiction to the experiments). Including hysteresis in the model allowed for testing and verification of the hypothesis that hysteresis was a significant phenomenon in the draining lysimeters. If protective barriers wet to the levels seen in lysimeter D9, hysteresis would be an important phenomenon to include in simulations.

Based on earlier work and the work conducted in FY 1992, additional studies are recommended to improve modeling of protective barriers. The recommendations are:

- Resolve the winter evaporation discrepancy. Accomplish this recommendation by comparing measured and simulated daily evaporation amounts for as many dates as possible (many dates will be unusable for this analysis because of precipitation or data gaps). Also compare the evaporation amounts relative to the calculated values of potential evaporation to determine whether a better method of calculating PE is needed.
- Apply the hysteresis model to lysimeters WL-2 and WL-4 to determine the significance of its effect and whether it should be included in the calibration process.

- Review available water retention data (laboratory and field) and available conductivity data (including data from the ultra centrifuge at Washington State University) to revise the hydraulic property descriptions if warranted.
- Having completed the above recommendations, calibrate the model using data from lysimeter WL-2 (ambient treatment). This lysimeter is least susceptible to the clothesline effect and most nearly approximates the condition of the protective barriers for the period of institutional control.
- Apply the newly calibrated model to lysimeter WL-4.
- Apply the newly calibrated model to lysimeter D9.
- Because of concerns with data from lysimeter D9, conduct a controlled laboratory infiltration experiment that replicates lysimeter D9 on a smaller scale. Monitor matric potentials and water contents at several locations and collect drainage. Simulate the experiment and compare simulation to measurements.

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APPENDIX

HYSTERESIS DATA

APPENDIX

HYSTERESIS DATA

TABLE A.1. Measured Saturation Values from Lenhard et al. (1991)
Experiment, 70 cm Above Base of Column.

<u>Measurement Time (h)</u>	<u>S_w</u>	<u>Measurement Time (h)</u>	<u>S_w</u>
0.09	0.961	8.33	0.547
0.14	0.973	8.41	0.671
0.2	0.965	8.47	0.722
0.24	0.966	8.53	0.74
0.32	0.981	8.63	0.737
0.44	0.957	8.93	0.722
0.56	0.932	9.24	0.737
0.7	0.684	9.54	0.733
1.11	0.412	9.84	0.725
1.35	0.354		
1.63	0.304		
2.15	0.293		
2.45	0.283		
2.76	0.271		
3.7	0.257		
4.15	0.172		
4.46	0.176		
4.76	0.187		
5.13	0.189		
5.33	0.185		
5.67	0.189		
5.79	0.175		
6.09	0.178		
6.39	0.173		
7.48	0.164		
7.77	0.167		
7.94	0.178		
8.15	0.273		

TABLE A.2. Simulated Saturation Values from Lenhard et al. (1991)
Experiment, 70 cm Above Base of Column.

Simulation Time (h)	S_w		
	No Air Entrapment or Hysteresis	Air Entrapment	Air Entrapment and Hysteresis
0.00	1.000	1.000	1.000
0.20	0.996	0.996	0.996
0.40	0.953	0.951	0.951
0.60	0.815	0.804	0.801
0.80	0.617	0.598	0.585
1.00	0.455	0.443	0.433
1.20	0.361	0.352	0.342
1.40	0.312	0.305	0.295
1.60	0.286	0.282	0.274
1.80	0.269	0.267	0.259
2.00	0.258	0.257	0.250
2.20	0.250	0.249	0.242
2.40	0.244	0.243	0.237
2.60	0.239	0.238	0.233
2.80	0.235	0.234	0.229
3.00	0.231	0.230	0.226
3.20	0.228	0.228	0.223
3.40	0.226	0.225	0.221
3.60	0.223	0.223	0.219
3.80	0.222	0.221	0.219
4.00	0.231	0.220	0.220
4.20	0.398	0.218	0.222
4.40	0.462	0.220	0.224
4.60	0.477	0.228	0.227
4.80	0.481	0.248	0.228
5.00	0.482	0.278	0.229
5.20	0.372	0.301	0.229
5.40	0.317	0.306	0.226
5.60	0.288	0.301	0.223
5.80	0.271	0.293	0.220
6.00	0.259	0.284	0.219
6.20	0.251	0.276	0.218
6.40	0.244	0.269	0.217
6.67	0.237	0.260	0.215
6.87	0.233	0.254	0.214
7.07	0.230	0.250	0.214
7.27	0.231	0.246	0.215
7.47	0.396	0.243	0.216
7.67	0.754	0.243	0.220
7.87	0.978	0.277	0.289
8.07	1.000	0.473	0.666
8.27	1.000	0.737	0.754
8.47	1.000	0.755	0.754
8.67	1.000	0.755	0.754
9.00	1.000	0.755	0.754
9.40	1.000	0.755	0.754
9.80	1.000	0.755	0.754

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