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Comparing Ground-Water Recharge Estimates Using Advanced Monitoring Techniques and Models

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Comparing Ground-Water Recharge Estimates Using Advanced Monitoring Techniques and Models

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ABSTRACT

Risk due to contaminant release and transport, as estimated by many multimedia environmental models, is highly sensitive to infiltration and ground-water recharge. Previous ARS-NRC studies developed methodologies, and showed the value of high-frequency monitoring of unsaturated zone water contents and piezometric levels to estimate infiltration and ground-water recharge. This study tested those methodologies through comparison of estimated ground-water recharge in a closed system using a highly monitored lysimeter (i.e., 14 by 20 by 3 meters). Specifically, near-continuous water content, water-table elevation, and meteorological data were collected to estimate infiltration and ground-water recharge and their attendant uncertainties. These highly-detailed monitoring data were evaluated to capture individual recharge-event characteristics (i.e., infiltration, drainage and evapotranspiration) and to estimate hydraulic parameters. Advanced monitoring techniques and models were used to compare hierarchical levels of information for assessing sensitivities and identifying uncertainty. The study included numerical simulations of ground-water recharge using the HYDRUS-2D code and the PNNL Water Balance model. The variation in input parameters and resulting recharge estimates derived from the different methods provide a framework for assessing uncertainty. Advanced monitoring instruments proved valuable in providing (1) an understanding of the soil water dynamics; (2) input for estimating hydraulic parameters for the various models, and (3) a realistic database for evaluating the modeling results. Comparison of results indicated that there was considerable variability of soil water dynamics in the near surface.

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EXECUTIVE SUMMARY

This technical report was prepared by researchers at the Agricultural Research Service (ARS) in cooperation with the NRC staff under an Interagency Agreement (IAA) between the ARS and the NRC's Office of Nuclear Regulatory Research. The objective of this effort was to investigate field instrumentation and methods for estimating "real-time" ground-water recharge and its attendant uncertainties. The research design was to utilize methods and datasets from existing field characterization and monitoring programs at the Beltsville Agriculture Research Center (BARC) to resolve technical issues identified by the NRC staff as relevant to estimating ground-water recharge at nuclear facilities. The licensing issues investigated were the need for transient estimates of ground-water recharge, and whether conventional steady-state approaches underestimate recharge arising from episodic hydrometeorological events. Specifically, the field study was designed to compare estimates of ground-water recharge against directly measured values in a closed lysimeter, and to identify sources of uncertainty (e.g., measurement uncertainty and conceptual-model uncertainty).

This research utilizes specific datasets from ongoing ARS monitoring programs for the period January to December 2002. The ARS and NRC staff selected appropriate datasets useful for analyzing uncertainties in estimating net infiltration and ground-water recharge. This report builds on NUREG/CR-6653, "Comparison of Estimated Ground-Water Recharge Using Different Temporal Scales of Field Data," (Timlin et al., 2000), and NUREG/CR-6729, “Field Studies for Estimating Uncertainties in Ground-Water Recharge Using Near-Continuous Piezometer Data,” (Timlin et al., 2001). These reports discussed the timing and quantity of ground-water recharge which can be estimated from measurements of hydrologic conditions (e.g., water content and piezometric head). Infiltration and redistribution of water are highly transient processes which can be estimated from these hydrologic measurements. The time scale for these processes is a function of rainfall characteristics, soil hydraulic properties, and antecedent water content. Due to temporal variability in infiltration rates and water redistribution, the time period varies over which ground-water recharge occurs. The accumulation and timing of rapid near-surface effects can translate into significant differences in ground-water recharge over long time periods. The earlier studies evaluated a common assumption that infrequent monitoring of highly transient events can lead to significant loss of information (e.g., timing and quantity of ground-water recharge). The research conducted was to test this assumption and determine the reduction in uncertainty by utilizing real-time, near-continuous data. The preceding research reports documented that frequent monitoring of hydrologic conditions can provide reliable data for estimating net infiltration and redistribution of water which reduces uncertainties in the estimation of ground-water recharge.

Related studies (e.g., Meyer and Gee, 1999) identified the importance of assessing: (1) preferential flow in the near surface, (2) temporal variations in net infiltration rate and water content, and (3) heterogeneities in the subsoil that may result in focused flow and fast transport pathways for site-specific modeling. Dose assessments for decommissioning sites using site-specific models should consider whether these three conditions exist. Real-time, near-continuous monitored data may be useful if these conditions exist at a decommissioning site in order to appropriately model infiltration and net ground-water recharge.

This study addresses technical issues (e.g., episodic ground-water recharge events which may enhance mobilization and transport) common to NRC staff reviews of site characterization and performance assessments of various sites, and provides research results as technical bases for resolving these issues. One important technical issue addressed in this report is the characterization of ground-water recharge using real-time, near-continuous databases that lend themselves to time-series analysis. The temporal density of these data is such that interpolation methodologies may not be necessary and thus, uncertainty is reduced. Uncertainty in this context refers to information loss due to intermittent and low frequency monitoring and to variability in soil hydraulic parameters. Real-time, near-continuous data provide a highly realistic characterization of the transient, and dynamic hydraulic processes and events. The field study was designed to identify sources of uncertainty (e.g., measurement uncertainty and conceptual-model uncertainty) encountered in various analytical and numerical simulation approaches for estimating ground-water recharge.

The research reported here uses real-time, near-continuous piezometric heads in a closed lysimeter to measure ground-water recharge. These measurements were compared to estimates of ground-water recharge using near-continuous, real-time water content measurements, meteorological models, and numerical soil process models. The real-time, near-continuous datasets contained in this report provide a sufficiently complete characterization of the piezometric fluctuations. Information and analytic results from this report can be used to evaluate monitoring programs which may be used to characterize ground-water recharge at decommissioning, uranium mill tailings, and waste disposal sites.

Significant conclusions are:

- Real-time, near-continuous monitoring data can provide insights into the hydrologic processes which can affect radionuclide transport for near-surface settings in humid temperate climates.
- Specific yield needed to convert changes in piezometric level to ground-water recharge flux is a significant source of uncertainty. This important parameter is extremely difficult to measure directly and is often inferred from rainfall and piezometer head data where it is assumed that evapotranspiration is negligible, and the porosity is invariant with depth. These assumptions contribute to uncertainty.
- While the data from the Neutron probes do show the general trends in water contents, they miss the dynamics of the infiltration events and so do not have enough information to assess drainage during individual infiltration events.
- Uncertainty in characterizing site behavior can be reduced by utilizing a network of measuring devices to capture the temporal and spatial variability inherent in this dynamic process.
- The real-time, near-continuous piezometer data often showed a very rapid response (e.g. < 20 minutes) in the water-table to rainfall events. This verifies the occurrence of significant episodic recharge for the shallow water-table at this site. This dynamic process was also verified for the Multi-sensor Capacitance Probe (MCP) data as described in NUREG/CR-6653 and NUREG/CR-6729.
- Based on a mass balance analysis of the MCP data (e.g., infiltration, losses due to drainage and evapotranspiration, and storage), the summation of positive and negative changes of volumetric water contents from the MCP data result in a consistent mass balance.
- On average, the infiltration calculated from the volumetric water content changes overestimated actual infiltration when compared to the rainfall.
- For the summer, when evapotranpiration is an important component of water loss in the soil profile, the spatial average of the MCP data greatly overestimates ground-water recharge. For the other seasons when evapotranspiration is minimal, the spatial average of the MCP data significantly underestimates ground-water recharge. Spatial variation in ground-water recharge estimates using MCP data is on the order of the mean value.
- The PNNL model provided values of ground-water recharge that were similar to those inferred from the lysimeter database using an estimated specific yield.
- HYDRUS2D simulation results could not be utilized for the summer and fall-winter seasons due to artificial boundary conditions imposed by pumping of water accumulating in the lysimeter.
- The largest source of uncertainty was due to evapotranspiration calculations. The following are two specific cases:

    - It was difficult to separate the evapotranspiration and drainage components during calculation of negative changes in soil water contents shortly after rainfall events. This was especially true for long duration rainfall events.
    - For the numerical model inputs and results, the largest source of uncertainty arose from the need to input estimated potential evapotranspiration. The uncertainty is propagated through the model's approach for calculating actual evapotranspiration (i.e., assumptions in plant water uptake and root distribution). Additional sources of uncertainty for the modeling results were due to incomplete knowledge of soil hydraulic properties.

- Each methodology has its own inherent uncertainties. We could not obtain a directly measured ground-water recharge. The Gee flux meter would have been a direct method for a specific location, but would not address spatial variability.

- A major unknown is the soil dynamics between the 40 and 100 cm sensor depths. The sensor revealed highly dynamic water content changes down to 40 cm. However, the sensor at 100 cm depth did not indicate these changes (except during major recharge periods).

Findings from this cooperative research project provide insights into data and conceptual model uncertainties at the lysimeter scale (12 x 20 x 3 to 4 meters). For example, the comparison of steady-state versus transient analyses provided insights into uncertainties due to conceptual model assumptions and measurements. The two numerical models used were: (1) the PNNL Water-Budget model developed by Pacific Northwest National Laboratory through a companion NRC-funded research project, and (2) the HYDRUS-2D code developed by the ARS-George E. Brown Jr. Salinity Laboratory. The datasets and the programs developed for this study are available as computer-readable files from the USDA-National Agriculture Library. A significant observation from this work is the value of using integrated and realistic models. The use of such models integrates point measurements within a real-time basis for water-content, pressure-head and water-level changes. Therefore, uncertainties can be identified and estimated from various site-specific datasets. This information can assist in review of steady-state versus transient model selection, procedures, and evaluation of their inherent uncertainties.

This study included high frequency, real-time observations of rainfall and soil-water contents at 16 locations within a lysimeter. The piezometric data could potentially be the most reliable indicator of ground-water recharge. This method would require more robust and detailed measurements of specific yield, however. This study has also shown that spatial variability can be a large contributor to uncertainty. Further studies should move to larger scales (i.e., watersheds) which capture spatial heterogeneities and complex subsurface processes (e.g., lateral unsaturated flow). Measurements should include real-time observations of piezometer fluctuations, drainage and evaporative losses in addition to rainfall, and more robust estimates of specific yield.

A significant observation from this work is the value of using an integrated and realistic model (e.g., the PNNL water-budget model). Such models may be used to integrate point measurements within a real-time basis for water-content, pressure-head and water-level changes. Therefore, uncertainties can be identified and estimated from various datasets using these models.

Practical implications from this study are that uncertainty sources can be identified using the various approaches identified in this report which would be useful in licensing reviews of infiltration and ground-water recharge estimates. Specifically, this report provides insights into data and conceptual model uncertainties. This study also identifies practical field instrumentation and analytical models for estimating ground-water recharge using real-time databases. This study also demonstrates temporal relationships in subsurface water flow, water-content redistribution and evapotranspiration. The complexities of these dynamic and transient processes are reflected by these data. The selection and use of analytic models for capturing these dynamic processes are demonstrated. This information can assist in review of steady-state versus transient model selection and evaluation of their inherent uncertainties.

FOREWORD

This technical report was prepared by Agricultural Research Service (ARS) researchers in cooperation with the NRC staff under an Interagency Agreement (IAA) between the ARS and the NRC's Office of Nuclear Regulatory Research. The objective of this effort was to investigate field instrumentation and methods for estimating realistic ground-water recharge and uncertainties to assist NRC staff in reviewing decommissioning activities at NRC-licensed facilities. Ground-water recharge which moves meteoric and surface water through the subsurface to the underlying regional water table is the initiating and driving process for leaching, mobilizing and transporting radionuclides in the subsurface. The research was designed to utilize methods and datasets from existing field characterization and monitoring programs at the Beltsville Agriculture Research Center (BARC) to evaluate various approaches being used to estimates ground-water recharge. The issues being investigated are whether realistic estimates of transient ground-water recharge are feasible, and if they are more appropriate than presently used steady-state approaches, which may underestimate recharge arising from episodic hydrometeorological events. As described below, this report is consistent with the NRC strategic performance goal in making NRC activities and decisions more effective, efficient and realistic.

Making NRC activities and decisions more effective, efficient and realistic - The report demonstrates, using detailed field datasets, that more realistic transient ground-water recharge estimates can be made using existing field instruments and methods, and how these various approaches can reduce uncertainties. The report provides the technical bases for selecting field instrumentation and analysis methods for conducting transient ground-water recharge estimates. The comparisons of transient to steady-state approaches indicate that presently used modeling assumptions and input often underestimate localized and time-dependent recharge. This information will assist NRC licensing staff, Agreement State regulators and licensees in their selection and review of environmental modeling efforts, and evaluation of their inherent uncertainties.

This NUREG/CR report builds on earlier research findings on infiltration and ground-water recharge estimation approaches using unsaturated zone instrumentation and analyses as documented in NUREG/CR-6729 (Timlin et al., 2001). This report focuses on state-of-the-science approaches using automated piezometer instrumentation to obtain near-continuous measurement of water-table fluctuation, and analytic methods for estimating "real-time" ground-water recharge rates. The report compares several estimation approaches: volumetric water content changes from near-continuous, real-time measurements; steady-state estimates using meteorological data; and two numerical simulation models using detailed, site-specific data. The comparison of steady-state versus transient analyses provided insights into uncertainties due to conceptual model assumptions and measurements. The two numerical models used were the PNNL Water-Budget model that was developed by Pacific Northwest National Laboratory through a companion NRC-funded research project, and the HYDRUS-2D code that was developed by the ARS-George E. Brown Jr. Salinity Laboratory. A significant observation from this work is the value of using integrated and realistic models. The use of such models integrates point measurements within a real-time basis for water-content, pressure-head and water-level changes. Therefore, uncertainties can be identified and estimated from various site-specific datasets.

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1. INTRODUCTION AND OBJECTIVES

1.1 Background

This work describes a Federal Interagency cooperative study between the U.S. Department of Agriculture - Agricultural Research Service (ARS) and the U.S. Nuclear Regulatory Commission (NRC) examining sources of uncertainties associated various approaches (i.e., field instrumentation and analytical methods) for estimating ground-water recharge. Specific research needs being addressed include: (1) estimation of ground-water recharge for variable site conditions and properties, (2) techniques for estimating error and uncertainty; and (3) a comparison of strategies for addressing spatial and temporal variability as they affect ground-water recharge estimates.

Ground-water recharge can be estimated for: discrete events using near-continuous monitoring data (e.g., episodic recharge) of water table height or water content or infrequent measurements (e.g. daily, weekly or monthly); periodic estimates (e.g., seasonal estimates); or over extended time periods using averages of long-term data (steady-state recharge). Associated with these time-dependent and time-independent estimates are inherent assumptions and related uncertainties attributed to the analytical method, measurement interval, and/or database.

This work has examined technical bases for estimating ground-water recharge at an extensively monitored lysimeter site at the Beltsville Agricultural Research Center that provides appropriate detailed datasets. At this site, the shallow water table is highly responsive to frequent episodic rainfall events and is closed to the outside system, except for the top boundary. Advanced monitoring instruments provided high-frequency data of vadose-zone water contents and piezometric levels to build confidence in estimating ground-water recharge in a system with known boundary conditions.

1.2 Objectives

The objective was to compare estimates of ground-water recharge and associated sources of uncertainty from methods developed in the two previous NUREG reports (Timlin et al., 2000; Timlin et al., 2001) with measurements of groundwater recharge in a large enclosed lysimeter.

2. DESCRIPTION OF FIELD SITE AND DATABASES USED

2.1 Lysimeter and Instrumentation Description

The research was conducted within a highly controlled and instrumented lysimeter (Figure 1) with dimension of 21.3 m x 13.7 m x 4.0 m (75 ft x 45 ft x 13 ft). The sides and bottom of the lysimeter are lined with plastic to prevent drainage and movement of water out of the lysimeter. This lysimeter was one of six originally constructed in a previous NRC-funded field study to assess means for controlling water infiltration through waste disposal unit covers in humid regions. As reported in NUREG/CR-4918, this lysimeter was identified as Lysimeter No. 3 which was constructed with a gravel layer at about 3-m depth between the plastic liner bottom and the sandy loam sub-soil. In 1999, the surface of the lysimeter was modified by ARS scientists to study the fate and transport of pathogens from manures (manure treatments had not been initiated as of December 2002). Thus the four surface slopes were changed to two slopes, with approximately 2 ft of the sandy loam soil being replaced with a silt loam soil (see Figure 1). Two eight-inch PVC pipes penetrate into the gravel layer and serve both as piezometer wells and as access wells for pumping accumulated ground-water from the lysimeter to maintain a specified depth to the "lysimeter water table". The lysimeter was planted with orchard and fescue grasses to simulate pasture conditions. The lysimeter slopes (10%) have gutters at the two lower edges to collect surface runoff, and direct it via PVC pipe to external large collection chambers (see Figure 2).

This lysimeter has been highly instrumented to quantify ground-water recharge and uncertainty. Instrumentation provides for real-time and near continuous (10 min. intervals) measures of the water table, soil water content, soil water potential and meteorological parameters. Lysimeter water table fluctuations were recorded with automated pressure transducers (Diver, by Eijkelkamp Agrisearch Equipment, The Netherlands) placed in two piezometer wells. Soil water dynamics was monitored with 16 Multisensor Capacitance Probes (MCP's, by Sentek Pty, Kent Town, South Australia): eight MCP's with sensors centered at depths of 10, 20, 30, and 40 cm, and eight with sensors centered at depths of 10, 20, 40, and 100 cm (see Figure 3). Each capacitance sensor integrated the soil water content over a 10-cm interval, e.g., the sensor centered at 10-cm integrates soil water content between 5- and 15-cm.

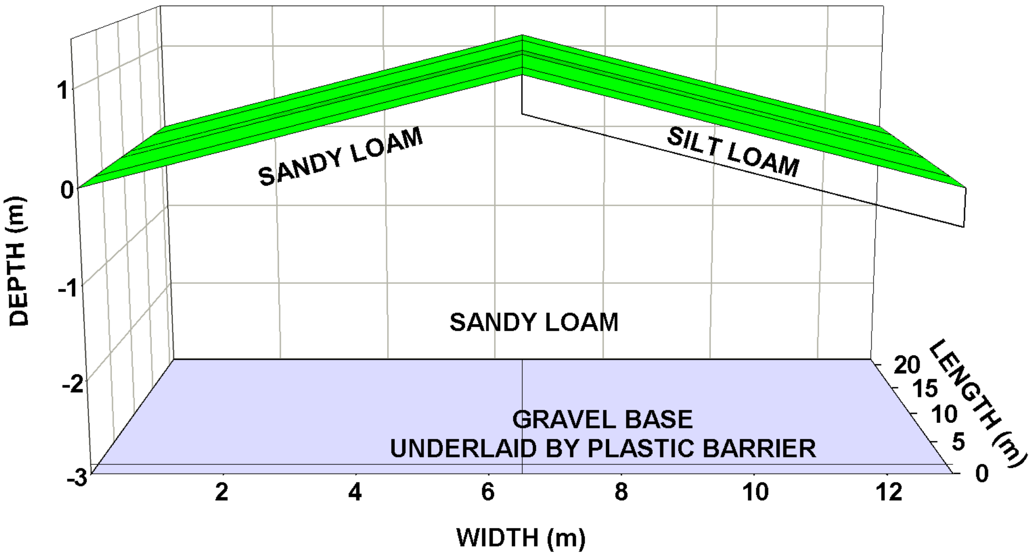

Figure 1. Three dimensional schematic of Lysimeter #3 showing slope (10°) of soil surface and distribution of soil textures.

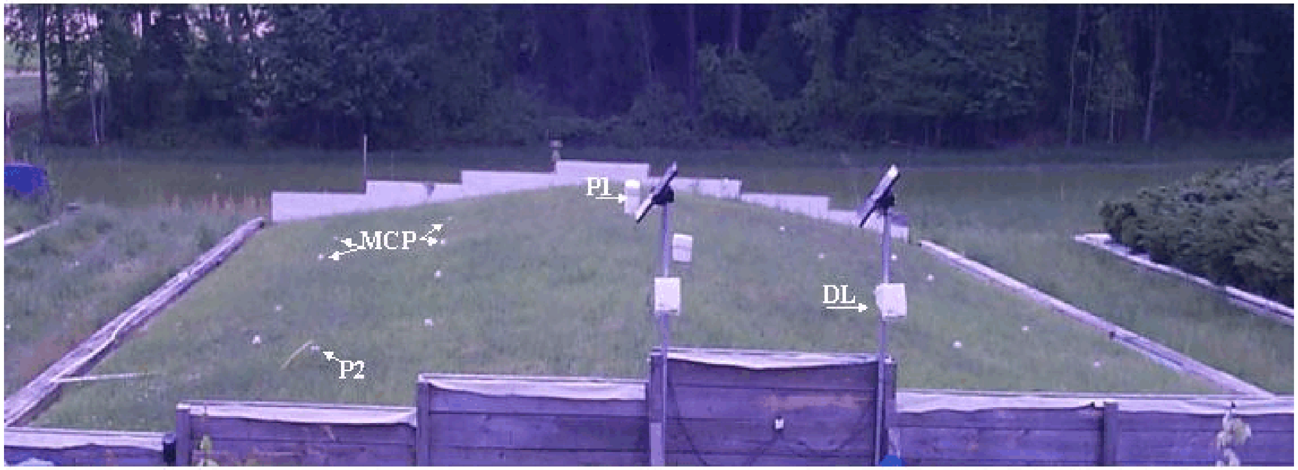

Figure 2. View of Lysimeter 3 showing MCP and Piezometer locations. Please note that Piezometer 4 is the middle lysimeter which is routinely used to pump down the local water table.

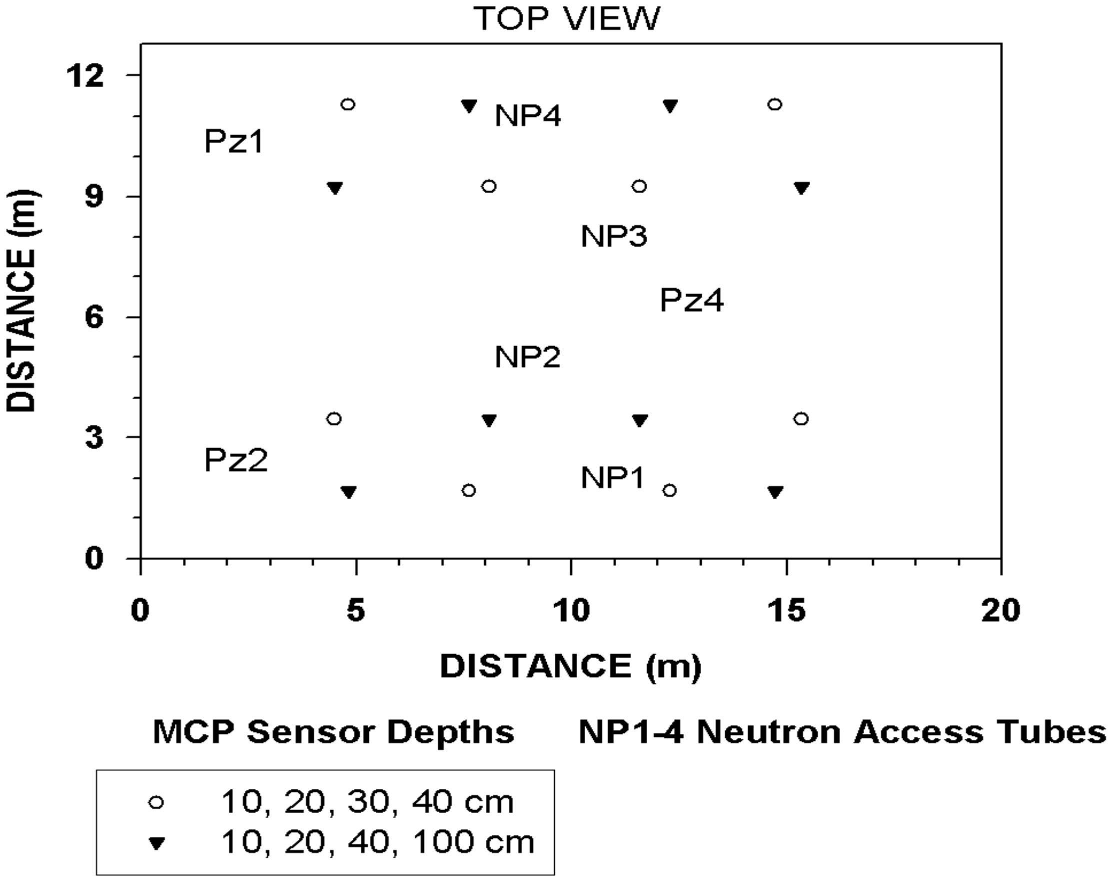

Figure 3. Schematic showing the top-view layout of the multisensor capacitance probes (MCP), Neutron probes (NP) and the three piezometer locations. The crest of the lysimeter is at 6.1 m on the Y axis.

Table 1. Instruments used in this study, types and frequency of variables measured, file names for the databases, and references describing the methodology.

Instrument	Parameter	Resolution	File name	Reference
Multisensor Capacitance Probe	Water content cm^3 cm^{-3}	10 minutes	LysimMCP.mdb	Paltineanu and Starr, 1997
Neutron probe	Water Content cm^3 cm^{-3}	monthly	LysimNP.mdb	SSSA Measurement methods (Dane and Topp, 2002)
Advanced tensiometer	Soil matric potential (kPa)	10 minutes	LysimAdvancedT	Hubbell and Sisson, 1998
Flux meter	Water flux cm d^{-1}	per 0.254 ml of water infiltrated	LysimFluxMeter	Gee et al., 2002
Piezometer	Water table elevation (cm)	10 minutes	LysimPiezom	Eijkelkamp
Weather station	rainfall (mm), temperature (C), solar radiation (Watts m-2)	rainfall 5 minutes, others 15 minutes	LysimWeather	Campbell Scientific

2.2 Databases Used

2.2.1 Meteorological Data

A Campbell (Campbell Scientific, Logan, Utah, USA) weather station near the site provided data on rainfall, air temperature, radiation, and wind speed and direction. Rainfall data were recorded at 5 minute intervals; radiation, temperature, and wind data were recorded at 15 minute intervals. Potential evapotranspiration was estimated using the Penman equation (Penman, 1963; Timlin et al., 2001) for 15 minute time intervals using radiation, temperature, and wind speed.

The meteorological data were grouped into three seasons. The winter-spring (*ws*) season represented the period from January 1 to April 30; the summer (*su*) season represented the period from May 1 through August 30; and the fall-winter (*fw*) season represented the period September 1 through December 31.

The weather data were further subdivided into discrete rainfall events; associated potential recharge periods were classified and given an identification number. A period for potential recharge during a rainfall event was defined as the time from the beginning of a rain event to the next time with rain that was at least 24 hours after the previous rain (see Figure 4). This screening procedure was carried out within the Statistical Analysis System (SAS), (SAS Inc, 1999) by calling the FORTRAN program "*ClassRn.for*" (see Timlin et al., 2001, Appendix B4). The program

"*ClassRn.for*" classifies the rainfall events by rainfall occurrence as shown in Figure 4.

Each potential recharge period was given an ID (*rainid*). The ID's were numbered consecutively for each recharge period. All rainfall events were screened to eliminate trace rainfall events with less than three 10-minute periods with insignificant rainfall (less than 0.5 mm). The ID, *rainid,* was always extended to the beginning of the next rain event. This provided for continuously labeled potential recharge periods. The rainfall ID's also allowed us to group calculations according to a recharge event ID. Rainfall data were merged with the SAS datasets containing the piezometer data.

Table 2. Summary of real-time rainfall data for 2002. The data are summarized by season with the time period for each season also given. The seasons are winter spring (ws), summer (su), and fall-winter (fw). PET was calculated using the Penman Equation (Penman, 1963).

Year	Season	First day of season	Rain (mm)	PET (mm)
2002	ws	Jan 1, 2002	211.3	366.4
	su	May 2, 2002	311.2	779.2
	fw	Sep 2, 2002	265.4	243.4
	Total		787.9	1389.0

2.2.2 MCP Data

Sixteen multisensor capacitance probes (MCP) were installed in the lysimeter (Figures 2 and 3) to monitor real-time, near-continuous, water contents throughout the lysimeter. Details of the MCPs are provided in Paltineanu and Starr, 1997). Figure 5 shows the type of data this sensor provides and how the soil water content responds to rainfall. Eight MCPs had sensors at 10, 20, 30 and 40 cm depths, and the other 8 probes at 10, 20, 40, and 100 cm depths (see Figure 6). The axial zone of influence for a sensor is 5 cm (2 in). Therefore, the zone of influence of a sensor is a 10 cm (4 in) layer. Infiltration rates were calculated for the profile using data from all 4 sensors (5-105 cm or 5-45 cm) using the methodology given in Table 1. The water contents were summed to obtain total storage of water in the profile (mm) at a given time. For the probes that did not have sensors at 30 cm depths, the water content at 30 cm was interpolated from the 20 and 40 cm measured water contents to provide uniform depth increments for the calculations. Figure 5 shows the type of data this sensor provides and how the soil water content responds to rainfall.

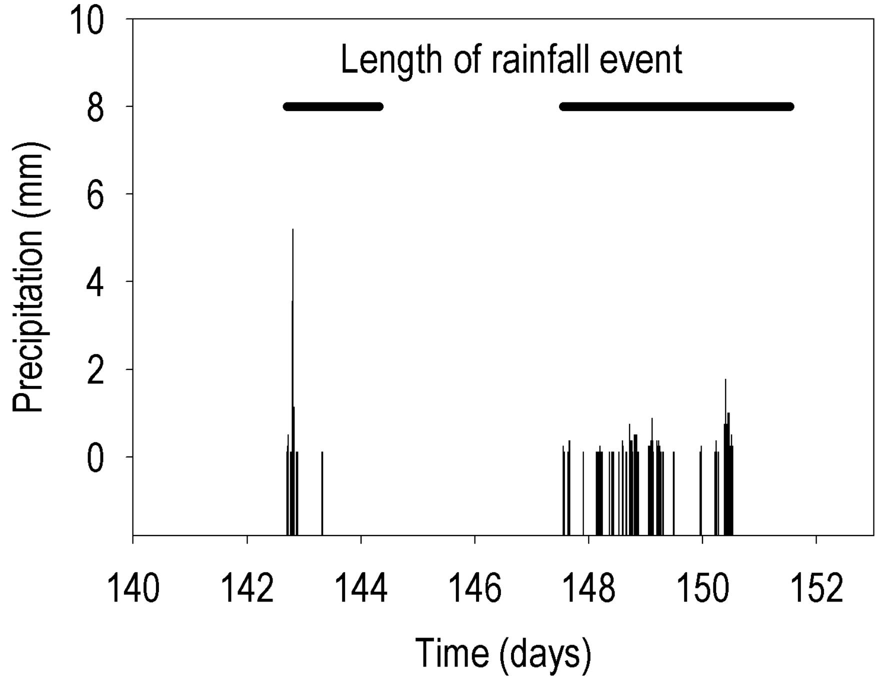

Figure 4. Schematic of method for discriminating rainfall events. This figure shows two discrete rainfall events that have been classified.

2.2.3 Neutron Probe Data

Four neutron probe access tubes were installed to 1 meter depths (see Figure 3 for locations). There were two probes installed on each side of the lysimeter, generally in the middle of the MCP probe array. Readings at 10 cm intervals were obtained bimonthly . The MCP data from nearby locations were used as a reference to calibrate the neutron probe readings.

2.2.4 Piezometer Data

Three piezometers, (locations shown in Figures 2 and 3) were installed in the lysimeter. The first piezometer was placed in an 0.2 meter diameter access well and was positioned at the crest of the lysimeter (see Figure 2). This first piezometer extended to the gravel base at the lysimeter bottom. The other two piezometers were positioned on opposite sides of crest. One of these was placed in the sandy loam material with the other in the silty loam material on the opposite side of the crest (see Figure 3). These two piezometers were placed in an 0.05 meter diameter access wells and positioned 2.5 meters from the lysimeter boundary edges, and were approximately 1 meter above the lysimeter bottom. All three were monitored every 10 minutes, using automated data loggers (Eijkelkamp Agrisearch Equipment, Arnheim, The Netherlands).

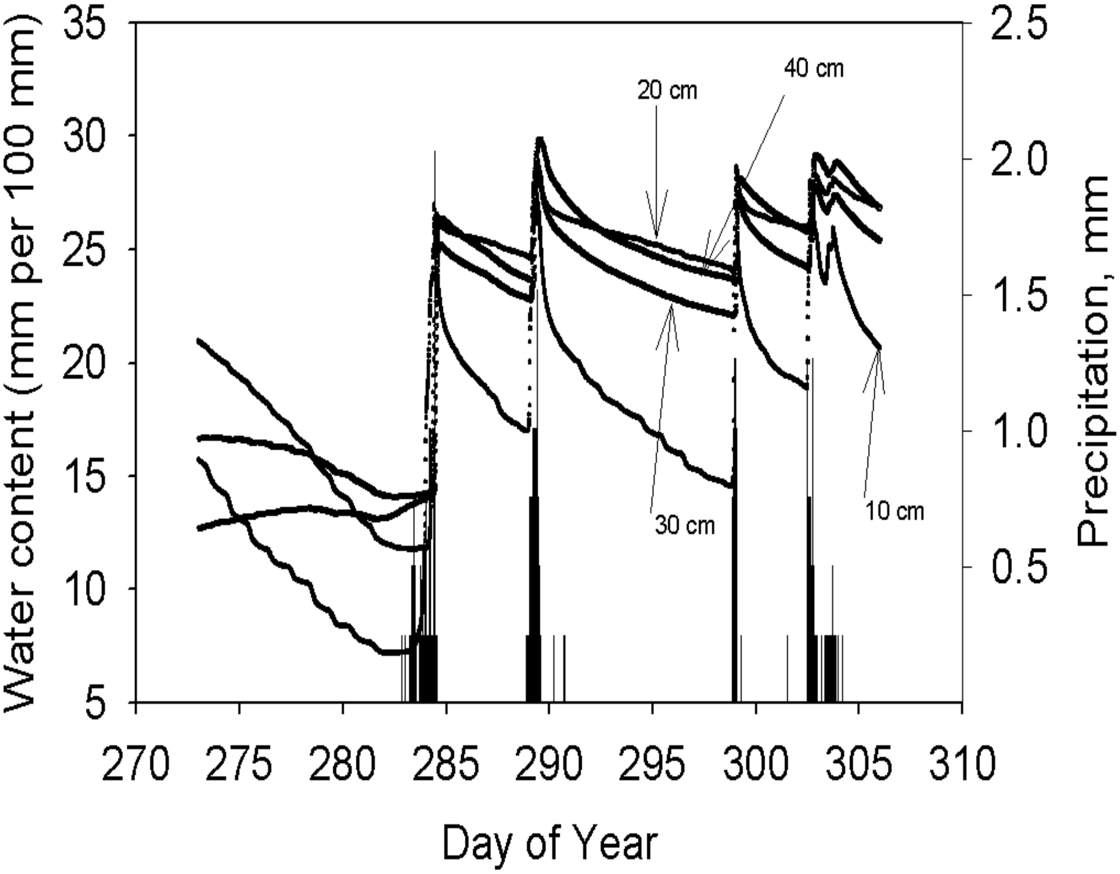

Figure 5. Dynamics of water contents measured over a 30-day period during October, 2002 in location L1P1. The data from the four depths are noted in the figure.

Figure 6. Schematic of MCP probe layouts with information on soil types and depth increments.

Table 3. Soil types and depths for the MCP probes shown in Figure 4. Refer to Figures 2 and 3 for locations of these probes in the lysimeter.

Soil	40 cm probes	100 cm probes
Sandy Loam	L1P1	L1P2[¶]
	L1P6[¶]	L1P5
	L2P2	L2P1
	L2P5	L2P6
Silt Loam	L1P3	L1P4
	L1P8	L1P7
	L2P4	L2P3[¶]
	L2P7[¶]	L2P8

[¶] Redistribution data were collected at these MCP locations.

Because the lysimeter is a closed system, the water level in the lysimeter was routinely lowered using a submersible pump. The design basis water level was at approximately the gravel base 1 meter above the bottom of the lysimeter. The accumulated inflow data were adjusted for the reduction in water level height due pumping which provided an ever increasing record of ground-water recharge. Resolution for the measured water levels was about 1mm or less.

2.2.5 Water Fluxmeter Data

Two water flux meters (Gee, 2002) were installed to provide an alternate means of estimating ground-water recharge (Figure 7). The entry point for the flux-meter funnel was set at 60 cm depth. Due to fluctuating water levels (noted above), the flux-meters were operational during only a portion of the monitoring period.

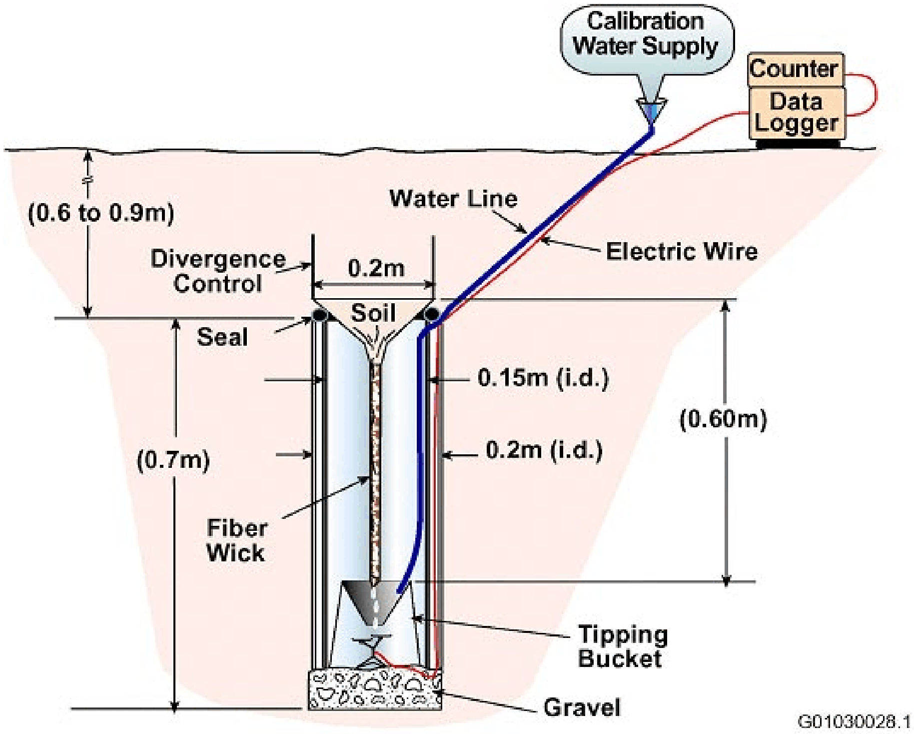

Figure 7. Schematic of the Glendon Gee Fluxmeter (from Gee and others, "A vadose zone water fluxmeter with divergence control," *Water Resources Research* 38(8): 35-41, 2002). Published 2002 by the American Geophysical Union. Reproduced/modified by permission of American Geophysical Union.

3. METHODOLOGY

This section describes the methods used to determine soil hydraulic properties and to estimate ground-water recharge. Underlying assumptions in this study were that there was no lateral subsurface movement of water and no surface runoff . Specific assumptions for each method are described in the text of this report. According to these assumptions, measurements of piezometric head changes around rainfall events can be expected to capture the changes in water table level that result from ground-water recharge. Net ground water recharge, however, was indirectly measured in the lysimeter using piezometric measurements of hydraulic head since a value of specific yield is used to convert cm of head to cm of water. Specific yield is the only relevant recharge parameter that needed to be estimated since recession of the water table did not occur in the closed system.

Net ground-water recharge was also estimated using indirect methods [e.g., percentage of annual precipitation (***%P)*** or precipitation minus evapotranspiration (***P-ET***)], more direct methods which relied upon real-time, near-continuous water content measurements [e.g., changes in water contents ($\Delta\theta$)], and numerical methods utilizing numerical models with varying levels of detail [e.g., HYDRUS-2D (Šimunek et al., 1999) and the PNNL Water-Budget model (Simmons and Meyer, 2000)]. These estimates were compared to direct measurements from the piezometer.

3.1 Methods used to Estimate Soil Hydraulic Properties

3.1.1 Estimation of Moisture Retention and Soil Hydraulic Conductivities

During October 2002, water was applied to four locations using a grid of compensated drippers (i.e., 2 L h^{-1} for each dripper) which resulted in a total application of ~10 cm h^{-1}. The dripper set up is shown in Figure 8. Application ceased after water contents reached near steady-state conditions to 40 cm as measured by MCPs. The soil surfaces at the sensor locations, e.g., L1P2, L1P6, L2P3, L2P7) (see Figures 2 and 3) were covered and the measurement interval decreased to 1 minute. Water contents were measured for 36 hours. Data showing drainage and redistribution of the soil water by soil texture are shown in Figures 9 and 10. The water content data were averaged by soil texture (e.g., sand and silt), and were also used to calculate fluxes through the boundaries defined by the sensor locations (i.e., 10, 20, 30, 40 and 100 cm) (Figures 11 and 12). The fluxes were calculated by differencing the water content data over the 1-minute time intervals.

These data were used to calibrate soil hydraulic properties (e.g., moisture retention and soil hydraulic conductivity as a function of matric potential) using the inverse methods provided with the HYDRUS-2D code. A simple one-dimensional profile (100 cm deep) was used with a constant head boundary condition at 100 cm. Although the water contents at 100 cm showed a slight rise over the time of measurements, this increase was relatively small. There were three horizontal layers, 0-15 cm, 16-90 cm and 90-100 cm. Input data for HYDRUS-2D were water content as a function of time for all layers (at one minute intervals), selected $h(\theta)$ pairs, and values of flux past 100 cm calculated from the MCP data. The flux rates calculated as a function of water content were used to guide selection of the hydraulic conductivities for optimization by HYDRUS-2D.

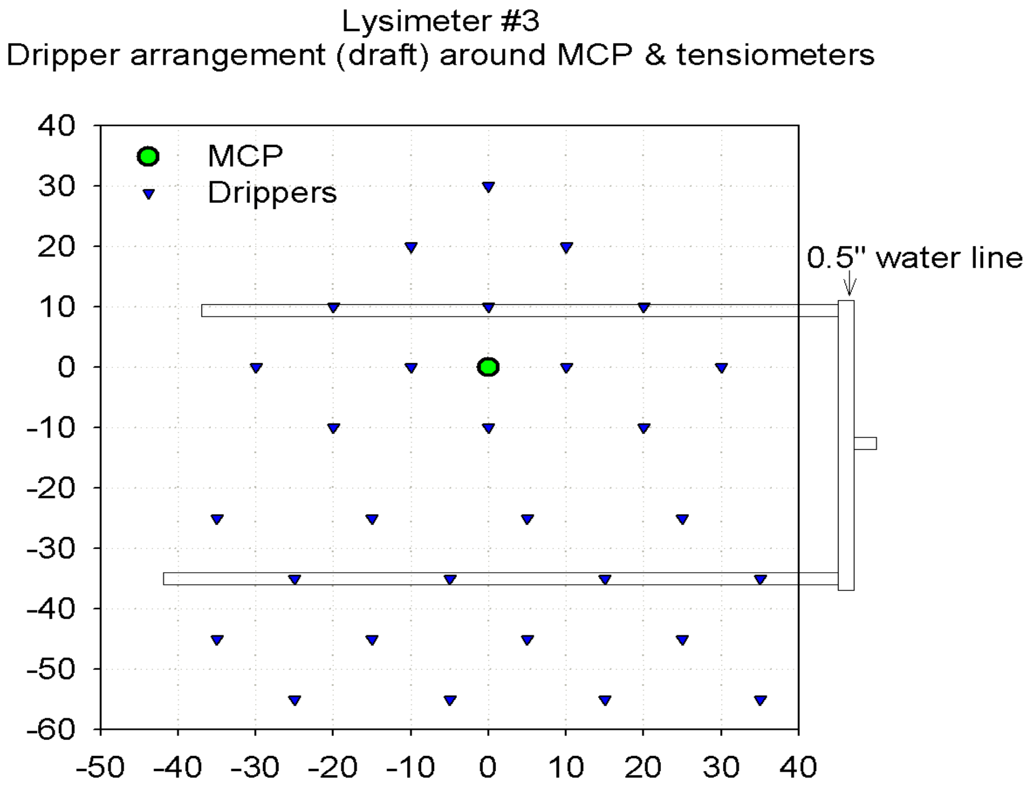

Figure 8. Layout of drippers for redistribution test. Dimensions are in cm.

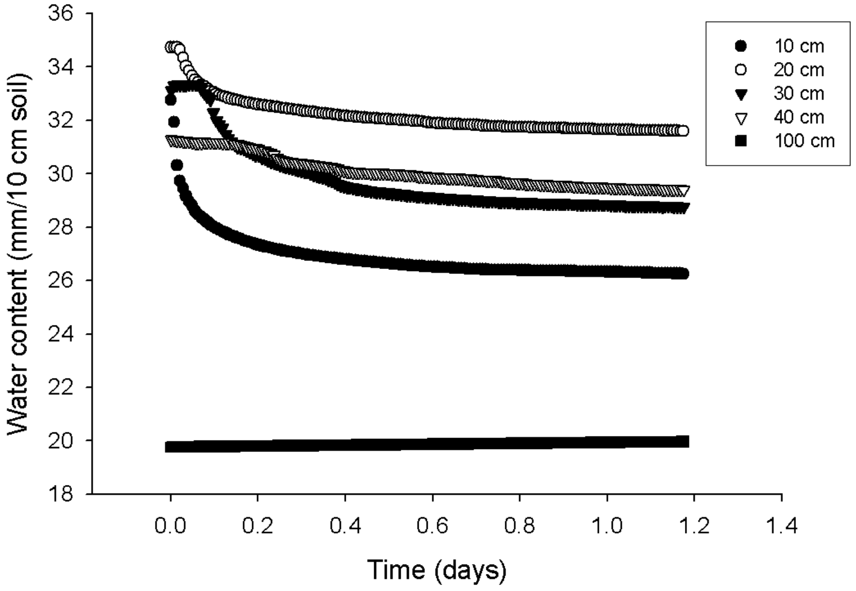

Figure 9. Redistribution as a function of time for the silty soil at 5 depths. The data are from spatial averages of 8 locations and temporal averages over 15 minute periods.

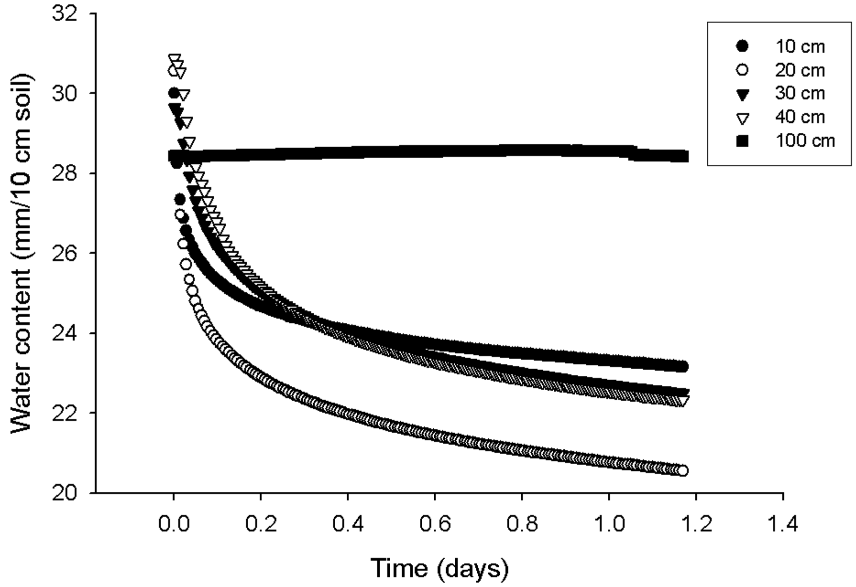

Figure 10. Redistribution as a function of time for the sandy soil at 5 depths. The data are from spatial averages of 8 locations and temporal averages over 15 minute periods.

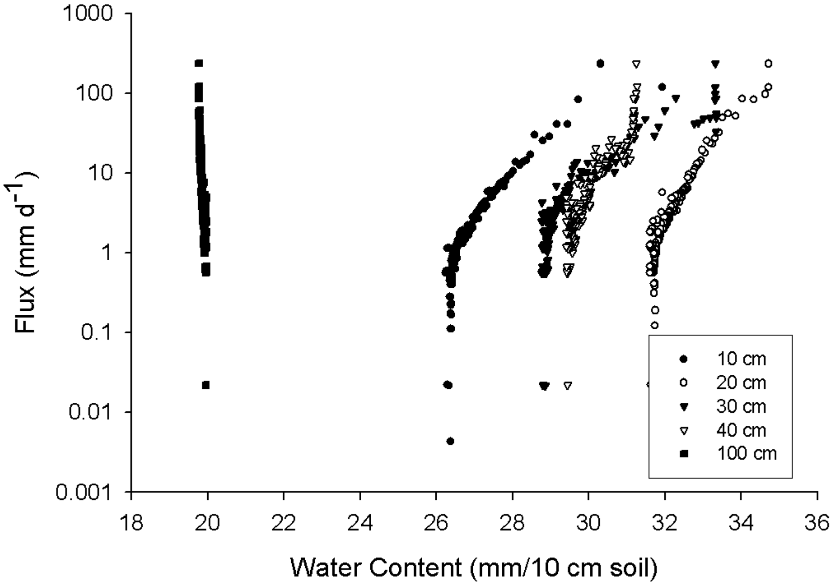

Figure 11. Flux rates from the redistribution test on the silty soil. Water contents were constant at the 100 cm depth indicating steady-state flow.

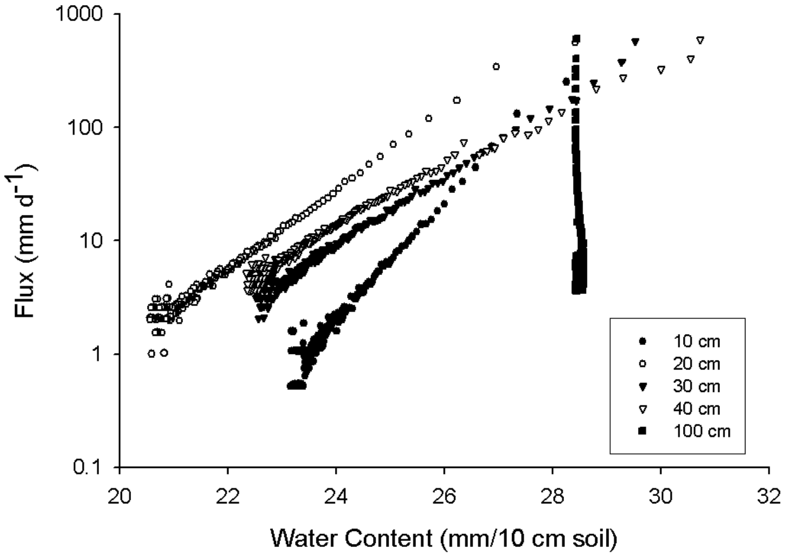

Figure 12. Flux rates from the redistribution test on the sandy soil. Water contents were constant at the 100 cm depth indicating steady- state flow.

3.1.2 Estimation of Specific Yield

The specific yield is used to estimate how high the water table will rise as a function of the net amount of water infiltrating from the surface, i.e., from rainfall or irrigation. This parameter is difficult to measure because the sample must be taken from deep in the profile. Since the amount of water pumped from the lysimeter was not measured, there were not enough data to calculate specific yield directly (i.e., procedure to pump water out and simultaneously measure the change in water table height to correlate with the volume of water removed).

The data in Table 4 provides information on representative values of specific yield, porosity and hydraulic conductivity for various soil and rock materials found in nature. The surface materials in the study site are silt and sandy loam soils (see Figure 1). The values of specific yield in Table 4 that correspond to silt loams and coarser textured materials are 8 to 23%. The values of specific yield in Table 4 are representative values and are likely to exhibit considerable variability.

For this lysimeter study, specific yield was estimated by evaluating values from several sources and choosing a value consistent with site conditions. An initial value of specific yield was obtained from the ratio of the change in water-table height and total rainfall for the period January - March 2002 when evapotranspiration was assumed to be minimal (see Table 2). A second estimate was derived from HYDRUS-2D by adding small increment of rainfall (i.e. 5 cm) without any evaporation to a profile in hydraulic equilibrium and then dividing the input by the resultant rise in the water table. Soil properties for a sandy loam media similar to that found in the lysimeter were used.

A value of specific yield derived from a rainfall/head relationship in early spring was estimated for the site to be 0.25. Since this value does not take into account any evaporation (which should not be large in the winter months) it provides an upper bound on the value of specific yield. Estimates from HYDRUS-2D were about 0.18. Data from Table 4 suggest that the value for fine sands to silts ranges from 0.23 to 0.08. Since the soil texture at the base of the lysimeter is sandy loam, we estimated specific yield to be about 0.19 from among these values. Since specific yield is estimated, a true value of "measured" ground-water recharge cannot be obtained.

3.2 Methods Used to Estimate Ground-Water Recharge

The following is a summary of the methods used. A schematic showing ground-water recharge as related to the different methods is shown in Figure 13. The SAS system (SAS, 1999) was used for calculations and database management.

A. **Time-Series analysis of piezometer changes**

> ***Changes in piezometric head*** (**$\Delta\underline{\nabla}$**). Piezometers were used to record water-table height at 10-minute intervals. The changes in head were calculated for each rainfall period as the difference between the head at the end of the last rainfall period and the head at the end of the current rainfall period. Since the lysimeter was closed, there was no drainage out of the lysimeter and thus it was not necessary to consider recession.

B. **Moisture Capacitance Probe (MCP) data**

> ***Volumetric soil water content changes*** (**$\Delta\theta_V$**). Measured soil water content (from MCP instruments) data were used to estimate ground water recharge. Infiltration and flux past the deepest sensor (40 or 100 cm, depending on location) were calculated using changes in water content over time.

C. **Steady-State methods** that rely on meteorological data

- 35% of precipitation (**%P**).
- Potential evapotranspiration subtracted from Precipitation (**P-PET**).

[PET was calculated using the Penman equation, (Penman, 1962)]

D. **Numerical methods**

Ground-water recharge was also estimated using predictive numerical models which require soil properties and meteorological data.

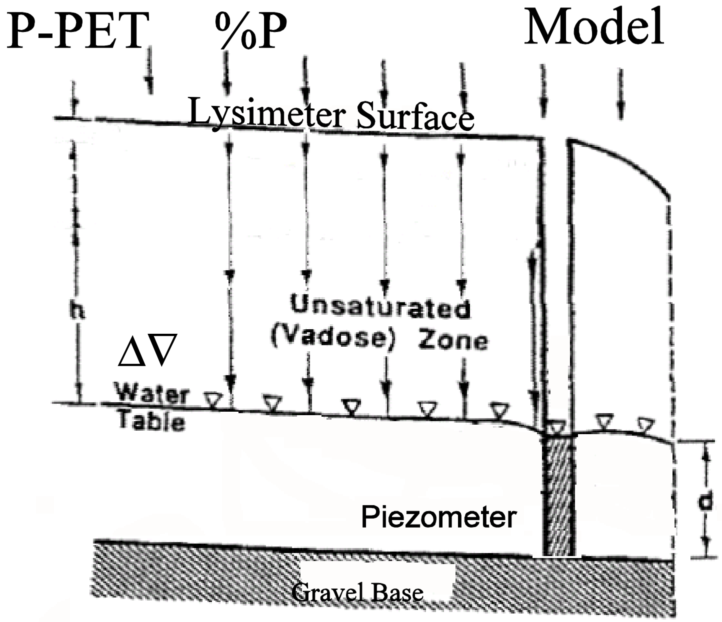

Figure 13. Schematic of the different recharge calculation concepts (adapted from Yu et al., 1993).

- ***HYDRUS-2D*** (Šimunek et al., 1999) finite-element description of soil water flow and contaminant transport.
- ***Water balance model*** (**WB**) (Simmons and Meyer, 2000) capacitance-based water flow model.

3.2.1 Ground-Water Recharge Estimate from Changes in Piezometric Head (ΔV)

The piezometer data were checked for errors and inconsistent values. In some cases, values were missing in a time series. We used interpolation (*Poc Expand,* SAS, 1999) to estimate values for the missing numbers. The number of interpolated values was less than 0.5% of the number of values in the series.

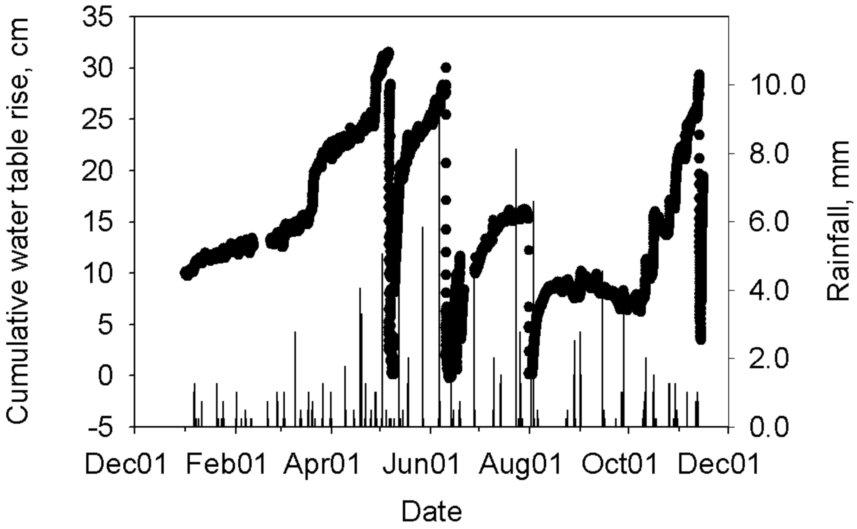

Figure 14. Cumulative ground-water amount (in cm of water) from raw piezometer data along with rainfall. Note the periodic drop in water table level and subsequent rise that resulted from pumping down the water table in the lysimeter from a localized region.

Because the system is closed, and there is no natural drainage, continued infiltration of water resulted in the water table rising to the surface. The water table came to approximately 2 meters below the crest at the center of the lysimeter at its highest point. At several times during the measurement period, therefore, the water table was drawn down by manual pumping. The data in Figure 14 show the water table fluctuations with pumping. The submersible pump which was installed in the 20-cm diameter piezometer evacuated water from the gravel base at the bottom of the lysimeter. This evacuation was localized to the gravel allowing the overlying soil to remain near saturated until the water table re-equilibrated. As a result, the water table at the piezometer/pump location would rise after draw-down as water drained back into the drained region from other parts of the lysimeter. The volume of water removed could not be measured since we did not have a tank large enough to contain all the water and the pumpdown period often lasted longer than 24 hours.

The piezometer readings were adjusted for these periods by adding back the drop in the water table and maintaining a constant water table head. In most cases there was no rainfall or apparent recharge during the time the water table was being pumped down (over a period of a week). In some cases we could not determine this for certain if there was a small rainfall although the effects would be small.

The piezometer readings before and after a rainfall event were accumulated and saved in order to calculate recharge. The recharge was calculated as the relative total increase in head since the beginning of the period multiplied by specific yield.

3.2.2 Ground-water Recharge Estimate from Real-time, Near-continuous Moisture Capacitance Probe Measurements

The *volumetric water content change method, $\Delta\theta$,* was chosen to estimate drainage of water from the soil profile as a representation of ground-water recharge. The soil depths for the calculations were 10, 20, 30, 40 and 100 cm. The bottom depths were 40 or 100 cm depending on the locations (Figure 6). The lateral zone of influence was about 15-20 cm. The data were reviewed and checked for missing and out-of-range values. Out-of-range and missing values were replaced (*Poc Expand*, SAS, 1997). The use of MCP data to estimate ground-water recharge was described and compared to other methods in previous reports [NUREG/CR-6653 (Timlin et al., 2000), and NUREG/CR-6729 (Timlin et al., 2001)].

Infiltration and drainage were calculated by summing differences in water storage over time. Since the water storage were recorded as mm of water per 10 cm of depth, the summation and differencing of water storage provide an estimate of the depth of water in mm that has been input or removed from the soil area around the soil moisture sensing system. For the purpose of calculations, the amount of water at each sensor was summed to provide a total amount of water stored in the profile (5 to 100-cm depth). Infiltration was calculated for each rain event by differencing the total amount of water stored in the profile measured at 10-minute intervals and summing the positive differences (i.e., increases in water storage). Drainage was calculated by summing all negative changes (i.e., losses as measured by decreases in water storage) in the amounts of soil water at each of the top three sensors during a rainfall event. In summary, positive differences were accumulated to estimate infiltration, and negative differences for drainage. Downward vertical flux (drainage) through the 40 or 100-cm depth (depending on the deepest sensor at a location) was defined as ground-water recharge. An advantage of this method is that internal fluxes tend to cancel each other out since summation of water contents over the profile is used.

Negative differences in water storage could have been due to evapotranspiration as well as drainage. To minimize error from calculating drainage when losses were really due to evapotranspiration, drainage was not accumulated when the water storage of the lowermost layer reached a lower limit (i.e., “drained water content”, see Timlin et al., 2000). This “drained water content” was obtained by tabulating the water storage of the lowermost layer (40 or 100 cm) at the end of each rainfall period. The median would represent an “expected” value of the drained water storage value from the population of drained water storage values. In order to choose a more conservative value, these water storage values were sorted and the value 1/3 from the maximum (a value representing conditions more wet than the median) was chosen as the drained water storage value. Since only water contents were measured, gradients were not available to determine direction and amounts of water movement. Water movement could only be determined using measured changes in water storage over time.

Differencing of data that are subject to random variation in the system may also introduce a large error when the differences are on the order of the error in the data. The noise in the MCP data was about 0.01 mm/ 100 mm soil (i.e., the difference between 30.51 and 30.52 mm of water may be due to random variation in the measurement). When the soil was very dry (~5.0 to 8.0 mm/100 mm soil) there were also diurnal variations in water storage on the order of 0.3 to 0.8 mm/100 mm soil probably because of redistribution of water in the soil due to hydraulic and thermal gradients. In order to minimize error due to these conditions, a three-point difference equation (Beyer, 1981) was used during the first part of the rainfall period:

$$\Delta \theta = \frac{1}{2}\left(\theta_{i-2} - 4\theta_{i-1} + 3\theta_i\right) \qquad \textbf{[1]}$$

Where *i* refers to the value at the current time. The differences for the initial part of the rainfall period, when water storage changes were relatively large, were calculated over 10 minutes periods. A two point difference method using hourly differences was used for periods after 24 hours:

$$\frac{1}{2}\left(- \theta_{i-1} + \theta_i\right) \qquad \textbf{[2]}$$

A mass balance of the calculated infiltration, losses (drainage and evapotranspiration) and storage was determined to investigate how conservative the calculations of water content changes from the MCP data were. The mass balance error was determined as:

$$error = \sum Positive\ changes - \sum Negative\ changes - Storage$$

where the storage is defined as the difference between the water content at the end of the rainfall period and that at the beginning of the rainfall period.

Table 4. Representative values of physical parameters associated with various types of aquifer materials [from Tables 2.1, 2.5 and 3.1 of Todd(1980) after Johnson (1967), Morris and Johnson (1967) and USGS Water-Supply Paper 813, from http://data.ecology.su.se/mnode/gwtable_1.htm].

Material	Porosity (%)	Specific Yield (S_y) (%)	Hydraulic Conductivity (m/day)
Coarse Gravel	28[r]	23	150[r]
Medium Gravel	32[r]	24	270[r]
Fine Gravel	34[r]	25	450[r]
Coarse Sand	39	27	45[r]
Medium Sand	39	28	12[r]
Fine Sand	43	23	2.5[r]
Silt	46	8	0.08[h]
Clay	42	3	0.0002[h]
Fine-grained sandstone	33	21	0.2[v]
Medium-grained sandstone	37	27	3.1[v]
Limestone	30	14	0.94[v]
Dolomite	26		0.001[v]
Dune Sand	45	38	20
Loess	49	18	0.08[v]
Peat	92	44	5.7[v]
Schist	38	26	0.2[v]
Shale	6		
Slate			0.00008[v]
Till (predominantly silt)	34	6	
Till (predominantly sand)	31	16	0.49[r]
Till (predominantly gravel)		16	30[r]
Tuff	41	21	0.2[v]
Basalt	17		0.01[v]
Weathered gabbro	43		0.2[v]
Weathered granite	45		1.4[v]

[v] - indicates vertical measurement of hydraulic conductivity, [h] - indicates vertical measurement of hydraulic conductivity, [r] - indicates measurement on a repacked sample

3.2.3 Steady-State Methods That Rely on Meteorological Data

When detailed piezometer and water content measurements are not available, ground-water recharge is often estimated from seasonal or annual meteorological data. These methods assume steady-state fluxes to the water table. Gross estimates of ground-water recharge are often estimated as a percentage of precipitation. An average of 10 to 15% has been cited for India (http://www.krishiworld.com/html/water_resources3a.html), and 41% for Hawaii (Shade, 1997). This percentage will vary with precipitation and soil type.

Two steady-state methods were used in this study: a percentage of seasonal precipitation (**%P**); and the difference between precipitation (P) and potential evapotranspiration (PET) rates (**P-PET**). Seasonal P and PET values were used. These are data that were aggregated over season (see Table 2.) and represent steady state values. The value of 35% for %**P** was chosen for Maryland for comparison purposes with other methods and because it was in the range consistent for a temperate, humid area. PET was calculated using the Penman equation (Penman, 1963; Timlin and others, 2001).

3.2.4 Numerical Methods

Net ground-water recharge can be estimated using predictive models which require soil properties and meteorological data. Input data for predictive models can be either directly or indirectly determined. There are different levels of aggregation and estimation of the input data and soil properties. Depending on the level of aggregation, additional errors may be introduced. The purpose of the modeling is to estimate cumulative net infiltration and recharge using measured meteorological data.

3.2.4.1 HYDRUS-2D Model

The HYDRUS-2D program (Šimunek et al, 1999) used in this study is a finite-element model which simulates soil water flow, and contaminant transport. HYDRUS-2D solves the Richards' equation for saturated-unsaturated water flow. The flow equation incorporates a sink term to account for water uptake by plant roots.

The hydraulic properties for HYDRUS-2D were determined by fitting an inverse solution to the redistribution data collected in October, 2002. These data were discussed in Section 3.1.1. The two soil layers were partitioned into three soil materials to the 0-15, 15-25 and 25-100 cm depth ranges to represent differences in soil properties due to compaction by overlying layers. A simple rectangular domain 50 cm in width by 100 cm depth was used. A constant head lower boundary condition was also used during redistribution since the water contents were nearly constant at the 100 cm depth.

Potential evapotranspiration (PET) values used in the simulations for ground-water recharge were estimated using the Penman equation (Penman, 1962). Based on a comparison of PET values from the measured water contents (summation of the negative differences of the MCP water contents) with values calculated with the Penman equation (Penman, 1962), the total evapotranspiration by a pan factor of 0.70. A crop coefficient of 0.85 was used to partition PET to evaporation and transpiration. During the winter-spring season, growth of the grass was limited due to low temperatures. It was assumed that grass growth would resume when the mean daytime temperature reached 10º C (about March 1). Until this time, values of transpiration were set to zero and evaporation was calculated as 15% of potential evapotranspiration.

The Feddes root water uptake model (Feddes et al., 1976) was used in HYDRUS-2D (see HYDRUS-2D documentation); the values are given in Table 5. These values were modified from the parameters for grass that were provided in the database of water uptake parameters available in HYDRUS-2D menus. The exact values for the parameters given in Table 5 were modified based on observations of water dynamics from the MCP probes. Root water uptake is zero for pressure heads less than the wilting point (see parameter P_3 in Table 5), and pressure heads greater than the parameter value of P_0. The value of the parameter P_0 defines the soil matric potential, above which, root activity ceases due to near saturated soil conditions. Water uptake is considered optimal between pressure heads P_{opt} and P_2, whereas for pressure heads between P_2 and P_3 (or P_0 and P_{opt}) water uptake decreases (or increases) linearly with pressure head. P_{2H} and P_{2L}, and R_{2H} and R_{2L} are the endpoints for an interpolative relationship to define potential water uptake (cm day^{-1}) as a function of soil matric potential (cm) to define how soil resistance limits water flow to the roots. For example, from Table 5, the maximum water uptake at -400 cm will be 0.5 cm day^{-1}. For matric potentials above -400 cm, the roots can extract water at the potential rate.

Table 5. Values of the Feddes root water uptake model used in HYDRUS-2D (see HYDRUS-2D documentation for details).

Parameter	Value
	--cm--
PO	-10
Popt	-25
P2H	-400
P2L	-1000
P3	-8000
r2H	0.5
R2L	0.1

The simulation considered a one-dimensional cross-section of the lysimeter (Figure 15) since we were interested in simulating the mean value for two textures (sandy loam and silty loam). A total of 1400 nodes, 2622 elements, 20 vertical columns and 70 horizontal columns were used. The minimum vertical spacing was 1 cm. The length was 100 cm wide at the top and 400 cm high. Two soil types were considered in separate simulations, sandy and silt textured.

3.2.4.2 PNNL Water Balance Model

The model, WatBudget (Simmons and Meyer, 2000, code and executable available at http://nrc-hydro-uncert.pnl.gov/code.htm.), is a simple, quasi-analytical Water-Budget written for MathCad version 8.0 (http://www.mathsoft.com/) for estimating daily water drainage from a bottom of a predefined soil depth. Meteorological data for 2002 were used as input. Soil hydraulic properties were inferred from the MCP database (Timlin and others, 2000). Properties similar to those used in HYDRUS-2D were used here.

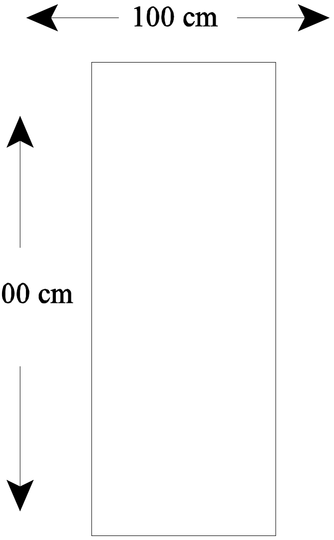

Figure 15. Layout of the soil domain in HYDRUS-2D for the lysimeter. A regular grid was used. The discretization was 1 cm at the surface increasing to 10 cm at the base.

4. GROUND-WATER RECHARGE ANALYSES AND RESULTS

There are numerous approaches for estimating ground-water recharge. Each approach has its own inherent sources of uncertainty. These sources may be due to measurement errors, model specification errors, parameter uncertainty, incomplete knowledge of the system, and assumptions not fully met. This study examined relative ground-water recharge rates given different sources of monitoring data and methods for analyzing these data. This examination utilized soil water and water table height data from a highly-controlled, closed system with the top boundary open to the atmosphere (i.e., large field lysimeter).

4.1 Analysis of Piezometer Data in Conjunction with Specific Yield Estimates

Figure 16 shows the ground-water recharge during 2001 based on direct measurements of piezometer changes, and the estimate of specific yield. The measurement error in the piezometer transducer is on the order of 1 mm. This is virtually insignificant compared to the total water level changes as shown in Figure 16. The main source of uncertainty is in estimating specific yield. The initial value was calculated when the water level was in the lowest portion of the lysimeter. Specific yield may be affected by vertical heterogeneities which would result in uncertainties in the depth of water recharge as the water level rises in the profile. Proximity to the surface of the soil can also affect the value of the specific yield (Nachabe, 2002)

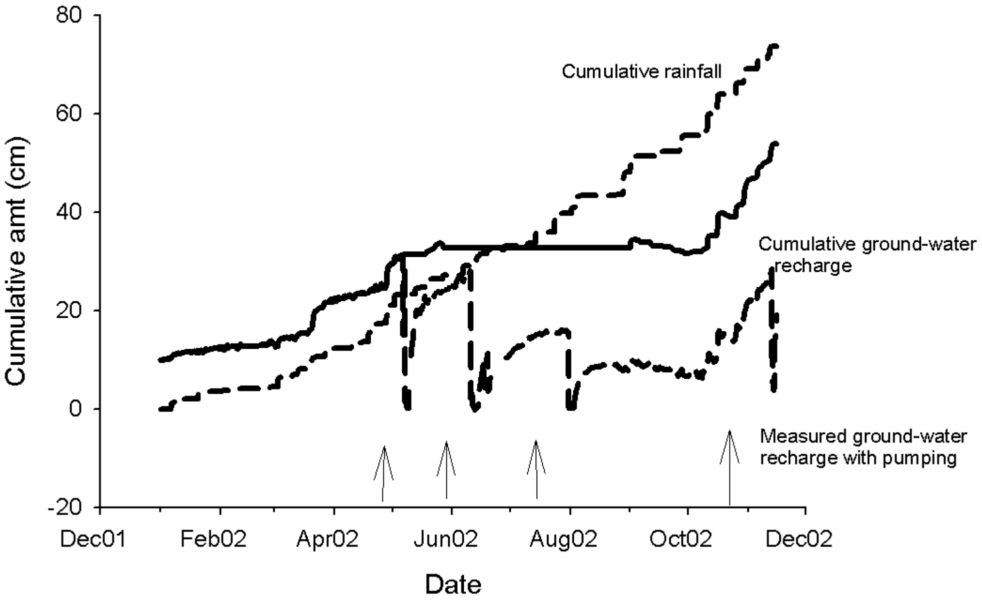

Figure 16. Ground-water recharge from piezometer measurements and cumulative rainfall. Water was removed from the lysimeter by periodic pumping. Note the pumping events indicated by the arrows. Additional water table rise occurred as water drained back into the piezometer well from saturated layers higher in the profile, and the pumped-out gravel base.

4.2 Ground-Water Recharge from Piezometer Heads and Rainfall

Only a small percentage of rainfall events resulted in significant ground-water recharge (Figure 17). These were generally rainfalls that occurred shortly after previous substantial rainfalls resulting in high antecedent water

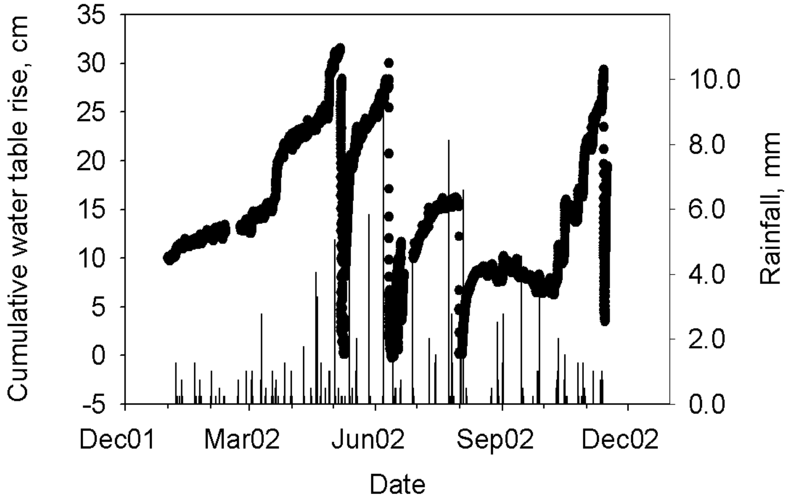

Figure 17. Adjusted water table level and individual 15 minute rainfall amounts.

contents. These events generally occurred outside the growing season (e.g., Spring-Winter and Fall-Winter season events) when the soil remained wet. Note that the largest rainfall events did not result in significant ground-water recharge because they occurred during the summer season when plant water uptake was at its maximum antecedent water conditions were relatively dry. Note that the frequency of rainfall was also less in the summer.

4.3 Neutron Probe Measurement of Water Content

The Neutron Probe data were collected at two week intervals and hence show the overall trends of the water contents but not the short time-scale dynamics. The MCP data are means from four locations. In most cases, the measured water contents from the two measurement methods nearly coincide for the times when data were available from both measurement methods. The largest differences were at the 100 cm depth. Here the Neutron Probe measurements do not indicate as much water uptake as the MCP data do. This could be due to differences in the soil volumes the two instruments measure. The zone of influence for the Neutron Probe is somewhat larger than that for the MCP sensor. The higher water contents measured by the Neutron Probe may represent an average over a larger volume and less influence of localized soil water dynamics. However, based on the large variability (to be discussed for this site in later sections, also see Timlin et al., 2000 and 2001) among the MCP probes these differences (Neutron Probe and MCP) are likely a function of the large spatial variability in water contents in the lysimeter.

The data from the Neutron Probes do show the general trends in water contents. That is, the decline in water content through August which is due to plant activity and an increase in soil water content from September through the fall season due to infiltration being higher than ET. Notably, the Neutron Probe data do not match the dynamics of the infiltration events and so do not have enough information to assess drainage during individual infiltration events. For example, depending on the time of measurement, the infrequent Neutron Probe data may also compare poorly with some of the smaller water contents that result from plant water uptake. Some information on antecedent and post-rainfall water contents would be necessary to estimate the amount of water that has passed through the root zone using a water balance approach and Neutron Probe data.

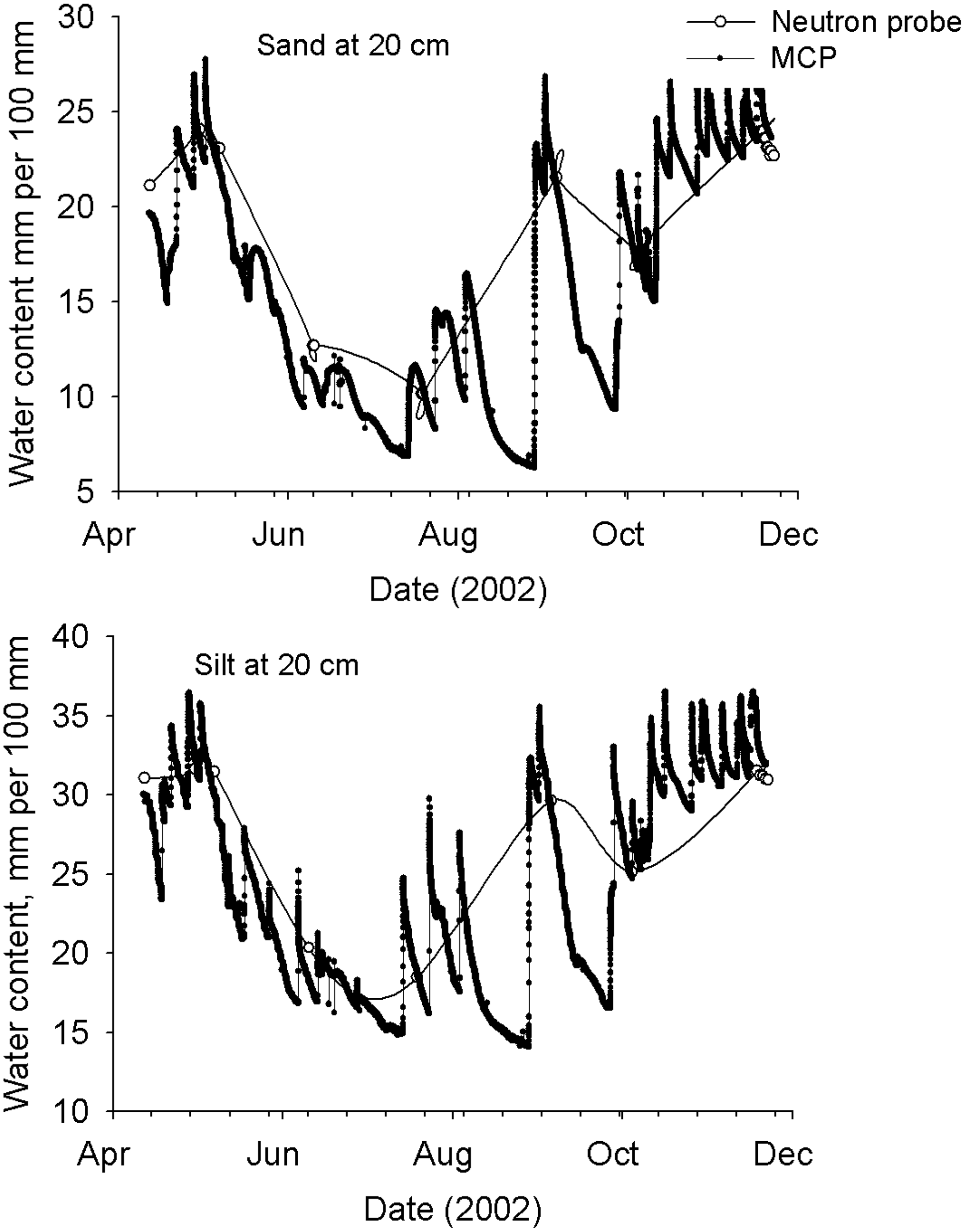

Figure 18. Comparison of Neutron Probe and MCP water content measurements at 20 cm.

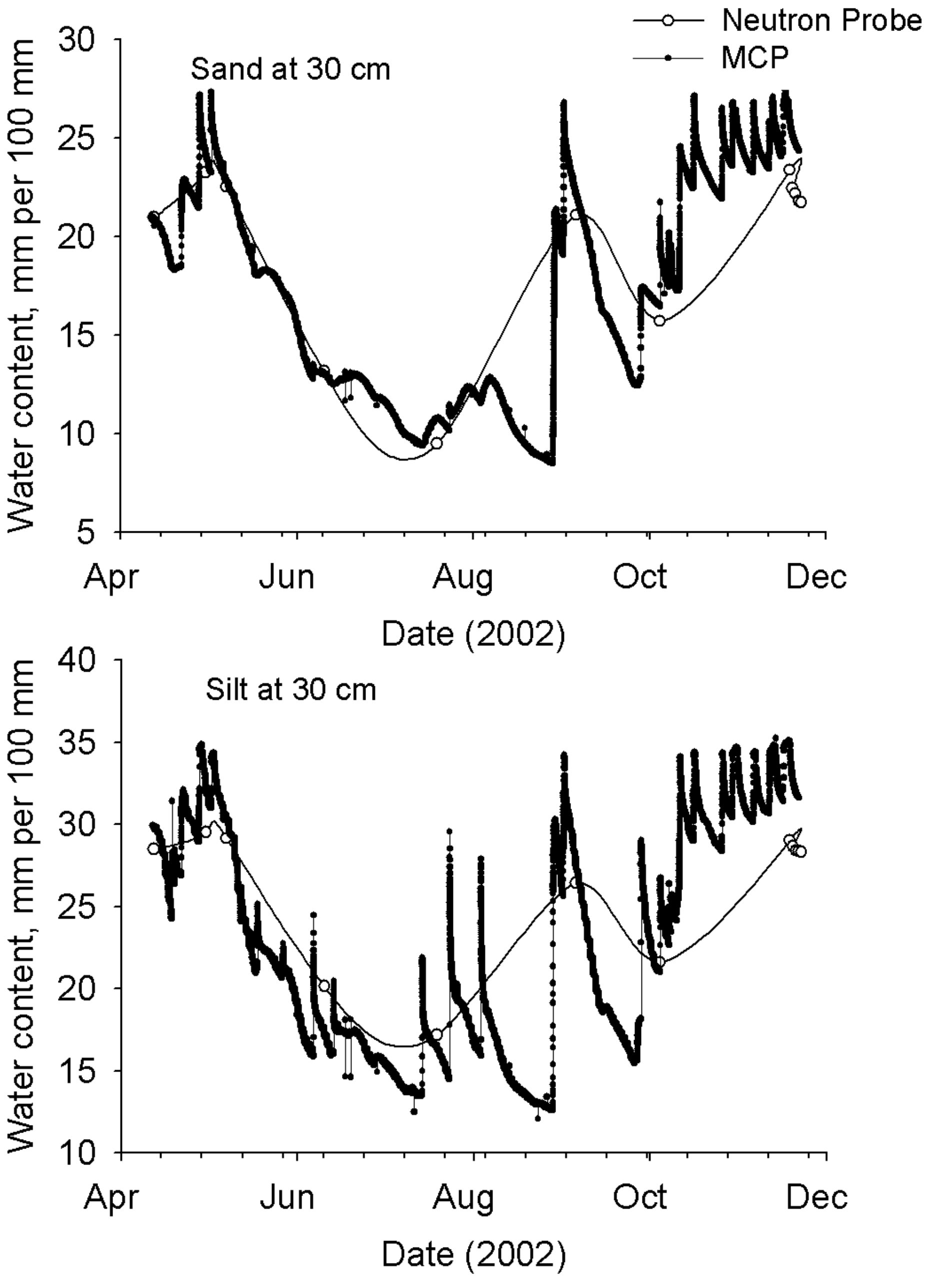

Figure 19. Comparison of Neutron Probe and MCP water content measurements at 30 cm.

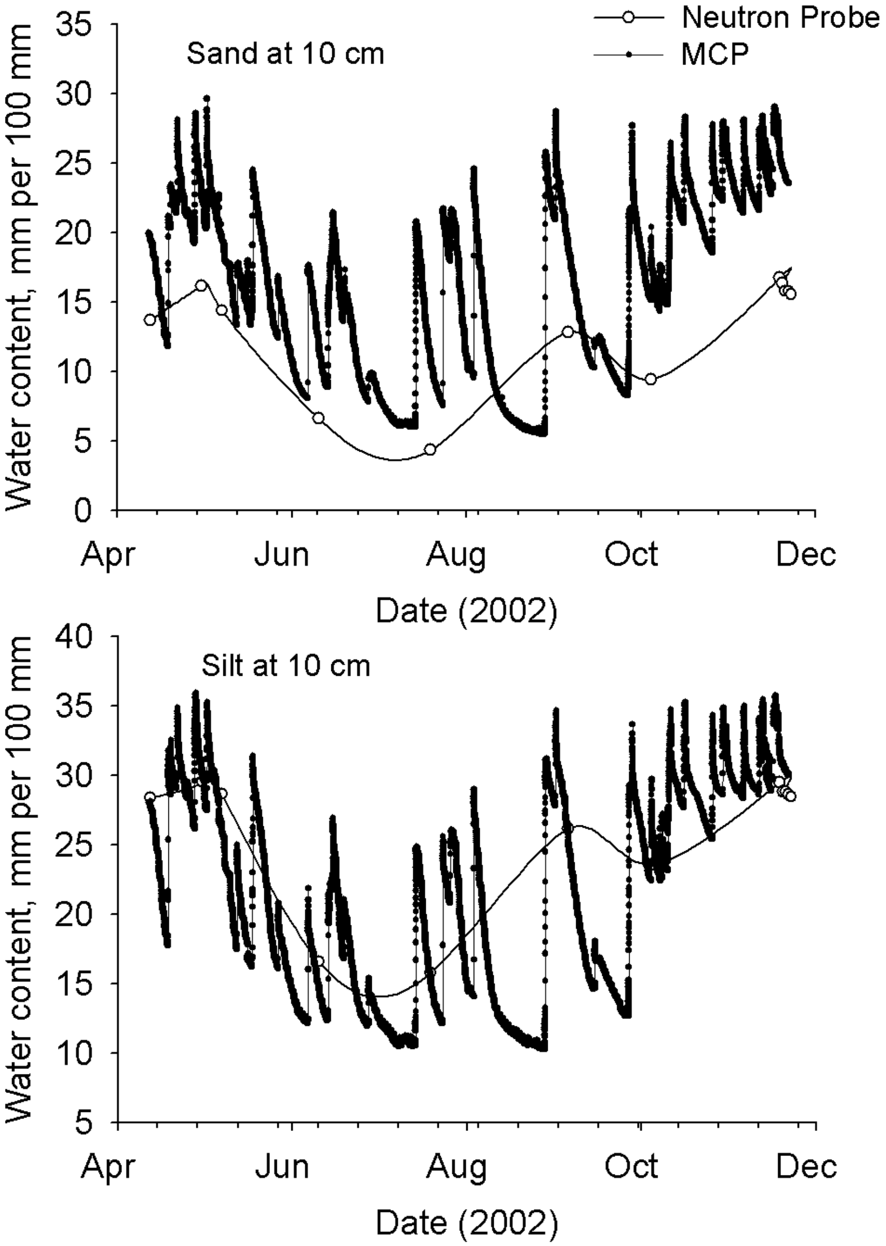

Figure 20. Comparison of Neutron Probe and MCP water content measurements at 10 cm.

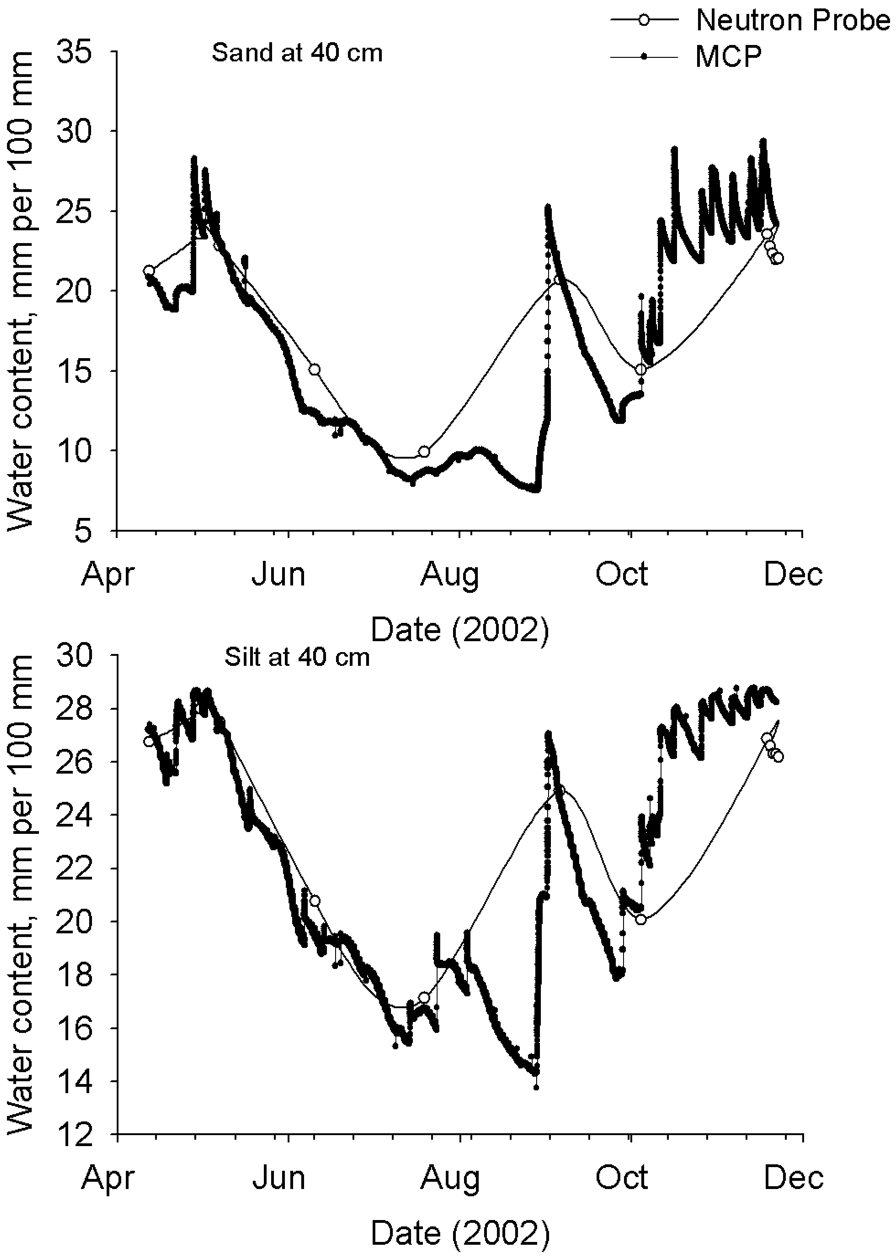

Figure 21. Comparison of Neutron Probe and MCP water content measurements at 40 cm.

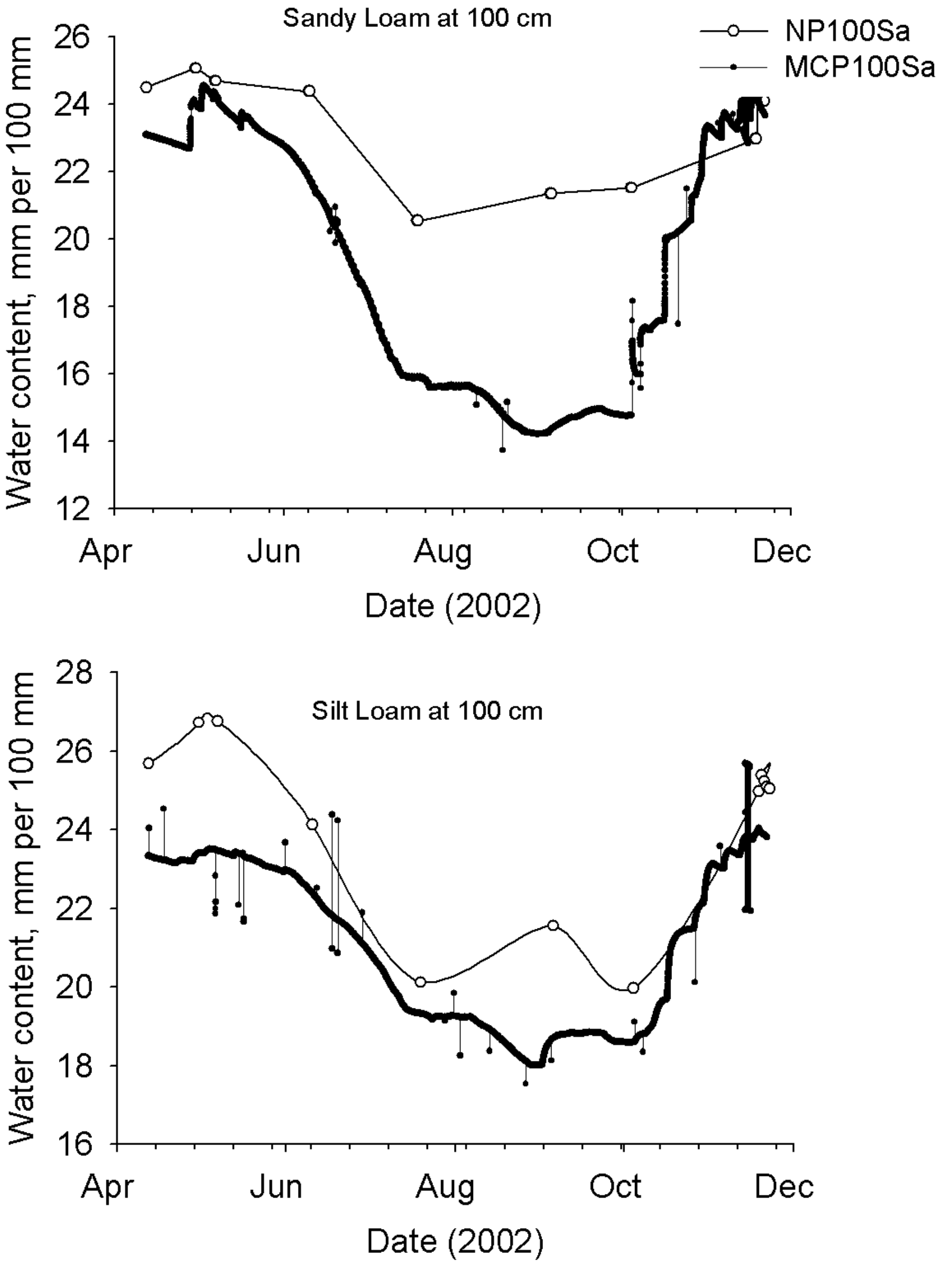

Figure 22. Comparison of Neutron Probe and MCP water content measurements at 100 cm.

4.4 Estimation of Ground-Water Recharge from Water Content

4.4.1 Redistribution of Water

Infiltration and redistribution tests were conducted to understand water redistribution in heterogeneous soils, and to parameterize water-retention curves for the numerical models. Water was applied using drippers but saturated conditions never appeared to have developed in the sandy soil. However, the silt loam soil appeared to develop some lateral flow. In the silt loam soil, MCP sensors near the water application sites showed slight increases in water contents indicating some lateral flow of water toward these locations. As a result, this data was not used to estimate soil hydraulic properties using HYDRUS-2D.

As shown in Figures 11 and 12, flux rate versus water content data appear very smooth which indicates negligible measurement errors (due to instrument variation). The vertical spacing and number of sensors may result in uncertainties in the estimated drainage fluxes. These data did provide good estimates of drainage fluxes as a function of water content. When generalizing to infiltration and redistribution conditions, errors may be introduced due to hysteresis and unknown hydraulic gradients.

4.4.2 Mass balance analysis of infiltration and drainage calculated from MCP data

Potential problems due to numerical errors arising from differencing data in the MCP database to obtain net infiltration and drainage estimates were evaluated using a mass-balance approach. Table 6 contains the results from the water balance of inputs, losses and storage of water calculated from the MCP probes. The errors, which are the differences between inputs and the sum of losses and storage are on the order of mm. This suggests that the differencing of the data did not result in major losses of information.

Previous studies using these methods [NUREG/CR-6653 (Timlin et al., 2000), and NUREG/CR-6729 (Timlin et al., 2001)] suggest that estimates of infiltration when the soil is very wet and water content not changing (steady state water content) may underestimate actual infiltration. Based on a mass balance approach it does appear that infiltration was not significantly underestimated for the data collected at this lysimeter. This is probably because the soil has a coarse texture and very high hydraulic conductivities.

These mass balance analyses results (Table 6), however, do not provide any information on errors in calibration or errors due to spatial variability. Note that calculated infiltration is generally larger than rainfall. If the rainfall amounts measured at the nearby rain gauge accurately reflects the rainfall at the lysimeter, then the MCP data overestimate infiltration. If infiltration is overestimated, this suggest that the losses measured from the MCP data (due to both drainage and evapotranspiration) are likely to be larger than they would have been if the infiltration estimates were closer to the rainfall values. As a result, estimates of ground-water recharge from the MCP data would be lower than recorded here. This assumes that the evapotranspiration estimates are close to actual.

4.4.3 Comparison of ground-water recharge estimates from MCP water contents with those from piezometer heads

A summary of the results for calculated ground-water recharge, infiltration, ET and storage from the MCP data are given in Table 7. Ground-water recharge estimates from the piezometer data are given here as well. For the purposes of this discussion drainage is defined as redistribution of infiltrated water past the depth of the lowermost sensor (40 or 100 cm), storage as the difference in water contents of the profile between the start and end of the rainfall period, profile as the vertical soil domain, and recharge as water reaching the water table. The units of water are cm. The MCP data largely underestimated ground-water recharge when compared to the piezometer data, except in the summer months when it overestimated ground-water recharge. The high ground-water recharge estimate for the silt-loam soil in the fall-winter season may be due to high infiltration calculated with the MCP data (Table 6). The high spatial variation results in a very wide range of estimated values. Ground-water recharge during summer months is highly over-estimated because of the difficulty in separating the ET from drainage. Generally, the sum of losses of water from the profile (internal drainage past 100 cm and ET) and storage, sum to the inputs (infiltration). The mean storage of water in the profile for the rainfall events varied from 2 to 7 cm during the non-summer months. This water could be partitioned to drainage or evapotranspiration depending on environmental conditions. If some or all is partitioned to drainage, this would increase the drainage estimate. The relative differences among the drainage and infiltration estimates for the two soils appeared to be larger than the actual evapotranspiration estimates. The higher ET in the summer season for the silty loam soil may be due to higher water availability. Since drainage and infiltration estimates are calculated from water contents early in the infiltration or drainage processes when water contents are changing rapidly, the differences may be due to the different dynamics for the two soils, or problems with the method of differencing or differences in sensor behavior between the two soils. Figure 23 shows the ground-water recharge estimated from water table elevation data in the fall-winter and suggests most of the rainwater went to ground-water recharge (based on the parallel nature of the lines).

4.5 Gee Fluxmeter

The Gee Fluxmeters (see schematic shown in Figure 7) installed in the lysimeter did not function properly since the rising water table rendered them inoperative when they became submerged. For this reason, only one instrument gave results that could be analyzed for at least one season of data. These results are shown in Figure 24. The overall estimate for the spring-winter season was about 17 mm which was about the same as from the piezometer heads. The flux-meter did not respond to wetting events the same as the piezometers and MCP sensors. There was a lag in the response at about mid-March with respect to the piezometer head. The flux-meter response seemed to be better synchronized to the rainfall around April 1 than the piezometer heads were but this may not have been a response to the April rainfall. The response may have been due to earlier rainfall which would indicate a delay with respect to the piezometer response approximately 7-8 days earlier. Note that the fluxmeter is also apparently delayed for the rainfall occurring near May 1. There seemed to be more of a delayed response by the water table which makes sense since the water table is below the flux-meter. The flux-meter also showed a response of about 40-50 mm at or after mid-May. This could indicate that there was a recharge event that was masked by the pumping of the water table. If this were the case, this would suggest that the MCP data did not over-estimate recharge to as large an extent as shown in Table 6.

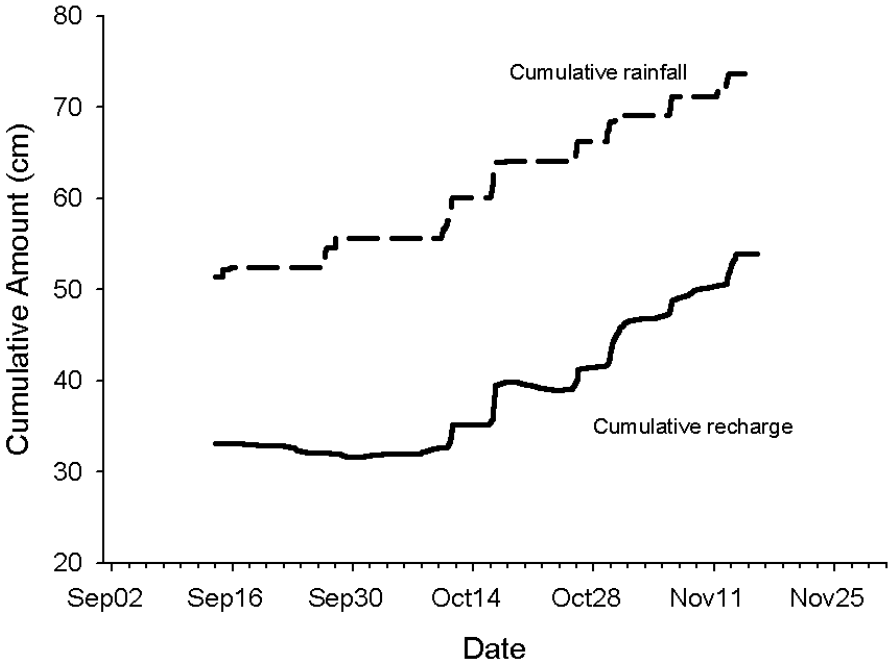

Figure 23. Fall 2002 recharge which covers ~200 mm of rainfall and 50 days of time resulting in a rise of the water table of approximately 100 cm.

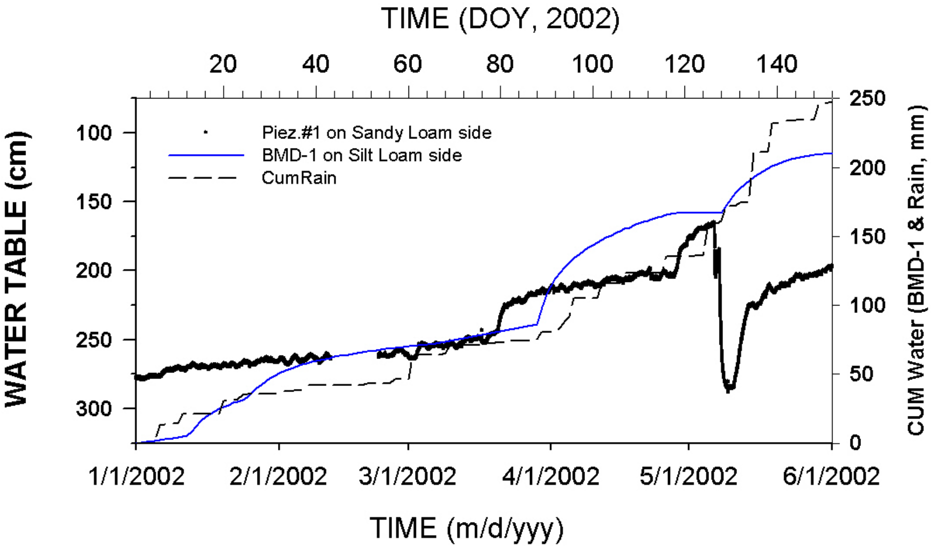

Figure 24. Ground-water recharge estimate from the Gee Fluxmeter for the first 6 months of 2002.

Table 6. Results from mass balance analysis of MCP data.

Soil	Season	Rain	Calculated infiltration		Calculated losses by drainage or ET		Storage		Error	
			Mean	Std	Mean	Std	Mean	Std	Mean	Std
sand	sw	21.1	26.5	9.54	22.97	8.24	3.52	6.67	-0.02	0.1
sand	su	30.2	31.51	12.67	37.69	14.11	-6.26	10.78	0.07	0.4
sand	fw	22.3	27.38	9.87	20.16	7.31	5.92	4.85	-0.03	0.0
silt	sw	21.1	32.88	13.15	31.32	13.43	1.63	5.06	-0.07	0.3
silt	su	30.2	45.04	10.72	51.01	12.58	-5.87	7.7	-0.1	0.2
silt	fw	22.3	26.18	5.72	18.75	5.57	6.69	3.53	-0.04	0.1

Table 7. Summary of recharge estimates, rainfall, calculated infiltration and evapotranspiration from the measured water table height (piezometer), MCP data (water content) and weather station data. Units are in centimeters.

Soil	Season[1]	Drainage			Inputs			Storage		Evapotranspiration		
		Measured from Piezometer	MCP			MCP infiltration				Actual		Potential
			Mean	Std	Rainfall	Mean	Std	Mean	Std	Mean	Std	
sand	sw	18.8	7.6	5.2	21.1	25.6	9.9	3.5	6.8	14.8	6.7	36.9
sand	su	2.9	6.0	4.9	30.2	29.1	10.8	-6.2	11.2	30.7	11.6	85.8
sand	fw	20.7	6.5	3.8	22.3	26.1	9.4	5.8	5.1	13.2	8.4	15.0
silt	sw	18.8	17.0	9.3	21.1	31.1	11.3	1.6	5.1	14.3	8.1	36.9
silt	su	2.9	9.0	10.4	30.2	44.1	11.0	-5.9	7.7	41.9	13.2	85.8
silt	fw	20.7	8.0	5.4	22.3	25.9	5.9	6.7	3.5	10.8	3.2	14.5

1. Seasons are sw-Spring-Winter, su-Summer, and fw-Fall-Winter

4.6 Analysis of Meteorological Data

Ground-water recharge was assumed to be 35% of the seasonal rainfall. This assumption proved realistic for the Spring 2002. However, estimates for the other seasons proved to be 10% for the Summer 2002 and 45% for the Fall-Winter 2002. It is apparent that there is no uniform percentage for estimating ground-water recharge for a given period from rainfall. This is due to variable rainfall rates and durations, as well as, antecedent soil water conditions and evaporative demand. Precipitation minus potential evapotranspiration estimates would also greatly underestimate ground-water recharge since a large ratio of the rainwater became recharge (Table 7).

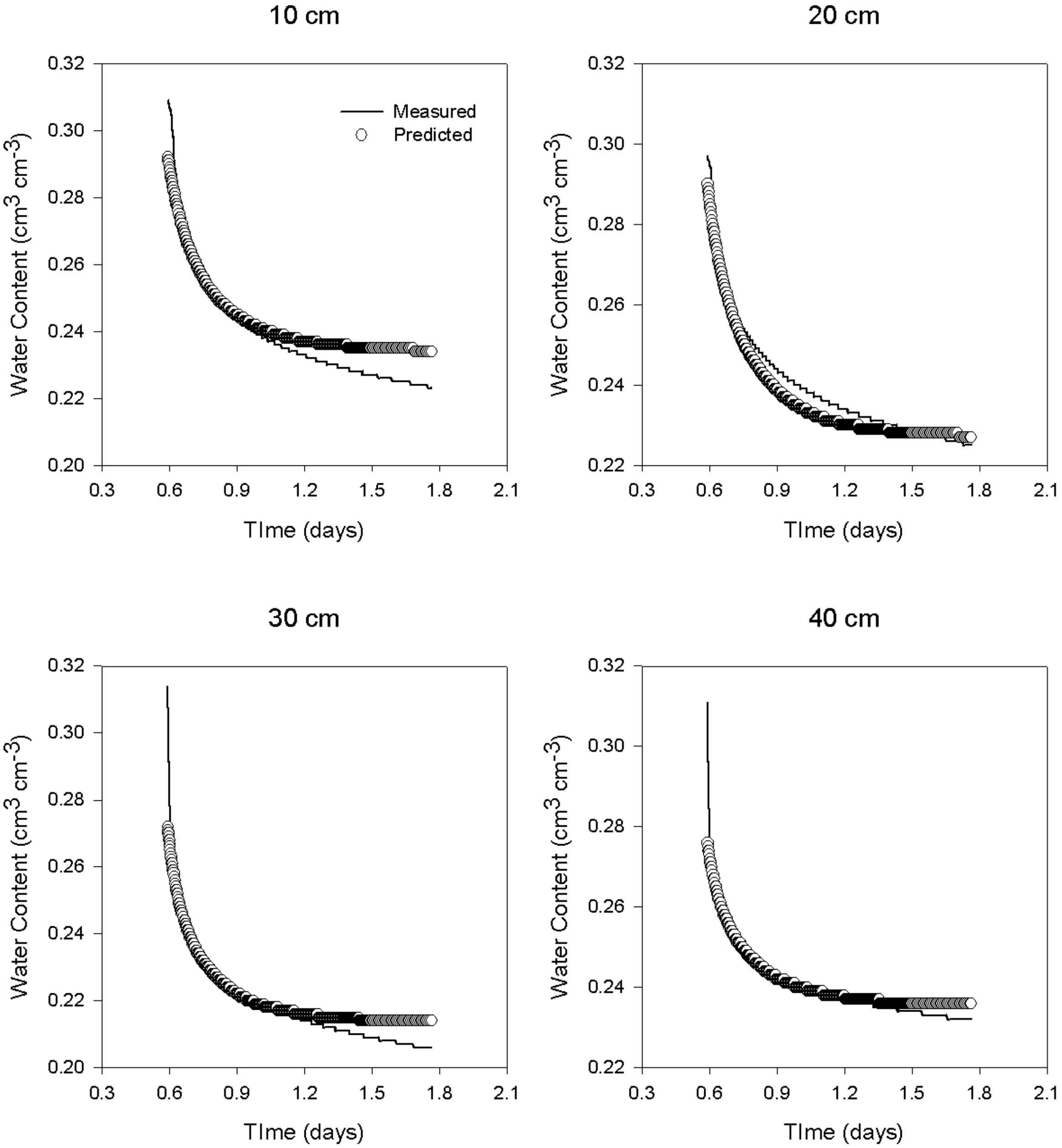

Figure 25. Measured water contents and water contents predicted by HYDRUS-2D for the optimal inverse solution.

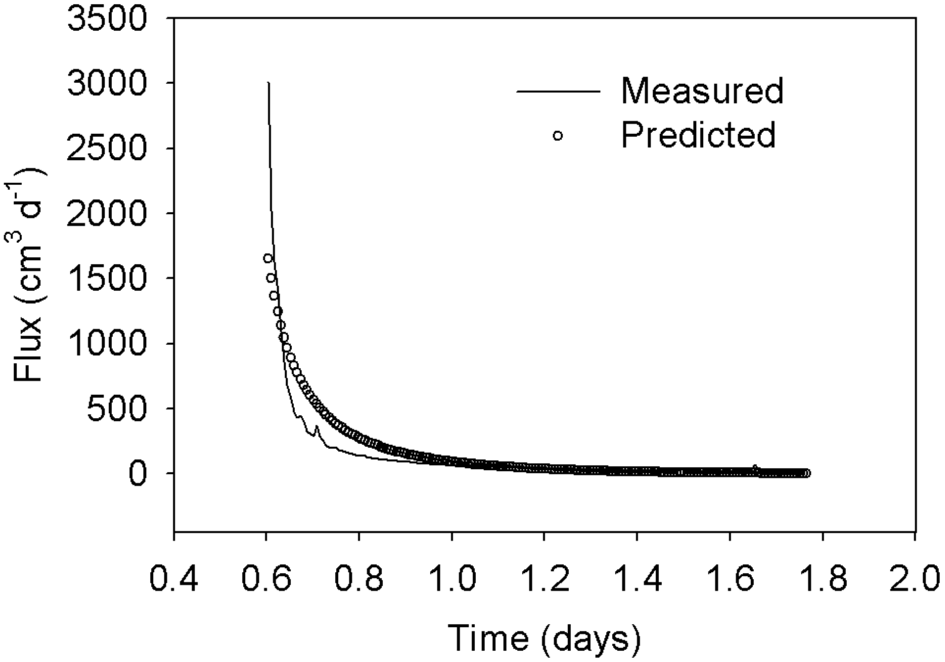

Figure 26. Measured flux past 100 cm and flux predicted by HYDRUS-2D for the optimal inverse solution

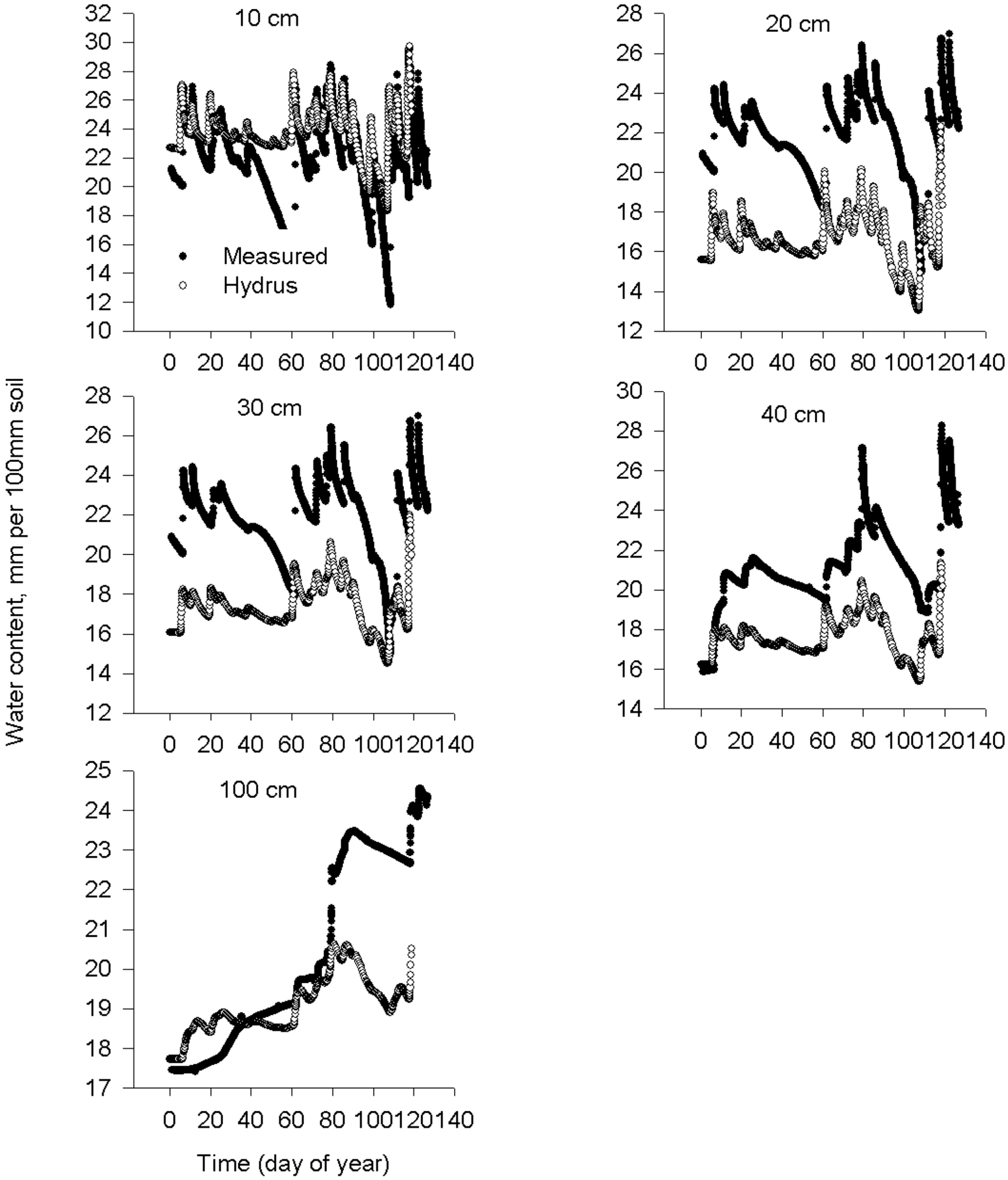

Figure 27. Measured water contents and water contents simulated by HYDRUS-2D for the sandy loam soil and winter/spring season for five depths.

4.7 HYDRUS-2D

4.7.1 Inverse solution for soil hydraulic properties

The results of the inverse analysis in terms of the fitted van Genuchten's parameters to describe the relationships between matric potential, and water content and hydraulic conductivity (van Genuchten, 1980) are given in Table 8. These were used as parameters for HYDRUS-2D. Based on Figure 12, it appeared that water contents from the 30 and 40 cm sensors behaved similarly so these were grouped into one layer (26-100 cm). It was assumed that the soil properties would be similar from 26 cm to the bottom of the lysimeter since other data were not available.

Three of the parameters could not be estimated with a confidence interval that did not encompass zero. These are marked with an asterisk. Values estimated from Figure 12 were used for the saturated hydraulic conductivities for the 0 to 15 cm, and 15 to 25 cm layers. The overall r^2 for the regression of observed versus fitted was about 0.83 and the fit to the water contents was good (Figures 25 and 26). The major discrepancies were at the end of the redistribution period. Here the trend of the measured water contents with time was to level off with only a slight slope while the simulated water contents continued decreasing with a larger slope. The fitted hydraulic properties given in Table 8 were used in the simulations to determine ground-water recharge.

Table 8. Parameters fitted to the van Genuchten equation for the sandy soil.

Depth (cm)	Residual water content Qs	Saturated water content Qs	alpha	n	Saturated conductivity Ks (cm day^{-1})	Pore connectivity factor
0-15	0.01	0.335	0.041*	1.12	800*¶	0.5
16-25	0.01	0.39	0.055	1.3	600*¶	0.5
26-	0.067	0.316	0.01	1.89	100	0.5

*These values had very wide confidence intervals suggesting an arbitrary fit.
¶ Values estimated from Figure 12 were used.

4.7.2 Simulations for Ground-Water Recharge Estimates using HYDRUS-2D

Simulations for the only sandy loam soil were carried out using the HYDRUS-2D model. The values of ground-water recharge were calculated from the difference between net surface flux (rainfall - evaporation from the soil) and root water uptake.

The occasional pumping of the water table in the summer and fall of 2003 resulted in a varying bottom boundary condition and hydraulic state that were difficult to account for in the model. Since the hydraulic properties of the bottom part of the profile were largely unknown it would have been difficult to account for the residual water that would have drained to the bottom of the lysimeter. Only simulations for the spring season were carried out (to May 6, 2002). The predicted and measured water contents for the sandy soil are given in Figure. 27. The one dimensional version of HYDRUS-2D (HYDRUS-1D) would have been a better choice since it allows a more flexible treatment of lower boundary conditions. Except for the 10-cm layer, the simulated water contents are much smaller than the measured ones. This is because matric potentials were not available when the hydraulic properties were optimized. This is not a major problem because we are mainly interested in the relative changes and dynamics of the water contents. Another difference is that the HYDRUS-2D water contents are point measurements at a particular depth, whereas the MCP data represent averages in approximately a 10 cm thick layer.

The data from HYDRUS-2D show several wetting events between days 80 and 120 at the 20 cm depth (Figure 27). The measured data show only small changes. This difference suggests that, in the measured data, either the wetting front never gets to the 20 cm layer or it drains as fast as it arrives. The latter is the most likely since we can see evidence of water reaching the lower depths. This difference could be due to the daily time step for the weather data input into HYDRUS-2D. For the simulations in HYDRUS-2D, the rainfall for the entire day is added in one time step that applies all the water at one time. As a result, the increase in water content over the time step will be larger than if smaller amounts of water were added over a number of time steps. In reality, a small amount of water is infiltrating and draining at the same time because of the relatively small rainfall amounts over longer time periods. By day 120, little water in the simulated results seems to have reached the 100 cm layer as evidenced by the drop in water table (data not shown).

HYDRUS-2D removed more water from the water table by root water uptake than was seen in the measured data. The measured water table height continued to increase during the spring season. The simulated water table height begins at 50 cm, goes to 75 by February (data not shown) then drops again to about 61 cm by the time the spring begins (day 120). This may be partially due to the high saturated conductivity of the soil in the lower part of the lysimeter (about 100 cm day^{-1}). Simulated plant activity also affects the water table. If the value for transpiration ii set to zero until March 1, then total water uptake by plant roots is less and the net ground-water recharge is more. This could increase the simulated recharge by more than 5 cm. When root activity is limited to the upper 20 cm of soil, there is still evidence of root water uptake from the 100 cm depth in simulations. This could probably be rectified by more careful selection of the plant parameters, especially root activity, for water uptake. This may also

Table 9. Effects of changes in parameters in HYDRUS-2D on ground-water recharge.

	Net water in (rain - surface evaporation)	Root uptake	Ground-water level	Drainage		Specific yield¶
				From water table height	From mass balance §	
	----------cm---------					
K_S as fit by inverse method	16.6	13.8	64.0	2.1	2.8	0.15
Reduce K_S by 1/2	16.6	13.8	64.5	2.2	2.8	0.15
Restrict root activity to the upper 20cm of soil	16.6	13.7	70.4	2.9	2.9	0.15
Parameters from soil catalog (sandy loam surface, silt lam bottom layer)	16.9	12.8	50.4	0	4.1	0.25

¶Specific yield was determined by running HYDRUS-2D without any evaporation, adding 10 cm of water and running the simulation until equilibration was reached. The specific yield was calculated by dividing the water input by the rise in the water table height. The value is specific to hydraulic parameters used.

§Calculated as (Net water in)-Root water uptake.

be due to high hydraulic conductivity in the lower layers of the lysimeter that facilitates rapid upward movement of water. Inclusion of a plant model where transpiration and soil evaporation could be calculated based on canopy activity may help improve the simulations. Changing the value of the hydraulic conductivity for the bottom-most layer from 100 cm/day to 50 cm/day does not have as much effect on the simulation results as does changing the root activity with depth.

The ranges of water contents in Figure 27 for both the measured and simulated data are roughly similar for both infiltration events. After long periods of water uptake by the plants, however, the measured water contents are much less than the simulated values. Based on these observations, it appears that the plants in the simulations are extracting water deeper in the profile rather than extracting water primarily out of the upper part of the profile as the measured data suggest. In the measured data, plant water uptake may have been limited by water availability several times during this period. Plant water uptake has not been limited by water availability in HYDRUS-2D in the base simulation (parameters optimized from redistribution data and 40 cm rooting depth). This observation is based on a comparison of actual and potential simulated fluxes. As a result, the predicted water uptake may be higher than was actually removed by the plants. This is likely a function of the relatively high hydraulic conductivity of the third layer (100 cm day^{-1}), 40 cm depth of water uptake by roots and the plant water uptake theory used by HYDRUS-2D.

Based on our observations, we varied several parameters of the model to quantify the effect on ground-water recharge. The results are shown in Table 9. The base simulation is given in the first row. Ground-water recharge is obtained from two sources, the difference between net flux into the soil (precipitation - evaporation from the soil surface) and net flux out of the soil (root water uptake). Note that, for our conditions (rainfall > evaporation) there is a net flux of water into the soil, i.e., the soil becomes wetter. Reduction of saturated conductiviey (K_S)by ½ makes little difference in the simulated ground-water recharge. This is probably because the saturated hydraulic conductivity is already very high. When root activity is restricted to 20 cm, the water table height is 5 cm higher than for the case with root activity to 40 cm in depth. There is no difference based on mass balance, however. This is probably because the water uptake is shifted to the upper part of the profile when root activity is restricted to the 0-20 cm depth. The storage is probably less in the upper part of the profile for this latter case. Water from the 20-40 cm layer that was not taken up went to the ground water. In this case, ground-water level was a better indicator of recharge than the mass balance method. This does depend, however on how much time it takes the infiltrating water to reach the ground-water as discussed below.

For the case where soil properties from the soil catalog are used (sandy loam) for the surface layers, the recharge based on the mass balance increases to 4.1 cm but no recharge is seen at the ground water level (Table 9). The saturated conductivity for the bottom of the lysimeter was 10 cm day^{-1} and so there was apparently not yet enough time for the water to reach the ground-water level via drainage. This is not realistic as compared to the measured data where ground-water response was almost immediate in response to rainfall. In terms of soil hydraulic properties related to moisture release, the parameters for the sandy loam soil from the catalog were more similar to that of a sand than the fitted parameters were. The values of *n* were higher for the upper two layers (1.2, 1.3 for the measured vs. 1.8 for the catalog soil) and lower for the bottom layer (1.8 for the measured and 1.4 for the catalog soil). The range between saturated and residual water contents was also slightly larger for the catalog soil parameters than for the fitted ones. The net water availability was less than for the soil with the fitted parameters. However, the actual water uptake was less than the potential uptake by about 1 cm for this soil. The overall difference in ground-water recharge was small however when compared to recharge using the fitted parameters (about 30% higher for the catalog soil).

The largest source of uncertainty associated with the approach of modeling with HYDRUS-2D appeared to be with how HYDRUS-2D models water uptake by plant roots using the Feddes water uptake model. This may be due to the fact that HYDRUS-2D simulated greater uptake of water from the water table than was seen in the measured data. Simulated water uptake by plants is sensitive to the choice of soil hydraulic properties and root activities. When root activities in the HYDRUS-2D model are kept constant, the choice of soil hydraulic properties appears to have a greater impact on sensitivity than choice of parameters related to root activity. Among the parameters for the soil hydraulic properties, the most sensitive appear to be those that are related to the slope of the water retention curve. The smaller the slope of the water retention curve (a large change in potential results in a small change in water content), the longer time water remains in the root zone. This retained soil water is then available to evapotranspiration processes. Soil properties that cause the water to drain to lower layers sooner (i.e., soils having steeper water retention curve slopes) result in more ground-water recharge.

A major component to the uncertainty for modeling water uptake with HYDRUS-2D was in the area of estimating and modeling root activity. When root activity is limited to the upper 20 cm of soil, there is still evidence of root water uptake from the 100 cm depth in simulations. This could probably be rectified by more careful selection of the plant parameters, especially root activity, for water uptake. Inclusion of a plant model where transpiration and soil evaporation could be calculated based on canopy activity may help improve the simulations. Changing the value of the hydraulic conductivity for the bottom-most layer from 100 cm day to 50 cm day does not have as much effect on the simulation results as does changing the root activity with depth.

4.8 PNNL Water-Budget Model

The PNNL Water-Budget Model[1] was used to calculate actual evapotranspiration and drainage using meteorological data from the site. The PNNL model estimates recharge by calculating a water balance using precipitation and evapotranspiration. The values of the parameters used in the model are given in Table 10. These input parameters were selected from the MCP data, the redistribution tests and HYDRUS-2D inverse solutions (Timlin and others, 2000). The saturated hydraulic conductivities were varied to provide an estimate of sensitivity in ground-water recharge as affected by this value. The results of the simulations for sensitivity analysis are given in Table 11. The drainage values are calculated directly by the program and given in the output file.

The ground-water recharge as a function of the different values of saturated hydraulic conductivity range from 14 to 8 cm as the saturated conductivity decreases from 6400 cm day^{-1} to 310 cm day^{-1}. The lower value is more representative of the lysimeter and is comparable to the data used in HYDRUS-2D. The differences in recharge as affected by changes in hydraulic conductivity are related to how long the water remains in the upper part of the profile where it is available to evapotranspiration processes. The longer the water remains in the root zone, the more likely it is to be evaporated or taken up by the plants. While the PNNL model does account for flux-limited evapotranspiration when the soil is dry, the water content when rainfall occurs is estimated from the water-budgeting procedure. The antecedent water content, the upper limit of water availability (commonly called "field capacity") and the rate at which water moves from surface horizons to subsurface horizons determines ground-water recharge estimates using this model. If the upper limit of available water is high and internal drainage rates low, more water remains close to the soil surface where it is available for evapotranspiration. As a result, less water will be available for ground-water recharge.

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[1] Pacific Northwest National Laboratory, Research Letter Report to NRC, Oct. 1999, Richland, WA.

Table 10. Values of parameters used in the PNNL Water-Budget Model.

Depth of root zone at Site (cm):	*dr*	100
Saturated volumetric water content	*ThetaS*	0.43
Saturated hydraulic conductivity	*Ks*	varies (see table 8)
Air entry soil-water pressure (cm):	*psis*	-10
Pore size distribution index of Brooks-Corey hydraulic properties	*m*	0.33
Soil dependent parameter of Philip infiltration equation:	*a*	0.333
Initial water content:	*theta_initial*	0.31
Value of water content at which evapotranspiration becomes less than the maximum:	*thetaf*	0.2
Power of ET decline from its maximum:	*p*	1
Wilting point	*Water content(15000)*	0.101

Table 11. Results from PNNL Water-Budget Model (units are in cm) with three different values of saturated conductivity (**K_S**).

Season[1]	Rainfall	Drainage	Actual ET	Potential ET
K_S= 6400 cm day^{-1}				
sw	21.1	14.1	12.4	23.3
su	30.2	2.7	27.2	64.5
fw	26.4	14.8	9.5	17.2
K_S = 640 cm day^{-1}				
sw	21.1	9.2	15.1	23.3
su	30.2	1.1	30.3	64.5
fw	22.3	8.6	10.7	17.1
K_S = 310 cm day^{-1}				
sw	21.1	7.7	16.0	23.3
su	30.2	0.8	31.2	64.5
fw	22.3	7.1	11.0	17.1

1. Seasons are sw- Spring-Winter, su- Summer, and fw- Fall-Winter

4.9 Comparison of Estimated Ground-Water Recharge from the Piezometer and MCP Data, and PNNL Water Budget Model

Summarized results of ground-water recharge from the piezometer and MCP data, the PNNL Water-Budget model and two steady state methods are given in Table 12. Ground-water recharge is the amount of water that reached the water table, Percent Rain (**%P**) and Rain-PET (**P-PET**) are two steady state methods used to estimate ground-water recharge, and MCP infiltration is an infiltration estimate calculated from MCP data. Ground-water recharge from the piezometer data is calculated using measurements of the water table but uses specific yield, that is an uncertain value. The recharge from the piezometer is considered a "measured value" against which estimates from the other methods are compared although it has its own level of uncertainty. These three methods are shown since these are the only methods for which there are complete results for all threes seasons.

The most notable observation from Table 12 is that, during the spring-winter and fall-winter seasons, a large percentage of the rain input became ground-water recharge. Note also that the MCP infiltration was somewhat higher than the measured rainfall. The rainfall gauge was not at the site although it was close by. The rainfall gauge could record less rainfall than actually fell. Because the rainfall gauge uses a "tipping bucket" to record rain fall, it could be "overwhelmed" by rapid tipping during intense rainstorms in which case the true number of tips would not be recorded. This would be likely during the fall-winter when there were a number of large rainfall events. If the MCP infiltration data were correct and the rainfall underestimated, then the proportion of rainfall that was recharge (from piezometer data) would be less. For example, if the winter-spring (sw) actual rainfall was closer to the 28 cm measured from the MCP probes than the 21.1 cm recorded at the rain gauge then the recharge of 18.8 cm would be a smaller proportion of the rainfall.

The different estimates of ground-water recharge are all different and cannot be compared to a "standard". The amount of "measured" recharge, the value to which the others are compared in this study actually depends on the value of specific yield chosen. The chosen specific yield (0.19) was somewhat more conservative than the one determined from the spring recharge. If a larger value of specific yield were chosen (i.e. greater than 0.19), the recharge would be closer to the measured rainfall and, in our view, possibly more unrealistic. The PNNL Water-Budget model provided excellent estimates of ground-water recharge but these were slightly less than the measured values for the spring-winter and fall-winter seasons. They were not too much larger than that calculated from the MCP data however. The recharge estimates from the MCP data for the summer and fall-winter were not different, this suggests that the use of these data may overestimate recharge during the summer growing months and underestimated it in the non-summer months. It was not clear from the data why the estimate for the fall-winter (fw) from the MCP data was so much smaller than the estimate from the winter spring (sw) when the estimates from the other methods are consistent among the different seasons. The results from the MCP data had a wide range of variability reflecting the variable soil conditions in the lysimeter. Based on the variability of the MCP results, single point measurements may not be reliable enough to base an estimate of ground-water recharge on. While there are uncertainties for all the methods and no one method seems to be a fully reliable estimate of ground-water recharge. The estimate from the piezometer data, however, would be consistent with actual recharge between seasons since it would only differ by a constant (that may vary a bit in time). This would be the most reliable value. A combination of the measurements may provide a bounding range for the actual values of ground-water recharge, but each method has an associated uncertainty.

Table 12. Summarized results of the ground-water recharge estimates (units are in cm) from the Piezometer and MCP data, PNNL water budget model and two steady state methods.

Season[1]	Rain	Recharge From Piezometer	Ground-Water Recharge Estimates					MCP infiltration	
			MCP						
			Mean	Std	PNNL	Percent Rain **(%P)**	Rain - PET **(P-PET)**	Mean	Std
sw	21.1	18.8	12.3	7.2	14.1	7.4	-15.5	28.3	10.6
su	30.2	2.9	7.5	7.6	2.7	10.6	-47.7	36.6	10.9
fw	22.3	20.7	7.2	4.6	12.8	7.8	0.3	26.0	7.6

[1] Seasons are sw- Spring-Winter, su- Summer, and fw- Fall-Winter.

5. CONCLUSIONS

Risk due to contaminant release and transport, as estimated by many multimedia environmental models, is highly sensitive to infiltration and ground-water recharge. Characterization of deep infiltration and ground-water recharge traditionally focuses on long-term estimates (e.g., annual or monthly). Because shallow water-tables in a humid climate are highly transient and dynamic, near-continuous water content, water-table elevation, and meteorological data would be useful to estimate infiltration and ground-water recharge and their attendant uncertainties. Previous ARS-NRC studies (see NUREG/CR-6653 and 6729) developed methodologies, and showed the value of high-frequency monitoring of unsaturated zone water contents and piezometric levels to estimate infiltration and ground-water recharge. These studies addressed technical issues (e.g., episodic ground-water recharge events which may lead to leaching and transport of radionuclides) common to the various sites, and provided research results as technical bases for resolving these issues.

These highly-detailed monitoring data were evaluated to capture individual recharge-event characteristics (i.e., infiltration, drainage, redistribution, and evapotranspiration) and estimation of hydraulic parameters. One important technical issue addressed in this report was the characterization of possible errors in ground-water recharge through comparison of different methods to estimate ground-water recharge using real-time, near-continuous databases. Furthermore, the temporal density of these data were such that interpolation methodologies may not be necessary and uncertainty is reduced. Uncertainty in this context refers to information loss due to intermittent and low frequency monitoring in monitoring locations. Real-time, near-continuous data provided a highly realistic characterization of the transient, and dynamic hydraulic processes and events.

This cooperative project provided insights into data and conceptual model variabilities at the lysimeter scale (12 x 20 x 3-4 meters). In the previous studies, incomplete knowledge of ground-water recession contributed to uncertainty in ground-water recharge estimates. Advanced monitoring techniques (e.g., multisensor capacitance probe) used in combination with a highly controlled closed lysimeter provided a more certain estimate of ground-water level. The two numerical models used were the PNNL Water-Budget model that was developed by Pacific Northwest National Laboratory through a companion NRC-funded research project, and the HYDRUS-2D code that was developed by ARS-George Brown Salinity Laboratory. The datasets and modeling results developed for this study are available from the USDA-National Agriculture Library.

This study included high frequency, real-time observations of rainfall and soil-water contents at 16 locations within a lysimeter. Potentially the piezometric data could be the most reliable indicator of ground-water recharge. This method would require more robust and detailed measurements of specific yield, however. This study has also shown that spatial variability in soil-water content measurements can be a large contributor to uncertainty. Further studies should move to larger scales (i.e., watershed) which capture spatial heterogeneities and complex subsurface processes (e.g. lateral unsaturated flow). Measurements should include real-time observations of piezometer fluctuations, drainage and evapotranspiration losses in addition to rainfall, and more robust estimates of specific yield. A significant observation from this work is the value of using integrated and realistic models (e.g. PNNL water-budget model, and HYDRUS-2D). The use of such models integrates point measurements within a real-time basis for water-content, pressure-head and water-level changes. Therefore, uncertainties can be identified and estimated from various datasets using these models. Models are helpful to evaluate the contribution of evapotranspiration to water loss and the reduction of net infiltration. In order to model evapotranspiration processes correctly, models need to be able to account for plant growth, canopy light interception, and root activity.

This study identifies practical field instrumentation and analytical models for estimating ground-water recharge using real-time databases. This study also demonstrates temporal relationships in subsurface water flow, water-content redistribution and evapotranspiration. The complexities of these dynamic and transient processes are reflected by these data. The selection and use of analytic models for capturing these dynamic processes are demonstrated.

Specific insights are:

- Real-time, near-continuous monitoring data can provide insights into the hydrologic processes which can affect radionuclide transport for near-surface settings in humid temperate climates.
- Specific yield needed to convert changes in piezometric level to ground-water recharge flux is a significant source of uncertainty. This important parameter is extremely difficult to measure directly and is often inferred from rainfall and piezometer head data where it is assumed that evapotranspiration is negligible, and the porosity is invariant with depth. These assumptions contribute to uncertainty.
- While the data from the Neutron probes do show the general trends in water contents, they miss the dynamics of the infiltration events and so do not have enough information to assess drainage during individual infiltration events.
- Uncertainty in characterizing site behavior can be reduced by utilizing a network of measuring devices to capture the temporal and spatial variability inherent in this dynamic process.
- The real-time, near-continuous piezometer data showed a very rapid response (e.g. < 20 minutes) in the water-table to rainfall events. This verifies the occurrence of significant episodic recharge for the shallow water-table at this site. This dynamic process was also verified for the Multi-sensor Capacitance Probe (MCP) data as described in NUREG/CR-6653 and NUREG/CR-6729.
- Based on a mass balance analysis of the MCP data (e.g., infiltration, losses due to drainage and evapotranspiration, and storage), the summation of positive and negative changes of volumetric water contents from the MCP data result in a consistent mass balance.
- On the average, the infiltration calculated from the volumetric water content changes overestimated actual infiltration when compared to the rainfall.
- For the summer, when evapotranpiration is an important component of water loss in the soil profile, the spatial average of the MCP data greatly overestimates ground-water recharge. For the other seasons when evapotranspiration is minimal, the spatial average of the MCP data significantly underestimates ground-water recharge. Spatial variation in ground-water recharge estimates using MCP data is on the order of the mean value.
- The PNNL model provided values of ground-water recharge that were similar to those inferred from the lysimeter database using an estimated specific yield.
- HYDRUS-2D simulation results could not be utilized for the summer and fall-winter seasons due to artificial boundary conditions imposed by sporadic pumping of water accumulating in the lysimeter.
- The largest source of uncertainty was due to evapotranspiration calculations. The following are two specific cases:

    - It was difficult to separate the evapotranspiration and drainage components during calculation of negative changes in soil water contents shortly after rainfall events. This was especially true for long duration rainfall events.
    - For the numerical model inputs and results, the largest source of uncertainty arose from the need to input estimated potential evapotranspiration. The uncertainty is propagated through the model's approach for calculating actual evapotranspiration (i.e., assumptions in plant water uptake and root distribution). Additional sources of uncertainty for the modeling results were due to incomplete knowledge of soil hydraulic properties.

- Each methodology has its own inherent uncertainties. We could not obtain a directly measured ground-water recharge. The Gee flux meter would have been a direct method for a specific location, but would not address spatial variability.
- A major unknown is the soil dynamics between the 40 and 100 cm sensor depths. The sensor revealed highly dynamic water content changes down to 40 cm. However, the sensor at 100 cm depth did not indicate these changes (except during major recharge periods).

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GLOSSARY

GLOSSARY OF TERMS AND NOMENCLATURE

Bulk density of soil	**Mass of dry soil per unit bulk volume including solids and pores (Mg M^{-3}) (after Soil Science Society of America (SSSA), 1997).**
Capacitance probe	**An instrument to measure soil water content using radio waves.**
Capillary fringe	**The zone of soil just above the plane of zero gauge pressure (water-table) that remains saturated or almost saturated with water. (SSSA, 1997)**
Effective porosity	**The saturated volumetric water content minus water content at 0.33 kPa.**
Evapotranspiration (ET)	**Loss of water from a land area through transpiration of plants and evaporation from the soil and surface water bodies. Evapotranspiration occurs at it's potential rate when water is not limiting. (after Wilson and Moore, 1998)**
Ground-water recharge	**The quantity of water that reaches the water-table.**
Hydrograph	**Graph showing hydraulic head vs. time**
Infiltration rate	**The actual rate at which the water enters the soil, cm d^{-1}. The infiltration rate is controlled by rainfall rate, soil properties and antecedent water content (after SSSA, 1997).**
Infiltration capacity	**This is the maximum rate at which water can infiltrate the soil at current soil conditions and water content (after SSSA, 1997).**
Multisensor Capacitance Probe (MCP)	**A field instrument inserted into the soil with capacitance sensors at discrete depth intervals capable of real-time, near-continuous monitoring of volumetric water content**
Near-continuous	**Measurement frequency that captures the temporal variance of the event being monitored.**
Net deep percolation	**Water that has migrated beyond the root zone and is not available for evapotranspiration.**
Neutron probe	**An instrument to measure soil water content using attenuation of radioactive decay products (after SSSA, 1997).**
Piezometer	**An open borehole used to measure the total ground-water potential as an elevation head.**
Piezometric head	**The total hydraulic head as measured in a piezometer, synonymous with the water-table elevation for an open borehole.**
Pressure transducer	**An electronic device that measures height of a water column in a borehole**
Real-time	**The actual time in which a physical process takes place with the recording of the event practically simultaneous with its occurrence. (After Merriam Webster, 1977)**

Recession	**The decline of the water-table following a rise due to a recharge event. (After Wilson and Moore, 1998)**
Recession coefficient	**A coefficient (k) that defines the rate of change in piezometric head with time (t^{-1}) for an exponential rate of recession. It is usually defined using a well hydrograph record.**
Soil water potential	**The work required to remove water from a soil matrix.**
Specific yield	**The volume of water extracted from the ground-water per unit area when the water-table is lowered a unit distance. The amount of water content change is characterized by the specific yield, S_y.**
Tensiometer	**A device for measuring soil water potential *in situ* (SSSA, 1997).**
Tension infiltrometer	**An instrument to measure soil hydraulic conductivity at saturation and at a range of unsaturated water contents near saturation.**
Total infiltration	**Total amount of water adsorbed by the soil (cm) equal to rainfall minus runoff. If plants are present the amount of infiltration can be increased if rainfall is diverted along a plant stem or leaf.**
Unsaturated zone	**A subsurface region between the land surface and the regional ground-water-table.**
Volumetric water-content (θ)	**The amount of water expressed as a ratio of water volume to soil volume (cm^3 cm^{-3}) (after Dingman, 1994) Also called water-content in this document.**
ψ	**Pressure potential of water in soil (kPa)**

NOMENCLATURE

Symbol	**Description**
%P	**Percent Precipitation**
$\Delta\ \theta$	**Change in water-content**
$\Delta\theta_v$	**Volumetric soil water-content changes**
$\Sigma+\Delta$	**Analysis of sum of positive changes during a rainfall period**
ARS	**Agricultural Research Service (U.S. Dept. of Agriculture)**
DOY	**Day of year**
ET	**Evapotranspiration**
fw	**Fall/Winter**
h	**potentiometric head**
IAA	**Interagency Agreement**
MCP	**Multisensor Capacitance Probes**
P-PET	**Precipitation minus Potential Evapotranspiration**
PNNL	**Pacific Northwest National Laboratory**
Rainid	**Rainfall period identifier**
RES	**Office of Nuclear Regulatory Research**
SAS	**Statistical Analysis System software (SAS Corporation, Cary, NC)**
su	**Summer**
S_y	**Specific yield**
WB	**Water Balance model**
ws	**Winter/Spring**