NUREG/CR-6653

Comparison of Estimated Ground-Water Recharge Using Different Temporal Scales of Field Data

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Prepared by
D. Timlin, J. Starr, USDA
R. Cady, T. Nicholson, NRC

U.S. Department of Agriculture
Agricultural Research Service
Beltsville Agricultural Research Center
Beltsville, MD 20705-2350

T. Nicholson, NRC Project Manager

Prepared for
Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research
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ABSTRACT

This study investigated field instrumentation [multi-sensor capacitance probes (MCP)] and analytical methods for estimating "real-time" infiltration and subsequent ground-water recharge and their attendant uncertainties. The research design was to apply a selected subset of existing field characterization data from the Beltsville Agricultural Research Center to technical issues identified by the NRC staff involving ground-water recharge estimates at nuclear facilities. The datasets allow comparisons of ground-water recharge estimates using near-continuous, water content measurements to recharge estimates based on less frequent water content observations (e.g. hourly or daily), intermittently measured piezometric data or analytical models. Drainage was underestimated by only using changes in water contents measured by MCP. Differences in water content did not always accurately represent fluxes when the system was at steady state. The estimate of net ground-water recharge decreased as measurement frequency decreased. The MCP data provided better estimates of recharge and timing than the piezometer data. Estimates of ground-water recharge were also compared to simulated recharge using a PNNL water budget model. The optimization of data in combination with a model can significantly reduce errors associated with using changes in water contents alone. A model optimized for hydraulic conductivity and moisture release parameters can calculate the fluxes using boundary conditions provided by the MCP and rainfall data. Further studies should move to larger scales (i.e., watershed) and lysimeters.

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EXECUTIVE SUMMARY

NUREG/CR-6653 was prepared by the Agricultural Research (ARS) researchers in cooperation with the NRC staff under their Interagency Agreement (IAA), and the governing Memorandum of Understanding (MOU). The objectives of both the MOU and IAA were to investigate field instrumentation and methods for estimating "real-time" net infiltration and subsequent ground-water recharge and their attendant uncertainties. The ARS monitoring program was originally designed to provide information on the hydrologic dynamics for plow tillage and no-tillage soils planted to corn. The field size was approximately 0.5 hectares and the time period for the water content measurements covers June 1995 to the present. The ARS and NRC staff determined that the database would be useful for analyzing uncertainties in estimating net infiltration and ground-water recharge associated with technical reviews of licensing nuclear facilities. The research design, therefore was to apply a selected subset (June 1995 to December 1996) of existing field characterization data and monitoring programs at the Beltsville Agriculture Research Center (BARC) to technical issues identified by the NRC staff involving ground-water recharge estimates at nuclear facilities.

This study addresses technical issues common to the various nuclear facility programs, and provides research results as technical bases for resolving these issues. One important technical issue addressed in this report was the characterization of uncertainty in estimates of ground-water recharge. Uncertainty in this context refers to information loss due to intermittent and low frequency monitoring. Infrequent monitoring of highly transient events can lead to significant loss of information (e.g., timing and quantity of ground-water recharge). Timing and quantity of ground-water recharge can be estimated from measurements of hydrologic conditions (e.g., water content and potential). Infiltration and redistribution of water are highly transient processes estimated from these hydrologic conditions. 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 over which ground-water recharge varies. The accumulation and timing of these rapid near-surface effects can translate into significant differences in ground-water recharge over long time periods. Therefore, 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.

The research results have identified state-of-the-science water balance monitoring instruments [e.g., multi-sensor capacitance probes (MCP)], analytic methods, and data needs for estimating "real-time" net infiltration and ground-water recharge rates. The MCP provided for collection of near- continuous measurements (10 minute intervals) on soil water storage and redistribution. The MCP is used specifically for water content profiling in this study. We consider only soil water content changes shortly before, during, and shortly after rainfall to estimate net water infiltration and subsequent ground-water recharge. Other components such as evapotranspiration and runoff do enter into the water balance. By considering only short time periods around rainfall events, evapotranspiration, though not zero is small relative to total changes in soil water content, and can be neglected. Drainage between rainfall periods is generally small relative to the amount of water infiltrated during rainfall especially when there is a large amount of rainfall. Measurements of water content changes around a rainfall period can then be expected to capture most of the water that goes to ground-water recharge. This study was not intended to replicate a water balance approach using the MCP data, therefore runoff was considered to be negligible. We believe this assumption was appropriate for this site under the given test conditions.

The datasets contained in this report provide the database of desired frequent monitored water content profiles. These datasets allow comparisons of ground-water recharge estimates using near-continuous water contents to recharge estimates based on less frequent water content observations (e.g. hourly or daily). These estimates of ground-water recharge using near-continuous measurements were also compared to more uncertain estimates of ground-water recharge from intermittently measured piezometric data or analytical models. Information from this report can be utilized to test conceptual models and analytical methods presently being used to review and evaluate net infiltration and ground-water recharge estimates at decommissioning, uranium mill tailings, HLW and LLW disposal sites.

Previous studies have identified the importance of assessing: (1) preferential flow in the near surface, (2) temporal variations in net infiltration and water content, and (3) heterogeneities that may result in focus 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 continuously monitored data may be useful if these conditions exist at a decommissioning site in order to appropriately model infiltration and net ground-water recharge. Therefore, real- time continuously monitored data may be useful if these conditions exist at a decommissioning site in order to appropriately model infiltration and net ground-water recharge

Lessons from the ARS-NRC study provided an estimate of the information loss attendant to differences in frequency of measurement of hydrologic conditions. A comparison was made among 10-minute, hourly, and daily MCP data measurements for estimating net ground-water recharge. The estimate of net ground-water recharge decreased non-linearly as measurement frequency decreased. The largest loss of information occurred between the hourly and daily frequencies. The difference in net ground-water recharge between the 10-minute and hourly frequencies was less than the difference between the hourly and daily frequencies. The net ground-water recharge was related to the measurement frequency. This suggests a scaling dependency that could be used to estimate loss of information due to measurement frequency.

The 10-minute MCP data provided estimates of net ground-water recharge that were relatively similar to those determined from piezometer data. The exact magnitude of the differences, however depend largely on the value of porosity determined to obtain mm of water from mm of water table height. The values of net recharge calculated from the piezometer data could be larger but are unlikely to be smaller than given in this paper. Infrequent measurements of water table height therefore, did not appear to result in as much information loss as infrequent measurements of water content did. This is probably because the piezometer measurements integrate over a longer period of time than the MCP measurements closer to the surface and are not susceptible to error during steady state conditions.

Estimates of ground-water recharge using the 10-minute MCP data were also compared to simulated ground-water recharge using a PNNL water budget model. The seasonal estimates of net ground-water recharge differed. The estimates of ground-water recharge in the winter using the MCP data were lower than the modeled recharge possibly due to more accurate characterization of evapotranspiration by the MCP data. There was also considerable error in estimating ground-water recharge using MCP alone. The MCP data would be more likely to underestimate net ground-water recharge in the winter when the soil tends to stay wet and water flow tends to steady state. In this case differences in water content do no always reflect actual drainage. This error can be minimized using a network of MCP sensors (lateral and vertical configurations). Frequent measurements of rainfall should be used with MCP water contents to estimate ground-water recharge using a detailed water balance model, e.g., the PNNL model. The optimization of hydraulic properties in combination with a simulation model can significantly reduce errors associated with using changes in water contents alone to estimate ground-water recharge. A model can provide the fluxes while the MCP and rainfall data provide the boundary conditions.

The spatial variability of calculated net ground-water recharge was also considerable and ranged from 10 to 70% of estimated recharge. This is due to differences in hydraulic properties as well as differences in surface soil characteristics that affect infiltration. In many cases the variability among locations was larger than the variability among the different measurement methods.

Significant conclusions are:

- Real-time, near-continuous monitoring data can significantly reduce uncertainties and provide insights into the hydrologic processes which can affect radionuclide transport for near-surface settings in humid temperate climates.
- Estimated net ground-water recharge decreased rapidly as measurement frequency decreased.
- Scaling behavior is evident in the relationship between estimated net ground-water recharge and frequency of measurements.

- The multi-senor capacitance probe (MCP) proved robust and reliable over ranges of site conditions and time periods for this multi-year study.
- Near-continuous, soil water content measurements for measuring net infiltration and estimating subsequent ground-water recharge are highly valuable for characterizing a dynamic hydrologic regime and for testing analytic and numerical models.
- Water budget models can provide reasonable estimates of ground-water recharge. However, appreciable errors may accumulate due to uncertainties in estimating site-specific evapotranspiration.
- Estimation of ground-water recharge using frequently measured water content data may underestimate fluxes of water in the system.
- Frequent measurements of rainfall should be used with MCP-measured water contents to estimate ground-water recharge using a detailed water balance model, e.g., the PNNL model.
- Optimization of data for hydraulic properties in combination with a model can significantly reduce errors associated with using changes in water contents alone to estimate ground-water recharge.

This cooperative project provided insights into data and conceptual model uncertainties at the site scale (hectare) for a shallow (less than 10 m) unsaturated zone. This report provides comparisons of "real-time" models against detailed, site specific water content data. Further comparisons of other infiltration models using these data sets are feasible. The datasets and the programs used in this study are available as computer readable files from the USDA-National Agriculture Library.

This study included high frequency, real-time observations of rainfall and water contents over a 0.5 hectare (1.25 acre) site. The MCP data proved valuable in estimating relative ground-water recharge but further questions remain as to accuracy of the calculations and the nature of their uncertainties. This study has also shown that spatial variability 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).

A more detailed water balance study should be conducted under controlled conditions using lysimeters. Measurements should include real-time observations of drainage and evaporative losses in addition to rainfall. This will provide information on fluxes in and out of the system and can be used to evaluate the accuracy of the MCP data in estimating ground-water recharge in combination with a mass balance model.

FOREWORD

This technical report, NUREG/CR-6653, was prepared by the Agricultural Research Service (ARS) researchers in cooperation with the NRC staff under an Interagency Agreement (IAA), and governing Memorandum of Understanding (MOU) between the ARS and the NRC's Office of Nuclear Regulatory Research. The objectives of this effort was to investigate field instrumentation and methods for estimating "real-time" net infiltration and subsequent ground-water recharge and their attendant uncertainties. The research design was to apply existing field characterization data and monitoring programs at the Beltsville Agriculture Research Center (BARC) to technical issues identified by the NRC staff involving ground-water recharge estimates at nuclear facilities.

The report identifies state-of-the-science infiltration instruments, e.g., multisensor capacitance probes, analytic methods, and data needs for estimating "real-time" net infiltration and ground-water recharge rates. The report also provides insights into data and conceptual model uncertainties at the site scale (hectare) for a shallow (less than 10 m) unsaturated zone. The report discusses comparisons of "real-time" models against detailed, site specific water content data. For example, a "real-time" transient water budget model, developed by Pacific Northwest National Laboratory through a companion NRC- funded research project, estimated net drainage which is an important factor in reviewing site-specific decommissioning assessments. The multisensor capacitance probe data collected in this study can be useful in evaluating other infiltration and drainage models. The datasets and the programs used in this study are available as computer readable files from the USDA-National Agriculture Library. A significant observation from this work is the value of near-continuous, soil water content measurements for measuring net infiltration and estimating subsequent ground-water recharge.

NUREG/CR-6653 is not a substitute for NRC regulations, and compliance is not required. The approaches, instrumentation and/or methods described in this NUREG/CR are provided for information only. Publication of this report does not necessarily constitute NRC approval or agreement with the information contained herein. Use of product or trade names is for identification purposes only and does not constitute endorsement by NRC or USDA/ARS.

Cheryl A. Trottier

Cheryl A. Trottier, Chief
Radiation Protection, Environmental Risk and Waste Management Branch
Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research

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1 INTRODUCTION

On May 27, 1997 the USDA/ARS and the U.S. Nuclear Regulatory Commission (NRC) signed a memorandum of understanding (MOU) to cooperate on a joint study for testing and evaluating infiltration estimation methods and instrumentation. An Interagency Agreement to implement the MOU became effective Sept. 2, 1997.

This cooperative study is in response to an NRC generic research need. This need has been documented in NRC technical licensing internal correspondence related to High-Level Radioactive Waste (HLW), Low-Level Radioactive Waste (LLW), Site Decommissioning Management Plans (SDMP), and uranium recovery. Specific needs identified in these include: (1) estimation of infiltration rates for various site properties and conditions; (2) techniques for estimating error and uncertainty; and (3) a comparison of different techniques for incorporating spatial and temporal variability.

This study seeks to address these technical issues and others common to the various nuclear facility programs, and will provide research products which assist in resolving them through development and transfer of information and datasets on infiltration and moisture migration and redistribution. This information will be utilized to test conceptual models and analytical methods presently being used to review and evaluate SDMP, HLW, and LLW disposal sites.

The Agricultural Research Service (ARS) of the Department of Agriculture is conducting field studies of infiltration through soils associated with experimental crops and tillage methods. ARS scientists are utilizing new technologies including a unique field instrument, the capacitance probe, to measure continuous real-time moisture migration and redistributions in response to surface meteorological events and processes. The field studies are being conducted at the Beltsville Agricultural Research Center (BARC).

ARS is presently evaluating a soil water field technique (i.e., capacitance probe) at their BARC field facilities. The ARS field project involves collection of soil water contents using the capacitance probe method along with two conventional field methods, the neutron probe and shallow water-table level measurements. At NRC-licensed facilities available field information on infiltration is often limited to shallow water-table level data and rarely neutron probe or tensiometer data. There has not been continuous real-time records at any site.

Presently RES is funding two projects related to water balance calculations: (1) PNNL has developed a "Hydrologic Evaluation Methodology" (Meyer et al., 1996) using numerical approaches for estimating net infiltration over a range of site conditions using soil textural data (e.g., USDA soil texture data through site hydraulic and transport testing data), and (2) the University of Arizona (UAZ) is examining and testing monitoring strategies for the unsaturated zone for various nuclear facilities (Young et al., July 1996). This cooperative research study, through an interagency agreement between the ARS and U.S. NRC, is designed to bring together the monitoring and numerical analysis issues that have been studied at PNNL and UAZ. This cooperative study utilizes the BARC databases to demonstrate to the NRC staff the practical aspects of water balance field studies and calculations.

2 INFORMATION NEEDS

In order to assess the safety of nuclear facilities, water balance calculations need to be performed as part of site characterization and facility performance analysis. The calculation of net infiltration and percolation rates and infiltration capacity of the soil are needed to determine the leaching and transport potential of subsurface waste. Drainage rates can be estimated using field methods such as the double-ring infiltrometer, or indirectly using soil moisture and water-table level data in conjunction with site precipitation and evaporation data. As part of the site characterization and performance analyses, uncertainty assessments needed to be determined in the net infiltration calculations

As part of NRC staff licensing reviews (i.e., LLW, DEIS for SDMP, and HLW), information on net infiltration estimations is needed. These reviews include analyses of the assumptions, data (or lack thereof) and methods for estimating net infiltration which affect the leaching and transport of radionuclides (Nicholson and Parrott, 1998).

3 PERFORMANCE MEASURES

Performance measures are the regulatory criteria for defining compliance. Associated with these performance measures are related hydrologic issues and uncertainties which need to be examined and resolved. The following discussion outlines the specific hydrologic issues and uncertainties for performance measures in the radioactive waste management program areas of low-level radioactive waste (LLW), decommissioning, high-level radioactive waste (HLW), and uranium recovery and tailings disposal.

Although a variety of derivative hydrologic measures and hydrologic issues are stated, the reader should keep in mind that the end point of the technical analysis is the performance measure for the licensed facility obtained through a performance assessment. The specific hydrologic measures and issues need only be explored and dealt with to the extent required by the performance assessment, taking into account the significant uncertainties and the hazard involved and that some uncertainties may be satisfactorily addressed through bounding analyses.

3.1 Low-Level Waste Disposal Sites

The performance measure in the current regulations for low-level waste (LLW) disposal sites is provided by a standard for protection of the population and the environment in 10 CFR 61.41. According to this standard, concentrations of radioactive material which may be released to the general environment in ground water, surface water, air, soil, plants, or animals must not result in an annual exceeding an equivalent of 25 millirems (mrem) to the whole body, 75 mrem to the thyroid, and 25 mrem to any other organ of any member of the public. In addition, the standard indicates that reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as reasonably is reasonably achievable (ALARA).

Regulatory guidance for demonstrating compliance with current regulations for LLW sites is provided in NUREG-1573. As stated in NUREG-1573 (p. 3-57), the objective of the ground water flow and transport analyses (including ground water models), in evaluating compliance with 10 CFR 61.41, is to assess concentrations of radionuclides released in the ground water at receptor locations so as to assess the annual dose to the average member of the critical group. NUREG-1573 (p. 3-58) further states that while regulatory compliance is based on the annual dose to the average member of the critical group, staff recommend that the ground-water transport analysis provide concentrations in well water at the site boundary that would have the composite concentration of radionuclides resulting in the highest dose.

Analysis of radionuclide concentrations in the ground water at specific sites is carried out usually involves addressing such site-specific hydrologic issues as infiltration through the disposal site cover, release of radionuclides from the waste, and flow and radionuclide transport in the unsaturated zone and in the saturated zone to the receptor points.

Uncertainties commonly encountered in the hydrologic analysis of LLW disposal sites include both data as well as conceptual uncertainties. Data uncertainties include the hydraulic properties of the cover (mainly permeability/hydraulic conductivity, service life); the hydraulic properties of the formations beneath the site (mainly permeability/hydraulic conductivity, anisotropy and inhomogeneity, effective porosity); retardation properties and coefficients; and pH values. Conceptual uncertainties may include lateral flow versus vertical flow and possible development of perched conditions in the unsaturated zone below the disposal facility; matrix versus fracture flow; structural controls on flow and radionuclide transport; inter-aquifer flow; and uncertainty related to changes in time-dependent variables (such as the water levels, concentrations, and pH). Data-related uncertainties are sometimes addressed by bounding analyses.

3.2 Decommissioning of Licensed Sites

The performance measure in the current regulations for decommissioning of licensed sites is provided by the standards in 10 CFR 20.1402 (for license termination including unrestricted use of the decommissioned site) and 10 CFR 20.1403 (license termination under restricted conditions for use of the decommissioned site). According to the standards in 10 CFR 20.1402, a site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a Total Effective Dose Equivalent (TEDE) to an average member of the critical group at receptor locations or human access points that does not exceed 25 mrem per year, including that from ground water sources of drinking water, and the residual radioactivity has been reduced to levels that are ALARA.

The standards in 10 CFR 20.1403 provide that a site will be considered acceptable for license termination under restricted conditions by satisfying certain provisions specified in the regulations. These include provisions pertaining to meeting the ALARA provision; legally enforceable institutional controls that provide reasonable assurance that the TEDE from the residual radioactivity will not exceed 25 mrem per year; financial assurance to assume and carry out any necessary control and maintenance of the site; submittal of a decommissioning or a license termination plan indicating intent to decommission in accordance with the regulations in 10 CFR Subparts 30.36(d), 40.42(d), 50.82(a) and (b), 70.38(d), or 72.54; and that if the institutional controls were no longer in effect, there is reasonable assurance that the residual activity to the average member of the critical group is ALARA, and would not exceed either 100 mrem per year, or 500 mrem per year provided that the licensee: (1) demonstrates that further reductions in residual radioactivity necessary to comply with the 100 mrem per year are not technically achievable, would be prohibitively expensive, or would result in net public or environmental harm; (2) makes provisions for durable institutional controls; and (3) provides sufficient financial assurance to enable a responsible government entity or independent third party, both to carry out periodic rechecks of the site to assure that the institutional controls remain in place as necessary to provide reasonable assurance that the TEDE from the residual radioactivity will not exceed 25 mrem per year.

Guidance for demonstrating compliance with the current regulations for decommissioning sites is provided in NUREG-1549. This guidance does not explicitly address how the ground-water analysis should be performed. However, guidance is provided for assessment of the dose for an individual located on site (e.g., using water extracted from a well located on the site with an intake point directly beneath the waste area), an individual located off site (e.g., using water extracted from a well located at the site boundary), or both. It should be pointed out, as reflected in NUREG-1549, the NRC recommended dose modeling approach is an iterative approach that involves a screening analysis initially, but eventually includes more site-specific analyses as warranted by the site conditions. The screening approach recommended in another regulatory document, NUREG-5512 (vol. 1), has a predefined ground-water conceptual model.

Uncertainties commonly encountered in the hydrologic analysis for decommissioning of licensed sites include both data as well as conceptual uncertainties that are similar to those encountered at LLW sites (see LLW Disposal Sites above).

3.3 High-Level Waste Disposal Sites

Currently the performance measure for high-level waste (HLW) disposal sites (other than Yucca Mountain) is provided in 10 CFR Part 60, which is based on the remanded EPA standard. However, this standard does not apply to the proposed high-level waste disposal site at Yucca Mountain, which is the only site under consideration for this purpose in the U.S. at this time. It is expected that the site-specific standard presently under development for the proposed Yucca Mountain site will specify the performance measure as the expected dose, or expected TEDE, to the average member of the critical group located 20 km hydraulically down-gradient from the repository. The site-specific standard under development for Yucca Mountain is expected to be specified at 25 mrem per year TEDE. The dose is "expected" to reflect various scenarios and parametric realizations appropriately weighted by their probabilities.

Hydrologic processes and flow and transport issues that may have to analyzed to assess the HLW repository performance include: infiltration from the ground surface under present and future climates; deep percolation from the root zone into the waste emplacement drift (an unsaturated, fractured and anisotropic zone above the repository); unsaturated zone flow across the emplacement drift ceiling and walls; thermal effects on the flow regime, hydraulic and transport properties of formations in the unsaturated zone; flow and retardation of radionuclides in the unsaturated zone below the repository; flow, diffusion, dispersion, retardation, and dilution of radionuclides in the saturated zone between the repository and the receptor group location; ground-water extraction and use and dilution of radionuclide concentration due to pumping.

Important hydrologic uncertainties that may have to be addressed in ground water and transport models of Yucca Mountain include the infiltration and deep percolation rates under current and future climates, which involves projecting precipitation and infiltration rates for thousands of years into the future; selecting appropriate flow and transport pathway(s) considering the potentiometric head gradients, potentiometric head anomalies, and important stratigraphic and structural controls (mainly faults) and aquifer properties (mainly anisotropy) on flow direction; modeling of flow that may be taking place in matrix and fractured domains; inter-aquifer flow (i.e., lateral flow between the tuff and the alluvium, as well as vertical flow between the tuff/alluvium and a deep carbonate aquifer); modelling of diffusion, dispersion, and retardation along the flow pathway; modelling unsaturated zone flow under heat-influenced flow conditions caused by raised temperatures for many years after closure of the repository; making a reliable estimate of the dilution rate due to mixing along the flow pathway and due to pumping at the receptor group locations; analyzing the impact of local recharge and possibly inter-basin flow on radionuclide concentration in the ground water; determining the hydraulic properties of a large number of hydrostratigraphic units that may be impacting radionuclide transport from the repository to the receptor locations; and assumptions regarding ground-water extractions.

3.4 Uranium Recovery/Tailings Disposal Sites

The performance measure for reviewing uranium recovery and tailings disposal sites can be divided into three areas: Title I dealing with DOE-remedial action programs of former mill tailings sites; Title II dealing with non-DOE mill tailings sites; and In Situ leach (ISL) uranium solution mining sites. In all three areas, concentration limits of specified chemical and radionuclide constituents are determined.

3.4.1 Title I

For Title I sites, the performance measures are provided by EPA in their 40 CFR 192. Specifically Subparts A, B and C of Part 192 provide the regulatory requirements for water resources protection. In implementing the EPA requirements, NRC staff has provided guidance which discusses the need to develop a hydrologic conceptual model.

The hydrologic conceptual model plays an important role in nearly every decision made regarding site decommissioning and safe long-term disposal. For example, at sites with existing ground-water contamination, the hydrologic conceptual model must be sufficiently detailed to provide a technical basis for selecting the appropriate restoration strategy and for determining the risks to human health and the environment. Specific criteria are provided in NRC staff guidance for determining an acceptable hydrological site conceptual site. The hydrologic conceptual model includes both ground-water and surface-water conditions, interactions, and behavior.

3.4.2 Title II

For Title II sites, performance measures are provided in the NRC requirements as specified in Appendix A of 10 CFR Part 40. According to the general license standards for custody and long-term care of residual radioactive material disposal sites outlined in 10 CFR 40.27, a detailed description is required of the final disposal site conditions, including ground-water characterization and any necessary ground-water protection activities or strategies. This description must be detailed enough so that future inspectors will have a baseline to determine changes to the site and when these changes are serious enough to require maintenance or repairs. If the disposal site has continuing aquifer restoration requirements, then the licensing process will be completed in two steps. The first step includes all items other than ground-water restoration. Ground-water monitoring, which would be addressed in the Long-Term Surveillance Plan (LTSP), may still be required in this first step to assess performance of the tailings disposal units. When the Commission concurs with the completion of ground-water restoration, the licensee shall assess the need to modify the LTSP and report results to the Commission. 10 CFR Part 40.65 outlines effluent monitoring reporting requirements. Appendix A to 10 CFR 40 contains specific criteria for ground-water monitoring and restoration activities.

For Title II sites, specific requirements for implementing the basic ground-water protection standards imposed by EPA (40 CFR Part 192, Subparts D and E) are provided in Appendix A to 10 CFR Part 40 (Criterion 5). Ground-water monitoring to comply with these standards is required by Criterion 7A. For selected constituents and properties, maximum values for ground-water protection are specified in Criterion 5C which identifies maximum concentration for a specified constituent or property.

3.4.3 In Situ Leach (ISL) Uranium Extraction

Guidance for demonstrating compliance with the current regulations for In Situ leach (ISL) uranium extraction license applications is provided in NUREG-1569. This guidance explicitly addresses the ground-water information and analysis that is specified in Regulatory Guide 3.46 "Standard Format and Content of License Applications, Including Environmental Report, for In Situ Uranium Solution Mining. NUREG-1569 identifies the NRC reviewer's proposed activities in reviewing a licensee submittal, specifically the areas of review, review procedures, acceptance criteria, evaluation findings and references. The ground-water issues in NUREG-1569 relate to ground-water quality restoration. The monitoring programs needed to assure ground-water quality restoration are discussed. The acceptance criteria for the ground-water quality are established based upon the background water quality prior to ISL mining and the governing EPA standards.

NUREG-1569 states that restoration goals are established in the application for each of the monitored constituents. The applicant has the option of determining restoration goals for each constituent on a well-by-well basis, or on a well field average basis. Restoration goals should be established for the ore zone and for any overlying or underlying aquifer that remains affected by ISL solutions. Performance measures for ISL sites can be classified into two groups; primary restoration goals and secondary restoration goals. For primary restoration standards, the primary goal for a restoration program is to return the water quality of the ore zone and affected aquifers to preoperational (baseline) water quality. It is unlikely that after restoration activities the ground-water quality will be returned to the exact water quality that existed at every location in the aquifer before ISL operations. Therefore, it is acceptable to use standard statistical methods to set the primary restoration goal and to determine compliance with it. At many sites, average parameters have been used to set primary restoration goals. It is also acceptable for the applicant to propose that the baseline conditions for each chemical species be represented by a range of concentrations. For example, a confidence interval of 99 is acceptable (i.e., there is only a one percent probability that the true baseline falls outside of the proposed restored water quality range). The reviewer shall ensure that statistical methods used to determine such confidence intervals are properly applied.

For secondary restoration standards since the ISL process requires changing the chemistry of the ore zone, it is reasonable to expect that ISL may cause permanent changes in water quality. For this reason, it is acceptable for the applicant to propose, as a secondary restoration standard, returning the water quality to its pre-ISL class of use (e.g., drinking water, livestock, agricultural, or limited use). Applications should state that secondary standards will not be applied so long as restoration continues to result in significant improvement in ground-water quality. It is acceptable to the staff if, on a constituent-by-constituent basis, secondary goals are determined by applying the lower of the State or EPA secondary and primary drinking water standards. For radionuclides not included in the drinking water standards, it is acceptable to determine, on a constituent-by-constituent basis, secondary standards from the concentrations for unrestricted release to the public in water, from Table 2 of 10 CFR Part 20, Appendix B.

If a ground-water parameter could not be restored to its secondary goal, an applicant could demonstrate to NRC that leaving the parameter at the higher concentration would not be a threat to public health and safety nor the environment, and that, on a parameter-by-parameter basis, water use would not be significantly degraded. Such proposed alternatives must be evaluated as a license amendment request only after restoration to the primary or secondary standard is shown not to be practical. This approach is consistent with the ALARA philosophy that is used broadly within NRC.

Uncertainties commonly encountered in the hydrologic analysis for Title I, Title II and ISL sites include both data, as well as, conceptual model uncertainties. The data uncertainties are similar to those encountered in ground-water quality monitoring programs (e.g., sampling methods, well screen location, and laboratory analysis). The uncertainties in the conceptual models are those encountered in the site characterization process, as well as, the process for determining model assumptions used in estimating input parameters, and data analysis of field tests (e.g., pump and pilot study tests) and compliance monitoring.

4 OBJECTIVE OF RESEARCH STUDY

The objective of this cooperative study is to examine uncertainties associated with estimates of net infiltration and ground-water recharge using near-continuous measurements of soil water content. These estimates were compared with discrete field data representative of datasets anticipated at nuclear facilities, e.g., infrequent soil water content measurements from neutron probes and groundwater levels. The focus is on examining uncertainties of the various values calculated from water budget approaches and changes in measured water contents. Specifically, these values are (1) drainage from the bottom of the profile, (2) total net infiltration[1], (3) infiltration rate, and (4) soil water content at which drainage occurs through to subsurface soil horizons. These values will be calculated using near-continuous measurements of water content, and compared with (1) values derived from less continuous measurements of water content, (2) values derived from less continuous measurements of water table height, (3) values derived from water budget models and use of indirect data such as infiltration rates and rainfall.

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[1] See Glossary for definition of terms (e.g. total net infiltration, infiltration rate, infiltration capacity, and effective porosity).

5 RESEARCH APPROACH

The research approach was to use near-continuous measurements of water content to estimate net infiltration and ground-water recharge. The near- continuous measurements on soil water storage and redistribution were obtained by a Multisensor Capacitance Probe (MCP) (Paltineanu and Starr, 1997) at 10-minute intervals. The MCP data are used specifically for water content profiling in this study. Water content profiles were used to estimate vertical fluxes and drainage from the bottom of the measured profile. We consider only vertical soil water content changes shortly before, during, and shortly after rainfall to estimate net water infiltration and subsequent ground-water recharge (as estimated by drainage from the bottom of the measured profile). Because of the nature of the site and the vertical water content profile estimates, components such as runoff and lateral subsurface flow do not enter into the calculations. During time periods around rainfall events, evapotranspiration, though not zero is small relative to total changes in soil water content, and can be neglected. Drainage between rainfall periods is generally small compared to the amount of water infiltrated during rainfall especially when there is a large amount of rainfall. Measurements of water content changes around a rainfall period can then be expected to capture most of the water that goes to ground-water recharge. This study was not intended to capture a complete water balance using the MCP data but to obtain site specific vertical fluxes and drainage components.

The technical approach was to analyze methods and their attendant uncertainties in estimating net infiltration leading to ground-water recharge. Table 1 provides the performance measure and intermediate values to be quantified in this research study. Figure 1 describes the use of near-continuous transient measurements to obtain the most realistic estimate of net deep percolation (q_4) and its contribution to ground-water recharge (q_w).

Table 1. Variables to be quantified when calculating ground-water recharge.

Intermediate values	Performance measure
net infiltration rate (q_1)	ground-water recharge (q_w)
infiltration capacity	
daily net infiltration	
net deep percolation (q_4)	

5.1 Methodology to estimate ground-water recharge

Ground-water recharge can be estimated using near-continuous measurements of the soil hydraulic state, (e.g. soil water content using capacitance probes) and from less frequent measurements using neutron probes or indirectly using water-table potentiometric observations. Alternatively 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 error may be introduced.

Table 2 provides a summary listing of field data sources, intermediate and final values of net infiltration estimates, and ground-water recharge (performance measure). Modeling parameter inputs that need to be measured or estimated are also listed.

Table 2. Data sources, and intermediate and final outputs for calculating ground-water recharge.

Field data sources	**Modeling parameter needed**	**Intermediate flux values from field data and simulation model**	**Final flux values from simulation model**	**Performance measure**
Soil water content (capacitance probe or neutron probe), rainfall and irrigation	*n/a*	*Net infiltration: rate, capacity, total infiltration*	*Best estimate of net deep percolation*[1]	*Best estimate of ground-water recharge*
Water table fluctuation, rainfall and irrigation	n/a	n/a	n/a	Estimate of ground-water recharge
Tension infiltrometer measurements, rainfall and irrigation	Measured conductivity (K_s, $K(\psi)$) at surface and estimated at depth, ET Surface slope, SCS Curves, Bulk density	Infiltration: rate, capacity, total	Net deep percolation	Estimate of ground-water recharge
Effective porosity	Estimated conductivity (K_s, $K(\psi)$) at surface and at depth ET Surface slope, SCS Curves, Bulk density	Infiltration: rate, capacity, total	Net deep percolation	Estimate of ground-water recharge

There are two kinds of ground-water recharge estimation approaches, transient and steady state. Steady state approaches typically use an annual or monthly water balance or use average soil state conditions and properties. Figure 1 portrays the conceptualization of the steady state approach for calculating the fluxes in the near surface (q_1), at non-intervening depths ($q_{2\text{-}4}$) and ultimately at the water table (q_w). Note that the flux calculation horizons correspond to the capacitance or neutron probe measurement horizons. This study uses near-continuous (i.e., transient) data to estimate ground-water recharge with the premise that significant recharge events take place during relatively short time periods when the soil is near saturation and corresponding flux rates are large. Hence the transient approach is believed to capture these processes. To use the transient approach to estimate net ground-water recharge, we have quantified the intermediate values listed in the first row of Table 2. The field data sources and analysis used are identified in row 1. As presented earlier, Figure 2 depicts the transient strategy. Table 3 lists components of the transient and steady-state analysis approaches. The steady-state approach uses estimated, long-term, and aggregated values for input. In contrary, the transient approach uses either directly measured or estimated values for input.

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[1] For the purpose of this study, deep percolation is defined as the loss of water from the layers with the MCP sensors and is considered an approximation of ground-water recharge.

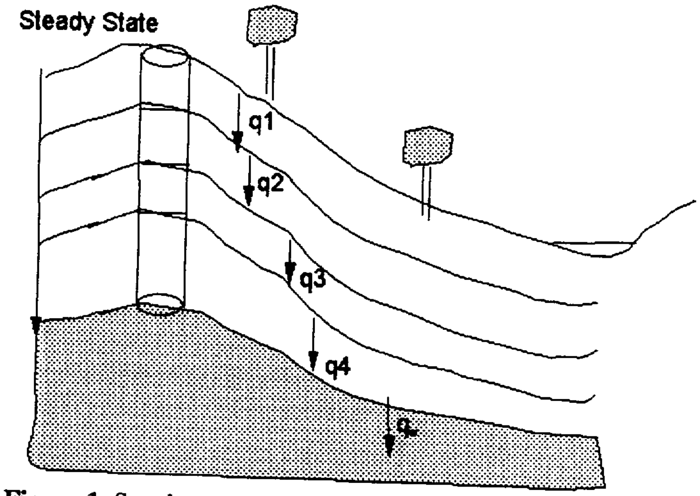

Figure 1. Steady state analysis approach. In this approach $q_1=q_2=q_3=q_4$.

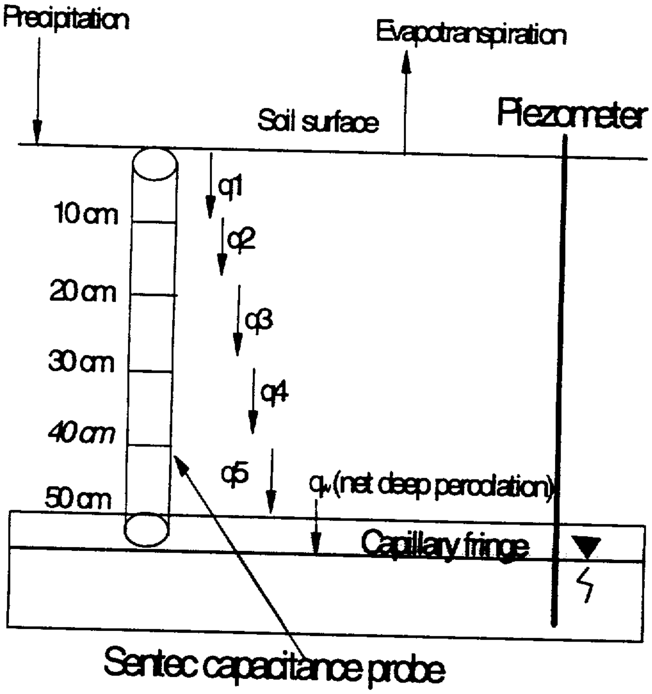

Figure 2 Depiction of transient approach using moisture capacitance probe data. *Water content at 40 cm has been interpolated from 30 and 50 cm measurements.* Here $q_1<>q_2<>q_3<>q_4<>q_5$.

Table 3. Comparison of Transient and Steady-State Approaches.

Transient Approach	Steady-State Approach
1. Detailed Meteorological Data (Rainfall for 15 minutes, other data on an hourly basis)	1. Constant long-term meteorological data using aggregate rates on a yearly basis
2. Soil properties (e.g., ψ-θ, or K-θ, K-ψ) measured or estimated from UNSODA, Rawls or Ahuja databases Estimations methods - soil texture - soil water content measurements - soil type	2. Estimated or aggregate soil properties for inputs (mean to maximum values of hydraulic parameters, average initial soil water content) UNSODA, Rawls or Ahuja databases Estimations methods - texture - water content measurements - soil type
3. Landform characteristics	3. SCS curve numbers for estimation of local runoff
4. Model selection based on level of confidence desired/inputs available - direct field data	4. Model selection appropriate for regional analysis (aggregated information) where local information not available
5. Calculate q_w, q_{1-4}, directly or using estimated input values collected at the same time scale as the meteorological data. Compare q_w to q_{1-4} to determine nature of events that result in ground-water recharge	5. Estimate q_w on an average, yearly basis

The field data sources identified in the first row of Table 2 provide the desired databases for the approaches listed in Table 3. These data allowed comparisons of ground-water recharge estimates using near-continuous water contents to recharge estimates based on less frequent water content observations (e.g. hourly or daily). Estimates of ground-water recharge using near-continuous measurements were also compared to more uncertain estimates of ground-water recharge using intermittently measured piezometric data or analytical models. These comparisons include analyses for a range of soil conditions and properties. Uncertainty methods from Meyer et al. (1997) can be applied to these data and the ground-water recharge estimates.

Table 4 lists the methods utilized to (1) measure infiltration rates and their inherent variability, and (2) estimate ground-water recharge. Table 5 provides a listing of datasets used in the calculation methods presented in Tables 2-4. Ground-water recharge estimated from the intensive capacitance probe measurements of soil water content are considered a direct estimate of transient ground-water recharge (for comparison purposes). This research generated values of probability and amounts of ground-water recharge for each rainstorm period and sensor location using this data. Further, amounts of ground-water recharge were generated using the other methods listed in Table 2. Comparisons of these probabilities constitute uncertainty estimates. These study results provide a distribution of ground-water recharge occurrences and amount. These probability distributions for the different methods can then be compared using statistical procedures.

Table 4. Methods to Measure Infiltration Rates and Their Variability.

Plot scale- point values			Aggregated and distributed values	
Direct measurement	**Indirect measurement**	**Methods using real-time hydro-meteorological data**	**Methods of aggregation and distribution**	**Methods of determining uncertainty**
Ponded infiltrometers	Using effective porosity to determine mean infiltration rate	Soil water distributions with time	Grouping by soil property (e.g., bulk density, pore size distribution, soil taxonomic class)	Classify variability according to identifiable soil properties and conditions (e.g., soil texture, climate, land use)
Ponded/tension infiltrometer		Changes in potentiometric levels	Determination of scaling factors	Use of scaling factors to assess uncertainties (Hopmans, 1987)

5.2 Legacy Data

The datasets listed in Table 5 include: a near-continuous, real-time record of soil moisture with depth using the capacitance probe; a discrete, specified time record of soil water content with depth using the neutron probe; a discrete record of water-level fluctuations in the shallow-water table; and continuous real-time precipitation and evaporation data. Sixteen multisensor capacitance probes (MCPs) and water monitoring system data have been collected across a 0.5 ha field site from 1995 through 1997, with the plot layout with instrumentation presented by Starr and Paltineanu (1998). During these three years, nine piezometer wells were manually monitored throughout the year. The following table provides a listing of measurement techniques, measurements made, and time period for the ARS database.

Information needs and appropriate analysis methods have been identified through review of appropriate ARS and NRC-contractor reports related to infiltration estimates, and are provided in Wierenga, et al., 1993; Meyer et al., 1996; Smyth et al., 1990; Young et al., 1996; and Ahuja and Garrison, 1996. Information on available infiltration databases is provided by Frasier (1996). The information is available in spreadsheets along with the data used in this study from the National Agriculture Library of the USDA under the title *Infiltration Uncertainty Datasets*

5.3 Data from Current Field Studies

Figure 3. shows the layout of the field experiment with plot locations. The MCP's were located in plots 3 - 6 and 21 - 24 as indicated by brackets in Figure 3.

Table 5. Status of ARS Datasets for Estimation of Uncertainties Associated with Infiltration Calculations.

Measurements	1993	1994	1995	1996	1997
Bulk Density 3" core	1-4, 4-7" BDJune93.				
Soil Texture 2" cores	✓				
Infiltration: Ponded (30cm): P-Tension(10cm)	✓ 5 times Jun-Nov	✓ 4 times Jun-Nov	✓ 3 times Jul-Nov	✓ 2 times Jun-Oct	
Capacitance Probes			✓	✓	✓
Piezometer (10)			✓	✓	✓
Weather Station	✓	✓	✓	✓	✓

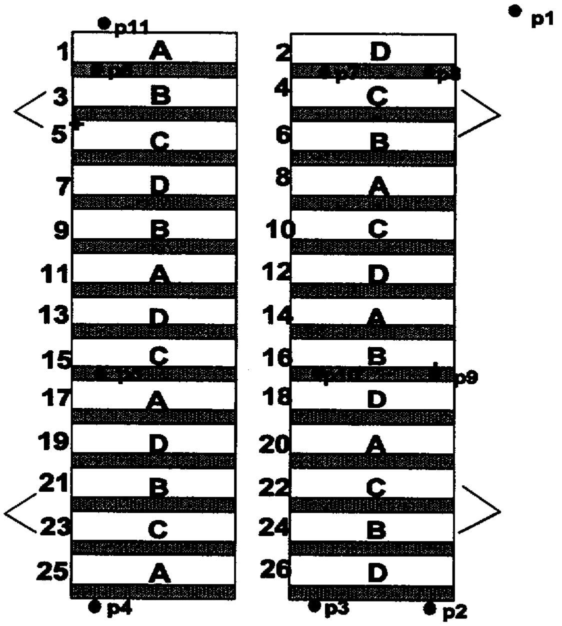

Figure 3. Layout and plot locations for the field studies.

Table 6. Description of treatments at the locations of the MCP sensors.

Treatment	Row location[1]	Tillage[2]
IN26	Row	Plow
IN36	Row	Plow
IN64	Row	No Till
IN74	Row	No Till
NT22	Interrow	No Till
NT23	Interrow	No Till
NT4	Interrow	No Till
NT5	Interrow	No Till
PT21	Interrow	Plow
PT24	Interrow	Plow
PT3	Interrow	Plow
PT6	Interrow	Plow
TR16	Traffic interrow	Plow
TR46	Traffic interrow	Plow
TR54	Traffic interrow	No Till
TR84	Traffic interrow	No Till

[1] Refers to location of probe, either in the plant row (Row) or in between plant rows (Interrow)
[2] Refers to tillage method. In NoTill the seed is drilled into the soil covered by residue of the previous crop.

5.4 Analytical Methods Used To Estimate Net infiltration

Information on available analytic methods for estimating net infiltration are described in Meyer et al., 1996; Smyth et al., 1990; and Ahuja and Garrison, 1996. There are a variety of analytical methods and simulation models which are available to calculate net infiltration (Meyer et al., 1997; Timlin et al., 1997; Rawls et al., 1983; and Rawls and Brakensiek, 1985). The selection of the analytic model or simulation code is based upon required detail for input and output, input data available, spatial scale, and reliability. Table 7 lists examples of available models. The EPA models listed in Table 7 are used in a steady state mode, all other models can be used in either steady state or transient mode.

Table 7. **Models to Estimate Net infiltration Using Measured or Estimated Parameters.**

Empirical equations and models	One-Dimensional numerical models	Multi-dimensional numerical models	Models with Uncertainty
Water balance	HELP, Transient Water Budget Model	2DSOIL SWMS2D	PNNL Model
Rawls' Green-Ampt models	1DSOIL		
Fayer and Jones (1990)	UNSAT-H		
EPA Models	SCS Model, Philip's Two-Term Model, Green-Ampt Models (Layered, Explicit, Constant flux, Infiltration/Exfiltration model (MathCad 6.0 Models) (See EPA Website http://www.epa.gov/ada/ninflmod.html for more information)		

The investigators have examined the available ARS field data sets from the capacitance probe studies at BARC and are selecting specific data sets for calculating; (1) total net infiltration [i.e., daily (or event), monthly and annual], (2) infiltration rate, (3) infiltration capacity, and (4) effective porosity. The focus is on selecting portions of the available data sets (i.e., capacitance probe, neutron probe and water level) appropriate for estimating uncertainties as derived from comparisons of the various calculated infiltration and effective porosity values. The data sets selected are documented as appendices.

5.5 Screening of Available Datasets with Respect to Analytical Methods Identified

The ARS investigators have screened available datasets for appropriate values to calculate time and space variability of infiltration and organized datasets from the weather station, piezometer, neutron probes, capacitance probes (Sentek data for daily and hourly measurements). An example of the data layout for the piezometer database and partial listing is in Table 8 and the MCP database in Table 9. The file names of the databases and a short description is given in Table 10. All data are available as SAS® libraries or Microsoft Access® databases from the National Agriculture Library of the USDA under the title *Infiltration Uncertainty Datasets* for those interested in retrieving and working with the raw data. SAS libraries were used for the capacitance probe data because of the large sizes and the need for post processing.

Table 8. Example of Piezometer data base . The column headings indicate piezometer location, units are cm from the land surface to water table. The full data set is available as a computer readable file.

Date	Cumulative time	Day of year	At Weather Sta	26A	26C	25A	15-17A	1-3A	2-4C	2-4A	16-18A	16-18	1A
4/18/1994	108	108	-87	-110	-103	-160	-133	-167	-108	-126	-104	-91	
4/20/1994	110	110	-100	-117	-107	-162	-150	-173	-144	-124	-110	-105	
4/21/1994	111	111	-103	-120	-109	-163	-151	-174	-145	-126	-110	-106	
4/22/1994	112	112	-105	-125	-111	-163	-160	-176	-145	-126	-113	-106	
4/27/1994	117	117	-118	-155	-125	-167	-180	-182	-159.5	-128.5	-113	-107	
5/6/1994	126	126	-143	-182.5	-159		-198	-191	-172.5	-135.5	-117	-115	
5/10/1994	130	130	-147	-188.5	-157		-197	-196	-177.5	-136.5	-116	-120	
5/16/1994	136	136	-153	-192.5	-165		-202	-194	-177.5	-134.5	-117	-120	
5/24/1994	144	144	-177	-198.5	-187		-210	-205	-185.5	-140.5	-118	-130	
5/31/1994	151	151	-181	-200.5	-187		-217	-211	-188.5	-153.5	-117	-135	
6/8/1994	159	159	-190	-202.5	-189		-219	-216	-198.5	-155.5	-119	-139	

Table 9. Example of the MCP data file (YR1995). SEC is time into the day as hour:min:sec(e.g., 193544=19:35:44), THETA is soil water content (mm), DEPTH is location of sensor (cm), TRT is treatment, SEASON corresponds approximately to 1-winter, 2- spring, 3- summer, 4- fall, and LAB is a label for one of the two dataloggers (micro, macro).

DAY	SEC	TIME	THETA	TRT	DEPTH	SEASON	LAB
172.	193544.	172.8165	41.30	IN26	50.	2.	micr
172.	193544.	172.8165	27.24	IN26	20.	2.	micr
172.	193544.	172.8165	37.96	IN26	30.	2.	micr
172.	193544.	172.8165	17.42	IN26	10.	2.	micr
172.	193545.	172.8165	37.96	IN26	30.	2.	micr
172.	193545.	172.8165	17.42	IN26	10.	2.	micr
172.	193545.	172.8165	27.235	IN26	20.	2.	micr
172.	193545.	172.8165	41.296	IN26	50.	2.	micr
172.	193645.	172.8172	17.421	IN26	10.	2.	micr
172.	193645.	172.8172	41.296	IN26	50.	2.	micr
172.	193645.	172.8172	37.956	IN26	30.	2.	micr
172.	193645.	172.8172	27.235	IN26	20.	2.	micr
172.	193745.	172.8179	37.956	IN26	30.	2.	micr
172.	193745.	172.8179	27.235	IN26	20.	2.	micr
172.	193745.	172.8179	41.296	IN26	50.	2.	micr
172.	193745.	172.8179	17.415	IN26	10.	2.	micr

Table 10. Databases available from the National Agriculture Library. Listing and descriptions of variables are available in the database. (Files with extensions *mdb* files are Microsoft Access, *sd2* extensions are SAS libraries).

File name	Description	Variables
Weather.mdb Weather.sd2	Meteorological Data	Date, radiation, temperature, humidity, vapor pressure, wind speed, rainfall
NeutronP.mdb NeutronP.sd2	Neutron Probe Data	Date, location, water content
YR1995.MDB YR1996.MDB YR1995.SD2 YR1996.SD2	Capacitance probe data for 1995-1996.	Day of year, time of day, water content, treatment, depth, season and data logger.
Infiltrometer.mdb Infiltrometer.sd2	Ponded and tension infiltrometer measurements	Date, plot, hydraulic conductivity at saturation and near saturated hydraulic conductivities.

Table 11. Methods used to calculate net infiltration and drainage using the ARS Datasets. Theta refers to the value of water content measured by the moisture capacitance probe (MCP).

	Method			
Value	MCP	Neutron (measures before and after rainfall)	Piezometer	Tension Infiltrometer
Infiltration rate (IR)	$(\text{theta}_{i-1}-\text{theta}_i)/(\text{time}_i-\text{time}_{i-1})$ (sum in profile)	rainfall rate[1] - runoff estimate (curve number)	n/a	rainfall rate - runoff estimate (curve number)
Infiltration capacity	max of IR	from Ks	n/a	direct
Cumulative net infiltration (cumIR)	Sum of positive changes in theta for profile	sum of measured water content (with rainfall and Ks)	n/a	rainfall +Infiltration rate
Effective porosity	theta_{max}-theta drained (24 hours after rainfall)	from saturated water content - drained water content	n/a	n/a
Net deep percolation	sum of negative changes in theta for profile	same (with rainfall)	n/a	from cumulative net infiltration
Ground-water recharge	from above	from above	measure	same as above

[1] Grey scale indicates where indirect estimates require additional information on soil hydraulic properties.

5.6 Calculation of Net infiltration Values

Table 11 provides a listing of the methods useful for calculating net infiltration values using available field data (e.g., ARS field database). These methods are appropriate for calculating: (1) total net infiltration [i.e., daily (or event), monthly and annual]; (2) infiltration rate; (3) infiltration capacity; and (4) values of effective porosity to predict infiltration rate; and for determining the use and distribution of effective porosity as a method to quantify the spatial and temporal variability of saturated conductivity and infiltration rates. The focus of this study is on calculating values that are sufficiently detailed to facilitate estimation of uncertainties using comparisons of the various calculated net infiltration and drainage values (see Tables 4 and 6) using MCP and piezometer data from the extensive ARS database. The ARS database includes temporal and spatial distributions of soil water contents obtained from capacitance probe and water level measurements; and temporal and spatial distributions of the direct infiltration measurements. Both the calculations and methods used are summarized in the appendices where the program listings are given.

6 UNCERTAINTY ESTIMATION PROCEDURES AND RESULTS

6.1 Meteorological Data

Table 12 summarizes the real-time rainfall data base and Table 13 shows the structure of the rainfall database and partial listing of the rainfall data.

Table 12. Summary of real-time rainfall data for 1995 to 1996. The data is summarized by season and the time period for each season is also given.

Year	Season	First day of season	Rain (mm)
1995	1	1	435.6
	2	173	169.9
	3	216	260.9
	4	273	382.3
	Total		1248.7
1996			
	1	1	216.4
	2	92	244.3
	3	167	684.2
	4	293	354.8
	Total		1499.8

Table 13. Real-time rainfall data for 1995. This shows the first part of the file. TimeRn is the decimal form of the time. Rain is in mm.

Day	Hour	TimeRn	Rain (mm)	Season
172	1350	172.58	0.130	2
172	1400	172.58	0.130	2
173	2310	173.97	0.130	2
173	2320	173.97	0.380	2
173	2330	173.98	0.250	2
173	2340	173.99	0.130	2
173	2350	173.99	0.760	2
173	2400	174.00	0.640	2

6.2 Calculations Using Measured Water Contents

The objective of the this analysis was to investigate the loss of information regarding ground-water recharge that results from sampling at less frequent intervals. The loss is evaluated by comparing probabilities of recharge events and recharge amounts calculated from water contents sampled at large time intervals (1 hour or 24 hours). The comparison was to values calculated from water contents sampled at 10-minute intervals.

The MCP database was checked for errors and missing data. Each yearly database was subdivided into four quarters approximating winter, spring, summer and fall. This was partially done to make the file sizes more manageable. All the calculations were carried out using SAS (SAS, 1997). The time periods for the quarters (seasons) are given in the partial rainfall listing Table 12. A SAS program was used to separate the water contents for the profile from one column of data to 5 columns, one for each water content. Since the water contents were measured at 10, 20, 30 and 50 cm (4, 8, 12, and 20 in), an interpolated value was calculated for 40 cm (16 in) as the average of the water contents at 30 and 50 cm. This provided for uniform thicknesses of layers.. Water contents were also summed over depths to provide a "profile water content". The sums were cumulative with depth, ie the first sum included only the soil with the first sensor (10 cm), the second sum included sensors 1 and 2 [i.e., to 20 cm (8 in)] and so on. The SAS program also broke up the files into individual files that included only a single treatment. Rainfall data were merged with the SAS data sets containing the MCP data. The SAS programs are given in the Appendices (2 thru 15).

Figure 1 shows the locations of the sensors for the moisture capacitance probe (10, 20, 30 and 50 cm or 4, 8, 12, and 20 in). 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 (0-50 cm or 20 in, Fig. 1) using the methodology given in table 4. The water content at 40 cm was interpolated from the 30 and 50 cm measured water contents to provide even depth increments for the calculations.

Rainfall events and 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 rain to the next time with rain that was at least 24 hours after the previous rain (Fig. 4). This screening procedure was carried out within SAS by calling the FORTRAN program "*ClassRn.for*" (see Appendix 2). The program "*ClassRn.for*" classifies the rainfall events by rainfall occurrence as shown in Figure 4.

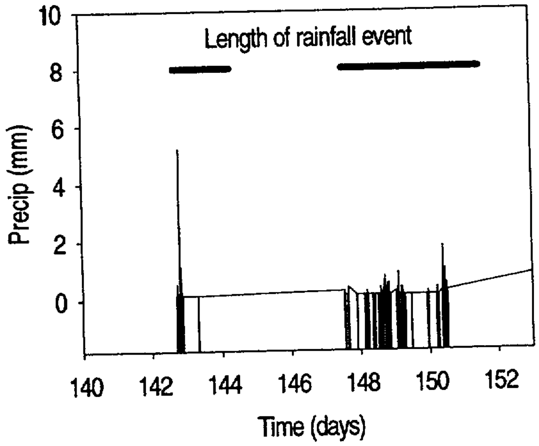

Figure 4. Schematic of method for discriminating rainfall events. This figure shows two discrete rainfall events have been classified.

Each potential recharge period was given an ID (*rainid*). The ID's were numbered consecutively for each recharge period. All the rainfall events were screened to eliminate trace rainfall events with less than three 10-minute periods with insignificant rainfall (less than 0.5 mm). This allowed us to group calculations according to a recharge event ID. Using the ID's as group indicators in SAS, cumulative net infiltration values were calculated for each recharge period.

Cumulative net infiltration was calculated for each recharge period by differencing the 10-minute summed water content measurements for the profile (to 50-cm depth) (see Figure 1) and summing the positive differences over the recharge period. Tables 14a and 14b show the first part of the measured and calculated data from one treatment in one of the database tables. The database table is split into two parts so it can be viewed on two pages.

Table 14a. Calculated data from the MCP database. THETA1, THETA2, etc are water contents (mm) at the depth of the sensor (10, 20, 30, and 50 cm). THETAD5 is the sum of THETA1 to THETA5. THETA4 is an average of depths 30 and 50 cm.

TRT	DAY	SEC	TIME (days)	THETA1	THETA2	THETA3	THETA4	THETA5	THETAD5
IN26	182.	152241.	182.640752	26.068	33.300	40.870	41.661	42.453	184.352
IN26	182.	153241.	182.647697	26.044	33.300	40.870	41.661	42.453	184.328
IN26	182.	154241.	182.654641	26.028	33.291	40.870	41.661	42.453	184.303
IN26	182.	155241.	182.661586	26.003	33.300	40.880	41.667	42.453	184.304
IN26	182.	160241.	182.66853	25.979	33.300	40.880	41.672	42.464	184.296
IN26	182.	161241.	182.675475	25.963	33.291	40.890	41.677	42.464	184.286
IN26	182.	162241.	182.682419	25.939	33.291	40.890	41.677	42.464	184.262
IN26	182.	163241.	182.689363	25.923	33.282	40.890	41.672	42.453	184.221
IN26	182.	164241.	182.696308	25.907	33.291	40.880	41.672	42.464	184.215
IN26	182.	165241.	182.703252	25.883	33.273	40.880	41.672	42.464	184.172
IN26	182.	170241.	182.710197	25.867	33.264	40.880	41.672	42.464	184.147
IN26	182.	171241.	182.717141	25.851	33.264	40.890	41.677	42.464	184.147
IN26	182.	172241.	182.724086	25.835	33.264	40.890	41.677	42.464	184.131
IN26	182.	173241.	182.73103	25.811	33.255	40.890	41.677	42.464	184.098
IN26	182.	174241.	182.737975	25.795	33.245	40.890	41.677	42.464	184.073
IN26	182.	175241.	182.744919	25.779	33.245	40.890	41.677	42.464	184.057
IN26	182.	180241.	182.751863	26.052	33.282	40.911	41.704	42.497	184.446
IN26	182.	181241.	182.758808	26.277	33.264	40.901	41.693	42.486	184.621
IN26	182.	182241.	182.765752	26.423	33.264	40.890	41.688	42.486	184.751
IN26	182.	183241.	182.772697	26.528	33.245	40.890	41.688	42.486	184.838
IN26	182.	184241.	182.77964	26.593	33.245	40.890	41.694	42.497	184.920

Table 14b. Second part of calculated data from MCP data. LAB is a label for the Sentek data logger, there were two dataloggers, *micro* and *macro*. RAIN is rainfall in mm, RAINID is the ID for the rainfall period, CUMR is the cumulative rainfall (mm) for the period defined by RAINID, and PCUMI is the cumulative net infiltration for the period defined by RAINID.

TIME	SEASON	LAB	RAIN (mm)	RAINID	CUMR (mm)	PCUMI (mm)
182.640752	2.	micr	0.127	3.	0.	0.000000
182.647697	2.	micr	0.127	3.	0.254	0.000000
182.654641	2.	micr	0.254	3.	0.635	0.000000
182.661586	2.	micr	0.254	3.	0.889	0.001459
182.66853	2.	micr	0.	3.	0.635	0.000730
182.675475	2.	micr	0.	3.	0.635	0.000730
182.682419	2.	micr	0.	3.	0.635	0.000730
182.689363	2.	micr	0.	3.	0.635	0.000730
182.696308	2.	micr	0.	3.	0.635	0.000730
182.703252	2.	micr	2.032	3.	4.699	0.000730
182.710197	2.	micr	2.032	3.	6.731	0.000730
182.717141	2.	micr	0.381	3.	5.461	0.000730
182.724086	2.	micr	0.508	3.	6.096	0.000730
182.73103	2.	micr	0.127	3.	5.842	0.000730
182.737975	2.	micr	0.	3.	5.715	0.000730
182.744919	2.	micr	0.	3.	5.715	0.000730
182.751863	2.	micr	0.	3.	5.715	0.779488
182.758808	2.	micr	0.	3.	5.715	0.740619
182.765752	2.	micr	0.	3.	5.715	0.825256
182.772697	2.	micr	0.	3.	5.715	0.869690

An objective of this work was to compare estimates of ground-water recharge by several methods, especially the MCP probe. Since the MCP probes were only installed to 50 cm depth, movement of water below this depth could not be observed. Therefore, for the purpose of this work, movement of water below 50 cm was defined as ground-water recharge. 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 content over time.

Drainage below a certain depth in a soil profile can be calculated from a mass balance DR=I-RO-ET-ST where DR is drainage, I is infiltrated water, RO is runoff, ET is evapotranspiration and ST is storage. For the site in this study there were no direct measurements of runoff though it was rarely observed. There were also no measurements of actual ET other than the MCP measurements. ET could not easily be separated from the estimates of infiltration and drainage. In order to minimize the effect of ET, short periods during rainfall were chosen where ET rates were expected to be low relative to drainage and infiltration. Hence for rainfall periods the mass balance equation could be reduced to DR=I-ST.

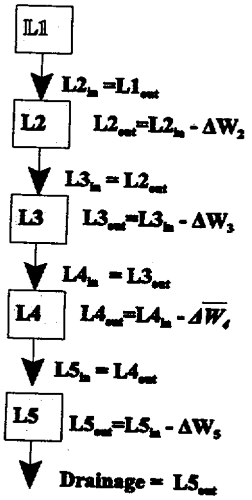

Figure 5 Schematic of calculation of drainage below 50 cm using individual layer mass balance approach

We considered five methods of calculating drainage below 50 cm. The first was based on the mass balance equation given above. Except for infiltration, only water contents at the beginning and end of the rain period are used for the mass balance method. The soil water storage for a rain event is calculated as the soil water content 24 hours after rainfall ended minus soil water content when rainfall was first recorded. This gives the total amount of water that was stored in the profile after each rain event. This storage has been summed over all the rain events to produce the value given in Table 15. This was water captured by the soil and available for plants but not significantly drainable. Net infiltration (Table 15) was calculated by summing all the positive changes in water content over a rainfall period. This net infiltration value probably underestimates true infiltration since some water movement takes place when the soil is wet and water content does not change to reflect the true water movement. This occurs during rainfall when drainage water is leaving the profile at the same time rain water is entering the profile. Evapotranspiration during the rainfall period may also reduce this value.

The second, third and fourth methods use different methods of summing 10 minute water content data to calculate drainage (columns labeled 2, 3 and 4 in Table 15). The second method was based on summing all negative changes (losses) in water content in the profile during a rainfall period. The third method was based on a layer by layer mass balance approach. A schematic of this method is shown in Figure 5. Here the amount of water entering a layer is equal to the amount leaving the layer above. The amount of water leaving a layer is calculated as the amount coming in (i.e., $L2_{in}$) minus the change in water content over a time period (ΔW - mm). The fourth method uses only changes in water content over time for the bottom layer (layer 5).

The fifth method uses the 'field capacity' concept (column labeled 4 in Table 15). Here field capacity is defined as a drained water content below which the hydraulic conductivity is small such that significant water movement does not occur. This value is estimated from the profile water content (sum of water contents for profile) 24 hours after rainfall ceases. These values are accumulated for all the rainfall periods then sorted from maximum to minimum. The lowermost value in the top one third of the distribution is chosen as the 'field capacity value' (see appendices 10 and 11). Net ground-water recharge is calculated by adding rainfall to the water content at the beginning of the rainfall period until field capacity is reached. The remaining water becomes drainage. This is formulated as FC-($P+TH_i$) where TH_i is initial profile water content. Only positive results are retained.

A comparison of the results of these different methods to calculate net recharge is given in Table 15. The three methods that use the profile data [drainage by profile mass balance, drainage by summation of negative changes, and drainage by layer mass balance (2,3 and 4)] gave consistent results. The use of field capacity gave results similar to the previous 3 methods though the variability was greater. The differences were not consistently smaller or larger. The three methods using negative differences in water content can over estimate net recharge when evapotranspiration is occurring over the rainfall period. The possible contribution from evapotranspiration can be as much as 5 to 8 mm per day but is usually less if there are clouds. Net recharge can be underestimated if water movement is occurring under steady state conditions in which case differences in water content will not reflect total water flow. On the other hand, use of field capacity can have errors if the net infiltration is different from precipitation as is the case for this site. Net infiltration can be more or less than precipitation at this site as shown in Table (15). This is because plant canopies can capture rainwater and result in a 'funneling' effect around the plant stem (Quinn and Laflen, 1983). Treatments with 'IN' in the label (Table 6) have sensors installed in the row and hence may reflect greater net infiltration than rainfall. Errors in estimation of 'field capacity' can also cause a consistent bias in net recharge estimations. However, calculations in this dataset using a field capacity value based on dynamic data should result in less error than results based on a field capacity estimated from soil texture or from soil water content at a particular soil water martric potential.

If we knew the flux through layer 5 we could calculate drainage to groundwater using information from that layer only. However, we only know water content. The use of only the bottom layer (layer 5) water content resulted in gross underestimation of drainage. This is because layer 5 is often at or near steady state so the amount of water going into the layer is close to the amount going out and the water content does not vary greatly. However, by using data from more layers more of the water passing through the profile can be accounted for. Calculations using the MCP data still cannot account for all the water passing through the profile when the soil is near saturated, however.

As was mentioned previously, total net infiltration was usually less than total rainfall (Tables 14b and 15). In some cases, however, the infiltrated water was greater than rainfall as in the locations where sensors were installed in row positions (IN and TR treatments). Here plant canopy interception of rainfall can increase the total rainfall intercepted by an area of soil (Quinn and Laflen, 1983). The two mass balance methods and the negative summation method give similar results for drainage past 50 cm (20 in). The negative summation method falls between the other two mass balance methods. The profile mass balance method is only useful, however, during periods close to rainfall events when ET is assumed to be minimal and soil water storage after rainfall can easily be defined.

The negative summation method was chosen to estimate drainage of water from the soil profile as a representation of ground-water recharge (bold column in Table 15). The negative summation method for the profile is the most direct method to estimate drainage for data measured over periods longer than 1 day. Another advantage of the negative summation method is that internal fluxes tend to cancel each other out since summation of water contents over the profile is used. To minimize the errors due to unknown evapotranspiration over longer time periods, calculations of drainage are discontinued when the water content of the lowermost layer reaches a set water content. This drained water content corresponds to the water content where changes in water content become small, usually 24 hours after a significant rainfall event. The SAS macro in Appendix 8 finds this value. All the methods incorporate some error.

Table 15. Comparison of different methods of calculating drainage from 0-50 cm layer. The water content data come from seasons 2 and 3 of 1995. Note that there may be slight differences in total rainfall among treatments if there were missing data during a rainfall event for a particular treatment. Total storage refers to the amount of water stored in the profile during a rainfall event calculated as the difference between the water content at the end of the rainfall period and the water content at the start of rainfall. This is summed over the seasons for a total storage. The numbers in parenthesis refer to the method by which the value was calculated (see text).

Treat-ment	Total rainfall	Total storage of infiltrated water	Total net infiltration	Drainage by profile mass balance (1)	**Drainage by summation of negative changes (2)**	Drainage by layer mass balance (3)	Drainage from changes in layer 5 alone (4)	Using field capacity and rainfall (5)
	------------------mm------------------							
IN26	428.8	221.6	336.2	114.6	**84.8**	89.6	15.3	128.7
IN36	428.8	238.6	418.5	179.9	**120.8**	125.2	15.0	100.8
IN64	428.8	193.7	423.7	230.0	**204.0**	207.2	16.7	162.5
IN74	428.8	227.0	590.4	363.4	**363.3**	367.4	17.0	125.5
NT22	430.0	172.5	296.2	123.7	**148.9**	151.4	14.2	133.9
NT23	430.0	182.2	269.7	87.5	**98.4**	101.0	16.4	124.3
NT4	430.0	166.8	329.1	162.3	**176.5**	182.4	11.2	164.5
NT5	430.0	272.3	390.9	118.6	**118.6**	122.0	16.8	152.0
PT21	430.0	210.9	290.1	79.2	**105.2**	109.6	13.8	108.2
PT24	430.0	138.4	186.6	48.1	**51.6**	54.0	23.7	138.4
PT3	430.0	254.9	389.8	134.9	**127.6**	131.2	10.6	85.4
PT6	430.0	153.8	235.4	81.7	**100.1**	104.6	12.5	123.1
TR16	428.8	259.8	407.6	147.8	**147.8**	163.2	11.4	133.4
TR46	428.8	169.1	235.3	66.2	**62.7**	69.5	9.8	152.2
TR54	428.8	86.4	166.4	80.0	**80.0**	89.8	24.5	216.0
TR84	428.8	176.0	354.1	178.1	**178.1**	183.8	12.4	171.7

One objective of this work was to estimate uncertainty in ground-water recharge when sampling frequency is decreased. Estimates of ground-water recharge for different measurement frequencies can be obtained using MCP data that have been sampled from the 10-minute data set at hourly and daily intervals. In order to sample enough water contents for the 24 hour interval the *rainid* had to be extended to include all times to the next rainfall. Normally drainage calculations are only carried out for 24 hours after the last rainfall. In order to minimize error due to inclusion of the unknown evapotranspiration, drainage was not calculated if the water content in the lowest [50 cm - (20 in)] layer fell below a "drained" water content. The drained water content was calculated as the minimum water content 24 hours after rainfall during seasons 1 and 4 when evapotranspiration was minimal (see Appendix 8). The sampled infiltration rates were saved in separate files.

Probabilities of drainage out of the 0-50 cm (20 in) layer were also calculated. Not all rainfall events would result in drainage past 50 cm. If cumulative drainage past 50 cm was more than 3 mm during a potential recharge period, this constituted an actual recharge event. Probabilities of recharge were calculated as the total periods with recharge divided by the total number of rainfall (recharge) events. These results are given in Figure 6. The seasons correspond to 1- winter, 2- spring, 3- summer, 4- fall, Table 12 gives corresponding days of year. Note that the estimated total ground-water recharge decreases when sample interval for water content increases from 10 minutes to 1 hour. The decrease in estimated recharge is greater when sampling interval increases from 1 hour to daily. Total estimated recharge varies by season and year. The total rainfall was 125 cm (49.2 in) in 1995 [81.5 cm (32.1 in) for seasons 2-4] and 150 cm (59 in) in 1996. The total rainfall was higher in 1996 than in 1995 as was the total ground-water recharge. The total estimated drainage going to ground-water recharge for seasons 2-4 in 1995 was 34.6 cm (13.6 in) and 74.6 cm (29.3 in) in 1996. Estimated recharge is about one half rainfall. Note also that in this area (Beltsville, MD, USA) the amount of recharge is typically the highest in the fall to winter periods mainly due to large scale storm events such as hurricanes and Northeasters.

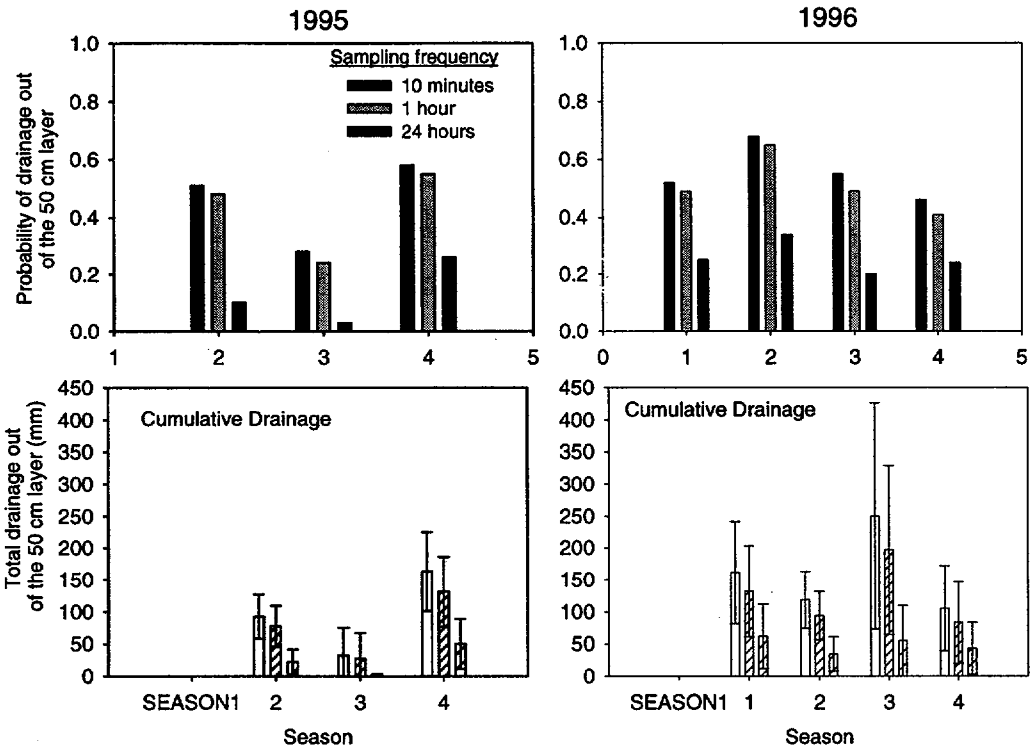

Figure 6. Estimated probabilities of ground-water recharge and amount as a function of sampling interval for the 1995 and 1996 MCP data. Seasons refer to winter-early spring (1), late-spring (2), summer (3) and late fall-early winter (4) (vertical lines for cumulative drainage represent the variability among the various treatments described in Table 6).

The reason for the these differences in recharge based on sampling interval is due to the characteristics of rainfall. Figure 7 shows cumulative precipitation and net infiltration along with infiltration rate during a rainstorm in 1996. Rainfall rate changes over small periods of time (here 10 minute periods are shown). In this example, sampling at intervals larger than 10 minutes may miss the peak in infiltration rate between 79.6 and 79.7 days.

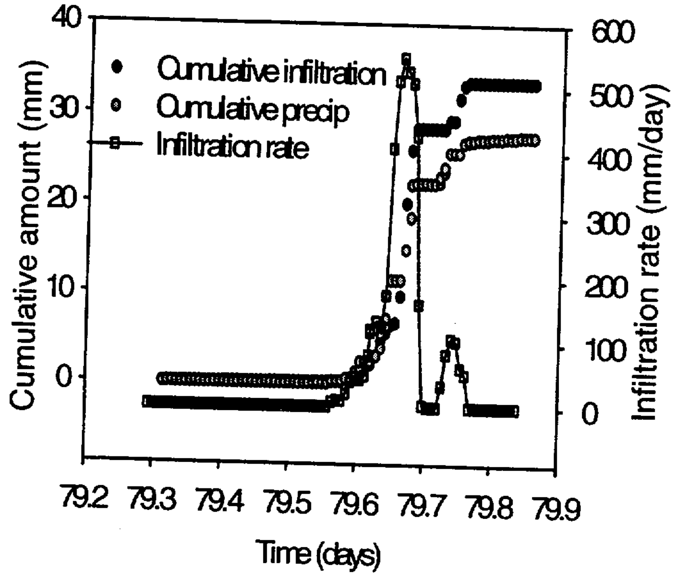

Figure 7. Cumulative precipitation and infiltration, and infiltration rate during rain.

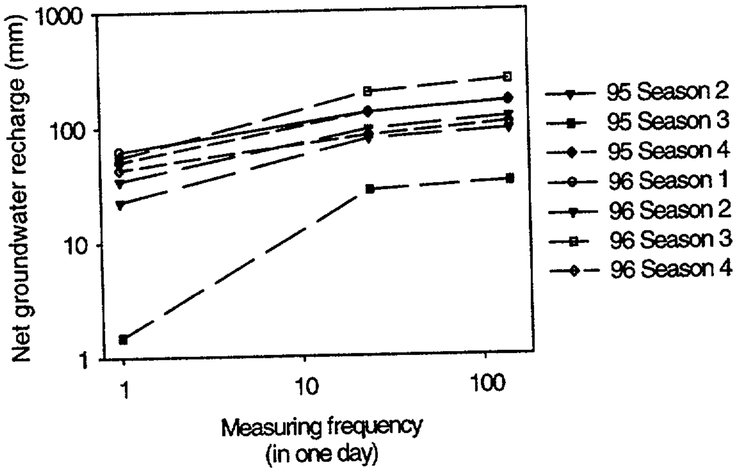

Figure 8 Scaling of estimated net ground-water recharge as a function of measurement frequency.

Figure 8 shows the relationship between the log of frequency of measurement versus the log of net ground-water recharge. The relationship suggests a scaling relationship between measurement frequency and net ground-water recharge. This scaling is possibly a function of rainfall patterns which have a fractal scaling property. This scaling relationship could possibly be used to estimate the loss of information due to change in measurement frequency.

Figure 9 shows the probability distributions for the fluxes sampled for the three methods. Note that all the fluxes are calculated using 10 minute data so the magnitudes are similar for the different sampling methods. The hourly and daily sampling intervals, however miss the larger values of flux. This stems from the transient nature of these larger values of flux. These larger values also contribute the most to ground-water recharge. Figure 10 shows the distribution of fluxes calculated from the infiltrometer data. The highest measured fluxes for the infiltrometer data

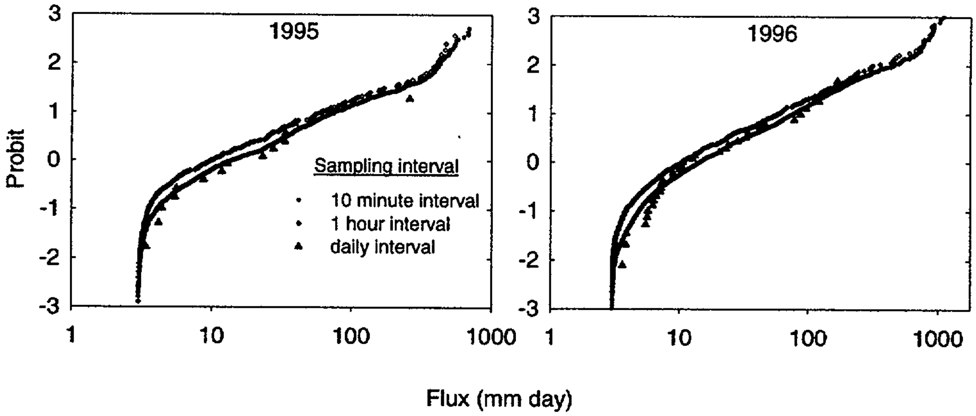

Figure 9 Probability distribution of fluxes calculated from the MCP data set for the three sampling intervals (Probits are standard deviations, i.e., 1= one standard deviation).

are 10 times larger than for the MCP data. The measured fluxes are higher because the infiltrometer data were measured under ponded conditions at the soil surface where the boundary flux was not limited amount of water. The boundary fluxes for the MCP data were limited by rainfall rate, and were calculated for the soil profile to the 50 cm depth. The infiltrometer data can give a good estimate of the maximum infiltration capacity at the surface. Also note in Figure 9, the highly non-linear distribution of fluxes for the MCP data where approximately half the fluxes are less than 10-15 mm/day. For the tension infiltrometer data in Figure 10, the lower half of the distribution consists of fluxes are less than 1000 mm/day.

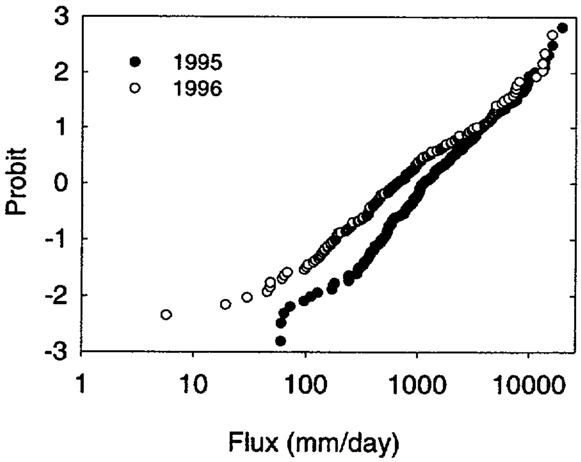

Figure 10. Probability distribution of fluxes from tension infiltrometer measurements from 1995 and 1996.

6.3 Water Table Measurements

The purpose of this analysis was to compare estimates of recharge derived from water table fluctuations to values calculated from the MCP database (see 6.2).

The water table data consisted of piezometer readings taken at infrequent intervals, from 1 to 7 days. These were measured as depth from the land surface to the water table. The data were analyzed by calculating all the differences between successive readings and saving the positive ones (where the water table came closer to the surface). The positive changes were summed over seasons (3 month periods) to obtain an approximate value of total recharge. The results are an average for the 11 piezometers.

Figure 11 shows the calculated net recharge measured as the total change in water table elevation as measured from the piezometers for three years of data. 1995 and 1997 were relatively drier than 1996 and showed less net recharge. Figure 6 shows estimated net recharge using the continuous MCP data, whereas Figure 11 shows net recharge using intermittent piezometric data. Direct comparisons for the figures are limited by the difference in measurement units where MCP data in Figure 6 are mm of water and the piezometer data are mm of water table height in the saturated matrix. Note the differences in net recharge between the 10 minute MCP and piezometric data shown in Figure 11. The relative differences in calculated recharge among the seasons and years are largely similar for both sets of measurements (i.e., MCP and piezometers).

Table 16 gives a more direct comparison of the drainage estimates using the MCP data and piezometer measurements, and gives their errors. We assumed a porosity of 0.10 % for the soil with the piezometers based on a bulk density of about 1.65 g cm^{-3}. Note the large range for both data sets. We would expect the piezometer estimates to be lower in the summer since the MCP estimates drainage past 50 cm and the piezometer estimates drainage to 150 cm (60 in). Plant water uptake in Seasons 2 and 3 would reduce the amount of water moving to 150 cm. In Seasons 1 and 4 we would expect the piezometers to show more net recharge since the MCP estimates would be low due to some steady state flow that is not captured by using differences in water content. The differences are not large which means either steady state losses are not high or the infrequent measurements of piezometer height has resulted in a loss of information, or the estimate of porosity was too high. It is likely that all these contributed to the differences.

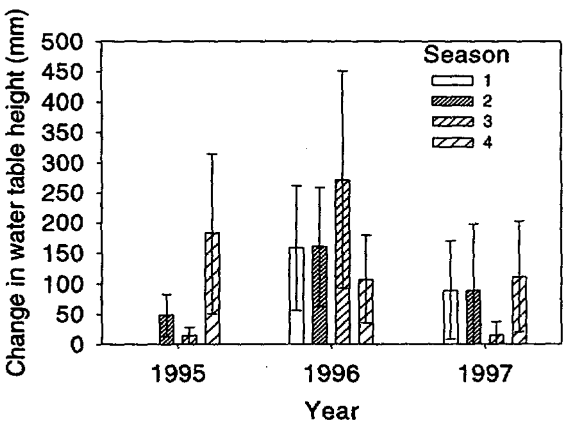

Figure 11 Estimated net ground-water recharge measured as change of water table height using intermittent piezometric data. Seasons refer to winter-early spring (1), late-spring (2), summer (3) and late fall-early winter (4) (vertical lines represent the variability of the estimated recharge among the piezometer locations given in Table 8).

Table 16. Comparison of MCP estimated drainage and standard deviations (Std Dev) and drainage estimated from piezometer data for 1995 and 1996. A porosity of 0.10 was used to convert cm of water table height to mm of water.

Season	MCP	Std Dev	Piezometer	Std Dev	MCP	Std Dev	Piezometer	Std Dev
		mm				mm		
	1995				1996			
1	-	-	-	-	161.7	71.2	158.6	123.3
2	92.6	34.4	48.3	34.9	118.6	37.5	160.5	117.7
3	32.5	42.9	14.1	13.4	249.9	132.6	271.3	214.2
4	163.4	62.0	182.5	132.2	105.7	63.5	107.4	86.6

6.4 Ground-water recharge from Water Budget Calculations

The PNNL Water Budget Model[1] (written for MathCad 8.0) was used to calculate actual evapotranspiration and drainage using weather data from the site. The values of the parameters used in the model are given in Table 17. These input parameters were selected from the MCP data and represent mean values. The results of the simulations are given in Figure 12. There are not large differences between the two methods. Estimated recharge by the model during Season 1 in 1995 is also shown for completeness. The PNNL Water Budget Model estimates drainage below 100 cm while the MCP method estimates drainage below 50 cm. During periods with little vegetative growth

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

the differences should not be as large as they would be during periods with significant evapotranspiration by roots, i.e., Seasons 2 and 3.

The simulated values are much less than the estimated ones for Seasons 2 and 3. Some of this difference is due to the fact that the PNNL model estimates drainage below 100 cm (40 in) while the MCP estimates are for drainage below 50 cm (20 in). A portion of the MCP drainage would never reach the 100 cm boundary as it would be available for plant uptake. However, the recharge estimated by the PNNL model for Season 4 in both years is larger than that estimated from the MCP data. This may be due to the dynamics of snowfall during this period and the effects of antecedent soil water content from the previous season. Also, the difference between drainage estimated from the MCP data and true drainage may be greater during winter periods than during the other three periods. This is because the soil water contents are likely to be high and water flow taking place without significant changes in water content. Overall the PNNL model does provide a fairly good representation of ground-water recharge when compared to recharge calculated from the MCP data. The differences between the PNNL model predicted recharge and recharge calculated from the MCP data are less than the differences between the daily sampled and 10 minute sampled data.

Table 17. 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*	7.56 cm hr^{-1}
Air entry soil-water pressure (cm):	*psis*	-35
Pore size distribution index of Brooks-Corey hydraulic properties	*m*	0.24
Soil dependent parameter of Philip infiltration equation:	*a*	0.333
Initial water content:	*theta_initial*	0.33
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

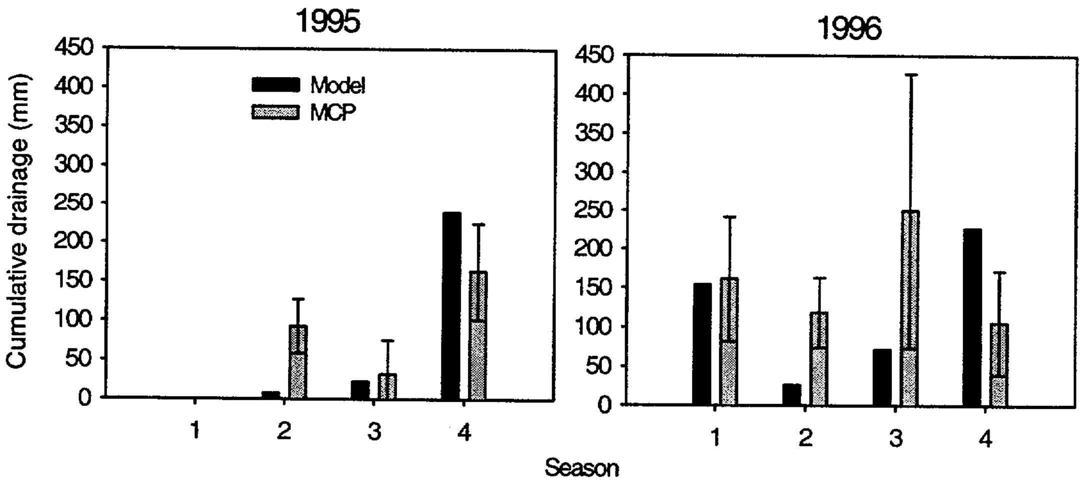

Figure 12. Ground-water recharge predicted by the PNNL model and calculated from MCP data. The vertical lines represent the variability of drainage estimates for the different treatments in the MCP data.

7 CONCLUSIONS

This report provides the technical basis, i.e., information and data bases, for assessing analytic and field methods for estimating net infiltration and net ground-water recharge and their associated uncertainties. Uncertainty in this context refers to information loss due to intermittent and low frequency monitoring. Infrequent monitoring of highly transient events can lead to significant loss of information, e.g., timing and quantity of ground-water recharge. This information is also valuable for making detailed comparisons among alternative field and analytic approaches to estimating ground-water recharge.

Timing and quantity of ground-water recharge can be estimated from measurements of hydrologic conditions (e.g., water content and potential). Infiltration and redistribution of water are highly transient processes estimated from these hydrologic conditions. The time scale for these processes is a function of rainfall characteristics, soil hydraulic properties, and antecedent water content. Temporal variability in infiltration rates and water redistribution causes variations of the time period over which ground-water recharge occurs. The accumulation and timing of these rapid near-surface events can translate into significant differences in ground-water recharge over long time periods. Therefore, frequent monitoring of hydrologic conditions is needed to provide reliable data for estimating net infiltration and redistribution of water which reduces uncertainties in the estimation of ground-water recharge.

In a related study, Meyer and Gee (1999) have identified the importance of assessing: (1) significant preferential flow in the near surface, (2) significant temporal variations in net infiltration and water content, and (3) significant heterogeneities that may result in focus 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 (Meyer and Gee, 1999). Real- time continuously monitored data may be useful if these conditions exist at a decommissioning site in order to appropriately model net infiltration and net ground-water recharge.

Lessons from this ARS-NRC study provide an estimate of the information loss attendant to differences in frequency of measurement of hydrologic conditions. In this study, the time frames for net recharge accounted for by the MCP and piezometer measurements differ. MCP data from the ARS site largely reflect near surface phenomena where changes in the near-surface hydrologic conditions are rapid. Piezometric data, however, reflect the effects of infiltration and redistribution of water over longer time periods. This is due to the time it takes for the water to travel from the soil surface to the water table. Compounding these temporal variations was the measurement frequency of the monitoring technique.

A comparison was made among 10-minute, hourly, and daily MCP data measurements for estimating net ground-water recharge. The estimate of net ground-water recharge decreased non-linearly as measurement frequency decreased. The largest loss of information occurred between the 10 minute and hourly frequencies. The difference in net ground-water recharge between the hourly and daily frequencies was greater than the difference between the 10 minute and hourly frequencies. As shown in Figure 9, the net ground-water recharge is related to the measurement frequency. This suggests a scaling that could be used to estimate loss of information due to measurement frequency.

The 10-minute MCP data provided estimates of net ground-water recharge that were relatively similar to those determined from piezometer data. The exact magnitude of the differences, however depend largely on the value of porosity determined to obtain mm of water from mm of water table height. The values of net recharge calculated from the piezometer data could be larger but are unlikely to be smaller than given in this paper. Infrequent measurements of water table height therefore, did not appear to result in as much information loss as infrequent measurements of water content did. This is probably because the piezometer measurements integrate over a longer period of time than the MCP measurements closer to the surface and are not susceptible to error during steady state conditions.

Because of the analysis methods used, net ground-water recharge may be underestimated when the soil is near saturation. This is due to the method of differencing water contents between two horizons. If the flux of water out of a horizon is equal to the flux in, no difference will be detected even though there has been drainage out of the horizon. This error could have reduced estimates of net infiltration by as much as 10 to 25%. If necessary, an estimate of this infrequent drainage when the soil is near saturated, can be obtained from analysis of the MCP data. This error can be minimized using a network of MCP sensors (lateral and vertical configurations). Frequent measurements of rainfall should be used with MCP water contents to estimate ground-water recharge using a detailed water balance model, e.g., the PNNL water budget model. The optimization of data in combination with a model can significantly reduce errors associated with using changes in water contents alone to estimate ground-water recharge. A model can provide the fluxes while the MCP and rainfall data provide the boundary conditions.

Significant conclusions are:

- Real-time, near-continuous monitoring data can significantly reduce uncertainties and provide insights into the hydrologic processes which can affect radionuclide transport for near-surface settings in humid temperate climates.
- The estimated net ground-water recharge decreased rapidly as measurement frequency decreased.
- Scaling behavior is evident in the relationship between estimated net ground-water recharge and frequency of measurements.
- The multi-sensor capacitance probe proved robust and reliable over ranges of site conditions and time periods for this multi-year study.
- Near-continuous, soil water content measurements for measuring net infiltration and estimating subsequent ground-water recharge are highly valuable for characterizing a dynamic hydrologic regime and for testing analytic and numerical models.
- Water budget models can provide reasonable estimates of ground-water recharge. However, appreciable errors may accumulate due to uncertainties in estimating site-specific evapotranspiration.
- Estimation of ground-water recharge using frequently measured water content data may underestimate fluxes of water in the system.
- Frequent measurements of rainfall should be used with MCP water contents to estimate ground-water recharge using a detailed water balance model, e.g., the PNNL water budget model.
- The optimization of data in combination with a model can significantly reduce errors associated with using changes in water contents alone to estimate ground-water recharge.

This cooperative project provided insights into data and conceptual model uncertainties at the site scale (hectare) for a shallow (less than 10 m) unsaturated zone. This report provides comparisons of "real-time" models against detailed, site specific water content data. Further comparisons of other infiltration models using these data sets are feasible. The datasets and the programs used in this study are available as computer readable files from the USDA-National Agriculture Library.

This study included high frequency, real-time observations of rainfall and water contents over a 0.5 hectare (1.25 acre) site. The MCP data proved valuable in estimating relative ground-water recharge but further questions remain as to accuracy of the calculations and the nature of their uncertainties. This study has also shown that spatial variability 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).

A more detailed water balance study should be conducted under controlled conditions using lysimeters. Measurements should include real-time observations of drainage and evaporative losses in addition to rainfall. This will provide information on fluxes in and out of the system and can be used to evaluate the accuracy of the MCP data in estimating ground-water recharge in combination with a mass balance model.

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GLOSSARY

GLOSSARY OF TERMS AND NOMENCLATURE (from Soil Science Society of America (SSSA), 1997)

Capacitance probe	An instrument to measure soil water content using high frequency 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)	Combined loss of water for a given area from soil and plants (SSSA, 1997).
Ground-water recharge	The quantity of water that reaches the water table.
Infiltration capacity	This is the maximum rate at which water can infiltrate the soil at current soil conditions and water content (after SSSA, 1997).
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).
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.
Soil water potential	The work required to remove water from a soil matrix.
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.
Bulk density of soil	Mass of dry soil per unit bulk volume including solids and pores (Mg M^{-3}) (after SSSA, 1997).
ψ	Pressure potential of water in soil (kPa)
θ	volumetric water content of soil (cm^3 cm^{-3})

APPENDIX 1 FORTRAN PROGRAM *ClassRn.FOR* USED TO CLASSIFY Rainfall EVENTS

```
C this program is to identify rainfall events
c
c    id1 signals first item in the rainfall group
c    ievt is event number
c    fInt (is the time period before a rainfall that is included

      Program class

      real*8 time(100000),rainf(100000)
      integer*4 rain(100000),i,tend(75),nobs,ii,index

      character*4 trt(100000),ptrt


      open (3,file='d:\NRC\sas_datasets\temp.dat')
      open (4,file='d:\NRC\sas_datasets\result.out')


      i=1
      ptrt='    '
      fINt=0.05/24.0
      numtrt=1
5     read (3,45, end=30) time(i),rainf(i),trt(i)
      if (i.eq.1) ptrt=trt(i)
      rain(i)=0
      if (trt(i).ne.ptrt) then
        if (trt(i).ne.'    ') then
          ptrt=trt(i)
          tend(numtrt)=i
          numtrt=numtrt+1
         endif
       endif
      i=i+1
      goto 5

30    Continue
      nobs=i-1
      tend(numtrt)=nobs
      tinfil=time(1)
      Do j=1,numtrt
       ievt=0
       id1=0
      infil_number=0

      do i=1,TEnd(j)
* first set the previous values of rain to 1 to begin
* classifying a rain event 6 hours before
* when the first non-zero infiltration amount is found
* id1 indicates that rainfall was prev 0 and event number
* has not been increased (currently in an event)
          if (rainf(i).gt.0.and.id1.eq.0) then
          if ((time(i)-tinfil).ge.1.0) then
            ievt=ievt+1

           endif
          rain(i)=ievt
          tinfil=time(i)
          index=i
          id1=1
          ii=index
```

```
c           while ((time(index)-time(ii)).le.fInt
c                 .and.(ii.gt.1)) do
c              rain(ii)=ievt
c              ii=ii-1
c           endwhile
          else if (rainf(i).gt.0) then
                 rain(i)=ievt
                 tinfil=time(i)
              endif

           if (rainf(i).le.0) then
             id1=0
             if ((time(i)-tinfil).le.(1.0)) rain(i)=ievt
            endif


          enddo
          tinfil=time(tend(j))
          enddo


       Do i=1,nobs
        write(4,*) time(i),rainf(i),rain(i)
        enddo

 45    format (f12.8,f18.10,1x,a4)

          end
```

APPENDIX 2 SAS PROGRAM *make macrovar from trt names.sas* to extract treatment labels and create macrovariable names for them

```
      /* this program will go through a data set and find all the treatment
 id's then
    creat macro variables for each. The purpose is to create a macro to
 classify rain
     only need to run through one year data since treatment names are the same
 in all.
     This program creates a file treat2.dat that contains the variable names.
 This file
     can be read in at later times.
 */

    options mlogic mprint mtrace symbolgen;
       data _null_;

          set sentek.yr1995 end=end;
          by trt;
            if first.trt then
               do;
               count+1;

                   /* create variables for the treatment name*/
                  call symput('TR_'||left(put(count,2.)), trim(trt));
                end;


           /* create a variable that contains the number of labels */
           if end then call symput('count',put(count,5.));
         run;


  %macro test;
       put "&&count";
    %do i=1 %to &count;
       put  "TR_&i" " " "&&TR_&i";

         %end;
  %mend;

filename testf 'treat2.dat';
data _null_;
  file testf;
    %test;

run;
quit;
```

APPENDIX 3 SAS PROGRAM *read macrovar names.sas* to create the macro variable names from stored labels

```
/* creates the macrop variables

   The variable names are of the form "TR_1"
   where TR_1 contains the value "IN26".
   These treatment variables and their values
   are stored in the file treat2.dat. This file
   should be in the workspace where the
   sas input files are.

   in the second macro the year (i.e. 96 97, is
   tacked on to the end of the variable name

   The default library name is Sentek
*/

/* remove the asterisk in this next statment for
   debugging puposes          */
* options mlogic mprint mtrace symbolgen;

filename varN 'treat2.dat';
Data _null_;
 infile varN;
 if _n_=1 then do;
   input var;
    call symput('count',put(var,5.));
  end;
 input variable $ value $;
  call symput(variable,trim(value));
 run;
```

APPENDIX 4 SAS MACRO LAYERW to reorganize data so that each layer is in a single column

```
/*=========================================================*/
/* yr=95 or 96 */
%macro layerW(yr=);

/* the purpose of this program is to output water contents with
   a separate column of data for each depth
*/

data d1 d2 d3 d5;
set sentek.YR19&yr;
if depth=10 then output d1;
else if depth=20 then output d2;
else if depth=30 then output d3;
else if depth=50 then output d5;
run;
proc sort data=d1;
by trt time ;
quit;
proc sort data=d2;
by trt time;
quit;
proc sort data=d3;
by trt time;
quit;
proc sort data=d5;
by trt time;
quit;

data sentek.LayerW&yr;
merge d1(rename=(theta=theta1)) d2(rename=(theta=theta2))
d3(rename=(theta=theta3)) d5(rename=(theta=theta5));
drop depth;
theta4=0.5*(theta3+theta5);
by trt time;

run;

proc datasets;
delete d1 d2 d3 d5;
quit;

proc sort data=sentek.layerw&yr;
by trt time;
quit;

%mend;
```

APPENDIX 5 SAS MACRO ExTrt to break up data set into individual data sets for each treatment

```
/* this macro breaks the individual treatments out of the
   one yearly file
*/

%macro extrt (fl=,yr=);
  %do i=1 %to &count;
    data &&tr_&i.._&yr;
      length trt$ 4;

      set sentek.&fl;
      if trt="&&tr_&i" then output &&tr_&i.._&yr;
    run;
  %end;
%mend;
```

APPENDIX 6 SAS MACRO *Mrg_Rain* to merge rain data with treatment water content data

```
%macro Mrg_Rain (rnyear=, yr=);
/* the purpose of this procedure is to merge the rain data sets with the
    individual data sets with cum infl data
    this is a faster version that will break up the file into 4 units and
    merge each separately
*/

/* data sets:
   &in contains the water content data
   temp table with rain data - contains rain times and associated lines fron
   &in with a nearby time - from proc sql
*/

  %do i=1 %to &count;

   %let in=&&TR_&i.._&yr;
   proc sql;
   Create table temp as select distinct &in..time, &rnYear..timern,
   &rnYear..rain from &in, sentek.&rnYear
   where  0< (((&in..time-&rnYear..timeRN)*60*24)) <=9.9 and time<>.;

  run;

 Proc sort data=temp;
  by timern;
  run;

 /* now find duplicate lines of data - may arise from the merge process
    the second duplicate is deleted

 */

 data temp;
  set temp;
  if timern=lag1(timeRN) then delete;
 run;

 proc sort data=&in;
   by time;
 run;

 proc sort data=temp;
  by time;
 run;

 data &in (drop=timern);
    merge &in temp ;
    by time;
   if rain=. then rain=0;
 run;

 proc sort data=&in;
   by time;
 run;

 %end;
 %mend;
```

APPENDIX 7 SAS MACRO *ClassRn* to identify and classify rain events. It also calculates the profile summed water content, cumulative infiltration and rain

```
%macro classRn (yr=);

/* the purpose of this procedure is to classify the rainfall events
   and give them a number so we can group on them. The classification is
   done in the fortran program classrn.for that is in the sas-sentec
directory.

*/

/*  starts here */


options noxwait xsync;
filename outf 'd:\NRC\sas_datasets\temp.dat';
filename inf 'd:\NRC\sas_datasets\result.out';

   %do i=1%to &count;
/* * temporary stuff (uncomment if a rerun in the middle is done);

       data &&tr_&i.._&yr (drop= rainid cumi cumr);
        set &&tr_&i.._&yr;
run;
*/

     proc sort data = &&tr_&i.._&yr;
      by time;
     run;

      data _null_;
      set &&tr_&i.._&yr (keep=rain time trt);
      file outF;
      put time 12.8 rain 18.10 ' ' trt $char4.;
      where time <> .;
 run;

   X 'd:\NRC\report\new\classrn.exe';


    data tinfil;
      infile inf;
      input time rain rainid;
    run;

    data &&tr_&i.._&yr;
      merge &&tr_&i.._&yr tinfil;
      by time;
     run;

   %end;


      proc datasets;
      delete tinfil;
      run;
     quit;


 /* =============================================== */
```

```
/* this section of the macro will calculate infiltration into the profile
   to determine if the rainfall event is significant or not

*/

  %do i=1 %to &count;

/* Count number of groups with only two or three small rainfall values */
   data &&tr_&i.._&yr;
    set &&tr_&i.._&yr;
      by rainid notsorted;
      if rainid <> 0 then
        Do;
         if first.rainid then do;
           rcnt=0;
          end;
         else do;
           if rain>0 then rcnt+1;
         end;
        End;
     run;

/* calculate cumulative sum of infiltrated water as a function of rainid */

     data &&tr_&i.._&yr (drop=d);
       set &&tr_&i.._&yr;
        by rainid notsorted;
          Thetad5=theta1+theta2+theta3+theta4+theta5;
          d=max(0,dif1(thetad5));
          if first.rainid then
            do;
             Pcumi=0;
             cumr=0;
             d=0;
            end;
              Pcumi+d;
              cumr+rain;
        run;


/* this resets the indicator where there are few (<=4) observations
    and less than .51 mm of rainfall
*/
    PROC SQL;
      create table temp as Select rainid, MAX(RCNT) as mxcnt, max(cumr) as
mxRn
        from &&tr_&i.._&yr
        group by rainid
           having MAX (RCNT) LE 4 and mxRn LT .51;
     quit;

/* prepare to merge the two data sets to add mxcnt as a variable */
     proc sort data=temp;
       by rainid;
      run;

      proc sort data=&&tr_&i.._&yr;
       by rainid time;
       run;

/* do the merge */
       data &&tr_&i.._&yr;
```

```
         merge &&tr_&i.._&yr temp;
          by rainid;
          run;

 /* reset rainid for rows where mxcnt is low */
         data &&tr_&i.._&yr;
           set &&tr_&i.._&yr;
           if mxcnt >0 then rainid=0;
        run;

        data &&tr_&i.._&yr (drop=mxcnt rcnt mxRn Thetad5);
         set &&tr_&i.._&yr;
       run;

        proc sort data=&&tr_&i.._&yr;
         by time;
       run;


      %end;
 %mend;
```

APPENDIX 8 SAS MACRO *drained* to find drained water content for layer 5

```
%macro drained(yr=);

   proc datasets;
    delete drtheta;
    quit;

  %do i=1 %to &count;

    data mxmin (keep=trt theta5 rename=(theta5=drth5));
      set &&tr_&i.._&yr;
      by rainid notsorted;
      if last.rainid and rainid<>0 then output;
    run;

    proc sort data=mxmin;
      by descending drth5;
     quit;

    proc sql;
      select int(count(mxmin.drth5)/3) into :num
     from mxmin;
     quit;


     data d1;
        set mxmin;
        if _n_=&num then output;
       run;

    proc append base=drtheta data=d1;
    run;
    quit;
    %end;
    %mend;
```

APPENDIX 9 SAS MACRO *DrainedP* to find drained water content for the profile

```
/* estimates the drained water content of the profile */

%macro drainP(yr=);

   proc datasets;
    delete drtheta;
    quit;

  %do i=1 %to &count;

    data mxmin (keep=trt thetad5 rename=(thetad5=drth));
      set &&tr_&i.._&yr;
      by rainid notsorted;
      thetad5=theta1+theta2+theta3+theta4+theta5;
      if last.rainid and rainid<>0 then output;
    run;

    proc sort data=mxmin;
      by descending drth;
     quit;

    proc sql;
      select int(count(mxmin.drth)/3) into :num
     from mxmin;
     quit;


    data d1;
       set mxmin;
       if _n_=&num then output;
      run;

  proc append base=drth_P data=d1;
  run;
  quit;
  %end;
  %mend;
```

APPENDIX 10 SAS MACRO *Sample* to sample the MCP data for hourly and daily values

```
%macro Sample (step=);

/* note :
     step=0 --- no sampling, use all data
      step=1 --  hourly sampling
      step=2 --  daily sampling


   this code will select a subset of the 10 minute data
   for hourly and daily measurements
*/


%if &step=1 %then %do;
    data temp;
    set temp;
    isec=int(sec/10000);
  run;

   data temp;
   set temp;
    by isec notsorted;
  if first.isec then output;
  run;

  data temp (drop=isec);
   set temp;
    if dif1(isec)=0 then delete;
   run;
  %end;

 %if &step=2 %then %do;

   data temp;
    set temp;
    if 153000<sec<154500 then output;
   run;

   data temp;
    set temp;
     if dif1(day)=0 then delete;
    run;

 %end;

 %mend;
```

APPENDIX 11 SAS MACRO *Cprob* to calculate probability of drainage and total drainage

```
/*=============================================================*/
* note :
     step=0 --- no sampling, use all data
      step=1 --  hourly sampling
      step=2 --  daily sampling
*/
%macro cProb(step=, yr=);
/* %let count=16;*/

%do i=1 %to &count;

/*   %let i=1;
    %let yr=95;
    %let step=0;
*/

/* this code will extend the rainid value until the
   next rainstorm */
   Data temp;
  set &&tr_&i.._&yr;
  retain rd rc;

   by rainid notsorted;

    if first.rainid and rainid<>0 then
        Do;
         rd=rainid;
         rc=cumr;
        End;
     if last.rainid and rainid<>0 then
        do;
         rd=rainid;
         rc=cumr;
        end;
    rainid3=rd;
    if rainid-rainid3<>0 then cumr2=rc;
    else cumr2=cumr;
  run;

data temp (drop =rd rc cumr2);
 set temp;
 if rainid3=.  then delete;
 cumr=cumr2;
run;

%sample(step=&step);

/* obtain the approximate drained water content of layer 5
   it is assumed that drainage is minimal when the layer is
   drier than this water content. This value is selected using from
   the data set 'drtheta'  which is created by the macro drained

/*

proc sql noprint;
  select drtheta.drth5 into :dr
  from drtheta, temp
```

```
  where drtheta.trt=temp.trt;
quit;


/* calculate cumulative infiltration and cumulative losses for the
   entire profile to 50 cm */
 data temp2 (drop=theta1-theta4); * (drop=d in out);
   set temp; /* (drop=cumr2 cumi2); */
   retain time0;
    thetad5=theta1+theta2+theta3+theta4+theta5;
    d=dif1(thetad5);
    d2=dif1(theta5);
    t=dif1(time);
    by rainid3;
   if first.rainid3 then
     do;
       t=0;
       d=0;
       d2=0;
       cumi=0;
       time0=time;
       drain=0;
     end;
        else
       do;
          in=max(0,d);
          out=-min(0,d);


 /* this is to eliminate possibility of counting upward flow and also 0 out
   small possible flows after two days*/

          if rainid3-rainid>0 then
             do;
               if theta5<(&dr)*0.85 then out=0;
             end;
           if rainid3-rainid=0 then
             Do;
               if theta5<(&dr)*0.60 then out=0;
                cumi+in;
             end;
           drain+out;

       end; /* else */
    run;


 /* this selects all the events for a total count */
  PROC SQL noprint;
 create table t1 as Select COUNT(TEMP2.cumi) as Q5_in,
 TEMP2.RAINID3, min(temp2.season) as season1, max(temp2.trt) as trt1
 from WORK.TEMP2
 group by TEMP2.RAINID3 having TEMP2.RAINID3 GT 0;
 quit;

 /* this selects events where there was a positive increase of water in
    of at least 1 mm and precip> drainage and rainfall >5 mm
 */
 PROC SQL noprint;
 create table t2 as Select COUNT(TEMP2.drain) as Q5_out,
 TEMP2.RAINID3,
 max(temp2.cumi) as infil,
```

```
max(temp2.drain) as drn,
max(temp2.cumr) as precip
 from WORK.TEMP2 where TEMP2.drain GT 3
group by TEMP2.RAINID3 having
Q5_out GT 1 and precip GT 5;
quit;

/* t3 contains the data on drainage, infiltration and rainfall */
data t3 (keep=rainid3 cumi drain cumr);
  set temp2;
  where rainid3>0 ;
  by rainid3 notsorted;
  if last.rainid3 then output;
 run;



data temp3;
  merge t1 (rename=(q5_in=infil_c)) t2 (rename=(q5_out=rech_c)) t3;
   by rainid3;
   if rech_c=. then rech_c=0;
   if drn=. then drain=0;
run;

data sum (keep=trt1 prob season1 cuminf Cumdrn SumRn);
  set temp3 nobs=n;
  by season1;
  if first.season1 then
    do;
       numR=0;
       cnt=0;
       CumDrn=0;
       SumRn=0;
       cuminf=0;
     end;
     CumDrn+drain;
     CumInf+cumi;
     if Rech_c>0 then numR+1;
     cnt+1;
     sumRn+CumR;
     if last.season1 then
      do;
       prob=numR/cnt;
       output;
      end;
 run;

   proc append base=prob&step data=sum;
   quit;

%end;

proc datasets;
 delete t1 t2 t3 temp temp2 temp3;
quit;

%mend;
```

APPENDIX 12 SAS MACRO *Summar* to summarize the probability and drainage data calculated using the macro CProb

```
/* this macro accumulates and summarized the results of the samping */

%macro summar(yr=);


data prob&yr;
  set prob0 (in=one) prob1 (in=two) prob2 (in=three);
  if one then set=1;
  if two then set=2;
  if three then set=3;
run;

proc sort data=prob&yr;
 by set season1;
run;



  proc means data=prob&yr;
   by set season1;
  var prob cumdrn;
   output out =m1 mean=prob cumd std=pstd cstd;
  run;

  data pmeans  (drop=_freq_ _type_);
   retain set season1 prob pstd cumd cstd;
   set m1;
  run;

proc datasets;
  delete m1;
 run;



 /*

   data allP (keep=season1 trt1 prob0 prob1);
 merge prob0 (rename=(prob=prob0)) prob1 (rename=(prob=prob1));
  by season1 trt1;
 run;
   */



 data p1 (rename=(prob=prob0 cumd=cumd0 pstd=pstd0 cstd=cstd0))
      p2 (rename=(prob=prob1 cumd=cumd1 pstd=pstd1 cstd=cstd1))
      p3 (rename=(prob=prob2 cumd=cumd2 pstd=pstd2 cstd=cstd2));
   set pmeans;
   if set=1 then output p1;
   if set=2 then output p2;
   if set=3 then output p3;
 run;

 data pmeans2 (drop=set);
   retain season1 prob0-prob2 pstd0-pstd2 cumd0-cumd2 cstd0-cstd2;
   merge p1 p2 p3;
    by season1;
```

```
 run;

proc datasets;
 delete p1 p2 p3 prob0 prob1 prob2;
run;

/* note the excel file will not be overwritten if it already
   exists! It should be deleted first if it does */

PROC DBLOAD DBMS=EXCEL DATA=WORK.PMEANS2;
PATH="D:\NRC\report\new\drain%eval(&yr).xls";
PUTNAMES YES;
LIMIT=0;
LOAD;
RUN;

%mend;
```

APPENDIX 13 SAS PROGRAM *In-outflxs by layer2.sas*, calculate drainage by different methods for comparison

```
/* some modifications - to calculate outflows by layer and to calculate a
storage term
  After Feb 3, 2000

  Use this program to compare various methods of calculating drainage

*/

  %macro loop2(yr=);
 proc datasets library=sentek;
  delete rec&yr;
     quit;
%do i=1 %to &count;
/*
%let i=2;
%let yr=95;
*/
/* find drained water content for the profile
    requires macro drainedP*/
proc sql noprint;
  select drth_p.drth into :drP
  from drth_p, &&tr_&i.._&yr
  where drth_p.trt = &&tr_&i.._&yr..trt;
quit;

/* find drained water content of lowermost layer
   requires macro drained
*/
proc sql noprint;
  select drtheta.drth5 into :dr
  from drtheta, &&tr_&i.._&yr
  where drtheta.trt = &&tr_&i.._&yr..trt;
quit;

/*     sumout = drainage by layer mass balance
       sumout2= sum of negative changes in layer 5
       sumout3= sum of negative changes in profile
       sumout4= drainage by tipping bucket method
       CumR   = cumulative rainfall
       PCumI  = cumulative infil for profile by summing pos changes in theta

*/
data zflux (keep=trt ctime cumr pcumi rainid sumout sumout2-sumout4 storage
thetad5 level theta5 dr);
  set  &&tr_&i.._&yr;
   retain init itime;
   by rainid notsorted;
   where rainid>0 and (season=2 or season=3);
    thetad5=theta1+theta2+theta3+theta4+theta5;
    d1=dif1(theta1);
    d2=dif1(theta2);
    d3=dif1(theta3);
    d4=dif1(theta4);
    d5=dif1(theta5);
    d6=dif1(thetad5);
    dr=&dr;
    level=&drp;
      if first.rainid then
```

```
          do;
           sumout=0;
           sumout2=0;
           sumout3=0;
           init=thetad5;
           in1=0;
           out1=0;
           itime=time;
          end;
          else
            do;
               if1=max(0,d1);
                of1=min(0,d1);
             if2=max(0,d2);
             of2=min(0,d2);
            if3=max(0,d3);
            of3=min(0,d3);
             if5=max(0,d5);
             of5=min(0,d5);
             of6=min(0,d6);
             in1=if1;
             out1=of1;
             in2=-of1;
             out2=max(0,in2-d2);
             in3=out2;
             out3=max(0,in3-d3);
             in4=out3;
             out4=max(0,in4-d4);
             in5=out4;
             out5=max(0,in5-d5);
             if theta5>0.6*dr then sumout+out5;
             else sumout+0;

             if -of5>0.0 then
              sumout2+of5;

              if theta5>0.6*dr then sumout3+of6;
               else sumout+0;

               storage=thetad5-init;
               ctime=time-itime;
           end;
      if last.rainid then
         do;

          sumout=min(sumout,pcumi);
          sumout3=-sumout3;
          sumout3=min(sumout3,pcumi);
          fill=cumr+init;
          sumout4=min(0,&drP-(cumr+init));
          output;
          end;
run;

   proc append base=sentek.rec&yr data=zflux;
  run;
quit;

%end;
data sentek.recsum&yr (keep=trt sum1-sum7 drain);
  set sentek.rec&yr;
  format sum1-sum7 drain 6.1;
```

```
   by trt rainid;
    if first.trt then
     do;
      sum1=0;
      sum2=0;
      sum3=0;
      sum4=0;
      sum5=0;
      sum6=0;
      sum7=0;
     end;
       sum1+pcumi;
       sum2+cumr;
       sum3+(sumout);
       sum4+(-sumout2);
       sum5+(-sumout3);
       sum6+max(0,storage);
       drain=sum1-sum6;
       sum7+sumout4;
    if last.trt then output;
run;
%mend;


%loop2(yr=95);
%loop2(yr=96);
```

APPENDIX 14 SAS PROGRAM *probability plot for infil by sample time to excel.sas* to calculate probability distributions for infiltration rates

```
* save data to excel to make a probability plot of infiltration rate
   for each treatment */

/* without these the system slows down */
options noxwait noxsync;


%macro probplt (yr=, step=);


/* loop begins here for each trt*/

/* note :
     step=0 --- no sampling, use all data
      step=1 --  hourly sampling
      step=2 --  daily sampling
*/



* %let count=16;
 %do i=1 %to &count;
    %if &&tr_&i=NT22 or &&tr_&i=PT24 %then %do;



*    get data;
    data temp;
      set &&tr_&i.._&yr;
      thetad5=theta1+theta2+theta3+theta4+theta5;
      d=min(0,dif1(thetad5));

      InF=d/dif1(time);
      if InF>3 and dif1(time)<30/24/60 then output;
      ;
     run;

/* select obs here for different measurement intervals */
     %sample(step=&step);


    * sort data;
     proc sort data=temp;
      by InF;
    run;

    * compute the normal quantiles;
    data temp;
      set temp nobs=n;
      linfil=log10(InF);
      y=(_n_-(3/8)) / (n+(1/4));
      y2=_n_/n;
      prob=probit(y);
    run;


    * make new data set;
    data temp (keep=prob InF linfil);
```

```
      set temp;
    run;

/* find last observation */
    data _null_;
     set temp nobs=n end=last;
       if last then call symput('nrows',trim(left(n)));
   run;

/* send the treatment id to excel as a column head */
    filename exout dde "excel|sheet1!r1c&ncol:r1c&ncol";
     data _null_;
     file exout;
      put "&&tr_&i-&yr-&step" ;
      run;


  filename exout dde "excel|sheet1!r2c&ncol:r%eval(&nrows)c%eval(&ncol+1)";


       data _null_;
        file exout;
        set temp;
        if linfil=. then delete;
        put  InF prob;
       run;
  %let ncol=%eval(&ncol+2);

   run;
%end;   /* do*/
%end;  /*i loop */

%mend; /*probplt */

/* start excel. Note you can also start excel and not open a
   spreadsheet. The spreadsheet could be opened in a later dde
   step. */


   x 'excel d:\nrc\Probplt.xls';
    data _null_;
      x=sleep(4);
    run;
%let ncol=1;

/* does two treatments each step (4 columns of data) */
%probplt (yr=95,step=0);
%probplt (yr=96,step=0);
%probplt (yr=95,step=1);
%probplt (yr=96,step=1);
%probplt (yr=95,step=2);
%probplt (yr=96,step=2);
```

APPENDIX 15 SAS PROGRAM *piezometer calcs.sas* to calculate changes in water table height from piezometer data

```
/* calculate changes in water table height from piezometer data
   calculate a derivative */

proc sort data =piez2;
  by trt year season ydate;
run;
quit;

data piez2;
  set piez2;
   by trt year season;
   difpm=dif1(height);
  if first.trt then difpm=0;
   difpm=max(0,difpm);

run;

/* calculate the total decreases in water table depth
   assume this is infiltration */

data test;
  set piez2;
  by trt year season;
   if first.season then cumW=0;
     cumW+difpm;
run;

/* now output the final results */

data CumW (keep =year season trt cumw);
  set test;
   by trt year season;
    if last.season then output;
run;

proc sort data=cumw;
 by year season;
quit;

proc means data=cumw;
 by year season;
  var cumw;
   output out =m1 mean=cumw std=cumwstd;
quit;

  data cMeans  (drop=_freq_ _type_);
   retain season year cumW cumwStd;
   set m1;
  run;

/* note that the file CMEans.xls won't be written over if
   it already exists - it should be erased first */
PROC DBLOAD DBMS=EXCEL DATA=WORK.CMEANS;
PATH='D:\NRC\SAS_DataSets\CMeans.xls';
PUTNAMES YES;
LIMIT=0;
LOAD;
RUN;
```

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11. ABSTRACT *(200 words or less)*

This study investigated field instrumentation [multi-sensor capacitance probes (MCP)] and analytical methods for estimating "real-time" infiltration and subsequent ground-water recharge and their attendant uncertainties. The research design was to apply a selected subset of existing field characterization data from the Beltsville Agricultural Research Center to technical issues identified by the NRC staff involving ground-water recharge estimates at nuclear facilities. The datasets allow comparisons of ground-water recharge estimates using near-continuous, water content measurements to recharge estimates based on less frequent water content observations (e.g. hourly or daily), intermittently measured piezometric data or analytical models. Drainage was underestimated by only using changes in water contents measured by MCP. Differences in water content did not always accurately represent fluxes when the system was at steady state. The estimate of net ground-water recharge decreased as measurement frequency decreased. The MCP data provided better estimates of recharge and timing than the piezometer data. Estimates of ground-water recharge were also compared to simulated recharge using a PNNL water budget model. The optimization of data in combination with a model can significantly reduce errors associated with using changes in water contents alone. A model optimized for hydraulic conductivity and moisture release parameters can calculate the fluxes using boundary conditions provided by the MCP and rainfall data. Further studies should move to larger scales (i.e., watershed) and lysimeters.

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