NUREG/CR-6729

Field Studies for Estimating Uncertainties in Ground-Water Recharge Using Near-Continuous Piezometer Data

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Field Studies for Estimating Uncertainties in Ground-Water Recharge Using Near-Continuous Piezometer Data

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ABSTRACT

This study investigated uncertainties in ground-water recharge estimates using real-time, near-continuous piezometer data [six piezometers instrumented with automated pressure transducers at 10-minute measurement intervals]. Analytical and numerical methods were used to compare ground-water recharge estimates. These methods included: (1) time-series analyses of hydrographs, (2) steady-state estimates using meteorological data only, and (3) the PNNL water budget model. The time-series analysis methods included: (1) *sum of positive changes in piezometric heads;* (2) *piezometric head changes corrected for hydrograph recession;* and (3) *variations in rainfall input.* The density of the data allowed for several estimates of recession coefficients and specific yields for each piezometer location. Higher estimates of ground-water recharge were obtained using real-time, near-continuous piezometer data than estimates derived strictly from meteorological data. This observation was also true for comparison with the water-balance method (PNNL model). Taking into account errors introduced by estimating the recession coefficients, the *sum of positive changes in head* is the most appropriate approach for estimating recharge at this site. For all the time-series methods, the variation in specific yield contributes to the uncertainty of ground-water recharge estimates on the order of 10 to 100%. The spatial variability in ground-water recharge was also a large contributor to uncertainty. The real-time, near-continuous piezometer data showed a very rapid response (e.g. < 20 minutes) in the shallow water table to rainfall events over short time intervals, and verified the occurrence of significant episodic recharge. Uncertainty in characterizing site behavior can be reduced by utilizing a network of measuring devices to capture the spatial variability inherent in this dynamic process.

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EXECUTIVE SUMMARY

This report was prepared by the Agricultural Research Service (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 (a glossary of technical terms is provided on page 37) and their attendant uncertainties. The calculation of infiltration rates, infiltration capacity, and ground-water recharge through the subsurface may be needed to determine the leaching and transport potential of radionuclides for the safety assessment of decommissioning and waste disposal facilities.

The ARS monitoring program was originally designed to provide information on infiltration 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. This report builds on NUREG/CR-6653, "Comparison of Estimated Ground-Water Recharge Using Different Temporal Scales of Field Data." The research reported here uses real-time, near-continuous piezometric heads to estimate ground-water recharge, whereas NUREG/CR-6653 reported on infiltration and ground-water recharge estimates using water content measurements from multi-sensor capacitance probes. These data come from existing field characterization data and monitoring programs at the Beltsville Agriculture Research Center (BARC) during the period June 1999 to December 2000.

Previous studies (e.g., Meyers and Gee, 1999) 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 in the subsoil that may result in focused flow and fast transport pathways for site-specific modeling. Dose assessments for decommissioning sites using site-specific models should consider whether these three conditions exist. This research investigated real-time, near-continuous monitored data that may be useful for assessing temporal variations in net infiltration and water content at a decommissioning site in order to appropriately model infiltration and net ground-water recharge.

In the past, characterization of deep infiltration and ground-water recharge has traditionally focused on long-term estimates (e.g., annual or monthly). A premise to this field study is that shallow water tables in a humid climate are highly transient and dynamic. Although annual estimates of ground-water recharge using water balance methods may be useful for deep unsaturated systems with infrequent rainfall events and very low antecedent water contents, they fail to capture significant episodic recharge events which may occur over short time periods (e.g., hourly or daily) in shallow ground-water systems. Another premise is that piezometer fluctuations recorded by automated field instruments and represented by real-time, near-continuous hydrographs, provide a direct method for estimating ground-water recharge for the shallow ground-water systems at the Beltsville site. Other less direct methods, such as automated multi-sensor capacitance probes (MCP) used to measure soil water contents, also provide real-time, near-continuous estimates but may not account for water movement in very wet soils. Finally, a network of automated piezometers over the ground-water recharge area can be used to characterize the spatial distribution and uncertainty of recharge.

This study addresses these technical issues (e.g., episodic ground-water recharge events which may enhance mobilization and transport) common to the various nuclear facility programs. Furthermore, this field study provides research results as technical bases for resolving these issues. One important technical issue addressed in this report was the characterization of ground-water recharge using real-time, near-continuous databases that lend themselves to time-series analysis. Furthermore, the temporal density of these data are such that interpolation methodologies may not be necessary and uncertainty is reduced. Uncertainty in this context refers to information loss due to intermittent and low frequency monitoring and to spatial variability in monitoring locations. Real-time, near-continuous data provide a highly realistic characterization of the transient, and dynamic hydraulic processes and events.

Timing and quantity of ground-water recharge can be estimated from measurements of hydrologic conditions (e.g., water content and piezometric head). 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 varies over which ground-water recharge occurs. The accumulation and timing of rapid near-surface effects can translate into significant differences in ground-water recharge over long time periods.

ARS scientists installed pressure transducers in six water-table piezometers to measure water levels at 10-minute intervals. Data were stored on data-loggers and retrieved at periodic intervals. This allowed simultaneous collection of near-continuous data in all piezometers regardless of the time of day or meteorological conditions. Coincident with this piezometric data, meteorological and soil water data were also available at the same time scale. These data were very appropriate for time series analysis. Along with direct calculations using time series analysis, conventional methods (e.g., percent of precipitation, precipitation - evapotranspiration, hydrograph recession analysis) were compared for estimating ground-water recharge and their attendant uncertainties.

The real-time, near-continuous datasets contained in this report provide a sufficiently complete characterization of the piezometric fluctuations. Estimates of ground-water recharge derived from these datasets were also compared to traditional, steady-state methods and/or analytic models. Information and analytic results from this report can be used to evaluate monitoring programs which may be used to characterize ground-water recharge at decommissioning, monitored retrievable storage (MRS), uranium mill tailings, high level radioactive waste (HLW) and low level radioactive waste (LLW) disposal sites.

The 10-minute piezometer data facilitated estimates of net ground-water recharge that varied greatly by location. In addition to the spatial variance, there was additional variability due to uncertainty in specific yield (the vertical rise of the water table per unit of water added to the water table). The values of net recharge calculated from the piezometer data could be quite variable. The spatial variability in ground-water recharge was a larger component of uncertainty than the lack of knowledge in specific yield.

Estimates of ground-water recharge using the 10-minute piezometer data were also compared to simulated ground-water recharge using a Pacific National Northwest Laboratory (PNNL) water budget model. The seasonal estimates of net ground-water recharge differed. As shown in Figures 10 and 11, the analysis for year 2000, the PNNL model consistently under estimated ground-water recharge as compared to more direct methods that use the piezometer data.

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.
- Pressure transducer devices in the piezometers proved robust and reliable over ranges of site conditions and time periods for this multi-year study.
- Real-time, near-continuous piezometric measurements can be used to estimate ground-water recharge independent of unsaturated zone measurements as long as the water level does not fall below the piezometer screen.
- Specific yield, estimated from a subset (spring season) of the real-time, near-continuous piezometer data showed considerable variation among locations and between years(1999, 2000) . This variation may contribute to the uncertainty of ground-water recharge estimates on the order of 10 to 100% (see Table 10).
- The spatial variability in ground-water recharge was a larger component of uncertainty than uncertainty due to specific yield.
- Upon analysis of piezometer data at different locations and at different seasons, uncertainty in characterizing site behavior can be reduced by utilizing a network of measuring devices to capture the spatial variability inherent in this dynamic process.

- The real-time, near-continuous piezometer data showed a very rapid response (e.g. < 20 minutes) in the water table to rainfall events. This verifies the occurrence of significant episodic recharge for the shallow water table at this site. This dynamic process was also verified for the MCP data as described in NUREG/CR-6653.
- The use of real-time, near-continuous piezometer data or MCP data results in higher estimates of ground-water recharge than use of meteorological data alone or water balance methods or other methods which use less frequently measured water content or piezometer data..

This cooperative project provided insights into data and conceptual model uncertainties at the site scale (hectare) with a shallow (less than 3 m) water table. This report presents detailed field datasets and their analysis using conventional methods (including time series analysis) to estimate variable ground-water recharge. Information and methods for determining specific derived parameters such as recession coefficients and specific yields are also presented. Further comparisons of other recharge 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 piezometric heads over a 0.5 hectare (1.25 acre) site. The piezometric data proved valuable in estimating relative ground-water recharge but further questions remain as to the accuracy of the calculations, and the nature of their uncertainties. This study has also demonstrated 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 piezometer fluctuations, drainage and evaporative losses in addition to rainfall. This proposed study would provide information on fluxes in and out of the system that can be used to evaluate the accuracy of both piezometer and MCP data in estimating ground-water recharge in combination with a mass balance model. A common assumption is that infrequent monitoring of highly transient events can lead to significant loss of information (e.g., timing and quantity of ground-water recharge). Future research should be conducted to test this assumption and determine the reduction in uncertainty by utilizing real-time, near-continuous data. The research demonstrated that frequent monitoring of hydrologic conditions can provide reliable data for estimating net infiltration and redistribution of water which reduces uncertainties in the estimation of ground-water recharge.

FOREWORD

This technical report was prepared by 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 objective of this effort was to investigate field instrumentation and methods for estimating "real-time" ground-water recharge and its attendant uncertainties. The research design was to 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 licensing issues being investigated are the need for transient estimates of ground-water recharge and whether conventional steady-state approaches miss recharge arising from episodic hydrometeorological events.

NUREG/CR-6729 builds on earlier research findings on infiltration and ground-water recharge estimation approaches using unsaturated zone instrumentation and analyses as documented in NUREG/CR-6653 (Timlin and others, 2000). This report focuses on state-of-the-science approaches which used automated piezometer instrumentation to obtain near-continuous measurement of water-table fluctuation, and analytic methods for estimating "real-time" ground-water recharge rates. The report also provides insights into data and conceptual model uncertainties at the site scale (hectare) for a shallow water table (less than 10 meter depth). The report discusses comparisons of estimation approaches using time-series analyses of hydrographs, steady-state estimates using meteorological data, and a water-budget model using detailed, site-specific data. The comparison of steady-state versus transient analyses provided insights into uncertainties introduced by analysis of infrequently measured data. The water-budget model used was developed by Pacific Northwest National Laboratory through a companion NRC- funded research project. The datasets and the programs developed for this study are available as computer-readable files from the USDA-National Agriculture Library. A significant observation from this work is that real-time, near-continuous piezometer measurements are very valuable for estimating ground-water recharge which captures episodic hydrometeorological events.

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1 INTRODUCTION AND OBJECTIVES

This report 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 infiltration 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. This report builds on NUREG/CR-6653, "Comparison of Estimated Ground-Water Recharge Using Different Temporal Scales of Field Data." The research reported here uses real-time, near-continuous piezometric heads to estimate ground-water recharge. These data come from existing field characterization data and monitoring programs at the Beltsville Agriculture Research Center (BARC) and come from the period June 1999 to December 2000.

Previous studies (e.g., Meyer and Gee, 1999) 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. Real-time, near-continuous monitored data may be useful if these conditions exist at a decommissioning site in order to appropriately model infiltration and net ground-water recharge.

In order to assess the safety of decommissioning and waste disposal facilities, infiltration and subsequent ground-water recharge calculations need to be performed as part of site characterization and facility performance analysis. The calculation of infiltration rates, infiltration capacity and ground-water recharge through the subsurface are needed to determine the leaching and transport potential of radionuclides associated with these facilities (Suen and Sullivan, 1993). Steady-state infiltration rates and properties can be determined directly using field methods such as the double-ring infiltrometer, or indirectly using soil water content and potential, and water-table fluctuation data in conjunction with site precipitation and evaporation data. Time-dependent infiltration and ground-water recharge estimates require "real-time" data. As part of the site characterization and performance analyses, uncertainty assessments need to be determined which include the effects of time-dependent infiltration and ground-water recharge calculations.

In recently completed research studies, the Agricultural Research Service (ARS) of the Department of Agriculture and RES staff (see Timlin and others, 2000) (reported in NUREG/CR-6653 "Comparison of Estimated Ground-Water Recharge Using Different Temporal Scales of Field Data") investigated field instrumentation [i.e., multi-sensor capacitance probes (MCP)] and analytical methods for estimating "real-time" infiltration and subsequent ground-water recharge and their attendant uncertainties. Similarly, the RES-funded study at Pacific Northwest National Laboratory (PNNL) (see Meyer and Gee, 1999) described information sources and analyses of soil hydraulic property distributions for use in dose assessment models related to decommissioning reviews. The PNNL scientists in their analysis emphasized the need to evaluate parameter and conceptual model uncertainties. Therefore, results from field studies can be used to confirm estimates of infiltration and ground-water recharge rates. Data derived from field studies in shallow ground-water systems may be helpful in assessing uncertainties related to decommissioning and waste disposal facility performance.

In the past, conventional approaches for characterizing deep infiltration and ground-water recharge focused on long-term estimates (e.g., annual or monthly). A premise to this field study is that shallow water tables in a humid climate are highly transient and dynamic. Therefore, an automated piezometer would provide real-time, near-continuous systematic data to quantify net ground-water recharge. Although annual estimates of ground-water recharge using water balance methods may be useful for deep unsaturated systems with infrequent rainfall events and very low antecedent water contents, they fail to capture significant episodic recharge events which may occur over short time periods (e.g., hourly or daily) in shallow ground-water systems. Another premise is that recording and analyzing piezometer fluctuations, as represented by real-time, near-continuous hydrographs, provides a direct method for estimating ground-water recharge for the shallow ground-water systems at the Beltsville site. Other less direct methods, such as automated multisensor capacitance probes (MCP) used to measure soil water contents, also provide real-time, near-continuous estimates but may not account for water movement in very wet soils. Finally, a network of automated piezometers over the ground-water recharge area can be used to characterize the spatial distribution and uncertainty of recharge.

The ARS is presently collecting and analyzing relevant infiltration and ground-water recharge data from field studies at their BARC field facilities. The field studies include data collection on a watershed scale and at a large, highly instrumented lysimeter (20 x 14 x 3 m) . For these studies, the databases developed include: a continuous real-time record of soil water content with depth using the capacitance probe; a non-continuous, specified time record of moisture content with depth using the neutron probe; a near-continuous, real time record of water-level fluctuations in the shallow-water table; and precipitation and evaporation data. In the watershed study, the water content data have been collected over many years, whereas the lysimeter study began in the summer of 2000. Piezometer measurements at the watershed study are planned for late 2001. It is anticipated that data will be collected for at least two additional years at the BARC field studies. At NRC-licensed facilities available field information on infiltration is often limited to intermittent shallow water-table level data and neutron probe or tensiometer data. Continuous real-time records are rarely available at any site.

Presently RES is funding two projects related to ground-water recharge estimation: (1) PNNL has developed and is presently testing a hydrologic parameter uncertainty assessment methodology which includes development of numerical approaches such as the PNNL Water Balance Model to estimate infiltration and ground-water recharge for a range of site conditions and soil hydraulic properties (e.g., hydraulic and transport parameter distributions organized by USDA soil texture class), and (2) the University of Arizona (UAZ) is developing and testing a methodology for assessing uncertainties related to conceptual ground-water models. The PNNL research focuses on hydrologic parameter uncertainties for dose assessments for decommissioning sites (Meyer and Taira, 2001). The PNNL report illustrates the use of site-specific data (such as reported in this report) to update parameter distributions used in dose assessment models (Meyer and Taira, 2001). This ARS-NRC cooperative field study and analysis is designed to utilize unique, real-time, near-continuous field datasets to augment uncertainty estimation approaches being developed at PNNL and UAZ. These BARC databases demonstrate the practical value of data-intensive infiltration and ground-water recharge field studies and calculations.

The objective of this particular field study was to examine uncertainties associated with five methods for estimating ground-water recharge: 1) Percentage of seasonal precipitation (**%P**); 2) Precipitation minus potential evapotranspiration (**P-PET**); 3) Changes in volumetric soil water content ($\boldsymbol{\Delta\theta_v}$) (using different temporal scales of water content measurements); 4) Piezometer measurements ($\Delta\nabla$) ; and 5) A water balance model (**WB**). Estimates using these five methods were compared to each other with the focus on understanding both their inherent and relative uncertainties.

2 DESCRIPTION OF FIELD SITE AND DATABASES USED

2.1 Field Site Description

This field study was conducted on a Mattapex silt loam (fine-loamy, mixed, mesic Aquic Hapludult) soil at the Henry Wallace Beltsville Agricultural Research Center, Beltsville, MD (Kirby et al., 1963). The plowed (Ap) horizon has about 35% sand, 56% silt, 9% clay, and 8 g organic C kg^{-1}. Textural analysis was performed, by soil horizon, using the Bouyoucos hydrometer method (Gee and Bauder, 1986). The 0.5-ha experimental site has a quasi-uniform 4% slope, with 26 plots (4.6 X 25 m) laid out on the contour. The experimental test plot site was previously tile drained at ~20-m intervals with clay tiles (~0.7-m depth) to a nearby embanked creek. The average annual precipitation is 1055 mm (derived from the 1949–1993 record) and is fairly evenly distributed throughout the year, but can be up to 200 mm in any given month. In the summer, precipitation often occurs during thunder-storms in which rainfall can be highly localized. The soil textures at the eight instrumented site locations are mostly silt loam at all depths (see Table 1). Plot 5 (Figure 1) has a somewhat coarser texture, grading to a loam soil at depths greater than 16 cm. The 50- to 70-cm depths at Plots 22 and 24 also have a coarser texture (sandy loam).

Figure 1. shows the layout of the field experiment with plot and automated piezometer locations (marked with a P).

Table 1 Soil textural class† near the eight capacitance probes (see Figure 1 for plot locations).

Plot	0–16 cm	16–30 cm	30–50 cm	50–70 cm
3	SiL	SiL to L	L to SL	L
5	SiL	L	L	L
4	SiL	SiL to L	SiL to L	SiL
6	SiL	SiL	SiL	SiL
21	SiL	SiL	SiL	SiL
23	SiL	SiL	SiL	SiL
22	SiL	SiL	SiL	SL
24	SiL	SiL	SiL	SL

†L loam, SiL silt loam, SL sandy loam.

Table 2 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).

File name	**Description**	**Variables**
Weather.mdb	Meteorological Data	Date, radiation, temperature, humidity, vapor pressure, wind speed, rainfall, evapotranspiration
NeutronP.mdb	Neutron Probe Data	Date, location, water content
MCP99-00.mdb	Near-continuous real time capacitance probe data for 1999-2000.	Day of year, time of day, water content, treatment, depth, season.

Table 3 Real time ARS datasets for estimation of uncertainties of ground-water recharge estimates associated with infiltration calculations.

Measurements	1995	1996	1997	1998	1999	2000
Capacitance Probes	✔	✔	✔	✔	✔	✔
Automated Piezometer (6)				✔ (1)	✔	✔
Manually read Piezometer	✔	✔	✔	✔		
Weather Station	✔	✔	✔	✔	✔	✔

2.2 Databases Used

The datasets listed in Table 2 include: a near-continuous, real-time record of water-level fluctuations in the shallow-water table, and precipitation, evaporation, radiation, temperature data, and soil moisture with depth using the capacitance probe. During the years 1996 to 1999, nine piezometer wells were manually monitored throughout the year. Table 3 provides a listing of measurement techniques, measurements made, and time period for the ARS database. The analytical methods used for the different data sources are summarized in Table 4. As shown in Table

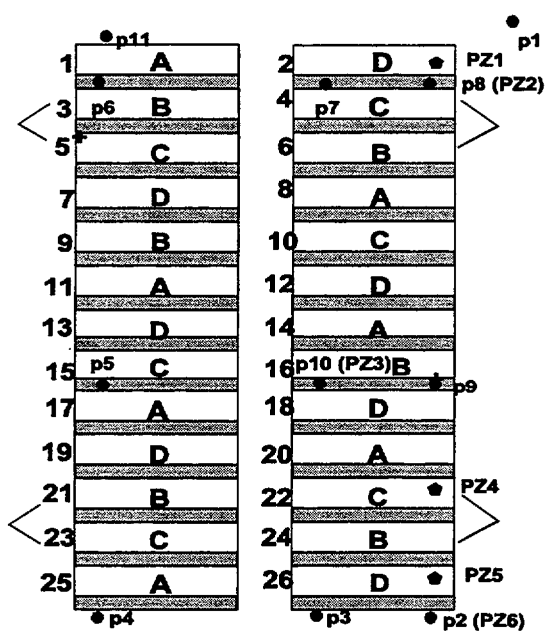

Figure 1. Layout and plot locations for the field studies. Filled circles indicate piezometer locations. Please see Table 5 and nomenclature section for definition of symbols. Piezometers noted with 'P' were not automated.

5, beginning in 1999 through 2001, the water-table levels were monitored at 10 minute intervals at six locations. Also, data from sixteen multisensor capacitance probes (MCPs) and six piezometers were monitored across a 0.5 ha

Table 4 Methods used to calculate net infiltration and drainage using the ARS Datasets. Θ refers to the value of water content measured by the moisture capacitance probe (MCP).

Value	Method	
	Multisensor Capacitance Probe	Piezometer
Infiltration rate (IR)	$(\theta_{i-1}-\theta_i)/(\text{time}_i-\text{time}_{i-1})$ (summed over profile)	n/a
Infiltration capacity	max of IR	n/a
Cumulative net infiltration (cumIR)	Sum of positive changes in θ for profile	Hydrograph analysis
Effective porosity	θ_{max}-θ drained (24 hours after rainfall, summed over profile)	n/a
Specific yield	n/a	Total positive change in piezometric head divided by rainfall amount for selected spring rainstorm periods
Net deep percolation	sum of negative changes in θ for profile (plant uptake of water accounted for)	Hydrograph analysis

field site from 1995 through 2000, with the plot layout with instrumentation presented by Starr and Paltineanu (1998). The analysis of the MCP data is documented in NUREG/CR-6653. More details are given in Appendix A.

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* II (change table with piezometer data).

2.2.1 Piezometer Data

From 1995 to 1998 there were eight piezometers that were read manually at 3 to 7 day intervals depending on the weather. If there was rainfall, the piezometers were read as soon as possible after the rainfall. Their locations are shown in Figure 1. Starting in 1998, pressure transducers (Druck Incorporated, Fairfield CT, USA) were installed in each tube to automatically monitor water-table levels (piezometric head). A 10-minute recording interval was used (Table 5). Data were recorded and stored by data-loggers and the data downloaded at frequent intervals (usually weekly). The measurement resolution of the transducers was ± 1 cm. In July of 2000, three of the piezometers (pp04, pp05, and pp06) and transducers were moved and installed on a transect on the east side of the field and renumbered (plots pl02, pl22, pl26, Figure 1 and Table 5). Piezometric heads and rainfall for one site over the course of a year (1999) are shown in Figure 2. This figure demonstrates the detail captured by the automated real-time, near-continuous piezometers. A short time period of data from the piezometer database is shown in Table 6 and a representative hydrograph for one rainfall period is shown in Figure 3 along with cumulative rainfall for the piezometer located at position pp02 (see Figure 1). The maximum piezometric head was 300 mm during this episodic rainfall event. This event occurred toward the end of the summer when the water table was just beginning to rise after the dry summer. The piezometric head at this location exceeded one meter later in the winter.

Table 5 Time periods for automatic piezometer readings collected at 10-minute intervals (note that piezometers at locations Pz4, Pz5, and Pz6 were moved in July 2000 to locations in Plot2, Plot 22 and Plot 26).

Start	End	Pz2	Pz4	Pz5	Pz6	Pz8	Pz10	Plot 2	Plot 22	Plot 26
Apr-98	Apr-99	X								
Apr-99	Jul-00	X	X	X	X	X	X			
Jul-00	continuing	X				X	X	X	X	X

Table 6 Example of piezometer data base. The column headings indicate piezometer location, depth to ground-water is mm from the land surface to water table. Head is the height of the water table above the bottom of the piezometer tube.

Date	Time	Location	Depth to ground water (mm)	Head (mm)
09/06/1999	18:10:00	pp02	-1880.	10.
09/06/1999	18:20:00	pp02	-1879.	11.
09/06/1999	18:30:00	pp02	-1879.	11.
09/06/1999	18:40:00	pp02	-1881.	9.
09/06/1999	18:50:00	pp02	-1880.	10.
09/06/1999	19:00:00	pp02	-1880.	10.
09/06/1999	19:10:00	pp02	-1878.	12.
09/06/1999	19:20:00	pp02	-1880.	10.
09/06/1999	19:30:00	pp02	-1879.	11.
09/06/1999	19:40:00	pp02	-1880.	10.
09/06/1999	19:50:00	pp02	-1880.	10.

The full data set is available as a computer readable file.

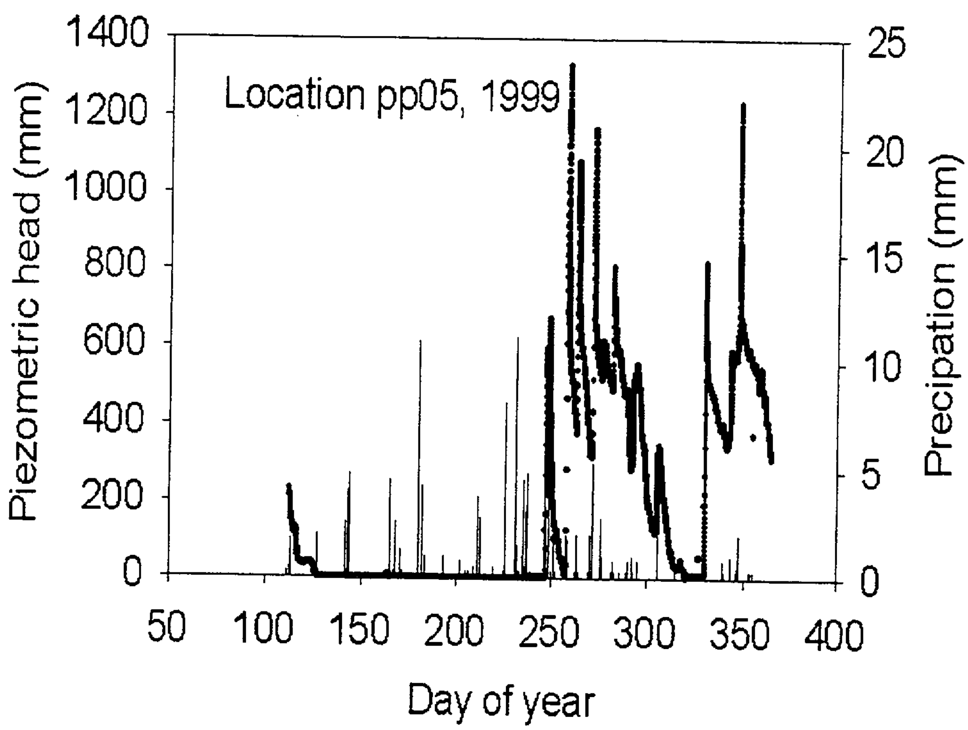

Figure 2. Hydrograph for an automated piezometer [dot symbols-(high density of symbols appear as a bold line)] and rainfall (vertical lines) for the piezometer located at site pp05. Note the rapid response to rainfall and the detailed fluctuations in water-table height. There was no measurable recharge during the period from day 125 to 250

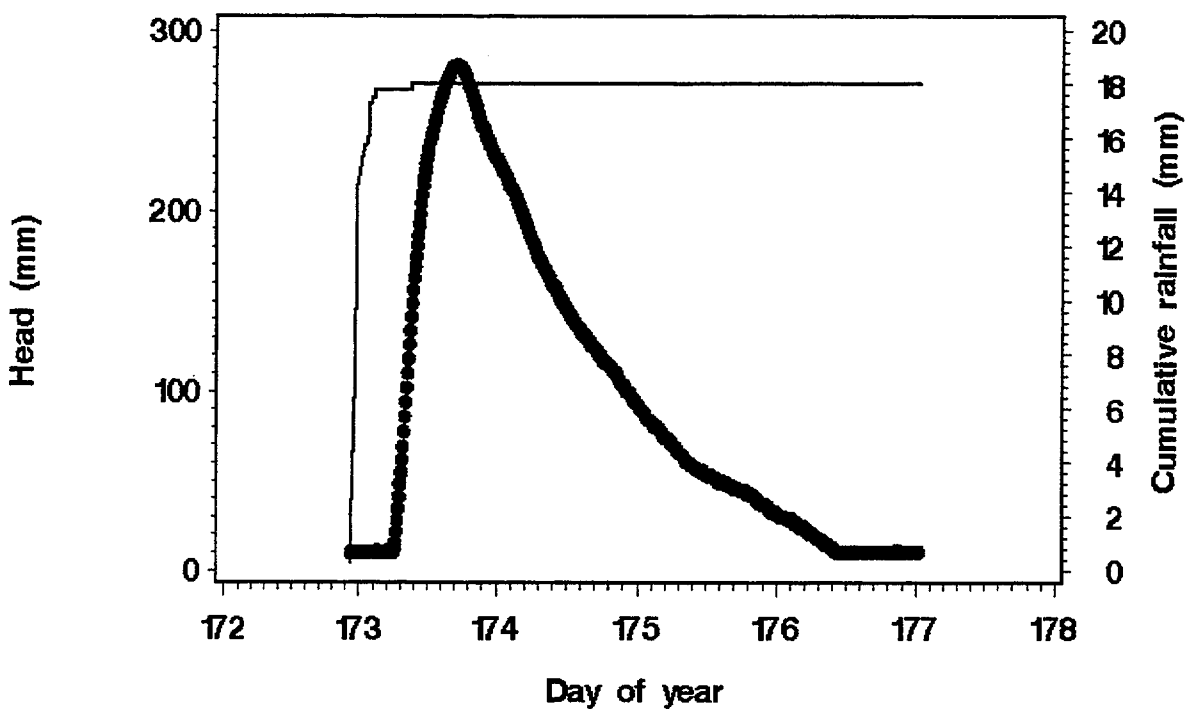

Figure 3. Representative hydrograph (bold dots) from piezometer pp02 for a rainfall (thin line) event during the summer of 2000. The recession is the falling limb of the curve beginning on day 174 and ending midway through day 176. Note the rapid rise (response) of the water table to the rainfall event and the slower drainage. Total rainfall was 18 mm.

2.2.2 Meteorological Data

A Campbell (Campbell Scientific, Logan, Utah, USA) weather station near the site provided data on rainfall, air temperature, radiation and wind speed and direction. Rainfall data were recorded at 5 minute intervals, radiation, temperature, and wind data were recorded at 15 minute intervals. Evapotranspiration was calculated using the Penman equation (Penman, 1963; Timlin et al., 2001, Appendix 16) for 15 minute time intervals using radiation, temperature, and wind speed.

The meteorological data were grouped into three seasons. The winter-spring (*ws*) season represented the period from January 1 to April 30; the summer (*su*) season represented the period from May 1 through August 30; and the fall-winter (*fw*) season represented the period September 1 through December 31. The time boundaries are given in Tables 7 and 8.

Table 7 summarizes the real-time weather data base and Table 8 shows the structure of the weather database and partial listing of the weather data.

The weather data were further subdivided into 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

Table 7 Summary of real-time rainfall data and temperature for 1999 to 2000. The data are summarized by season and the time period for each season is also given. The seasons are winter spring (ws), summer (su), and fall-winter (fw). ET was calculated using the Penman Equation (Penman, 1963)

Year	Season	First day of season	Rain (mm)	ET (mm)
1999	ws	01/01/1999	535.94	338.74
	su	05/07/1999	212.34	684.73
	fw	09/04/1999	370.07	265.40
	Total		1118.4	1288.9
2000	ws	01/01/2000	266.19	293.39
	su	05/02/2000	379.48	577.54
	fw	09/02/2000	171.96	261.14

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 (Statistical Analysis System, SAS Inc, 1998) by calling the FORTRAN program "*ClassRn.for*" (see Appendix B4). The program "*ClassRn.for*" classifies the rainfall events by rainfall occurrence as shown in Figure 4.

Each potential recharge period was given an ID (*rainid*). The ID's were numbered consecutively for each recharge period. All 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). The ID, *rainid,* was extended to the beginning of the next rain event. This provided for continuous potential recharge periods. The rainfall ID's also allowed us to group calculations according to a recharge event ID.

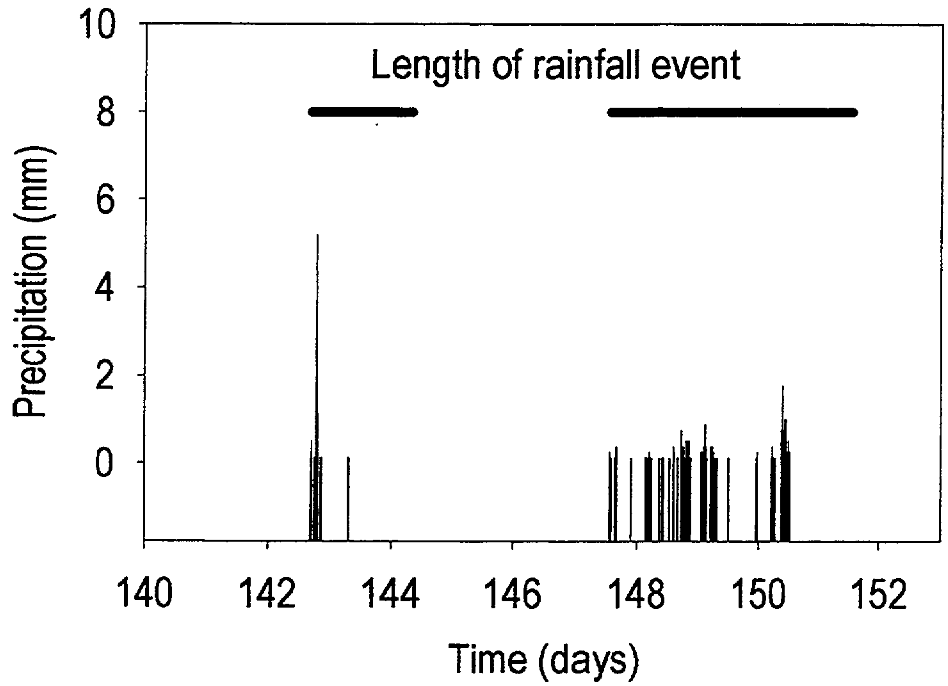

Figure 4. Schematic of method for discriminating rainfall events. This figure shows two discrete rainfall events that have been classified.

At certain times, freezing of the soil and snowfall delayed water movement to the water table. While these periods did represent significant recharge, these periods were eliminated from the analysis. This was done to facilitate comparisons among periods with similar conditions. The rainfall period was not used in the analysis if more than 25% of the days within the period had 4 or more hours of temperatures below freezing.

Rainfall data were merged with the SAS data sets containing the piezometer data.

2.2.3 MCP Data

These data have been discussed in Timlin and others, 2000. Additional information is given in Appendix A along with updated results.

Table 8 Real-time rainfall and data from a selected time on September 9, 1999. Rain and ET are in mm. **Rain ID** is the rainfall period.

Day	Time	Rain (mm)	ET(mm)	Season	Rain ID
09/06/1999	18:10:00	0.000	0.000243	fw	52
09/06/1999	18:20:00	1.016	0.000160	fw	52
09/06/1999	18:30:00	0.254	0.000076	fw	52
09/06/1999	18:40:00	0.000	0.000039	fw	52
09/06/1999	18:50:00	1.270	0.000020	fw	52
09/06/1999	19:00:00	1.016	0.000000	fw	52
09/06/1999	19:10:00	1.016	0.000000	fw	52
09/06/1999	19:20:00	0.762	0.000000	fw	52

3 METHODOLOGY

General assumptions for this study were: no lateral subsurface movement of water and runoff was considered to be negligible. Specific assumptions for each method are described in the text of this report. Measurements of piezometric head changes around rainfall events can then be expected to capture most of the water that goes to ground-water recharge. Estimation of ground-water recharge under freezing conditions were not considered. We believe these assumptions were appropriate for this site under the given field conditions.

The piezometer data were checked for errors and inconsistent values. In some cases there were missing values in a series. The missing values were filled in using *Poc Expand* (SAS, 1997, see Appendix B5). The number of interpolated values were less than 0.5% of the number of values in the series.

Net ground-water recharge was estimated using indirect methods (percentage of annual precipitation or precipitation -evapotranspiration) or more direct methods which relied upon real-time, near-continuous piezometer measurements ($\Delta\underline{\nabla}$). Figure 1 shows a diagram of the piezometer locations. Figure 3 is a representative hydrograph showing the water-table response following a rainfall event. This methodology involves a time-series analysis of the hydrograph.

3.1 Methods Used to Estimate Ground-Water Recharge

The following is a summary of the methods used. A schematic showing ground-water recharge as related to the different methods is shown in Figure 6. SAS Programs for the different methods are listed in Appendix B.

A. **Time-series analysis of hydrographs**

Changes in piezometric head ($\Delta\underline{\nabla}$). Piezometers were used to record water-table height at 10 minute intervals.

- ***Recession analysis method***: Final head - initial head + **recession** (estimated from hydrographs during drainage) (Dingman, 1994) (***R***)
- ***Sum of positive changes*** during a rainfall period ($\Sigma+\Delta$)
- ***Impulse-response*** (Dingman, 1994 p. 340) (***I_R***)

B. **Steady-state methods** that rely on meteorological data

- ***35% of precipitation*** (*%***P**)
- Potential evapotranspiration subtracted from Precipitation(**P-PET**)
  PET was calculated using the Penman equation

C. **Numerical methods**

- ***Water balance model*** (**WB**) (Simmons and Meyer, 2000) Net ground-water recharge was also estimated using predictive models which require soil properties and/or meteorological data.

D. **Other**

- ***Volumetric soil water content changes*** ($\Delta\theta_v$). Three approaches used measured soil water content (from MCP instruments) data to estimate ground water recharge. These varied in the level of temporal detail. (For this study, flux at the 50-cm depth was defined as ground-water recharge (see Appendix A) .

3.2 Time-Series Analysis of Hydrographs

3.2.1 Recession Analysis Method (*R*)

The predictive models required an estimate of the recession rates describing the decrease in head with time on the recession limb of the hydrograph. The recession rate parameters were estimated directly from selected hydrographs and from the data using regression analysis. The data were segregated by location and rainfall event and then filtered to retain only heads where there were negative head changes over one hour. An autoregressive model was used to determine the recession parameter:

$$h_i = a \, h_{(i-1)} + \varepsilon \qquad [1]$$

here a is the autoregressive parameter that defines the change in head (h) in time period, i as a function of the head in the previous time period (i-1) and ε is the lack of fit error. Recession of piezometric head (h) when there is no rainfall can be described as (Dingman, 1994):

$$h_i = h_{(i-1)} \exp(-k \; \Delta T) \qquad [2]$$

A comparison of equations [1] and [2] suggest that the coefficient, k, can be determined from the autoregressive parameter, a where $k=ln(a)/\Delta T$. The coefficients, k, were calculated for each rain event using SAS; the program is listed in appendix B. Cumulative head adjusted for recession was calculated from equation [2] as:

$$cum\_h_i = h_i - \sum_{j=1}^{i} RC_j \qquad (i_{1......n})$$

$$\text{where:} \qquad [3]$$

$$RC_j = h_j \times \left(1 - \frac{1}{\exp(-k\Delta T)} \right)$$

where cum_h_i is cumulative head to time i, the piezometric head that results when there is no recession. Since the *recharge*, RC_i is less than zero, it must be subtracted from head, h_i to add the recession back to the piezometric head at each time step. When the summation is completed over the data series *{i=1, n}* for one rainfall event the final head, cum_h_n (when multiplied by specific yield) represents the water added to the water table through deep percolation.

The recession coefficient can vary significantly among rainfall events, locations and years (Table 9). The recession coefficient k, a flow parameter, is lognormally distributed. In order to provide an estimate of uncertainty due to the recession parameter, recession was characterized using non-parametric methods. These were:

1. The recession coefficient, k, is a median of all the recession coefficients from all the rainfall events calculated for a location ($\mathbf{R}_1$),
2. The recession coefficient is the median of recession coefficients from only the rain events in the winter/spring. This evaluates the effect of using a recession coefficient calculated from data from a single time period ($\mathbf{R}_2$), and
3. The individual recession coefficients from each rainfall event were used ($\mathbf{R}_3$).

The recession coefficient also varies with the water-table elevation (Figure 5). The recession coefficient increases as water-table elevation decreases. There are several possible explanations for this observation. These include an increase in permeability in the deeper layers of soil. Another reason is that as piezometric head is decreasing, both lateral and vertical inputs will also be decreasing. The head will appear to decrease faster because there is less water coming into the water table as it recedes.

3.2.2 Analysis of Sum of Positive Changes During a Rainfall Period (Σ+Δ)

The increase in piezometric head due to ground-water recharge can be calculated by taking differences of head over 10 minute periods and then summing the positive differences. The changes in head remain positive and there is no recession due to drainage. In practice the differences are calculated by differencing the value of piezometric head from 6 time periods in the past (1 hour) and the current value of head. The differencing is still done with the 10 minute data so there is no loss of fine-scale information. The use of the 1 hour lag will reduce the fluctuations in the differences.

The data are so dense in time that there is little loss in information by segregating the data into increasing (recharge) and decreasing (recession) components. When recession is added back to a hydrograph there should be no change in water table with time (plateau) or only positive changes (recharge).

3.2.3 Impulse-response Method (*I_R*)

This method is described by Viswanathan (1984). This method uses the time series of rainfall and the hydrograph in autoregression. In this model the head at any time i, is a function of the head at a previous time, i-1, and the rainfall at time i, and previous times, i-1, i-2, etc. The model is given as:

$$h_i = a_1 h_{i-1} + b_1 P_1 + b_2 P_{i-1} + b_3 P_{i-2} + b_4 P_{i-3} + \varepsilon \quad [4]$$

where h is piezometric head, P is rainfall, and ε is the error. Here i is the lag, i.e., the previous time period. The piezometer data used in this study were collected at 10-minute intervals, therefore the i's refer to 10 minute time periods. For example *i-1* is the rainfall in the previous 10 minute period and *i-2* is the rainfall in the previous 20 minute period. Generally, Viswanathan (1984) recommended that the time period for the lag of rainfall (*i-1*, *i-2*, etc) extend to one to two days in the past depending on how long it takes the rainfall to infiltrate the soil, percolate through the root zone, and reach the water table.

The coefficients for RC (estimated recharge), i.e., b_1, b_2, etc. theoretically define how high the water table rises for each unit of rainfall. Viswanathan reported that the recharge to ground water due to rainfall could be estimated as:

$$\Delta h_i = b_1 P_i + b_2 P_{i-1} + b_3 P_{i-2} \quad \textbf{[5]}$$

Table 9 Medians and quartiles for the recession coefficients for 1999 and 2000 (units are d^{-1}).

Year	Location	Upper quartile	Median	Lower quartile
1999	pp02	-0.801	-0.371	-0.117
1999	pp04	-0.249	-0.162	-0.119
1999	pp05	-0.569	-0.290	-0.164
1999	pp06	-0.161	-0.113	-0.069
1999	pp08	-0.689	-0.287	-0.204
1999	pp10	-0.544	-0.411	-0.317
2000	pl22	-0.231	-0.161	-0.102
2000	pl26	-0.218	-0.125	-0.069
2000	pp02	-0.269	-0.095	-0.054
2000	pp04	-0.174	-0.095	-0.074
2000	pp05	-0.214	-0.098	-0.062
2000	pp06	-0.202	-0.087	-0.072
2000	pp08	-1.319	-0.252	-0.101
2000	pp10	-0.4136	-0.2908	-0.2011

Note that the coefficient *a* for h_{i-1} in Eq. [4] defines the recession of head during the time period from *i-1* to *i*. Extending this analogy, Viswanathan concluded that total recharge *could be* calculated as:

$$RC = S_y \left(\sum_{i=1}^{n} b_i \right) P_i. \qquad [6]$$

where S_y is specific yield and n is the number of time series coefficients in Eq.[5]. It was shown by Viswanathan that the coefficients *b* in Eq. [5] and [6] are time variant and need to be adjusted for season.

In order to calculate the coefficients, b_i, the data were grouped by season and autoregression was applied for each season. The measurement interval of the data of Viswanathan was daily. The 10-minute rainfall data used here have a much higher autocorrelation than daily data. As a result, the use of 10 minute lags would not be statistically efficient. Six lags of rainfall were used, namely 10, 20, 30, 60, 120, and 1440 (one day) minute periods. Based on observation of the hydrographs it appeared that rainfall had an immediate effect on the piezometer readings due to the shallow depth of the table (less than 2 meters). The effects of rainfall on the hydrographs after a period of one day were not seen.

The resulting coefficients for rainfall were summed and multiplied by total rainfall for the season and specific yield as in Eq. [6]. This provided an estimate of recharge.

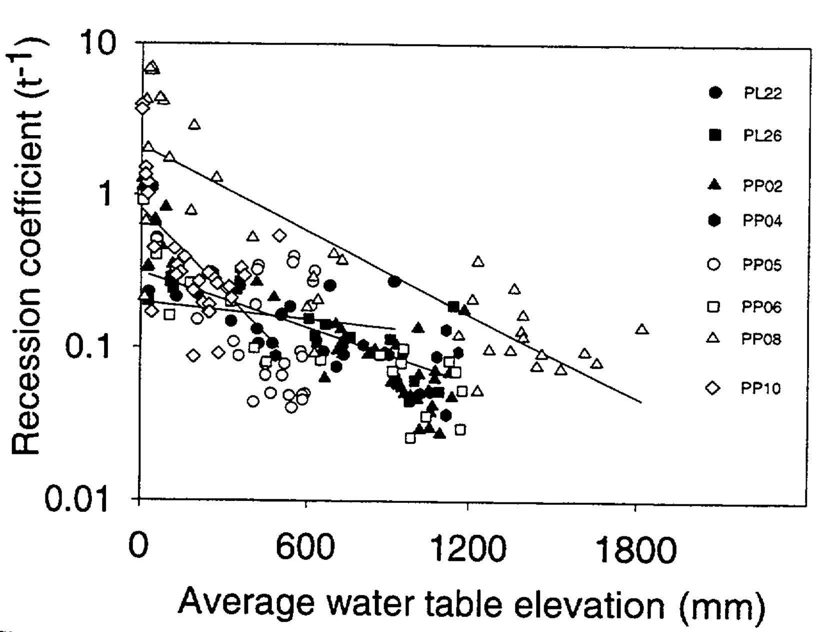

Figure 5. Relationship between recession coefficient as determined from Eq. [2] and average water-table elevation.

3.2.4 Estimation of Specific Yield

The specific yield is used to estimate how high the water table will rise as a function of the net amount of water infiltrating from the surface, i.e., from rainfall or irrigation. This parameter is difficult to measure because the sample must be taken from deep in the profile.

Three rain events in the fall of 1999 and three rain events in the spring of 2000 were chosen for specific yield estimation. It was assumed the soils would be saturated at this time such that most of the rain input at the soil surface would reach the water table. The hydrographs for these rainfall events also did not display any unusual or anomalous features. The total increase in piezometric head was calculated by summing the positive changes in head and subtracting the piezometric head at the beginning of the rain event period from this value. This increase in head was divided by the total rainfall for the period to provide an estimate of specific yield (S_y). Values for the two years are given in Table 10. Notice the large standard deviation for some of the locations. The specific yields for locations pp02, pp04, and pp05 are not significantly different from each other. The smallest values for both years are associated with location pp08.

Table 11 provides information on representative values of specific yield, porosity and hydraulic conductivity for various aquifer materials. The common subsurface materials in the study site are silts, clays and gravels. The smallest values of specific yield in Table 11 correspond to silts and clays. The values of specific yield in Table 11 are representative values and are likely to exhibit considerable variability. The calculated specific yield values in Table 10 vary from 2 to 10%; this is within the range of specific yield for silts and clays in Table 11 (3 to 8%).

Table 10 Calculated Specific yields for piezometer data

	S_y 1999		S_y 2000	
Piezometer	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
		%		
pp02	4.4	1.6	5.8	1.8
pp04	3.4	1.0	4.2	1.2
pp05	4.3	1.3	4.7	0.8
pp06	9.1	7.1	5.3	2.1
pp08	1.5	0.5	2.5	0.9
pp10	0.2	9.2	6.0	2.0

Table 11 Representative values of physical parameters associated with various types of aquifer materials (from Tables 2.1, 2.5 and 3.1 of Todd(1980) after Johnson (1967), Morris and Johnson (1967) and USGS Water-Supply Paper 813, from http://data.ecology.su.se/mnode/gwtable_1.htm.

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

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

3.3 Steady-State Methods That Rely on Meteorological Data

When detailed piezometer and water content measurements are not available, ground-water recharge is often estimated from seasonal or annual meteorological data (see Section 2.2.3). These methods assume steady-state fluxes to the water table. Two steady-state methods were used: a percentage of seasonal precipitation (%P); and the difference between precipitation (P) and potential evapotranspiration (PET) rates (P-PET). Seasonal P and PET values were used. Specifically for this site, 35% was used as a percentage of rainfall that reaches the water table on an annual basis. PET was calculated using the Penman equation (Penman, 1963; Timlin and others, 2001).

3.4 PNNL Water Budget Model

Net ground-water recharge can be estimated using predictive models which require soil properties and meteorological data. Input data for predictive models can be either directly or indirectly determined. There are different levels of aggregation and estimation of the input data and soil properties. Depending on the level of aggregation, additional error may be introduced.

The purpose of the modeling is to estimate cumulative net infiltration and recharge using a simulation model and measured meteorological data. The model, WatBudget (Simmons and Meyer, 2000), is a simple, quasi-analytical water budget written for MathCad v. 8.0 (http://www.mathsoft.com/) for estimating daily water drainage from a bottom of a predefined soil depth. Meteorological data from 1996 through 2000 were used as input. Soil hydraulic properties were inferred from the MCP database (Timlin and others, 2000).

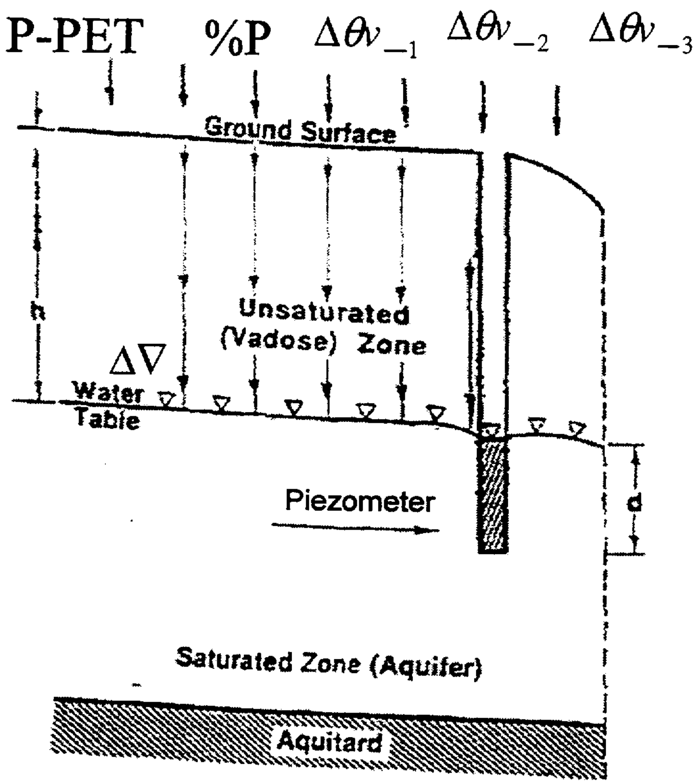

Figure 6. Schematic of the different recharge calculation concepts (adapted from Yu et al., 1993). Please note that d is the water table head measured by the transducer at the base of the piezometer.

4 UNCERTAINTY ANALYSIS AND RESULTS

4.1 Ground-Water Recharge Estimates Using Real-Time, Near-Continuous Piezometer Data

4.1.1 Calculation of Recession from Hydrographs

Hydrographs (see Figure 2) show piezometric head fluctuations. Based on ground-water studies, water is draining from the shallow aquifer to the nearby creek even as the water table rises. Later, as water loss exceeds input, the water-table elevation, as measured in the hydrograph, recedes. In order to calculate total ground-water recharge, the recession during this input must be calculated (Dingman, 1994). Figure 7 shows the results of several methods (described in Section 3) that account for this recession. This figure shows "hydrograph with recession." Note that among the time-series methods that use a recession coefficient, the maximum head with recession is generally higher than the measured maximum head. Theoretically, the recession-adjusted piezometric head should be level (invariant with time). However, when the recession coefficient is derived from the median of the Spring season values, the adjusted piezometric head is almost level (slightly time variant). When the overall median recession coefficient is used, the adjusted piezometric head varies greatly (positive or negative time variant). Generally, the use of the summation of positive changes, produces the most consistently level (relatively time invariant) adjusted piezometric head. The use of the overall median of the recession coefficient may provide a higher or lower estimate of recession than the use of the recession coefficient from the event itself.

When recession is added back to the hydrograph the result should only show either positive increases in head or be level where only recession is occurring. The use of positive changes in head and a recession coefficient from the individual rain event gives hydrographs (Figure 7) with characteristics closest to this ideal. Use of an overall median recession coefficient in these examples overestimates recession in the example. The estimate of net ground-water recharge is the difference between the initial and final points of the adjusted hydrograph (see Figure 7). When the final points of the curve are too high (as when the overall median of the recession coefficient is used), the adjusted piezometric head is overestimated. Therefore, this results in an overestimated ground-water recharge for these examples.

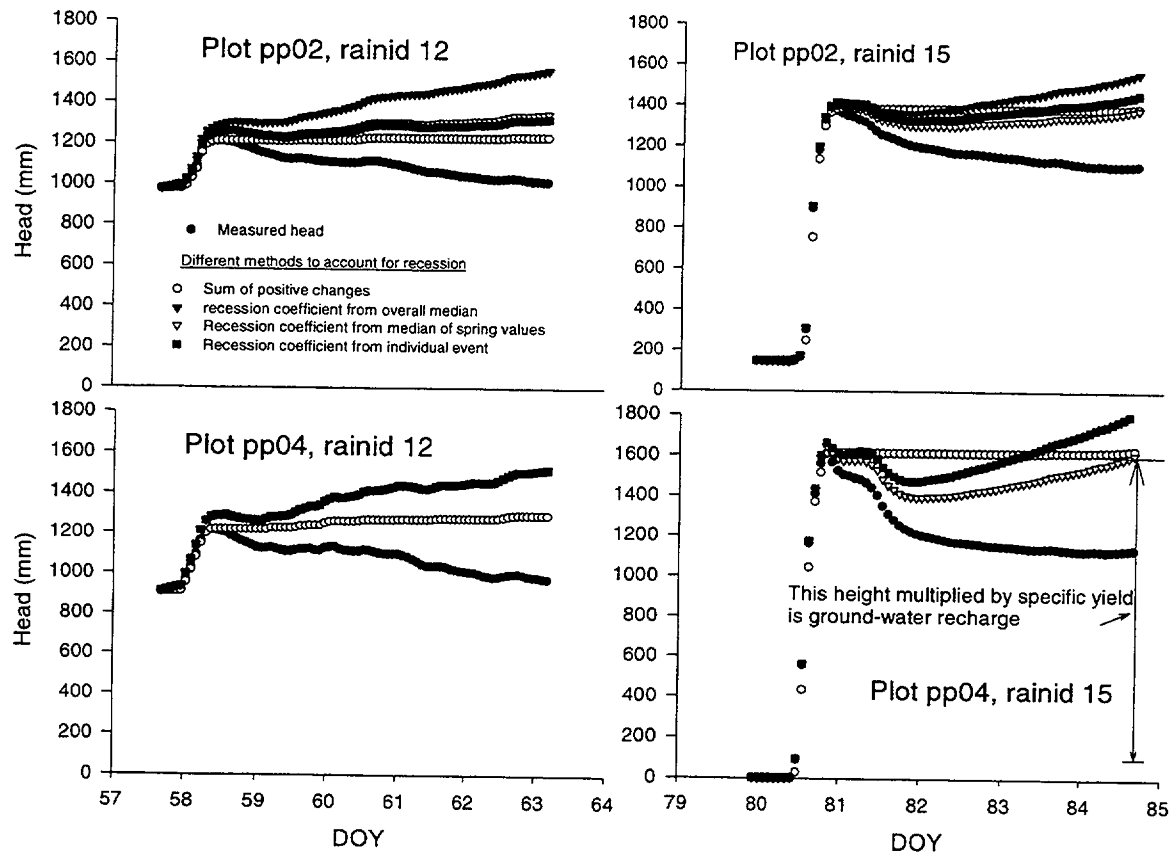

Figure 7. Hydrographs showing measured piezometric head, and head adjusted for recession. The examples are from two locations and two representative rainstorms. Ground-water recharge is calculated as the difference between the initial head and final head adjusted for recharge (from Dingman 1994).

4.1.2 Recharge Estimates from Piezometer Data

Figures 8 and 9 show the comparative analysis of the different steady-state and transient time-series methods used to estimate net ground-water recharge. The estimated recharge patterns were different for the two years of record and by season. For 1999, as shown in Figure 8, most of the ground-water recharge occurred in the fall/winter season. Unfortunately, piezometer data were incomplete for the entire winter/spring season and the incomplete data indicated no ground-water recharge. For 2000, as shown in Figure 9, there were large estimates of ground-water recharge for all three seasons. The smallest estimates were for the fall/winter season. Year 2000 was atypical because most of the rainfall occurred in the summer season (i.e., la niña).

Net ground-water recharge estimated by the steady-state meteorologically-based methods was generally much less than that estimated by the time-series analysis methods using real-time, near-continuous piezometric data. According to the analysis, there was rarely any seasonal recharge estimated by the **P-PET** method. This is probably because rainfall is not uniformly distributed over the season. The soil water decreases between rainfall events and the soil does not support potential rates of evaporation so that actual evapotranspiration can be much lower than potential. This is especially true during the spring and summer months when there is an actively growing crop and ET is large. When rainfall occurs, the amount of rainfall is often sufficient to wet the soil to saturation allowing further rainfall to become ground-water recharge. The estimates based on a percentage of rainfall (**%P**) often underestimated ground-water recharge but produced values of recharge higher than the **P-PET** method. The use of a value of 35% to proportion rainfall to ground-water recharge is somewhat arbitrary but illustrates the problems with assuming that a constant proportion of rainfall becomes ground-water recharge. While the mean value for a year or for a number of years can give reasonable "average" estimates of ground-water recharge, it is still highly inaccurate for estimation of seasonal or event-based recharge. Based on yearly averages, one could conclude that "on the average" recharge is small, but in actuality, significant ground-water recharge for specific events or periods occurs.

Among the time-series analysis methods, there were differences in mean values, however the variance was so high that it is difficult to ascertain a significant difference in these methods. The impulse-response method (**I_R**) estimates were consistently lower than for the other time-series methods. The summation of positive changes in head method (**Σ+Δh**) was the simplest time-series method to implement. The recession coefficient methods (R_1,R_2 and R_3) were the most complicated time-series methods. A disadvantage of the recession coefficient and impulse-response methods was the need to estimate parameters which introduces uncertainty.

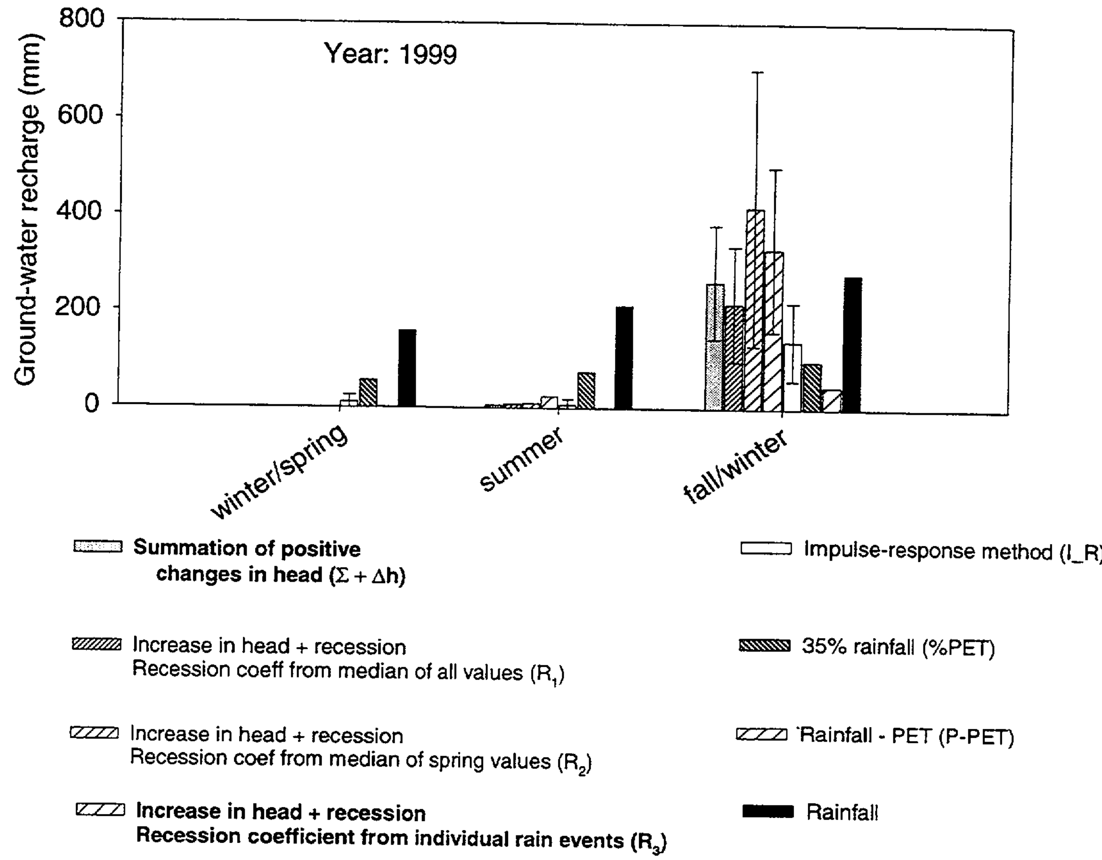

Figure 8. Ground-water recharge estimated using near-continuous piezometer and meteorological data for 1999. Note that the method of **P-PET** estimated no recharge for the winter/spring and summer seasons.

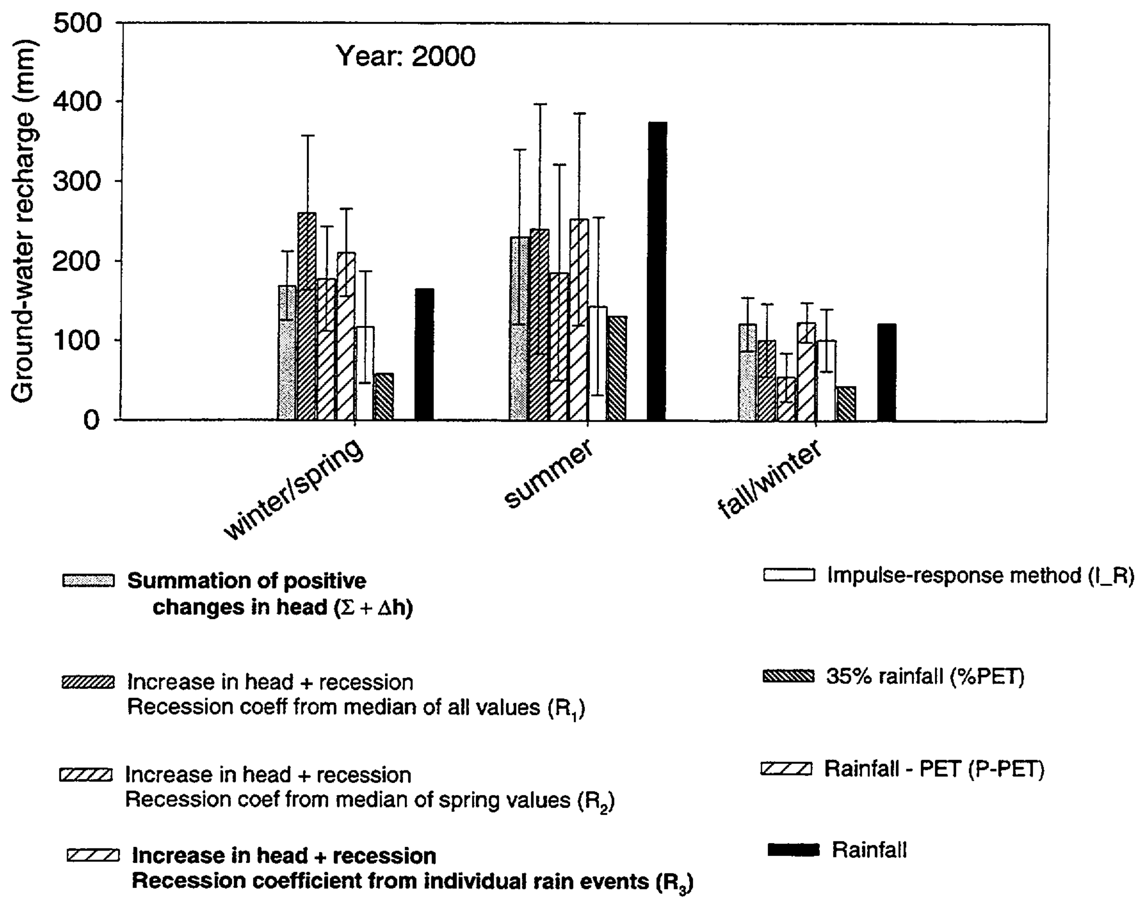

Figure 9. Ground-water recharge estimated using near-continuous piezometer and meteorological data for 2000. Note that the method, **P-PET**, estimated no ground-water recharge for the three seasons.

4.2 The PNNL Water Budget Model

The PNNL Water Budget Model[1] was used to calculate actual evapotranspiration and drainage using meteorological data from the site. The values of the parameters used in the model are given in Table 13. These input parameters were selected from the MCP data and represent mean values (Timlin and others, 2000). The results of the simulations are given in Figures 10 and 11. Surprisingly, there are little differences in the PNNL model recharge estimates for the three seasons in 2000, even though there were large differences in rainfall and in the time-series estimates. This observation may be explained by dependence of the PNNL model on daily meteorological data and evapotranspiration estimates, whereas the time-series estimates used real-time, near-continuous piezometer data. Also, the PNNL model estimates recharge by calculating a water balance using precipitation and evapotranspiration. While it does account for flux-limited evapo-transpiration when the soil is dry, the water content when rainfall occurs is estimated from the water budgeting procedure. The antecedent water content, the upper limit of water availability (commonly called "field capacity") and the rate at which water moves from surface horizons to subsurface horizons determines ground-water recharge estimates using this model. If the upper limit of available water is high of internal drainage rates low, more water remains close to the soil surface where it is available for evapotranspiration. As a result, less water will be available for ground-water recharge.

As demonstrated in the earlier application of the PNNL model (Timlin and others, 2000), the PNNL model gave similar estimates for net ground-water recharge as that estimated from MCP data. 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 is 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 (Timlin and others, 2000). However when compared to time-series estimates based on real-time, near-continuous piezometer data, the PNNL model strongly underestimates recharge. This suggests that the MCP data may also underestimate recharge during fall/winter and winter/spring periods for reasons given above. This assumes that the characteristics of the 1995-1997 meteorological data are not greatly different from the 1999-2000 year record.

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

Table 12 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

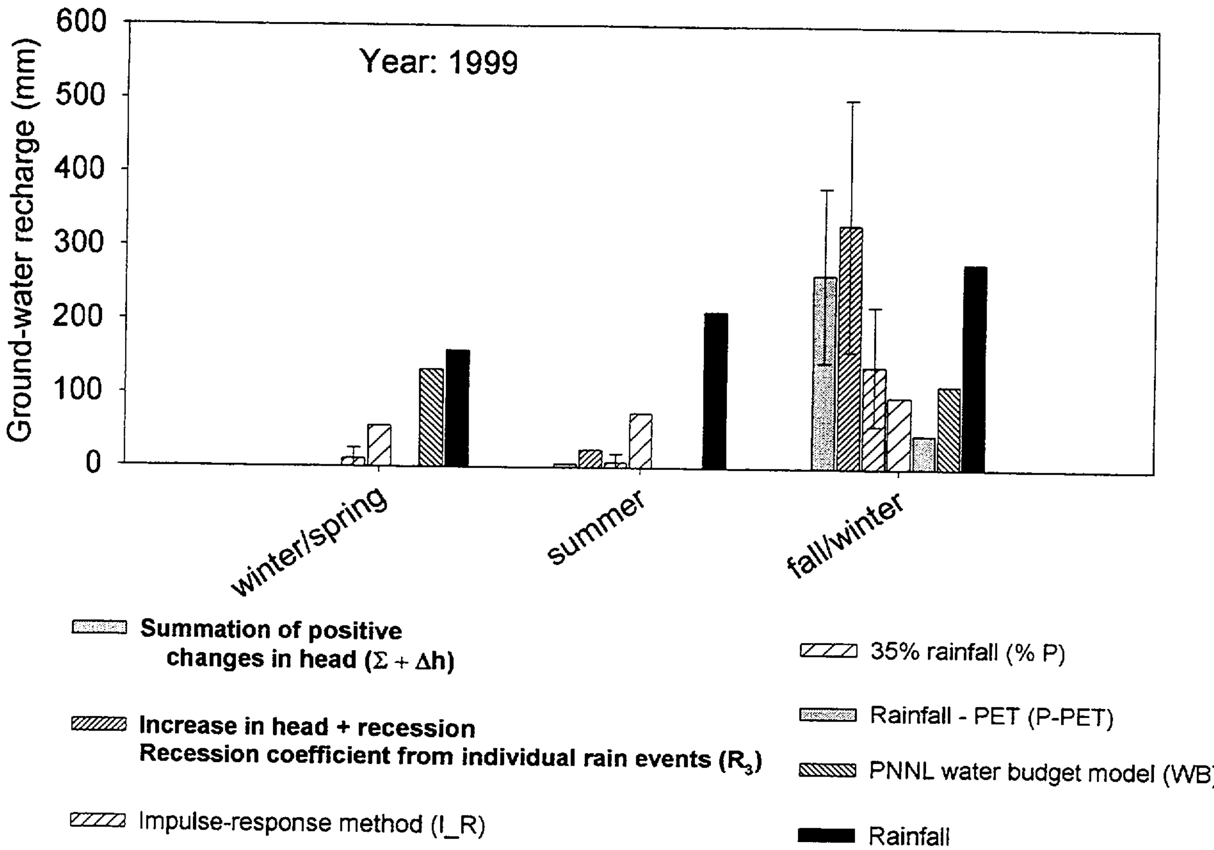

Figure 10. Ground-water recharge for the year 1999 estimated from near-continuous piezometer data and estimated using the PNNL water budget model. There were few piezometer data for the winter/spring season.

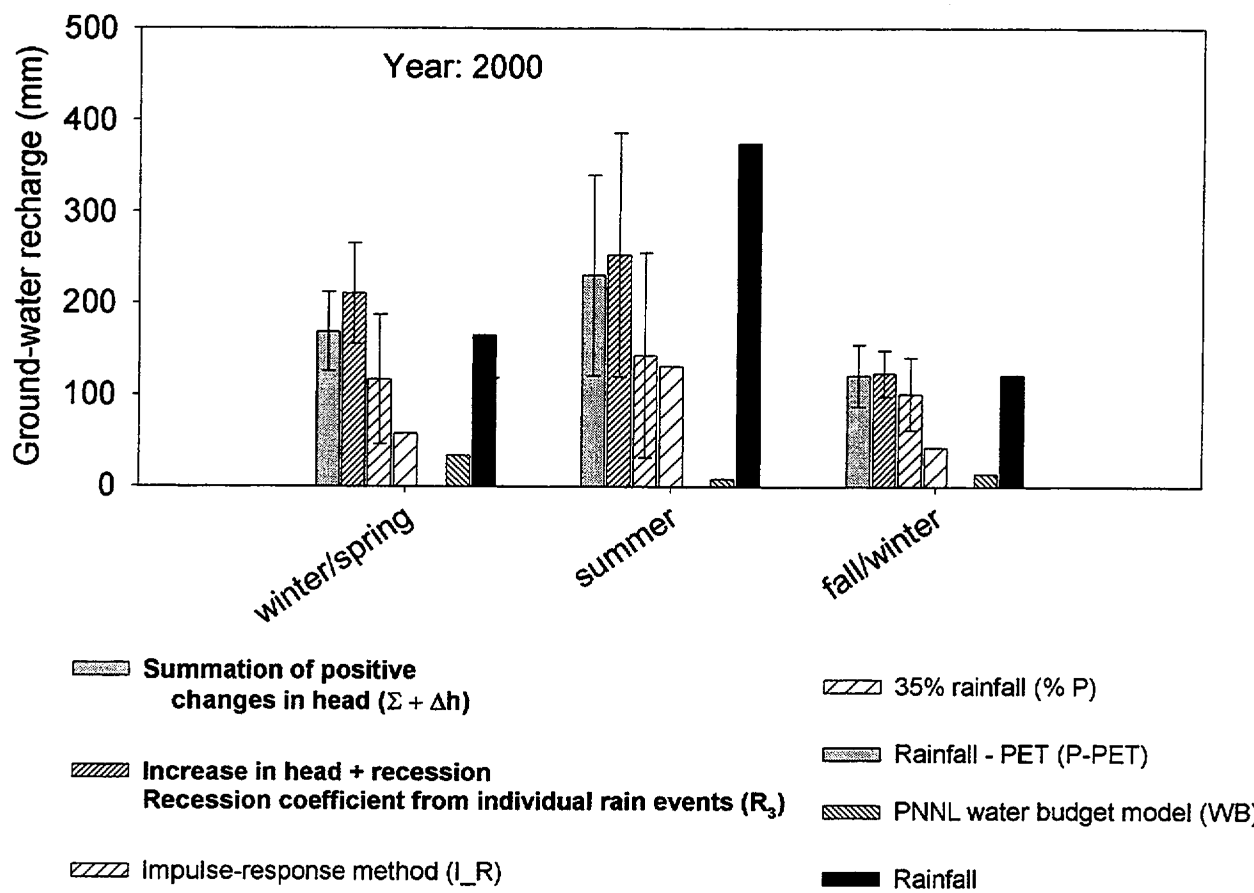

Figure 11. Ground-water recharge for the year 2000 estimated from near-continuous piezometer data and estimated using the PNNL water budget model.

4.3 Discussion

Results shown above provide site-specific insights into the inherent and relative uncertainties of ground-water recharge estimates from different methods of analysis using real-time, near-continuous field data. At this site, infiltration and percolation of rainfall to the water table was relatively rapid (typically on the order of 10 to 30 minutes). The consistently wet seasonal period for this site, when significant recharge occurred, was typically during winter. During this period, the water table often rose to within 0.5 meters of the surface in the downslope area. The use of near-continuous piezometer data allowed for estimation of specific yield and recession coefficients for a range of time periods. The variations in the specific yield could result in 10 to 100% ranges in ground-water recharge estimates. For example, if two specific yield values, e.g., 0.02 and 0.04, are obtained they would result in a 100% difference in ground-water recharge estimates. The recession coefficients also varied within a recharge event, as well as among recharge events and piezometer locations. The availability of specific yield and recession coefficient distributions provides for a bounding distribution of recharge estimates.

The two-year database used in this study represented two extremes in hydrometeorological conditions for this site. For example, in 1999 rainfall was minimal which resulted in very little measured ground-water recharge except during the fall-winter season. In contrast, rainfall in 2000 was much higher than average resulting in significant ground-water recharge for all seasons (this is shown in Figures 7 and 8). An important consideration is the instrument placement depth in the piezometer relative to the anticipated water-table fluctuations. For this study, the transducers in the piezometers were able to capture near-surface fluctuations but were unable to record recharge when the water table was deeper than the transducer placements.

The analysis methods which use real-time, near-continuous piezometer data almost always estimated higher ground-water recharge than the steady-state meteorological data analysis methods. Among the time-series methods used, the ground-water recharge estimates were not significantly different from each other. The estimates determined from the impulse-response method were nearly always lower than those determined from the other time-series analysis methods (this is shown in Figures 7 and 8). The coefficient of variation of the recharge estimates was almost 100%. These variations were observed over piezometer locations and rainfall events. There appears to be as much variation in recharge estimates among piezometer locations as there is among rainfall events.

For the steady-state meteorologic methods, the estimated recharge was much lower than for the above time-series analysis methods. The precipitation minus potential evapotranspiration method predicted no recharge in almost all of the periods. This method is not conservative for this site, and consistently underestimates recharge. Similarly, the estimation of recharge as a percentage of rainfall is flawed for this site. This is due to the variation in rainfall amounts and time periods.

The estimates of recharge using the PNNL Water Budget model in 1999 were similar to the piezometer estimates in the summer and slightly less in the fall/winter season. There were no piezometer data for the spring season of 1999 so a comparison cannot be made. There was a large amount of rainfall in the first two months of 1999, however, so it is likely there was significant ground-water recharge as indicated by the PNNL model. The estimates from the PNNL Water Budget model were all less than the estimates from the piezometer data in the year 2000. This discrepancy may be explained by differences in rainfall and ET and their seasonal distributions between the two years. The year 1999, especially the summer and late spring was very dry whereas 2000 was very wet. The rainfall in 2000 was greatest in the summer and spring where ET was highest with less rainfall in the fall and winter. The PNNL model can overpredict actual evapotranspiration if the drainage rate is low and/or the upper limit of available water is high. These conditions can allow more water to remain in the upper part of the profile and available for evapotranspiration. This can be compensated for by increasing the drainage rate. The PNNL model was roughly calibrated for this site by comparison with the MCP data (Timlin et al., 2000) and showed reasonable predictions for those years and in comparison with estimates from the MCP data. The model performance could be improved by a more accurate calibration process.

5 CONCLUSIONS

This study addresses technical issues (e.g., episodic ground-water recharge events) 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 ground-water recharge using real-time, near-continuous databases that lend themselves to time-series analysis. Furthermore, the temporal density of these data are such that interpolation methodologies may not be necessary and uncertainty is reduced. Uncertainty in this context refers to information loss due to intermittent and low frequency monitoring and to spatial variability in monitoring locations. Real-time, near-continuous data provide a highly realistic characterization of the transient, and dynamic hydraulic processes and events.

In the past, characterization of deep infiltration and ground-water recharge has traditionally focused on long-term estimates (e.g., annual or monthly). Because shallow water tables in a humid climate are highly transient and dynamic, the use of automated piezometers provided real-time, near-continuous systematic data for quantifying and assessing uncertainties in net ground-water recharge. Recording and analyzing piezometer fluctuations, as represented by hydrographs, provided a direct method for estimating ground-water recharge for the shallow ground-water systems at the Beltsville site. Finally, the network of automated piezometers were used to characterize the spatial distribution and uncertainty of recharge.

Timing and quantity of ground-water recharge can be estimated from measurements of hydrologic conditions (e.g., water content and piezometric head). 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 occurs varies. The accumulation and timing of these rapid near-surface effects can translate into significant differences in ground-water recharge over long time periods.

ARS scientists installed pressure transducers in six water-table piezometers to measure water levels at 10-minute intervals. Data were stored on dataloggers and retrieved at periodic intervals. This allowed simultaneous collection of near-continuous data in all piezometers regardless of the time of day or meteorological conditions. Coincident with this piezometric data, meteorological and soil moisture data were also available at the same time scale. These data were very appropriate for time series analysis. Along with time series analysis, conventional methods (e.g., percent of precipitation, precipitation - evapotranspiration, hydrograph recession analysis) were compared for estimating ground-water recharge and their attendant uncertainties. Several interpretive parameters were obtained from the datasets. First, hydrographs were developed to visualize recession curves. Then recession curve coefficients were calculated for recharge events (i.e., hours to days) using an autoregressive model. The total maximum piezometric head was determined for a recharge event by adding back the recession to the measured heads. Specific yield was calculated using three discrete Spring recharge events where all of the rainfall was assumed to result in recharge. For each recharge event, the specific yield was calculated as the rainfall input divided by the total increase in piezometric head.

General assumptions for this study were: no lateral subsurface movement of water and runoff was considered to be negligible. Specific assumptions for each method are described in the text of this report. Measurements of piezometric head changes around rainfall events can then be expected to capture most of the water that goes to ground-water recharge. Estimation of ground-water recharge under freezing conditions were not considered. We believe these assumptions were appropriate for this site under the given field conditions.

The real-time, near-continuous datasets referenced in this report provide a sufficiently complete characterization of the piezometric fluctuations. Estimates of ground-water recharge derived from these datasets were also compared to traditional, steady-state (using meteorological data) methods and/or analytic models. Information and analytic results from this report can be used to evaluate monitoring programs which may be used to characterize ground-water recharge at decommissioning, uranium mill tailings, HLW and LLW disposal sites.

The 10-minute piezometer data provided estimates of net ground-water recharge that varied greatly by location. In addition to the spatial variance, there was additional variability due to uncertainty in specific yield (the volume of water extracted from the ground-water per unit area when the water table is lowered a unit distance). The values of net recharge calculated from the piezometer data were also quite variable. However, on balance, the spatial variability in ground-water recharge was a larger component of uncertainty than the lack of knowledge in specific yield.

Estimates of ground-water recharge using the 10-minute Piezometer data were also compared to simulated ground-water recharge using a PNNL water budget model. The seasonal estimates of net ground-water recharge differed. As shown in Figure 13 (1999), the estimates for ground-water recharge calculated using the PNNL water budget model were generally within the variance of the estimates from the piezometer data. In the year 2000 (Figure 14) the PNNL model under estimated ground-water recharge as compared to those methods that use the piezometer data. This discrepancy may be explained by differences in rainfall and ET and their seasonal distributions between the two years. The year 1999 was very dry whereas 2000 was very wet. The rainfall in 2000 was greatest in the summer and spring where ET was highest with less rainfall in the fall and winter. The PNNL model can overpredict actual evapotranspiration if the drainage rate is low enough to allow more water to remain in the upper part of the profile and available for evapotranspiration. This can be compensated for by increasing the drainage rate. The PNNL model was roughly calibrated for this site by comparison with the MCP data (Timlin et al., 2000) and showed reasonable predictions for those years and in comparison with estimates from the MCP data. The model performance could be improved by a more accurate calibration process.

Significant conclusions are:

- It was demonstrated that the study area was in a ground-water recharge zone. Therefore, some of the piezometers did not always indicate ground-water recharge because the water table fell below the piezometer monitoring zone. This lowering of the local water table was prevalent in the summer. In this case, the multisensor capacitance probes would be a better indicator of ground-water recharge.
- Real-time, near-continuous monitoring data can reduce uncertainties in ground-water recharge and provide insights into the hydrologic processes which can affect radionuclide transport for near-surface settings in humid temperate climates.
- Pressure transducer devices in the piezometers proved robust and reliable over ranges of site conditions and time periods for this multi-year study.
- Real-time, near-continuous piezometric measurements for estimating ground-water recharge are highly valuable for characterizing a dynamic hydrologic regime, and can be used to estimate ground-water recharge independent of unsaturated zone measurements.
- Real-time, near-continuous piezometer measurements may underestimate ground-water recharge in the summer if the water table drops below the piezometer screen interval.
- Specific yield was estimated from the real-time, near-continuous piezometer data. There was considerable variation among locations and time. This variation may contribute to the uncertainty of ground-water recharge estimates on the order of 10 to 800% (see Table 10).
- The spatial variability in ground-water recharge was a larger component of uncertainty than the lack of knowledge in specific yield.
- Upon analysis of piezometer data at different locations and at different seasons, uncertainty in characterizing site behavior can be reduced by utilizing a network of measuring devices to capture the spatial variability inherent in this dynamic process.
- The real-time, near-continuous piezometer data showed a very rapid response (e.g. < 20 minutes) in the water table to rainfall events for both wet and dry soil conditions. This verifies the occurrence of significant episodic recharge for the shallow water table at this site. This dynamic process was also verified for the MCP data as described in NUREG/CR-6653.
- When comparing different methods for estimating ground-water recharge (see Figure 14), the method of "Summation of Positive Changes in Head ($\mathbf{\Sigma+\Delta h}$)" and the method of "Increase in Head + Recession ($\mathbf{R_3}$)" gave similar results. Taking into account errors which may be introduced by the estimation of the recession

coefficients, the "Summation Method" would be the most appropriate approach for estimating recharge at this site.

- The use of real-time, near-continuous piezometer data or MCP data results in higher estimates of ground-water recharge than use of meteorological data alone or water balance methods or other methods which use less frequently measured water content or piezometer data.

This cooperative project provided insights into data and conceptual model uncertainties at the site scale (hectare) with a shallow (less than 3 m) water table. This report references detailed field datasets and their analysis using conventional methods (including time series analysis) to estimate variable ground-water recharge. Information and methods for determining specific derived parameters such as recession coefficients and specific yields are also presented. Further comparisons of other recharge 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 piezometric heads over a 0.5 hectare (1.25 acre) site. The real-time, near-continuous piezometric data proved valuable in estimating relative ground-water recharge but further questions remain as to the 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 piezometer fluctuations, 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 both piezometer and MCP data in estimating ground-water recharge in combination with a mass balance model.

While none of the methods provided a true measure of ground-water recharge, results suggest that real-time, near-continuous soil water content data reduce uncertainties and provide insights into the hydrologic processes which can affect transport of contaminants. Episodic ground-water recharge events occurred over very short time scales (on the order of hours). In order to characterize the recharge event, 10-minute interval measurements are needed. The peak water table elevations would be routinely missed using hourly or daily measurements. The automated piezometers proved robust and provided reliable water-level fluctuation measurements over ranges of site conditions and time periods for this multi-year study. The piezometer data provided excellent information for directly estimating ground-water recharge. These data also provided valuable information for determining indirect parameters, e.g., specific yield and recession coefficients, and their variability. A common assumption is that infrequent monitoring of highly transient events can lead to significant loss of information (e.g., timing and quantity of ground-water recharge). Future research should be conducted to test this assumption and determine the reduction in uncertainty by utilizing real-time, near-continuous data. The research demonstrated that frequent monitoring of water table levels can provide reliable data for estimating net infiltration and redistribution of water which reduces uncertainties in the estimation of ground-water recharge.

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GLOSSARY

GLOSSARY OF TERMS AND NOMENCLATURE

Bulk density of soil	Mass of dry soil per unit bulk volume including solids and pores (Mg M^{-3}) (after Soil Science Society of America (SSSA), 1997).
Capacitance probe	An instrument to measure soil water content using radio waves.
Capillary fringe	The zone of soil just above the plane of zero gauge pressure (water table) that remains saturated or almost saturated with water. (SSSA, 1997)
Effective porosity	The saturated volumetric water content minus water content at 0.33 kPa.
Evapotranspiration (ET)	Loss of water from a land area through transpiration of plants and evaporation from the soil and surface water bodies. Evapotranspiration occurs at it's potential rate when water is not limiting. (after Wilson and Moore, 1998)
Ground-water recharge	The quantity of water that reaches the water table.
Hydrograph	Graph showing hydraulic head vs. time
Infiltration rate	The actual rate at which the water enters the soil, cm d^{-1}. The infiltration rate is controlled by rainfall rate, soil properties and antecedent water content (after SSSA, 1997).
Infiltration capacity	This is the maximum rate at which water can infiltrate the soil at current soil conditions and water content (after SSSA, 1997).
Multisensor Capacitance Probe (MCP)	A field instrument inserted into the soil with capacitance sensors at discrete depth intervals capable of real-time, near-continuous monitoring of volumetric water content (see capacitance probe and figure A1)
Near-continuous	Measurement frequency that captures the temporal variance of the event being monitored.
Net deep percolation	Water that has migrated beyond the root zone and is not available for evaportranspiration.
Neutron probe	An instrument to measure soil water content using attenuation of radioactive decay products (after SSSA, 1997).
Piezometer	An open borehole used to measure the total ground-water potential as an elevation head.
Piezometric head	The total hydraulic head as measured in a piezometer, synonymous with the water-table elevation for an open borehole.
Pressure transducer	An electronic device that measures height of a water column in a borehole
Real-time	The actual time in which a physical process takes place with the recording of the event practically simultaneous with its occurrence. (After Merriam Webster, 1977)
Recession	The decline of the water table following a rise due to a recharge event. (After Wilson and Moore, 1998)

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

NOMENCLATURE

(Symbols used throughout this report)

Symbol	Description
%P	Percent Precipitation
$\Delta \theta$	Change in water content
$\Delta\theta_v$	Volumetric soil water content changes
$\Sigma+\Delta$	Analysis of sum of positive changes during a rainfall period
ARS	Agricultural Research Service (U.S. Dept. of Agriculture)
DOY	Day of year
ET	Evapotranspiration
fw	Fall/Winter
h	potentiometric head
I_R	Impulse-Response method
IAA	Interagency Agreement
k	Recession coefficient
MCP	Multisensor Capacitance Probes
P-PET	Precipitation minus Potential Evapotranspiration
PNNL	Pacific Northwest National Laboratory
ppxx	Piezometer label for piezometers installed after July 2000 where 'xx' refers to the identifying number
Pzxx	Piezometer label for piezometers installed before July 2000 where 'xx' is the identifying number.
R	Recession analysis method
Rainid	Rainfall period identifier
RES	Office of Nuclear Regulatory Research
Rx	Recession methods to estimate ground-water recharge where 'x' refers to the method #
SAS	Statistical Analysis System software (SAS Corporation, Cary, NC)
su	Summer
S_y	Specific yield
WB	Water Balance model
ws	Winter/Spring

APPENDIX A: Ground-Water Recharge Estimates Derived from MCP Data

A.1 Estimates of Ground-Water Recharge Using Frequent MCP Water Content Data

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.

Sixteen multisensor capacitance probes (MCP) were installed in the field in July, 1998. Figure 1. in the main document shows the layout of the field experiment with plot locations. A description of the treatments and plot numbers are given in Table A.1. The MCP's were located in plots 3 - 6 and 21 - 24 as indicated by brackets in Figure 1. There were a total of 16 MCP probes with four sensors. The MCP probes measured water contents at 10, 20, 30 and 50 cm depths and 10-minute intervals. This provided a near-continuous, real-time record of soil moisture with depth and a range of temporal scales of water content were available.

Table A. 1 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 No-Till the seed is drilled into the soil covered by residue of the previous crop.

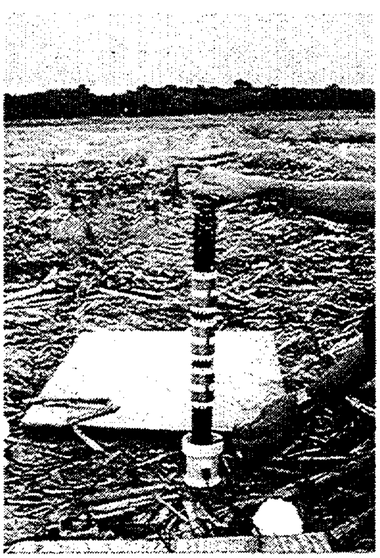

Figure A.1 Multi-sensor Capacitance Probe (MCP) in a field setting. The sensors are the metallic rings.

A photo showing the sensors and electronic components of the capacitance probe as it is installed into the polyvinyl chloride (PVC) access pipe is given Figure A.1. 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)

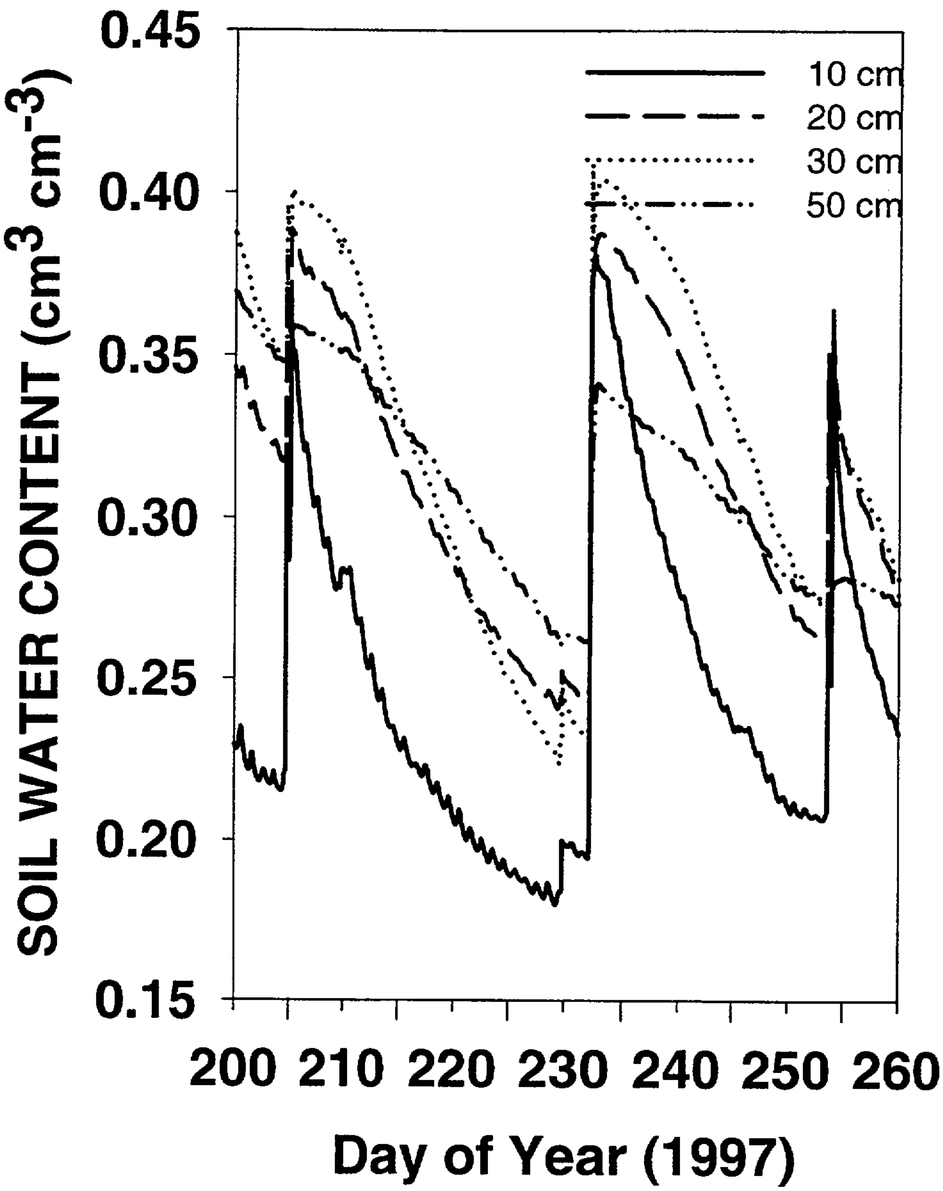

Figure A.2 Typical MCP data showing water content changes as a function of time for four soil depths. Note the rapid response to rainfall at days 2-5, 234 and 255. Diurnal variations in water content are also visible.

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. Figure A.2 shows the type of data this sensor provides.

All the calculations were carried out using SAS (SAS, 1997). Since the water contents in the MCP database 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, i.e. 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 programs are given in the appendices of the NUREG that discusses these data (Timlin and others, 2000).

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 A.2) and summing the positive differences over the recharge 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.

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 cumulative ET was expected to be small relative to drainage and infiltration. Hence for rainfall periods the mass balance equation could be reduced to DR=I-ST.

A.1.1 Summation of negative changes ($\Delta\theta_V$_1):

The differences in profile water content over 10 minute periods were calculated and the negative differences were summed. These calculations were only carried out during times of rainfall up to 24 hours after rainfall ceased. Drainage set to zero when the water content at the lowermost layer was less than a minimum amount (50% of drained water content) or when a rainfall event was less than 3mm.

A.1.2 Layer mass balance ($\Delta\theta_V$_2):

The procedure was to calculate influxes and outfluxes of water from layer to layer (i.e., 10, 20, 30 and 50) then accumulate the outflux from the lowermost layer. A schematic of this method is given in Figure A.3. 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).

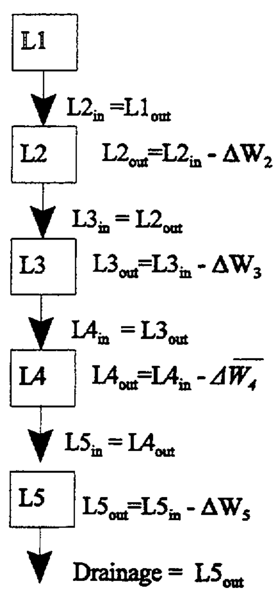

Figure A.3 Schematic of layer mass balance approach to calculate drainage from MCP data.

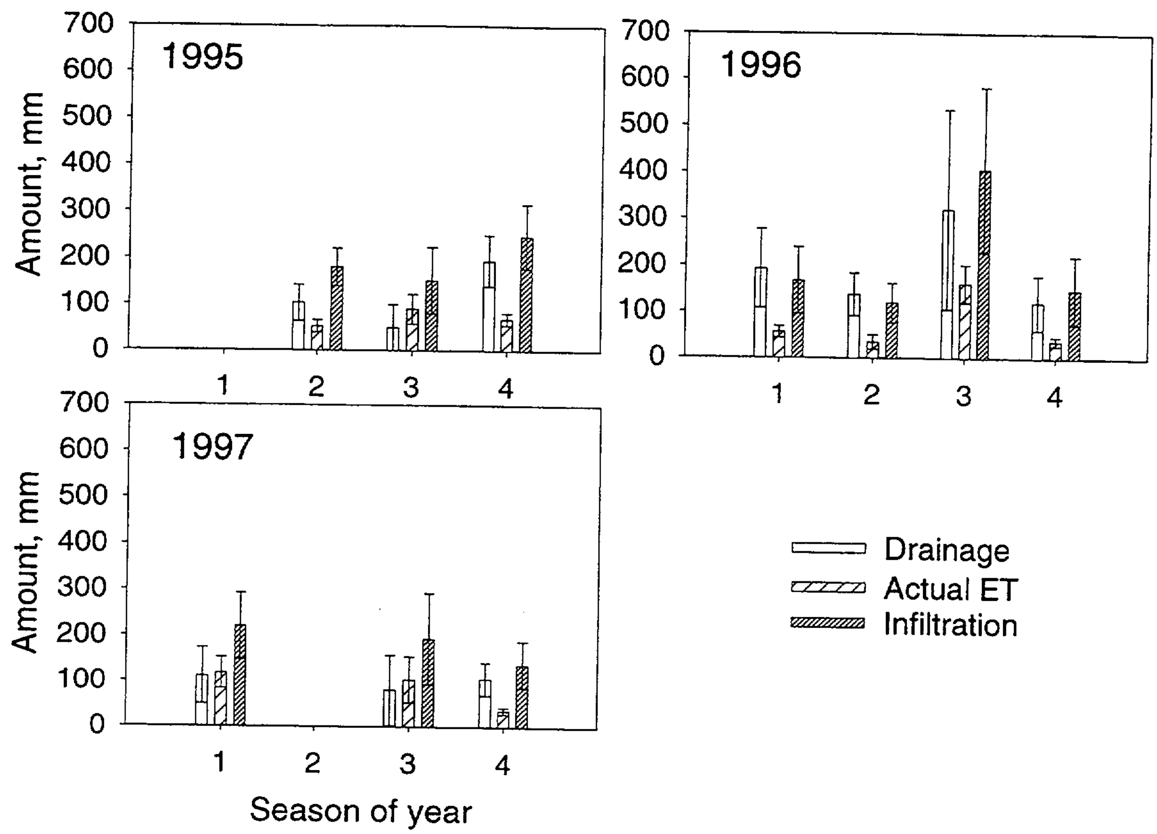

Figure A.4 Drainage, actual ET and total infiltration estimated from the MCP data.
Seasons refer to late winter-early spring (1), late-spring (2), summer (3) and late fall-early winter (4). This figure shows that there is a reasonable mass balance where:
Net Infiltration ~= Drainage+Actual ET

A.1.3 Field capacity approach ($\Delta\theta_V$_3):

In this method, rainfall is added to antecedent soil water content (from MCP data) and the soil filled to "field capacity" (drained water content). Excess water is net drainage to groundwater, as commonly used with infrequent neutron probe data.

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 was 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' as cm of water in the profile (see appendices 10 and 11 in Timlin and others, 2000). Net ground-water recharge is calculated by adding rainfall to the water in the soil profile 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.

Figure A.4 shows drainage, infiltration and ET based on these calculations. Infiltration is the sum of rainfall and ET is calculated from negative changes in water content during daytime hours and 24 hours after rainfall. Based on a visual inspection of the figure the calculated drainage appears similar to the sum of infiltration and ET.

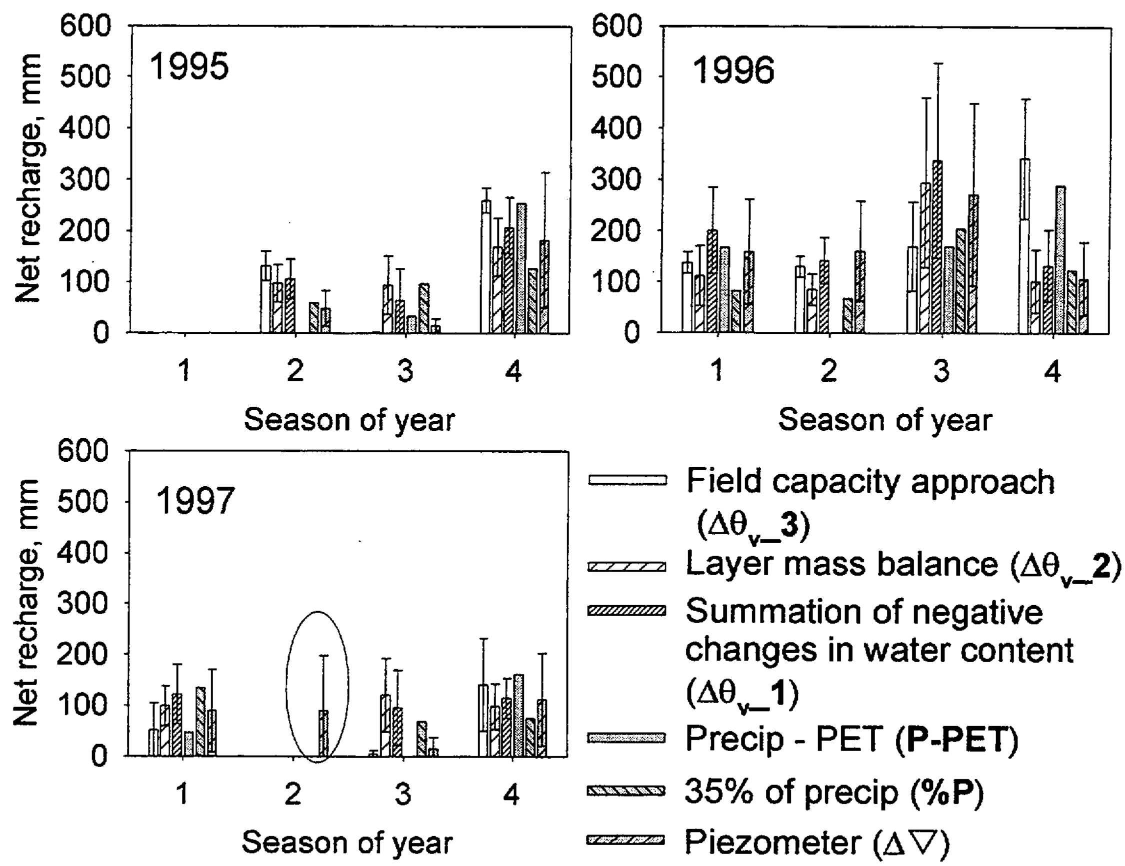

Figure A.5 Comparison of different methods to estimate net recharge using MCP data.
Bars with a white background represent estimates of net recharge using frequent MCP data. Note that methods using infrequent and approximate input data generally result in less estimated recharge during seasons 2 and 3 when plant growth was active (1995 and 1996). In 1997 there were no MCP data for season 2 (see inside oval) but the piezometer data suggest significant recharge. The error bars represent the range of recharge estimates from MCP or piezometric measurements. This is due to the locations of the probes and differences in surface soil conditions.

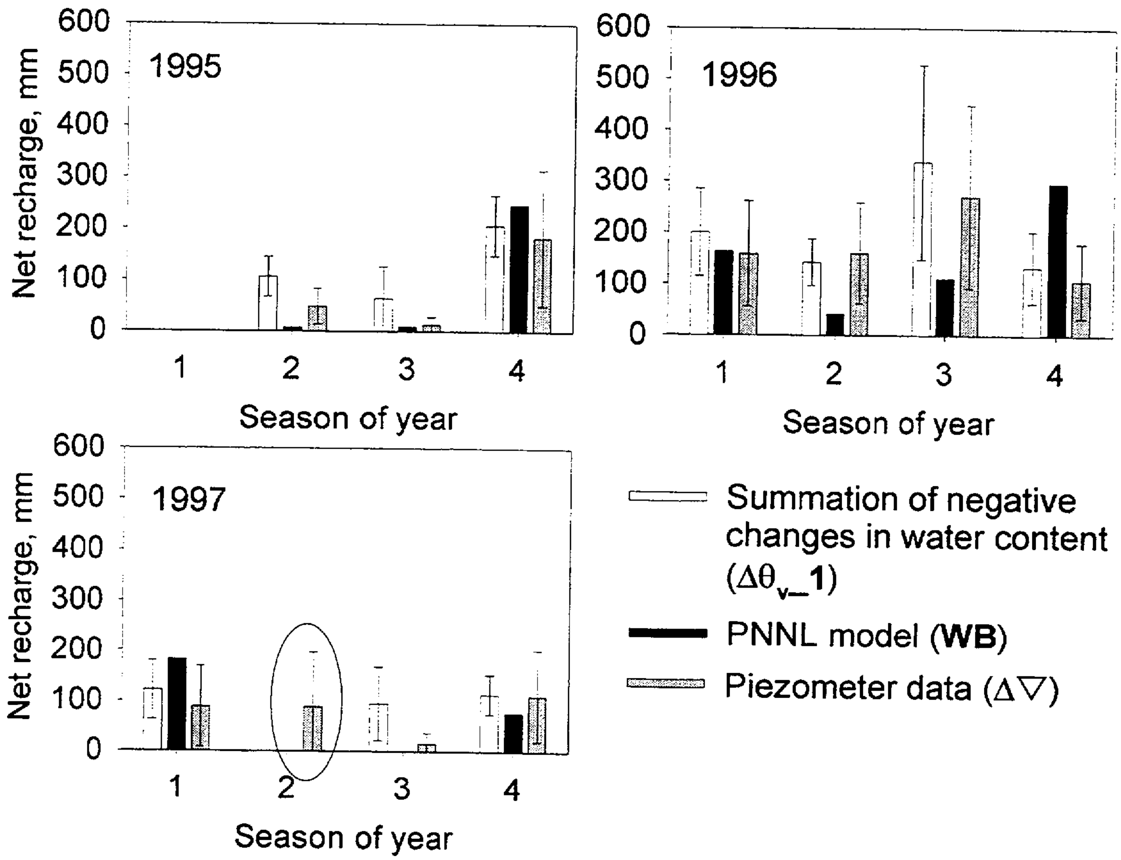

Figure A.6 Comparison of estimated net ground-water recharge using MCP data (summation of negative changes in the profile - $\Delta\theta_{v\_1}$), and the PNNL Water Budget Model. During 1997, season 2 the model predicted no recharge. There were no MCP data for comparison but the piezometer data indicated significant recharge. The differences are mainly due to how the model handles evapotranspiration.

Figure A.5 shows estimates of net recharge for the different methods. These methods used the MCP data and estimates using summary weather data. The bars with a white background represent estimates of net recharge using frequent MCP data. Note that methods using infrequent and approximate input data generally result in less estimated recharge during seasons 2 and 3 when plant growth is active (1995 and 1996). In 1997 there were no MCP data for season 2 (marked with an oval) but the piezometer data suggest significant recharge. The error bars represent the range of recharge estimates from MCP measurements. This is due to the locations of the probes and differences in surface soil conditions.

A.1.4 The PNNL Water Budget Model

The ground-water recharge estimates derived from the PNNL water budget model were closest to those derived from the MCP data during the winter and spring months (seasons 1 and 4) when ET rates were the lowest (Figure A.6). During the spring of 1997, (season 2) the PNNL model predicted no recharge. Although there were no MCP data for comparison for this time, the piezometer data indicated significant recharge. The differences during the summer months are thought to be mainly due to how the model handles evapotranspiration.

Appendix B SAS Programs

Appendix B.1 Read_weather_data.sas

```
/* read weather data into sas library

  rain and et data are in the weather.mdb in
  the folder indicated
  The date and time are formatted to ddmonyy and
  hh:mm

*/

%macro read_weather(yr=);

/*  we need macro variables to hold the long and short forms of year (2000 and 00) */

data _null_;
y=substr("&yr",3,2);
put y=;
call symput('yrShrt',trim(y));
 %put &yrShrt;
 %put &yr;
 run;

%put &yrshrt;

%if %sysfunc(exist(sentek2.weather&yr))=1 %then
  %do;
        proc datasets lib=sentek2;
          delete weather&yr;
        quit;
  %end;

   PROC IMPORT OUT= sentek2.weather&yr
       DATATABLE= "5sta-&yrShrt-10Min"
       DBMS=ACCESS2000 REPLACE;
/* use your own path here */
   DATABASE="d:\NRC\weather\farm_crew\weather.mdb";
        RUN;
/* note that data from the weather database have midnight equal
  to the previous day. Here we take midnight (hour =2400) and
  add a day to make it the next day and change 2400 to 0
%let yr=2000;

*/
data sentek2.weather&yr (drop=time1 minute begin day hour );
set sentek2.weather&yr;
format date date9. time time8.;
%let yr2=%eval(&yr-1);
begin="31Dec&yr2"d;
date=day+begin;
```

```
 if hour=2400 then
  do;
   date=date+1;
          hour=0;
          end;
 time1=int(hour/100);
 minute=hour-time1*100;
 time=hms(time1,minute,0);
 run;

proc sort data = sentek2.weather&yr;
 by date time;
 quit;

/* get rid of the one value that overlaps into the next year */
  data sentek2.weather&yr (drop = b_year);
   set sentek2.weather&yr ;
   retain b_year;
   if _n_ = 1 then b_year=year(date);
   if b_year-year(date) < 0 then delete;
  run;

  /* now add season information %let yr=1998; */
 data sentek2.weather&yr;
   set sentek2.weather&yr;

   if date <"01May&yr"d then season = 'a_sw';
  if "01May&yr"d <=date <"01Sep&yr"d then season='b_su';
  if "01Sep&yr"d <=date<= "31Dec&yr"d then season='c_fw';
/*   if date > "30Oct&yr"d then season='fw'; */
 run;

%mend;
%read_weather(yr=1998);
%read_weather(yr=1999);

%read_weather(yr=2000);
/* now set the date */
```

Appendix B.2 Read Piezometer Data from MSAccess Database

```
/* use this to import piezometer data
  note that piezometer data have been adjusted for the depth
   of the tube to the water table and the height of the
    tube above the ground in the database - this is done
          via a query
 output: piezomYY piezometer data where YY is 00 or 99 for the year
       datetimeYY dates and times in 10 minute intervals from Jan 1 to Dec 31
          This file is used to provide time values as place holders for missing
          piezometer data
            */

PROC IMPORT OUT= WORK.piezometer
        DATATABLE= "qryPiezomDepthAdj"
        DBMS=ACCESS2000 REPLACE;
   DATABASE="D:\NRC\piezometer data\piezometer.mdb";

RUN;
proc sort data=piezometer;
 by loc date time;
 quit;


data piezometer;
 set piezometer;
 format time tod6.;
 format date date7.;
 format loc $char4.;
 date = datepart(date);
 time=timepart(time);
 run;

data piezom1999 piezom2000;
 set piezometer;
 year =year(date);
 if year=1999 then output piezom1999;
 if year=2000 then output piezom2000;
 drop year;
 run;

/* this set of code will create a temporary table with
  all the date and time values. After merge we will be able
  to tell when there are missing data
  */
/* get treatment names from a file */

%macro date(yr=);
data datetime&yr (keep=date time doy);
format date date9. time time7.;
 do i=0 to 365;
  do j=0 to 23;
```

```
    do k=0 to 50 by 10;
      date=intnx('Day',"01Jan&yr"d,i);
      time = intnx('hour','00:00:00't,j);
      time=time+intnx('minute','00:00:00't,k);
            DOY=(date-"01Jan&yr"d + time/3600/24);
           if year(date)=&yr then output;
          end;
        end;
 end;
 run;

 /* get count of rows in the piezom_info file ( # of locs) */
 proc sql noprint;
  select count(loc) into :cntloc
  from sentek2.piezom_info
  where year=&yr;
 %put &cntloc;
 quit;

 data trt (keep=loc);
  set sentek2.piezom_info;
  where year=&yr;
 run;

  data date&yr;
   set datetime&yr;
    format loc $char4.;
    do obsnum=1 to &cntloc;
            set trt point=obsnum;
           output;
           end;
         run;
proc sort data = date&yr;
 by loc date time;
 quit;

 proc sort data=piezom&yr;
  by loc date time;
  quit;

data sentek2.piezom&yr;
 merge piezom&yr date&yr;
  by loc date time;
  run;

 %mend;

%date(yr=2000);
%date(yr=1999);
```

Appendix B.3 Merge Weather and Piezometer Data.sas

```
%macro mrg_rainP (yr=);
/* the purpose of this procedure is to merge the weather data sets with the
   Piezometer data

*/


/* data sets:
  Piezom&yr contains the Piezometer depth data (mm)
  Weather&yr contains the weather data (rain and ET and freeze info)
  Pzomyr&yr.All contains the merged piezometer and weather data
  - contains rain times and associated lines fron
  &in with a nearby time - from proc sql
  uses same weather files as mcp data - all from the field crew
  For 1999 and 2000, Piezometer data were collected at the same
  times as the weather data so time sync is not needed.
*/

/* now temp contains the time and date data for one treatment
  there is no need to find matching times for all treatments
  Note that sas treats times as seconds past midnight and dates
  as days from Jan 1, 1960 (as per my configuration?)

*/



Proc sort data = sentek2.piezom&yr;
  by date time;
  quit;

/* weather data may be more complete for the year
      than piezometer
                 */
 data sentek2.piezom&yr.all
       (label= 'Piezometer and weather data ') ;
                              merge sentek2.weather&yr sentek2.piezom&yr ;
              by date time;
          *if loc='' then delete;
  run;
```

Appendix B.5 ClassRain.Sas

```
options mlogic mprint mtrace symbolgen;
```

```
%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 default directory.
  This program is compiled as a dll and the SAS function "call module" executes it.
  This module requires a file called sascbtbl.dat which provides information
  about the dll that sas needs to call it. The following are the contents of the
  file used in this program:
     ROUTINE CLASS minarg=0 maxarg=0 MODULE=classrn;

  module is the name of the subroutine in the dll that is called. There are no
  arguments so minarg=maxarg=0


  2/13/01 I re-did this so the rainid is calculated from the weather file
  In this way, the id's will be consistent for all the
  data files that are merged with it (including piezometer)


          Rainid must be adjusted for periods with very little rainfall,
          this is done in this macro. We don't adjust for small amounts
          of infiltration though.

  &yr is a 4 digit year, i.e., 1998
  Input - weather&yr (weather data),
  output weather&yr._2 complete weather data with rainid
            This data file is renamed to the weather&yr file
                             in the macro CLEAN if all the calculations are OK.
      weather&yr._Sum contains summary weather data for
                      each rainfall period (total rain and et, proportion
                          of days with 4 hours of freezing weather


  temporary files:
  rainid - holds rainid values
          out holds data to be sent to class rain program and date, time values
            for merge
  freeze contains proportion of days with freezing weather in rain event




*/

/* starts here */



filename outf 'temp.dat';
filename inf 'result.out';
filename err 'error.log';
```

```
filename sascbtbl 'sascbtbl.dat';

/* delete table if existing */
    %do;
      %if %sysfunc(exist(sentek2.mcpresult&yr.)) %then
          %do;
            proc datasets lib=sentek2;
            delete mcpresult&yr;
            quit;
                                    %end;
            %end;

   /*
For debugging....
          %let i=1;
   %let yr=2000;
          %put &&tr_&i;
*/

 /* round DOY for later merging
   output rainfall and doy to send to class_rain
   program */
 data out (drop=freeze et start);
  set sentek2.weather&yr;
  start=mdy(1,1,year(date));
         /* note results are in seconds */
         DOY=(date-start+time/3600/24);
   doy=round(doy,0.000001);
            run;

   proc sort data = out;
    by doy;
   run;

    data _null_;
    set out;
    file outF;
    put DOY 12.8 rain 15.7 ;
    where doy <> . or rain <> .;
run;

/* the dll is called here. */
 data _null_;
 call module('*E','CLASS');
run;

  data _null_;
   infile err;
   input errormsg $;
         /* error message should be 'OK' if there is no problem */
   put errormsg=;
  run;
```

```
/* this is a temporary file, in the end we will store the rainid's with
   the weather data */
   data rainid (drop=rain label= 'RainID indexed to weather time');
     infile inf;
     input doy rain rainid;
      doy=round(doy,0.000001);
           run;

/* now merge rainid data back to the out dataset to obtain date and time values
   The out dataset contains DOY and date and time from
   note that doy must have the same precision in both datasets to allow 1:1 matching
   We use DOY to allow us merge a shortened data set (out) that has dates and times.
    Once dates and times are associated with rainids, the merging with the original data
    set is more straightforward and precision problems are less likely
 */

data rainid (drop=rain);
  merge out rainid;
  by doy;
  run;


data sentek2.weather&yr._2;
  merge sentek2.weather&yr
      rainid  ;
          by date time;
          * if time=. then delete;
          run;

/* this section of the macro will calculate total rainfall during
   a rainfall event to determine if the rainfall event is
   significant or not
*/


/* Count number of groups with only two or three small rainfall values */
  data sentek2.weather&yr._2 (drop=ndayS);
   set sentek2.weather&yr._2;
          retain ndayS;
     by rainid notsorted;
     if rainid <> 0 then
       Do;
         if first.rainid then
          do;
           rcnt=0;
                               cumr=0;
                               cumet=0;
                               ndayS=DOY;
         end;
                              if rainid>0 then
            do;
             nday=doy-ndayS;
             cumet + et*10;
```

```
                    end;
   if rain>0 then do;
      rcnt+1;
                  cumr+rain;
              end;
   End;
run;

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



/* 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 sentek2.weather&yr._2
      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=sentek2.weather&yr._2;
    by rainid date time;
    run;

/* do the merge */
    data sentek2.weather&yr._2;
     merge Sentek2.Weather&yr._2 temp ;
      by rainid;
      run;

/* reset rainid for rows where mxcnt is low */
     data sentek2.weather&yr._2;
      set sentek2.weather&yr._2;
      if mxcnt >0 then
          do;
           rainid=0;
                          end;
   run;


   data sentek2.weather&yr._2 (drop=mxcnt rcnt mxRn);
```

```
set sentek2.weather&yr._2;
run;

proc sort data=sentek2.weather&yr._2;
 by date time;
run;


/* this code will extend the rainid value until the
  next rainstorm */
  Data sentek2.weather&yr._2 (drop=rd);
   set sentek2.weather&yr._2;
   retain rd;

    by rainid notsorted;

  if first.rainid and rainid<>0 then
    Do;
     rd=rainid;
    End;
  if last.rainid and rainid<>0 then
    do;
     rd=rainid;
    end;
  rainid_2=rd;
        if rainid_2=. and rainid=0 then rainid_2=0;
 run;

/* find average freeze values for the rainfall periods */
proc sql;
   create table freeze as Select
          sum(freeze)/count(date) as AvFreeze,
    rainid_2
          from sentek2.weather&yr._2
          group by rainid_2
    having rainid_2 >0;
          quit;

   proc sort data=sentek2.weather&yr._2;
    by rainid_2 date time;
    run;

/* do the merge */
    data sentek2.weather&yr._2;
     merge Sentek2.Weather&yr._2 freeze ;
      by rainid_2;
      run;

  proc sort data=sentek2.weather&yr._2;
          by date time;
        quit;
```

```
            proc datasets;
             delete freeze;
             delete temp;
             delete rainid;
             quit;

 %mend;

 %macro Clean(yr=);
/* the purpose of this macro is to rename the weather files with
  rainid to the original weather file name
 %let yr=1998;
  */

/* check that rainfall id does not change within a season
  change season boundary if so %let yr=2000;
  */
data temp (drop=pseason) ;
  set sentek2.weather&yr._2 ;
  by rainid_2 notsorted;
   retain pseason;
   if _n_=1 then pseason=season;
   if first.rainid_2 then pseason=season;
    else season=pseason;
  run;

data sentek2.weather&yr._sum (keep=rainid_2 date time
          cumr cumet nday Avfreeze season);
            set temp;
            by rainid_2 notsorted;
            if last.rainid_2 and rainid_2<>0 then output;
          run;

data sentek2.weather&yr (label= 'Weather data and RainID ') ;
            set sentek2.weather&yr._2 (drop = cumr cumet);
            run;

            proc datasets lib=sentek2;
             delete weather&yr._2;
                    quit;
%mend;


%classrn(yr=1998);
%classrn(yr=1999);
%classrn(yr=2000);

%clean(yr=1998);
%clean(yr=1999);
%clean(yr=2000);
```

Appendix B.4 Fortran Program Used to Classify Rain 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
C  this is the most recent edition (2/2/01) added code for
c  error checking

C note that the variables are in common statements. When using large arrays SAS
C will crash if the variables are not placed in a common statement.

      subroutine class()

      real*8 time(60000), rainf(60000)
      integer rain(60000),i,tend(75),nobs,ii,index

      character*4 trt(60000),ptrt

      common /varble/ time, rainf, rain

      open (5,file='error.log')
      open (3,err=60,file='temp.dat',status='old')
      open (4,err=60,file='result.out',status='unknown')


      i=1
      ptrt='  '
      fINt=0.05/24.0
      numtrt=1
5     read (3,45, end=30,err=60) time(i),rainf(i)
      rain(i)=0
      i=i+1
      goto 5

30    Continue
      nobs=i-1
      if (nobs.eq.0) goto 60
      tinfil=-1
      ievt=0
      id1=0
      infil_number=0

      do i=1,nobs
* 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


   Do i=1,nobs
    write(4,46) time(i),rainf(i),rain(i)
    enddo
    Write (5,'(A2)') 'OK'

   goto 61

c  error messages here
60   write(5,'(a5)') 'error'

61   continue
   close(3)
   close(5)
   close(4)
   RETURN
45   format (f12.8, f15.7)
46   format (f12.8, F15.7, i4)

   end
```

Appendix B.5 Calc_data_cleanup 1999.sas

```
/* cleanup bad data
  Some of the data are out of range so this must be cleaned up
  after out of range data are set to missing, the SAS procedure
  EXPAND is used to interpolate sequences of missing data for drainage
  periods where the heads are consistently decreasing.

  The input table has weather data merged with it. Some plotting is done
  to view the transformations */

/* prepare to make plots */
symbol1 c=DEFAULT
  i=none
  v=dot
  cv=RED
  h=0.05
  ;
symbol2 c=DEFAULT
  i=join
  v=dot
  cv=GREEN
  h=0.05
  ;
symbol3 c=DEFAULT
  i=NONE
  v=circle
  cv=BLUE
  h=0.05
  ;
symbol4 c=DEFAULT
  i=needle
  v=none
  cv=BLACK
  h=0.05
  ;
* symbol5 c=DEFAULT
  i=NONE
  v=DOT


;
axis1
  color=blue
  width=2.0
  ;
axis2
  color=blue
  width=2.0
  /*order=(0 to 50 by 10)*/
  ;
axis3
  color=blue
```

```
  width=2.0
  ;
axis4
  color=red
  width=2.0
  ;


data temp;
 set sentek2.Piezom1999All;
 if rainid_2 >0 then use=1;
 old_head=head;
 run;
 data temp2 ;
  set temp;
  if loc='pp02' then
  Do;
   if rainid_2 in (29 31 33 34 35 36 37 38 39
               40 41 42 43 44 45 46 47 48 49
               50 65) then
     do;
       Head=0;
                    use =0;
                    end;
          if rainid_2 in (56 ) then
            do;
             if abs(head-lag1(head)) >20 then del=1;
             if abs(head-lag2(head))>20 then del=2;
             if abs(head-lag3(head))>20 then del=3;

     end;
            if rainid_2=64 and DOY >310 then head=0;
  end; /* pp02 */

if loc = 'pp04' then
  do;
    if rainid_2 in ( 28 29 31 34 35 65) then
      do;
        Head=0;
                    use =0;
      end;
          if rainid_2=64 and doy >307 then head =0;
          if rainid_2=71 and 349.6 < DOY <350.7 then head =.;
          if rainid_2 =72 and 353.2 <doy < 354.3 then head =.;
          if rainid_2 in (56 ) then
           do;
            if abs(head-lag1(head)) >20 then del=1;
            if abs(head-lag2(head))>20 then del=2;
            if abs(head-lag3(head))>20 then del=3;

    end;

          end; /* pp04 */
```

```
if loc = 'pp05' then
 do;
 if rainid_2 in (29 31 33 34 35 36 37 38 39
          40 41 42 43 44 45 46 47 48 49 50) then
   do;
    Head=0;
              use =0;
              end;
       if rainid_2 in (56) then
        do;
         if abs(head-lag1(head)) >20 then del=1;
         if abs(head-lag2(head))>20 then del=2;
         if abs(head-lag3(head))>20 then del=3;

   end;
       end; /* pp05 */

if loc = 'pp06' then
 do;
       if Rainid_2 in (28 29 30 31) then
   do;
    Head=0;
              use =0;
              end;
       if rainid_2 in (56) then
        do;
         if abs(head-lag1(head)) >20 then del=1;
         if abs(head-lag2(head))>20 then del=2;
         if abs(head-lag3(head))>20 then del=3;

   end;


       end; /* pp06 */

if loc = 'pp08' then
do;
 if rainid_2 in (28 29 30 31 61 65) then
   do;
    Head=0;
              use =0;
              end;
       if rainid_2 in (70) then
        do;
         if abs(head-lag1(head)) >20 then del=1;
         if abs(head-lag2(head))>20 then del=2;
         if abs(head-lag3(head))>20 then del=3;

  end;
 end; /* pp08 */
```

```
 if loc = 'pp10' then
   do;
    if rainid_2 in (64 65 69) then
     do;
       Head=0;
                    use =0;
           end;

          end; /* pp10 */


     if del <> . then head = .;
          run;

data temp2 (rename=(time=hs));
 set temp2;
 run;
proc sort data=temp2;
 by loc rainid_2 date hs;
 quit;

proc expand data = temp2 out=temp3 method=join;
by loc rainid_2;
convert head;
run;



data temp4;
 merge temp2 temp3;
  by loc rainid_2 date hs ;
  run;
/* calculate a moving average here */
proc expand data = temp4 out = temp5 ;
by loc rainid_2;
convert head = head_movave / transform=(cmovave 3);
quit;

data piezom1999all (drop=head_movave del time rename=(hs=time));
 set temp5;
  head=head_movave;
  run;

proc sort data = piezom1999all;
 by loc date time;
 quit;

goptions device=win;
proc gplot data=piezom1999all;
 plot old_head * doy=1
     head * doy =2
                /overlay
                 legend;
```

```
where loc='pp04';
 run;
quit;



  data temp;
   set test;
   run;
data test;
merge Piezom1999All temp;
 by date time;
 run;
```

Appendix B.6 Calc_data_cleanup 2000.sas

```
/* cleanup bad data
 cleanup bad data
  Some of the data are out of range so this must be cleaned up
  after out of range data are set to missing, the SAS procedure
  EXPAND is used to interpolate sequences of missing data for drainage
  periods where the heads are consistently decreasing.

  The input table has weather data merged with it. Some plotting is done
  to view the transformations

 */

symbol1 c=DEFAULT
  i=none
  v=dot
  cv=RED
  h=0.05
  ;
symbol2 c=DEFAULT
  i=join
  v=dot
  cv=GREEN
  h=0.05
  ;
symbol3 c=DEFAULT
  i=NONE
  v=circle
  cv=BLUE
  h=0.05
  ;
symbol4 c=DEFAULT
  i=needle
  v=none
  cv=BLACK
  h=0.05
  ;
* symbol5 c=DEFAULT
  i=NONE
  v=DOT

;
axis1
  color=blue
  width=2.0
  ;
axis2
  color=blue
  width=2.0
  /*order=(0 to 50 by 10)*/
  ;
```

```
axis3
  color=blue
  width=2.0
  ;
axis4
  color=red
  width=2.0
  ;


data temp;
 set sentek2.Piezom2000All;
 if rainid_2 >0 then use=1;
 old_head=head;
 run;
 data temp2 ;
  set temp;
   if loc='pp02' then
   Do;
    if rainid_2 in (29 30 31 32 33 34 36 39 64 65 68) then
     do;
      Head=0;
                    use =0;
                    end;
          if 186 <= DOY <= 192 then head = 0;
          if Rainid_2=41 and head <20 then head=.;
          if rainid_2 in (41 42 43) then
            do;
             if abs(head-lag1(head)) >20 then del=1;
             if abs(head-lag2(head))>20 then del=2;
             if abs(head-lag3(head))>20 then del=3;

    end;
  end; /* pp02 */

if loc = 'pp04' then
  do;
    if rainid_2 in (8 27 30 32 33 34 38 39 43 ) then
      do;
       Head=0;
                   use =0;
      end;

         end; /* pp04 */


if loc = 'pp05' then
  do;
 if rainid_2 in (29 30 31 32 33 34 39) then
   do;
    Head=0;
                  use =0;
                  end;
```

```
        if rainid_2 =38 then if doy >187.2 then head=.;
        if Rainid_2=41 and head <20 then head=.;
        if rainid_2 in (41 42) then
         do;
          if abs(head-lag1(head)) >20 then del=1;
          if abs(head-lag2(head))>20 then del=2;
          if abs(head-lag3(head))>20 then del=3;

   end;
        end; /* pp05 */

if loc = 'pp06' then
 do;
        if Rainid_2=41 and head <20 then head=.;
        if rainid_2 in (41 42) then
         do;
          if abs(head-lag1(head)) >20 then del=1;
          if abs(head-lag2(head))>20 then del=2;
          if abs(head-lag3(head))>20 then del=3;

   end;


        end; /* pp06 */

if loc = 'pp08' then
 do;
  if rainid_2 in (13 14 27 28 29 30 31 32 33 34 50 43 51 52
            60 62 63) then
   do;
    Head=16;
                use =0;
                end;
        if Rainid_2=41 and head <20 then head=.;
        if rainid_2 in (40 41 42) then
         do;
          if abs(head-lag1(head)) >20 then del=1;
          if abs(head-lag2(head))>20 then del=2;
          if abs(head-lag3(head))>20 then del=3;

   end;
 end; /* pp08 */



if loc = 'pp10' then
  do;
  if rainid_2 in (13 14 26 33 38 39 40 51 52 53
            54 55 57 60) then
   do;
    Head=0;
                use =0;
        end;
```

```
          if Rainid_2=41 and head <20 then head=.;
          if rainid_2 in (41 42 69) then
           do;
            if abs(head-lag1(head)) >20 then del=1;
            if abs(head-lag2(head))>20 then del=2;
            if abs(head-lag3(head))>20 then del=3;
     end;

         end; /* pp10 */


     if del <> . then head = .;
           run;

data temp2 (rename=(time=hs));
 set temp2;
 run;
proc sort data=temp2;
 by loc rainid_2 date hs;
 quit;

proc expand data = temp2 out=temp3 method=join;
by loc rainid_2;
convert head;
run;



data temp4;
 merge temp2 temp3;
  by loc rainid_2 date hs ;
  run;
/* calculate a moving average here */
proc expand data = temp4 out = temp5 ;
by loc rainid_2;
convert head = head_movave / transform=(cmovave 3);
quit;

data piezom2000all (drop=head_movave del time rename=(hs=time));
 set temp5;
  head=head_movave;
  run;

proc sort data = piezom2000all;
 by loc date time;
 quit;

goptions device=win;
proc gplot data=piezom2000all;
 plot old_head * doy=1
     head * doy =2
                /overlay
                 legend;
```

```
where loc='pl22';
 run;
quit;



  data temp;
   set test;
   run;
data test;
merge Piezom2000All temp;
 by date time;
 run;
```

Appendix B.7 Make Macrovar from Trt Names for Piez Data.sas

```
/* 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 sentek2.piezom2000all end=end;
    by loc;
     if first.loc then
       do;
       count+1;

         /* create variables for the treatment name*/
         call symput('LOC_'||left(put(count,2.)), trim(loc));
        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 "LOC_&i" " " "&&LOC_&i";

     %end;
%mend;

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

run;
quit;
```

Appendix B.8 Read Macrovar Names for Piezometer Data.sas

```
/* creates the macro variables for the Piezometer data

  The variable names are of the form "LOC_1"
  where LOC_1 contains the value "PL02".
  These treatment variables and their values
  are stored in the file Piez_loc.dat. This file
  should be in the workspace where the
  sas program files are.


  The default library name is Sentek2
*/

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

options mlogic mprint mtrace symbolgen;
filename varN 'Piez_loc.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 B.9 Calc_char_specific_yield.sas

```
/* this code summarizes rainfall events to obtain
   an estimate of cumulative drainage using simple methods
         for a few select rainfall events to characterize specific
         yield

         Input tables are PiezometerYYYYall where YYYY is year.
    Output are  SpecyieldYYYY and spyieldmean
         */
data temp;
 set sentek2.piezom1999all;
  /* add %if statment here when making macro */
   where rainid_2 in (57 59 68); /* for 1999 */
  run;

data sentek2.specYield1999 (keep = loc rainid inc dec cumr phi date avfr);
  set temp;
  by loc rainid;
  format inc dec 6. cumr 6.2 phi 6.3;
  where rainid >0;
  /* divide del by 6 for lag6 */
   del=head-lag6(head);
          if first.rainid then
           do;
            inc=0;
            dec=0;
            del=0;
            cumr=0;
            cnt=0;
            avfr=0;
            end;
          if del > 0 then inc+del/6;
          if del <=0 then dec + del/6;
             cumr+rain;
                    cnt+1;
                    avfr+Freeze;
          if last.rainid then
    do;
             phi=cumr/inc;
                    avfr=avfr/cnt;
      if avfr < 0.25 then output;
                    end;
         run;

proc sql;
 create table temp1999 as
  select loc,
       mean(phi) as phi,
       std(phi) as std
                    from sentek2.Specyield1999
                    group by loc;
```

```
                    quit;


data temp;
 set sentek2.piezom2000all;
  /* add %if statment here when making macro */
   where rainid_2 in (12 15 17); /* for 2000 */
    run;

data sentek2.specYield2000 (keep = loc rainid inc dec cumr phi date avfr);
  set temp;
  by loc rainid;
  format inc dec 6. cumr 6.2 phi 6.3;
  where rainid >0;
  /* divide del by 6 for lag6 */
   del=head-lag6(head);
        if first.rainid then
          do;
           inc=0;
           dec=0;
           del=0;
           cumr=0;
           cnt=0;
           avfr=0;
           end;
        if del > 0 then inc+del/6;
        if del <=0 then dec + del/6;
           cumr+rain;
                  cnt+1;
                  avfr+freeze;
        if last.rainid then
    do;
            phi=cumr/inc;
                   avfr=avfr/cnt;
      if avfr <0.25 then output;
                  end;
        run;

proc sql;
  create table temp2000 as
   select loc,
        mean(phi) as phi,
        std(phi) as std
                    from sentek2.SpecYield2000
                    group by loc;
                    quit;

data sentek2.spYieldMean;
 merge temp1999 (rename=(phi=phi_1999 std=std_1999))
     temp2000( rename=(phi=phi_2000 std=std_2000));
 by loc;
 format phi_1999 std_1999 phi_2000 std_2000 6.3;
 run;
```

Appendix B.10 Calc_recession_param.sas

```
/* find parameters for recession using autoregression
  We will find a parameter that applies to the entire data
  set
  input piezomyyyyall
  Output - recess_sumyyyy where yyyy is a four digit year
*/
   /* divide del by 6 for lag6 */
/*        %let yr=2000; %let i=6; %let count=8;*/
%macro coefCal(yr=);

 %do i=1 %to &count ;
 %put i;
   %if &i=1 %then
     %if %sysfunc(exist(sentek2.recess_sum&yr)) %then
        %do;
         proc datasets lib=sentek2;
         delete recess_sum&yr
         quit;
                          %end;


/* %let locv=pp08; %let i=1; in(2 12 15 17 22 41 42 44 45 47 56 58)*/
data temp ;
  set sentek2.piezom&yr.all;
   by rainid_2 notsorted;
   where rainid_2 >0
            and loc= "&&loc_&i";
  if date <"01Mar&yr"d then season = 'fw';
   if "01Mar&yr"d <=date <"01Jun&yr"d then season='sp';
   if "01Jun&yr"d <=date<= "30Oct&yr"d then season='Su';
   if date > "30Oct&yr"d then season='fw';

   r1=lag1(rain);
   r2=lag2(rain);
   r3=lag3(rain);
   r4=lag4(rain);
   r5=lag5(rain);
   r6=lag6(rain);
   r3=lag3(rain);
   r28=lag28(rain);
   h1=lag1(head);
   h6=lag6(head);
 del=head-lag6(head);
 if first.rainid_2 then
    do;
          t1=0;
          t2=0;
     del=0;
          h1=.;
          h6=.;
```

```
        r1=.;
        r2=.;
        r3=.;
        r4=.;
        r5=.;
        r6=.;
        end;
      if del > 0 then t1+del/6;
      if del <=0 then t2 + del/6;
      run;

   proc sort data=temp;
      by season date time;
      quit;

/* get average freezing conditions */
 proc sql;
  create table freeze as
      select rainid_2, sum(freeze)/count(doy) as avfreeze
      from temp
      group by rainid_2;
      quit;

proc sort data = temp;
 by rainid_2;
 run;

 data temp2;
  merge temp freeze;
   by rainid_2;
 if  avfreeze > 0.25 then delete;
   run;

proc sort data=temp2;
 by season date time;
 run;

proc autoreg data = temp2 outest=est noprint;
model head= h1 rain r1 r3 r6 /*r1 r2  r3 r4 r5  r6 r7 r8 r9 r10 r11 r12
        r136r14 r15 r16 r17 r18 r19 r20
        r21 r22 r23 r24 r25 r26 r27 r28 */ /lagdep=h1 noint;
  output out=p p=yhat pm=ytrend;
title "Autoregression for plot &&loc_&i , year &yr and season= #byval(season)";
  by season;

quit;
run;

data r_coef (keep=loc season h1 rain  r1 r3 r6 rainVar);
 set est;
  loc = "&&loc_&i";
 rainVar=rain + r1+r3+r6;
```

```
run;


proc sql;
     create table sumhead as
            select season, sum((t1)) as IN,

                   sum((t2)) as out,
                   sum(rain) as sumr
            from temp2
      group by season
      ;

            quit;

/* now put the two datasets together to obtain coefficients
  from autoregression as well as an estimate of the summation
  of positive changes
  */

  data all;
   merge r_coef sumhead;
         by season;
         run;

         %if i=1 %then
           %do;
             data sentek2.recess_sum&yr;
              set all;
                   run;
                  %end;
                  %else
             %do;
                   proc append data=all
           base=sentek2.recess_sum&yr;
                          quit;
                  %end;
%end; /* loop over i*/

/* now extract the coefficients */
data sentek2.recess_coef&yr (keep = coef loc);
  set sentek2.recess_sum&yr;
   if season='sp' then coef=h1;
         if loc in ('pl22' 'pl26') and season = 'Su' then coef=h1;
         coef=log(coef)*6*24;
         if coef=. then delete;
         run;


%mend;


%coefcal(yr=2000);
```

```
%let yr=2000;
```

Appendix B. 11 Calc_recession_param Using Autoregression.sas

```
/* find parameters for recession using autoregression
  We will find a parameter that applies to the entire data
  set

  revised this to calculate using only negative changes in water
  content and don't use rainfall
  input piezomyyyyall
  Output - sentek2.recess_sumyyyy where yyyy is a four digit year
         sentek2.recess_coefYYYY.neg_spring
            Recession coefficients from just the spring
         sentek2.recess_medianYYYY.neg_all
           Recession coefficients from all the events
*/
  /* divide del by 6 for lag6 */
The purpose of this program is to calculate

/* For debugging
  %let yr=2000; %let i=3; %let count=8;*/
%macro coefCal2(yr=);

 %do i=1 %to &count ;
 %put &i;
   %if &i=1 %then
     %if %sysfunc(exist(sentek2.recess_sum&yr.neg)) %then
        %do;
         proc datasets lib=sentek2;
         delete recess_sum&yr.neg
         quit;
                              %end;


/* %let locv=pp08; %let i=4; %let yr=2000;
 in(2 12 15 17 22 41 42 44 45 47 56 58)*/
data temp ;
 set sentek2.piezom&yr.all;
  by rainid_2 notsorted;
  where rainid_2 >0
             and loc= "&&loc_&i";

  h1=lag1(head);
  h6=lag12(head);
 del=head-h6;
 if first.rainid_2 then
    do;
     del=0;
           h1=.;
           h6=.;
           t1=0;
           t2=0;
           end;
```

```
            if del > 0 then t1+del/12;
            if del <=0 then
                do;
          t2 + del/12;
                              output;
                      end;
           run;

/* get average freezing conditions
  avfreeze has already been incorporated into the
  piezometer database
  */

data temp2;
 set temp;
  if avfreeze >0.25 then delete;
  run;

/*  use autoregression to determine the recession coefficient */
proc autoreg data = temp2 outest=est noprint ;
model head= h6  /lagdep=h6 noint;
  output out=p p=yhat pm=ytrend;
title "Autoregression for plot &&loc_&i , year &yr and season= #byval(season)";
  by rainid_2;

quit;
run;

data r_coef (keep=loc rainid_2 h6);
 set est;
  loc = "&&loc_&i";
 run;

/* find average head during drainage */
proc sql;
     create table Drainhead as
            select rainid_2, season, avg(head) as avhead,
      min((t2)) as drain
             from temp2
      group by rainid_2, season
      ;

            quit;

/* now put the two datasets together to obtain coefficients
  from autoregression as well as an estimate of the input as
  a summation of positive changes
  */

  proc sort data = r_coef;
   by rainid_2;
         quit;
```

```
        proc sort data = drainhead;
         by rainid_2;
         quit;

  data all;
   merge r_coef drainhead;
        by rainid_2 ;
        if drain=0 then h6=0;
        if  0.75 > h6 >1 then delete;
    if abs(drain)=<10 then delete;
        run;

/* this section combines the data sets created for each loop of the macro
   into a permanent dataset
*/
        %if &i=1 %then
          %do;
            data sentek2.recess_sum&yr.neg;
             set all;
                 run;
               %end;
               %else
           %do;
                 proc append data=all
         base=sentek2.recess_sum&yr.neg;
                       quit;
                %end;
 %end; /* loop over i*/

/* now extract the coefficients */
data sentek2.recess_coef&yr.neg_spring (keep = rainid_2 k loc season avhead);
   set sentek2.recess_sum&yr.neg;
   if season='a_sw' then k=h6;
        if &yr = 2000 then
        if loc in ('pl22' 'pl26') and season = 'b_su' then k=h6;
        k=log(k)*24; /* with rainfall used h1 so divided by 6 here */
        if k=. or k=0 then delete;
        run;

proc sort data= sentek2.recess_coef&yr.neg_spring;
  by loc k ;
  quit;

data sentek2.recess_coef&yr.neg_spring ;
set sentek2.recess_coef&yr.neg_spring  ;
 by loc ;
  if first.loc then n=1;
   else n+1;
 run;

data sentek2.recess_coef&yr.neg_all (keep=k loc season rainid_2 avhead drain);
 set sentek2.recess_sum&yr.neg;
 k=log(h6)*12; /* with rainfall used h1 so divided by 6 here */
```

```
        if k=. or k=0 then delete;
 run;
 /* put k's in ascending order to find median */

 proc sort data =sentek2.recess_coef&yr.neg_all;
  by loc k;
  quit;

data sentek2.recess_coef&yr.neg_all ;
set sentek2.recess_coef&yr.neg_all  ;
 by loc ;
  if first.loc then n=1;
   else n+1;
  run;

/* now summarize median coef into a table  %let i=4; %let yr=2000; */
%do i=1 %to &count;

proc sql noprint;
  select count(k) into :cntk
   from sentek2.recess_coef&yr.neg_all
        where loc = "&&loc_&i";
        %put &cntk;
        quit;
/* find midpoint of vector of K values
  This will be the location of the median*/
 %let ii= %sysevalf(&cntk/2+1,integer);
 %put &ii;
 /* now select out the median */
proc sql noprint;
 create table t1 as
 select loc, rainid_2, k, season
  from sentek2.Recess_coef&yr.neg_all
  where loc = "&&loc_&i"  and n=&ii;
quit;
        %if &i=1 %then
          %do;
            data sentek2.recess_median&yr.neg_all;
             set t1;
                 year=&yr;
                 run;
                %end;
                %else
           %do;
                  data t1;
                   set t1;
                   year=&yr;
                  run;

      proc append data=t1
        base=sentek2.recess_median&yr.neg_all;
                    quit;
              %end;
```

```
%end; /* loop */
/* add labels here */
proc datasets lib=sentek2;

modify recess_coef&yr.neg_spring
      (label="recession coefficients from spring events for &yr");
modify recess_median&yr.neg_all
    (label="Medians of recession coefficients from all the events in &yr");
modify recess_coef&yr.neg_all
     (label ="Recession coefficients from all events for &yr" );
modify recess_sum&yr.neg
     (label="summarized output from autoregression for &yr");


quit;

%mend;


%coefcal2(yr=2000);
%coefcal2(yr=1999);

/* now summarize for both years */
data sentek2.recession_K (label='summarized recession parameters for both years');
set sentek2.Recess_coef2000neg_all (keep= rainid_2 loc season avhead k
                            in=a)
    sentek2.Recess_coef1999neg_all(keep= rainid_2 loc season avhead k
                            in=b) ;
by loc;
if a then year=2000;
if b then year=1999;
run;
proc sort data= sentek2.recession_k;
 by year loc;
 quit;

proc univariate data=sentek2.recession_k;
var k;
id loc;
output out=sentek2.k_medians median=k_med q1=k_q1 q3=k_q3;
by year loc;
quit;


%let yr=2000;
```

Appendix B.12 Calc_recharge_with_recession.sas

```
/* calculate recharge by accounting for recession
 Four methods are used:
  1. use median recession coefficients from the year, Rec_med
  2. use median from the spring or winter whichever is available, Rec_sp
  3. use coefficients from individual rainstorms, Rec_ind
  4. Use sum of positive heads
 output:
where &yr is year
 sentek2.drain_sum&yr.neg  (calculated summed and predicted heads)
 sentek2.recharge&yr (summarized recharge (mm) comparison data (by
               rainid and season)

requires:
   recession coefficient:
     sentek2.recess_coef&yr.neg_spring
      sentek2.Recess_median2000neg_all
   Piezometer data:
    sentek2.piezom&yr.all
%let i=3; %let yr=2000;
*/

%macro Recharge(yr=);

%do i=1 %to &count;
   %if &i=1 %then
     %if %sysfunc(exist(sentek2.drain_sum&yr.neg)) %then
        %do;
          proc datasets lib=sentek2;
          delete drain_sum&yr.neg
          quit;
                              %end;

data temp ;
  set sentek2.piezom&yr.all;
  where rainid_2 > 0 and avfreeze <= 0.25
     and loc= "&&loc_&i";
run;
/* have incorporated the avfreeze into the piezometer data */
/* get rid of rainid's where there might have been freezing */
/*
proc sql ;
   create table freeze as
          select rainid_2, sum(freeze)/count(doy) as avfreeze
          from temp
          group by rainid_2;
          quit;


data temp2;
 merge temp freeze;
```

```
  by rainid_2;
 if  avfreeze > 0.25 then delete;
  run;

proc sort data=temp2;
 by  rainid_2 date time;
 run;

*/

/* %let i=8; %let yr=2000; */
/* find count of entries of K for a location
  we can either use the median of values from the spring
  only (spring=1) or a median from the whole year
  %let spring=0;
*/
 /* get spring coef */
     proc sql noprint;
        select count(k) into :cntk
        from sentek2.recess_coef&yr.neg_spring
              where loc = "&&loc_&i" ;
              %put &cntk;
            quit;
/* find midpoint of vector of K values
  This will be the location of the median*/
    %let ii= %sysevalf(&cntk/2+1,integer);
    %put &ii;
 /* now select out the median */
    proc sql noprint;
      select k, rainid_2 into :sp_beta, :sp_rid
      from sentek2.Recess_coef&yr.neg_spring
      where loc = "&&loc_&i"  and n=&ii;
      %put &sp_beta &sp_rid;
     quit;
 /*end spring coefficients inspring */

 /* get yearly median coefficient */

     proc sql noprint;
      select k, rainid_2 into :Med_beta, :m_rid
      from sentek2.Recess_median2000neg_all
             where loc= "&&loc_&i";
                    %put &Med_beta &m_rid;
    quit;

/* for the individual coefficients we need a table for
 lookup per each rainfall event
 */

data coeff_all (drop=n);
 set sentek2.recess_coef&yr.neg_all;
  where loc="&&loc_&i";
 run;
```

```
proc sort data =coeff_all;
    by rainid_2;
          quit;


/* now find first value of head in each rainevent */

data mins (keep=rainid_2 minH maxH);
 set temp;
 retain maxH minH;
 by rainid_2;
  if first.rainid_2 then
    do;
     minH=head;
     maxH=head;
    end;
    if head>maxH then maxH=head;
    if last.rainid_2 then output;
  run;



data temp2 ;
 merge mins temp coeff_all;
 by rainid_2;
 if k=. then k= &med_beta;  /* take care of missing values */
 dif = maxh-minh;
 if maxH-minH <=20 then delete;
 run;
/* the coefficient comes from autoregression and assumes a time interval
  of 10 minutes
  */
data  rech_plot (keep=date doy head cumh11 cumh22 cumh33 posh2 loc n rainid_2)
    recharg (keep=season loc rainid_2 cumh1-cumh3
          cumh11 cumh22 cumh33 posh rec_med rec_sp rec_ind
                              hmax delt tinit doy head coef1-coef3
          label = 'cumulative heads to calculate recharge');
                              retain tinit hmax;
 set temp2;
 by rainid_2;
 coef1=&med_beta;
 coef2=&sp_beta;
 coef3=k;
 coef1=exp(coef1/6/24);
 coef1=(1-1/coef1);
 n=_n_;
 coef2=exp(coef2/6/24);
 coef2=(1-1/coef2);

 coef3=exp(coef3/6/24);
 coef3=(1-1/coef3);

 h1=lag6(head);
```

```
 del=head-h1;
 if del<0 then del=0;
 if first.rainid_2 then
     do;
       cumh1=0;
                   cumh2=0;
                   cumh3=0;
                   posh2=minh;
                   h1=0;
                   hmax=0;
                   tinit=doy;
                  end;
         cumh1+coef1*(head);
         cumh2+coef2*(head);
         cumh3+coef3*(head);
     cumh11=head-cumh1;
          cumh22=head-cumh2;
          cumh33=head-cumh3;
         posh2+del/6;
         if head >hmax then
       do;
        hmax=head;
        tinit=doy;
                          end;
if last.rainid_2 then
     do;
          rec_med= max(cumh11-minh,0);
          rec_sp=  max(cumh22-minh,0);
          rec_ind= max(cumh33-minh,0);
          posh=max(posh2-minh,0);
          delt=doy-tinit;
      output recharg;
                  end;
/* output data to make individual plots of recharge
 %if &yr=2000 %then
 %do;*/
           if loc ='pp04' and rainid_2 in (12 15) and &yr=2000
          then output rech_plot;
           if loc ='pp02' and rainid_2 in (12 15) and year(date)=2000
          then output rech_plot;
 /* %end; */
run;
%if &i=1 %then
          %do;
            data sentek2.drain_sum&yr.neg;
             set recharg;
                   run;
                   data sentek2.rech_plot;
                   set rech_plot;
                   run;
                  %end;
                  %else
           %do;
```

```
                    proc append data=recharg
            base=sentek2.drain_sum&yr.neg;
                            quit;
                            proc append data=rech_plot
            base =sentek2.rech_plot;
                     quit;
                   %end;

 %end;
 proc sort data=sentek2.drain_sum&yr.neg;
  by loc season rainid_2;
  quit;

 /* now merge the specific yields and rain to calculate an amount
   and compare to rainfall %let yr=1999;
          */
         data sentek2.recharge&yr (keep=rainid_2 loc posh rec_med
                   rec_sp rec_ind sy posh_orig);
          merge sentek2.drain_sum&yr.neg
      sentek2.spyieldmean (rename=(phi_&yr=sy) );
          by loc;
           rec_med=rec_med*sy;
           rec_sp=rec_sp*sy;
           rec_ind=rec_ind*sy;
           posh_orig=posh;
           posh=posh*sy;
          run;
/* now get rain and et %let yr=2000; */

          proc sql noprint;
           create table wdat as
                  select rainid_2, season, sum(rain) as cumr,
                       sum (et*10) as cumet,
                                   sum(freeze)/count(date) as AvFreeze
                  from sentek2.weather&yr
        /*        where avfreeze <=0.25 */
                 group by rainid_2, season;
   quit;

proc sort data=sentek2.recharge&yr;
by rainid_2;
quit;

/* now add rainfall to the recharge data */
 data sentek2.recharge&yr;
  merge sentek2.recharge&yr wdat;
   by rainid_2;
         if rainid_2=0 then delete;
         if avfreeze > 0.25 then delete;
         run;

proc datasets library=sentek2;
 modify recharge&yr
```

```
      (label="summarized recharge (mm) comparison data (by rainid and season for &yr");
modify drain_sum&yr.neg
      (label = "Summary data by loc on recharge - includes heads for &yr" );
modify rech_plot (label='data for plotting cumulative heads for &yr');
quit;
%mend;



%recharge(yr=2000);
%recharge(yr=1999);

proc means data = sentek2.drain_sum2000neg noprint;
by loc season;
 var dif;
 output out=means2000 mean=mean std=dev n=num;
 quit;


Data test (keep=posh hmax hpred head);
 set recharg;
  coef=-1/(coef3-1);
  coef=log(coef)*24*6;
  hpred=exp(coef*delt)*hmax;
  run;
symbol1 c=DEFAULT
        i=NONE
        v=DOT;
axis1
      color=blue
      width=2.0;
axis2
    color=blue
    width=2.0;
 axis3
color=blue
width=2.0;

proc gplot data=WORK.TEST;
   plot hpred * head /
                        haxis=axis1
                        vaxis=axis2
                         frame;
 run;
quit;
```

Appendix B.13 Calculate Recharge by Input-response.sas

```
/* program to calculate ground-water recharge using the
   inpulse response method

   output tables (where YYYY is year)
   recharge_Imp-resp_sumYYYY summed rainfall coefficients by loc
         */

/* extract out data set  - turn this into a macro later
   will have to make seasons as well


%let i=3; %let yr=2000;
*/

%macro imp_res(yr=);

%do i= 1 %to &count;

Data temp;
set sentek2.piezom&yr.all;

 where loc="&&loc_&i" and rainid_2 >0 and avfreeze <=0.25;
 if rain=. then rain=0;
 run;
/* get rid of rainid's where there might have been freezing
 no longer need this as avfreeze has been added to the
 piezometer data
 */

/*
 proc arima data = temp;
 identify var=rain;
 quit;
 */
/* this section of code summarizes rainfall events to obtain
   an estimate of cumulative drainage using simple methods
         for a few select rainfall events to characterize specific
         yield
         */


 data temp2 ;
 set temp;
  r1=lag1(rain);
  r2=lag2(rain);
  r3=lag3(rain);
  r4=lag4(rain);
  r5=lag5(rain);
  r6=lag6(rain);
  r12=lag12(rain);
```

```
  r144=lag144(rain);


 h1=lag1(head);
 h6=lag6(head);
 run;

 proc autoreg data = temp2 outest=est noprint;
 model head= h1 rain r1 r2 r3 r6 r12 r144
                  /lagdep=h1 noint;
   output out=p p=yhat pm=ytrend;
  by season;
 quit;
 run;

 data r_coef (keep=rain season r1-r3 r6 r12 r144 loc);
  set est;
  loc= "&&loc_&i" ;
 run;

 proc transpose
   data=r_coef name=source
  out=r_coeftransp;

  var rain r1-r3 r6 r12 r144;
  by season loc;
  quit;

 proc sql;
   create table t as
              select season, loc, sum(col1) as SumR_coef
        from R_coeftransp
        group by season, loc;
              quit;

%if &i=1 %then
  %do;
    data sentek2.recharge_Imp_resp_sum&yr
      (label='summed coefficients from the impulse response method');
               set t;
                      run;
           data sentek2.recharge_imp_resp_coef&yr
          (label='Coefficients from the impulse-response method');
                set r_coef;
     run;
          %end;
          %else
           %do;
            proc append base=sentek2.recharge_Imp_resp_sum&yr
               data = t;
                     quit;
```

```
            proc append base=sentek2.recharge_imp_resp_coef&yr
              data=r_coef;
            quit;
        %end;

    %end;



    %mend;

    %imp_res(yr=2000);
    %imp_res(yr=1999);
```

Appendix B. 14 Calculate Recharge from Piezometers.sas

```
/* program to calculate ground-water recharge from
   piezometer using eq 8.30 of digmans book
    R = h_i - h_i-1 (exp[-k dt]) where dt = t(h_i)- t(h_i-1)
          I used the autoregression program to develop the method and equations

          The idea is that the time between two rainfall events is dt. Since the
          data is real-time and frequent there is no need to use long time
          periods
          */

/* extract out data set  - turn this into a macro later
   will have to make seasons as well*/

Data temp (drop=dpth );
set sentek2.piezom2000all_copy;

  where loc='pp08'and 140 < DOY;
  /* data has some duplication we have to get rid of */
  if rain=. then rain=0;
/* if _n_=1 then cr=0;
   cr+rain;
   format test time7.;
          doy=round(doy,0.000001);
          test = minute(time);
          if test=0 and mod(hour(time),24)=0  then
      do;
                    rain=cr;
            output;
                    cr=0;
                   end;   */
run;

proc arima data = temp;
identify var=rain;
quit;
data temp3;
set temp;
where use=1;
run;
/* this section of code summarizes rainfall events to obtain
   an estimate of cumulative drainage using simple methods
         for a few select rainfall events to characterize specific
         yield
         */
data temp2 (keep = rainid_2 inc dec cumr phi date doy pred);
 set temp;
 by rainid_2;
 where rainid_2 >0;
/* divide del by 6 for lag6 */
  del=head-lag(head);
```

```
if first.rainid_2 then
  do;
   inc=0;
   dec=0;
   del=0;
   end;
if del > 0 then inc+del;
if del <=0 then dec + del;
if last.rainid_2 then
do;
   pred=0.03*inc;
   phi=cumr/inc;
if avfreeze <0.05 then output;
   end;
run;
```

```
data temp2 ;
set temp3;
 by rainid_2;
 /* divide del by 6 for lag6 */

     r1=lag1(rain);
 r6=lag6(rain);
 r3=lag3(rain);
/* r4=lag4(rain);
 r5=lag5(rain);
 r6=lag6(rain);
 r7=lag7(rain);
 r8=lag8(rain);
 r9=lag9(rain);
 r10=lag10(rain);
 r11=lag11(rain);
 r12=lag12(rain);
 r13=lag13(rain);
 r14=lag14(rain);
 r15=lag15(rain);
 r16=lag16(rain);
 r17=lag17(rain);
 r18=lag18(rain);
 r19=lag19(rain);
r20=lag20(rain);
r21=lag21(rain);
 r22=lag22(rain);
r23=lag23(rain);
r24=lag24(rain);
 r25=lag25(rain);
r26=lag26(rain);
r27=lag27(rain);
```

```
*/  r28=lag28(rain);

h1=lag1(head);
h6=lag6(head);

del=head-lag6(head);
if first.rainid2 then del=0;
          if del > 0 then t1+del/6;
          if del <=0 then t2 + del/6;

          run;

proc autoreg data = temp2 outest=est;
model head= h1 rain r1 r28/*r1 r2  r3 r4 r5  r6 r7 r8 r9 r10 r11 r12
             r136r14 r15 r16 r17 r18 r19 r20
             r21 r22 r23 r24 r25 r26 r27 r28 */ /lagdep=h1 noint;
  output out=p p=yhat pm=ytrend;
  where use=1;

quit;
run;

data r_coef (keep=rain  r3 r28 );
 set est;
 run;

proc transpose
 data=r_coef
 out=r_coeftransp;
 quit;

proc sql;
           select use, max((t1)) as IN,

                min((t2)) as out,
                sum(rain) as sumr
           from temp2
    group by use having use=1;
        /*  where 50.1875< doy < 59.21 */;
    select sum(col1) as SumR_coef from R_coeftransp;
          quit;
```

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T.J. Nicholson, NRC Project Manager

11. ABSTRACT *(200 words or less)*

This study investigated uncertainties in ground-water recharge estimates using real-time, near-continuous piezometer data [six piezometers instrumented with automated pressure transducers at 10-minute measurement intervals]. Analytical and numerical methods were used to compare ground-water recharge estimates. These methods included: (1) time-series analyses of hydrographs, (2) steady-state estimates using meteorological data only, and (3) the PNNL water budget model. The time-series analysis methods included: (1) sum of positive changes in piezometric heads; (2) piezometric head changes corrected for hydrograph recession; and (3) variations in rainfall input. The density of the data allowed for several estimates of recession coefficients and specific yields for each piezometer location. Higher estimates of ground-water recharge were obtained using real-time, near-continuous piezometer data than estimates derived strictly from meteorological data. This observation was also true for comparison with the water-balance method (PNNL model). Taking into account errors introduced by estimating the recession coefficients, the sum of positive changes in head is the most appropriate approach for estimating recharge at this site. For all the time-series methods, the variation in specific yield contributes to the uncertainty of ground-water recharge estimates on the order of 10 to 100%. The spatial variability in ground-water recharge was also a large contributor to uncertainty. The real-time, near-continuous piezometer data showed a very rapid response (e.g. < 20 minutes) in the shallow water table to rainfall events over short time intervals, and verified the occurrence of significant episodic recharge. Uncertainty in characterizing site behavior can be reduced by utilizing a network of measuring devices to capture the spatial variability inherent in this dynamic process.

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