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Field Studies to Confirm Uncertainty Estimates of Ground-Water Recharge

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Field Studies to Confirm Uncertainty Estimates of Ground-Water Recharge

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ABSTRACT

Little is known regarding data requirements and model uncertainties for evaluating surface and subsurface fluxes at the small watershed scale, common to nuclear facility sites. This field study was conducted to evaluate data and monitoring approaches for determining both short- and long-term ground-water recharge estimates on different spatial and temporal scales. Four methods for estimating within-field ground-water recharge were evaluated: (1) simple mass budget method of precipitation less evapotranspiration, surface runoff, and soil water storage measured with multiple capacitance probes (MCP) (***water budget method***); (2) negative changes in soil water storage less evapotranspiration (***MCP-ET method***); (3) ***stream flow*** hydrograph ***separation method***; and (4) 35% of the observed precipitation (***35% P***). Estimates of recharge were determined and compared for the 12-month period of observations of soil moisture, precipitation, meteorological variables, surface runoff, and stream flow which were recorded every 10 minutes at an intensively-monitored, agricultural-production site in Beltsville, Maryland, where all of the surface- and subsurface-water discharge into a first-order stream. The recharge amount estimated from the *water-budget method* for the whole observation period was from 20% to 25% of precipitation which is close to recent ground-water recharge estimates for Maryland and Pennsylvania obtained with different methods. Overall average percentage of rainfall used for recharge from a single recharge event was 35.3%. The *MCP-ET method* gave about twice as much recharge from a single event as compared with the *water-budget method*, most probably because of lateral movement of water with focused flow. The *stream flow-separation method* provided base flow estimates that on average were close to the values derived from spatially averaged soil water budget estimates. The other two methods, *MCP-ET* and *35% P*, gave much larger recharge estimates than the *stream flow separation method*. Overall, using MCP data provided real-time, near-continuous estimates of soil water storage and high accuracy in delineating the recharge events. The high-spatial variability of estimated ground-water recharge over the watershed area is an indication of soil and hydrologic variability and suggests that simple averaging techniques may generate unreliable watershed-wide ground-water recharge estimates.

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FOREWORD

This technical report was prepared by scientists from the U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS), in cooperation with research staff from the U.S. Nuclear Regulatory Commission (NRC), under an Interagency Agreement (IAA) between the ARS and the NRC's Office of Nuclear Regulatory Research. The objective of this study was to investigate sources of uncertainty in estimating ground-water recharge at the small watershed scale. Ground-water recharge is the quantity of water that reaches the water table, and is an important mechanism for mobilizing and transporting near-surface contaminants to the saturated zone where drinking water wells may exist. The research was designed to utilize methods and datasets from existing field characterization and monitoring programs at the Beltsville Agriculture Research Center (BARC) to evaluate various approaches used to estimate ground-water recharge. Detailed datasets were selected from an ongoing ARS field study involving a wide variety of soil-, ground-, and surface-water instruments and methods that are used to estimate ground-water recharge and assess uncertainties. This information supports reviews, by the NRC's licensing staff, of nuclear facility sites where ground-water recharge affects radionuclide leaching and transport. The issues being investigated focus on which combinations of field methods, instruments, and analytical approaches provide reliable means to estimate ground-water recharge, and what attendant uncertainties they may have.

This report builds on earlier research findings on infiltration and ground-water recharge estimation approaches using field instrumentation networks and analyses, as documented in NUREG/CR-6836, "Comparing Ground-Water Recharge Estimates Using Advanced Monitoring Techniques and Models" (Timlin et al., 2003). This report focuses on applying those methods and analyses at the watershed scale using datasets derived from automated hydrological, meteorological, and soil-water instruments used to measure local conditions and processes that affect recharge. Such instruments are important tools for obtaining near-continuous measurements of soil-water contents, water-table fluctuations, and stream flow, which enable scientists to estimate "real-time" ground-water recharge rates. The scientists then used these highly detailed datasets to estimate recharge over a 12-month period using four estimation approaches, known as; (1) the simple mass-budget method, (2) soil-water changes coupled to evaporative losses, (3) the stream-flow hydrograph method, and (4) percentage (e.g., 35%) of measured precipitation. The use of such approaches integrates point measurements within a real-time basis to compare recharge estimates and their uncertainties over the watershed area. These uncertainties can be greatly reduced using site-specific, subsurface flow measurements to estimate recharge, rather than a percentage of annual precipitation (the method commonly used at nuclear facilities). Although these approaches and applications were originally designed for reviewing radionuclide transport at complex decommissioning sites, they are also useful for assessing nuclear facility site characteristics, designing ground-water monitoring programs, and selecting remediation strategies to preclude migration of radionuclide releases to the accessible environment.

This study is consistent with the NRC's strategic performance goal of making the agency's activities and decisions more effective, efficient, and realistic by identifying and estimating uncertainties. Toward that end, this report uses examples relevant to decommissioning analyses, and demonstrating that potential sources of uncertainty in ground-water recharge estimates can be identified and reduced using site-specific datasets and appropriate analyses. It documents the state-of-the-science in field instrumentation and methods for estimating ground-water recharge. This information is assisting NRC licensing staff and regional inspectors in their technical reviews of subsurface migration of radionuclide releases involving ground-water recharge.

This report is not a substitute for NRC regulations, and compliance is not required. Consequently, the approaches and methods described in this report are provided for information only, and publication of this report does not necessarily constitute NRC approval or agreement with the information contained herein. Similarly, use of product or trade names is for identification purposes only, and does not constitute endorsement by either the NRC or USDA/ARS.

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EXECUTIVE SUMMARY

To assess facility performance of decommissioning and waste disposal facilities, accurate estimates of infiltration and ground-water recharge are needed along with their corresponding uncertainties. A variety of approaches are presently available for estimating ground-water recharge typically based on surface water hydrographs, soil water dynamics in the unsaturated zone, and ground-water data (Timlin et al., 2000, 2001, and 2003; Scanlon et al., 2002). Unfortunately, little is known regarding data requirements and model uncertainties for evaluating surface and subsurface fluxes at the small watershed scales, which are typical of waste disposal sites. There is substantial uncertainty in determining hydrologic impacts at scales larger than small plots (Simmons et al., 1979; Sharma et al., 1980; CAST, 1992). This uncertainty is a result of a high degree of spatial and temporal variability resulting from heterogeneous soils and variable climatic conditions. Additionally, subsurface soil horizons can influence water movement and plant growth by triggering preferential funnel flow (Kung, 1990, 1993; Ju and Kung, 1993, Gish et al., 2005). Matrix and preferential flow processes interact to create hydrologically active zones that are responsible for the rapid flux of soluble chemicals to ground water (Kung et al., 2000; Gish et al., 2004). The quantification of the subsurface hydrology is critical to understanding and evaluating small watershed-scale fluxes of water and chemicals.

Although water and chemical studies have been conducted on a wide range of scales, lysimeters and plots of less than 1 ha are common (Timlin et al., 2000, 2001, and 2003; Burgoa and Wauchope, 1995). At present, there is still a controversy as to whether water and chemical results from lysimeters or plots can be accurately extrapolated to the watershed scale (Burgoa and Wauchope, 1995). At the field and watershed scales surface and ground water are governed by complex interactions of several factors, such as: (1) initial soil water contents; (2) soil properties, primarily texture and organic matter content; (3) intensity and duration of the precipitation event; (4) hydrologic properties of the surface soil, primarily surface slope, landscape position, and surface crusting; and (5) subsurface stratigraphy (Burgoa and Wauchope, 1995). As a result, there is a need to evaluate field processes at a scale germane to waste disposal operations so that data requirements and modeling approaches can be adequately evaluated with regard to ground-water recharge.

This study utilizes hydrologic datasets from an existing and intensively monitored small-scale agricultural production watershed at the USDA Beltsville Agricultural Research Center, which is of comparable size to common waste disposal facilities. Real-time and near-continuous datasets consisting of soil moisture profiles, meteorological energy balance data, and stream flow data from May 2001 to April 2002 were used to estimate ground-water recharge at the small watershed scale. This site provided (1) data of real-time near continuous monitoring of soil moisture in at several depths in 24 locations with 10 min frequency year-around, (2) discharge data from stream flow gauging stations, (3) meteorological information from eddy-covariance tower as well as from the class I weather station, (4) several years of yield maps, (5) exhaustive information on the land use and crop management, (5) data of the ground penetration radar surveys used to delineate subsurface flow and transport pathways.

The main objective of the study was to evaluate three methods for calculating in-field ground-water recharge - (1) the water budget method, (2) MCP-ET method, and (3) 35%P method - were evaluated. These three within-field estimates were then compared to graphical stream flow separation methods as illustrated by Dingman (1994).

A critical finding was that the recharge event defined as the time interval between two consecutive local minima on soil water storage series was an efficient temporal unit to estimate the groundwater recharge. Substantial differences were found between in-field methods of recharge estimation. The interpretation of the differences between the methods was possible based on their inherent differences as suggested by Risser et al. (2005). The soil water budget method estimates of ground-water recharge were the closest to the recharge observed in the stream using the stream flow separation method. The MCP-ET method overestimated ground-water recharge. Therefore, the water budget and stream flow separation methods can be used to estimate ground-water recharge at the small watershed scale. The other methods performed poorly because of these uncertainties: (1) 35%P method generally overestimated ground-water recharge because the method assumes that surface conditions (e.g. crop cover, infiltration rates) are the same throughout the year; (2) MCP-ET method frequently overestimated ground-water recharge, a result of the assumption that there is no subsurface lateral run-on and uniform evapotranspiration across the field. With this latter method, the conveying of subsurface water from one location to another generates higher water storage values than can be explained from observed precipitation amount. As a result, the MCP-ET method fails to account for soil heterogeneity and complex landscape interactions.

Event-based estimates of ground-water recharge showed the dependence on the rainfall amount. Percentage of rainfall that was directed to groundwater was decreasing with the increasing amount of rainfall when the in-field MCP-based methods were used, but tended to increase when the hydrograph separation methods were applied. The recharge amount estimated from the water budget for the whole observation period was from 175 mm to 220 mm and constituted from 20% to 25% of precipitation which is close to recent groundwater recharge estimates for Maryland and Pennsylvania obtained with different methods. The average estimated percentage of rainfall used for recharge for a single recharge event depended on the amount of rain and was 56%, 40%, 28%, 11% and 11% for rainfalls 0 to 10 mm, 10 to 20 mm, 20 to 30 mm, 30 to 60 mm, and larger than 60 mm, respectively. Overall average percentage of rainfall used for recharge from a single recharge event was 35.3%.

There was high spatial variability of net infiltration and ground-water recharge at the two temporal scales of analysis (event and seasonal), indicating the soil and hydrologic variability of the site in terms of the presence or absence of clay lenses, subsurface preferential flow paths, and seepage zones. Spatial variability in ground-water recharge at local or watershed scale is critical for contaminant transport because focused recharge and preferential flow allow contaminants to migrate rapidly through the unsaturated zone to underlying aquifers. Delineation of zones with high and low ground-water recharge is important for defining zones that may be critical or vulnerable to contamination and determining how fast the chemicals move to the stream. Locations that had subsurface flow channels tended to have high ground-water recharge estimates because of good drainage after rainfall events.

All field-data based methods have an inherent uncertainty caused by variability associated with spatial distribution of evapotranspiration, precipitation, and surface runoff. The one-dimensional schematization of the soil water transport can be insufficient as it ignores lateral surface and subsurface pathways of water movement in groundwater and in the vadose zone.

Real-time, near continuous hydrologic datasets from watersheds that are at least greater than one hectare can provide details of the spatial variability of the site in terms of infiltration capacity, surface runoff, and ground-water recharge. Additional spatially dense information, such as yield maps, remote sensing imagery, and ground penetration radar mapping can provide invaluable information for the interpretation of the results from different recharge estimation methods.

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GLOSSARY

Capacitance probe	An instrument used to measure soil water content using radio waves.
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 its potential rate when water is not limiting.
Event/Potential ground-water recharge period	A period for potential ground-water recharge during a rainfall event was defined as the time from the beginning of a rain event to the next time with rain that was at least 24 hours after the previous rain.
Ground-water recharge	The quantity of water that reaches the water table.
Hydrograph	Graph showing flow rate of water versus time.
Multi-sensor Capacitance Probe (MCP)	A field instrument inserted into the soil with capacitance sensors at discrete depth intervals capable of real-time, near-continuous monitoring of volumetric water content.
Near-continuous	Measurement frequency that captures the temporal variance of the event being monitored.
Real-time	The actual time in which a physical process takes place with the recording of the event practically simultaneous with its occurrence.
Total infiltration	Total amount of water entering the soil (cm) equal to rainfall minus surface runoff.
Volumetric water content	The amount of water expressed as a ratio of water volume to soil volume (cm^3 cm^{-3}).

ABBREVIATIONS

ARS	Agricultural Research Service (U.S. Department of Agriculture)
AWK	Aho Kernighan Weinberger computer programming language
ET	Evapotranspiration
FAO	Food and Agricultural Organization
fw	Fall/Winter
IAA	Interagency Agreement
MCP	Multi-sensor Capacitance Probes
Rain-id	Rainfall period identifier
Ro	Surface runoff water
SAS	Statistical Analysis System software (SAS Corporation, Cary, NC)
ST	Soil water storage
su	Summer
USDA	U.S. Department of Agriculture
Ws	Winter/Spring

SYMBOLS

ROMAN SYMBOLS

di	depth
Em	evapotranspiration rate
ET	evapotranspiration
Fm	runoff rate
Iij	total infiltration losses
Nj	number of time intervals
P	precipitation
Qr	ground-water recharge
RED	recharge event duration
Rm	rainfall intensity
Si	total soil water storage
SW	soil water storage
Tj	time

GREEK SYMBOLS

θ	soil moisture content
θ_T	soil water content
$\Delta\theta$	change in soil water content
Q_r	ground-water recharge

1 INTRODUCTION

1.1 BACKGROUND

In order to assess subsurface flow and transport as they relate to environmental system performance at decommissioning sites, accurate estimates of infiltration and ground-water recharge are needed along with their corresponding uncertainties. A variety of approaches are presently available for estimating ground-water recharge typically based on surface water hydrographs, soil water dynamics in the unsaturated zone, and ground water data (Timlin et al., 2000, 2001, and 2003; Scanlon et al., 2002). Unfortunately, little is known regarding data requirements and model uncertainties for evaluating surface and subsurface fluxes at the small watershed scale, which are typical of many decommissioning sites. There is a need to evaluate data requirements and model approaches at the small watershed scale where near-continuous hydrologic fluxes and soil water dynamics are being monitored.

Drainage and water infiltration can be estimated using different methods such as double-ring infiltrometers, soil water content profiles, temporal fluctuations in water-table heights, site precipitation, and evaporation data (Timlin et al., 2003; Bazuhair and Wood, 1996). Ground-water recharge estimates can be subject to large errors and uncertainties because there is no direct way of measuring it. Therefore, when possible, more than one method should be used to verify the estimates and uncertainties associated with ground-water recharge (Timlin et al., 2003). In 1998, the United States Department of Agriculture - Agricultural Research Services (USDA-ARS) developed a 21 ha (52 acres) hydrologically bounded production site that feeds a riparian wetland and first-order stream (Walthall et al., 2001; Angier et al., 2001). Research at this location is associated with the "Optimizing Production Inputs for Economic and Environmental Enhancement site (OPE3) and contains infrastructure for monitoring soil water dynamics, surface water, and energy fluxes at 10 minute intervals (Gish et al., 2005; Prueger et al., 2005). Because this site contains process oriented data at small temporal and spatial scales, and because fluxes are continuously monitored, it provides an optimum resource for evaluating data and model requirements that will adequately simulate observed infiltration and ground-water recharge processes.

There is substantial uncertainty in determining hydrologic impacts at scales larger than small plots (Simmons et al., 1979; Sharma et al., 1980; CAST, 1992). This uncertainty is a result of a high degree of spatial and temporal variability resulting from heterogeneous soils, variable climatic conditions, changing surface conditions due to plant growth, canopy, and residue accumulation/decomposition. Subsurface soil horizons affect water movement and plant growth, by triggering preferential funnel flow processes (Kung, 1990, 1993; Ju and Kung, 1993). Matrix and preferential flow processes can interact to create hydrologically active zones that are responsible for the rapid flux of soluble chemicals to ground water (Kung et al., 2000; Gish et al., 2004). Protocols for determining where and when these surface and subsurface flow pathways interact on a field scale are still in their infancy. Recently, an experimental protocol using primarily ground-penetrating radar, GPR, and digital elevation maps, DEM, to identify the location of subsurface convergent flow pathways was developed (Gish et al., 2002, 2005). The quantification of the subsurface hydrology is critical to understanding and evaluating small watershed-scale fluxes of water and chemicals.

1.2 Objectives

The main objective of this study was to confirm data requirements and modeling procedures for estimating infiltration and ground-water recharge at the small watershed scale, which would be representative of data sets anticipated at decommissioning and waste disposal facilities. The focus of this study was on using real-time hydrologic data averaged over various time domains with different hydrologic models of varying complexities used to evaluate infiltration and ground-water recharge at the small watershed scale. Protocols developed from previous ARS-NRC Interagency Agreement research studies (Timlin et al., 2000, 2001, 2003) were used. Specifically, this study examined three methods for estimating ground-water recharge within the field: (1) soil water mass budget method, (2) moisture capacitance method less evapotranspiration, and (3) 35% of the observed precipitation method. These three methods were compared with the graphical stream flow hydrograph separation method (Dingman, 1994). Ground-water recharge estimates using these methods were analyzed and compared to each other on different spatial and temporal scales with a focus on understanding their inherent relative uncertainties.

2 DESCRIPTION OF FIELD SITE AND DATABASES USED

2.1 Experimental Site

Most of the data (Appendix A) used in this study were obtained from a 3.6 ha (8.9 acres) field, which is part of a 21-ha (51.9 acres) agricultural research site located at the USDA, Beltsville Agricultural Research Center, Beltsville, Maryland. As shown in Figure 2-1, the research site has four fields (A, B, C, and D) that are part of the "Optimizing Production inputs for Economic and Environmental Enhancement" (OPE3) study. The OPE3 site seeks to compare agricultural production systems at a scale large enough to capture the spatial variability of crop and soil parameters, yet small enough for the watersheds to be in similar climatic and geologic settings. About 74% of the site has a slope < 2% and only 2% of the site has a slope > 3%. The soils are sandy textured with buried clay lens (coarse-loamy, siliceous, semiactive, mesic, Typic Hapludult). The soil profile predominantly consists of sandy loam Ap-horizon for the top 0.30 m, followed by a loam Bt-horizon that continues down to 0.80 m, a loamy sand C-horizon from 0.80 to 1.20 m, and fine textured clay loam lens from about 1.20 to 2.50 m (Gish et al., 2002). Subsurface flow pathways were identified and delineated using ground-penetrating radar (GPR) data and digital elevation maps (DEM). For a detailed description of identification and delineation of subsurface flow pathways refer to Gish et al. (2002). Figure 2-2 shows the identified subsurface flow pathways and locations of soil moisture multi-sensor capacitance probes in field B.

2.2 Instrumentation and Databases Used

Twelve soil moisture multi-sensor capacitance probes (MCP) (Sentek Pty, Kent Town, South Australia) installed in field B were used in this study. The probes were installed in areas with high, medium, and low infiltration capacities based on electromagnetic measurement values. The locations of the probes are indicated in Figures 2-1 and 2-2, L refers to probes installed in areas where infiltration capacity was high (low electromagnetic values), M refers to probes installed in areas where infiltration capacity was medium (medium electromagnetic values), and H refers to probes installed in areas where infiltration capacity was low (high electromagnetic values). A sample of soil moisture data measured with a probe is given in Appendix A-1.

Soil moisture sensors were installed at different depths depending on the infiltration capacity of the probe location (Table 2-1). For example, Figure 2-3 shows a sample of 6 probes with installation depths of soil moisture sensors depending on the location of the probes (whether on high, medium or low infiltration capacity). The probes had sensors centered at 10, 30, 50, 80, 120, 150, and 180 cm depths that measured soil moisture contents at 10–minute intervals. The sensors provided a near-continuous, real-time record of soil moisture content with depth throughout the year. Each sensor integrated the soil water content over a 10-cm interval, e.g. the sensor centered at 10-cm integrated soil water content between 5 and 15 cm. Since only two-thirds of the soil probes had sensors below 80 cm (Figure 2-3), net infiltration and ground-water recharge were computed using sensors located at 10, 30, 50, and 80 cm depths.

Surface runoff water from field B was measured at the outlet of the watershed with a 45.7 cm H-flume equipped with a flow meter and a water sampler (ISCO, Lincoln, Nebraska).

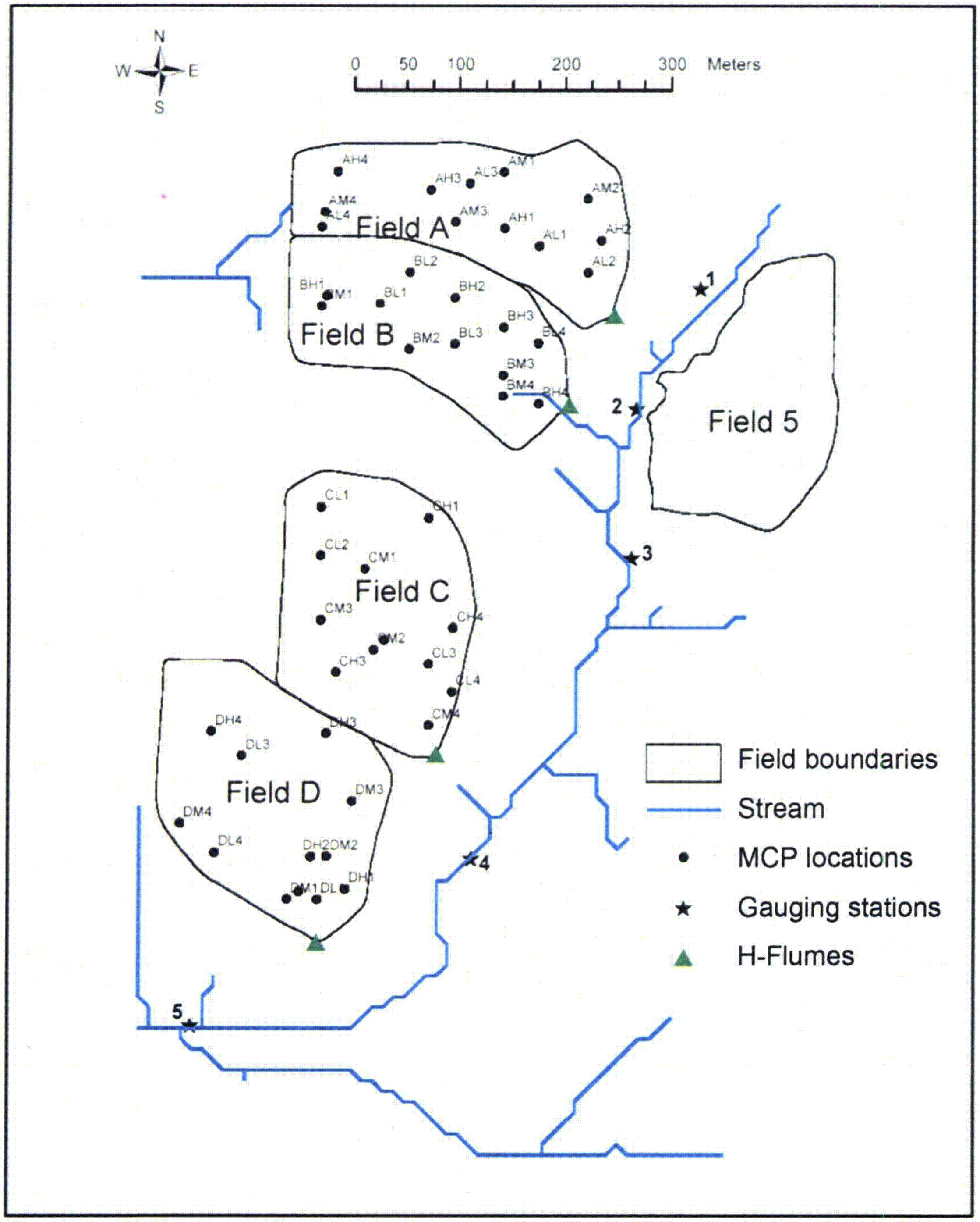

Figure 2-1. Layout of fields, soil moisture measuring probes, stream flow gauges, and surface runoff H-flumes at the research site. Note that L (as in AL, BL, or CL etc) refers to probes installed in areas where infiltration capacity was high [low electromagnetic (EM) values]; M refers to probes installed in areas where infiltration capacity was medium (medium EM values); H refers to probes installed in areas where infiltration capacity was low (high EM values). Only soil moisture data collected in field B were used in this study.

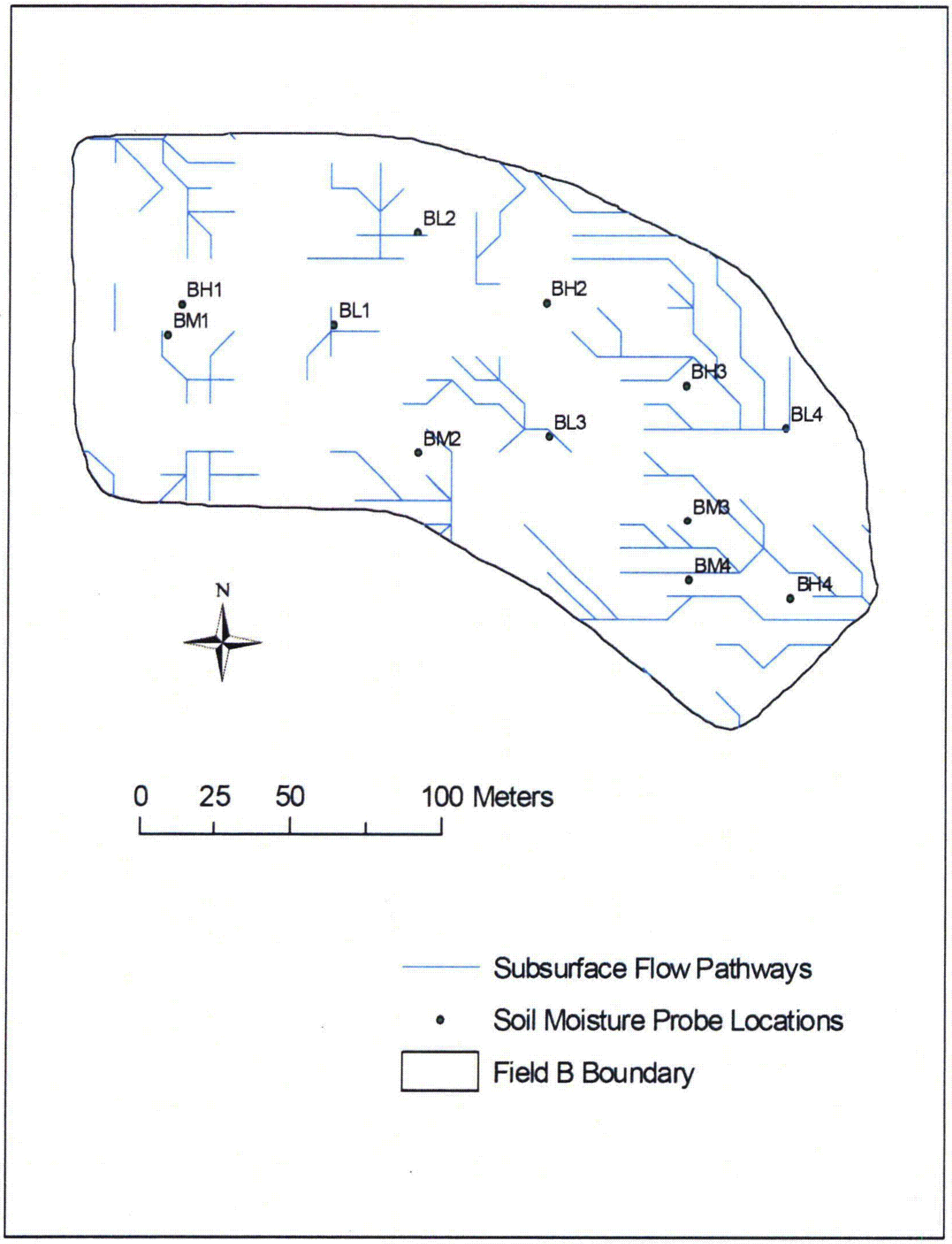

Figure 2-2. Subsurface flow pathways and locations of soil moisture multi-sensor capacitance probes (MCP) in field B.

Table 2-1. Installation depths of soil moisture sensors depending on the infiltration capacity estimated with the electromagnetic induction (EM-38)

Depth	Location and Depth of Probes Based on Infiltration Capacity											
	High Infiltration Capacity				Medium Infiltration Capacity				Low Infiltration Capacity			
	L1	L2	L3	L4	M1	M2	M3	M4	H1	H2	H3	H4
10 cm	■	■	■	■	■	■	■	■	■	■	■	■
30 cm	■	■	■	■	■	■	■	■	■	■	■	■
50 cm	■	■	■	■	■	■	■	■	ns	ns	ns	ns
80 cm	■	■	■	■	ns[£]	ns	ns	ns	■	■	■	■
120 cm	■	■	■	■	■	■	■	■	ns	ns	ns	ns
150 cm	■	■	■	■	■	■	■	■	ns	ns	ns	ns
180 cm	■	■	■	■	■	■	■	■	ns	ns	ns	ns

[£] ns means no soil moisture sensor installed at that depth.

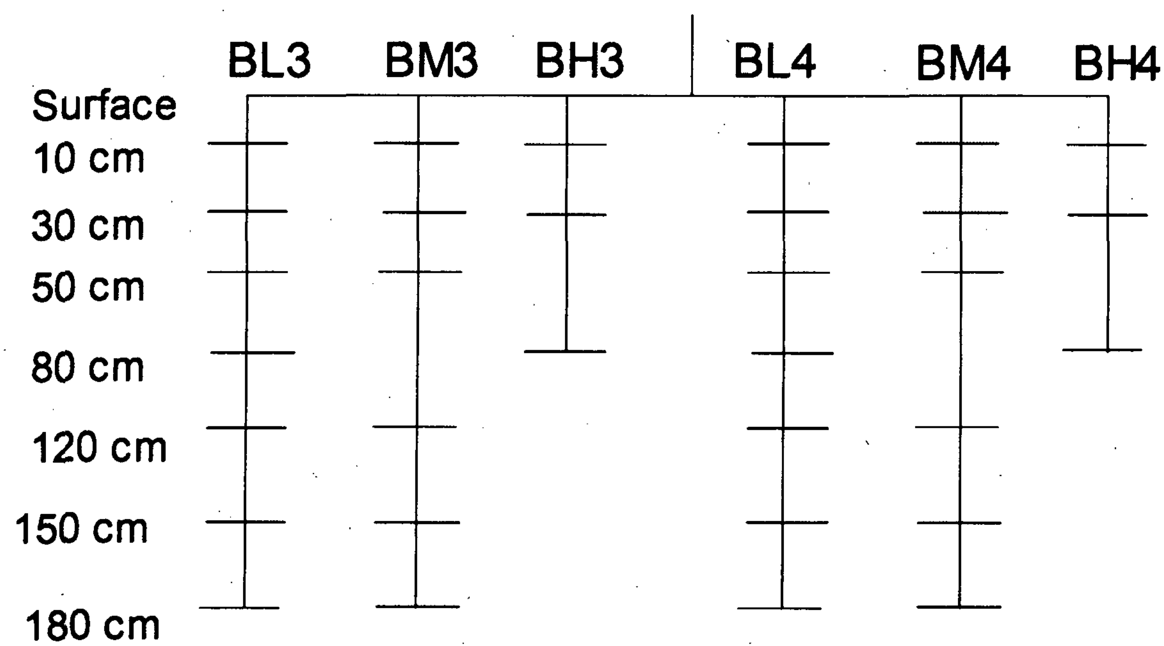

Figure 2-3. Installation depths of soil moisture sensors on a sample of 6 probes (out of 12) in the soil profile depending on the infiltration capacity of the probe location. Note that B refers to field B, L refers to probes installed in areas where infiltration capacity was high [low electromagnetic (EM) values]; M refers to probes installed in areas where infiltration capacity was medium (medium EM values); H refers to probes installed in areas where infiltration capacity was low (high EM values).

Amount of surface runoff was measured automatically and continuously. (Appendix A-2 shows a sample of surface runoff data from field B). The fields at the OPE3 site drained into a riparian wetland forest, which contained a first-order stream. The riparian wetland contained about 180 observations wells and five in-stream weirs that were used to quantify water and chemical fluxes in the first-order stream. A gauge placed in the stream at station 3 measured stream flow at 10-minute intervals. Appendix A-3 shows a sample of stream flow data measured in a first-order stream. The watershed area contributing to the observed flow at station 3 was delineated in Arc-Map using digital elevation maps (DEM) and knowledge of the subsurface flow pathways draining the production fields. Delineated watershed area for station 3 includes the riparian area and parts of fields A, B and 5 with a total drainage area of 12.4 ha (30.6 acres) (Figure 2-4).

An energy balance weather station inside field B was the source of detailed meteorological data. This stations measured water and energy inputs at short time intervals (10 minutes): soil temperature, soil heat flux, air temperature, relative humidity, 3-D wind speed profile, rainfall, long and short wave solar radiation, net solar radiation, saturation and actual vapor pressure, evapotranspiration, and CO_2 fluxes. Appendix A-4 shows a sample of meteorological data measured at the study site. Some of the equipment at the station was turned off during off-season (when the temperatures were very low and when there was no crop).

The second source of the meteorological data used in this study was the weather station located about 4.8 km (3 miles) from the research site (Timlin et al., 2001) from May 2001 to April 2002. Daily ET was computed using the Penman-Monteith method as documented by FAO (Allen et all., 1998). The daily values were integrated over time to obtain the cumulative ET as a function of time from the beginning of the observation period. The cumulative ET curve was used for interpolation to obtain ET over the recharge estimation periods.

The Penman-Montheith estimates were compared with the ET estimates from the energy balance for periods of time when the latter were available. Results of the comparison are shown in Fig. 2-5. The coefficient of determination of 0.60 shows that there were no dramatic differences between the Penman-Monteith ET estimates and energy balance-based ET estimates (Figure 2-5). The Penman Monteith method tended to generate values larger than the energy balance method, especially for low ET.

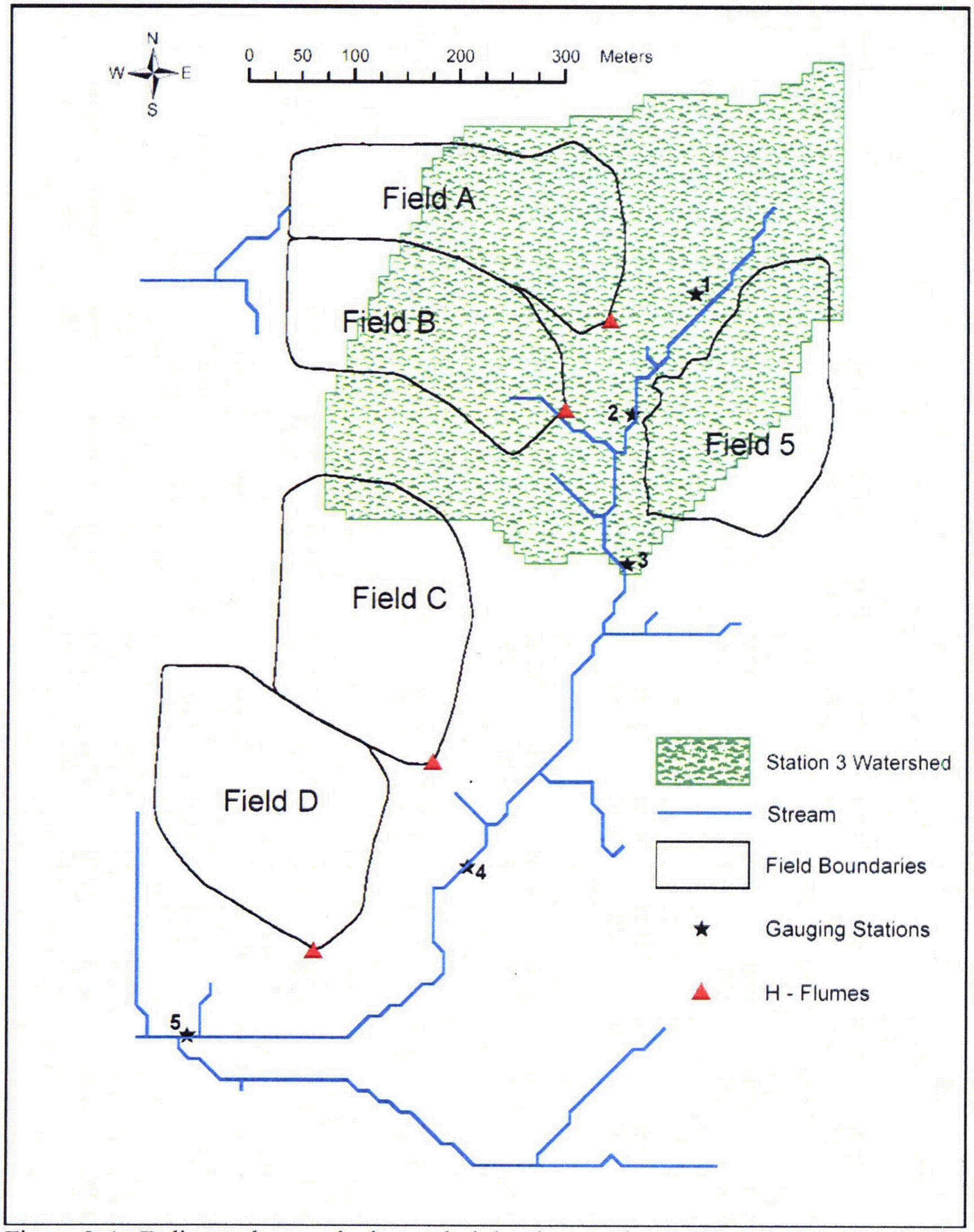

Figure 2-4. Delineated watershed area draining into station 3. Note that the area mainly consists of the riparian area around the stream and fields A, B, and 5. Parts of fields A and B drain into the other side of the research site. Field 5 is very flat (slope <0.5%), hence no surface runoff from that area.

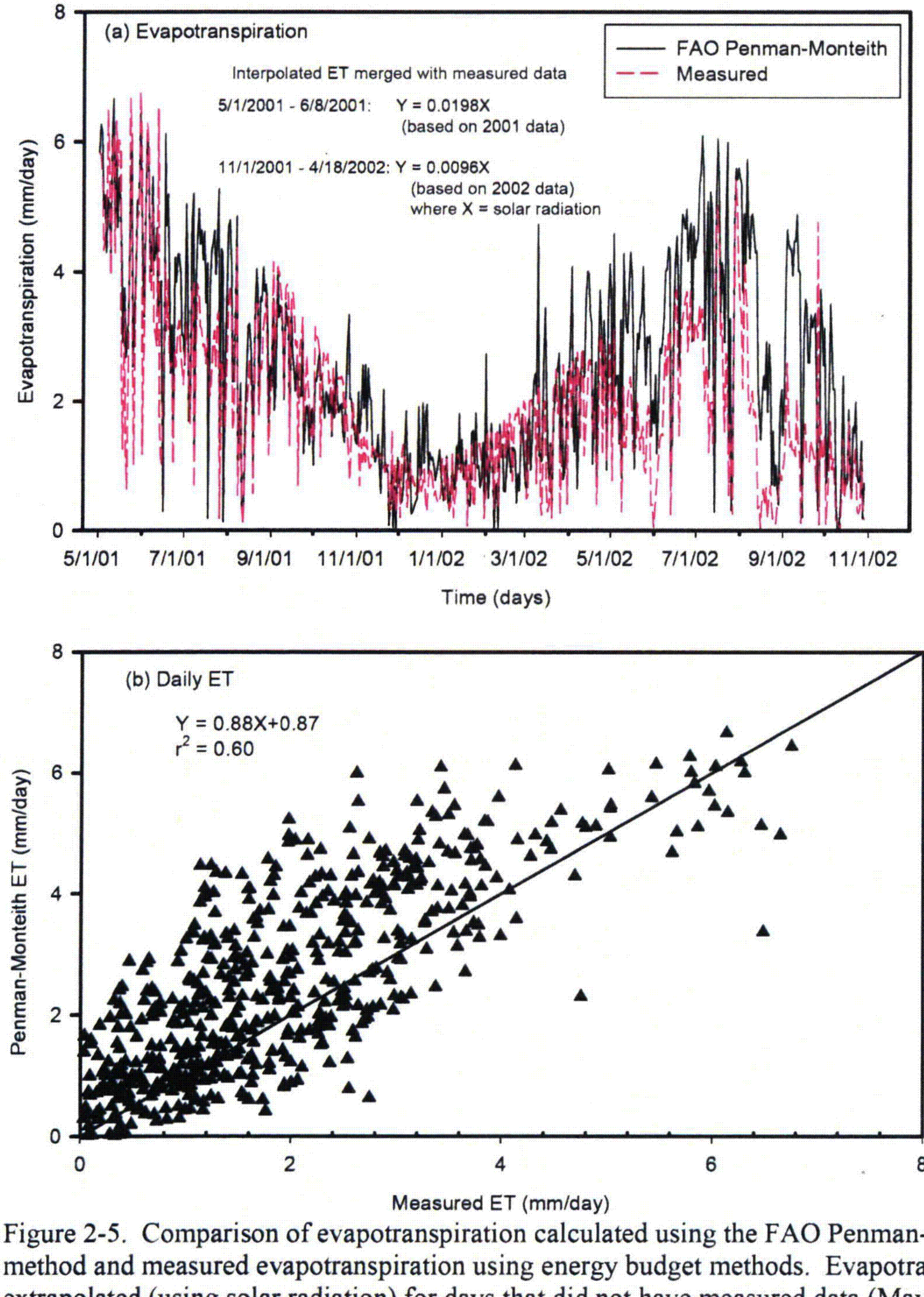

Figure 2-5. Comparison of evapotranspiration calculated using the FAO Penman-Monteith method and measured evapotranspiration using energy budget methods. Evapotranspiration was extrapolated (using solar radiation) for days that did not have measured data (May 1 - June 8, 2001 and January 1 - April 18, 2002).

3 GROUND-WATER RECHARGE ESTIMATION METHODS

This section describes the methods used to estimate ground-water recharge at the research site. The following methods were used to indirectly estimate ground-water recharge in the field: (1) soil water budget; (2) soil moisture multi-sensor capacitance probes less evapotranspiration method; (3) the hydrograph separation method as illustrated by Dingman (1994); and (4) 35% of observed precipitation. Note that only 12 distinct (out of 50) stream flow hydrographs were separated into surface runoff and ground-water recharge components using the Dingman and Modified Dingman methods. The hydrographs selected did not have smaller hydrographs in them.

3.1 SOIL WATER BUDGET WITH MOISTURE CAPACITANCE PROBES

The soil water budget and MCP-ET methods use soil water dynamic information from the moisture capacitance probes. The moisture capacitance probes measured soil water content at depths d_1=10, d_2=30, d_3=50, d_4=80, d_5=120, d_6=150, and d_7=180 cm depths to estimate net infiltration and ground-water recharge. Amount of soil water in each soil profile layer was calculated by multiplying the thickness of the profile layer by the measured volumetric soil moisture content at each sensor every 10 minutes throughout the year (integrating the soil moisture over the soil depth profile). Layer thicknesses Δ_i (i=1,2,...,7) for the probes at 10, 30, 50, 80, 120, 150, and 180 cm were set to Δ_1= 20, Δ_2=20, Δ_3= 25, Δ_4= 25, Δ_5= 35, Δ_6= 30, and Δ_7= 30 cm. The total soil water storage S_i in soil from the surface to the depth d_i is the summation of individual soil water contents for all layers above this depth and can be represented as:

$$S_i = \sum_{k=1}^{i-1} \Delta_k \theta_k + \frac{1}{2} \Delta_i \theta_i \qquad (3\text{-}1)$$

For a period of time T_j the total infiltration losses I_{ij} below the depth d_i were computed from the soil water budget equation:

$$I_{ij} = \sum_{m=1}^{N_j} R_m \Delta t + \sum_{m=1}^{N_j} F_m \Delta t - \sum_{m=1}^{N_j} E_m \Delta t - \Delta S_{ij} \qquad (3\text{-}2)$$

Here, N_j is the number of 10-min intervals within the T_j time period, R_m, m=1,2,...N, is the rainfall intensity (cm min^{-1}) during the m^{th} 10-min interval, F_m, m=1,2,...N, is the runoff rate (cm min^{-1}) during the m^{th} 10-min interval, E_m, m=1,2,...N, is the evapotranspiration rate (cm min^{-1}) during the m^{th} 10-min interval, Δt=10 min is the time between consecutive measurements of soil water contents, ΔS_{ij} is the change in soil water storage in the soil layer from 0 to d_i over the time interval T_{ij}.

Estimating recharge with the equation (3-2) required (a) selection of time intervals T_j over which the water budget is computed, and (b) selection of the depth at which infiltration losses from soil can be equated to the groundwater recharge, i.e. to the amount of water reaching groundwater.

Selection of time intervals to compute soil water budget

To select the budget time intervals we inspected graphs of soil water storage time series S. An example of such a graph is shown in Fig. 3-1 for the location BL1 and layer of 0 to 80 cm. A characteristic multi-peak time series of soil water storage could be observed on this graph and similar graphs for other locations. Each peak was located between two local minima at the time series and consisted from discernible rising and falling limbs. The time intervals between these two minima of soil water storage were used to compute the soil water budget. Such time interval usually would start with the rainfall, include period without rainfall or with small rains that do not affect the soil water storage significantly, and end in the beginning of the next relatively strong rainfall (Fig. 3-2). For the sake of brevity, we use the term "recharge event." for such time intervals.

Using minima on the soil water storage time series to select water budget computation intervals allows one to ensure that the soil water budget layer has lost all the water that has entered the soil since the rainfall event began. In such a case the infiltration losses can be reliably related to a specific amount of water received during a rainfall event. The latter is not the case if water budget is computed using some temporal grid with equal times for budget computations. Consider, for example, the time interval [t_a, t_b] in Fig. 3-2 that is within the raising limb of the soil water storage graph. Computing water budget over this time interval does not cover the whole rainfall event and therefore does not allow relating infiltration losses to the amount of water within the rainfall event between times t_1 and t_2. Another example is given by the time interval [t_c, t_d] in Fig. 3-2 which is within the falling limb of the soil water storage graph where the loss of soil water is caused by the evapotranspiration and infiltration. It is difficult to relate this loss to the rainfall amount received between times t_1 and t_2 because not all the rain water that entered soil has been lost yet. Also, using recharge events allows one to avoid making arbitrary decisions on whether the rainfall events have to be separated or combined together in the infiltration loss computations.

The peaks on the water storage time series could be accurately delineated only because frequent near real time observations. The values of soil water storage at maximums and minimums in soil water time series were digitized manually using the Surfer software (Golden Sofware, Golden, Colorado[1]) for each location and each depth.

Selection of depth interval to compute soil water budget

The depth of the water budget layer selected to assure that the upward capillary flow through this depth could be neglected and no substantial waster losses for evapotranspiration occurred below this depth. To define the depth of the water budget layer, we computed soil water storage changes at ascending and descending limbs of soil water storage time series at depths 120 cm, 150 cm and 180 cm, and plotted them against changes at depth of 80 cm for the same periods of time. Computed increments of soil water storage were very close to the 1:1 line (R^2=0.981) as shown in the example for location BL1 at Fig. 3-3. This means that recharge event-based infiltration amounts at depths of 120, 150 and 180 cm were approximately equal to

[1] The use of trade, firm, or corporation names in this publication (or page) is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

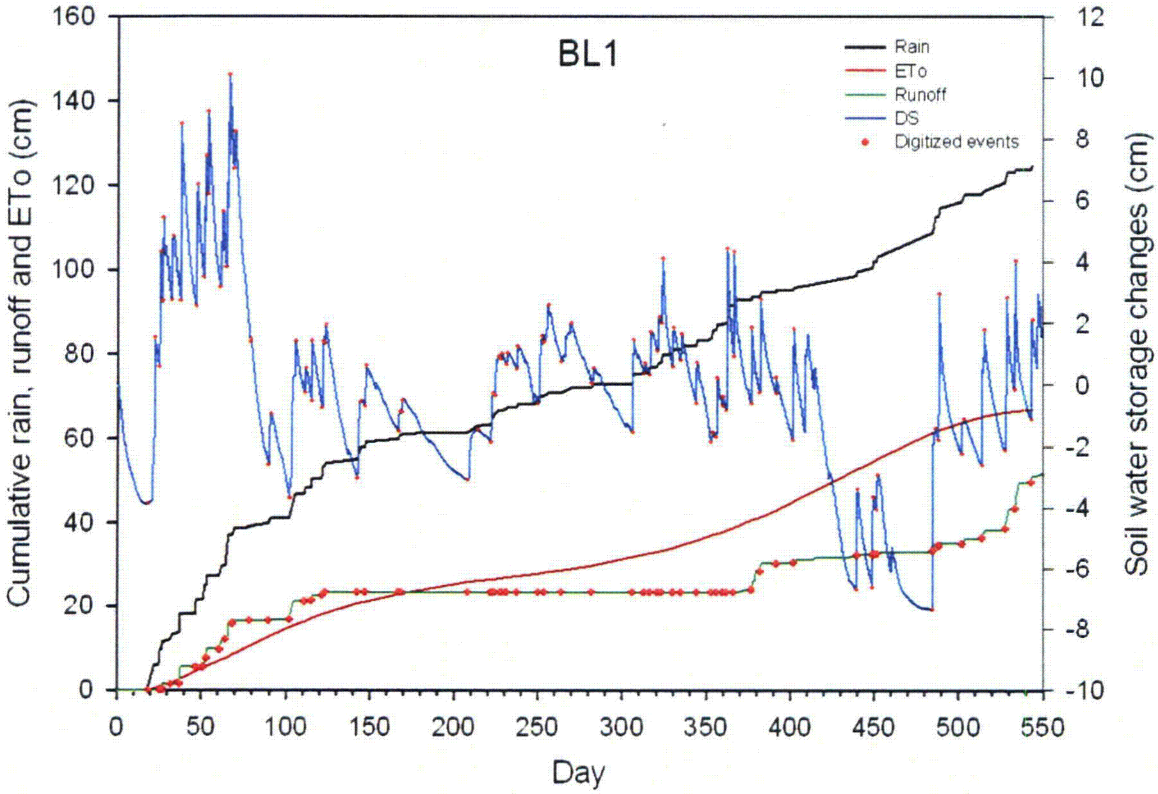

Figure 3-1. Selection of the recharge events from soil water storage time series at the location BL1. Dots mark minima and maxima on the soil water storage time series used to define recharge events.

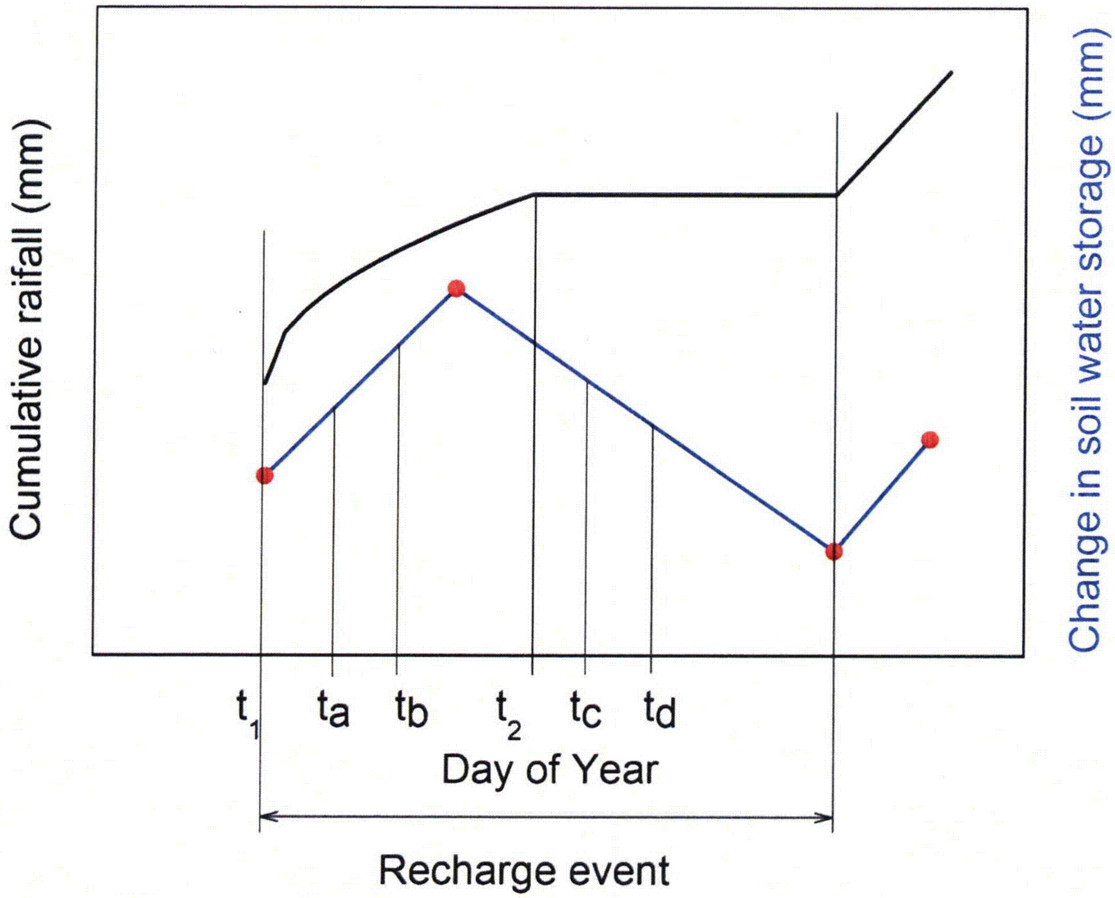

Figure 3-2. Schematics of the recharge event selection. Comments are in the text.

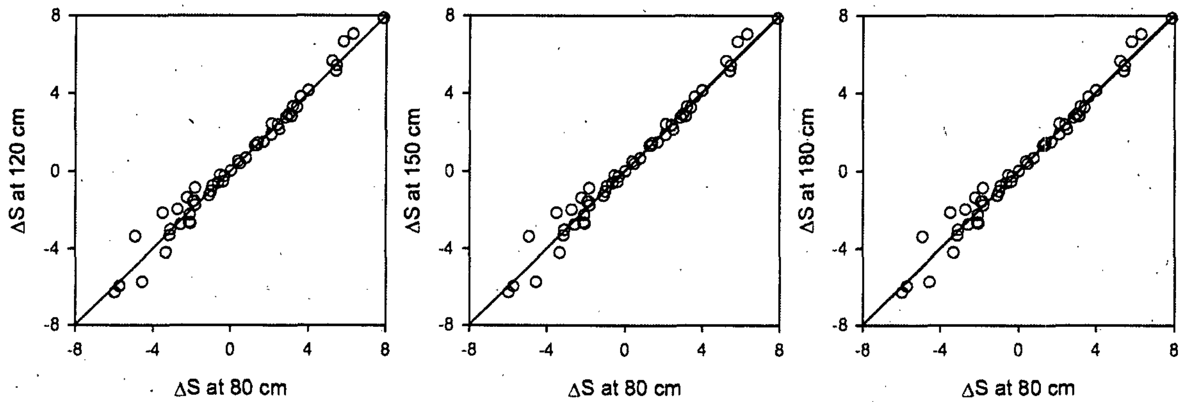

Figure 3-3. Relationships between changes of soil water storage in different soil layers for location BL1.

infiltration amounts at the depth of 80 cm. That implies that water that left the soil profile at the 80-cm depth, was transmitted downward and eventually contributed ground water. Therefore, to evaluate groundwater recharge in experimental conditions of this site, the soil water budget could be computed for the top 80-cm soil layer. Rainfall, ET and surface runoff were assumed to be constant throughout the field when Eq. (3-2) was applied. Runoff rates were estimated by dividing runoff volumes to the ARCGIS-generated contributing area of the runoff flume on field B.

3.2 RECHARGE ESTIMATES WITH MCP-ET METHOD

This method computes groundwater recharge as the difference between the decrease of soil water storage at the falling limb of the recharge event (Figure 3-2) and the total evapotranspiration over the falling limb duration. The implicit assumption is that the rainfall fills the soil with water, and that no substantial losses of water occur over the soil storage raising limb duration. ET was computed on daily basis.

3.3 STREAMFLOW HYDROGRAPH SEPARATION METHOD

The graphical separation method was used to separate 12 stream flow hydrographs between May 1, 2001 and April 30, 2002. In this method, the watershed area as well as hydrograph shape and base flow are used to calculate groung-water recharge.

Appendix D illustrates the graphical stream flow hydrograph-separation technique as shown in Dingman (1994). From the point of initial hydrograph rise, a line that slopes upward at a rate of {(0.05 ft^3 s^{-1}) A mi^2 h^{-1}, where A is the area in square miles} was drawn and extended until it intercepted the hydrograph. A second horizontal line was drawn from the point of initial hydrograph rise and extended up to the end the hydrograph period. The horizontal line represented continuous constant stream flow before, during, and after the rain event. The area between these two lines represents the amount of direct ground-water recharge due to the rainfall event (Appendix C). For the sake of brevity, the two hydrograph separation methods are termed Dingman and Modified Dingman.

3.4 PERCENT OF OBSERVED PRECIPITATION (35%P) METHOD

Previous studies have shown that percentage values used in this method vary with the amount of precipitation, soil type and place. For example percentage values ranged from 1 to 35% in Iran, 10 to 15% in India, 41% in Hawaii (Bazuhair, et al., 1996). In this study, 35% of effective precipitation was used because Timlin et al. (2001) found 35% precipitation to be comparable to measured ground-water recharge for Beltsville, MD. Ground-water recharge was estimated as:

$$Q_r = 0.35P \tag{3-3}$$

where Q_r is ground-water recharge (mm) and P is precipitation (mm). In this method ground-water recharge was estimated as a percentage of precipitation during the rainfall event.

4 RESULTS AND DISCUSSION

The results are presented on two temporal scales: (1) recharge event-based, and (2) seasonal: spring, summer, fall and winter.

4.1 PRECIPITATION, EVAPOTRANSPIRATION, AND SURFACE RUNOFF

Ten-minute values of precipitation, evapotranspiration, and surface runoff were aggregated on the recharge event basis. The results are shown in Fig. 4-1.

Total of 394 recharge event durations (REDs) were delineated for 8 locations that had soil moisture sensors at 80 cm. The statistical distribution of the recharge event durations was close to lognormal (Fig. 4-1a). The median duration was close to 1 week (6.38 d), 25% of REDs were shorter than 4 days, and 25 % of RED were longer than 11 days. The statistical distribution of rainfall values was close to lognormal except that it was truncated in the range of large rains (Fig. 4-1b). The median rainfall was about 14 mm, 25% of rainfalls were smaller than 9 mm, and 25% of rainfalls were larger than 22 mm. No significant relationship between RED and rainfall was observed (Fig. 4-1c).

Runoff constituted from 0 to 10 % of the rainfall (Fig. 4-1c). The relationship between the runoff amount and rainfall was weak (Fig. 4-1d) with the quadratic regression

$$\text{Runoff(mm)} = 0.168363991\cdot\text{Rainfall(mm)} + 0.0051641470881\cdot\text{Rainfall(mm)}^2 \qquad (4\text{-}1)$$

having R^2=0.473. The evapotranspiration values over REDs were distributed approximately lognormally (Fig. 4-1e) with the median value of 5.7 mm, 25% of cumulative over RED evapotranspiration values over RED were less than 2.5 mm and 25% of ET of cumulative over RED evapotranspiration values over RED were larger than 11 mm.

The linear relationship between evapotranspiration (ET) and RED

$$\log_{10}\text{ET (mm)} = 0.12+1.04\cdot\log_{10}\text{RED(d)} \qquad (4\text{-}2)$$

was moderately strong with R^2=0.632.

Total amount of rainfall, evapotranspiration and runoff over the 365 days of the observation period was 909 mm, 386 mm, and 276 mm, respectively.

Data on soil water storage changes for eight locations are shown in Fig. 4-2. There is noticeable similarity in soil water storage time series measured at different locations. Time series from different location appear to be approximately shifted relative to each other. Such temporal stability of soil water storage can be used to select monitoring sites and estimate missing data as shown in Pachepsky et al. (2005).

4.2 RECHARGE ESTIMATES WITH THE SOIL WATER BUDGET METHOD

The recharge amount estimated from the water budget method for the whole observation period was from 175 mm to 220 mm and constituted from 20% to 25% of the total precipitation. These values are close to literature groundwater recharge estimates for Maryland and Pennsylvania obtained with different methods. Dine et al. (1995) report the groundwater recharge of 21% of yearly precipitation for the Piedmont part of the Howard County, MD, whose southern county line is located 5 miles to the north from the research site. Risser et al. (2005) reported the range of 21% to 28% of precipitation for small heavy instrumented watershed in Central Pennsylvania.

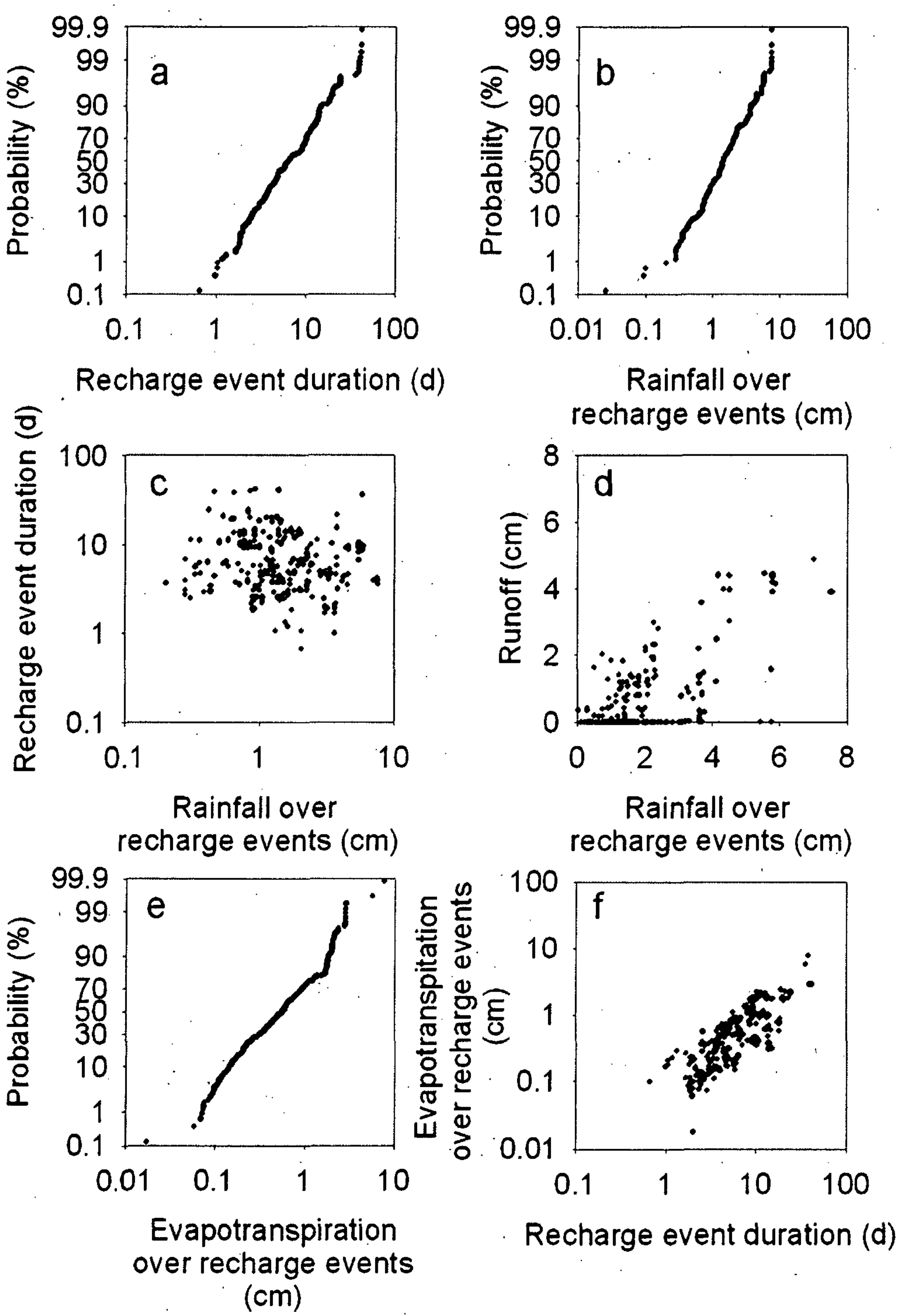

Figure 4-1. Statistics of soil water budget components integrated over recharge events.

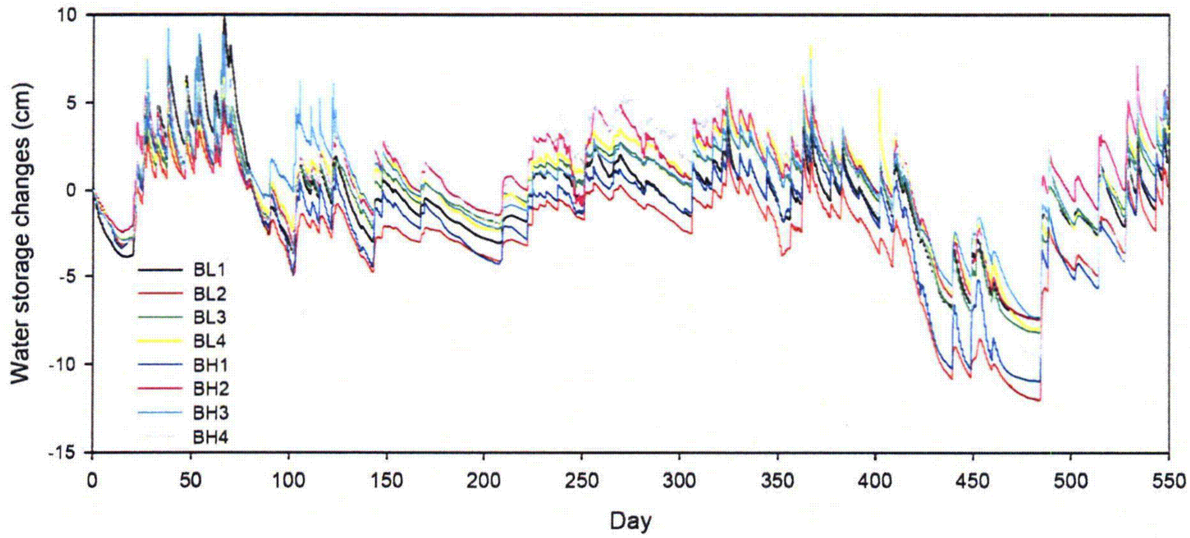

Figure 4-2. Changes in soil water storage in 0-80 cm soil layer during the period of observations.

Event-based estimates

The estimated percentage of rainfall going to recharge during a single recharge event is shown in Fig. 4-3 as a function of the amount of rain during a rainfall event. Overall, the recharge percentage in rainfall decreased with the amount of rain. About 60 % of smallest rainfalls of 0 to 10 mm was used for recharge whereas recharge constituted only about 10% of rainfall when rainfall were larger than 30 mm. No statistically significant dependence of the estimated recharge on the soil water content in the beginning of the recharge event was found.

Sources of uncertainty in the water budget method estimates

Variability of recharge estimates reflects field soil heterogeneity that results in differences in its ability to retain and transmit water. It also stems from violations of simplified assumptions used to compute the water budget.

The amount of evapotranspiration measured at the weather station and surface runoff measured at the outlet were assumed to be uniformly distributed over the entire field. However, previous studies have shown both budget components are spatially distributed.

Spatial differences in evapotranspiration can be manifested as either spatially different biomass values or yield variability (Figure 4-4). Figure 4-5 shows an infrared image of corn biomass superimposed on adjusted corn yields for 1999 (drought growing season). The red color shows high biomass and the white color shows low biomass within field B. Yields were greater than mean inside the black polygons and less than mean outside the black polygons. Therefore, the areas with high biomass (inside the black polygons/red colors) will produce higher evapotranspiration than the low biomass areas.

High surface runoff values at the outlet of the field did not reflect that the soils are not uniformly saturated nor that surface runoff is coming from isolated regions of the field (Gburek and Sharpley, 1998; Gburek et al., 2002). The presence of subsurface channels or preferential flow pathways could have also contributed to high or low soil water storage in some areas, which these methods were not able to represent. Furthermore, Chinkuyu et al. (2004 and 2005) observed that although the present hydrologic and water quality models could be calibrated to describe field-scale surface runoff processes, they did so at the expense of accurately representing the soil moisture profile. Consequently, before accurate predictions of surface and leachate fluxes can be made, the present water hydrologic and quality models need to divide the landscape into different hydrologic zones, each with their own representative moisture profiles and characteristics.

The dynamics of perched water can lead to violations of the assumption about one-dimensional flow used in the water budget computations and about the water not returning back to the budget layer in the capillary fringe. Consider the example of time series shown in Fig. 4-6 for the location BL1 over the time period from July 4 to August 5 2001. The total rainfall over this period of time was 10.7 cm, the runoff loss was 4.8 cm, and ET was 7.2 cm. Therefore, evaporation and runoff exceeded rainfall by 1.6 cm. Application of Eq. (3-1) results in the infiltration losses of 6.5 cm which exceeds the rainfall-less ET-less runoff amount by 7.5 cm. We suppose that these losses are related to the perched water dynamics rather than to infiltration. Fig. 4-6 shows that water content at the 80 cm depth decreased from the saturated water content 0.303 to values about 0.06 cm^3cm^{-3}. This decrease lead to the decrease in soil water storage about (0.303-0.06)*30/2 = 3.6 cm. Therefore, the infiltration loss of 3.6 cm of soil water below 80 cm was not related to precipitation. This data subset provides also an example of the computed

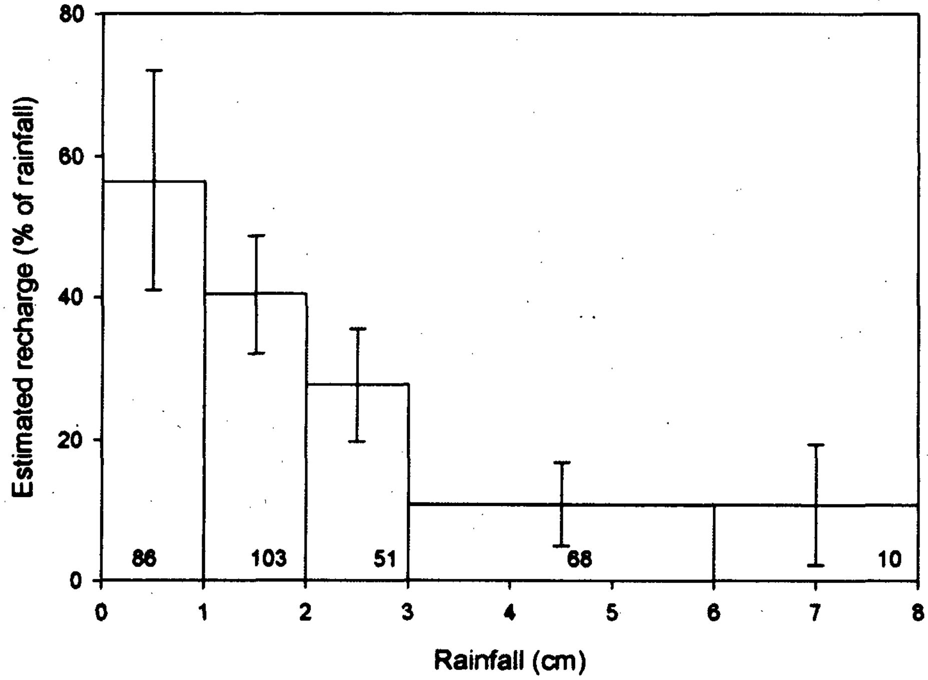

Figure 4-3. Fraction of precipitation used for recharge for different rainfall amounts. Error bars show the standard error. Numbers show the total number of recharge events for each rainfall amount range.

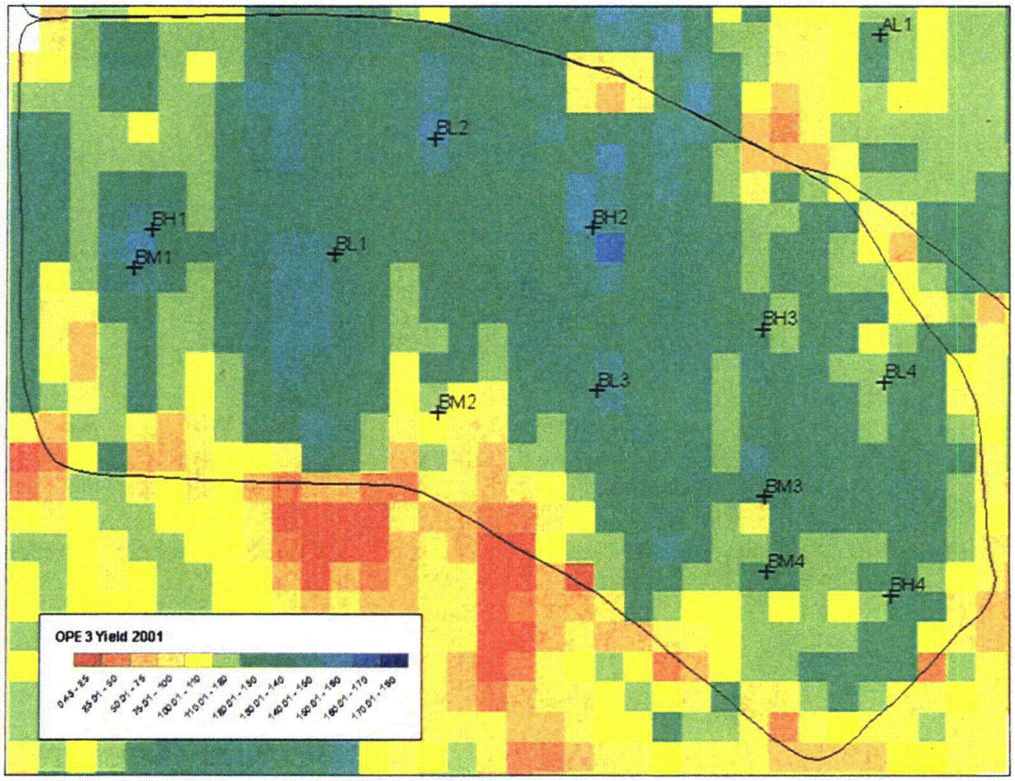

Figure 4-4. Spatial distribution of corn yields in field B in 2001. Note that the red to yellow colors represent low corn yield areas and the dark blue colors represent high corn yield areas. The red areas near and below location BM2 has seepage zones (subsurface water emerges on the surface and flows out of the field as surface runoff) and had very little if any plant growth during 2001 due to water logged conditions.

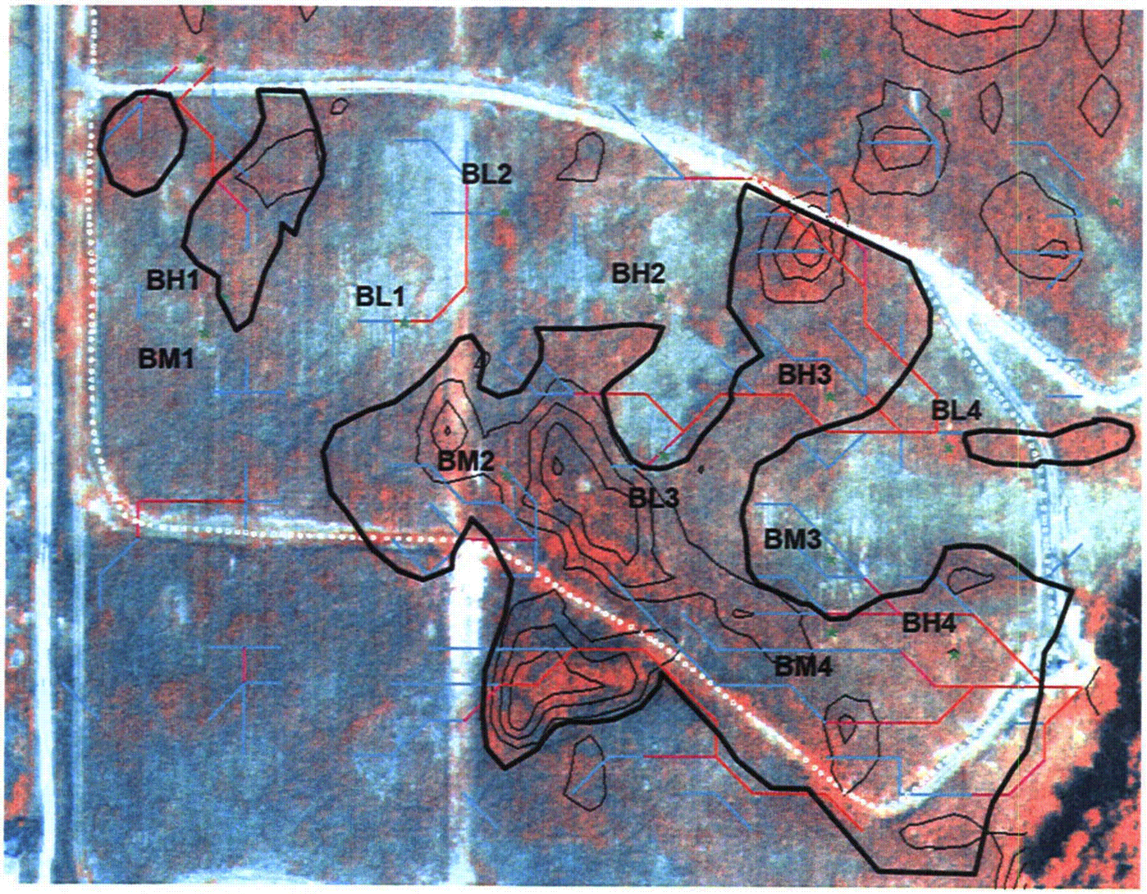

Figure 4-5. Color infrared image of corn biomass taken in August 1999 – drought growing season. Red color shows high biomass and white color shows low biomass. Yields were greater than mean yield inside black polygons and less than mean yields outside the black polygons.

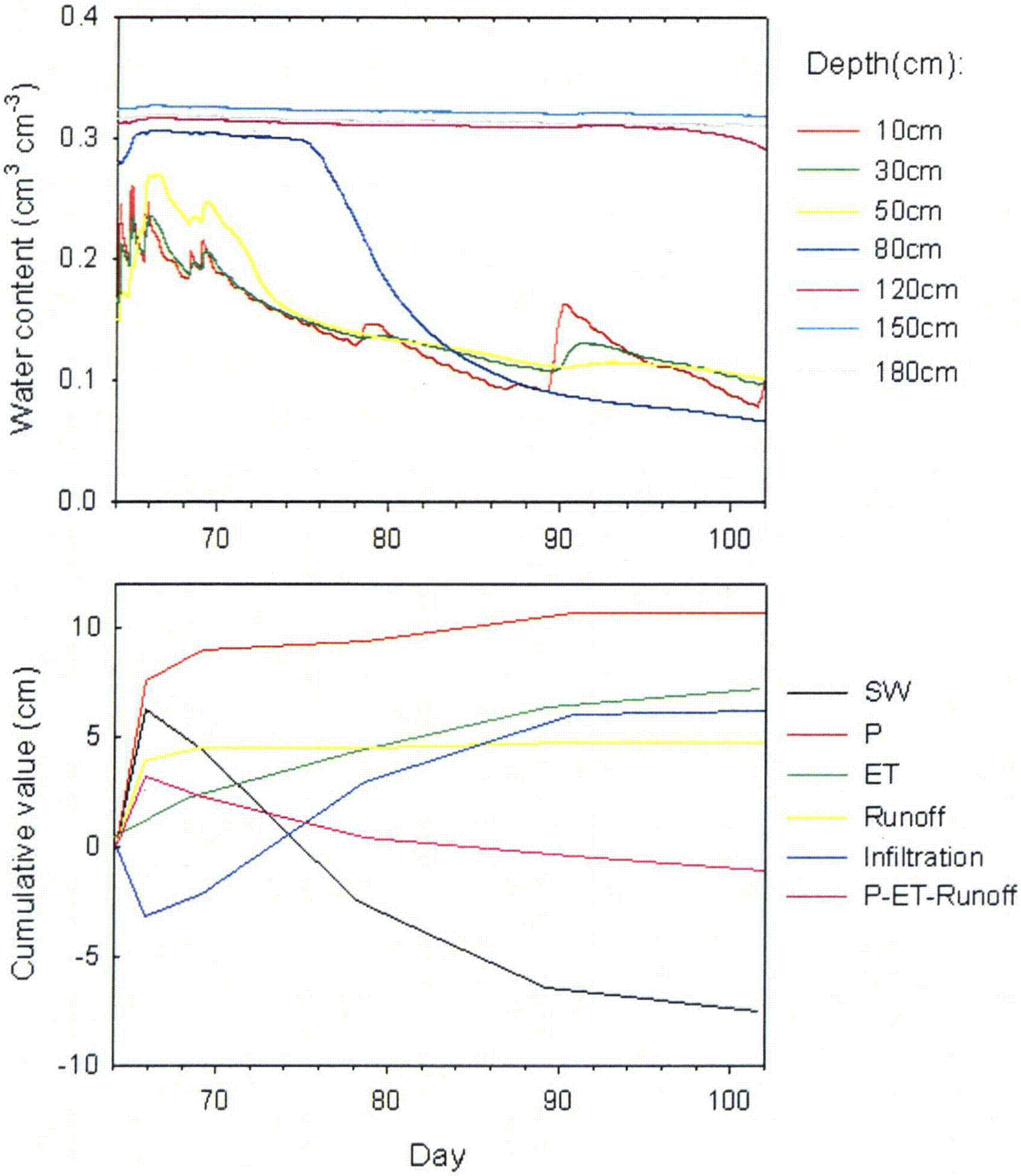

Figure 4-6. Soil water budget in presence of perched water.

"negative infiltration." Looking at the period from 52 to 64 day, one computes the infiltration of -3.1 cm, which in actuality represents the inflow of water during the rain from perched water below 80 cm.

Finally, it is not known what part of the study area is represented by each MCP. Therefore, it is not clear what weights have to be assigned to the estimated recharge from individual MCP to evaluate the recharge from the field.

4.3 MCP-ET METHOD

The recharge amount estimated from the MCP-ET for the whole observation period was from 225 mm to 650 mm and constituted from 26% to 75% of the total precipitation in eight observation locations. The estimated recharge was 29%, 26%, 29%, 57%, 44%, 56%, 74%, and 75% of rainfall at locations BL1, BL2, BL3, BL4, BH1, BH2, BH3, and BH4 respectively.

Event-based estimates

Because the total recharge with the MCP-ET methods was quite different between the group of locations BL1, BL2, BL3 and the rest of locations, the event based analysis was done separately for the these two groups. At locations BL1-BL3 the average recharge percentages decrease from 70 % for small rains less than 10 mm to about 25% for large rains. At locations BL4 , BH1, BH2, BH3, BH4 the estimated recharge percentages are about two times larger than at BL1, BL2, BL3. Overall average recharge percentage was 47% at locations BL1, BL2, BL3, and 83% at the rest of locations.

Sources of uncertainty in the "MCP-ET" estimates

The uncertainty in MCP-ET recharge estimates stems partly from the same reasons as for the water budget method, i.e. spatial variability in plant evapotranspiration and soil hydraulic properties. Note that BL1, Bl2, and BL3 are all located in regions showing low biomass and low yields in Fig. 4-5. The evapotranspiration in these areas was lower than that estimated with the Penman-Monteith equation, and therefore the actual difference between the decrease of water storage at the falling limb and cumulative evapotranspiration was even larger than the MCP-ET method estimated (Fig. 4-7a).

An additional source of uncertainty is the subsurface water redistribution in presence of subsurface pathways. This may cause (a) horizontal subsurface loss of water from a sensor and lead to soil water losses seemingly larger than the rainfall less runoff amount, and (b) water from other areas of the field likely reaching the sensors through subsurface flow pathways. At locations, BH1-BH4 large recharge percentages were in many cases caused by the subsurface run-on which was manifested by the larger than rainfall increase of soil water content during the rising limb of the soil water storage.

4.4 STREAM FLOW SEPARATION METHODS

Actual ground-water recharge was estimated by using stream flow hydrograph separation techniques. Two hydrograph-separation techniques were used to separate 12 distinct stream flow hydrographs into direct runoff and ground-water recharge: Dingman and Modified Dingman methods. Most calculated recharge estimates were less than 100% of precipitation (Figure 4-8). The Modified Dingman method considers only the ground-water recharge directly caused by a rain event while the Dingman method includes recharge due to both current and previous rain

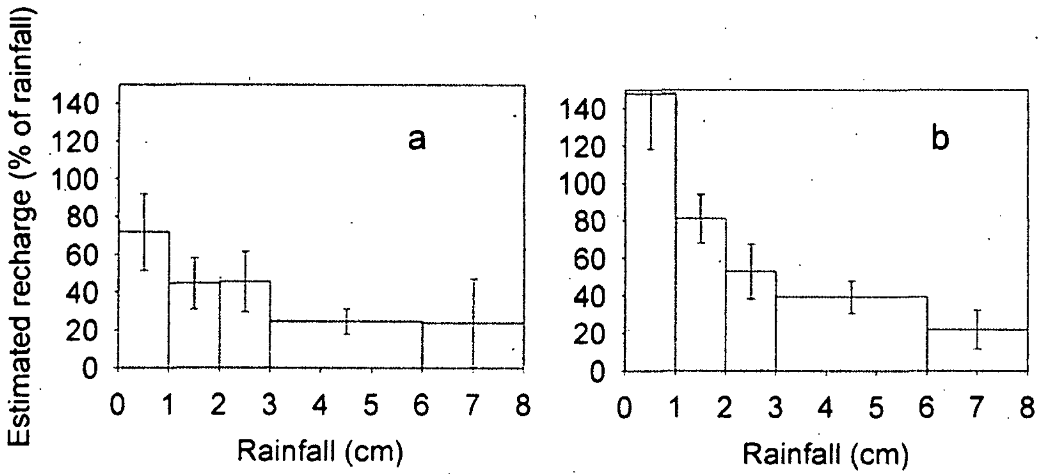

Figure 4-7. Fraction of precipitation used for recharge for different rainfall amounts at locations BL1, BL2, and BL3 (a) and at the rest of locations (b). Error bars show the standard error.

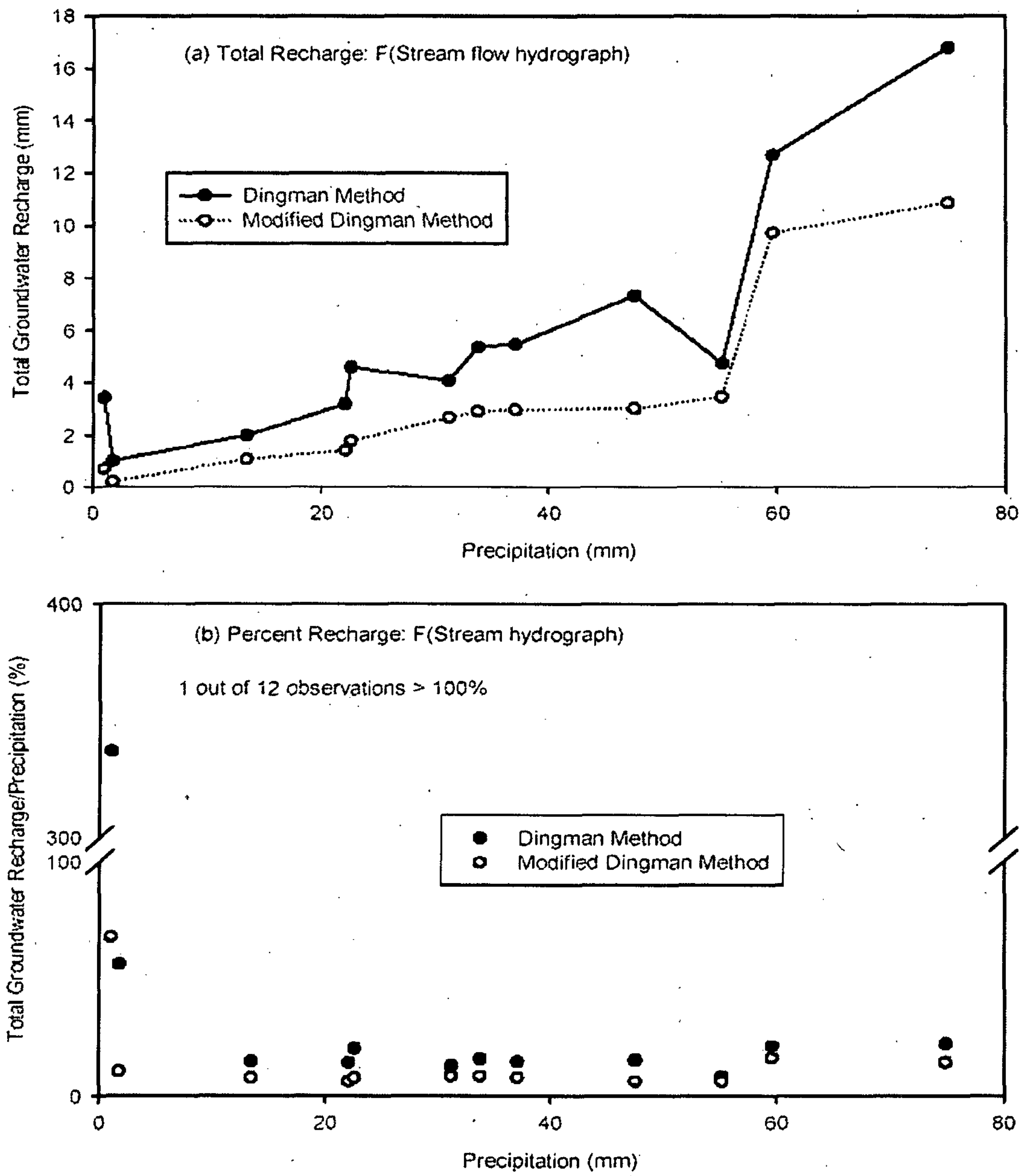

Figure 4-8. Ground-water recharge estimated with Dingman and Modified Dingman stream flow hydrograph separation methods. Twelve distinct stream flow hydrographs at station 3 were separated and analyzed in this study. Figure 4-8a shows total ground-water recharge versus precipitation, and Figure 4-8b shows ground-water recharge expressed as a percent of precipitation. High percent values were obtained at low rainfall events probably because of base flow from previous storms.

events. As might be expected the Modified Dingman method estimated lower ground-water recharge than the Dingman method (Figure 4-8). With a shallow, small primary stream draining only 12 ha, the continuous base flow (horizontal line in the Modified Dingman method) would fluctuate often because it could be affected by preferential flow (funnel flow) and intermittent flow. In addition, both methods show that ground-water recharge increased as precipitation increased (Figure 4-8). Overall, the Digman method provided values of recharge in the range 5% to 15% of the rainfall for hydrographs that have been processed and corresponded to about 45% of all rainfalls.

4.5 COMPARISON OF GROUND-WATER RECHARGE ESTIMATES

Because recharge events and hydrograph durations did not coincide, we compared the hydrograph-based recharge with recharge obtained from corresponding rainfall events by using average percentages of rainfall shown in Fig. 4-3. Specifically, we computed ratio

$$Q = (\text{Recharge from hydrograph separation})/(f_{water\ budget} * \text{Rain}/100.) \quad (4\text{-}2)$$

where $f_{water\ budget}$ was the recharge average percentage for the given rainfall from Figure 4-3, and rainfall and recharge from hydrograph are both in mm. The average ratio Q over 12 hydrographs was 1.04 and the standard error was 0.2. On average, the hydrograph separation provided recharge values similar to these from water budget. This is comparable with data on the agricultural watershed in Pennsylvania (Risser, Gburek and Folmar, 2005) where the daily water budget provided the recharge of 312 mm, whereas the mean-annual base flow obtained with different methods from streamflow-hydrograph separation ranged from 229 mm to 295 mm, and therefore the recharge from water budget was from 6% to 36% larger than the recharge estimated by the streamflow hydrograph separation.

The MCP-ET method provided recharge values larger than the water budget method. At low-yielding locations BL1, BL2, and BL3 where the subsurface run-on probably was not substantial, average recharge percentage was about 10% larger than the water budget. The average yearly recharge percentage was about 44% compared with 35% from the water budget method. At high-yielding locations, where the lateral transport pathways have been bringing additional rainwater, the MCP-ET-computed recharge was substantially larger than the water budget recharge. The MCP-ET method provided much larger recharge values than the streamflow separation. At the low yielding locations and high yielding locations, the average ratio of MCP-ET estimates and srtreamflow separation-based estimates was about 2.5 and about 4, respectively. The average ratio of 35%P estimates and srtreamflow separation-based estimates was about 2.5.

4.6 SEASONAL ESTIMATES

Estimated average recharge per single event by seasons is shown in Table 4-1. The absolute recharge per recharge event was about two times larger in winter and spring as compared with summer and fall, with the difference being statistically significant ($P<0.05$). The 35% method provided values that were on average larger than the water budget values in spring, summer, and fall, but not in winter.

Absolute averages ($P<0.05$) could be statistically proven only for winter recharges which average was significantly larger than spring or summer average. In terms of seasonal ground water recharge relative to rainfall, the average fall values were significantly larger than summer values but did not differ significantly from other seasons.

Table 4-1. Average recharge estimated with the water budget method from a single recharge event in different seasons

	Absolute recharge per event (cm)			Percentage of rainfall	
	Water budget method	MCP-ET method	35%P method	Water budget method	MCP-ET method
Spring	0.71±0.16[¶]	1.98±0.16	1.22	21± 9	87±10
Summer	0.38±0.20	0.90±0.11	0.66	43±14	76±13
Fall	0.29±0.09	0.42±0.04	0.42	37± 9	48±10
Winter	0.68±0.09	0.80±0.05	0.45	44± 7	62± 7

[¶]average ± standard error

5 SUMMARY AND CONCLUSIONS

To assess facility performance of decommissioning and waste disposal facilities, accurate estimates of infiltration and ground-water recharge are needed along with their corresponding uncertainties. Because the ground-water recharge is nearly impossible to measure directly, a variety of methods have been used to estimate recharge and, in some cases, base flow has been used as an approximation of recharge. This report describes the results of the study by the US Department of Agriculture in cooperation with the US Nuclear Regulatory Commission to compare commonly used methods for estimating groundwater recharge at a agricultural watershed in Beltsville, MD. The site is representative of a humid-continental climate in the North Eastern United States. This site has been selected because it provides (1) data of real-time near continuous monitoring of soil moisture in at several dept in 24 locations with 10 min frequency year-around, (2) discharge data from stream flow gauging stations, (3) meteorological information from eddy-covariance tower as well as from the class I weather station, (4) several years of yield maps, (5) exhaustive information on the land use and crop management, (5) data of the ground-penetration radar surveys used to delineate subsurface flow and transport pathways.

Three methods for calculating in-field ground-water recharge - (1) mass budget method, (2) MCP-ET method, and (3) 35%P method - were evaluated. These three within-field estimates were then compared to graphical stream flow separation methods as illustrated by Dingman (1994).

This research indicated that the recharge event defined as the time interval between two consecutive local minima on soil water storage series was an efficient temporal unit to estimate the groundwater recharge. Substantial differences were found between in-field methods of recharge estimation. The interpretation of the differences between the methods was possible based on their inherent differences as suggested by Risser et al. (2005). The soil water budget method estimates of ground-water recharge were the closest to the recharge observed in the stream using the stream flow separation method. The MCP-ET method overestimated ground-water recharge. Therefore, the water budget and stream flow separation methods can be used to estimate ground-water recharge at the small watershed scale. The other methods performed poorly because of these uncertainties: (1) 35%P method generally overestimated ground-water recharge because the method assumes that surface conditions (e.g. crop cover, infiltration rates) are the same throughout the year; (2) MCP-ET method frequently overestimated ground-water recharge, a result of the assumption that there is no subsurface lateral run-on and uniform evapotranspiration across the field. With this latter method, the conveying of subsurface water from one location to another generates higher water storage values than can be explained from observed precipitation amount. As a result, the MCP-ET method fails to account for soil heterogeneity and complex landscape interactions.

Event-based estimates of ground-water recharge showed the dependence on the rainfall amount. Percentage of rainfall that was directed to groundwater was decreasing with the increasing amount of rainfall when the in-field MCP-based methods were used, but tended to increase when the hydrograph separation methods were applied. The recharge amount estimated from the water budget for the whole observation period was from 175 mm to 220 mm and constituted from 20% to 25% of precipitation which is close to recent groundwater recharge estimates for Maryland and Pennsylvania. The average estimated percentage of rainfall used for recharge for a single recharge event depended on the amount of rain and was 56%, 40%, 28%, 11% and 11% for rainfalls 0 to 10 mm, 10 to 20 mm, 20 to 30 mm, 30 to 60 mm, and larger than 60 mm, respectively. Overall average percentage of rainfall used for recharge from a single recharge event was 35.3%.

There was high spatial variability of net infiltration and ground-water recharge at the two temporal scales of analysis (event and seasonal), indicating the soil and hydrologic variability of the site in terms of the presence or absence of clay lenses, subsurface preferential flow paths, and seepage zones. Spatial variability in ground-water recharge at local or watershed scale is critical for contaminant transport because focused recharge and preferential flow allow contaminants to migrate rapidly through the unsaturated zone to underlying aquifers. Delineation of zones with high and low ground-water recharge is important for defining zones that are critical or vulnerable to contamination and determining how fast the chemicals move to the stream.

All field-data based methods have an inherent uncertainty caused by uncertainties associated with quantifying spatial distribution of evapotranspiration, precipitation, and surface runoff. The one-dimensional schematization of the soil water transport can be insufficient as it ignores lateral surface and subsurface pathways of water movement in groundwater and in the vadose zone.

Real-time, near continuous hydrologic datasets from watersheds that are at least greater than one hectare can provide details of the spatial variability of the site in terms of infiltration capacity, surface runoff, and ground-water recharge. Additional spatially dense information, such as yield maps, remote sensing imagery, and ground penetration radar mapping can provide invaluable information for the interpretation of the results from different recharge estimation methods.

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APPENDIX A: SAMPLES OF DATABASES MEASURED AT THE RESEARCH SITE.

APPENDIX A-1. SAMPLE OF SOIL MOISTURE DATA MEASURED WITH MULTI-SENSOR CAPACITANCE PROBES.

```
Moisture Data ASCII output
Logger ID: L400
Sampling Interval: 10 minutes
Probe location BL4
Sensor Locations
"BL4: 10[B1], 30[B2], 50[B3], 80[B4], 120[B5], 150[B6], 180[B7]"

Output in mm/mm or %
```

Date	Time	10cm	30cm	50cm	80cm	120cm	150cm	180cm
5/1/2001	0:05	13.79255	20.83608	19.27601	23.22437	20.00253	24.34502	31.00945
5/1/2001	0:15	13.79777	20.83608	19.26964	23.22437	20.00253	24.34502	31.00945
5/1/2001	0:25	13.79777	20.82941	19.26964	23.22437	20.00253	24.34502	31.00945
5/1/2001	0:35	13.80300	20.82941	19.26964	23.22437	20.00253	24.33769	31.00075
5/1/2001	0:45	13.79777	20.82941	19.26964	23.22437	20.00253	24.34502	31.00945
5/1/2001	0:55	13.80300	20.82275	19.26964	23.21719	20.00253	24.33769	31.00075
5/1/2001	1:05	13.80300	20.82275	19.26964	23.22437	20.00253	24.33769	31.00075
5/1/2001	1:15	13.80822	20.81609	19.26327	23.21719	20.00253	24.33769	31.00075
5/1/2001	1:25	13.80822	20.81609	19.26327	23.21719	20.00253	24.33769	31.00075
5/1/2001	1:35	13.80822	20.81609	19.26327	23.21719	20.00253	24.33769	31.00945
5/1/2001	1:45	13.80822	20.81609	19.26327	23.21719	20.00253	24.33769	31.00075
5/1/2001	1:55	13.81345	20.80943	19.25691	23.21719	20.00253	24.33769	31.00075
5/1/2001	2:05	13.81345	20.80943	19.25691	23.21719	20.00253	24.33769	31.00075
5/1/2001	2:15	13.81345	20.80277	19.25691	23.21719	19.99585	24.33769	31.00945
5/1/2001	2:25	13.81345	20.79611	19.26327	23.21719	20.00253	24.33769	31.00075
5/1/2001	2:35	13.81868	20.79611	19.26327	23.21719	20.00253	24.33769	31.00075
5/1/2001	2:45	13.81868	20.79611	19.25691	23.21002	19.99585	24.33769	31.00075
5/1/2001	2:55	13.81868	20.78946	19.25691	23.21002	20.00253	24.33769	31.00075
5/1/2001	3:05	13.82391	20.78946	19.25691	23.21002	19.99585	24.33769	31.00075
5/1/2001	3:15	13.82391	20.78946	19.25691	23.21002	20.00253	24.33769	31.00075
5/1/2001	3:25	13.82391	20.78946	19.25691	23.21719	19.99585	24.33769	31.00075
5/1/2001	3:35	13.82391	20.78946	19.25691	23.21719	19.99585	24.33769	31.00075
5/1/2001	3:45	13.82391	20.78280	19.25054	23.21002	20.00253	24.33035	31.00075
5/1/2001	3:55	13.82914	20.78280	19.25691	23.21002	19.99585	24.33035	31.00075
5/1/2001	4:05	13.82914	20.77615	19.25054	23.21002	19.99585	24.33769	31.00075
5/1/2001	4:15	13.82914	20.77615	19.25054	23.20285	19.99585	24.33035	31.00075
5/1/2001	4:25	13.82914	20.76950	19.25054	23.21002	19.99585	24.33769	31.00075
5/1/2001	4:35	13.82914	20.76950	19.24418	23.21002	19.99585	24.33035	31.00075
5/1/2001	4:45	13.83437	20.76950	19.24418	23.21002	19.99585	24.33035	31.00075
5/1/2001	4:55	13.83437	20.76950	19.25054	23.20285	19.99585	24.33035	30.99206
5/1/2001	5:05	13.83960	20.76950	19.24418	23.20285	19.99585	24.32301	30.99206
5/1/2001	5:15	13.83960	20.76285	19.23781	23.20285	19.99585	24.33035	30.99206
5/1/2001	5:25	13.83960	20.76285	19.23781	23.20285	19.98918	24.33035	30.99206
5/1/2001	5:35	13.83960	20.75620	19.23781	23.20285	19.99585	24.33035	31.00075
5/1/2001	5:45	13.83960	20.75620	19.23781	23.20285	19.99585	24.32301	31.00075
5/1/2001	5:55	13.84484	20.75620	19.23145	23.20285	19.98918	24.33035	30.99206
5/1/2001	6:05	13.84484	20.75620	19.23145	23.20285	19.98918	24.32301	30.99206
5/1/2001	6:15	13.85007	20.74955	19.23145	23.19567	19.99585	24.32301	31.00075
5/1/2001	6:25	13.85007	20.74955	19.22509	23.19567	19.98918	24.32301	31.00075
5/1/2001	6:35	13.85007	20.74955	19.23145	23.19567	19.99585	24.32301	31.00075
5/1/2001	6:45	13.85007	20.74290	19.22509	23.19567	19.98918	24.32301	30.99206
5/1/2001	6:55	13.85007	20.73626	19.22509	23.20285	19.98918	24.32301	31.00075
5/1/2001	7:05	13.85531	20.73626	19.22509	23.19567	19.98918	24.32301	30.99206
5/1/2001	7:15	13.85531	20.72961	19.21874	23.20285	19.98251	24.32301	30.99206
5/1/2001	7:25	13.86055	20.72961	19.21874	23.19567	19.98918	24.31568	31.00075
5/1/2001	7:35	13.86579	20.72961	19.22509	23.19567	19.98251	24.31568	30.99206
5/1/2001	7:45	13.86579	20.72961	19.21874	23.19567	19.98251	24.31568	30.99206
5/1/2001	7:55	13.87102	20.72961	19.21874	23.19567	19.98918	24.31568	31.00075
5/1/2001	8:05	13.87102	20.72961	19.21874	23.19567	19.98251	24.31568	31.00075
5/1/2001	8:15	13.87102	20.72297	19.21874	23.19567	19.98918	24.30834	31.00075
5/1/2001	8:25	13.88150	20.72297	19.21237	23.19567	19.98918	24.31568	30.99206
5/1/2001	8:35	13.87626	20.72297	19.21237	23.19567	19.98918	24.31568	30.99206
5/1/2001	8:45	13.88150	20.72297	19.21237	23.19567	19.98918	24.30834	30.99206
5/1/2001	8:55	13.88150	20.71633	19.21237	23.18850	19.98918	24.31568	30.99206
5/1/2001	9:05	13.87626	20.71633	19.21237	23.18850	19.98251	24.31568	31.00075
5/1/2001	9:15	13.87626	20.71633	19.22509	23.18850	19.98251	24.30834	30.99206
5/1/2001	9:25	13.87102	20.70969	19.22509	23.18850	19.98251	24.30834	30.99206
5/1/2001	9:35	13.86579	20.70969	19.22509	23.18850	19.98251	24.30834	30.99206

APPENDIX A-2. SAMPLE OF SURFACE RUNOFF DATA MEASURED AT THE FIELD OUTLET.

```
                              Sample_runoff.txt
DAILY SUMMARY    Site #2401099061   FD B 2001    Sat 31 Mar 2001

 Level  ASCII Data

 Total Flow:       40821 l
 Average Flow:      0.47 l/s
 Minimum Flow:      0.37 l/s @ 21:00
 Maximum Flow:      0.73 l/s @ 09:20

 Hourly Average Flow
 00:00-01:00:     0.50 l/s     12:00-13:00:     0.50 l/s
 01:00-02:00:     0.49 l/s     13:00-14:00:     0.48 l/s
 02:00-03:00:     0.49 l/s     14:00-15:00:     0.44 l/s
 03:00-04:00:     0.48 l/s     15:00-16:00:     0.44 l/s
 04:00-05:00:     0.47 l/s     16:00-17:00:     0.41 l/s
 05:00-06:00:     0.47 l/s     17:00-18:00:     0.41 l/s
 06:00-07:00:     0.46 l/s     18:00-19:00:     0.40 l/s
 07:00-08:00:     0.47 l/s     19:00-20:00:     0.40 l/s
 08:00-09:00:     0.57 l/s     20:00-21:00:     0.38 l/s
 09:00-10:00:     0.70 l/s     21:00-22:00:     0.38 l/s
 10:00-11:00:     0.66 l/s     22:00-23:00:     0.38 l/s
 11:00-12:00:     0.57 l/s     23:00-00:00:     0.37 l/s

          0.00      0.20      0.40      0.60      0.80      1.00
            +----+----+----+----+----+----+----+----+----+----+
00:00-01:00 =========================
01:00-02:00 =========================
02:00-03:00 =========================
03:00-04:00 =========================
04:00-05:00 ========================
05:00-06:00 ========================
06:00-07:00 =======================
07:00-08:00 ========================
08:00-09:00 =============================
09:00-10:00 ===================================
10:00-11:00 =================================
11:00-12:00 =============================
12:00-13:00 ==========================
13:00-14:00 ========================
14:00-15:00 =======================
15:00-16:00 ======================
16:00-17:00 =====================
17:00-18:00 =====================
18:00-19:00 ====================
19:00-20:00 ====================
20:00-21:00 ====================
21:00-22:00 ===================
22:00-23:00 ====================
23:00-00:00 ===================
            +----+----+----+----+----+----+----+----+----+----+
          0.00      0.20      0.40      0.60      0.80      1.00

                              (l/s)
```

APPENDIX A-3. SAMPLE OF STREAM FLOW DATA MEASURED AT STATION 3.

Date	Time	Level(cm)	Q(L/s)		Date	Time	Level(cm)	Q(L/s)
10/26/2001	0:00:00	9.358	4.189		10/26/2001	8:00:00	10.534	5.559
10/26/2001	0:10:00	9.614	4.469		10/26/2001	8:10:00	10.445	5.447
10/26/2001	0:20:00	9.511	4.355		10/26/2001	8:20:00	10.479	5.491
10/26/2001	0:30:00	9.479	4.321		10/26/2001	8:30:00	10.1	5.028
10/26/2001	0:40:00	9.413	4.249		10/26/2001	8:40:00	9.912	4.807
10/26/2001	0:50:00	9.602	4.456		10/26/2001	8:50:00	9.962	4.865
10/26/2001	1:00:00	9.246	4.071		10/26/2001	9:00:00	9.92	4.816
10/26/2001	1:10:00	8.956	3.772		10/26/2001	9:10:00	9.93	4.827
10/26/2001	1:20:00	8.958	3.774		10/26/2001	9:20:00	9.833	4.716
10/26/2001	1:30:00	9.018	3.835		10/26/2001	9:30:00	9.49	4.332
10/26/2001	1:40:00	9.166	3.987		10/26/2001	9:40:00	9.522	4.367
10/26/2001	1:50:00	9.308	4.136		10/26/2001	9:50:00	9.069	3.887
10/26/2001	2:00:00	9.531	4.376		10/26/2001	10:00:00	8.571	3.396
10/26/2001	2:10:00	9.908	4.802		10/26/2001	10:10:00	9.664	4.524
10/26/2001	2:20:00	9.893	4.785		10/26/2001	10:20:00	9.623	4.479
10/26/2001	2:30:00	9.965	4.868		10/26/2001	10:30:00	9.466	4.306
10/26/2001	2:40:00	10.067	4.988		10/26/2001	10:40:00	9.55	4.398
10/26/2001	2:50:00	10.029	4.943		10/26/2001	10:50:00	10.091	5.017
10/26/2001	3:00:00	10.333	5.309		10/26/2001	11:00:00	9.977	4.882
10/26/2001	3:10:00	10.334	5.311		10/26/2001	11:10:00	9.94	4.839
10/26/2001	3:20:00	10.321	5.294		10/26/2001	11:20:00	9.921	4.817
10/26/2001	3:30:00	10.17	5.112		10/26/2001	11:30:00	9.882	4.772
10/26/2001	3:40:00	10.219	5.170		10/26/2001	11:40:00	9.81	4.690
10/26/2001	3:50:00	10.191	5.136		10/26/2001	11:50:00	9.715	4.582
10/26/2001	4:00:00	10.059	4.979		10/26/2001	12:00:00	10.071	4.993
10/26/2001	4:10:00	9.882	4.773		10/26/2001	12:10:00	10.345	5.324
10/26/2001	4:20:00	9.96	4.863		10/26/2001	12:20:00	10.363	5.346
10/26/2001	4:30:00	9.92	4.816		10/26/2001	12:30:00	9.872	4.761
10/26/2001	4:40:00	10.119	5.051		10/26/2001	12:40:00	9.877	4.767
10/26/2001	4:50:00	10.105	5.034		10/26/2001	12:50:00	9.971	4.875
10/26/2001	5:00:00	10.327	5.302		10/26/2001	13:00:00	9.82	4.701
10/26/2001	5:10:00	10.158	5.097		10/26/2001	13:10:00	9.83	4.713
10/26/2001	5:20:00	10.034	4.949		10/26/2001	13:20:00	9.798	4.675
10/26/2001	5:30:00	9.972	4.876		10/26/2001	13:30:00	8.528	3.355
10/26/2001	5:40:00	9.951	4.852		10/26/2001	13:40:00	4.566	0.754
10/26/2001	5:50:00	9.894	4.786		10/26/2001	13:50:00	4.307	0.656
10/26/2001	6:00:00	9.805	4.684		10/26/2001	14:00:00	4.353	0.672
10/26/2001	6:10:00	9.822	4.703		10/26/2001	14:10:00	4.432	0.702
10/26/2001	6:20:00	9.867	4.755		10/26/2001	14:20:00	4.372	0.679
10/26/2001	6:30:00	10.015	4.927		10/26/2001	14:30:00	4.323	0.662
10/26/2001	6:40:00	10.365	5.348		10/26/2001	14:40:00	4.337	0.667
10/26/2001	6:50:00	10.311	5.282		10/26/2001	14:50:00	4.353	0.673
10/26/2001	7:00:00	10.359	5.341		10/26/2001	15:00:00	4.323	0.662
10/26/2001	7:10:00	10.399	5.390		10/26/2001	15:10:00	4.197	0.617
10/26/2001	7:20:00	10.464	5.472		10/26/2001	15:20:00	4.25	0.635
10/26/2001	7:30:00	10.607	5.652		10/26/2001	15:30:00	4.359	0.675
10/26/2001	7:40:00	10.737	5.819		10/26/2001	15:40:00	4.335	0.666
10/26/2001	7:50:00	10.616	5.663		10/26/2001	15:50:00	4.298	0.652

APPENDIX A-4. SAMPLE OF METEOROLOGICAL DATA MEASURED AT THE RESEARCH SITE.

OPE3 Site								
Soil heat flux, evapotranspiration, and carbon dioxide concentrations are also measured.								
(day)	(mm/dd/yy)		(m/s)	(Deg)	(C)	(%)	(W/m2)	(mm)
AWS Time	Stime	Hr/Mn	Wspeed	Wdir	AirTemp	RH	Rad_net	Precip
185.6944	7/3/2000	1640	1.56	214.7	29.22	58.71	71.60	0
185.7083	7/3/2000	1700	0.97	213.2	29.25	61.20	87.40	0
185.7222	7/3/2000	1720	1.07	212.9	29.17	61.50	80.00	0
185.7361	7/3/2000	1740	1.23	240.0	29.01	61.23	60.56	0
185.7500	7/3/2000	1800	0.41	250.8	28.75	60.12	38.50	0
185.7639	7/3/2000	1820	0.51	295.7	28.19	62.77	13.57	0
185.7778	7/3/2000	1840	2.07	339.3	27.73	61.22	9.04	0
185.7917	7/3/2000	1900	1.80	349.6	27.22	62.21	-2.58	0
185.8056	7/3/2000	1920	1.52	356.7	26.83	63.10	-12.88	0
185.8194	7/3/2000	1940	2.20	326.3	26.31	65.56	-14.09	0
185.8333	7/3/2000	2000	1.26	301.9	25.32	72.90	-23.79	0.508
185.8472	7/3/2000	2020	0.89	269.0	23.40	87.50	-17.99	0.508
185.8611	7/3/2000	2040	1.30	173.1	22.44	95.00	-11.98	4.826
185.8750	7/3/2000	2100	1.63	122.6	22.02	97.10	-11.03	1.016
185.8889	7/3/2000	2120	1.18	121.9	21.68	97.60	-14.03	0
185.9028	7/3/2000	2140	0.29	125.7	21.49	97.40	-13.28	0
185.9167	7/3/2000	2200	1.48	297.4	21.62	97.50	-11.29	0.254
185.9306	7/3/2000	2220	1.05	350.3	21.77	97.90	-10.06	0.762
185.9444	7/3/2000	2240	0.22	46.3	21.82	98.20	-13.79	0.254
185.9583	7/3/2000	2300	0.20	55.5	21.76	98.30	-16.64	0
185.9722	7/3/2000	2320	0.51	172.9	21.67	98.60	-14.02	0.254
185.9861	7/3/2000	2340	0.49	195.2	21.56	98.80	-12.29	0
186.0000	7/4/2000	0	0.20	188.4	21.51	99.00	-8.59	0
186.0139	7/4/2000	20	0.20	188.1	21.56	99.10	-8.06	0
186.0278	7/4/2000	40	0.20	188.4	21.51	99.10	-12.45	0
186.0417	7/4/2000	100	0.20	188.7	21.52	99.20	-13.64	0
186.0556	7/4/2000	120	0.20	188.6	21.46	99.20	-9.40	0
186.0694	7/4/2000	140	0.22	188.7	21.45	99.30	-8.42	0
186.0833	7/4/2000	200	0.22	190.3	21.62	99.40	-7.81	0
186.0972	7/4/2000	220	0.66	206.2	21.84	99.40	-7.02	0
186.1111	7/4/2000	240	0.75	242.6	22.14	99.50	-7.55	0
186.125	7/4/2000	300	0.20	160.4	22.11	99.30	-8.65	0
186.1389	7/4/2000	320	0.20	152.8	22.06	99.30	-9.41	0
186.1528	7/4/2000	340	0.20	191.9	21.95	99.20	-10.78	0
186.1667	7/4/2000	400	0.20	250.1	21.86	99.20	-10.31	0
186.1806	7/4/2000	420	0.46	248.9	21.87	99.10	-9.64	0
186.1944	7/4/2000	440	0.20	239.5	21.90	99.00	-8.86	0.254
186.2083	7/4/2000	500	0.20	232.8	21.89	99.00	-6.58	0

APPENDIX B. SAS CODE FOR DIFFERENCING SOIL MOISTURE PROBE DATA

SAS CODE FOR DIFFERENCING SOIL MOISTURE PROBE DATA.

```
/* This part produces sas dateformats */
Data water_content;
infile 'C:\All_Probes_Combined.txt';
Format date2 date8. time2 time5. datetime datetime15.;
input indate $quote18. Location $ Storage;
date1=substr(indate,1,10);
time1=substr(indate,12,5);
date2=input(date1,mmddyy10.);
time2=input(time1,time5.);
datetime=dhms(date2,0,0,time2);
run;

/* this section will create a datatable with all possible combinations
  of dates and locations to detect missing data in the
  soil water and rainfall data */
%macro datetime;
%if &done=0 %then %do;
data datetime (keep=date time datetime location);
format location$3. date date9. time time5. datetime datetime15.;
 do i=0 to 729; /* this accounts for leap years */
  do j=0 to 23;
   do k=0 to 50 by 10;
    date=intnx('Day',"01Jan01"d,i);
    time = intnx('hour','00:00:00't,j);
    time=time+intnx('minute','00:00:00't,k);
    datetime=dhms(date,0,0,time);
    location='BH1' ;
    output;
    location='BH2' ;
    output;
    location='BH3';
    output;
     location='BH4';
    output;
     location='BL1' ;
    output;
     location='BL2' ;
    output;
      location='BL3' ;
    output;
     location='BL4' ;
    output;
      location='BM1' ;
    output;
      location='BM2';
```

```
      output;
       location='BM3';
      output;
        location='BM4';

     end;
   end;
 end;

 run;
 %end;
%mend;
/* set done=0 if you want to recreate this table or create it for the
  first run of this program
*/
%let done=0;
%datetime;
proc sort data=water_content; by location datetime ; quit;
Data adj_water (drop=min  /*olddatetime olddate oldtime*/);
length location $3;
retain olddatetime datetime olddate date  oldtime time; /* use of retain statement here will
reorder the columns
 so that datetime is the first column and datetime2 is the second. This makes it
 easier to compare the columns */

set water_content (drop = indate time2 date1 time1 date2);

format time time5. oldtime time5. olddate date8. date date8.  olddatetime datetime15.  ;
 olddatetime=datetime;
 olddate=datepart(datetime);
 oldtime=timepart(datetime);
 min=minute(olddatetime);
 date=datepart(dateTime);

 /* the goal here is to round the minute value to a
    10 minute boundary    */
 min=round(min/10,1.0)*10;
 time=hms(hour(oldtime),min,0);
 if time='24:00:00't then
    do;
      date=date+1;
      time='00:00:00't ;
    end;
datetime=dhms(date,0,0,time);
date=datepart(datetime);
time=timepart(datetime);
```

```
   /* may add 1 day and go over a year boundary. We lose this
  value but it is not critical */
if year(olddate)~=year(date) then delete;
run;
/* Format Rainfall data from May 1 2001 to April 30, 2002 */
Data Rainfall;
infile 'C:\Raindata.txt';
Format date2 date8. time2 time5. datetime datetime15.;
input indate $quote18. rain rain_id;
date1=substr(indate,1,10);
time1=substr(indate,12,5);
date2=input(date1,mmddyy10.);
time2=input(time1,time5.);
datetime=dhms(date2,0,0,time2);
run;

/* this one for rainfall data */
proc sort data=rainfall; by datetime ; quit;
Data adj_rain (drop=min  /*olddatetime olddate oldtime*/);
retain olddatetime datetime olddate date  oldtime time; /* use of retain statement here will
reorder the columns
 so that datetime is the first column and datetime2 is the second. This makes it
 easier to compare the columns */

set rainfall (drop = indate time2 date1 time1 date2);
format location $3. time time5. oldtime time5. olddate date8. date date8.  olddatetime
datetime15.  ;
 olddatetime=datetime;
 olddate=datepart(datetime);
 oldtime=timepart(datetime);
 min=minute(olddatetime);
 date=datepart(dateTime);

 /* the goal here is to round the minute value to a
   10 minute boundary    */
 min=round(min/10,1.0)*10;
 time=hms(hour(oldtime),min,0);
 if time='24:00:00't then
   do;
     date=date+1;
     time='00:00:00't ;
   end;
datetime=dhms(date,0,0,time);
date=datepart(datetime);
time=timepart(datetime);
   /* may add 1 day and go over a year boundary. We lose this
```

```
 value but it is not critical */
if year(olddate)~=year(date) then delete;
/* need to add a line for each treatment to assist in merge */
location='BH1' ;
      output;
      location='BH2' ;
      output;
      location='BH3';
      output;
       location='BH4';
      output;
       location='BL1' ;
      output;
       location='BL2' ;
      output;
       location='BL3' ;
      output;
       location='BL4' ;
      output;
        location='BM1' ;
      output;
        location='BM2';
      output;
       location='BM3';
      output;
       location='BM4';
              output;

run;
proc sort data=adj_water; by datetime location;
proc sort data=adj_rain; by datetime location;
proc sort data=datetime; by datetime location;
/* now merge data */
data all (drop=olddatetime olddate oldtime);
 merge adj_water adj_rain;
 by datetime location;
 run;

/* now merge with datetimes */
data cleaned_data;
merge datetime all;
by datetime location;
if datepart(datetime)< '01May01'd then delete;
if datepart(datetime)> '30Apr02'd then delete;
run;
```

```
proc sort data=cleaned_data;
 by datetime location;
 quit;

data forChanges;
 set cleaned_data;
 if rain_id=0 then delete;
 run;

Proc sort data = forchanges;
by Location Rain_id datetime;
Quit;

Data Changes ( label= 'cumulative rainfall infil and drainage');
set forchanges;
Retain infil drain prev;
By location rain_id;
where rain_id>0;
If first.rain_id then  do;
  prev=storage;
  infil=0;
  Drain=0;
  cumr=0;
 end;
 cumr+rain;
 Diff=storage-prev;
 If diff<0 then drain+diff;
  else infil+diff;
  prev=storage;
Run;
/* prepare to merge et by outputting daily summaries */
proc sort data=changes; by location rain_id datetime; quit;

data daily;
 set changes;
 by location rain_id date;
 if last.date then output;
 run;

proc sort data=changes; by location rain_id; quit;
Data byRainid (drop=diff storage prev rain label= 'aggregated infil and runoff by rain_id');
Set changes;
By location rain_id;
If last.rain_id then output;
Run;
```

```
proc gplot data=byrainid;
plot infil*cumr=location;
plot drain*cumr=location;
where rain_id>0;
run;
quit;

/* Organize data by events */
Data By_Event;
Set byRainid;
proc means data = By_Event;
by Location date rain_ID;
var Infil cumr drain;
output out = new_sum
sum = Total_Infil Total_Rain Total_Recharge;
quit;

data Analysed;
set new_sum;
file 'C:\Daily_Summary_Infil_Recharge_Results.txt';
put date  location $ rain_id Total_Rain 10.5 Total_Infil 10.5 Total_Recharge 10.5;
run;
```

APPENDIX C. GRAPHICAL STREAM FLOW SEPARATION METHODS.

GRAPHICAL STREAM FLOW SEPARATION METHODS.

Figure C-1a shows the Dingman (1994) method. From the point of initial hydrograph rise, a line that slopes upward at a rate of {(0.05 ft^3 s^{-1}) A mi^2 h^{-1}} was drawn and extended until it intercepted the hydrograph (red long-dash line) (A is watershed area). The area below the red line represented base flow (ground-water recharge). Figure C-1b shows the modified Dingman method whereby: (1) from the point of initial hydrograph rise, a line that slopes upward at a rate of {(0.05 ft^3 s^{-1}) A mi^2 h^{-1}} was drawn and extended until it intercepted the hydrograph (red long-dash line) (A is watershed area), and (2) from the point of initial hydrograph rise a horizontal line was extended until the end of the storm period (green medium-dash line). The area between these two lines represented the amount of ground-water recharge due to the rainfall event.

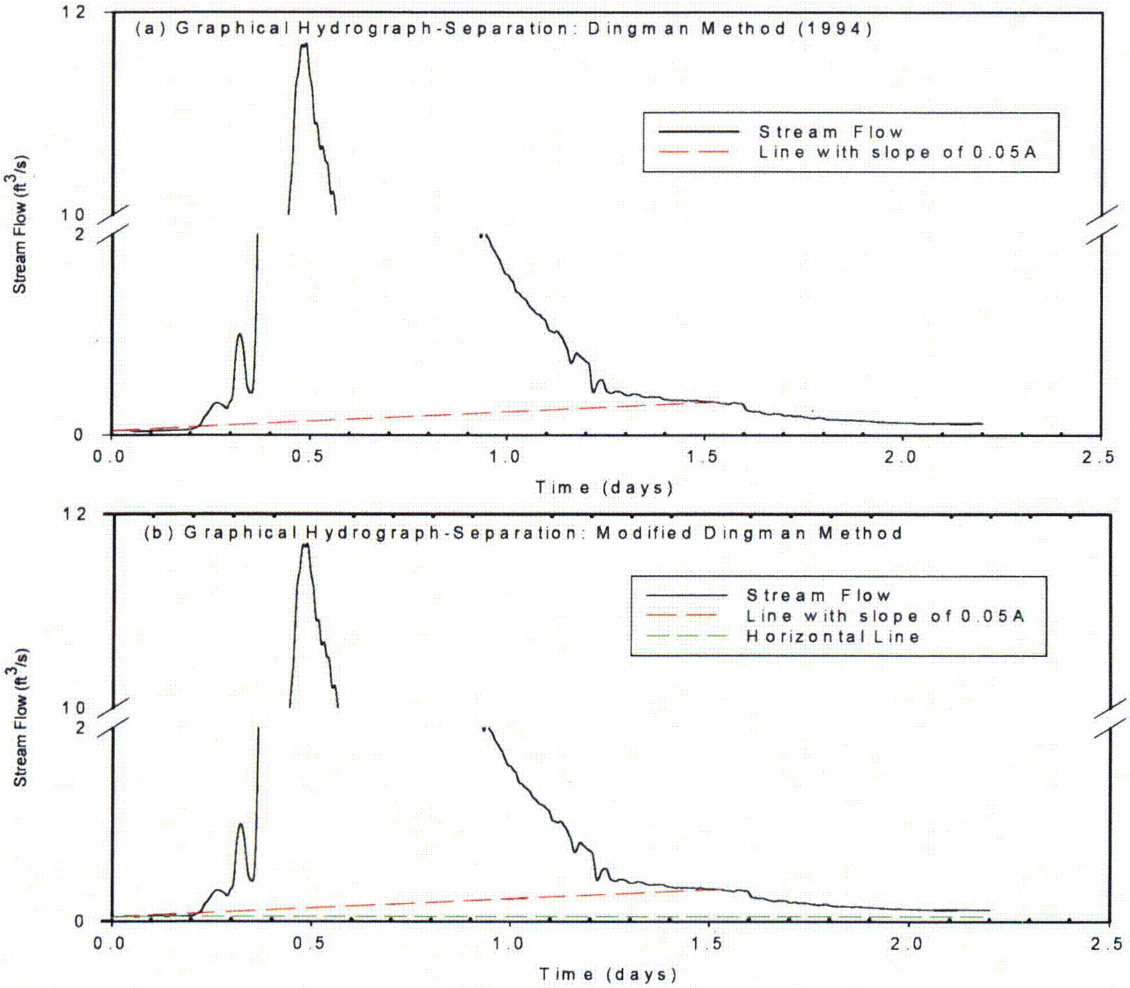

Figure C-1. Graphical stream flow hydrograph separation techniques

APPENDIX D. SPATIAL AND TEMPORAL CORN YIELD VARIATION.

SPATIAL AND TEMPORAL CORN YIELD VARIATION.

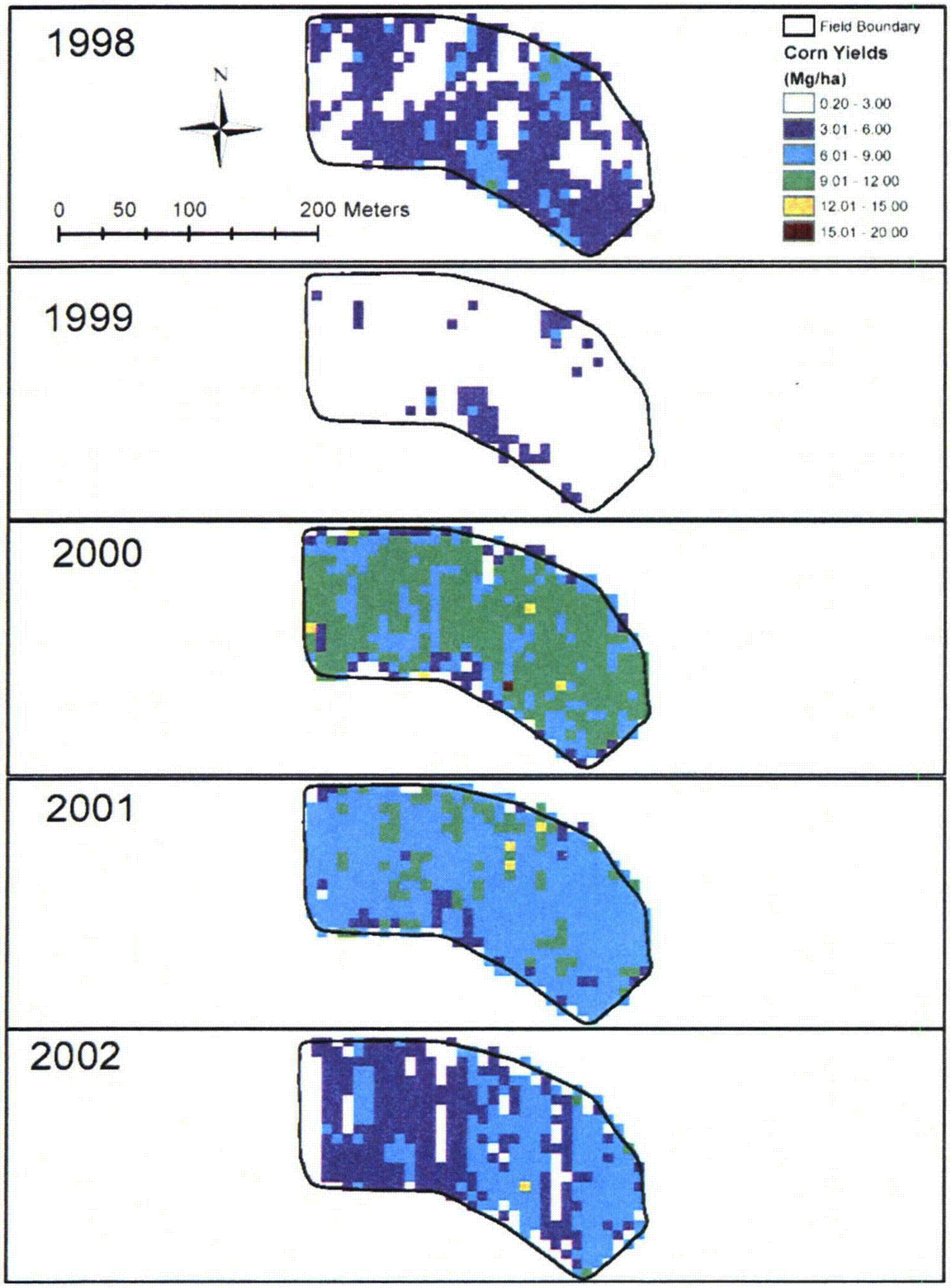

Figure D-1. Spatial corn yield variation from 1998 to 2002. Note that 1998 and 1999 were drought, 2000 was wetter than normal, 2001 was normal, and 2002 was dry.

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T.J. Nicholson, NRC Project Manager

11. ABSTRACT *(200 words or less)*

Little is known regarding data requirements and uncertainties for evaluating vadose zone water fluxes at the field scale, common to nuclear facility sites. This field study evaluated four methods for estimating within-field groundwater recharge: (1) water budget method; (2) the streamflow separation method; (3) negative changes in soil water storage less evapotranspiration; and (4) 35% of the observed precipitation. We used the 12-month observations of soil moisture with multiple capacitance probes (MCP), meteorological variables, surface runoff, and streamflow, recorded every 10 minutes at an agricultural production site in Beltsville, Maryland, where the subsurface water discharges into a first-order stream. The MCP provided high accuracy in delineating the recharge events. For the whole observation period, the recharge amount from the water budget method was from 20% to 25% of precipitation, and the average percentage of rainfall used for recharge from a single recharge event was 35.3%. The base flow estimates from the streamflow separation method on average were close to the recharge values from soil water budget method, whereas the other two methods gave much larger recharge estimates. The observed spatial and temporal variability of estimated groundwater recharge suggests that simple averaging may generate unreliable field-scale groundwater recharge estimates.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

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