Effectiveness Monitoring Report

MWMF Tritium Phytoremediation Interim Measures

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This report was written by the United States Forest Service[1] to describe and present the results of monitoring activities during irrigation operations for the calendar year 2001 of the MWMF Interim Measures Tritium Phytoremediation Project.

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List of Acronyms and Abbreviations

CLM = Ceptometer measurements
DOE = Department of Energy Savannah River Operations Office
EMP = Effectiveness Monitoring Plan for the Tritiated Water Management Facility
ER = Environmental Restoration Division
ET = Evapotranspiration
FSSR = USDA Forest Service, Savannah River
LAI = Leaf Area Index
LFC = Leaf Fall Collector
MWMF = Tritiated Water Management Facility (Mixed Waste Management Facility)
O&M Plan = Operations and Maintenance Plan
ORG = Open Rain Gauge
ORWBG = Old Radioactive Waste Burial Ground
NOAA = National Oceanic and Atmospheric Administration
PAR = Photosynthetically Active Radiation
PDX = Pressure transducer
PM = Penman-Montieth equation
PT = Priestly-Taylor equation
SCR = Subcanopy Rain gauges
SRS = Savannah River Site
SREL = Savannah River Ecology Lab
SRTC = Savannah River Technology Center
SSL = Soil Suction Lysimeter
STR = Surface Time Domain Reflectometry
SWD = Soil Water Deficit
SWV = Soil Water Vapor tubes
TDR = Time Domain Reflectometry
TEN = Tensiometer
VZP = Piezometer
WSRC = Westinghouse Savannah River Company

I. Executive Summary

System Effectiveness During CY2001: The ET efficiency of each monitoring plot was calculated for each sample date based upon the cumulative tritium applied minus the tritium content in the soil profile assuming no significant flux below the 3-m depth. Efficiencies were similar among monitoring plots with varying irrigation schedules between May and August, ranging from 56% to 80%, but increased to above 80% in November and December during the drought. The efficiency for CY2001 is based on pond evaporation and retention, and the 657 Ci applied in irrigation using the December cumulative ET efficiency of 81.2% to partition the tritium as follows:

Transferred to the Atmosphere	
ET from Vegetation	= 534 Ci
Pond Evaporation	= 79 Ci
Total	= 613 Ci
Temporary Retention	
Soil (0 to 2-m)	= 92 Ci
Pond Water	= 51 Ci
Total	= 143 Ci
Flux Below Effective Root Zone	
Soil (2 to 3-m)	= 31 Ci

Evapotranspiration: The overall ET demand was 113 mm above normal, with extremely high rates during the period from late September through December. The unadjusted ET deficit for the 2001 period was 620 mm, which is 28% higher than the 30-year average of 485 mm.

Rainfall Measurement: During the calendar year 2001, total rainfall for the SRS was 916 mm compared with the average of 1225 mm and was the second lowest of record in the 50 year history. The fall period from October through December was only 30% of normal.

Pond Water Balance Measurements: Pond overflow occurred only in the first part of April. Apparent seep inflow over weekly intervals ranged from below 10-gpm to over 90-gpm, and was not related to pond elevation. Peaks in apparent seep inflow corresponded to periods of rainfall. The monthly mean inflow ranged from 32 to 52 gpm.

Irrigation Measurements: The metered flow rate exceeded the theoretical flow (flow rate per head x the number of mini-sprinklers x operating time) by an estimated 9.8%. The maximum monthly application was 2,700,882 gallons during August and the minimum was 953,300 gallons in December. The total amount of water applied was 14,407,080 gallons during the nine-month period of operation in CY2001.

Vegetation Measurements: Vegetation on the plots is largely evergreen species and is dominated by loblolly, slash pine, laurel oak and sweetgum. Leaf fall for pines on the plots corresponded to the respective basal area of pines and peaked in November. The leaf area index determined by the ceptometer ranged from 4.4 to 4.9 during June on irrigated stands and 1.0 to 3.9 on non-irrigated stands.

Canopy Interception: About 60% of smaller rain events (~1 mm) to 18% of the moderate storms (~10 mm) are intercepted and evaporated directly to the atmosphere. As much as 5 mm was intercepted in larger storms (~50 mm). The mean values were similar among irrigated plots and averaged 12.3%.

Soil Moisture Measurements: Water uptake at depth occurred throughout the season. TEN and TDR were able to detect ET deficits resulting from under irrigation in April, June, August and October-November periods. Measurements of water uptake and the SWD during October-December indicate that the vegetation was actively transpiring and utilizing water throughout the profile as rates greater then originally estimated.

Tritium Measurements: Based on metered flow and adjusted pond activity, a total of 657 Ci were applied through the irrigation system. The increase in pond tritium activity to over 15,000 pCi/ml coincided with lower rainfall and decreased pond elevation. Tritium activity in the soil increased systematically over the period. The average activity at the 295-cm depth ranged from ~100 to 700 pCi/ml in December 2001. Tritium content integrated over 0 to 3-m layer was inversely related to the depth to clay.

II. Background

This report provides results from monitoring activities for the tritium phytoremediation project as part of the MWMF SWP interim measures during CY2001 irrigation operations. The purpose of this effectiveness monitoring report is to provide the information on instrument performance, analysis of CY2001 measurements, and critical relationships needed to manage irrigation operations, estimate efficiency and validate the water and tritium balance model. Cornell University is developing a 1-D and a 3-D water and tritium balance model utilizing the monitoring data to parameterize and validate the model simulations. These results are provided in separate reports.
The Savannah River Ecology Lab performs screening level analysis for tritium. The information covered in this report relates primarily to the following objectives as outline in the Effectiveness Monitoring Plan (WSRC 2001a):

1) Monitoring the effectiveness of the remedial action by measuring the flow of water and tritium activities into and from the pond.
2) Measuring periodically the tritium activity in soil, air, and vegetation on the irrigated watershed.
3) Determining a monthly and seasonal mass balance for the tritium between the various environmental media.
4) Determining the relationship between the irrigation rates, irrigation frequency, weather, vegetation, and soil conditions-heterogeneity and the partitioning or transfer of tritiated water between evaporation and other transport.

Figure 1 provides a layout of the tritium phytoremediation project area. This area consists of 30 irrigation plots over approximately 21 acres. Table 1 provides instrumentation cluster designations and the respective plots on which they exist. These clusters are the basis for plot monitoring data presented in this report. Four reference clusters are located in non-irrigated areas adjacent (Figure 2).

Table 1. Instrumented Plots and Associated Clusters

Plot Number	*Cluster Numbers*
13	1, 2, 3
27	4, 5, 6
22	7, 8, 9
16	10, 11, 12
19	13, 14, 15
4	16, 17, 18
C1	19
C2	20
C3	21
C4	22

Figure 1. Map of Project Area with Designated Irrigation Plots.

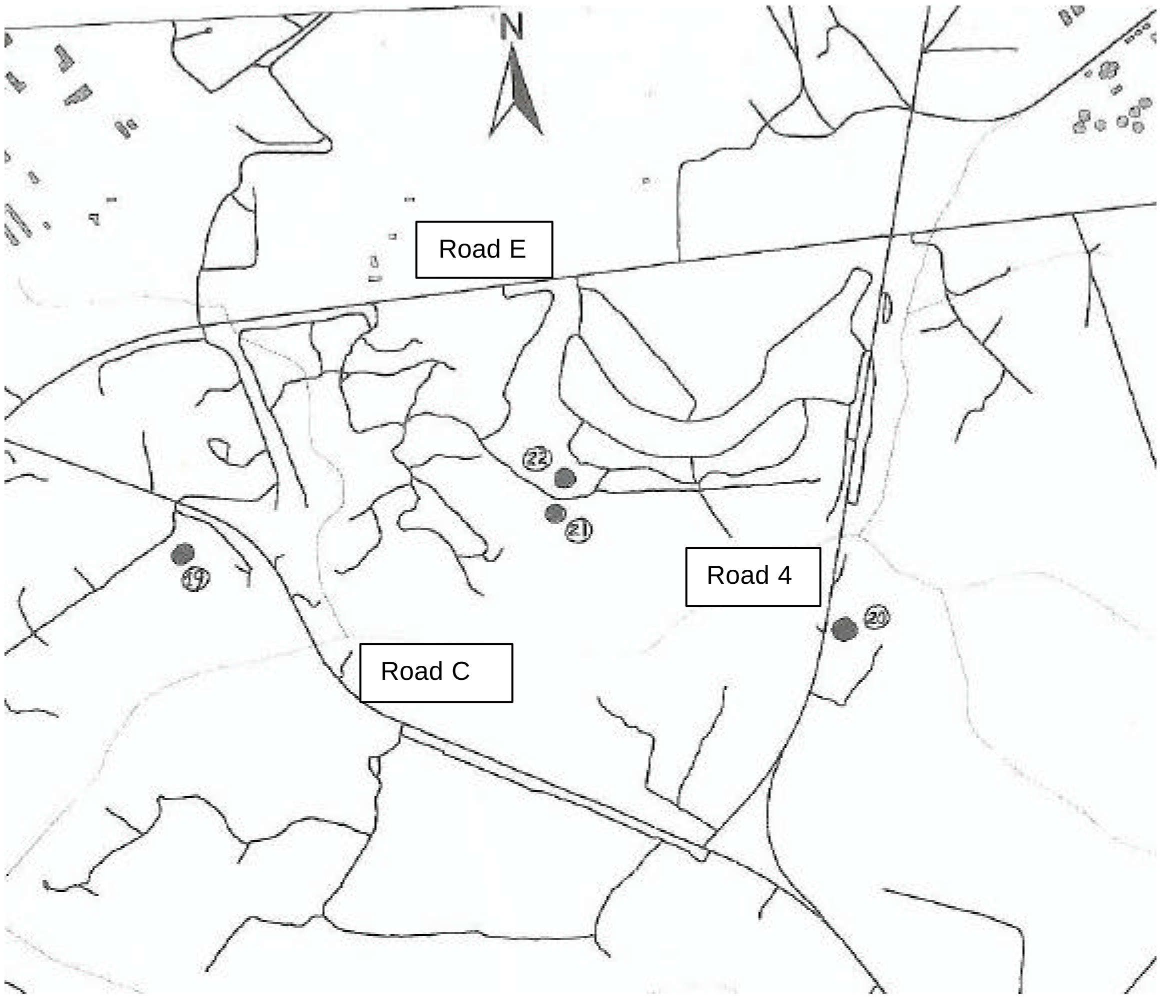

Figure 2. Map of Project Area with Designated Control or Reference Plots and Clusters.

III. Instrumentation Performance and Analysis

A. Evapotranspiration

Purpose: The purpose of the evapotranspiration (ET) calculation and supporting meteorological measurements (N-Area) is to provide a quantitative estimate of the amount of irrigation, precipitation, and stored soil water that can be potentially transpired by the vegetation or lost by surface evaporation. Surface evaporation occurs both from the pond and the wetted soil surface. Historical average ET and rainfall was used operationally (WSRC 2001b) to plan the summer irrigation schedule, provide missing value estimates for summer, and to regulate winter irrigation rates in the absence of real time daily ET values. During the growing period (mid-April to mid-October), calculated daily ET from meteorological observations at N-Area, minus observed rainfall, is used to determine a cumulative soil water deficit (SWD). The SWD provides an estimate of the water balance for the irrigated plots[1]. In conjunction with the soil water measurements, it is used to control irrigation to prevent over-watering that would increase tritiated water flux below the root zone and create anaerobic conditions.

Evapotranspiration Estimates

N-Area Meteorological Data: The meteorological system at N-Area or Central Climatology is located several miles south of the MWMF irrigation project. The system measures solar radiation, wind, humidity, temperature and rainfall. Wind, humidity and temperature used for ET calculations are measured at the 2-meter height. The system and quality assurance procedures are described in detail elsewhere (WSRC 1993). Readings are taken at 15-minute intervals and averaged to output an hourly mean value between 9 am of the previous day and 8 am of the following day. Even though the system is not immediately adjacent to the project, it provides high quality, reliable, and inexpensive meteorological data representative of atmospheric and radiation conditions that control evapotranspiration at SRS.

Historical Averages: Pan evaporation is a standard empirical method to estimate ET. Historical data from Blackville, SC (Table A1) is used to determine an historical average daily ET during winter months to regulate irrigation until a current weather-driven method is developed. The historical procedure (see Allen et al. 1998) involves reducing actual pan evaporation rates by a local “pan factor” (e.g. 0.8) and then multiplying the value by a local crop factor (e.g. 0.45) to approximate evaporation from the wetted soil surface. The method makes a conservative assumption that transpiration from the vegetation during winter does not contribute significantly to ET. Historical average ET deficit based on 30-year Augusta weather data and a simple forest water balance model is shown in Figure A1. When integrated over the year, on average there is approximately a 500-mm evapotranspiration deficit that could be met by applying tritiated water.

1. The operator’s SWD was calculated as a linear function of ET, which is only true near field capacity.

Table A1. Historical Average Monthly Pan Evaporation in Millimeters. Source: Edisto Experiment Station, Blackville, SC (1963-1992).

By	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mon	48	67	112	151	174	188	191	164	132	103	67	51
Day	1.53	2.39	3.62	5.02	5.62	6.27	6.16	5.28	4.41	3.33	2.24	1.64

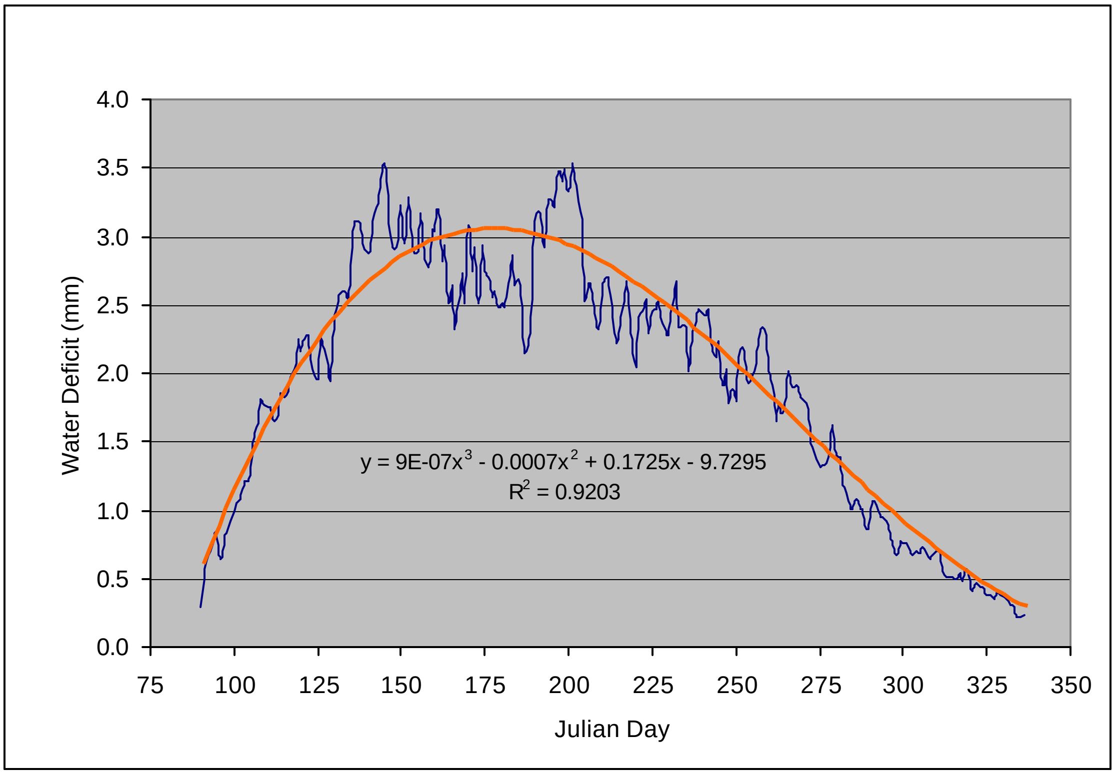

Figure A1. Average Daily ET Deficit by Priestly-Taylor Method (30-Year Average Augusta, GA). Source: Susan Riha, Cornell University

Evapotranspiration Calculation Methods

<u>Penman-Montieth Method</u>: The Penman-Montieth (PM) method is a modification of the standard Penman equation (Montieth 1965) originally developed to estimate evaporation from surface water. The equation integrates solar radiation, wind, temperature and water vapor density. It is suitable for both hourly, daily or longer interval estimates, and is sensitive to changes in wind, temperature, and dew point. The PM equation can be used to estimate evapotranspiration (λE) from a plant canopy. It requires inputs of net radiation (Rn), water vapor density deficit of the air, bulk surface resistance (r_{vs}), and resistances to heat and vapor transfer (r_h and r_{va}) in the boundary layer above the canopy. The equation is as follows:

$$\lambda \cdot E := \frac{s \cdot Rn + \frac{\rho \cdot c}{r_h} \cdot (\rho satv - \rho v)}{s + \gamma \cdot \left(1 + \frac{r_{vs}}{r_{va}}\right)}$$

where:

λE and Rn are in units of watt m^{-2}
r_h, r_{vs} and r_{va} in s m^{-1}
ρsatv is the saturated vapor density at the temperature of the air in kg m^{-3}
ρv is the actual vapor density for the air in kg m-3
s is the slope of the saturated water vapor density curve between the temperature of the surface and the temperature of the air.
ρ is the vapor density of the air in kg m-3
c is the specific heat at constant in joule kg-1 K-1
λ is latent heat of vaporization joule kg-1
γ is the psychrometric constant

The term r_{vs}, the bulk surface resistance, includes stomatal resistance to water vapor transfer, as well as aerodynamic resistance to vapor transfer within the canopy. A value of 0 implies there is no bulk surface resistance. In the absence of measured data for canopy leaf area and resistance, a value of 0 was used in the 2001 calculations.

Priestly-Taylor: The Priestly-Taylor (PT) method (Priestly and Taylor 1972) is a simplification of the PM method for estimating evapotranspiration over longer intervals of weeks or months that has been determined suitable for use in humid environments for conifer forests (Shuttleworth 1992, Melkonian and Riha 1996). The primary advantage of the method is that it does not require water vapor density or wind data, which is often not available locally or historically. The PT method is currently used by the Georgia Environmental Monitoring Network to calculate ET from local weather stations. The PT method was used by Cornell University to establish long term ET and SWD patterns for SRS from meteorological data at Augusta, GA (Figure A1).

The Penman equation simplifies to the Priestly-Taylor equation when the aerodynamic component of the Penman equation (ρc /ρrh) (ρsatv- ρv) is small or constant, which generally means windspeed is low and rva (resistance to vapor transfer) is therefore high. The aerodynamic component is replaced by a constant - α (1.26 is often used for short well-watered grass). The equation is:

$$\lambda \cdot E := \alpha \frac{s \cdot Rn}{s + \gamma \cdot}$$

During 2001, no modifications to the PT or PM equations were made to compensate for vegetation development, such as leaf area, canopy resistance or non-linear soil water extraction rates by using a “crop factor” (Allen et al. 1998) because the appropriate data to make such adjustments did not exist for CY 2001. Therefore, the values represent daily estimates of maximum evaporation. The ET estimates are driven largely by the radiation balance calculations. The non-modified PM ET estimates were used to estimate surface water evaporation from the pond during 2001. The process for computing net radiation, the major driver for ET, is provided in the Visual Basic macro program (MetdataCalc_2M_DLST.xls) developed to process the N-Area data (Appendix A). The procedure for downloading and converting data is described in WSRC-RP-4213 Rev 0. 2001.

Evapotranspiration Monitoring

Monthly Analysis: Daily ET was calculated beginning in late March 2001 using both the PT and PM methods. Table A2 reports the monthly ET for April 2001 through December 2001 and basic comparative statistics. The average daily ET ranged from a low 1.49 mm in December to a high of 7.05 mm in August. In comparison with the long-term 30-year record from Augusta, the months of July (+ 23.3 mm) and August (+46.7 mm) showed large positive deviations in ET that extended throughout fall. The overall deviation for the nine-month period was +113.2 mm above the norm. Because of the method of calculation, this difference is due to increased solar radiation (reduced cloudiness) and higher temperatures associated with the extreme drought conditions.

Table A2. Monthly ET Values for April 2001 through December 2001. The PT cumulative ET, average daily PT ET, maximum and minimum values, deviation from the long term average, the cumulative PM ET, percent difference between the PT and unmodified PM calculation, and the number of missing value days are shown.

Month	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
	mm	mm	mm	mm	mm	mm	mm	mm	mm
PT ET	133.4	181.1	189.5	214.3	218.7	140.4	110.6	69.1	46.3
Daily Ave ET	4.45	5.84	6.32	6.91	7.05	4.68	3.57	2.30	1.49
Max Daily ET	6.77	8.59	9.29	9.89	8.93	7.21	5.65	3.29	2.59
Min Daily ET	0.59	3.58	3.02	1.89	3.34	1.30	1.82	0.70	0.20
Dev. 30-yr Ave	-2.6	+8.1	+4.5	+23.3	+46.7	+6.4	+13.0	+10.0	+3.3
PM ET	141.0	189.0	182.1	203.7	216.6	136.4	124.4	76.3	54.6
% (PM-PT)/PM	+5.4	+5.5	-4.5	-5.5	-1.0	-3.0	+11.1	+10.4	+11.2
Missing Values	0	8	3	2	1	0	0	3	0

Comparison of Methods: The PM method incorporates data on dew-point and wind and as such would be expected to show higher ET values than the PT method under weather conditions in which the air masses are dry and windy. The observed deviations between the two methods are relatively minor and can be related to regional climatic trends. Specifically, larger values of ET were consistently calculated during October through December for the PM method, corresponding to the change from the ocean-gulf air masses dominant during summer to the drier more continental air masses in winter (this trend is being maintained through spring 2002). The differences are expected to be important in regulating winter irrigation using current weather data since the overall ET rate is low, and potentially more effected by daily wind, temperature, dew-point, and solar radiation.

B. Rain Gauge Measurements and Rainfall Analysis

Purpose: Rainfall is measured to meet several objectives. Rainfall data is collected to track and manage the daily water balance or ET deficit during summer season, and to avoid over-watering following periods of high rainfall. Data is used as input to the water balance simulation model being developed by Cornell University to calculate the water balance, including derivation of "crop factors", canopy interception terms, tritiated water mixing, and water and tritium fluxes to the air and below the root zone. Rainfall data is also used to derive hydrologic response parameters for the pond and seep discharge components. On average, there are about 75 rainfall events per year > 2-mm at SRS, which is the minimum needed to exceed canopy storage. In CY 2001, there were 63 storm events > 2-mm. Historical records for rainfall for the SRS are readily available through the SRTC Weather Center (Shrine) and from NOAA for Augusta, GA and Blackville, SC to compare or simulate climatic effects on operations.

Rain Gauge Equipment and Performance

N-Area Rain: Rainfall is collected by the SRS at N-Area using a Belfort Model 5-405HAX-1 Tipping Bucket rain gauge (WSRC 1993). Rainfall is recorded continuously and cumulative rainfall for the previous hour is output to a file. During 2001, this was the primary source of rainfall data used to maintain the daily water balance for controlling the operation of the irrigation system. If data was missing or major discrepancies were observed between the local sub-canopy gauges (SCRs) and N-Area due to localized storm effects, the open area SCRs or 200-F Area gauges were used as substitute values. The N-Area gauge is located about 3 miles south of the MWMF project. Performance of the instrument is maintained to standards established by SRTC Atmospheric Technologies Group.

During the period from April through December 2001, only 5 days of rainfall record were missing due to instrumentation problems. On those dates, substitute rainfall reported at the 200-F Area facility, which is approximately a mile north of the MWMF project, was used. The 200-F Area instrument is a simple plastic gauge and no quality control or calibration is conducted. Rainfall is recorded daily at the end of each 24-hour period. The data is accessed electronically through the SRTC Weather Center.

Sub-canopy Rain Gauges: In order to develop an empirical canopy interception equation for calculating the water balance and tritium flux, SCRs were installed. These devices also provide easily measured rainfall on the project area as back-up for the water balance. Instruments are located at each of the 18 monitoring clusters that are irrigated, two locations on the watershed in open areas (sediment basin and pond), and at three of the non-irrigated reference sites. The SCR located at the pond (PD) and the SCR located at the sediment basin (SB) provide the reference values for the instruments as well as real time rainfall data for the project. The procedure, WSRC-RP-2001-4214 Rev. 0, describes the equipment, maintenance and collection methods for the SCRs. The devices consist of a screened funnel mounted on top of a 10-gallon carboy between 1.5 meters above the ground. Rainfall data is collected within 24 hours of an observed rainfall event, unless rainfall occurs on an extended weekend. In general, the recorded day of collection was 24-48 hours after an event.

During 2001, no major operations or maintenance problems were experienced. During April and May, spray from some of the irrigation heads was observed to be impacting some funnels, which may have caused overestimates of sub-canopy rain. Corrections were made to the angle and elevation of the mini-sprinkler heads to minimize the problem. Several rain events were also lost because of operational time constraints. Because of their simple design, the devices are largely unable to detect rainfall events less than 1 mm. It normally takes several hours following an event to measure and record the rainfall values.

<u>Open Rain Gauges</u>: Three automatic recording, tipping bucket open rain gauges (ORGs) are installed. These are Davis Instruments Rain Collector II (#7852) gauges coupled to a Hobo data logger made by Onset Computer Corp. Two are on the MWMF project FMB watershed adjacent to the open area SCRs, and one is located on the clear-cut control site about ½ mile east of the area. These instruments provide a continuous and inexpensive, but more accurate rainfall record on the project area for calculating the water balance and tritium fluxes. The equipment, maintenance, and collection methods are described in WSRC-RP-2001-4259 Rev. 0. Since the instruments are currently logged remotely and downloaded at intervals of several months, the data is not available in real time and cannot be used to regulate daily irrigation operations. It usually takes about an hour to periodically download and transfer the files for all three ORGs.

During 2001, ORG #1 located at the sediment basin did not record data from January through June for undetermined reasons. The logger was reset and data was recorded between July 3rd and December 24th, however it was later determined (March 2002) that the tipping bucket reed sensor was impaired by debris. The rainfall readings are considerably less than ORG #2 located at the Pond or ORG #3 located at control cluster 20 (clear-cut). The ORG #1 values were considered unreliable for 2001 and were not used in any analysis. Both ORG #2 and #3 performed well until November 1, 2001 when ORG #2 was not reset properly and data was not recorded for the remainder of the calendar year. Between March 16 and October 31st, ORG #2 recorded 3,543 events or 708.6 mm of rain, while ORG #3 recorded 3,621 events or 724.2 mm of rain. Those values represent only a 2.2% deviation between instruments. ORG #2 and #3 were used by Cornell University for their 2001 model simulation runs (Cornell University March 2002) because of the reliability and continuity in the data. Because of the problems experienced in 2001, procedures have been changed to download the gauges every 30 days and to clean the instruments more frequently to avoid data gaps and quality problems.

Rainfall Comparison between Instruments

Percent Deviation: The rainfall totals obtained from the various instruments were compared in order to determine the consistency and variation among devices and the effects of spatial separation on observed rainfall. Because some instruments record continuously (N-Area, ORGs) while others record total values for an event (SCRs), or periodic values (200-F Area), a comparative data set was created by rainfall event over one or more days. The continuous recording ORG #3 was used to define a rain event start and end day. The total rainfall observed between those times was totaled for the other instruments. The data was separated into a summer set (May 15-October 14) and a non-summer set (October 15-May 14) as a result of the dominant influence of convective storm cells on summer rain that are known to be spatially variable (Table B1). As a result of missing data, some events are not included in the comparison.

Table B1. Rainfall Instrument Comparisons for Summer and Non-summer Periods. Comparison is based upon a total of 34 discrete rainfall events. Percent deviation is calculated as the difference in mean values for the events divided by the average.

	May 15-October 14	**October 15-May 14**
Instrument Comparison	% Deviation	% Deviation
SCR (PD) vs. SCR (SB)	9.9	4.5
ORG #2 vs. ORG #3 [1]	2.2	-------
N-Area vs. 200-F Area	60.7	21.2
N-Area vs. ORG #3, #2	56.4	17.0
200-F Area vs. ORG #3, #2	29.7	21.0
SCR (PD+SB) vs. ORG #3, #2	7.6	9.8

1. Comparison period March 16 to October 31, 2001 for ORG #2 vs. ORG #3.

As expected, there was good agreement between instruments that were located physically near each other on the project area. The smallest deviation occurred between the two continuously recording gauges (ORG). The same pattern was observed for the SCRs. Given the simplicity and limitations of the SCRs they performed well. Simple linear regression of the SCRs vs. ORGs gave and $R^2 = 0.97$, and a fitted equation of SCR = 0.9636 ORG. The result indicated that the SCRs slightly underestimate actual rainfall; however, they provide reliable data for maintaining the operational water balance and calculating interception.

Winter vs. Summer: The higher deviation in summer between the two SCRs was due to only one event. In general, both the N-Area and 200-F Area deviations were reasonable during the non-summer period. From May through October, the deviations are too large to provide reliable estimates of rainfall on the project area. This result is reflected in the monthly rainfall values reported in Table B2. Although the N-Area and 200-F Area rainfall data is provided at no cost, and it is available daily, there is a need to set-up standard continuously recording gauges at the project site with real-time rainfall data collection for maintaining the daily water balance. Alternatively, the existing gauges (ORG) can be converted to transmit data in real time. In the interim, especially during the summer months, the SCRs at the pond and sediment basin should be used. The 200-F Area should continue to be used as a substitute for missing data.

Rainfall Deviations and Monthly ET Deficit

Annual and Monthly Rainfall: During the calendar year 2001, total rainfall for the SRS (773-A) was 916 mm (Source: SRTC Atmospheric Technology Group), compared with the average of 1225 mm and a low of 732 mm in 1954. Total rainfall for SRS in 2001 was the second lowest of record in the 50 year history. When rainfall at the MWMF project site (ORG #3) is compared to the long-term monthly means for SRS, major deviations, in terms of reduced rainfall, are evident for April, August, October, November and December (Table B2). When compared to the range of precipitation observed over the last several decades, the period from April to December 2001 was only 78% of normal. However, the fall period from October through December was only 30% of normal.

Table B2. Monthly Rainfall at the MWMF Irrigation Project (ORG #3) and N-area During April to December 2001. Long-term data taken from SRTC Shrine Climate Data for 773-A for the period 1952-2001.

Month	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
	mm	mm	mm	mm	mm	mm	mm	mm	mm
Rain ORG #3	31.6	97.8	137.6	179.4	53.4	114.8	28.0	25.4	15.6
Rain N-Area	35.6	117.4	163.7	127.7	126.2	68.6	14.0	22.5	14.8
1952-2001 Ave.	82.6	93.7	115.8	130.8	123.7	103.6	73.9	66.3	88.1
Dev. (ORG-Ave.)	-51.0	+4.1	+21.8	+48.6	-70.3	+11.2	-45.9	-40.9	-72.5
Maximum	208.3	276.9	276.6	291.6	313.4	221.2	498.4	197.6	245.6
Minimum	14.5	33.8	22.6	22.9	26.4	12.5	0.0	5.3	11.7

Monthly ET Deficit: When the rainfall is combined with the monthly ET estimates for 2001 (Table B3), an indication of the relative water balance conditions can be obtained for each month and the potential for irrigation. The monthly ET deficit for the 2001 period was about 620 mm, which is 28% greater (drier) than the 30-year average (Cornell University October 2001) of 485 mm. The average equivalent depth of irrigation water using the rate based on operating time and the uniform flow per head mm (see Irrigation Measurements) was 583 mm. If the equivalent depth of irrigation is compared to the adjusted ET (0.9) using the Cornell 1-D model estimates, the scheduled irrigation (583 mm) is slightly higher than the calculated actual ET for the year (558 mm). This result suggests very little excess drainage occurs if irrigation flow is carefully regulated using ET deficits (Cornell University Report March 2002).

Table B3. Monthly Unadjusted ET Deficit (ET-Rainfall) for the Period of April to December 2001 Compared with the 30-year Average from Augusta, GA (Source: Cornell University Report October 2001). Rainfall values are taken from ORG#3.

Month	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
	mm	mm	mm	mm	mm	mm	mm	mm	mm
ET Deficit 2001	101.8	83.3	51.9	34.9	165.3	25.6	82.6	43.7	30.7
30-Yr Average	41.3	87.2	83.0	89.6	73.4	57.4	31.4	14.1	8.0
Dev. From Ave.	+60.5	-3.9	-31.1	-54.7	+91.9	-31.8	+51.2	+29.6	+22.7

Cautionary Note: During periods of extended or extreme drought, the calculated ET deficit can easily exceed the actual soil water deficit (SWD). The maximum SWD at anytime is limited by the available water content in the rooted soil profile and can be determined by integrating the water content between wilting point and field capacity over the root zone. Wilting point is the water content at which water is held so tightly in soils that plants cannot take it up, while field capacity is the maximum water content that soil can hold before gravity drainage starts. For the MWMF, that value depends on the soil texture and rooting in each cluster, but is estimated to be approximately 300 mm. In addition, extraction of soil water by vegetation becomes non-linear as soil water content declines below field capacity. Plant stomata close in response to soil water stress and leaf fall can occur, reducing transpiration. Water uptake is also shifted to deeper horizons with lower root densities. While the 1-D simulation model approximates these relationships in the calculations, the simple daily ET deficit or SWD in the spreadsheet maintained by the operators currently does not. Therefore, the SWD calculated using the operator's daily water balance spreadsheet should be used cautiously and the estimates checked against the measured soil water content using the time domain reflectometry.

C. Pond Water Level Measurements and Pond Water Balance

Purpose: Pond water balance measurements are taken to meet several objectives. Hourly electronic recordings of the pond water level are made to track changes in pond surface area and volume in order to calculate water and tritium evaporation, seep inflow, change in storage and retention as well as watershed response parameters (base flow, peak flow, runoff coefficients). When operating, daily manual measurements of the pond water level are used to estimate irrigation capacity and potential storage. The manual measurements also provide missing values for the electronic data. Rainfall data is used to derive hydrologic response parameters for the pond and seep discharge components. Determining the rate of seep inflow is critical to the daily operations of the system in addition to planning the size of the irrigation system to minimize the tritium flux to Fourmile Branch. No measurements existed prior to 1999 to estimate the stream or seep inflow. An average estimated for 1993-1997 by tritium dilution within Fourmile was 83.9 gpm. A single measurement of base flow in 1999 gave a value of 40 gpm, and a peak flow of about 360 gpm following a storm event (Blake 1999).

Instrumentation and Performance

WL-80: Pond water level measurements during 2001 were collected electronically using a WL-80 (WL) sensor manufactured by Remote Data Systems. The procedure, WSRC-RP-2001-4220 Rev. 0., describes the equipment, maintenance and collection methods for the WL. The WL operates by electrical capacitance and is downloaded every 20 days. It has sensitivity in tenths inch and is independent of atmospheric pressure and temperature. The zero point (214.36-ft) was set at 0.50 feet above the overflow of the dam (213.86-ft). The sensor was set to record every hour. During 2001, the WL was the primary source used to calculate pond volume and surface area. The device operated from April through December. It takes about 30 minutes to download and reset the instrument.

Several significant problems were experienced with the WL. The most serious problem occurred in early May through June 20th. During the period the average daily WL elevation did not track the average daily Staff Gauge (SG) values. There was almost a two-foot discrepancy between the SG and WL elevation when the pond was first drawn down to a low level (SG ~ 2.5 ft) in May. The cause is unknown, but maybe related to transient surface contamination on the new wire sensor. On June 20th there was a step change between consecutive readings that resulted in a subsequent close correspondence between the WL and SG, which lasted until November 23rd. Daily pond elevation between May 1st and June 20th was estimated from SG readings or logbook operator records and interpolated for missing days to calculate seep inflow.

On one occasion (September 12th-19th), a lightning strike nearby may have caused the WL to stop recording. Between November 23rd to 26th, anomalous high readings were logged indicating about a one foot rise in pond elevation which did correspond with a 17 mm rain event, but the magnitude of change in elevation was not reflected in either the

SG or pressure transducer (PXD) measurements (Figure C1). Based upon previous experience with other WL devices at SRS, the anomalous event is probably the result of static electricity that built up across the battery terminals. The problem can be corrected by replacing the battery more frequently and by shorting static electricity across the terminals. Data was lost between December 13^{th} and 16^{th} because the storage limit (21 days) was exceeded. The SG readings were used to estimate the daily average pond depth for those periods. During 2002, procedures for maintaining and downloading the WL will be modified to avoid these problems. The daily SG readings, although less accurate and incomplete, provided a useful method for cross checking for errors in the electronic instruments.

Pressure Transducer: A more sensitive pressure transducer (PXD-261) manufactured by In Situ, Inc. attached to a Hermit 3000 data logger that was installed for comparison with the WL. The PXD is a pressure transducer that is sensitive to hundreds of an inch (~1mm), but must be corrected for barometric pressure. The sensor was set to record every 30 minutes and was downloaded monthly. The elevation of the reference or "zero" point for each device was established independent of the WL. There are no written procedures for the PXD.

In general, there was good agreement and tracking between the more expensive PXD device and the WL (Figure F1). The simple linear correlation between the two devices (PXD (ft) = -3.70304 + 1.01795 WL (ft), $R^2 = 0.998$) is very close to a one to one relationship with a very slight tendency for the WL to read higher than the PXD. The latter is believed to be the result of a small discrepancy (~ 2 cm) between the reference elevation points of the instruments. The potential error in reference point elevation affects the absolute value of pond volume and area. However, it has a smaller impact on calculating periodic changes in volume that are used to estimate seep inflow and hydrological response parameters because of the linear relationship between elevation and volume (Figure C2). It is clear that the WL is not sensitive enough to measure very fine changes in pond volume (< 5,000 gallons) that may result from evaporation, rainfall or leakage. For example, in the summer, the PXD was able to detect very small decreases in pond depth in the late afternoon and night resulting from evaporation of water from stored energy during the day.

Staff Gauge: A manual staff gauge (SG) was installed along the catwalk in the pond. Readings in intervals of hundreds of feet were made twice each day, once in the morning and once in the afternoon. The absolute elevation of the pond (feet) is determined by adding 208.13 to the SG reading. No problems were experienced with the SG. The average daily readings from the SG were strongly correlated to the average WL readings from July through December. The simple linear regression equation is "SG (ft) = (0.08154 x WL (inches)) + 5.8968" ($R^2 = 0.98$), where the WL readout is in inches below the zero point.

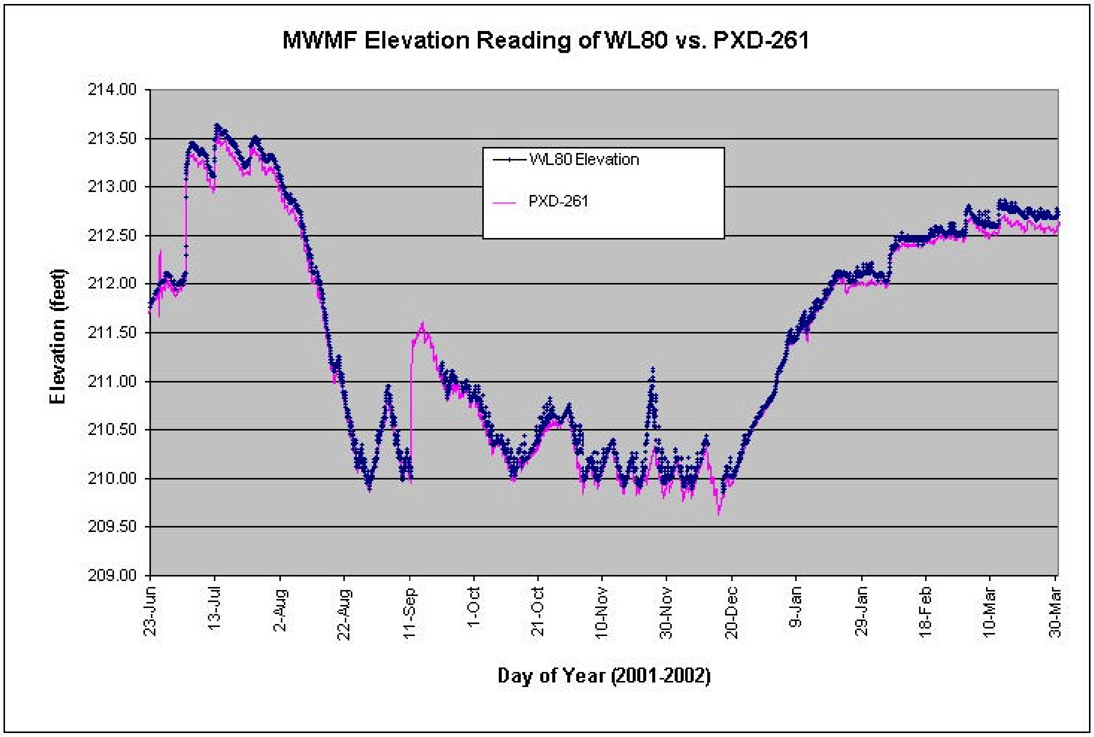

Figure C1. Elevation Comparison of WL-80 and PXD-261 Water Level Sensors at the MWMF June 2001 to March 2002.

Pond Depth vs. Pond Volume and Area

The relationship between pond water elevation, pond volume and surface area was established by a survey of the elevation and position of the pond water margin during 1999-2000 as the pond filled following closure of the sheet pile dam valve. The volume was determined with a smoothed 3-D grid and the surface area with a smoothed 2-D grid. The volume and surface area between measured points at intervals of hundreds-of-a-foot was interpolated.

The maximum elevation of the pond at the overflow point is 213.86 feet. The maximum pond volume and surface area at that point is 2,540,550.4 gallons and 83330.5 square feet respectively. Pond volume and area are calculated by adding a reference or zero point elevation for the instrument to the WL, PXD, or SG readings. The general relationships are shown in Figures C2 and C3.

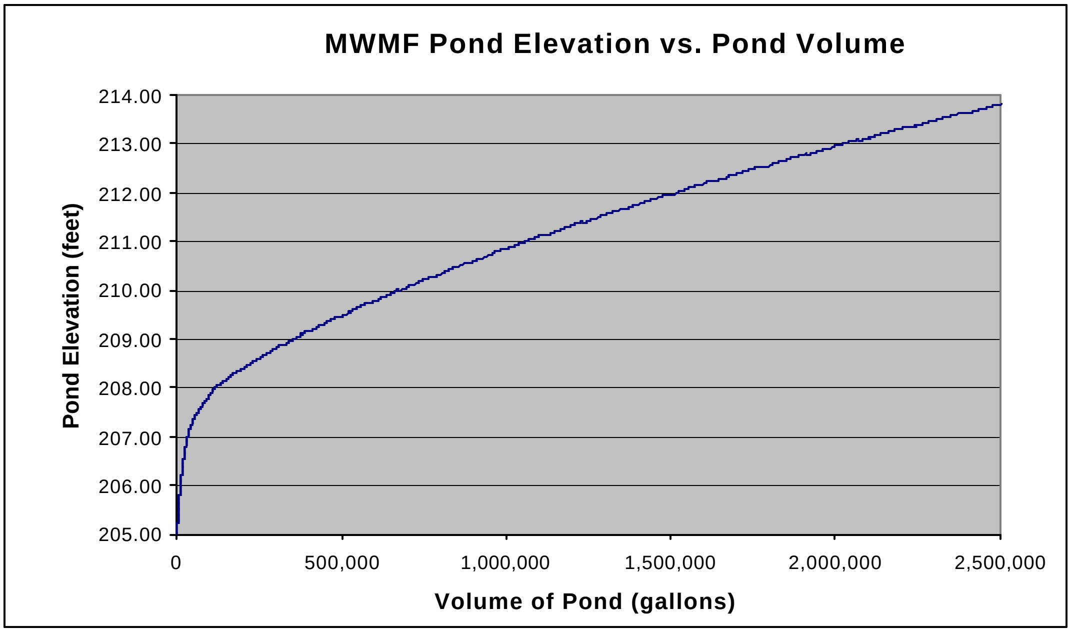

Figure C2. MWMF Pond Elevation vs. Pond Volume. Source: Mark Amidon, SGS.

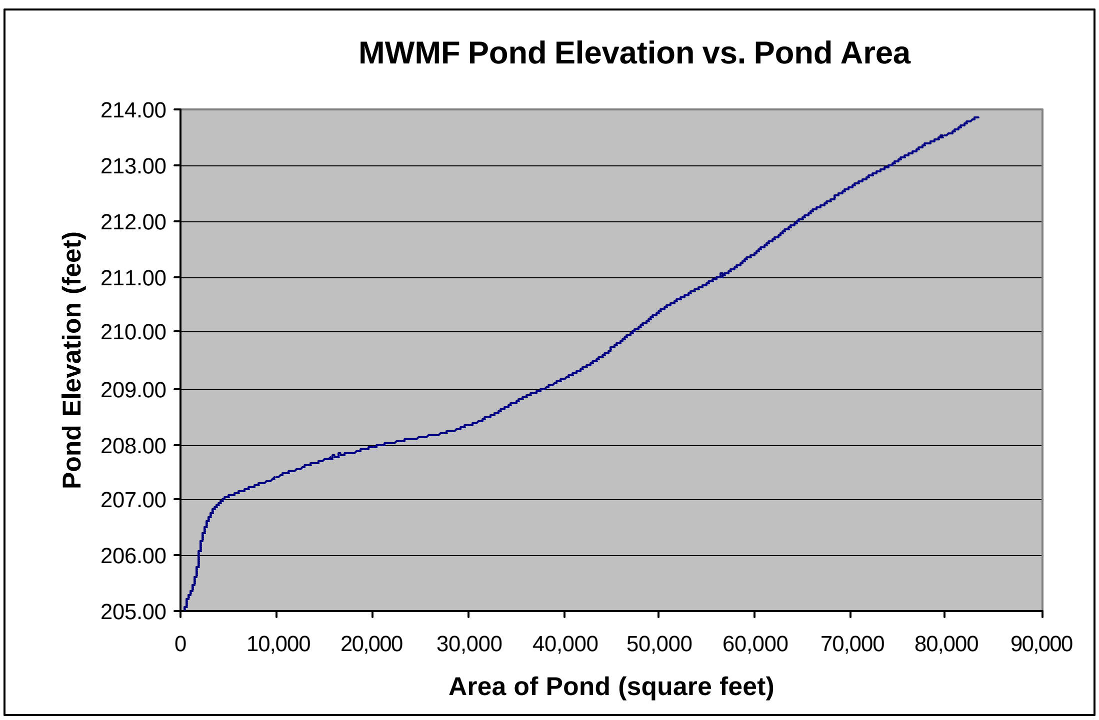

Figure C3. MWMF Pond Elevation vs. Pond Surface Area. Source: Mark Amidon, SGS.

Apparent Seep Inflow

Basic Equation and Methods: Because of discrepancies in the WL data, uncertainties on the volume of irrigation applied, and limited information on pond leakage, it is not possible to make precise calculations of seep inflow over short intervals (hours, days) for 2001. Additionally, analysis of hydrological parameters involving storm discharge and run-off coefficients requires a longer period of record with more rainfall events. As a result, the analysis for 2001 refers to "apparent seep inflow". It is expected that more rain events, coupled with better quantitative measurements of leakage during 2002, will result in sufficient data for calculating more precise seep inflow values and a periodic (monthly) tritium balance.

The apparent seep inflow rate was calculated for the pond over weekly intervals. The equation as derived from the Effectiveness Monitoring plan is as follows:

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Seep Discharge = Irrigation + Evaporation + Overflow (Leakage)
+ ∇Pond Volume - Rainfall
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The *irrigation volume* is the metered flow-rate volume of water applied to the plots during the week and includes leakage associated with pipe breaks, popped sprinklers, or animal caused leaks. The *evaporation volume* is the calculated PM evaporation rate for each day, times the surface area of the pond, summed over the interval. The 30-year average Priestly-Taylor rate was substituted for days with missing data. While no *overflow volume* occurred during the period from late April through December, significant leakage through the dam was visible. The *leakage volume* was estimated using a small flume with a stilling well in the channel just below the dam. Data was collected from November 2001 through February 2002 to estimate leakage. The *change in pond volume* was calculated as the difference between the pond volume at the end of the week minus the pond volume at the end of the previous week. The pond elevation used was the numerical average of the WL readings for that day, or the average SG reading, if WL data was not available. The *rainfall volume* for the interval was equal to the daily rain total obtained from the ORG#2 or ORG#3 instruments, times the surface area of open water in the pond, summed over the interval.

Seep Inflow vs. Rainfall and Pond Depth: There is a general trend for the apparent seep inflow rate of water to increase in response to rainfall (Figure C4). Apparent seep inflow over weekly intervals ranged from below 10-gpm to over 90-gpm. The increase associated with rain is not always proportional to the magnitude or timing of the event. There is also no simple relationship between pond elevation and the seep inflow rate (Figure C5), as might be expected since the effect of pond elevation on the tritiated plume seep gradient is confounded with rainfall events, evaporation rate, water table depth and a non-linear fill and leakage rate from the pond. Determination of the change in tritium content in the pond over the interval is the best method for estimating the tritiated water seep inflow rate and its relationship to pond elevation.

Several factors account for the variability in the seep inflow rate of water during 2001 that are not factored into the analysis. First, no accounting is made of the soil water deficit that will normally influence subsurface runoff. Second, the calculated inflow rate is sensitive to the accuracy of the change in pond volume and the irrigation volume. An error in the average pond elevation reading at the beginning or end of the interval has an impact on the apparent inflow rate. A more accurate estimate is obtained by using the pond elevation just following irrigation, and again, just before irrigation, instead of the average for the day. However, the uncertainties and missing values during 2001 precluded that approach. Third, non-linear effects resulting from leakage through the dam and the "de-watering" and "re-watering" of pores in the confining soils and sediments are not included in the calculations at this time. Fourth, the effect of overflow from the sediment basin on the inflow rate and pond dynamics is unknown, as no records exist. The sediment basin collects runoff from the area above Road E, including the old waste burial grounds. Some of the variances and anomalies in pond hydrology may be related to the overflow-discharge from the sediment basin to the pond. The construction of a storm-water bypass in the winter of 2002 to route the discharge below the pond is expected to minimize the influence of the sediment basin on the pond hydrology.

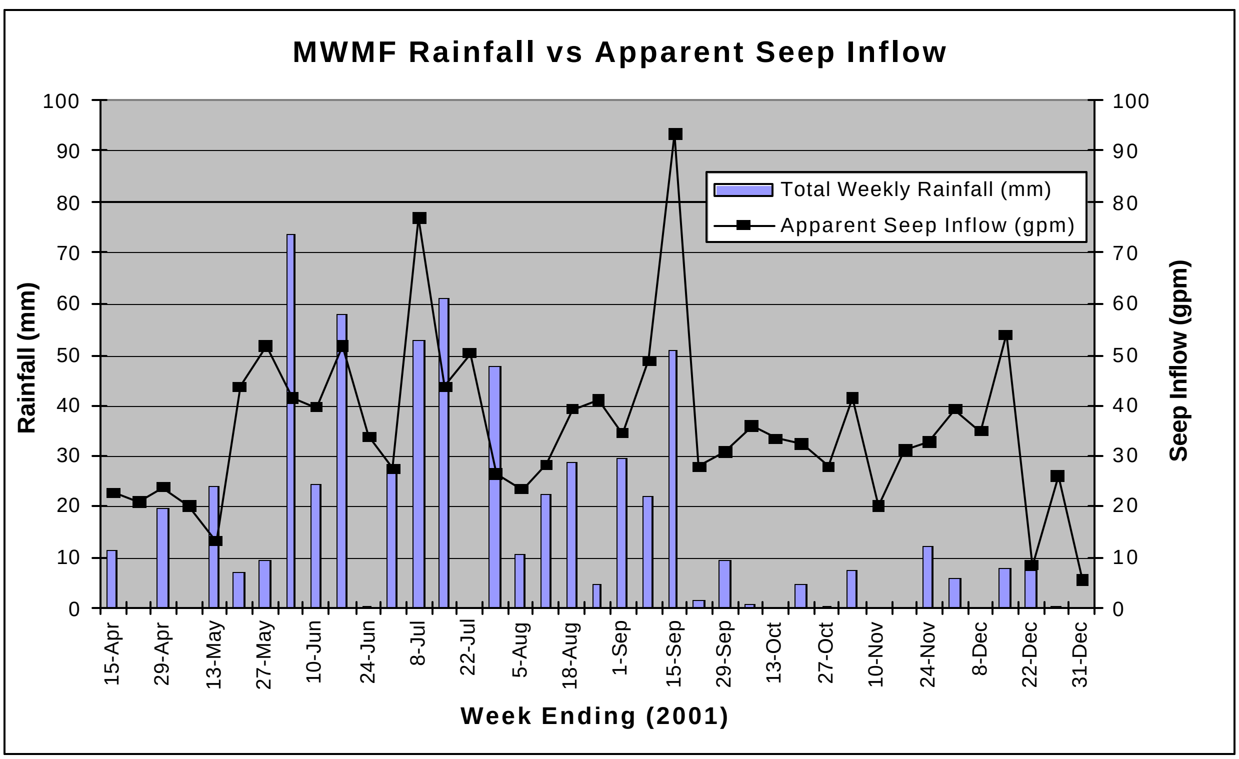


Figure C4. MWMF Rainfall vs. Apparent Seep Inflow for CY2001. A fixed leakage rate estimate of 2-gpm was not included.

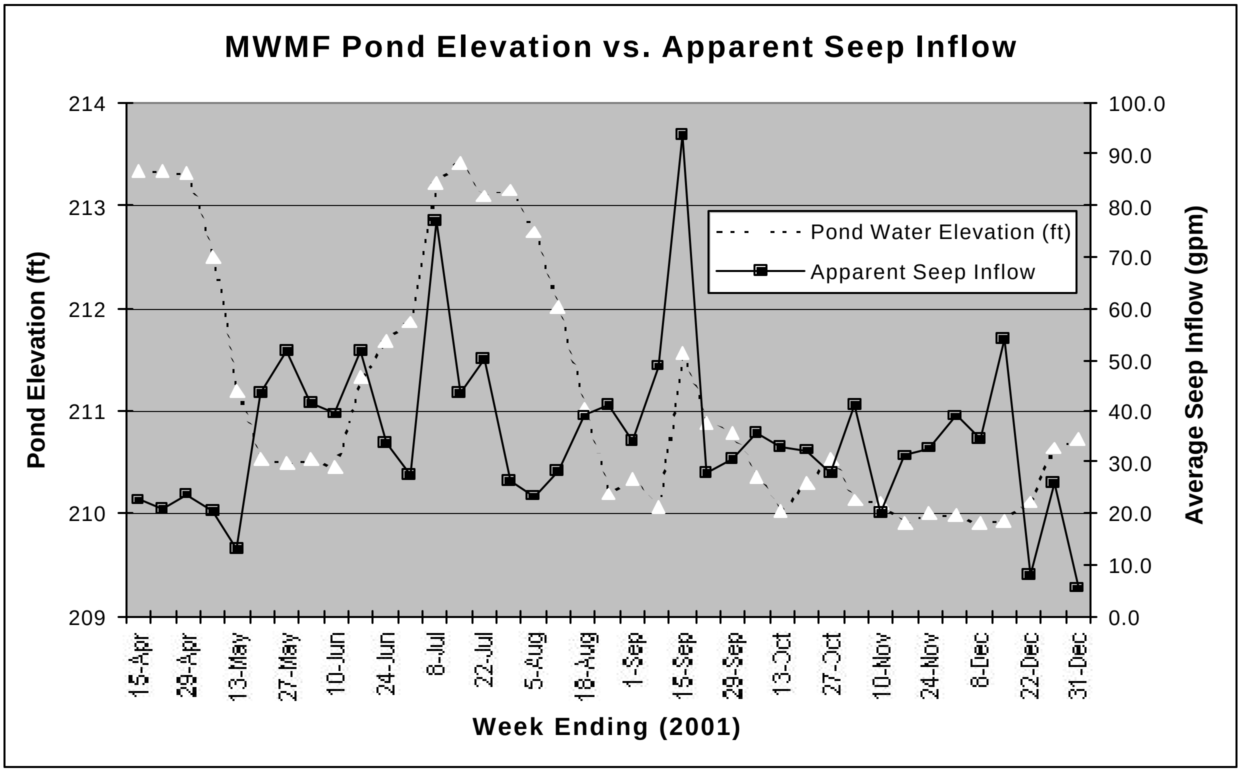


Figure C5. MWMF Pond Elevation vs. Apparent Seep Inflow for CY2001. A fixed leakage rate estimate of 2-gpm was not included.

<u>Seep Inflow by Month</u>: The pond water balance and apparent seep inflow was calculated for monthly intervals and is displayed in Table C1. Excluding April, in which pond volume estimates and irrigation rates are subject to significant uncertainties and using 2-gpm to account for leakage, the average monthly inflow ranges from about 32-gpm to 52-gpm. The apparent seep inflow shows a decline in October, November and December, corresponding to the extended drought in which rainfall was 30% of normal. The average for the interval over the year is 38.9-gpm. The actual inflow to the pond may be expected to be about 40-gpm annually under normal precipitation conditions. Even considering the extended drought, the inflow rate is much less then the predicted discharge using tritium dilution in Fourmile Branch, but it is still greater than the 27-gpm estimated from a simple Precipitation-Evapotranspiration calculation for the watershed (Blake 1999).

Table C1. MWMF Apparent Seep Inflow in Both Gallons and GPM by Month for 2001.

Month (Days)	***Apr*** (21)	***May*** (28)	***Jun*** (35)	***Jul*** (28)	***Aug*** (35)	***Sep*** (28)	***Oct*** (28)	***Nov*** (35)	***Dec*** (30)
Source	Gal x 1000	Gal x 1000	Gal x 1000	Gal x 1000	Gal x 1000	Gal x 1000	Gal x 1000	Gal x 1000	Gal x 1000
Irrigation	853.9	2573.5	1229.0	1021.1	2777.9	1787.6	1268.0	1780.6	973.3
Evaporation	212.5	246.2	297.2	333.0	350.0	171.8	145.6	107.3	61.7
Rainfall	61.1	54.4	243.1	280.2	135.2	111.8	6.8	35.9	17.8
Ñ**Pond Vol.**	-324.9	-1472.1	669.5	911.4	-1315.8	175.4	-106.7	-196.1	274.8
Leakage[1]	60.5	80.6	100.8	80.6	100.8	80.6	80.6	100.8	86.4
Seep Inflow	740.9	1373.7	2053.4	2066.0	1777.7	2123.6	1380.8	1756.7	1378.4
	Gpm	Gpm	Gpm	Gpm	Gpm	Gpm	Gpm	Gpm	Gpm
Seep Inflow	24.5	34.1	40.7	51.2	35.3	52.2	34.2	34.9	31.9

1. Leakage rate estimated at an average rate of 2-gpm (Barton, Pers. Commu.)

D. Irrigation Measurements and Equipment Performance

Purpose: An accurate estimate of the irrigation water applied is a critical component of the effectiveness monitoring. The values enter into nearly every calculation related to project management. The quantities are used in the model calibration and validation to partition the water and tritium between soil and air. When combined with the pond tritium activity they provide the means to directly estimate effectiveness for the project. Monitoring of irrigation applied is also conducted to effectively manage the amount and distribution of water in relation to the planned irrigation schedule and the calculated ET deficit. The irrigation plan and schedule for summer and winter CY2001 is in Appendix J of the Operations and Maintenance Plan (WSRC 2000b, Rev 0.)

Instrumentation and Performance

Metered Flow Rate: Irrigation monitoring was conducted using a Flowmaster TWC 100-C flow controller, a Data Industrial Model 200 flow sensor, and TUCOR remote access software (TUCOR-RAS). The flow sensor was installed in the discharge pipe approximately 10 pipe diameters from flow disturbance. The flow sensor is an impeller type. The instrument has a range from 0.5 to 30 ft per sec and is accurate within 1% of full scale if installed and operated properly. The sensor was factory calibrated. In operation, the flow meter feeds input to the TUCOR controller and it output to the panel for visual display. The TUCOR controller records the final flow rate just prior to the end of the irrigation cycle and operating time for the selected plots. In order to calculate total flow, the operating time must be known, and since two or more plots are irrigated at the same time the flow must be proportioned between the plots. The total flow is equal to the final flow meter reading times the operating time. The flow is proportioned among plots by using the relative proportion of sprinkler heads in each plot. For example, if one plot contains 40 heads and the other 60, the flow is split 40:60.

During CY2001, several problems were encountered with this method. While installed, the meter did not function properly or functioned intermittently for during April, so that flow was calculated using the alternative method (Flow Rate per Head). Since the system only records flow-rate at the end of the cycle, there is no means for integrating variable flow or averaging over the cycle. When the system was functioning properly, and there were no leaks or line breaks, the operators stated that the method and the alternative, Flow Rate per Head, agreed. If leaks occurred from line breaks, popped heads, or animal damage, the excess water was allocated to the individual plots in the same manner as if the water was uniformly applied through the sprinklers. The latter method will always lead to over estimation of the uniform depth of application.

In a comparison of the total flow to individual plots using metered flow rate versus the alternative or ideal flow rate per head, the metered flow was on average 9.8% higher than the ideal flow. Operator observations indicate that the discrepancies occurred when lines broke, heads popped, or animal damage was significant. One or two popped heads could alter flow by 20-30 gpm. The latter introduces a level of uncertainty in the uniform water application depth compared with the planned irrigation schedule and ET deficit. The interpretation of soil moisture, tritium and modeling are also affected by the uncertainty.

Flow Rate per Head: Based on robust uniformity tests (~89% CU), the Ein-dor 861-120 was used with a pressure regulator (Model 500-20) and anti-drip device (Model 530-h) on a rectangular spacing of 16.4 x 16.4 ft (5 x 5 m), and a minimum riser height of 24 inches. Under these conditions, the system will apply approximately 0.52 gpm per head or 4.8 mm per hour. When the original mini-sprinkler heads were selected and tested, the flow rate per head was compared with the mean depth in catch cans placed throughout the test stand. The measured depth was within 1-2% of the theoretical application rate under most test conditions. The flow rate per head times the operating time, times the number of mini-sprinkler heads per plot is used as an alternative method for determining total flow and the depth of application. It is the primary method for the operators to track the SWD and for the water balance model calibration and validation.

Table D1. Number of Mini-sprinkler Heads by Plot for CY2001.

PLOT NUMBER	***NUMBER OF HEADS***	***FLOW RATE PER HEAD***	***ESTIMATED FLOW RATE PER PLOT***	***AREA***
		GPM	GPM per PLOT	ACRES
1	150	0.52	78.0	0.93
2	68	0.52	35.4	0.42
3	97	0.52	50.4	0.60
4	109	0.52	56.7	0.67
5	93	0.52	48.4	0.57
6	112	0.52	58.2	0.69
7	112	0.52	58.2	0.69
8	112	0.52	58.2	0.69
9	82	0.52	42.6	0.51
10	107	0.52	55.6	0.66
11	166	0.52	86.3	1.02
12	140	0.52	72.8	0.86
13	138	0.52	71.8	0.85
14	168	0.52	87.4	1.04
15	83	0.52	43.2	0.51
16	76	0.52	39.5	0.47
17	94	0.52	48.9	0.58
18	112	0.52	58.2	0.69
19	130	0.52	67.6	0.80
20	100	0.52	52.0	0.62
21	92	0.52	47.8	0.57
22	138	0.52	71.8	0.85
23	146	0.52	75.9	0.90
24	102	0.52	53.0	0.63
25	149	0.52	77.5	0.92
26	143	0.52	74.4	0.88
27	96	0.52	49.9	0.59
28	78	0.52	40.6	0.48
29	80	0.52	41.6	0.49
30	104	0.52	54.1	0.64
Total # Heads=	3377			20.85

Because of the irregular topography and shape of the irrigation plots and the variability in the spacing between heads in the field, a decision was made to calculate the acres irrigated and the application depth (mm per day) per plot based upon an ideal spacing (16.4 x 16.4 feet). The latter results in 162 heads per acre. Table D1 provides a list of heads and associated area for each plot during CY2001. Since in many cases the head spacing is wider than the ideal, except in the area around the monitoring clusters, the area irrigated based on the number of heads is probably less than the actual area.

Irrigation Water Applied

Total and Monthly Irrigation: Figure D1 shows the cumulative total irrigation applied for the year over the project area. At total of 14,407,080 gallons was applied using a combination of flow per head (April) and metered flow-rate (May-December). This number includes all water distributed to the plots whether applied uniformity through the sprinklers or as leaks in lines. Maximum irrigation occurred in May and August (2,700,882 gal), during periods of low rainfall and high cumulative ET deficit (Figure D2). A combination of low ET deficits, low pond levels and mechanical problems with the filtration system reduced substantially the applied irrigation in June and July (Table B3). The decline in irrigation during September to a minimum in December (953,300 gal) reflects the shift to the winter irrigation schedule. However, as a result of the drought, more water was applied during the fall than scheduled. There were fewer rainy days and additional water was applied in late October because the soil moisture devices indicated that the soil was drying well below field capacity following the shift to the winter irrigation schedule.

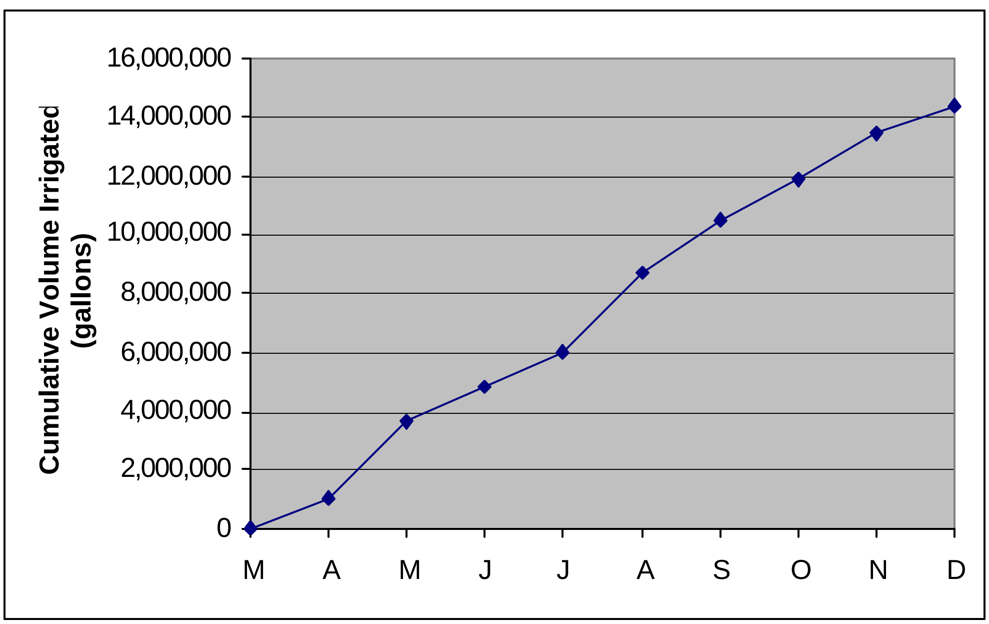


Figure D1. Cumulative Total Irrigation Applied to Project Area Based on Flow per head for April and Metered Flow for all other Months (End of Month Total).

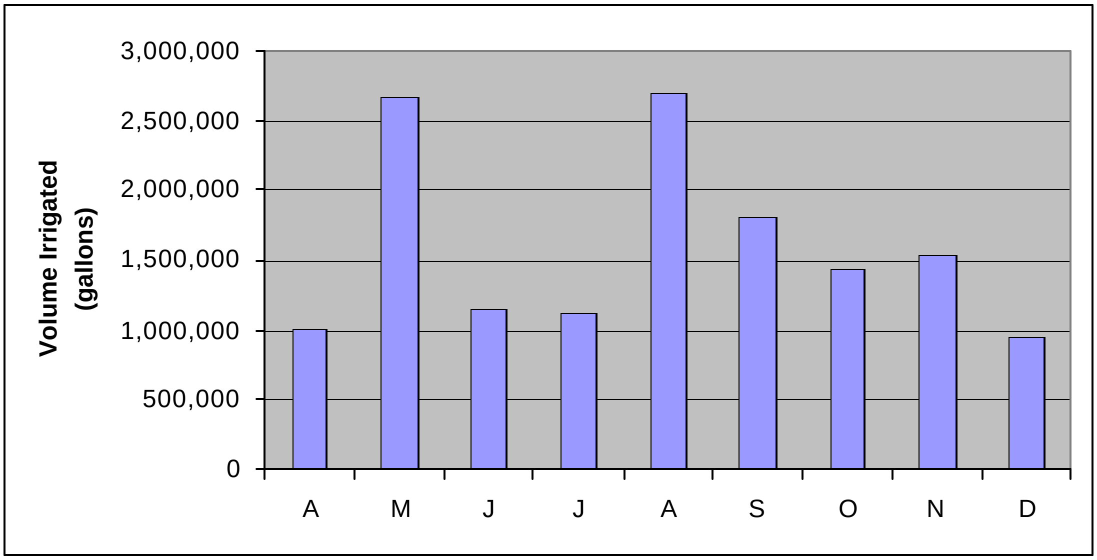


Figure D2. Total Irrigation Volume Applied by Month for All Plots.

Depth Applied by Method: The depth and distribution of irrigation water by month and by plot is shown in Table D2. Using metered total flow, the average depth of irrigation ranged from 43-45 mm in April and December to a high of 120-121 mm in May and August. These values correspond to an average daily rate of about 1.5-mm per day to 4-mm per day. The average total application across the project area of 20.9 acres (nominal) was 643 mm. Using flow per head, the average depth of irrigation ranged from 1.2 mm in December to 3.7 mm per day in August. The average total application over the project area was estimated at 583 mm.

When the amount of irrigation applied is compared with the alternative method, the total difference is about 9.8%. The variance is the largest in October (19.4%) and December (27.5%). Metered total flow gives volumes greater than that expected based on time of operation and the average flow per head. Based on operator comments the difference appears to occur largely when line breaks, popped heads, or animal damage is significant. In the latter case the irrigation water is not being distributed uniformly and can result in local areas of excess water leading to saturated-flow and tritium movement below the root zone. In addition, localize excesses of tritiated water can cause abnormally high readings of tritium at depth whether taken by soil cores, soil vapor tubes or lysimeters.

The total unadjusted ET deficit is 620 mm (Table B3) for the same period. The adjusted ET deficit based on a crop factor of 0.9 is 558 mm. The planned irrigation schedule was regulated for the operators by the alternative method, and appears to have successfully matched the ET deficit for the period. In contrast, the metered flow is substantially greater than the ET deficit. Because the distribution is non-uniform, it is difficult to interpret the impact on the over all water balance for the project area.

Table D2. Irrigation Depth for CY2001 by Month and by Plot.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total[1]	Total[2]
1	54	131	65	54	124	90	69	66	41	694	641.3
2	52	123	63	52	128	92	66	76	42	695	646.6
3	51	113	59	46	114	82	61	74	33	633	644.8
4	34	135	16	48	105	69	69	39	74	590	509.7
5	49	128	60	51	128	92	69	84	37	697	637.4
6	55	128	65	55	135	99	69	79	42	727	644.7
7	55	139	69	59	134	78	74	89	31	728	656.9
8	48	119	58	54	129	87	71	75	41	681	644.4
9	49	128	58	52	127	91	66	81	39	691	649.2
10	50	129	58	53	128	89	70	77	39	693	643.2
11	51	124	59	56	130	77	68	85	39	689	618.7
12	49	122	58	58	130	92	70	84	42	705	641.0
13	32	142	47	47	126	61	74	75	66	668	552.0
14	51	121	57	55	140	94	75	77	34	702	631.4
15	54	122	54	58	130	93	66	76	43	696	637.1
16	34	143	48	73	126	61	74	75	66	699	557.1
17	51	129	57	51	140	88	70	80	39	705	649.3
18	50	124	59	49	128	93	65	76	42	686	631.4
19	34	135	18	47	109	69	70	39	74	593	505.2
20	0	0	0	52	3	11	0	0	79	146	114.0
21	0	0	0	1	102	0	0	0	0	103	48.2
22	56	123	52	44	109	74	65	50	38	611	556.4
23	44	130	61	56	130	96	69	77	28	692	651.0
24	52	123	58	48	124	92	69	83	44	694	640.2
25	48	123	59	48	131	85	64	74	41	671	643.2
26	38	126	57	45	122	96	66	77	32	659	643.9
27	55	126	57	49	97	79	71	58	35	626	552.0
28	51	128	57	50	128	100	71	80	43	709	635.0
29	51	129	56	54	131	100	71	79	43	714	634.4
30	53	116	58	53	128	91	69	81	42	691	637.1
Ave[1]	45	120	52	51	121	81	65	69	43	643	
Ave[2]	44.3	109.8	48.6	46.4	111.8	74.3	53.3	62.1	32.6		583.2
Dev. (%)	1.6	8.9	6.8	9.5	7.9	8.6	19.4	10.5	27.5		9.8
Gal x 1000[1]	1,008.2	3,677.1	4,831.8	5,960.3	8,661.2	10,466.4	11,914.1	13,453.8	14,407.1	14,407.1	13,007.9[2]

1.Values based on metered total flow.
2.Values based on flow per head

Irrigation Water Applied by Deficit Schedule

Irrigation scheduling is the single most important variable which can be controlled on a daily basis, and which has the greatest potential impact to both the efficiency of tritium transfer between the soil and the atmosphere. Irrigation scheduling also has a major impact on operations of the system in terms of hours and days of operation. One alternative method for regulating the irrigation schedule is the amount of soil water or ET deficit, defined as cumulative ET-precipitation during the period, which is allowed to accumulate prior to irrigation. For example, during May the average daily ET may be 4-mm per day. Operationally over a six-day period, one can apply irrigation daily to just balance the ET, or allow it to accumulate for two days and apply 8-mm every two days, or allow it to accumulate for three days and apply irrigation twice at 12-mm. In all scenarios, the same total amount of irrigation, 24-mm, is applied. The outcome in terms of efficiency and vegetation health is expected to be different. Based on model simulations by Cornell University, irrigation triggered by moderate deficits were expected to be more efficient than low ET deficits. Three schedules were utilized during CY2001: 6-mm (Plots 22 and 27), 12-mm (Plots 13 and 16), and 18-mm (Plots 4 and 19) where irrigation was expected to take place 4-6 days (6-mm), 2-3 days (12-mm), and 1-2 days per week (18-mm) depending upon weather. All remaining plots were irrigated based on a 6-mm estimated water deficit schedule. Plots 22 and 27 were expected to track the operational plots. Plots 20 and 21 were irrigated separately under a joint project conducted by Clark-Atlanta University and the Savannah River Ecology Lab.

Volume and Depth: Table D3 shows the irrigation equivalent depth based on total metered flow and flow per head for the instrumented plots. Depending upon the method utilized, the application rate varies. Using the flow per head, the 18-mm plots received about 8% less total water over the season than the 6-mm or 12-mm. Using metered flow, the 6-mm and the 18-mm are similar, but the 12-mm clearly received about 10% more water. The flow per head was used in the Cornell University 1-D modeling to calibrate the parameters for the estimation of water uptake, whereas the metered flow was used for calculating tritium efficiencies in terms of total curies applied (see Tritium Measurements).

Table D3. Volume and Equivalent Depth Based on Metered Flow and Flow per Head.

Plot	***Area***	***Metered Flow Volume***	***Equivalent Depth of Irrigation***	***Flow per Head Volume***	***Equivalent Depth of Irrigation***
	acres	gallons	mm	gallons	mm
27	0.59	394,929	626	348,380	552
22	0.85	555,243	611	505,540	556
13	0.85	607,195	668	501,903	552
16	0.47	351,594	699	280,037	557
19	0.80	507,641	593	432,159	505
4	0.67	422,769	590	365,517	510

Summer vs. Fall: If the equivalent application depths are compared between September and December by method, the equivalent depth varies insignificantly (201-209) mm, using flow per head. For metered flow the equivalent rates are 234 mm (6-mm), 274 mm (12-mm) and 251 (18-mm). These seasonal differences, as well as other factors, may be important in interpreting whether scheduling had a real effect on water uptake and tritium efficiencies.

E. Vegetation Measurements, Leaf Area and Leaf Fall Analysis

Purpose: Vegetation measurements during CY2001 were collected to give a baseline estimate of the species composition, size and stocking level on each plot and across the irrigated area. Changes in growth (diameter cores) and mortality over 3 to 5 years will give an indication of the general health of the trees in relation to irrigation treatment. Additionally, baseline data can be related to water uptake and tritium ET efficiencies and provide a method to adjust water balance model parameters. The procedures used in the vegetation survey are given in WSRC-RP-2001-4245 Rev. 0.

Leaf fall data are collected to provide annual estimates of maximum leaf area index (LAI) in addition to those provided by the direct method of light interception via the ceptometer. The calculated leaf area index is incorporated into the Penman-Monteith calculation to determine actual ET. LAI measurements obtained by the ceptometer (CLM) give direct estimates of standing leaf area for seasonal adjustments to ET, such as during the winter when soil moisture deficits are too small to estimate actual ET, and they also measure the variation among plots needed to adjust parameters in the 1-D model. Leaf fall data provides information on the actual transition period between summer and winter transpiration. Leaf fall data also establish the optimal time for light interception measurement. Finally, the actual pattern of leaf fall can be a sensitive method for comparison of irrigation schedules. Both under watering (drought) or over watering can result in excessive leaf fall.

Instrumentation and Performance

Leaf Fall Collectors: The leaf fall collectors (LFCs) consist of a simple laundry basket at each cluster. Leaf material that falls into the basket is collected each month, separated into hardwood and pine, and then died and weighed. The procedure, WSRC-RP-2001-4221 Rev. 0, describes the equipment, maintenance and collection methods for the LFCs. During CY2001, the LFCs functioned as designed. Holes were drilled in the bottom to improve drainage, and mesh screen was inserted to lift the litter off the bottom to facilitate drying. No operational problems were found with the devices. However, in some clusters non-leaf material (acorns, catkins, and other debris) was dried and weighed with the leaf material, rather than being removed. This error may have resulted in over estimates of leaf fall and LAI. Samples in which extraneous material was identified in the comment line were removed from the analysis. It takes approximately ½ day per month, to collect, dry and weigh the material.

Ceptometer: The ceptometer measures the interception of photosynthetically active radiation (PAR) by the vegetation. The device is manufactured by Decagon Devices, Inc., Pullman, WA and is an AccuPAR Linear PAR/LAI ceptometer (Serial Number A/P 1545). During CY2001, no measurements of light interception were made. Measurements were made in February, March and June of 2002. The procedure, WSRC-RP-2001-4242 Rev 0., describes the equipment, maintenance and collection methods for the CLM. No problems with the equipment were observed during the CY2002 period. However, the procedure was found to have an instruction missing to include a measurement of diffuse radiation, which has been corrected. Cornell University used a standard procedure to estimate diffuse and direct radiation in order to calculate LAI. It takes approximately ½ day to complete a complete set of measurements each period.

Vegetation Characterization

Basal Area Variation: The average species composition, and stocking (basal area or BA) on each plot is shown in Table E1 for the dominant species. The total BA falls within the normal range for typical upland pine and mixed hardwood stands at SRS. The control or reference stands have considerably less BA. The mixed hardwood (C1), the stocking is less than the irrigated plots and may influence comparisons in water use. Although an effort was made to visually select representative stands for monitoring and irrigation scheduling was randomly assigned, it is clear that vegetation differences exist. The average BA for the irrigation schedules ranks 6-mm > 12-mm >18-mm.

Species Composition: The 18-mm has a larger relative component of laurel oak and slash pine then the 6-mm plots and a small proportion of loblolly pine. The 12-mm plots fall in between the latter. The reduced BA in the 18-mm and 12-mm would be expected to reduce LAI and water uptake, however water use and tritium uptake may also be affected by the species composition. In particular, the larger component of laurel oak and slash pine may influence leaf retention and root distributions.

Table E1. Average Species Composition, Basal Area and Percent Stocking on Each of the Monitoring Clusters in October 2001.

			Species Composition (% of Total BA)				
Irrigation		**Basal Area**	**Loblolly Pine**	**Slash Pine**	**Laurel Oak**	**Sweetgum**	**Water Oak**
Schedule	**Plot #**	**ft^2/ac**	**%**	**%**	**%**	**%**	**%**
18-mm	4	120.6	31	6	52	10	6
	19	149.6	22	39	34	2	1
12-mm	13	127.6	44	0	36	15	0
	16	156.5	33	44	21	1	0
6-mm	22	186.2	81	3	6	8	1
	27	176.7	77	2	7	8	2
Control	C-1	74.2	28	7	42	0	22
Control	C-2[1]	0.8	0	0	0	38	0
Control	C-3	40.9	94	0	0	0	6
Control	C-4	53.5	93	0	0	6	0

1. Black cherry comprises 62% of the clear-cut site. Planted loblolly pine seedlings were too small to measure in 2001.

Leaf Fall Analysis

Seasonal Patterns: Leaf fall data was analyzed from July 2001 through April 2002 to provide as close to a full season of data as possible. Published specific leaf areas (SLA), or leaf area per unit weight were used to convert dry weights to leaf areas. For pine, the SLA used was 0.0115 $m^2\ g^{-1}$ (Jokela & Martin, 2002). The plots include a variety of hardwood species each with different SLA. Data from vegetation survey of stem basal area at the project site gave an estimate the proportion of hardwood at each instrument cluster. Predominate hardwoods were laurel oak and sweetgum with small amounts of water oak. No other hardwood species comprised more than one percent of the basal area at any instrument cluster. Laurel and water oak have similar SLA (0.0101 $m^2\ g^{-1}$), which is distinct from sweetgum (0.0075 $m^2\ g^{-1}$). To calculate hardwood leaf area, the proportion of hardwood basal area comprised of laurel and water oak on each plot was multiplied by the hardwood leaf litter dry weight value, and then in turn by the laurel-water oak SLA. The remaining proportion was multiplied by the sweetgum SLA. The sum of the two values estimated total hardwood leaf area. LAI was calculated by dividing the amount of leaf area collected in each basket by the area of the basket opening.

Leaf fall showed expected seasonal patterns (Figure E1). The seasonal peak occurred in mid-November for both species groups. This is consistent with published information for pine and for hardwood species (Per. Commu. M. Burke, USFS Center for Forest Wetlands). The leaf fall pattern for the control clusters was similar to irrigated clusters indicating that irrigation in general has no obvious influence of the timing of leaf fall during transition from summer to winter (Table E2).

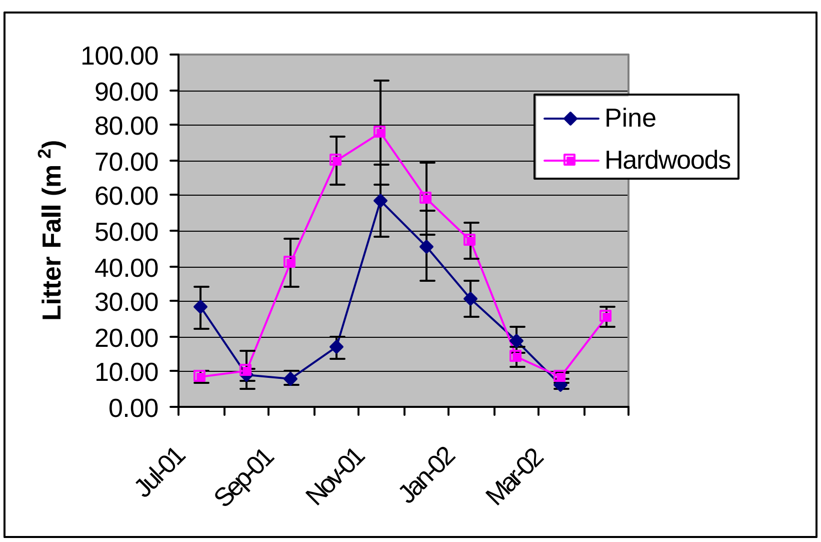


Figure E1. Seasonal Patterns for Pine and Hardwood Leaf Fall on 18 Irrigated Clusters Between July 2001 and April 2002.

It is notable that the pines, as well as the two oak species, retain a large portion of their foliage through December. The relationship is also reflected in the soil moisture data (see Soil Moisture), and suggests that transpiration rates may continue at fairly significant levels through the fall enabling summer irrigation schedules to be extended. . The peak in pine needle fall in July on the control sites is typical during summer drought period in natural stands.

Table E2. Monthly Changes in Pine and Hardwood (Hdwd) Leaf Fall Dry Weight (grams per m^2) for Irrigated and Control Clusters Between July 2001 and March 2002. For non-irrigated plot values the clear-cut cluster (20) was excluded.

Clusters	Group	7/13 2001	8/6 2001	9/14 2001	10/16 2001	11/16 2001	12/5 2001	1/17 2002	2/9 2002	3/11 2002
Controls	Pine	26.1	8.0	8.3	20.9	51.3	35.5	16.4	14.4	2.5
Irrigated	Pine	28.0	10.0	8.9	17.5	58.1	46.5	30.5	18.0	6.0
Controls	Hdwd	5.1	5.2	40.0	75.6	103.9	-----	49.6	18.7	8.2
Irrigated	Hdwd	9.0	10.5	41.0	70.0	78.5	59.5	47.0	13.0	9.0

Leaf Area Estimates: The average annual leaf fall collected over several years provides an estimate of the maximum stand LAI, since some leaf fall is occurring even during the spring and summer. The calculation is based upon the assumption that there is 100% turnover in the foliage during the year. Most hardwoods loose new leaves yearly, but pines and laurel oak generally retain new foliage for 1.5 to 2.0 years. As a consequence the initial estimates of maximum LAI will be underestimated for these stands. For the nine-month period, the calculated average pine LAI on irrigated clusters is 2.6 (m^2 m^{-2}), and is lower than hardwood LAI of 2.9 relative to the percentage of pine basal area on the plots, which averages 62% and ranges to above 80%. The total leaf fall (g m^{-1}) for the nine month period was positively related to the average BA on the irrigated plots (Table E1, Figure E3). For the control stands, the pine LAI ranges from 3.4 on the mixed pine hardwood stand (C1), and 1.63 (C4) on the young pine stand to 1.34 on the older thinned pine stand (C3). The equivalent hardwood range is 3.6 (C1), 3.3 (C4) and 2.9 (C3).

Ceptometer LAI: The total LAI estimates using the ceptometer are given in Table E3 for three measurement dates in FY2002. While the LAI is lower during the winter period, it is still fairly high, reflecting the predominance of pine and laurel oak as well as the influence of bare stems and branches that also intercept light. The LAI for June 2002 is indicative of the full canopy conditions. The values range from a low of 3.85 to 4.93 on the irrigated plots. This contrasts with slightly lower LAIs (2.87 and 3.90) on the two control stands with closed canopies (C1-19 and C4-22). Ceptometer LAI in March and June of 2002 generally follow the BA for the various plots. The differences in stocking and species composition probably account for the observed variation in ceptometer LAI, rather than treatment effects of irrigation.

The LAI values in general are typical of natural stands with no additional nutrients, but low compared to more intensively managed stands, which range from 6 to over 10 m^2 m^{-2}

up to (Jokela and Martin 2000). These data suggest there is potential to increase the leaf area, and potentially water use and tritium transfer to the air, by intensifying management activities such as fertilization and competition control.

Table E3. LAI (m^2 m^{-2}) Estimated from Light Interception Using the Ceptometer in February, March and June of 2002. Source: Susan Riha, Cornell University.

	Irrigation	***Date of Measurement***		
Plot	Schedule	2/25/2002	3/6/2002	6/11/2002
4	18 mm	1.81	2.93	4.39
19		3.45	3.89	4.86
13	12 mm	3.15	3.12	4.93
16		3.71	3.31	4.72
22	6 mm	3.71	3.31	4.72
27		2.42	2.21	4.84
C1	Control	3.11	3.02	2.87
C2	Control	0.04	0.13	1.06
C3	Control	0.26	1.01	1.06
C4	Control	------	3.01	3.90

Comparison of Irrigation Schedules: The peak leaf fall (Figure E2) and total leaf fall (Figure E3) for the 6-mm irrigation schedule is greater over the period of measurement than for the other schedules. The peak leaf fall and the total leaf fall for pines under the 12-mm schedule is also slightly greater than for the 18-mm schedule. Because of the confounding effects of initial stocking (BA), species composition, and total applied irrigation water (see Irrigation Measurements) it difficult to infer whether the total leaf fall or the peak magnitude is a result of the irrigation schedule. The total leaf fall (Figure E3) is related to the overall average stand BA (Table E1). The magnitude of the peak leaf fall in November for the pine is also directly related to the total BA of pine in each schedule (percent pine BA times total BA), suggesting that initial differences in BA and species composition account for the observed variation. The July peak in pine litter fall on the 6-mm irrigation schedule may have resulted from the shut down of the irrigation system (low pond level), which may have induced some pine leaf fall in the loblolly pines.

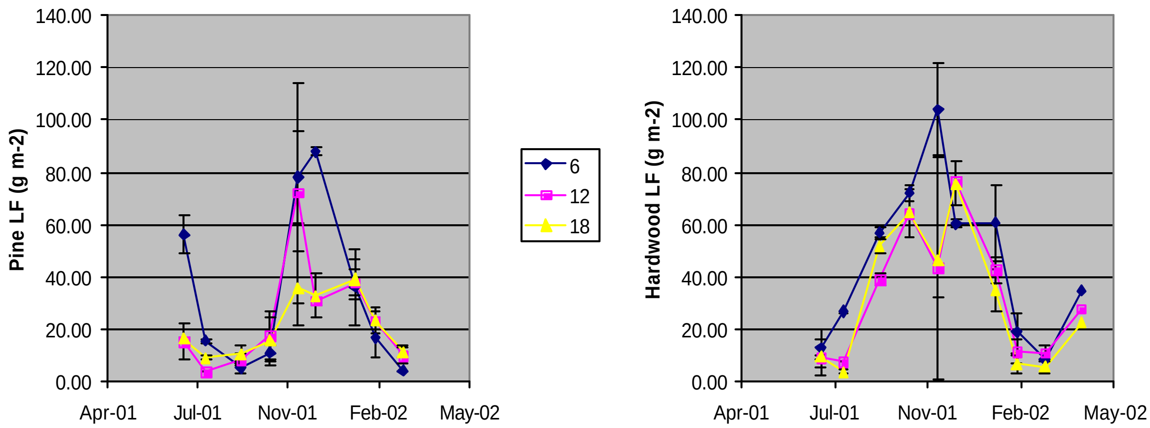


Figure E2. Seasonal Leaf Fall Patterns for Each of the Irrigation Schedules.

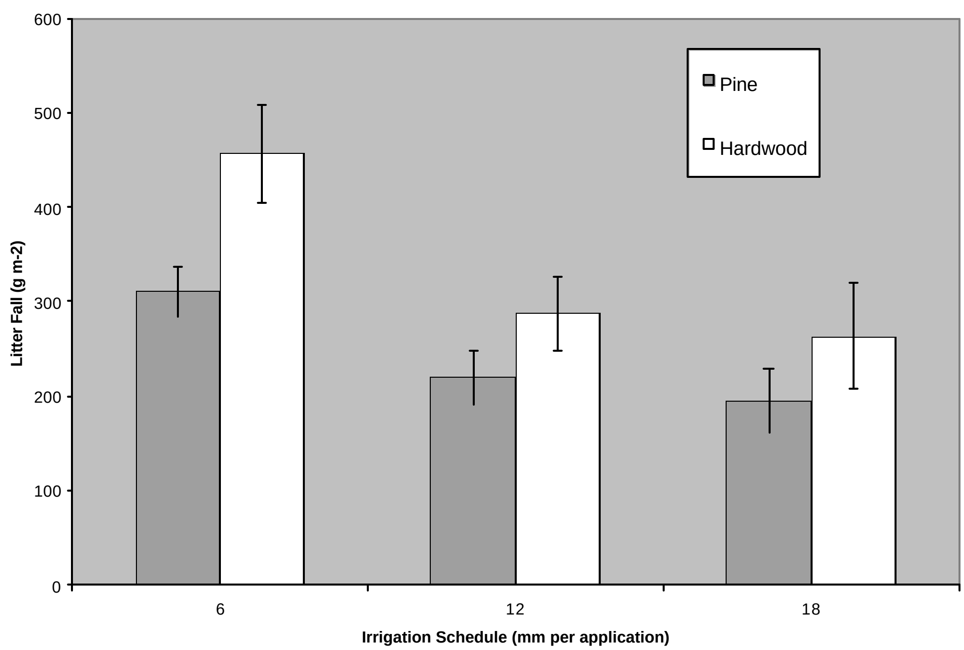


Figure E3. Cumulative Total Leaf Fall from July 2001 to April 2002 for Each of the Irrigation Schedules.

F. Canopy Interception of Rainfall

Purpose: Interception of rain by forest vegetation can have a major impact on the water balance. It is not unusual for 10-20% of the annual rainfall to be intercepted by conifer canopies and evaporated directly (Rutter et al. 1975). Rainfall that is intercepted and evaporated directly into the atmosphere does not enter the soil. Therefore, soil moisture recharge and sub-surface flow is reduced. The latter is a major reason that conifers, like loblolly pine, have higher apparent ET rates and lower sub-surface discharge. In 2001, in the absence of interception data, a fixed value representing average canopy capacitance was selected. A capacitance value of 1.3 mm per 24-hr event was used during the growing season (April-October) and 0.8 mm per 24-hr event during the non-growing season (November-March) to adjust the water balance until actual interception equations were derived. These values estimate only the ability of the canopy to retain water, but do not include the interception and evaporation process.

Calculated Interception

As a Function of Rainfall: To develop an empirical interception equation, the relationship between the measured rainfall in the open SCRs (pond and sediment basin) were compared with the values obtained below the canopies in the irrigated and reference stands for each rain event. A simple polynomial regression was used to fit the values measured in the gauges below the canopies with the average in the open gauges. The data set was split to represent growing period (April-October, 23 events) when the forest canopy is at the maximum, and the non-growing period (November-March, 11 events) when the canopy is generally at the minimum leaf area (Table F1). Figure F1 represents the relationship between open rainfall and the average interception by the forest. In contrast to the fix value of 1.3 or 0.8 mm, measured interception is considerably larger and varies with storm size. As much as 5 mm was intercepted for larger storm events, which is similar to other observations in loblolly pine (Rogerson 1967). About 60% of smaller rain events (0.5-1 mm) to 8-10% of the larger events (50-60 mm) are intercepted and evaporated directly to the atmosphere.

Summer vs. Winter : Only a slight difference was observed between the interception equations developed for each period (Table F1). A significant percentage of the stands are pine and laurel oak that retained foliage through December. Branch and stem surfaces also contribute significantly to interception. The non-growing period equation shows slightly lower interception across the range of storms.

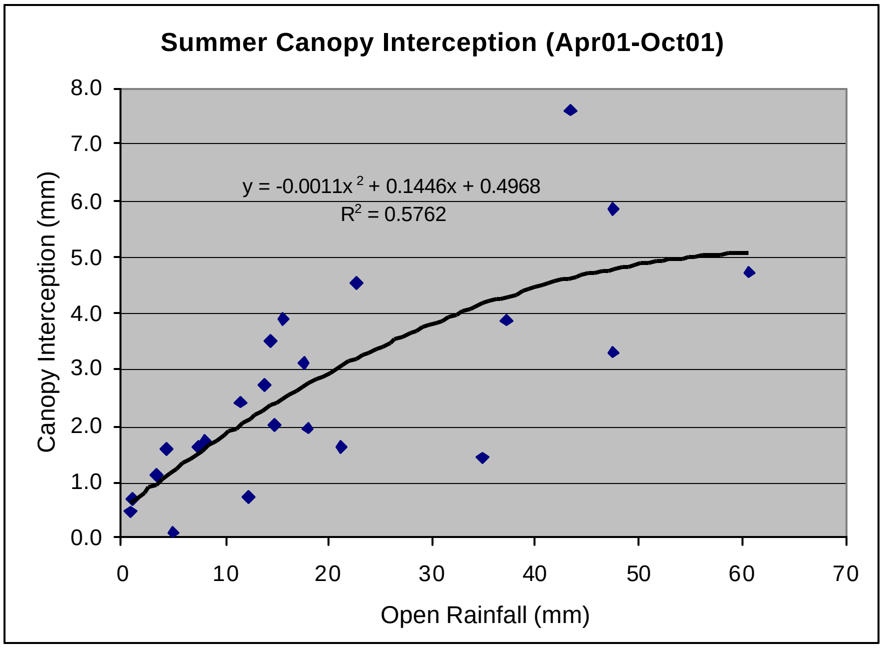


Figure F1. Growing Period Canopy Interception on Irrigated Clusters at MWMF.

Table F1. Calculated Rainfall Interception by the Forest Canopy at the MWMF Project Area. Equations based on 34 specific events comparing open SCRs at the PD and SB with SCRs located at the 18 irrigated clusters. Interception (x) fitted to rainfall (y) using 2nd order polynomial.

Summer (April-October) Interception = $-0.0011x^2 + 0.1446x + 0.4968$, $R^2 = 0.58$							
Rainfall Event (mm)	1	10	20	30	40	50	60
Interception (mm)	0.64	1.83	2.95	3.85	4.52	4.98	5.21
Intercepted (%)	64	18.3	14.7	12.8	11.3	9.9	8.7
Winter (October-March) Interception = $-0.0016x^2 + 0.1679x + 0.0776$, $R^2 = 0.92$							
Rainfall Event (mm)	1	10	20	30	40	50	60
Interception (mm)	0.24	1.60	2.79	3.67	4.23	4.47	4.39
Percent Intercepted	24	16.0	14.0	12.3	10.6	9.0	7.3

Variation Between Clusters: The variation in the percentage of rain intercepted between the six monitored plots ranged from 10.1 % to 16.4% (Table F2). There is no indication of plot related differences in average values. Overall variation in interception ranged from –3.8 % (Cluster 16) to +33.7% (Cluster 5). This range in interception is typical of tree crops and it can have major impact on soil water flux and chemical leaching potential (Alva et al. 2000). Analysis of the cluster variation in relation to vegetation conditions (pine vs. hardwood, basal area, etc) will be conducted in 2002.

Table F2. Percent of Rainfall Intercepted by Irrigated Monitoring Plots and Clusters. Average values derived from 34 rainfall events during 2001.

Plot	*(Cluster)*	*(Cluster)*	*(Cluster)*	Mean
04	(16)	(17)	(18)	
% Intercepted	**-3.8**	**6.3**	**27.8**	**10.1**
13	(1)	(2)	(3)	
% Intercepted	**17.3**	**14.4**	**7.1**	**12.9**
16	(10)	(11)	(12)	
% Intercepted	**27.1**	**9.2**	**-3.0**	**11.1**
19	(13)	(14)	(15)	
% Intercepted	**18.0**	**7.4**	**13.3**	**12.9**
22	(7)	(8)	(9)	
% Intercepted	**11.4**	**8.8**	**14.4**	**11.5**
27	(4)	(5)	(6)	
% Intercepted	**1.3**	**33.7**	**14.2**	**16.4**

G. Soil Moisture Measurements

Purpose: Monitoring soil water content in the irrigation plots is conducted to meet several objectives. The rate of soil water uptake provides a direct method for determining actual ET as a function of weather, soils and vegetation in order to calibrate the water balance model. The rate of water update by depth within the soil profile is used to estimate an effective root density through inverse modeling. The root density determines the uptake of tritium within the profile and the lower bound of tritium uptake. Monitoring soil water content at same time that sampling is conducted on soils, lysimeters or vapor tubes for tritium activity gives a method for converting soil water tritium activity to estimate the mass of tritium in the soil. Finally, soil moisture potential is monitored to give a sensitive and direct measure of the deviation of the irrigated plots from field capacity as a result of irrigation scheduling or rain. Excessive irrigation results in increased tritium flux below the root zone, and water logging or anaerobic conditions, while under irrigation may reduce the capability to manage the seep discharge to Fourmile.

Instrumentation and Performance

Vertical Time Domain Reflectometry: Vertical time domain reflectometry (TDR) is designed to measure the soil water content within the soil horizons occupied by the tree roots. TDR measurements were collected electronically using a Trime, Inc. sensor (T-3) and meter (FM). To relate measured water content to soil water potential, soil samples from each cluster were collected and analyzed for soil texture and particle size within the profile (Cornell University October 2001). Assuming the soil was in equilibrium with gravitational water potential, the water content at field capacity for each cluster was estimated by selecting the average water content at the selected measurement depth during March of 2001. The water release curve to wilting point was estimated from standard equations published for the soil texture and series. Measurement at 25-cm, 55-cm, 135-cm, 155-cm and at the base of the tube were made twice each week during CY2001. The procedure WSRC-RP-2001-4217 Rev. 0 describes the equipment, maintenance and collection methods for the TDR. It takes approximately ½ day to make one set of field measurements.

During CY2001, limited performance problems with the equipment were found. The TDR sensor (T-3) has a spring-loaded stainless steel plate that is forced against the inside of the tube to minimize air space. After a period of months, several tubes were observed to have large amount of friction that made it difficult to push the sensor easily to the correct depth and then to rotate the sensor 180 degrees to take a second reading. When the sensor was rotated, the resulting torque on the coaxial cable damaged the cable, requiring repair. A back-up instrument was purchased to minimize down time, and then the sensor was replaced.

During the initial few weeks, subsurface water seeped into the base of a few tubes, causing erroneously high water content readings. These tubes had the base plug removed and re-installed. While the duplicate measurements between tubes within a cluster at a selected depth were similar, on several occasions a value of zero was recorded in one of the two tubes. The latter may be the result of localized air pockets, but are more than likely electronic or sensor problems that should have been checked by re-measurement. Similar to other monitoring activities, corrections and modification to the procedures need to be made. The latter include the addition of a measurement at 100 cm to improve calculations of water uptake for model calibration. For CY2002, it was also proposed to track integrated TDR values over the rooting profile for each plot vs. the field capacity value (e.g. 300 mm) determined by Cornell University in order to monitor the actual changes SWD in real time.

Surface Time Domain Reflectometry: Surface time domain reflectometry (STR) is designed to measure the soil water content at the surface between 0 to15 cm that cannot be obtained by the TDR. STR measurements were collected electronically using a Trime, Inc. P-3 Probe and FM meter. The procedure, WSRC-RP-2001-4217 Rev 0 describes the equipment, maintenance and collection methods for the STR. The measurement is made by pushing the 15-cm probe into the soil its' full length. Four readings are collected at each cluster. Measurements are collected twice per week within a 2-m radius of each tensiometer instrument group. It takes approximately 2 hours to make one complete set of field measurements.

Several significant problems were observed in using the instrument. The operators had difficulty inserting the 15-cm probes into dry soil to their full length. In addition, they would occasionally use pre-established holes. Both effects cause the wave-guide to sense the water content (zero) in the air space around the probes, which results in low water content readings. The tips of the probes were also damaged twice as a result of the degree of force used to push them into the soil. The high variability in readings, coupled with the sensitivity of the data to operator experience, triggered a decision to drop the STR from the monitoring program and to estimate surface water content indirectly from the TDR and tensiometers.

Tensiometers: Tensiometers (TEN) were installed to monitor the soil water potential at 15-cm, 30-cm, and 45 cm below the soil surface. The principle of operation assumes that the TEN is at equilibrium with the soil water potential. Because the TEN is very sensitive to water content near field capacity (0 to –800 mbar), it provides a direct measure of over or under irrigation. TEN were constructed and installed by Cornell University, and data were collected electronically using a pressure sensor manufactured by Soil Measurement Systems, Tucson, AZ. Measurements were made twice per week. The procedure, WSRC-RP-2001-4218 Rev. 0, describes the equipment, maintenance and collection methods for the TEN. It takes approximately 2 hours to collect a set of observations.

Because of the simplicity of the device few major problems were experienced with the TEN. If the soil dries below the air entry point (~ -800 millibars) for the ceramic cup, the column of water will drain into the soil. The TEN were routinely refilled on monthly schedule or weekly if the soil was dry. Several TEN were replaced that may have had fractured ceramic cups. Minor problems occurred when the electronic pressure sensor contacted the water in the tube and when the sensor needle became plugged. A second sensor was purchased to provide a back-up. Procedures should be modified to ensure routine cleaning and maintenance of the electronic sensor at least annually. For CY2002, it was proposed to track average TEN values for each plot vs. the field capacity range established by Cornell (-40 to –100 millibars) to monitor irrigation directly in real time.

Piezometers: The piezometer (VZP) gives an estimate whether the soil pores are either saturated or at field capacity at the 2-m and 3-m sampling depth for tritium. In addition, monitoring of the VZP gives a measure of the depth, frequency, and position within the watershed of saturated soil conditions resulting from rain or over irrigation. The VZP consist of a 285-cm PVC pipe and a piece of slotted pipe at the base, which allows water to enter the tube. VZP measurements were collected electronically using a Solinst Model 101 - water level meter (10PMPIN). The procedure, WSRC-RP-2001-4219 Rev. 0, describes the equipment, maintenance and collection methods for the VZP. Observations were collected monthly at the time sampling was conducted for soil tritium. It takes approximately 1 to 2 hours to complete a set of measurements. Because of the simplicity of the device, no significant problems with the instrument were observed.

Soil Moisture Dynamics

Cornell University conducted a detailed analysis of the soil moisture patterns and a quantitative assessment to calibrate the water balance model in two reports (October 2001, and March 2002). This summary and analysis is intended to highlight the seasonal patterns, changes with soil depth, illustrate the sensitivity of the TDR and TEN instruments, and summarize the spatial variability.

Seasonal Patterns: The seasonal patterns in soil moisture dynamics can be best illustrated by comparing representative changes in TEN over the period (Figures G1, G2, G3) with the calculated SWD (Figure G4). For the TEN, three major periods of measurable SWD were detected. These correspond late-April to early May, mid-June to mid-August and mid-September through late November. These periods in general correspond to the periods in which the calculated SWD deficit was the highest (Figure G4). The magnitude of both the measured and calculated deficits are relatively small even during the highest SWD periods. The latter suggests that irrigation was able to maintain the soils near field capacity except in the fall when the irrigation was reduced in conjunction with the implementation of the reduced winter schedule. The data for the TEN also illustrate periods in which there is no measurable SWD (~ -40 mbars) or saturated conditions (~ 0 to –40 mbars). These conditions were observed in February through March, late May to early June, early September from rain and in late December as a result of over irrigation.

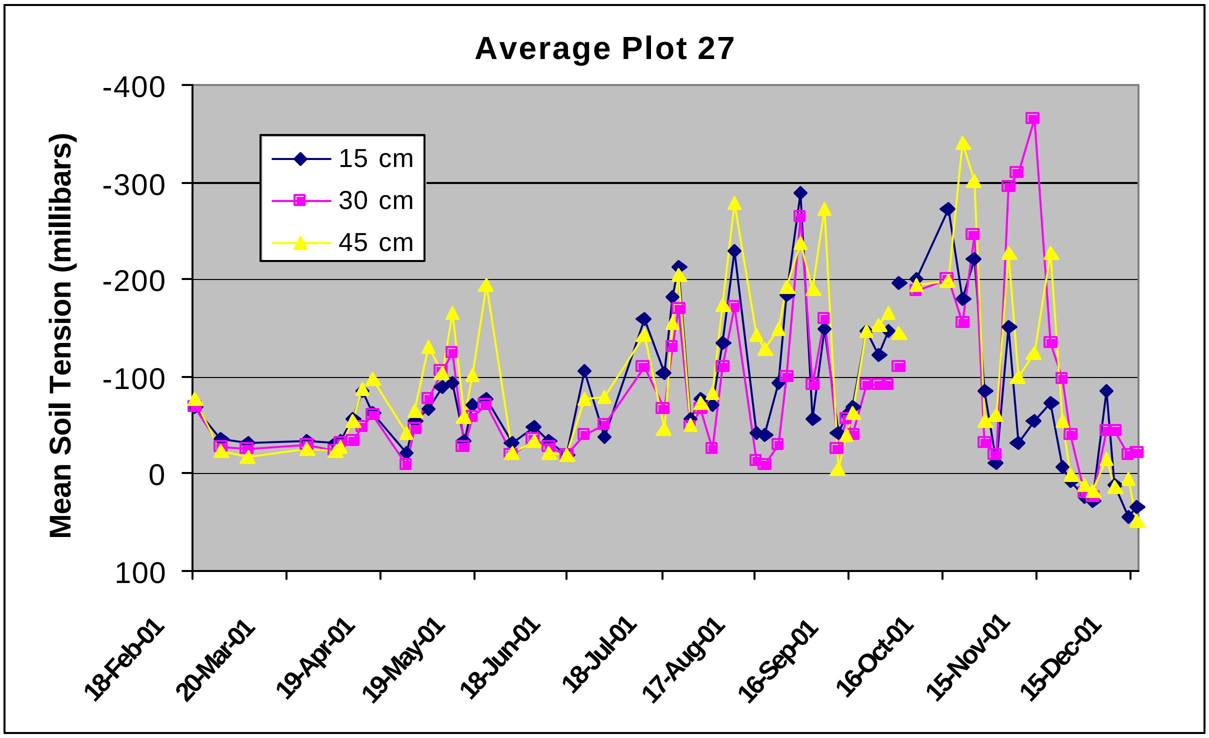


Figure G1. Average Tensiometer Reading (N=6) by Depth for Plot 27 (6-mm).

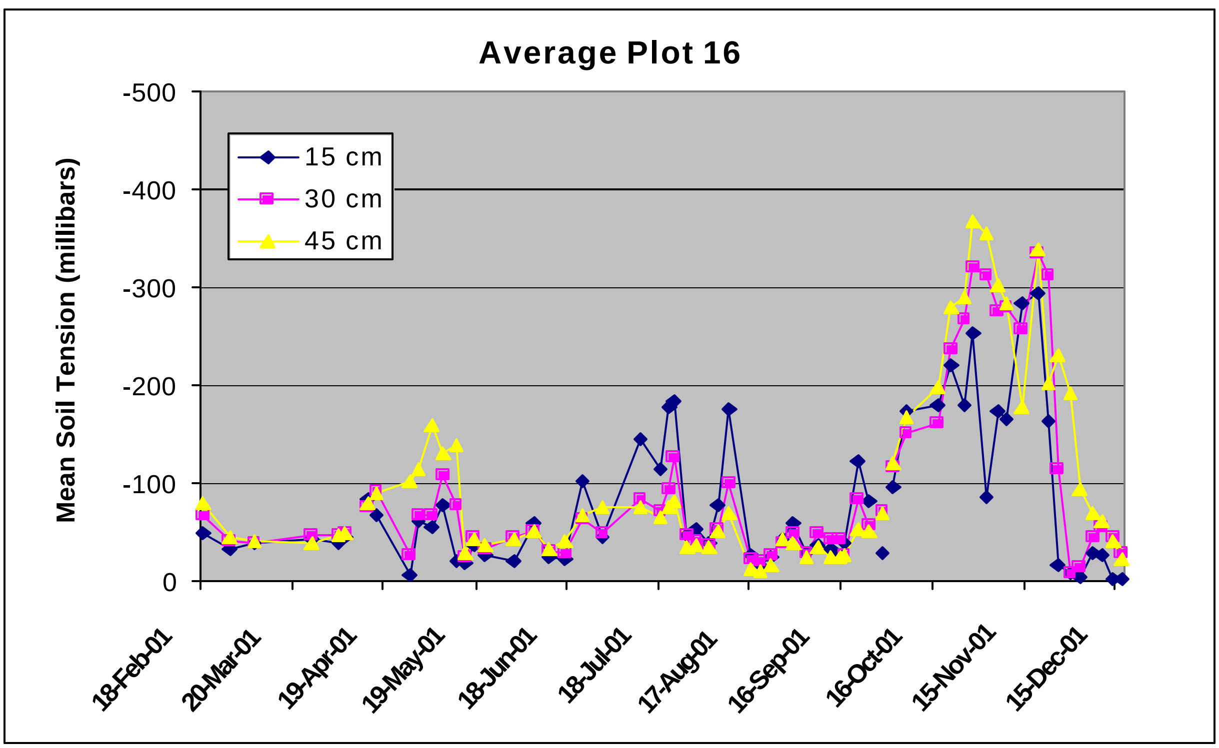


Figure G2. Average Tensiometer Reading (N=6) by Depth for Plot 16 (12-mm).

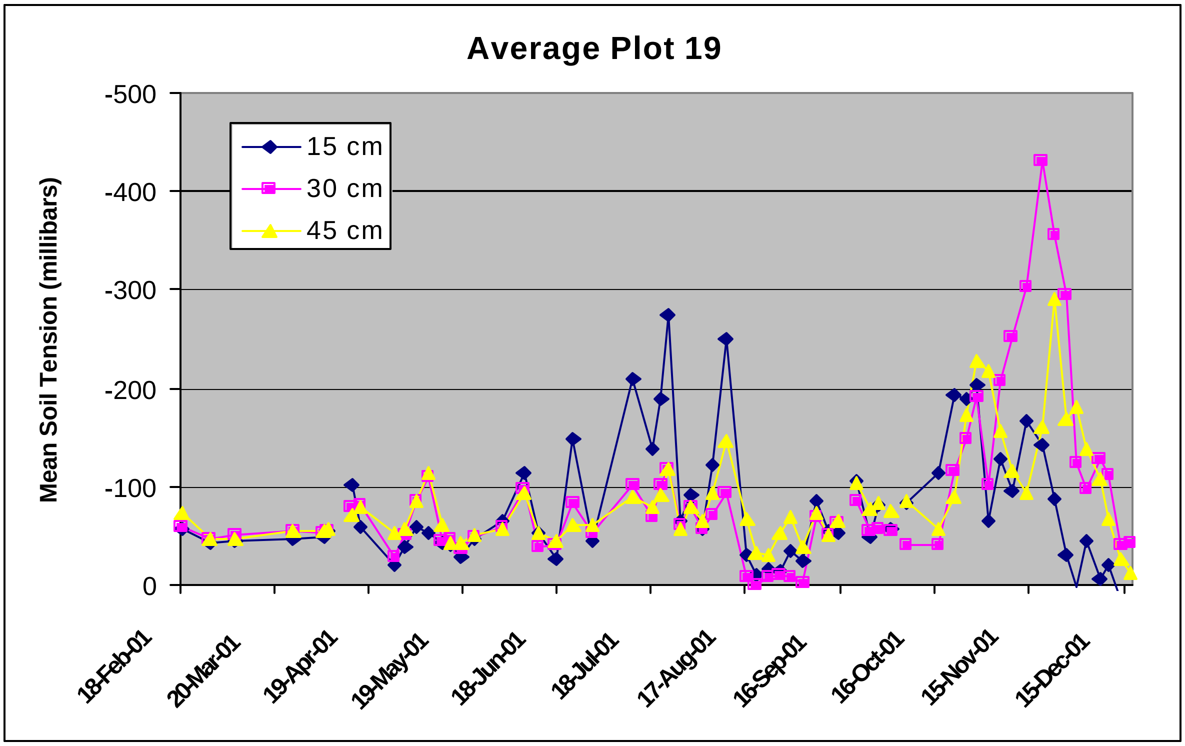


Figure G3. Average of Tensiometer Reading (N=6) by Depth for Plot 19 (18-mm).

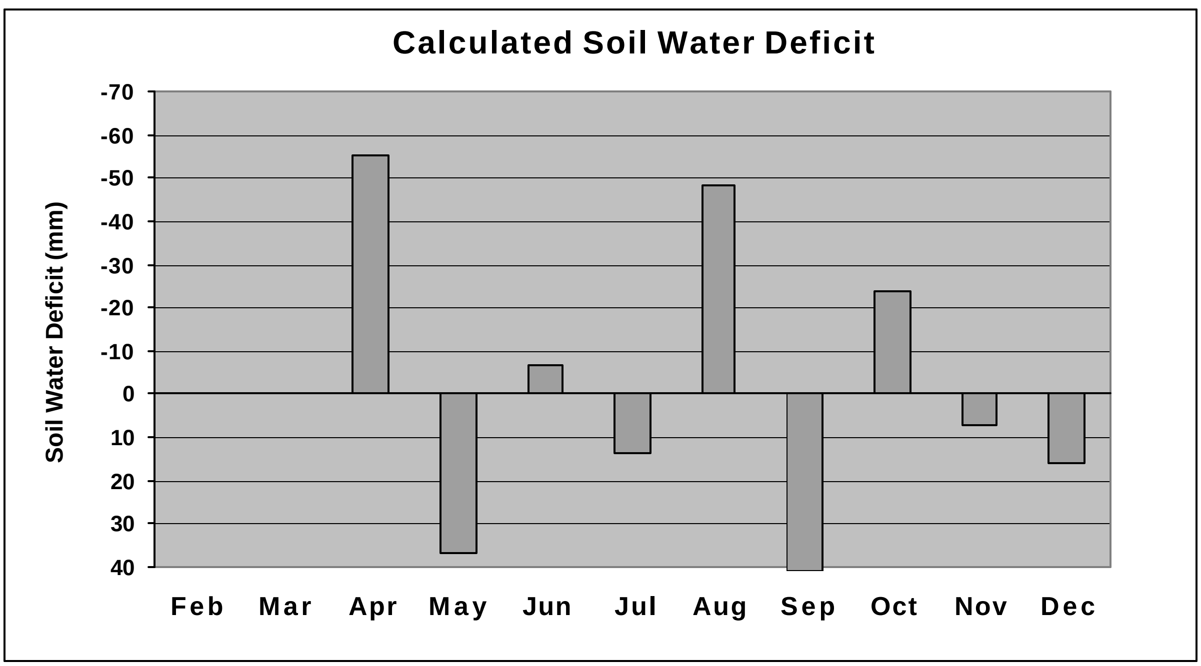


Figure G4. Calculated Average SWD for Six Irrigated Monitoring Plots. SWD = ET times 0.9 (crop factor) less rainfall and irrigation (flow per head x operating time).

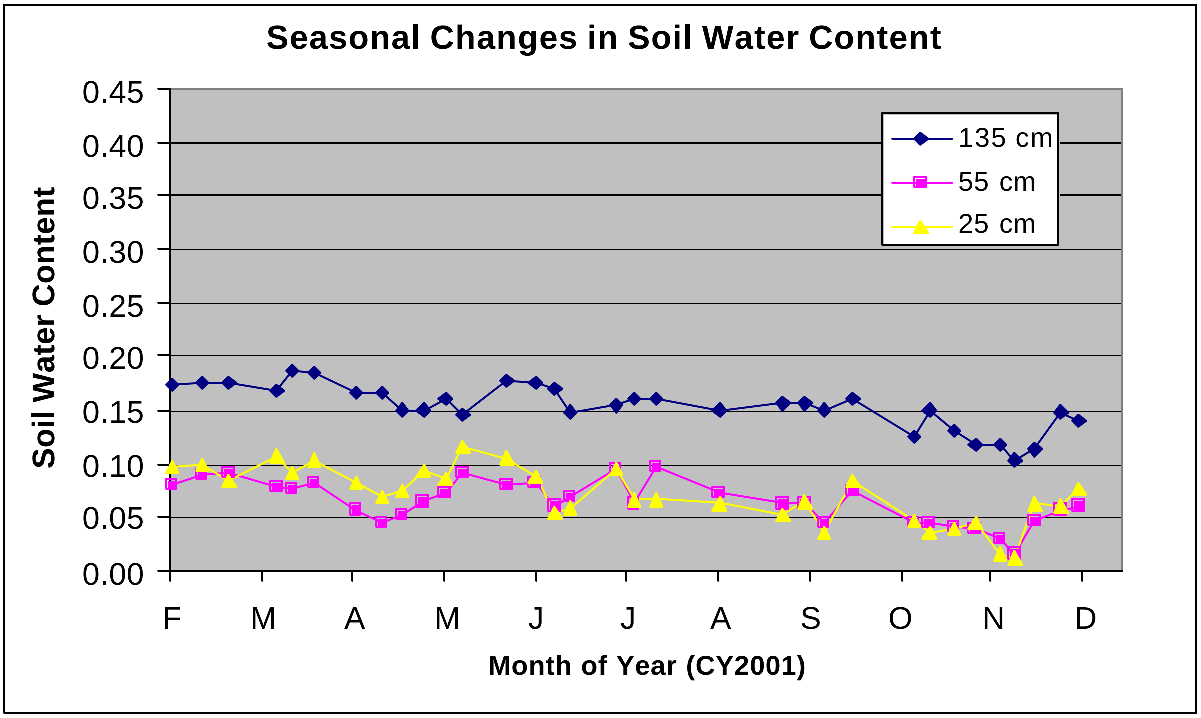


Figure G5. Average TDR Soil Water Content by Depth (N=6), Plot 19 (18-mm).

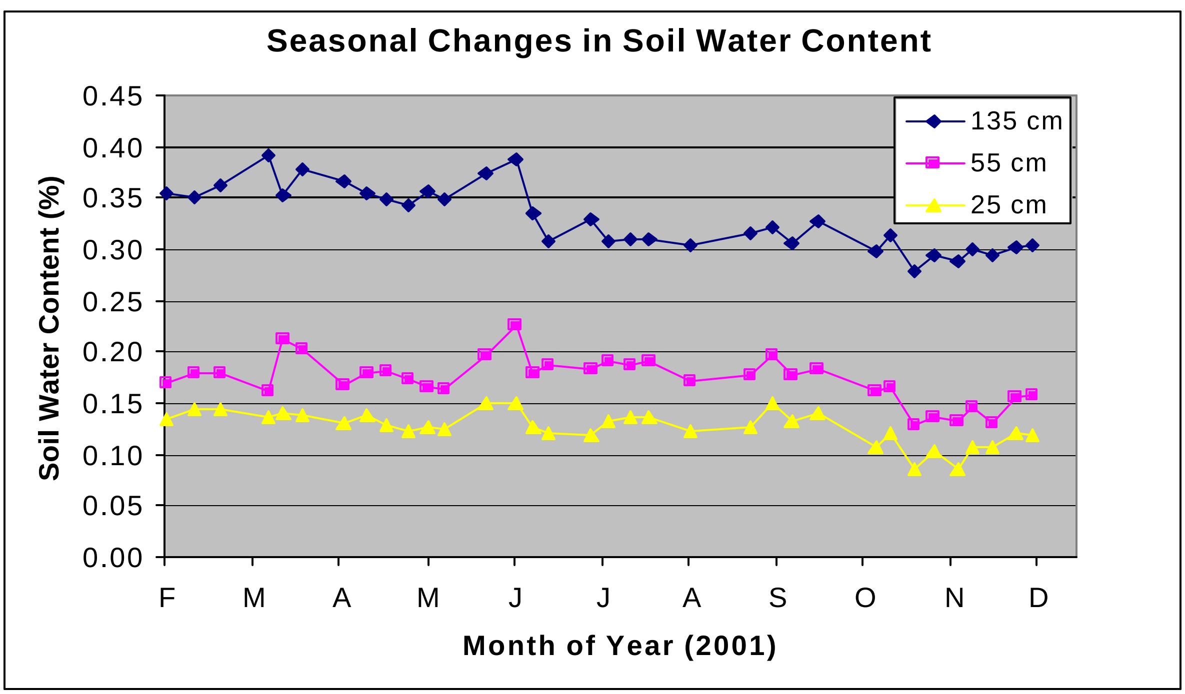


Figure G6. Average TDR Soil Water Content by Depth (N=6), Plot 22 (6-mm).

Comparable seasonal changes in the TDR values are illustrated in Figures G5, G6 and G7. It is more difficult to identify the deficit periods since larger reductions in soil water content are needed to detect the deficits and measurements must be integrated over the entire profile. The most obvious and consistent reduction in soil water is evident in October-November. The April-May reduction is also evident at all depths. The reduction is soil water content in June-July is represented by a sharp decline in water content at the 135-cm level indicating water uptake deeper in the soil profile on most plots.

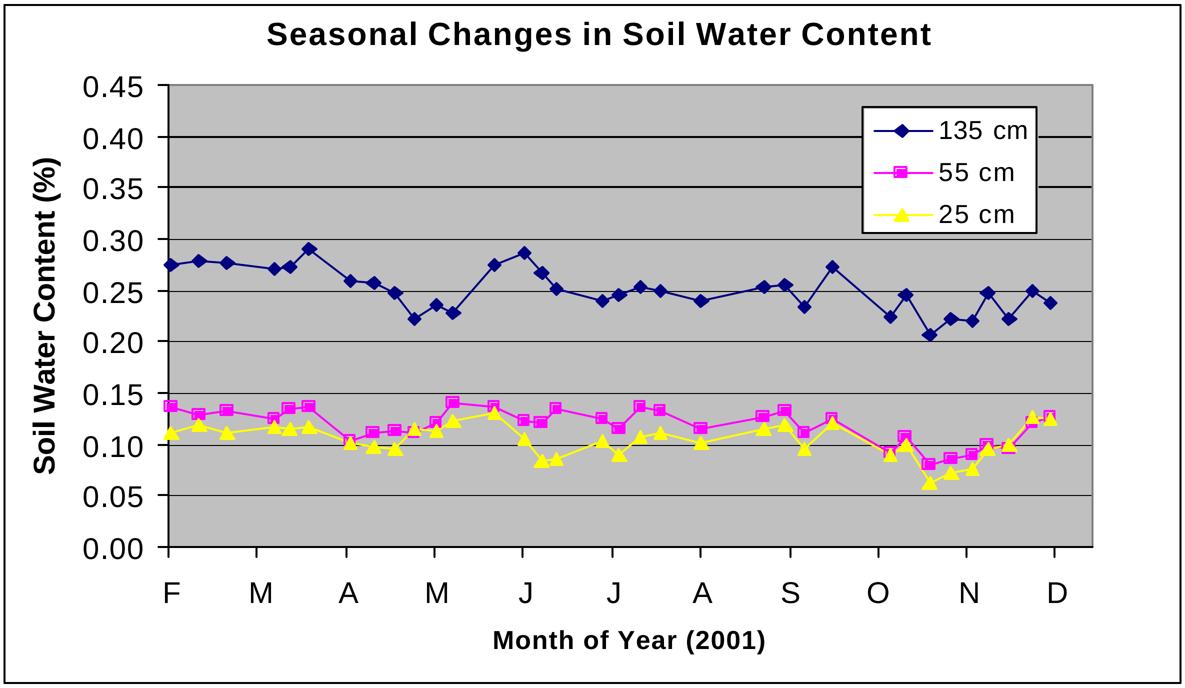


Figure G7. Average TDR Soil Water Content by Depth (N=6), Plot 16 (12-mm).

Soil Depth: TDR measured changes in soil water content within two representative clusters and for selected dates are illustrated in Figures G8 and G9. Assuming the March 7th date approximates field capacity for these clusters, a rapid reduction in soil water content in April is clear followed by re-wetting of the soil in May. The May pattern is followed by another reduction in June, and a re-wetting in July. Subsequent observations demonstrate the drought effects in October and the inability to match the water uptake with the planned winter irrigation schedule. Evidence that the profile is being re-wetted in December from irrigation and rain is indicated by the dramatic increase in water content. As a result of the large dynamics at the 1-meter level, it was recommended by Cornell University to add an addition TDR measure at 100-cm to more accurately determine actual water uptake. These Figures also demonstrate the effects associated with soil texture and potential root distribution. Cluster 12 has a clay content that is higher than cluster 15.

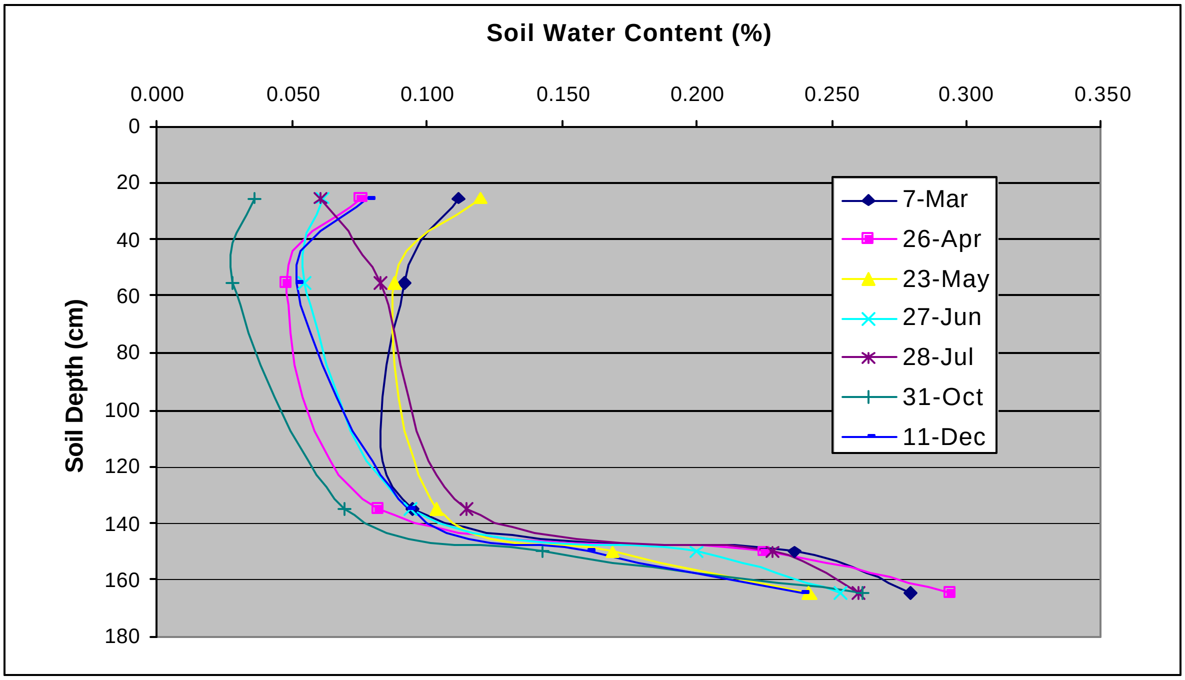


Figure G8. Changes in TDR Soil Water Content with Depth Plot 19, Cluster 15.

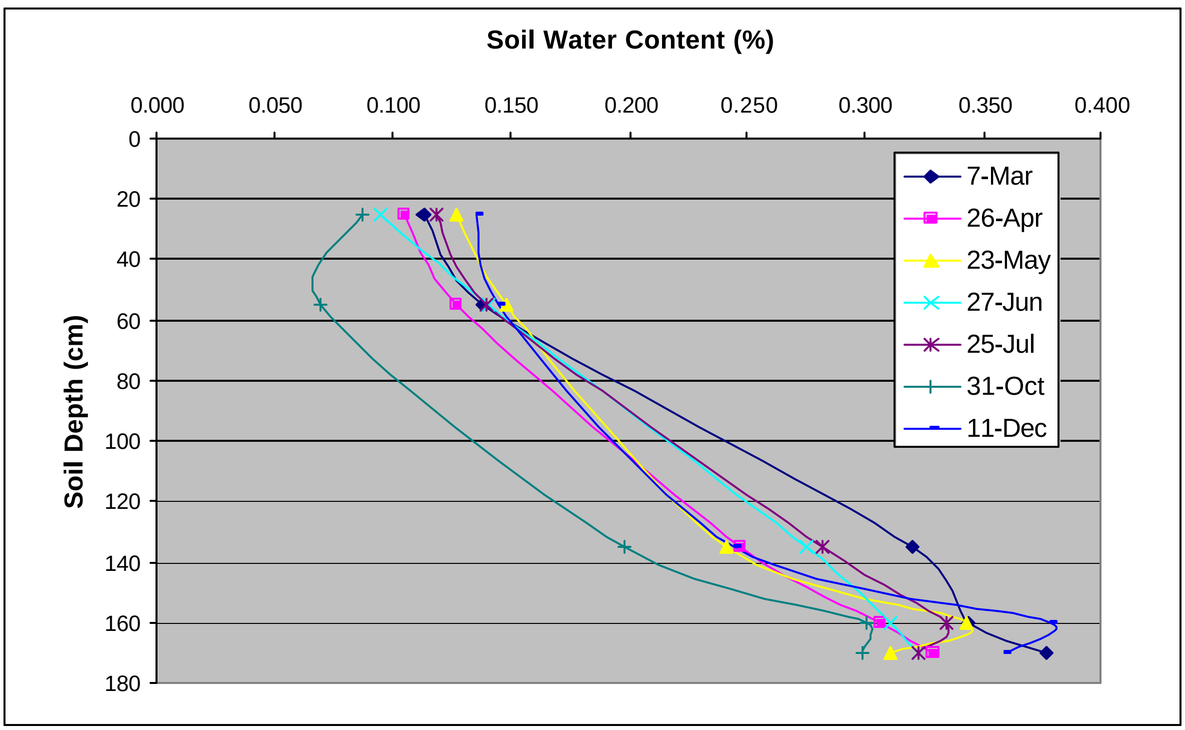


Figure G9. Changes in TDR Soil Water Content with Depth Plot 16, Cluster 12.

Spatial Variability: The approach to soil moisture monitoring was successful largely due to the large number and frequency of observations that allowed for more accurate mean values to be calculated for each plot. Figure G10 shows the range in standard deviation between instrument observations for the TEN. For the TEN, spatial variability is largely the result of variations in precipitation directly impacting the local instrument group (see Canopy Interception) and the uniformity of irrigation as well as local root distributions. The standard deviation is about 50% of the mean value between two instruments as the soils dry. For the TDRs these factors are also important, but in addition, variations in soil water content are imposed by spatial variability in soil texture and organic matter. The latter is evidenced by the large change in average water content with depth with each profile as well as differences between water content at the same depth resulting from variances in the depth to clay (Table G1). Plots 16 and 22 have considerably more clay content at the 135-cm depth than the other plots. The coefficient of variation (STD/Mean) was 30% on average.

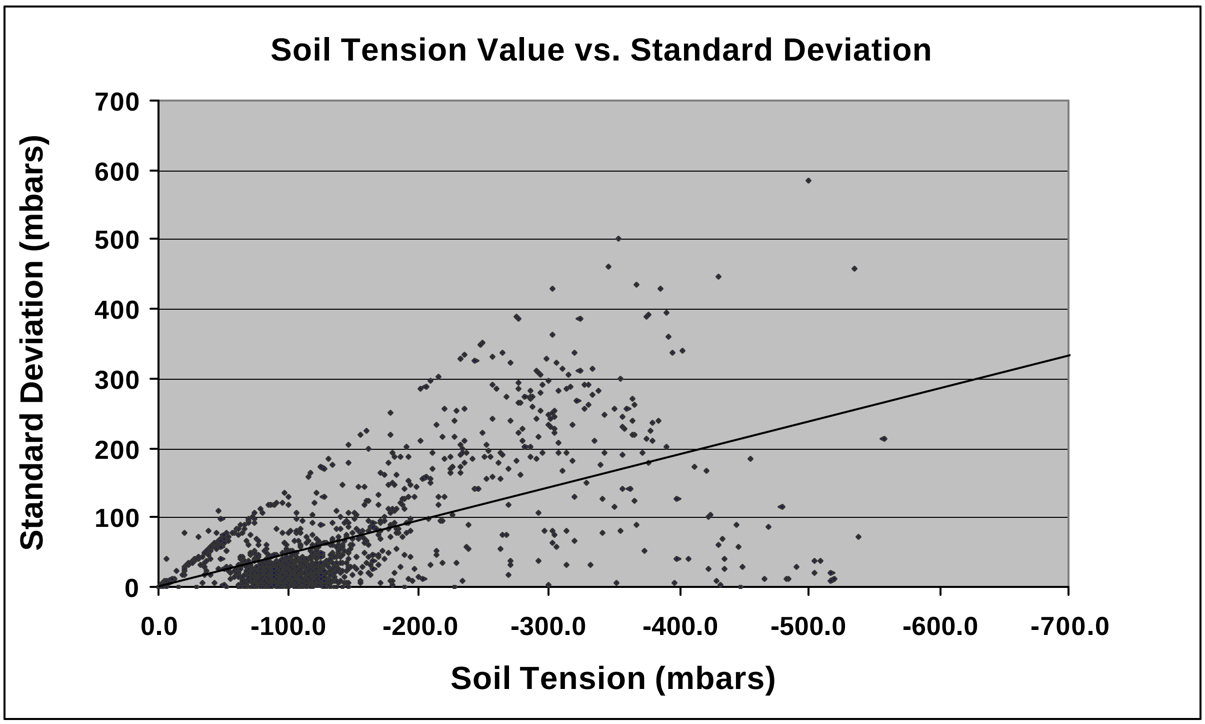


Figure G10. TEN (millibars) Values vs. Standard Deviation (N =1300). Deviation calculated between two observations (N=2) at the same cluster and depth.

Table G1. Mean TDR Percent Water Content (N= 34), Within Plot Standard Deviation (N=3) by Depth over CY2001 and Average Depth to Clay. Clay content transitioned from <10% to 22-28% at the selected depth.

		Plot Number					
Depth		**4**	**13**	**16**	**19**	**22**	**27**
25-cm	Mean (%)	0.067	0.097	0.104	0.070	0.127	0.096
	STD	0.012	0.040	0.022	0.009	0.028	0.036
55-cm	Mean (%)	0.069	0.115	0.118	0.064	0.174	0.127
	STD	0.030	0.057	0.016	0.018	0.059	0.074
135-cm	Mean (%)	0.201	0.237	0.251	0.154	0.330	0.252
	STD	0.086	0.119	0.021	0.105	0.020	0.047
145 to	Mean (%)	0.231	0.186	0.334	------	0.345	0.270
162-cm	STD	0.090	0.095	0.022	-------	0.142	0.069
162 to	Mean (%)	0.253	0.265	0.347	0.243	-------	0.207
174-cm	STD	0.029	0.092	0.021	0.079	-------	0.059
Depth to	Mean (cm)	123.3	78.3	81.7	116.7	63.3	56.7
Clay	Range	95-150	45-160	45-125	100-125	30-100	15-125

<u>Comparative Performance of TDR and TEN</u>: The TEN were more sensitive to minor changes in soil water potential associated with water uptake or precipitation. The TEN readily detected three major periods of SWD deficit (Figure G4) in which precipitation did not maintain soil water content at field capacity. TEN measurements during October-December indicate that vegetation was transpiring at rates much higher than estimated based on the 30-year average ET rate and a soil evaporation factor of 0.45. Additional water was applied based on these measurements. However, these results emphasize the need for better estimates of winter ET and a real time system for tracking weather driven ET. The TEN also indicated periods in which the surface soil was either at or above field capacity as a consequence of excess precipitation. As a consequence, the TEN were suitable to provide an empirical field method for cross checking ET deficit calculations and the management of the irrigation scheduling.

Because of limited TDR instrument sensitivity (± 2%), the spatial variability in soil texture, the need for a reference soil water content, and a requirement for multiple observations per tube-depth, it is difficult to easily detect comparatively small SWD near field capacity with the TDR without detailed numerical analysis. To estimate the SWD, changes in soil water content must be integrated over the soil profile and compared to the reference values at field capacity. The TDR provides a direct measure of water content for calculating uptake to meet modeling objectives and converting tritium activity to content. The TDR is unsuited for regulating irrigation unless the soils are allowed to dry well below field capacity and the time intervals for adjusting irrigation rates in the ranges of 3-4 weeks.

Piezometer Results: Due to the generally dry conditions throughout the year, few VZP were observed to contain free water (24 of 231 observations). No standing water above 3-m level was observed on the April, May, October, November, and December sample dates. Table G2 summarizes the VZP data that were obtained by date and cluster. In general, saturated soil conditions in the subsoil of the irrigated plots were closely associated with period of high rainfall just prior to measurement. The number of VZP in Table G2 (parenthesis) showing saturated conditions corresponded generally to prior rainfall. Approximately 50 mm of rain occurred in the week before March 13th (8). About 25 mm occurred in the week before June 28th (1), 61 mm on July 12-13th before July 16th (3), 44 mm in the week before the August 18th (4), and 100 mm in the 10 days prior to September 12th (7).

With the exception of March 13th, and July 18th, the control sites did not demonstrate saturated conditions. Plot C-1 (cluster 19) occurs in a low area and would be expected to drain slowly. The VZP in plot 22 (cluster 6) had the most frequent number of saturated observations. This instrument is low topographically and situated close to a water bar on the adjacent road. With the exception of cluster 6, the depth to free water appears to have been largely below the root zone (> 2-meters). Saturated soil in the surface 3-m zone does not appear exist during summer/fall periods under non-irrigated conditions or to persist under irrigated conditions when prior rainfall amounts and/or the storm size are small.

Table G2. VZP Observations with Detectable Free Water Measured.

Date	Cluster	To Free Water (feet)	Date	Cluster	To Free Water (feet)
1-Mar-01	C3-21	5.73	**16-Aug-01**	6	5.6
				8	9.5
13-Mar-01	6	6.3		15	9.8
	7	8.55		17	9.8
	10	5.55			
	11	9.18	**12-Sep-01**	2	5.25
	13	9.71		5	8.19
	14	8.23		6	3.53
	16	8.95		7	4.4
	C1-19	6.16		9	8.7
				11	5.75
28-Jun-01	6	6.2		12	5.75
18-Jul-01	6	6.08			
	C1-19	9.3			
	C2-20	9.85			

H. Tritium Measurements and Instrument Performance

Purpose: The purpose of the tritium sampling on the project area was to provide estimates of tritium activity in the various environmental media over time, specifically the pond and irrigation water, the soil profile within and below the root zone, and the vegetation. The tritium activity coupled to the water flux gives a method for determining effectiveness of the interim measures by enabling the uptake and transfer of curies to the atmosphere or below the root zone, and in the residual mass in the soil to be estimated. Tritium activities in the soil profile and vegetation over the season provide a unique method for validating the water balance model, which is an essential tool in calculating the partitioning of tritium between the air and soil.

Instrumentation and Performance

General: Three sampling techniques were used to determine the tritium activity at various depths within the soil profile: soil suction lysimeters (SSL), soil water vapor tubes (SWV), and surface soil samples. Six of the 30 irrigation plots are instrumented with soil water collection instruments at various depths. Each of the instrumented plots contains three clusters of instruments, resulting in a total of 18 clusters. Three control clusters located outside of the area (Clusters 19, 20, and 21) were also instrumented to provide baseline tritium activity in the soil. Table 1 gives the designated plots, as shown in Figures 1 and 2, and subsequent cluster numbers. The Savannah River Ecology Laboratory (SREL) performed all tritium activity analyses according to methods described in Appendix B of the Effectiveness Monitoring Plan (WSRC 2001a). The detect limit for the method ranges from 5 to 15 pCi/ml, and the quantification limit is approximately 20 pCi/ml (John Seaman, Per. Commu.).

During CY2001, only limited vegetation samples were collected with the objective of testing the methodology (clipping vs. intact, crown position, species, etc.) for collecting transpiration samples from the foliage rather than the planned stem samples. The vegetation sampling results will be discussed by Cornell University as part of the model validation.

Soil Suction Lysimeters: SSL are standard devices that are used routinely in contaminate sampling in the vadose zone (Faybishenko 2000). The SSL are model 1920F1/1920F1K1 Pressure-Vacuum Soil Water Samplers manufactured by Soil Moisture Equipment, Inc. They are designed to allow a sample of pore water in the soil to be collected periodically for the analysis of tritium. The SSL were originally selected as the primary standard for measurement of the amount and distribution of tritium in the soil profile. During the interim measures the operations plan for irrigation scheduling was to maintain the soil at, or just below field capacity. It was believed that the SSL could therefore provide routine soil water samples, even during the summer months. SSL were placed at five depths in the soil. The mid-point of the ceramic cups are at 50, 100, 150, 200, and 300 cm below the soil surface. The procedure, WSRC-RP-2001-4215 Rev. 0 describes the equipment, maintenance and collection methods for the SSL. Samples were collected monthly. It takes approximately 3 hours to pull a vacuum on the tubes and a comparable amount of time to pump water samples from the SSL.

The performance of SSL was primarily limited by the fact that the pore water pressure in the soils was too low to allow for consistent sample collection even though the monitoring plots were irrigated. Similar results were reported by other studies during 2001, as a result of the abnormally dry conditions. Approximately 35% of SSL did not yield a sample during CY2001 (Table H1). The trend of increasing failures over the calendar year is attributed to persistent drought conditions. There was no trend in SSL failure with depth. Samples for tritium analysis were collected through October 2001 (Appendix I), but the samples were not used for any of the effectiveness calculations. During a single sampling event in November of 2002, 53% of the SSL provided a water sample further supporting the effect of the dry soil conditions on recovery.

Table H1. Number and Percent SSL Failures by Month. Failures include both the inability to hold a vacuum or provide a water sample.

Sample Date	***Number of SSL Failures***		***Percent of SSL Failures***
17-Feb	28		26.7
19-Mar	22		20.1
20-Apr	33		31.3
16-May	36		34.3
18-Jun	22		20.1
17-Jul	31		29.5
14-Aug	47		44.8
11-Sep	51		48.5
10-Oct	61		58.1
All	331		35.0

SSL sample collection was also limited by the inability to pull a vacuum on some of the instruments. The latter suggest damage or defects in the ceramic cup. In addition, the protective covers tended to accumulate water inside in the fall months as a result of condensation of moisture from the air. The problem occurred on both irrigated and non-irrigated clusters but was more notable on the former. The sample collection tubes, which exit from the soil, are protected by a short PVC collar (~6 inches) and cap. The collar is grouted at the base around the tubes. The cap protects the tubes from irrigation and rainwater, but creates an environment for condensation to take place.

Finally, as with the SWV, some of the very high tritium activities at depth (200 and 300-cm, Appendix H) that were observed initially may be a consequence of leaks (preferential flow). These abnormal distributions were seen in the June samples for clusters 1,3,8,7,11, and 18. Since there is no casing per se for the SSL, leaks or preferential flow can result if the backfill around the small sample tubes was not packed properly, or excessive water applied from popped head, broken lines or animal damage. The magnitude of the latter problem was so extensive based on operator logs that it is impossible to determine if the high activities are an instrumentation problem or a consequence of the irrigation operation and performance. Some naturally occurring preferential flow is expected, but because the soils are sandy and largely structure-less, it was not expected to be a dominant factor especially near field capacity.

Soil Water Vapor Tubes: The SWV were constructed and installed by the Forest Service using the design and recommendations of Brian Looney and Joe Rossabi (WSRTC). The mini-pump flow rates and condensation mechanism are also based on their design. Tritium activity of the soil water vapor phase is assumed to be in equilibrium with the tritium activity in the soil water at the sample depth. Air is drawn at a rate of approximately 1.5-liters per minute through a condensation tube in an ice chest for about 48 hours. The soil water vapor tube consisted of 1-inch PVC pipe with a 15-cm screen at the bottom of slotted pipe. The pipe extended about 60-cm above the ground. The soil vapor tubes were located at 5 depths below the surface: 25, 55, 135, 205 and 295 cm. Individual sample lines and mini-pumps were re-used only on the identical sample tube. The procedure, WSRC-RP-2001-4216 Rev. 0, describes the equipment, maintenance and collection methods for the SWV. Samples were collected monthly. It takes approximately 3 hours to set up the system and begin the sampling on the tubes and a comparable amount of time to collect and transfer the samples from the SWV.

With the exception of one mini-pump that failed, the system mechanical and electrical performance was excellent and few operational problems were observed. Samples were collected even from fairly dry soils as a result of the fact that the water content in soil pore spaces can be very high at equilibrium soil water potential. Sample volumes were smaller in the winter than summer as a result of the smaller differences in temperature related dew point between the soil and ice chest in winter.

However, several performance problems did influence sample values. Because the pipes were elevated several feet above the soil, several of the mini-sprinklers in close proximity to the pipes were pushed lower than the pipes and sprayed directly against the side of the pipe. This situation created concentrated flow down the side of the pipe. Since the mini-sprinkler heads were initially installed at the correct height above the SWV, it is also evident that these specific emitters separated or popped-off frequently resulting in large excesses of tritiated water to be applied near the SWV. The operators would have forced the supporting rods deeper into the soil when replacing the emitters, eventually pushing them below the top of the SWV. The result was an opportunity for irrigation water with high tritium activity to penetrate down to the sample level. Following a field survey, a list of specific sample depths, clusters and plots that may be influenced by this problem was identified (Table H2). Some of the exceptionally high tritium activities at the 135-cm may be in part associated with this effect. The elevations of the emitters near the SWV were corrected in late January, 2003.

In addition to spay problems, leaks or preferential flow can result if the backfill around the pipe was not packed properly. Abnormally high readings compared to other depths and cluster values were found at 3-m in May (cluster 1) and 2-m in June (cluster 17), but disappeared at the next sampling event. As with the SSL, excessive water applied from popped head, broken lines or animal damage can saturate the soil near the instruments. The magnitude of the latter problem was so extensive based on operator logs that it is impossible to determine if the high activities are an instrumentation problem or a consequence of the irrigation operation and performance.

Table H2. Specific Depths, Clusters and Plots Influenced by Low Mini-sprinkler Riser Spray on SWV Pipes.

Plot	***Cluster***	***Depth***	***Comment***
4	18	205-cm	Riser too low and adjacent to sample pipe
13	3	135-cm	Riser too low and adjacent to sample pipe
16	11	135-cm	Pipe adjacent to tree stem that is intercepting irrigation spray
19	14	135-cm	Pipe near riser with spay angle aimed down instead of horizontal
22	7	205-cm	Riser adjacent to sample pipe
22	7	295-cm	Riser adjacent to sample pipe
27	5	135-cm	Riser too low and adjacent to sample pipe

Surface Soil Sampling: Neither the SWV nor the SSL could be used to sample at depths less than 25-cm. Therefore, the tritium activity in the surface (0 to 15-cm) soil layer was estimated from soil cores. The objective was to validate the assumption that the tritium activity in the surface soil is equal to average pond activity during the previous period (see IV. System Effectiveness). The latter value is subject to dilution by rainwater and other physical process like diffusion of tritium into air as a result of the partial pressure gradient from the soil to air. The calculation of total tritium in the soil profile involves integration of the water content and tritium activity over the entire profile. The surface soil activity is bounded by the assumption that the tritium activity in the surface soil is equal to average pond activity during the previous period.

A 15-cm soil probe with a cut-away barrel was used to collect the samples within each cluster. A sample was collected every 2-m along a line-transect through each cluster and resulted in six cores. The samples from each cluster were combined and homogenized to yield a composite sample. The procedure, WSRC-RP-2001-4244 Rev. 0, describes the equipment, maintenance and collection methods for the surface soil sample. Samples were collected only once on December 4, 2001. It takes approximately 3 hours to complete a set of samples from the irrigated cluster. Changes in the Sampling Plan (WSRC 2001c) resulted in the decision to drop surface soil sampling in favor of sampling through the profile. The associated procedure has been modified (WSRC RP-2002-4244 Rev.1). Given the simplicity of the procedure, no problems were observed.

Pond Water: The Forest Service obtained pond water at the catwalk, and tank water after filtration during the normal monthly soil sampling events. Since the initial results of the routine sampling by EMS demonstrated that the tritium activity of the pond varied considerably over weekly periods, the calculations of tritiated water management effectiveness were based on the EMS data. Analytical and sampling procedures are outlined in the Sampling Plan (WSRC 2001c). Daily pond activity was determined by interpolation between the EMS data points. Sampling was conducted in the pond by lowering a bucket into the pond off the catwalk. No instrumentation or performance problems were noted, although previous observations indicated that pond tritium activity varies with the location from which pond water is collected and therefore must be standardized. Tank water was collected at a small discharge valve at the base of the tank

Tritium Applied

Tritium Activity in Pond: Tritium activity in the pond water and tank water was closely correlated over the period. The linear r^2 was 0.96 for the 10-months and the equation is Tank (pCi/ml) = 1.0064 (Pond (pCi/ml)) +790.9, indicating that the slope of the relationship was essentially 1:1. There is a slight underestimate of tritium in the irrigation. Rain or surface re-charge may not mixing uniformly with the seeps so that surface samples are somewhat diluted. However, the average tritium activity in the EMS pond samples appears to accurately represent the activity in the water applied through irrigation despite potential spatial variation within the pond.

Tritium activity in the pond varied substantially over the period (Figure H1). Average monthly activity fell during March and early April to about 6000 pCi/ml, probably as a result of the influx of rainwater. The pond was at the highest level during March and April (overflow). The pond activity gradually increased in May and June to about 11,500 pCi/ml as the pond elevation decreased (Figure H2) and then decreased again in July and August to about 8,000 pCi/ml as the pond refilled following significant rainfall and limited irrigation. Pond activity increased as pond level decreased and precipitation fell in the fall, remaining at a high level of approximately 15,000 pCi/ml.

Pond activity is closely associated with pond elevation, which is directly influenced by rainfall. Almost 100 mm of rain received in early July corresponds with a subsequent dramatic decrease in pond tritium activity (Figure H2) due to rainfall dilution. This pattern is repeated in early September when another 100 mm of rain fell. The relationship is strong enough to suggest that the relative contribution of seepage from the subsurface contaminate plume compared to fresh water from rainfall increases as the pond elevation declines. Because noticeable changes in pond activity occurred over weekly intervals, the need exists for frequent pond sampling in order to accurately determine the activity of the applied irrigation water and the total curies managed by the system.

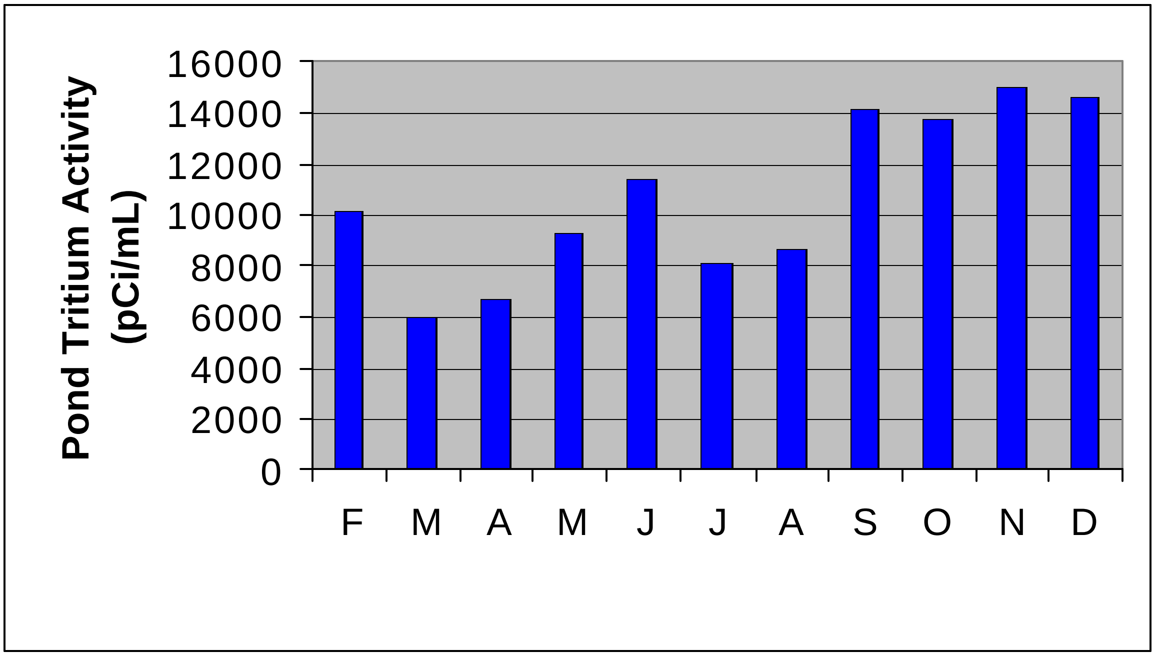


Figure H1. Average Monthly Tritium Activities for Pond Samples Collected during CY2001.

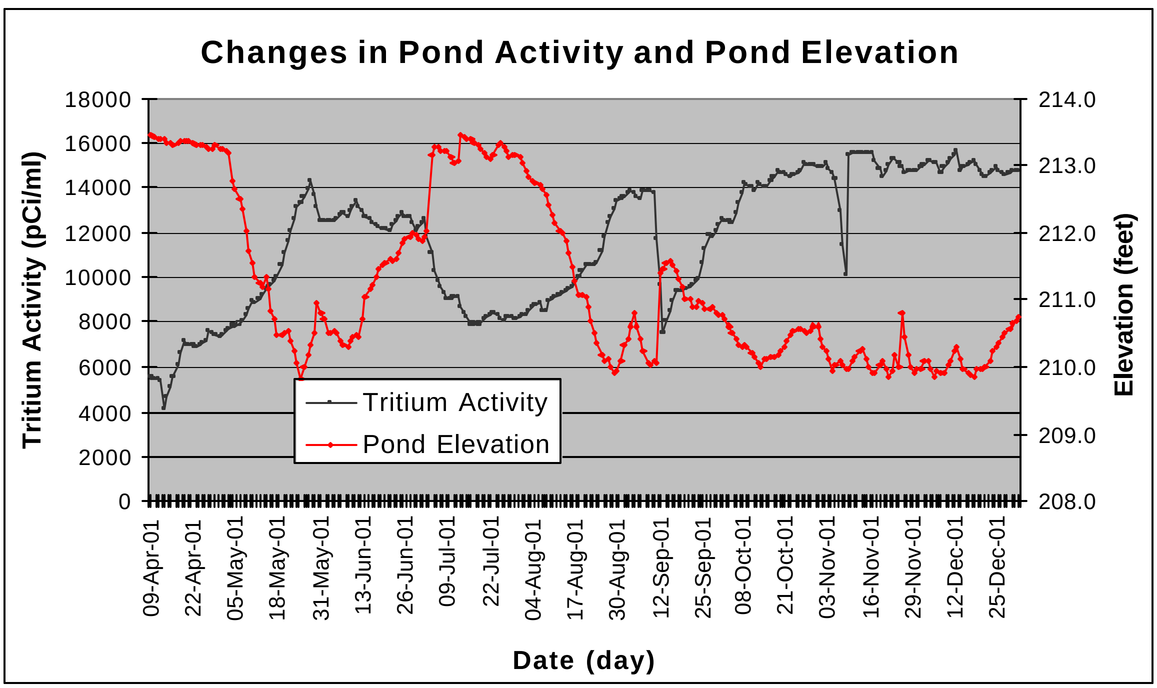


Figure H2. Average Weekly Tritium Activities for Pond Samples Collected during CY2001.

Tritium Applied in Irrigation: The total tritium applied through the irrigation system was calculated by multiplying the daily irrigation amounts (metered total flow-rate) by the average pond activity. The equation relating Tank activity to Pond activity was used to adjust the applied curies. Figure H3 shows the cumulative amounts by month over the period. A total of 657 curies of tritium were applied to all plots through the irrigation system. The latter includes leaks and non-uniform application previously estimated at 9.8% of the total flow (see Irrigation Measurements). The application of tritium remained steady through the fall despite the drop in the rate of water applied as a direct result of higher than average pond activity (Figure H2).

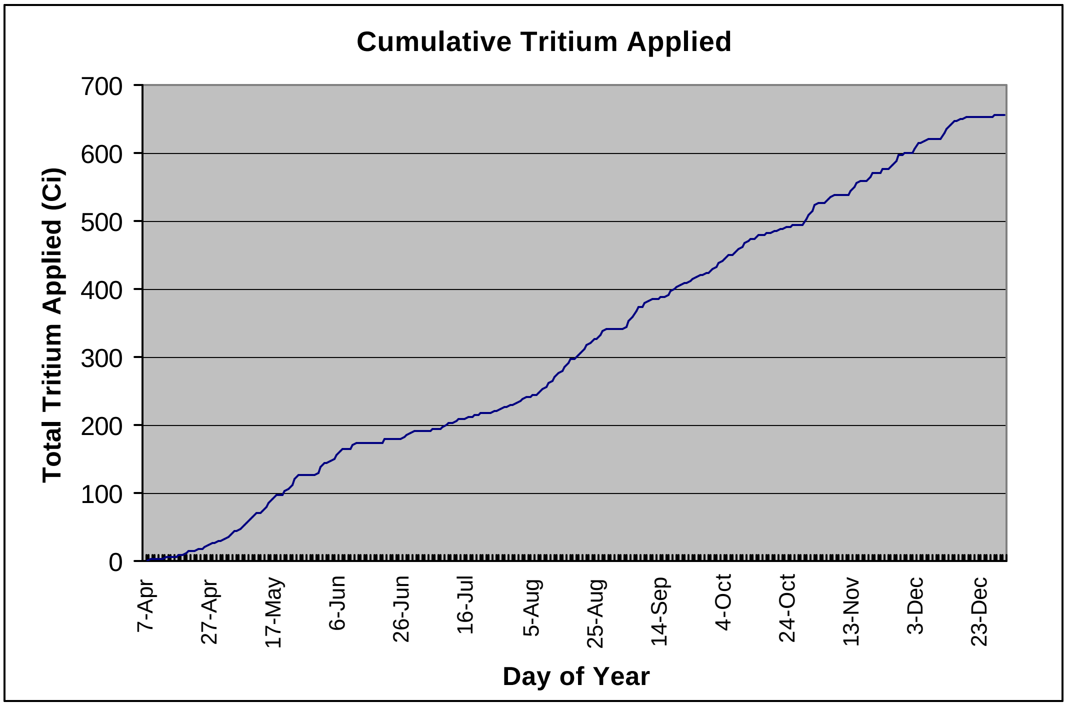


Figure H3. Total Tritium Applied by Irrigation During CY2001.

Tritium Applied by Deficit Schedule: Based on irrigation data (metered total flow) and adjusted pond water tritium activities, the cumulative amount of tritium applied to each instrumented plot was determined. The total amount applied was converted to a per unit area bases (Table H3) using the ideal spacing area (Table D3). In general, the rate of tritium applied increased in the fall as a result of much higher pond activities. There is a direct relationship between total water applied (TableD3) and total tritium applied through December. Initial differences between plots tended to carry through until December. By the end of December, the plots rank as follows: 12-mm > 6-mm > 18-mm.

Table H3. Cumulative Total Tritium Applied by Plot (pCi per m^2).

	Plot 27	***Plot 22***	***Plot 13***	***Plot 16***	***Plot 19***	***Plot 4***
16-May-01	1.1e9	9.5e8	6.9e8	1.2e9	8.9e8	1.1e9
21-Jun-01	2.4e9	2.0e9	1.6e9	3.0e9	1.6e9	1.9e9
18-Jul-01	2.8e9	2.4e9	1.8e9	3.3e9	1.8e9	2.1e9
15-Aug-01	3.2e9	2.7e9	2.1e9	3.8e9	2.1e9	2.5e9
12-Sep-01	4.2e9	3.6e9	2.8e9	5.0e9	2.9e9	3.4e9
10-Oct-01	5.1e9	4.6e9	3.2e9	5.7e9	3.6e9	4.3e9
15-Nov-01	6.0e9	4.9e9	3.7e9	6.5e9	4.3e9	4.9e9
7-Dec-01	6.9e9	5.4e9	4.5e9	8.0e9	4.6e9	5.3e9

Tritium in Soil

Calculation Method: The amount of tritium in the soil profile was determined from the SWV data for each sample period by integration of tritium content over the 3 m depth interval. The amount of tritium at the soil surface boundary was assumed to be equal to the average activity of the pond water over the previous week. No compensation was made for surface mixing with rainwater during that period in the initial calculations. The latter results in an overestimation of the actual soil surface tritium activity (pond tritium activity > actual surface activity diluted with rainwater), particularly for the months of May through September in which 24 to 60 mm of rainwater was received in the week prior to sampling. Tritium content at depths of 0.25-m, 0.55-m, 1.35-m, 2.05-m, and 2.95 m were determined by multiplying tritium activities from samples collected from SWV by the soil water content measurements taken with vertical TDR. At depths where no TDR data was available, the soil water content was assumed to be at field capacity values (e.g. 0.28 at 2 m and 0.36 at 3 m). A polynomial curve-fitting technique was used to develop an equation no greater than fourth order for tritium over the soil profile. The criteria for an acceptable polynomial equation that best fit the tritium data was a correlation coefficient greater than 0.8. The resulting equation was integrated over the 0 to 3-m range to determine total tritium content in the soil profile monthly for each cluster from May to December 2001.

Tritium Content in Controls and Pre-Irrigation: Table H4 shows the results of SWV tritium analysis on the three control sites and on the monitoring plots during the months prior to irrigation. Limited background quantities of tritium were discovered on the control sites over the entire period. Most observations were non-detects (less then 5 to 15 pCi/ml). However, there seemed to be a consistent detection of around 40 pCi/ml at the 295-cm level in C-21, which is the thinned pine stand adjacent to the project area. The average pre-irrigation activity was below the detection limit for the two months prior to operations. While some testing of the irrigation system occurred in the fall of 2000, these events had no apparent impact on the baseline tritium levels. Monitoring and analysis of the SWV and SSL on the control plots was discontinued in 2002.

Table H4. Average SWV Tritium Activities on Control and Pre-Irrigation Monitoring Clusters by Depth. Control values are averages for February to December 2001. Pre-Irrigation values are for February and March 2001. ND= Non-Detect (<5 to 15 pCi/ml)

	Plot								
Depth	C-1 pCi/ml	C-2 pCi/ml	C-3 pCi/ml	4 pCi/ml	19 pCi/ml	13 pCi/ml	16 pCi/ml	22 pCi/ml	27 pCi/ml
25-cm	ND	ND	20.5(1)	ND	ND	ND	ND	ND	ND
55-cm	ND	ND	ND	ND	ND	ND	ND	ND	ND
135-cm	ND	ND	ND	ND	ND	ND	ND	ND	ND
205-cm	ND	ND	34.2	ND	ND	ND	ND	ND	ND
295-cm[1]	59.1(1)	52.6(1)	39.9	ND	ND	ND	ND	ND	ND

1. Values followed by (1) are represented by one sample value from the six samples measured.

Distribution of Tritium in Soil Profile: Figure H4 show average tritium content in the soil profile as a function of soil depth for SWV samples collected from May to December 2001. Detailed tritium activities by cluster and depth are given in Appendix J. Subsequent to the initial measurement in May, the content shows a decline to 55-cm, but then an increase at the 135-cm depth. The latter depth is within the subsurface clay layer for most clusters (Table G1). The incipient increase in clay content begins anywhere from 15-cm to 150-cm. The total water content nearly doubles at the 15-cm to 150-cm level (Table G1), and there is reduced hydrologic conductivity at the clay layer, which retains irrigation water that comes from the soil surface by preferential flow (both natural and artificial due to irrigation line leaks, etc.). The tritium content at the 135-cm layer gradually declines in November. By December, the tritium content follows an expected distribution based on simple dilution and dispersion.

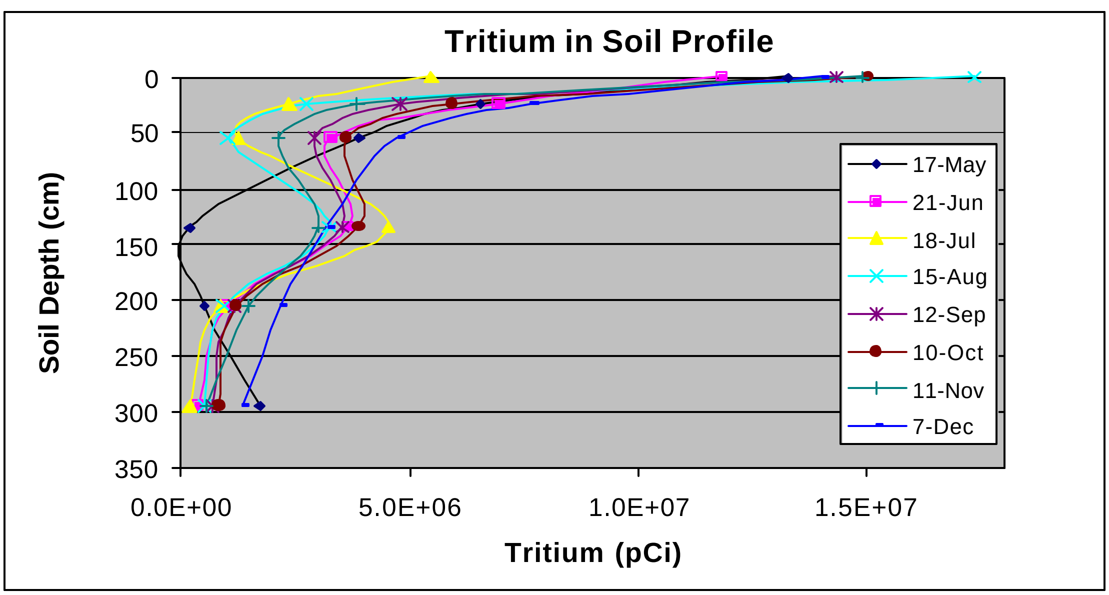
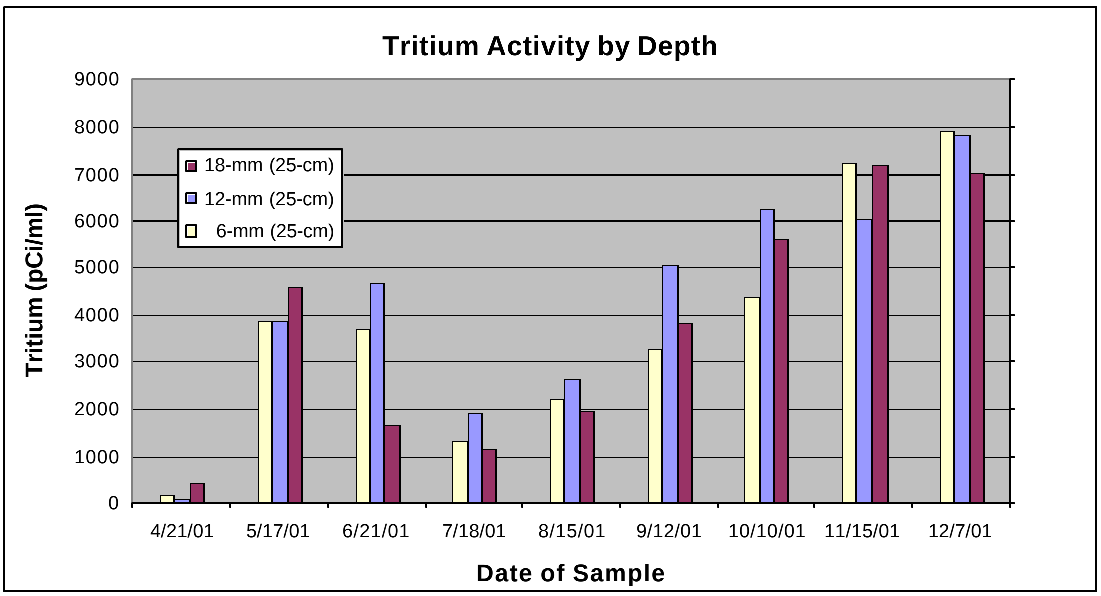
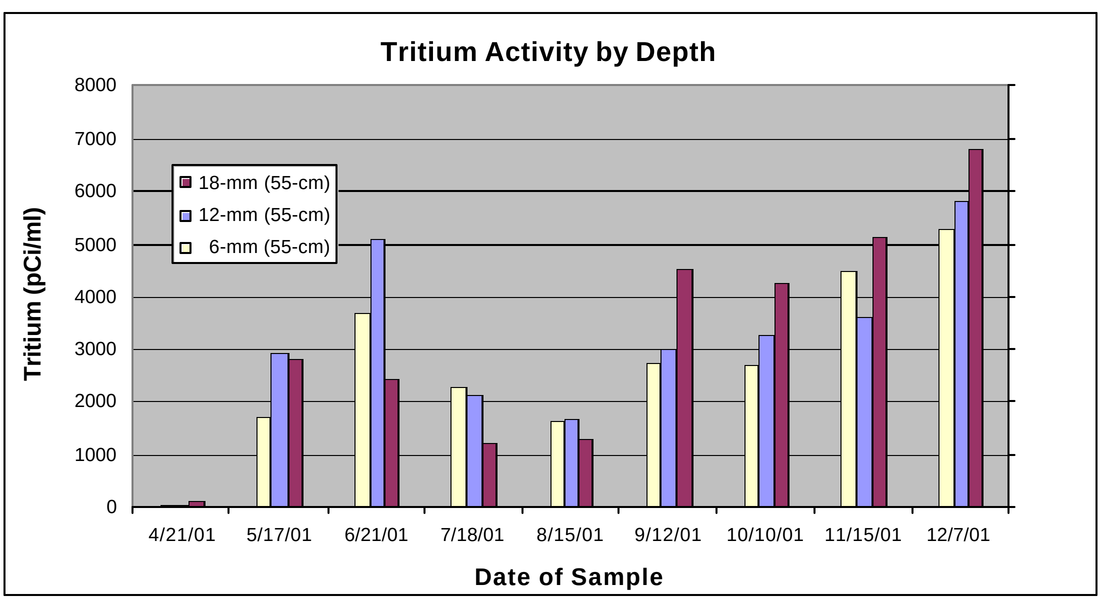


Figure H4. Average Distribution of Tritium Per Unit Volume ($3m^3$) in Soil Profile from May to December Based on SWV Values.

The high initial activities at all depths observed on some plots and clusters (Figure H5a-e) probably represent a combination of excess irrigation and leakage. The occasional presence of tritium activity at the lower layers in May and June, especially around the 2-m and 3-m sample depth, is probably an indication of a small amount of leakage in the SWV casings. The sustained high activities at 135 and 205-cm layers occurs at the transition from sand to the more clayey layer (Table G1) and may represent retention of preferential flow and accumulation of lateral flow. With the exception of an early peak, tritium activity in the soil increased systematically at 25, 55, and 295-cm depths during the period, whereas activity at 135-cm and 205-cm remained fairly constant after May. No systematic differences in activity among irrigation scheduling treatments or plots were observed at 25, 55, or 135-cm. However, the average activity at the 295-cm depth varied inversely with the average depth to clay on the plot and ranged from~100 to 700 pCi/ml in December 2001.





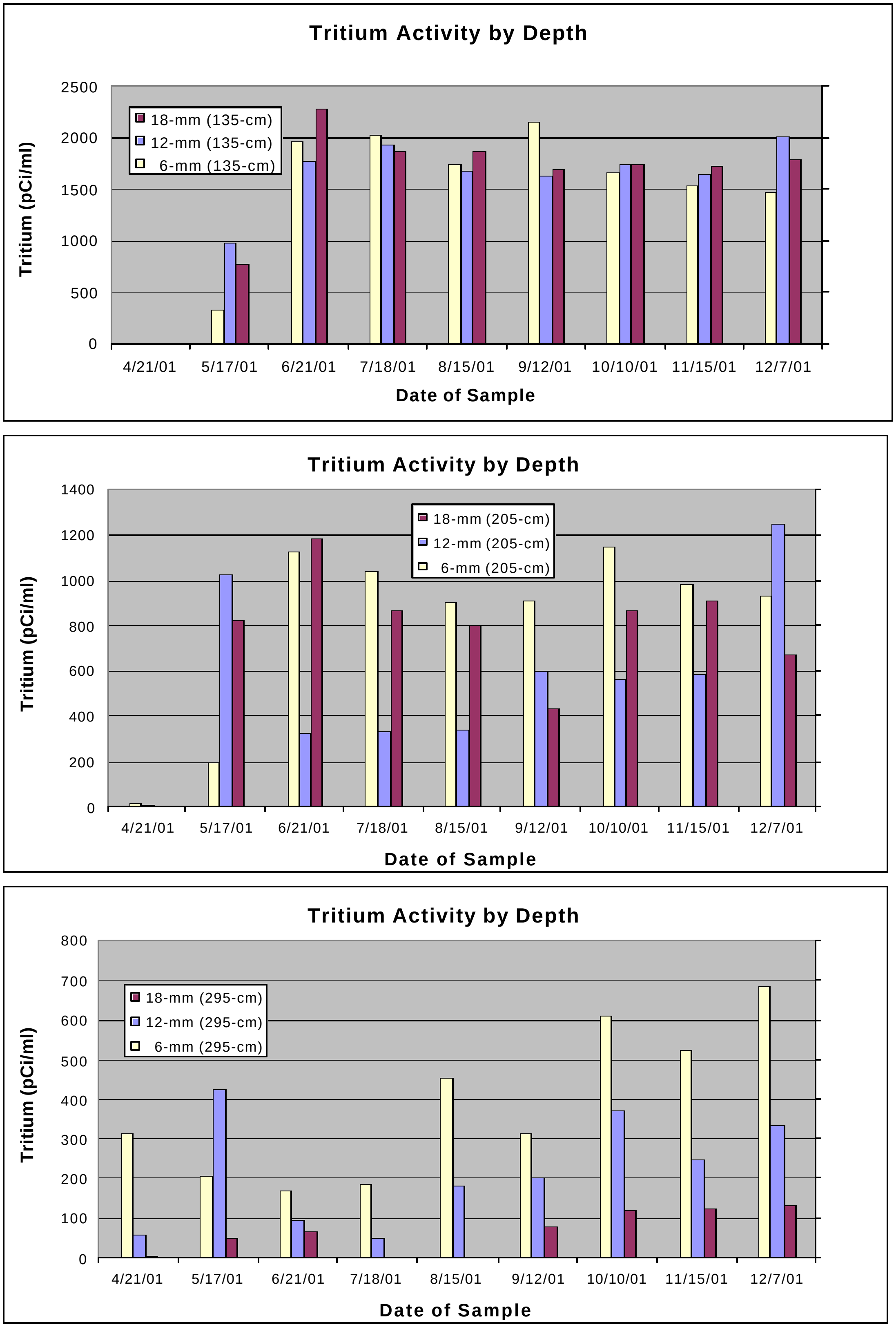


Figure H5a-e. Mean Tritium Activity by Depth, Sample Date and Irrigation Schedule.

<u>Tritium Content in Surface Soil</u>: The calculation of tritium content in the soil surface profile (Figure H4) currently assumes that the activity at the surface is equal to the average activity of the pond water applied as irrigation in the previous week. However, the surface activity is affected by other physical processes, including mixing and dispersion with rainwater and diffusion into the air as a consequence of the partial pressure gradient between tritium in water and air. The assumption was tested using a single set of surface soil samples collected on December 4, 2001.

Table H5 summarizes the mean and standard deviation for each irrigated plot. The expected value based on the prior week adjusted pond activity is 15,600 pCi/ml. Clearly, the measured values are less than the unadjusted pond activity. The expected values were re-calculated using a simple mixing function. On November 23rd and 25th a total of 17 mm of rain was received on the plots. These two rain events were sufficient to displace or completely re-fill the surface soil pores in the sands to a depth of 15-cm with non-tritiated water. The expected values for each plot were then re-calculated using the proportion of tritiated (irrigation) to non-tritiated water (rain) multiplied by the average pond activity. Irrigation amounts were summed for November 25th to December 3rd using the average application depth ((minutes x 0.52 gal/min/head x 162 heads/ac)/1069.7 gal/mm/ac)).

Table H5. Average Tritium Activity in the Surface Soil of Irrigated Monitoring Plots.

	Soil Cores		***Expected***	***SWV 15-Nov 25-cm***		***SWV 7-Dec 25-cm***	
Plot	Mean pCi/ml	Std Error pCi/ml	Mean pCi/ml	Mean pCi/ml	Std Error pCi/ml	Mean pCi/ml	Std Error pCi/ml
27	7,710	743	8,334	7,462	838	8,174	1,340
22	7,612	436	8,334	4,627	1,408	7,594	1,785
13	9,323	188	9,834	5,686	501	7,962	429
16	9,640	275	9,834	6,393	1,480	7,716	1,530
4	6,628	156	5,088	5,725	1,478	6,529	1,962
19	5,944	293	5,088	8,610	2,667	7,519	1,201

The mean values for the soil cores follow the expected values for the tritium based on a mixing function. The surface activity cannot be assumed to be equal to pond water alone. The expected values are within the standard error of the mean for the soil cores with exception of the 18-mm plots (4 and 19). The poorer correspondence may be the result of just a single small (7.2 mm) application during the period. These results suggest that the surface activity can be estimated by knowing the relative contribution of rain to irrigation, the adjusted pond activity and the water content of the surface soil. The SWV data from 25-cm for the two sample dates are not representative of the soil core values.

<u>Tritium Content by Deficit Schedule</u>: Based on the calculation method identified previously, the total tritium content at each sample date (excluding February, March and April) and cluster was determined. Clusters 2 (Plot 13), 7 (Plot 22), 11 (Plot 16), and 18 (Plot 4) were excluded from the analysis on the dates identified because the calculated tritium in the soil profile exceeded the tritium applied through irrigation or were within

10%, indicating leaks or instrumentation problems. Table H6 shows the cumulative increase in tritium content within the soil profile over the interval. The tritium content in the soil remained fairly constant or stable between August and December. This result is most likely a consequence of the drought conditions coupled with the reduced irrigation rate in conjunction with the winter schedule.

Table H6. Mean Estimated Cumulative Tritium Content in Soil (0 to 3-m depth) by Monitoring Plot (pCi/3m^3).

	Plot 27	*Plot 22*	*Plot 13*	*Plot 16*	*Plot 19*	*Plot 4*
16-May-01	1.9e8	3.6e8	4.1e8*	3.4e8	4.1e8	4.0e8*
21-Jun-01	7.8e8	2.5e8*	4.9e8*	3.5e9	5.9e8	3.1e8*
18-Jul-01	9.7e8	2.9e8**	4.8e8	4.7e8*	4.8e8	8.0e8*
15-Aug-01	6.8e8	8.7e8	4.7e8	1.1e9	9.2e8	8.7e8
12-Sep-01	1.1e9	1.1e9	1.4e9	9.0e8*	1.0e9	5.7e8
10-Oct-01	1.0e9	1.1e9**	7.8e8	9.3e8*	4.6e8	8.8e8
15-Nov-01	2.8e8	1.4e9	1.3e9	1.1e9	6.7e8	5.4e8
7-Dec-01	1.5e9	1.3e9*	1.1e9	1.1e9	4.6e8	1.0e9

* 2 clusters per plot were used to calculate mean, ** 1 cluster per plot represented by given value.

The tritium content in the soil profile in December was closely related to the average depth to clay (Figure H6). Plots that had the shallowest depth to sand tended to have the highest tritium content over the 0 to 3-m layer. Therefore, impacts from the irrigation schedule are confounded by the soil physical properties of the plots, as well as vegetation differences, such as root distribution and species composition.

<u>Soil Core vs. Soil Water Vapor Tubes</u>: Some concerns exist about the accuracy of the SWV method. The SWV sample the soil air, which is assumed to be in equilibrium with the tritium activity in the soil water near the SWV. The air-flow rate was reduced to ~1.5 l/min to minimize this potential problem of non-equilibrium. In addition, the flow of air is assumed to be isotropic through the soil volume, which is probably not valid in the more clayey layers. Either of these assumptions may contribute to errors or discrepancies. In July CY2002, both soil cores and SWV were sampled at the same time. Duplicate soil cores were taken and combined from the same depth within the central radius of the SWV to minimize spatial separation. Soil samples were collected at approximately 55, 135 and 295-cm on Plot 4 (Cluster 16), Plot 19 (Cluster 15), Plot 13 (Cluster 3), Plot 16 (Cluster 10), Plot 22 (Cluster 8, and Plot 27 (Cluster 5). The latter clusters did not have apparent instrument problems or indications of excessive leaks in the vicinity. The relationship between the two methods is shown in Figure H7. In general there is a good correspondence given the inherent variability in the system. The mean deviation between the two methods is somewhat related to the depth of sample. The SWV gave higher mean values (+ 1,160 pCi/ml) for samples collected at 55-cm, whereas the SWV gave lower mean values for samples collected at 295-cm (-437 pCi/ml). The results suggest that the SWV provide representative data for soil tritium, but the inherent variability is so large that additional evaluation and sampling comparison is needed to confirm the relationship.

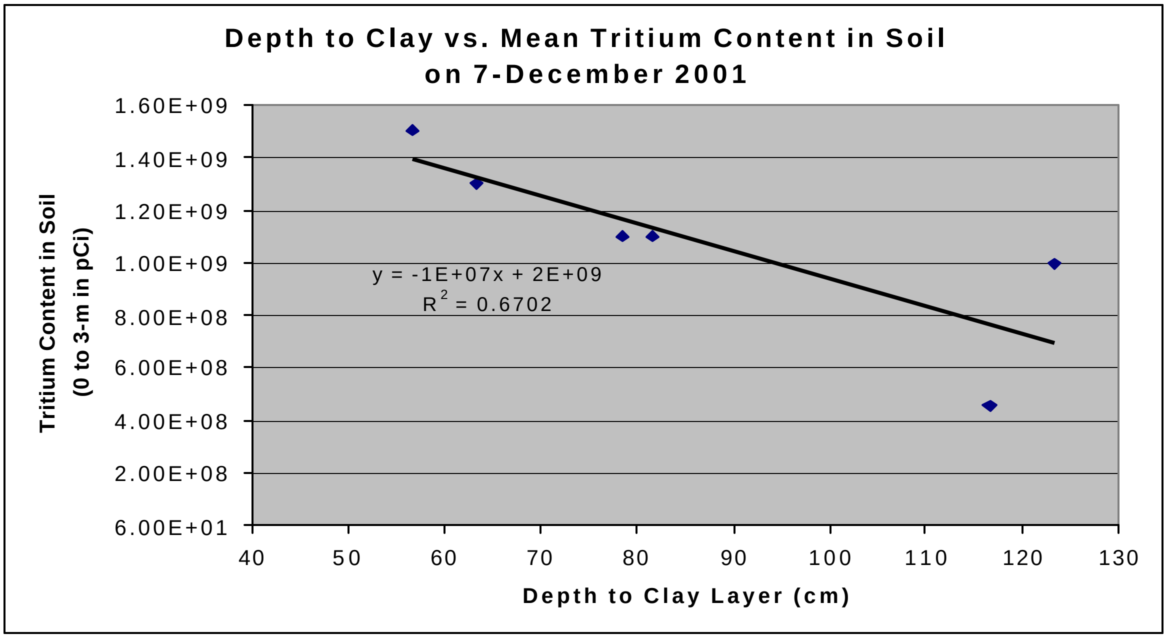


Figure H6. Mean Tritium Content in the 0 to 3-m Soil Layer in Relation to the Depth to Clay. Depth is average for three monitoring clusters per plot. Clay content transitioned from <10% to 22-28% at the selected depth.

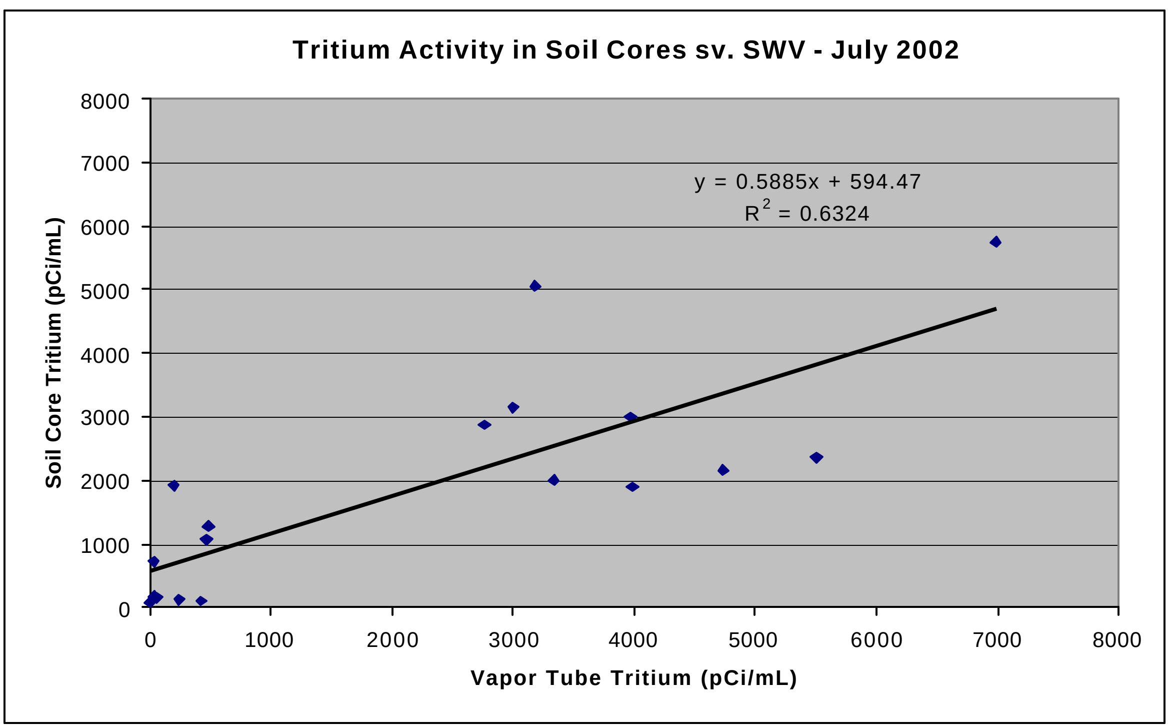


Figure H7. Tritium Activity in Soil Cores Compared with SWV for Selected Clusters in July 2002 at 55, 135 and 295-cm.

IV. System Effectiveness

Purpose: The purpose of the system effectiveness analysis is to determine the overall efficiency of the phytoremediation process with respect to the disposition of the water and tritium during the period. Effectiveness analysis partitions the tritium and water between the various environmental media, such as the pond, air, root zone and the soil below the root zone. The tritium flux and activity below the root zone is a critical constraint in assessing system performance. The tritium contained in the soil below the active root zone will eventually be returned through subsurface flow to the pond, to near-surface groundwater, or to Fourmile Branch unless it decays during the return interval. In addition, the effectiveness evaluation and analysis identifies opportunities to improve performance and optimize the remediation process.

Partitioning Between Soil and Atmosphere

General Assumptions: Because there are two unknowns (ET and subsurface flux) that cannot be easily measured, the effectiveness of the system cannot be determined routinely from simple empirical measurement of the tritium balance in the various environmental media. The partitioning of tritium flux between the atmosphere and below the root zone will be accomplished routinely by simultaneous modeling of water and tritium uptake within the root zone, the evapotranspiration process, tritium mixing and dispersion in the soil, and water flow through the soil. The water balance model being developed by Cornell University will allow the partitioning and optimization to be performed (Cornell University Report, March 2002).

As a result of the drought, which limited water flux below 3-m, and the lack of tritium in the soil profile at start-up, ET efficiency could be estimated under certain general assumptions:

- All of the tritium applied was either lost to the atmosphere by ET or remained in the soil profile between the 0 to 3-m layer.
- No lateral flow occurred between plots that could increase or reduce the tritium activity in the profile.
- The tritium activity at the boundary surface between the soil and the atmosphere was equal to the average pond activity over the prior week.
- The determination of soil water (v/v) was determined by TDR data for that date. The water content at the surface was equal to the water content at 25-cm.
- The amount of tritium applied to each plot was equal to the adjusted pond activity times the metered total flow normalized by the ideal area (Tables D1, D2, D3).
- Clusters 2, 7, 11, 18 were eliminated from the analysis on selected dates because more tritium was calculated to be in the soil than had been applied (Table H2), most likely as a result of system leaks and preferential flow of irrigated water to greater depths in the soil profile than were typical.

- The amount of tritium in the vegetation or wood was assumed to be a negligible fraction (WSRTC RP-2001-00466 Rev 0).

The boundary assumption has been shown to be invalid (Table H5) when considering the entire 0 to 15 cm layer. Therefore, the tritium content in the soil was over estimated for those months in which significant rainfall was received immediately prior to sampling (May, June, July, August and September). The data also suggest that a small amount of tritium was measured at 3-m (Figure H4) resulting in the possibility of some flux below the measured depth. However, independent modeling of the water and tritium flux below the root zone by Cornell University (March 2002) indicated that very little water, and similarly very little tritium movement below the root zone occurred because of the drought (see Figures G8 and G9). There is a discrepancy between application depth based on metered flow exceeds the depth based on flow per head by 9.8%. This additional water is probably not applied uniformly on the plots. Finally, the actual area irrigated per plot is larger than the area based on sprinkler spacing, except around the monitoring clusters, which were carefully placed at the design spacing. This difference would reduce average application depth.

Given the limitations imposed by the assumptions, the tritium applied was partitioned between the soil and the atmosphere for each date, cluster and plot. The method for calculating tritium applied by irrigation and tritium content in the soil was described previously (see Tritium Measurements). The basic equation for determining ET efficiency is as follows:

ET Efficiency = ((Total H^3 Applied - Total H^3 Soil Content) / (Total H^3 Applied)) x 100

The total tritium applied is the cumulative amount applied to date for each plot. The soil content is the total tritium in the 0 to 3-m layer (Table H6).

<u>By Deficit Schedule and Month</u>: The average efficiency by plot for each sample date is shown in Table I1. Excluding negative values from the analysis, efficiencies range from 56 to 87 % depending upon month and plot. The mean by irrigation schedule shows no apparent difference between May and August (Figure I1). The mean across all plots ranged from about 56 to 80% during this period in which rainfall was near normal and was close to the expected ET efficiency (Blake 1999). During the fall drought period, during which rainfall was 30% of normal, the ET efficiencies increase consistently from 70% to 81.2% in December. This trend coincides with the increasing SWD during the fall and extraction of stored water throughout the soil profile (Figures G8 and G9).

Figure I2 depicts the relationship between cumulative annual ET efficiency in December, which integrates both summer and fall, and the average depth to clay (see Table G1). The close relationship between the calculated ET efficiency and the depth to clay indicates that the observed differences in ET efficiency among the three irrigation schedules is confounded with soil physical properties. This result coupled with the differences in vegetation composition, stocking (Table E1), and irrigation amounts suggests that while differences in ET efficiency between the irrigation schedule plots exist, they are more likely explained by inherent physical and biological characteristics of the soils and vegetation on the plots. This result benefits operations by increasing the flexibility in applying irrigation water, at least during periods in which SWD occur. The lower frequencies may be important in reducing soil saturation and anaerobic conditions in the root zone for sustaining long-term land application (Crites et al. 2000).

Table I1. Cumulative Tritium ET Efficiency (%) on Monitoring Plots by Sample Date for 2001.

Schedule	*Plot*	*16-May*	*21-Jun*	*18-Jul*	*15-Aug*	*12-Sep*	*10-Oct*	*15-Nov*	*7-Dec*
	4	62.2	83.3	62.5	64.8	83.4	79.3	89.0	81.1
	19	53.8	62.4	73.8	56.4	65.3	87.1	84.2	90.1
18-mm	**Ave.**	**58.0**	**72.9**	**68.1**	**60.6**	**74.4**	**83.2**	**86.6**	**85.6**
	13	40.8	69.6	73.9	77.8	50.9	75.5	65.1	75.8
	16	72.3	88.3	85.7	71.3	81.9	83.8	83.2	86.2
12-mm	**Ave.**	**56.5**	**79.0**	**79.8**	**74.5**	**66.4**	**79.6**	**74.1**	**81.0**
	22	62.4	87.8	87.8	68.2	68.8	74.1	70.6	75.5
	27	83.4	67.9	67.9	78.8	74.6	79.7	95.3	78.7
6-mm	**Ave.**	**72.9**	**77.9**	**76.8**	**73.5**	**71.7**	**76.9**	**83.0**	**77.1**
All Plots	Mean	62.5	76.6	74.9	69.5	70.8	79.9	81.2	81.2

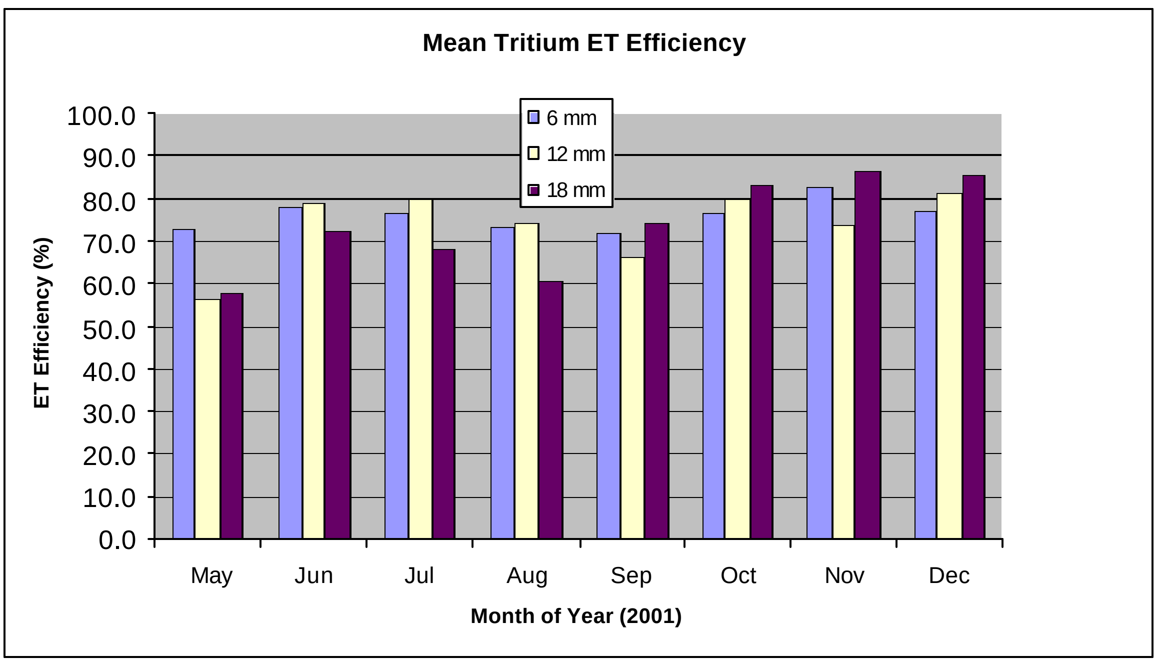


Figure I1. Mean Tritium ET Efficiency by Month and Irrigation Schedule.

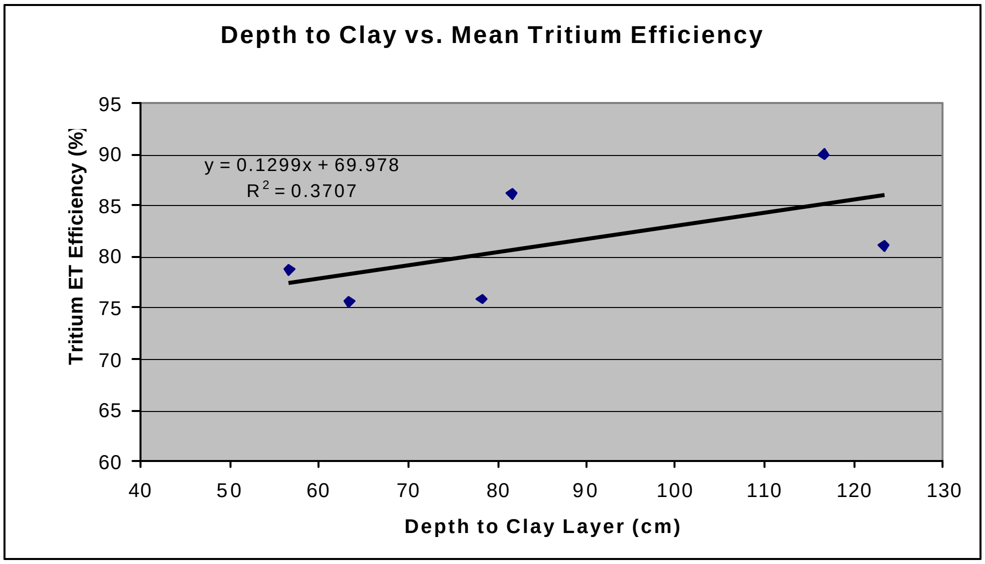


Figure I2. Mean Tritium Efficiency in Relation to the Average Depth to Clay. Depth is average for three monitoring clusters per plot. Clay content transitioned from <10% to 22-28% at the selected depth.

It is not clear whether the differences in efficiency can be exploited in terms of design and optimization of system performance. The differences were only obvious during the fall period during which significant SWD were measured. Modeling of water uptake and associated root distributions (inverse modeling) by Cornell University (March 2002) shows that the depth to clay influences relative water uptake. Soils with a deeper clay layer are extracting larger amounts of water at depth relative to those with shallow clay layers. However, this could be confounded with the vegetation composition,since the 18-mm and 12-mm plots also containing relatively more laurel oak and slash pine.

Effectiveness Estimate

<u>Vegetation ET and Soil Content of Tritium</u>: The average ET efficiency for each month was applied to the cumulative amount of tritium applied in the irrigation water for the period. The latter assumes that scheduling per se had no effect and that the monitoring plots are a representative of the watershed as a whole. Figure I3 shows the cumulative change in tritium partitioning between the soil and atmosphere. The effect of the drought coupled with the reduced winter irrigation schedule combined to increase the total tritium flux to the atmosphere. Using the average ET efficiency for December, then of the 657 curies of tritium applied, approximately 536 curies were transferred to the atmosphere via ET on the watershed. The tritium remaining in the vadose zone can be partitioned between that in the effective root zone, which is subject to vegetation uptake and transpiration, and that below the root zone that will return through subsurface flow. Integration of the December tritium content between the surface to 2-m, and 2 to 3-m was conducted on 14 of the 18 clusters. Of the 121 curies remaining in the soil profile,

approximately 31 curies are in the vadose zone below the effective root zone, and 92 curies remain in the effective root zone.

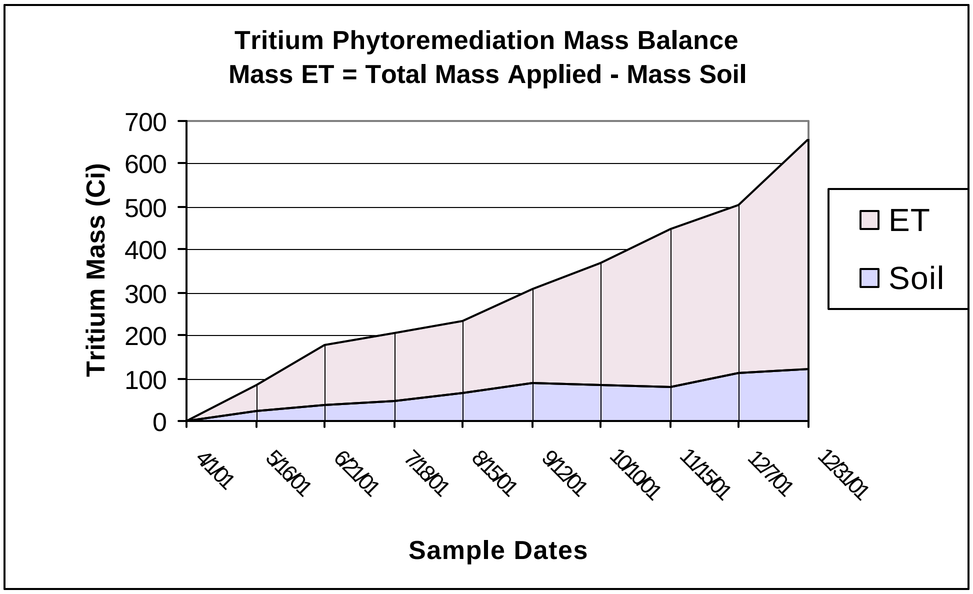


Figure I3. Cumulative Tritium Partitioning of Irrigation Water for All Plots During CY2001.

Pond Evaporation and Storage: The pond contributes to system effectiveness by direct evaporation of tritiated water to the atmosphere. In addition, tritiated water retained in the pond on December 31st did not discharge to Fourmile Branch. The amount of tritium lost to the atmosphere by evaporation was estimated by multiplying the daily quantity of water evaporated using the PM equation (see Table C3) by the pond tritium activity (Figure H4). It was assumed that rainwater mixed uniformly and instantaneously so that pond activity was equal to surface activity, and the partial pressure gradient had no influence on loss (Horton et al. 1971). The tritium lost from the pond surface by month and the total tritium content retained in the pond at the end of the month is displayed in Table I2. For the CY2001, 79 Ci of tritium were transferred to the atmosphere from the pond and 51 Ci of tritium was retained in the pond water at the end of December. Of the total amount of tritium transferred to the atmosphere, 13% was contributed from the pond surface.

Table I2. Pond Evaporation and Storage of Tritium During CY2001.

Month	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
Evaporation of Tritium (Ci)	7.5	10.3	12.2	12.6	11.8	7.8	8.2	4.9	3.6
Pond Storage of Tritium (Ci)	62.4	88.1	68.5	65.4	36.5	45.2	44.2	37.6	51.0

CY2001 Effectiveness: The following is the estimate for CY2001 based on pond evaporation and retention, and the 657 Ci applied in irrigation, of which 81.2% was removed from the system via evapotranspiration.

Transferred to the Atmosphere	
ET from Vegetation	= 534 Ci
Pond Evaporation	= 79 Ci
Total	= 613 Ci
Temporary Retention	
Soil (0 to 2-m)	= 92 Ci
Pond Water	= 51 Ci
Total	= 143 Ci
Flux Below Effective Root Zone	
Soil (2 to 3-m)	= 31 Ci

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Appendices

A. Locations and Installation Dates of Designated Instrumentation.
B. Thirty-year Average Daily ET from Augusta, GA Developed by Cornell University Based on the Priestly Taylor Method.
C. Cornell University October 2001 report.
D. Cornell University March 2002 report.
E. Pond Elevation vs. Pond Volume and Surface Area
F. Vertical TDR Data Averaged By Plot for CY2001
G. Surface TDR Data Averaged by Plot for CY2001.
H. Tensiometer Data Averaged by Plot for CY2001.
I. Tritium Data for Soil Lysimeter Samples for CY2001.
J. Tritium Data for Soil Water Vapor Tubes for CY2001.