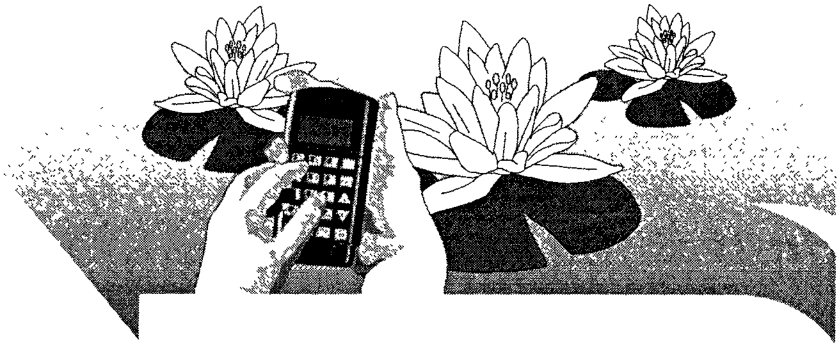
FINAL
CONTRACT REPORT

EVALUATION OF METHODS TO CALCULATE A WETLANDS WATER BALANCE



W. LEE DANIELS, ANGELA CUMMINGS,
MIKE SCHMIDT, AND NICOLE FOMCHENKO
Department of Crop and Soil Environmental Sciences
Virginia Polytechnic and State University

GARY SPEIRAN AND MIKE FOCAZIO
United States Geologic Survey

G. MICHAEL FITCH
Virginia Transportation Research Council

V · I · R · G · I · N · I · A
VTRC
TRANSPORTATION RESEARCH COUNCIL

VIRGINIA TRANSPORTATION RESEARCH COUNCIL

Standard Title Page - Report on State Project

Report No.	Report Date	No. Pages	Type Report:	Project No.:
			Final Contract Report	21545
VTRC 01-CR1	August 2000	62	Period Covered: July 1995 -June 1999	Contract No.

Title:
Evaluation of Methods to Calculate a Wetlands Water Balance

Authors:
W. Lee Daniels, Angela Cummings, Mike Schmidt, Nicole Fomchenko,
Gary Speiran, Mike Focazio, and G. Michael Fitch

Performing Organization Name and Address:

Virginia Tech
Department of Crop and Soil Environmental Sciences
244 Smyth Hall
Blacksburg, VA 24061-0404

Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903

Sponsoring Agencies' Name and Address

Virginia Department of Transportation
1401 E. Broad Street
Richmond, VA 23219

Supplementary Notes

Abstract

The development of a workable approach to estimating mitigation site water budgets is a high priority for VDOT and the wetlands research and design community in general as they attempt to create successful mitigation sites. Additionally, correct soil physical, chemical and biological properties must be restored that are appropriate to the intended wetlands biota in order for the sites to function similar to a natural sites that they are replacing. The major objectives of this research program were to evaluate the currently recommended procedures for estimating wetland water balances and to characterize the soil and hydrologic regime present at natural and constructed sites and their interaction with wetlands biota.

This report records our efforts to develop an estimated overall water budget at VDOT's Ft. Lee mitigation site along with a summary of our previous water budget studies at Manassas. Detail on supporting studies is also provided along with an overall summary of multi-year research results and implications. In this report, the terms *water balance* and *water budget* are used almost interchangeably. In our view, however, water budgets are developed by humans to interpret actual wetland water balances.

It was concluded that the use of the Pierce (1993) approach for developing mitigation wetland water budgets is prone to a number of errors in surface water charging estimates and ET estimates via the Thornthwaite method. The Pierce approach is most appropriate for estimating water budgets in surface water driven emergent/shrub-scrub systems with little ground water flux that rely upon berms or other water control structures to detain and pond water over impermeable soils or strata. Additionally it was found that the development of soil redox features, particularly the quantity and distinctness of oxidized rhizospheres can be reliably used to interpret hydric soil development sequences in mitigation wetlands. However, the reestablishment of an appropriate mitigation site wetness regime to one that appears to meet jurisdictional wetness criteria will not always guarantee the success of desirable hydrophytic vegetation over time.

FINAL CONTRACT REPORT

EVALUATION OF METHODS TO CALCULATE A WETLANDS WATER BALANCE

W. Lee Daniels, Angela Cummings, Mike Schmidt, and Nicole Fomchenko
Department of Crop and Soil Environmental Sciences
Virginia Polytechnic Institute and State University

Gary Speiran and Mike Focazio
United States Geological Survey

G. Michael Fitch
Virginia Transportation Research Council

Contract Research Sponsored by
Virginia Transportation Research Council

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia)

Charlottesville, Virginia

September 2000
VTRC 01-CR1

NOTICE

The project that is the subject of this report was done under contract for the Virginia Department of Transportation, Virginia Transportation Research Council. The opinions and conclusions expressed or implied are those of the contractors, and, although they have been accepted as appropriate by the project monitors, they are not necessarily those of the Virginia Transportation Research Council or the Virginia Department of Transportation.

Each contract report is peer reviewed and accepted for publication by Research Council staff with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

ABSTRACT

The development of a workable approach to estimating mitigation site water budgets is a high priority for VDOT and the wetlands research and design community in general as they attempt to create successful mitigation sites. Additionally, correct soil physical, chemical and biological properties must be restored that are appropriate to the intended wetlands biota in order for the sites to function similar to the natural sites that they are replacing. The major objectives of this research program were to evaluate the currently recommended procedures for estimating wetland water balances and to characterize the soil and hydrologic regime present at natural and constructed sites and their interaction with wetlands biota.

This report records our efforts to develop an estimated overall water budget at VDOT's Ft. Lee mitigation site along with a summary of our previous water budget studies at Manassas. Detail on supporting studies is also provided along with an overall summary of multi-year research results and implications. In this report, the terms *water balance* and *water budget* are used almost interchangeably. In our view, however, water budgets are developed by humans to interpret actual wetland water balances.

A general planning approach to mitigation site water budgeting has been developed by Pierce (1993) and is used widely by regulators and consultants. It was concluded that this approach for developing detailed site-specific mitigation wetland water budgets is prone to a number of errors in surface water charging estimates and ET estimates via the Thornthwaite method. The Pierce approach is most appropriate for estimating water budgets in surface water driven emergent/shrub-scrub systems with little ground water flux that rely upon berms or other water control structures to detain and pond water over impermeable soils or strata. Additionally, it was found that the development of soil redox features, particularly the quantity and distinctness of oxidized rhizospheres can be reliably used to interpret hydric soil development sequences in mitigation wetlands. However, the reestablishment of an appropriate mitigation site wetness regime to one that appears to meet jurisdictional wetness criteria will not always guarantee the success of desirable hydrophytic vegetation over time.

FINAL CONTRACT REPORT

EVALUATION OF METHODS TO CALCULATE A WETLANDS WATER BALANCE

W. Lee Daniels, Angela Cummings, Mike Schmidt, and Nicole Fomchenko
Department of Crop and Soil Environmental Sciences
Virginia Polytechnic Institute and State University

Gary Speiran and Mike Focazio
United States Geological Survey

G. Michael Fitch
Virginia Transportation Research Council

BACKGROUND

This report summarizes results through June of 1999 from our multi-year wetlands mitigation research program with the Virginia Department of Transportation (VDOT), the Virginia Transportation Research Council (VTRC), and the United States Geological Survey (USGS). Since 1995, this research program has focused upon water budget analyses for mitigation wetlands, and this is the final and cumulative report. Over the past project year (July 1998 to June 1999), we completed our monitoring and analyses of the water balance and associated soil hydrologic conditions at the Ft. Lee mitigation wetland. Earlier reports (Daniels et al., 1996, 1998) also focused upon a natural wetland site in Manassas that is currently under development to be converted and/or expanded to forested wetlands in the next year. The Ft. Lee site was constructed in 1991 and was the focus of an ongoing oversight debate with the U.S. Army Corps of Engineers, particularly with regard to its long-term predicted water balance. By placing the water budget work at these particular sites, we were able to take advantage of other project-related construction planning and monitoring programs, which greatly aided our efforts. As discussed in our previous reports and in this final summary document, accurate water budgeting is an essential component of effective mitigation site design. However, before this report, very little guidance has been available to VDOT and the regulatory community regarding the effectiveness of various water budgeting procedures and water budget component estimators.

Historically, wetlands were viewed as systems that impeded development and that should be drained and reclaimed for other purposes (Fretwell et al., 1996). In recent years, however, wetlands have become valued for unique habitat, water-quality improvement, flood attenuation, and other purposes. Consequently, the U.S. Army Corps of Engineers developed regulations to protect wetlands. Although these regulations are intended to prevent the loss of existing wetlands, destruction of wetlands cannot be avoided in certain instances. To mitigate the effects of such wetlands losses, these regulations require the replacement of destroyed wetlands with wetlands constructed where wetlands previously were not present or with wetlands restored from previously drained or destroyed wetlands. The regulations require replacement of each acre of destroyed wetlands with new wetlands. A mitigation ratio of 1:1 to up to 5:1 is common for replacement:original wetlands. Replacement wetlands generally must be of the same type as those destroyed, which requires the return of appropriate wetness and soils conditions.

Water is an important component in establishing a wetland. The exact role of water in many wetlands, however, is poorly understood. In order to create or restore wetlands of a specific type, a water budget must be evaluated to ensure that the wetland is designed to have sufficient water seasonally to maintain the wetland. The Norfolk District of the Corps of Engineers provided guidelines to evaluate wetland water budgets (Westbrook, 1994). These guidelines make assumptions and suggest simple methods for quantifying components of a water budget. In some cases, the methods might be inadequate for estimating wetland water budget components. Consequently, wetlands could be improperly designed in these cases, resulting in failure to establish the desired type of wetland. Therefore, other methods for estimating certain components of wetland water budgets may be necessary.

Mitigation wetlands are also required to develop hydric soil conditions, which are presumably related to the attainment of an appropriate wetland water balance. Evidence of hydric soil conditions is also required for regulatory release of permit conditions. However, very few studies of hydric soil development in mitigation wetlands and estimated rates of formation have been reported to date. In fact, before this study, no data were available for Virginia conditions on the genesis of hydric soil features over time and their relationship to reconstructed wetness regimes.

When one identifies hydric soils in the field, soil color is one of the easiest indicators to observe. Red and yellow indicate oxidized iron and zones of aeration. Gleyed (gray) colors occur where organic matter content is low and iron has been reduced and removed. Variegated redoximorphic color patterns are common in poorly drained (PD) soils and usually indicate a fluctuating water table (Buol & Rebertus, 1988). Subsoil color and redoximorphic features are primarily a function of iron reduction, which require anaerobic conditions, an energy source, and anaerobic microbes (Bouma, 1983).

In the Coastal Plain of North Carolina, Daniels et al. (1971) found pale brown and very pale brown (10 yr 6/3 and 7/3) redox concentrations that were prominent in Typic Paleudults at depths saturated 25% of the time, whereas redox depletions developed at depths saturated for 50% of the time. In Aquults, reduced matrices occurred at depths saturated for more than 50% of the time. Faulkner and Patrick (1992) reported a strong agreement between soil profile characteristics, hydrologic regimes, and wetland status of sites in alluvial bottomlands in Louisiana and Mississippi. Overall, the quantitative data (soil redox potential and water table depth) supported the qualitative field indicators (soil profile characteristics). Schelling (1960) reported that depth to specific gray redox depletions estimated the mean wet season high water table. Simonson and Boersma (1972) found that depth to faint and distinct redox features strongly correlated with a high degree of saturation. Overall, the use of field indicators to determine moisture regimes assumes that a strong and direct correlation exists between redox potential, O_2 content, water table depth, and color (Megonigal et al., 1993). However, the length of saturation required at a given depth is far less certain (Genthner et al., 1998).

The application of redoximorphic features as indicators of soil wetness has been rigorously investigated in natural soils. However, very little work related to redox features and constructed wetland hydrology has been conducted to date. Constructed wetlands are manmade systems, often with altered hydrology. The validity of redox features to indicate soil wetness in a constructed wetland needs to be examined further. Atkinson et al. (1998) observed redox features, including depleted matrices and oxidized rhizospheres, in 10- to 30-year-old accidental depressional wetlands resulting from surface mining activities. Soil chroma was directly influenced by the duration of inundation. Permanently flooded sites exhibited lower chroma than sites with intermittent or semi-permanent flooding conditions.

Vepraskas et al. (1999) examined soils in constructed wetlands in Illinois to see if they functioned as hydric soils and evaluated chemical and morphological changes in created wetlands to monitor hydric soil indicator development within constructed wetlands. In a constructed deep marsh, soils in and along the marsh edge were classified as hydric 5 years after construction. Redox potentials and well records indicated that soils in the marsh and along its edge met the hydric soil definition throughout the study, upland positions did not, and areas in the transition zones met the definition in some years. After 5 years, depleted matrices were fully developed and consistently identified as hydric soils. This study was conducted at a demonstration project where the hydrologic regime could be controlled. Most mitigation wetlands are subject to seasonal flooding and dry down, which greatly affect the timing and duration of saturation. Therefore, the rate of iron oxidation and reduction and redox feature development would be affected.

In a constructed floodplain wetland, Vepraskas et al. (1995) found that redox depletions and pore linings could be used to identify jurisdictional wetland boundaries in constructed wetlands saturated for relatively short periods of time (7 to 14 days). Increased abundance and size of redox depletions were found to be related to soil organic matter levels greater than 3%. Redox features were not observed in areas with less than 1.5% organic matter. As discussed earlier, redoximorphic feature development is site specific, varying with organic matter content, temperature, and chemical characteristics.

PURPOSE AND SCOPE

The development of a workable approach to estimating mitigation site water budgets is a high priority for VDOT and the wetlands research and design community in general. In particular, we need to be able to look at a designated compensation site before grading commences (or before the land is actually purchased) and predict what the soil wetness regime will be across the site after the final grading and development is complete. Additionally, correct soil physical, chemical, and biological properties must be restored that are appropriate to the intended wetlands biota. In fact, preconstruction water budget modeling is required by the Corps of Engineers, but they do not require a specific method. When this research program was initiated, we queried VDOT's Norfolk District on this issue and they provided us with an example method by Westbrook (1994) that is based largely on a more detailed method described by Pierce (1993). This method generally assumes limited ground water inputs/outputs, estimates surface run-on via the Soil Conservation Service (SCS) Runoff Curve approach, predicts evapotranspiration (ET) via the Thornthwaite (1948) algorithm, and then assumes that berms or other water control structures will detain water at sufficient depths to support wetland hydrology over the growing season. Over the initial phases of our statewide VDOT wetlands research program (in the early 1990s), we evaluated several approaches to estimate actual site water budgets more precisely. However, we were not able to identify an acceptable approach that we believed was adaptable to the nature and scale of mitigation sites created by VDOT. In particular, we found virtually no available research data to corroborate the critical and site-specific ET component of water budgets. We also identified an overall lack of information on the mechanics and procedures required to excavate, grade, and fill mitigation sites to insure that post-development soil properties will be appropriate for wetlands plantings.

Therefore, the overall objectives of this research program were:

1. To evaluate the currently recommended procedures for estimating wetland water balances and to compare the results obtained to actual wetland water balance data from natural and constructed wetland sites.

2. To characterize the soil and hydrologic regime present at natural and constructed sites and their interaction with wetlands biota.

3. To compare site-specific ET estimates for the study sites as developed by a variety of alternative approaches.

4. To develop and verify site-specific overall water balances for our research sites.

5. To characterize the soil and hydrologic regime at the Ft. Lee mitigation site with respect to hydric soil morphological development rates and the effects of soil wetness regime on soil development and mitigation planting success.

In this report, we provide a detailed description of our efforts to develop an estimated overall water budget at the Ft. Lee site along with a summary of our previous water budget studies at Manassas. Detail on supporting studies is also provided along with an overall summary of multi-year research results and implications. In this report, the terms *water balance* and *water budget* are used almost interchangeably. In our view, however, water budgets are developed by humans to interpret actual wetland water balances.

This work has been cooperative among Virginia Tech, USGS, and VTRC. The USGS work reported is subject to further USGS revision. The results and conclusions reported at the end of this report are based on the Virginia Tech/VTRC interpretation of all data sets available for this project over time and do not necessarily reflect the official opinion of the USGS.

RESEARCH AT THE FORT LEE MITIGATION SITE

Site Description

The Ft. Lee mitigation site is a large (13.8 ha) constructed non-tidal forested wetland adjacent to I-295 North, southwest of Richmond in Prince George County, Virginia. The site lies entirely within the Coastal Plain physiographic province (Figure 1). Data recorded in Hopewell, Virginia, from 1951 to 1978 show that the average growing season lasts from March 22 until November 6 based on air temperature. The average daily temperature is 15° C and the average winter temperature is 5° C. Annually, the county receives an average of 1.13 m of precipitation, with 50% falling between April and September (SCS, 1985).

The Ft. Lee mitigation area is paired with a natural forested wetland that lies between the mitigation site and Cabin Creek, a second-order Coastal Plain stream. Plio-Pleistocene estuarine-fill deposits underlie the entire site (Mixon et al., 1989). The Soil Survey of Prince George County, Virginia (SCS, 1985), has mapped the reference area as map unit 14-Kinston complex. These are deep, PD soils formed from loamy fluvial sediments on floodplains, with a slope ranging from 0% to 2%. These soils do not have a well-developed subsoil because of a high water table and periodic, brief flooding events. According to the standard series criteria, from November to June, the water table rises to within 0.3 m of the soil surface in these soils for a brief to long duration. Flooding events are rare to common in frequency, with events most commonly occurring from November to June. Soils of the Kinston complex are so intermingled with Bibb and Chastain soils that they were not mapped separately. Included throughout the unit are both sandy (Bibb series) and clayey (Chastain series) PD soils. Also included in the complex are small areas of well drained Emporia soils and somewhat poorly drained Slagle soils (SCS, 1985). The Kinston series is classified as Fluvaquentic Endoaquepts and it is listed as a hydric soil (National Technical Committee for Hydric Soils, 1995).

The original side slope and upland that were excavated to form the mitigation site were mapped as 25B-Slagle sandy loam, 2% to 6% slopes and 11B-Emporia fine sandy loam, 2% to 6% slopes, respectively. The Slagle soils are deep, somewhat poorly drained soils on side slopes, classified as Aquic Hapludults. Slagle is not classified as a hydric soil. The Emporia soils are deep, well-drained soils on uplands and are classified as Typic Hapludults, also non-hydric.

The final surface of the mitigation area was formed in 1991 by excavating the adjacent hillside down to the presumed water table level under the original uplands. Final grade elevations were based on limited winter well observations recorded by VDOT from 1990 to 1991. Twenty-five centimeters of upland topsoil was added to achieve final grade in November 1991. The site was originally seeded in tall fescue (*Festuca arundinaceae* Schreb.) and has since been planted with forested wetland species such as red maple (*Acer rubrum* L.) and bald cypress (*Taxodium distichum* L.).

A narrow strip of natural wooded wetland lies between the created wetland and Cabin Creek. Land surface is low and flat across the natural wetland with several natural depressions. A drainage ditch was constructed near the north end of the created wetland connecting the created wetland and Cabin Creek. Land surface west of the interstate is 6 to 12 m higher than that of the created wetland. Four culverts drain from the west under the interstate into the created wetland.

Water in the wetland is derived from (1) precipitation that falls directly on the wetland, (2) surface water runoff from the interstate, (3) surface water runoff and ground water discharge that flows through the four culverts that drain under the interstate, (4) ground water that discharges from seeps on the slope between the interstate and the wetland, and (5) ground water that flows through the surficial aquifer and discharges to the wetland. The magnitude of these sources changes seasonally and annually. Water discharges from the wetland to the east toward Cabin Creek by (1) ground water flow through the surficial aquifer, (2) surface water flow through the drainage ditch and surface depressions on the eastern side of the wetland, and (3) surface water flow across the extensive low area on the eastern side of the wetland. Water also discharges from the wetlands as ET. Like the magnitude of the sources of water, the magnitude of discharge through the different pathways changes seasonally and annually.

At the lowest level of standing water at which surface water flows from the wetland to Cabin Creek, surface water primarily flows through the drainage ditch at the north end of the wetland. As the level of the standing water increases, surface water also flows through the natural depressions along the east side of the wetland. At even higher levels of standing water, surface water then flows across much of the extensive low area on the east side of the wetland.

Methodology

Water Balance Measurements and Analyses

Data collection began in May 1996 and ended in June 1999. Collection of different types of data began at different times. Collected data include (1) precipitation, (2) stage of water in one of the culverts under the interstate, (3) periodically measured ground water levels from wells located across the site, (4) continuously measured ground water levels from one well located near the center of the site, and (5) energy balance measurements from near the center of the site (Figure 2).

Precipitation

Precipitation data were collected by use of a tipping-bucket rain gage installed in March 1998 (Figure 2). Data were collected from March 1998 through June 1999. The summer and fall of 1998 were especially dry, resulting in a low precipitation total of 0.90 m. Since precipitation is expressed on a water level basis for overall water budgeting, no corrections for wetland area were needed.

Surface Water Additions and Losses

A stage gage was installed at the third culvert under the interstate (heading north) in March 1998 (Figure 2). The purpose of the stage gage was to determine the amount of surface water flow into the wetland from one of the sub-basins that contributes water to the wetland. This surface water flow was to be used to estimate the total surface water flow into the wetland from all contributing sub-basins. To determine the surface water flow at a gage, a stage-discharge relation needs to be developed for the range of stage measured at the gage. Because the small size of the sub-basin caused stage to rise and fall rapidly during precipitation periods, personnel were unable to be at the site and measure flow during precipitation periods. A water truck was used to provide flow through the culvert that could be measured for developing a rating. The maximum flow from the truck, however, was not sufficient for developing the rating. Consequently, surface water flow to the study site could not be estimated.

Another initial intent of the study was to measure surface water flow from the site continuously. Backwater from Cabin Creek, flow through the multiple depressions, and flow across the extensive low area, however, precluded the continuous measurement of surface water flow from the site without the use of extensive instrumentation and field measurements that were beyond the scope of funding of the project. Therefore, surface water inputs for the derived water budget was estimated using the SCS runoff curve method (U.S. Department of Agriculture, 1973). The SCS runoff method provides a relationship between rainfall and runoff for a watershed area. Based on the soil type, land use and antecedent soil moisture content (AMC), the SCS method provides a relationship to reduce the runoff from the maximum of accumulated rainfall. The relationship, $Q = (P - 0.2S)^2/(P + 0.8S)$, provides the runoff (Q) based on the precipitation (P) and potential maximum soil retention (S). The value of S changes based on land use, soil type (four classes), and AMC. Three AMC conditions are used: I for dry periods, II for average moisture periods, and III for wet periods. These ratings depend on the season (i.e., growing or dormant) and the cumulative rainfall for the 5 days before a storm event (Fomchenko, 1998).

The watershed that contributes to the Ft. Lee wetland was delineated from a topographic map and estimated to cover 33.8 ha. From observations and the topographic map, this area (part of the Ft. Lee Military Reservation) appears to be wooded, although the entire watershed has not been surveyed. A soil group of C, moderately high runoff potential, was used. Depending on the AMC, this resulted in S values of 9.61, 4.29, and 1.76 for AMC I through III, respectively. The runoff was converted from the volume basis to a water level over 12.42 ha, the area of the wetland. Owing to the dry year (98/99) modeled, surface water inflow was low, with most inflow coming in a few storm events during the winter. The lack of precipitation was compounded by the AMC almost entirely being in the dry classification. Under this estimate with AMC I, a minimum storm event of 0.048 m is needed for any runoff to occur. Therefore, the few large storms (>0.025 m) during the summer resulted in relatively insignificant amounts of runoff loading to the wetland.

Ground Water

Monthly ground water levels were measured in wells across the site (Figure 2) by Virginia Tech throughout the study period. Later in the study, the USGS augmented this data collection effort by measuring water levels during the middle of each month. These water levels reflect general seasonal changes in ground water levels across the site and can be used to construct water table maps of the site. Water levels were also measured continuously in one well (FL2) where land surface is slightly elevated near the center of the site (Figure 2). Water levels from this well show detailed seasonal and short-term changes in ground water levels that can be used for various purposes.

ET

Instrumentation for measuring meteorological data was installed in May 1996 (Figure 2). These data are required for an energy balance used in calculating ET rates by the Bowen ratio and other methods discussed later. Collected data included air temperature and specific humidity at 1 and 2 m above land surface, net radiation, wind speed, wind direction, soil temperature at two locations, soil heat flux, and the temperature of standing water in the wetland at two locations. Data were measured and recorded every 15 minutes. Not all data are needed for direct use in the Bowen ratio method but were collected for use in the other methods (e.g., Blaney-Criddle) or for the evaluation of possible limitations of the Bowen ratio method.

Estimated Annual Water Budget

One of our major overall objectives for the past project year at Ft. Lee was to develop an approximate water budget for the site using the best available site-specific data and estimation procedures. The estimated water budget presented here was developed based upon the site specific data gathered by USGS as discussed in the previous section along with various estimation approaches for surface water inputs and outputs where on-site measurement was not possible. For the purposes of this study, we chose the period from May 1, 1998, to April 30, 1999, to construct this estimated water budget for the Ft. Lee wetland. This was a very dry year, but regardless, we feel that the derived budget and relative component proportions tell us quite a bit about the overall hydrologic regime of this site.

A water budget balances all of the inputs and outputs of water into a system, in our case, the Ft. Lee mitigation wetland. A general water budget can be expressed as:

$$P + SWI + GWI = ET + SWO + GWO \pm \Delta S$$

where

P = precipitation

SWI = surface water inflow

GWI = ground water inflow

ET = evapotranspiration

SWO = surface water outflow

GWO = ground water outflow

ΔS = change in storage (Fomchenko, 1998).

Depending on the components of interest and the available data, this general equation can be modified. In our case, ground water was treated as a net flux and soil storage was neglected since well levels were similar on May 1, 1998, and April 30, 1999. This makes our specific water balance formula:

$$\pm \Delta GW = P + SWI - ET - SWO.$$

Each component of a water budget can be either measured in the field or estimated. Although estimates of components such as ET and surface and ground water fluxes are commonly used, they may add significant errors to the water budget. Fomchenko (1998) showed large differences between various estimates of ET and surface water inflow with the measured values in a wetland in Manassas. For this reason, our confidence in certain components of the Ft. Lee water budget is much better than in others.

The Bowen ratio method is widely accepted for determining ET and is often used as a control to develop and compare other, less costly, alternatives (Munro, 1979). Therefore, the Bowen ratio estimate was used for the majority of the estimated water budget. However, during the period of 9/28/98 to 1/28/99, this estimate was not available. During this period, the Blaney-Criddle estimate for the monthly average values was used instead.

Soil-Hydrologic Studies

For detailed soil/wetness regime studies, three transects were established across a previously determined wetland saturation gradient (obtained from well records), beginning at the western side of the mitigation site extending through the reference area to Cabin Creek. Within each transect, five pits were excavated to 1.0 m. Pit locations corresponded with existing wells and were based on well records and dominant vegetation types. Along each transect, two pits were located in very poorly drained (VPD) areas, one in the mitigation wetland and one in a similar area within the reference wetland. Two pits were located in poorly drained (PD) areas of the mitigation wetland and reference wetland, and one pit was excavated in a somewhat poorly drained (SWPD) area of the mitigation wetland. There were no SWPD areas observed within the reference wetland.

The soils were described and classified according to National Cooperative Soil Survey procedures (Soil Survey Staff, 1994) in July 1998. Special attention was placed on the degree and extent of redoximorphic features and overall pedogenesis within each horizon. Quantitative counts were made for redoximorphic features by horizon within a 0.01-m^2 sample area of each horizon. In horizons thinner than 0.1 m, a 0.0025-m^2 sample area was used. Qualitative notes were made on the abundance, size, and color of redoximorphic features by horizon.

Results/Discussion

Water Balance Measurements and Analyses

Precipitation

Daily and monthly precipitation varied temporally (Figures 3 and 4, respectively). The greatest daily precipitation was 0.070 m on December 13, 1998 (Figure 3). Monthly precipitation ranged from 0.017 m in October 1998 to 0.194 m in March 1998 (Figure 4). Annual precipitation was 1.023 m for March 1998 through February 1999. Because the spring of 1998 ended a wet period and the summer of 1998 began a dry period, the annual precipitation was only 0.839 m from June 1998 through May 1999.

Ground Water Levels

Ground water levels reflect seasonal and short-term response to (1) ground water recharge by precipitation and standing water, (2) ground water inflow to and outflow from the site through the surficial aquifer, (3) ground water discharge by ET, and (4) ground water discharge to standing water in the wetland (Figure 5).

Seasonal Water-Level Fluctuations. Ground water levels were higher in the winter and spring than in the summer because (1) rates of discharge by ET were lower in the winter than in the summer, (2) ground water recharge rates from precipitation were higher in the winter and spring than in the summer, and (3) precipitation produced greater amounts of surface runoff to the wetland in the winter and spring than in the summer (Figure 5). Because ground water and surface water are hydraulically interconnected, surface runoff to the wetland recharged the ground water when ground water levels were low. Conversely, ground water discharged to the standing water in the wetland when ground water levels were high.

Ground water levels generally were near land surface during the winter and spring, declined to as much as 0.9 m below land surface in the summer and varied in the fall depending on the year. Ground water levels declined less in the summer of 1996 than the summers of 1997 and 1998. Ground water levels generally remained less than 0.25 m below land surface during the summer of 1996 and were near land surface by late summer. Extended dry periods during the summers of 1997 and 1998 contributed to declines in ground water levels to more than 0.75 m below land surface. Declines were to greater depths in the summer of 1997 but extended over a longer period during the summer of 1998. Ground water levels returned to near land surface in the early fall of 1997 but remained low until late fall of 1998.

Diurnal Water-Level Fluctuations. When standing water and soil moisture are limited, ET draws water from the water table through unsaturated soil to the roots and land surface causing ground water levels to fluctuate in daily (diurnal) cycles (Figure 6). Flow from the water table through the soil results from a combination of capillary action and other processes that cause flow through unsaturated soil. Diurnal cycles in ground water levels reflect the combined effects of discharge by ET and ground water flow to and from the site. Ground water is supplied for ET by ground water flow through the aquifer to the site and ground water storage. Declines in ground water levels from one day to the next reflect the decrease in ground water storage.

Changes in the characteristics of graphs of diurnal cycles reflect changes in the hydrology. During certain periods, a continuous net discharge of ground water through the aquifer took place creating a continuous, rather uniform rate of decline in ground water levels (July 16 through 21, 1997, for example). No diurnal cycles were evident at these times. Such declines show little effect of ET, probably because standing water and soil moisture supply most of the water for ET. During periods when these sources of water become limited, diurnal cycles are evident. These cycles have various characteristic patterns. In a pattern common when diurnal cycles first appear at the site, ground water levels decreased during the day when ET was high but changed little during the night when ET was low (July 10 and 11, 1997, for example). This indicates that discharge by ET controlled ground water levels during the day, but ground water inflow and outflow through the aquifer were approximately in equilibrium during the night. During yet other periods, ground water levels declined during the day as a result of discharge by ET from the ground water and rose during the night as a result of a net ground water inflow through the aquifer (July 12 through 15, 1997, for example). Although ground water likely flowed from the site through the aquifer at these times, a greater amount of water flowed to the site through the aquifer than from the site. This relative change in ground water inflow and outflow after precipitation probably resulted from a decrease in ground water discharge to Cabin Creek and an increase in ground water discharge through ET.

Ground water and soil moisture were the primary, if not the only, sources of water for ET at these times. Much of the soil moisture probably was ground water that remained in the soil as water levels declined and the soil became unsaturated. Discharge from the ground water by ET can occur even when the water table is below the root zone because water flows from the water table through the unsaturated soil to the roots.

Water Table Elevation and Ground Water Flow Directions. Although the elevation of the water table changed seasonally, the direction of ground water flow changed little through the year. The water table generally sloped to the north and east, indicating the flow of ground water in that direction toward Cabin Creek (Figures 7 through 10). During periods of standing water in the wetland, the elevation of the water table at most locations is similar to the elevation of the standing water. Because much of the standing water flows from the site through the ditch to Cabin Creek at the northeast corner of the wetland, standing water flows through the wetland to the north and east, similar to the direction of the slope in the water table.

ET

This report compares ET rates calculated by the Bowen ratio method with potential ET rates calculated by the Thornthwaite and Blaney-Criddle methods. In estimating potential ET, it is assumed that water availability does not limit ET. When sufficient water is not available, actual ET should be less than potential ET.

These methods are designed to calculate ET rates for different periods. The Bowen ratio method is used to calculate daily ET rates. In contrast, the Thornthwaite and Blaney-Criddle methods can be used to calculate only monthly rates of potential ET. Thus, daily rates calculated by the Bowen ratio method were summed by month for comparison with rates calculated by the Thornthwaite and Blaney-Criddle methods. ET rates calculated by the Bowen ratio method are also used to evaluate the use of diurnal ground water fluctuations for calculating ET rates.

Latent heat flux is the principle determination required for the Bowen ratio method. The latent heat flux for the Ft. Lee site followed diurnal and seasonal cycles in response to daily and seasonal changes in solar radiation (Figure 11). The latent heat flux is negative during the daytime, indicating a flux toward land surface. This flux is used in ET. The daily duration and magnitude of the negative latent heat flux are greater in August than December because the duration of daylight is longer and the sun is higher in the sky in August than in December. The effects of seasonal changes in the latent heat flux are also evident in the seasonal changes in rates of ET (Table 1, Figure 12). Monthly ET calculated by the Bowen ratio method ranged from 0.024 m in January 1998 to 0.200 m in June 1996. Peak monthly ET in 1997 and 1998 was 0.171 m in June and 0.152 m in July, respectively.

The Thornthwaite and Blaney-Criddle methods calculate potential ET from empirical relations among ET, mean monthly air temperature, and mean day length. The Blaney-Criddle method also uses a crop factor because it was developed to estimate the water needed by irrigated crops in the western United States. Consequently, the utility of the Blaney-Criddle method in the humid east is uncertain (Dunne & Leopold, 1978). A crop factor for pastures of 2.0 was used to estimate ET in this report. This factor is in the middle of the range of values of possible factors.

Monthly rates of potential ET calculated by the Thornthwaite and Blaney-Criddle methods were greatest in July, in contrast to the peak in ET calculated by the Bowen ratio method in June in 1996 and 1997 and in July in 1998 (Figure 12). Peak ET probably occurred in June in some years because the available energy for ET is greatest in June when days are the longest (Bowen ratio method) and temperatures are greatest in July (the Thornthwaite and Blaney-Criddle methods). Possible limitations resulting from water availability (discussed later) may also be a factor.

Monthly rates of potential ET calculated by the Thornthwaite method were less than monthly ET calculated by the Bowen ratio method in 22 of the 26 months (Figures 12 and 13). Monthly potential ET calculated by the Thornthwaite method ranged from 0.087 m less than that calculated by the Bowen ratio method in June 1996 to 0.24 m more than that calculated by the Bowen ratio method in September 1997. Potential ET calculated by the Thornthwaite method averaged 0.033 m per month less than that calculated by the Bowen ratio method for the period. The difference between Thornthwaite and Bowen ratio values was greatest early in the growing season. This generally was a time when standing water was present and ground water levels were high. The relatively low values calculated by the Thornthwaite method are of particular note because the Thornthwaite method estimates potential ET, which is the maximum ET likely to occur. Because ET rates calculated by the Thornthwaite method are low, the Thornthwaite method probably is not a good method for estimating ET at the Ft. Lee site and possibly at other wetland sites.

Thornthwaite values were greater than Bowen ratio values only in July, August, and September 1997 and August 1998 (Figure 12). The Thornthwaite values were likely greater than the Bowen ratio values during these months because these were extremely dry months. During these months, ET could become limited by the availability of water because precipitation was limited, standing water was not present in the wetlands, and ground water levels were low most of time during these months. The likelihood of this limitation is supported by the relation between daily ET calculated by the Bowen ratio method and daily maximum ground water levels (Figure 14). The maximum rate of ET decreased from about 8.89 mm per day when ground water levels were near land surface to 3.81 mm per day when ground water levels were 0.9 m below land, indicating that ground water can seasonally limit ET. Conversely, the large variability in ET at a given depth indicates that ET is also controlled by other factors. One of the major factors, as previously indicated, is the daily and seasonal change in energy availability.

Potential ET that was calculated by the Blaney-Criddle method was highly variable compared to Bowen ratio values (Figures 12 and 15). Blaney-Criddle values were less than Bowen ration values during 17 of 26 months. In general, Blaney-Criddle values were less than Bowen ratio values from fall through spring and were greater than Bowen ratio values in the summer (Figure 12). The Blaney-Criddle values ranged from 0.086 m less than the Bowen ratio value in April 1999 to 0.051 m greater than the Bowen ratio value in August 1998. Blaney-Criddle values averaged only 10.92 mm per month less than Bowen ratio values. Although the average difference between Blaney-Criddle and Bowen ratio values was about one third of the difference between Thornthwaite and Bowen ratio values, the range in differences between monthly values was similar (Figures 13 and 15). Unlike values from the Thornthwaite method, values from the Blaney-Criddle method can be adjusted by adjusting the crop factor. Such adjustment could improve estimates of ET by use of the Blaney-Criddle method. Research into these factors, however, would be necessary.

Diurnal cycles in ground water levels (Figure 6) can be used to estimate ET (White, 1932). In this method, water for ET is assumed to be derived from ground water inflow and the daily change in ground water storage. The equation for determining ET from ground water levels is:

$$ET = Sy\,(24h + s)$$

where

ET = daily ET rate

Sy = specific yield

h = average hourly rise in ground water levels when not affected by ET

s = net fall (+) or rise (-) in the water table over a 24-hour period.

Values of h and s are derived from the water level hydrographs. Specific yield, the ratio of the volume of water the soil will yield by gravity drainage to the volume of soil, can be obtained from laboratory tests, pumping tests, or the literature. The specific yield of sand typically ranges from 0.1 to 0.3 (Walton, 1970). By using the range of specific yield given by Walton (1970), ET values would vary by a factor of three. Consequently, specific yield is an important part of the determination of ET but typically has a high degree of uncertainty.

In the 1996 progress report, the likelihood of changes in specific yield with aquifer depth was proposed and used to estimate ET from ground water levels. Based on further analysis of the system, however, the apparent change in specific yield with aquifer depth likely results, in part, from the effects of water for ET derived from a combination of soil moisture, ground water, and standing water. When the level of standing water in the wetland is at its highest level, land surface around well FL2 is inundated, and water in the well is near the level of the standing water. As the level of standing water declines, increasing amounts of land surface around well FL2 become exposed. Thus, when standing water is present and ground water levels are high, both ground water and standing water provide water for ET. The resulting specific yield is a composite of that of the aquifer and that of the standing water. The specific yield of the standing water would be that fraction of the standing water not occupied by vegetation and would approach one. As water levels decline, water for ET is provided by increasing amounts of ground water and soil moisture and decreasing amounts of standing water. Consequently, specific yield decreases from that of the standing water to that of the aquifer.

This theory was evaluated by calculating values of specific yield from daily ET values determined by the Bowen ratio method and continuous ground water levels from well FL2. This information was applied to the equation for calculating ET from ground water by rearranging the equation to solve for specific yield,

$$Sy = ET/(24\mathrm{h} + s)$$

Specific yield that was calculated from this equation generally was greater than 0.3 when ground water levels were near land surface as indicated by the 1998 example (Figure 16). Ground water levels rose rapidly in response to precipitation, generally peaking the day of the precipitation (Figures 16A and 16B). For several days after the precipitation, diurnal cycles were not present in ground water levels and specific yield could not be calculated. As ground water levels declined, calculated specific yield declined to between 0.04 to 0.10 (Figure 16C). When ground water levels were shallower than – 0.15 m, the standing water was an important source of water for ET (Figure 17). Below a depth of about – 0.25 m, standing water appears to become a minor factor affecting ground water levels and ET near well FL2. At these depths, ground water and soil moisture appear to be the main sources of water for ET. Part of the soil moisture that is removed by ET results from drainage from the soil that is not replaced by unsaturated flow from the water table. By accounting for this water as ground water ET, the calculated specific yield remains artificially high. Only as this "excess" soil moisture is removed so that ground water is the only source of water for ET does the calculated specific yield accurately represent that of the aquifer. Thus, the lower calculated specific yields (0.04 to 0.10) probably best represent the specific yield of the aquifer. The spikes in the graph of specific yield (Figure 16C) commonly were periods when precipitation had added to the soil moisture. When soil moisture was again accounted for by ground water ET, calculated specific yield increased.Although the difference between specific yields of 0.04 and 0.10 is small in terms of the possible range in specific yield, it is large in relative ET predictive terms.

This difference is critical when calculating ET from ground water fluctuations. Use of a specific yield of 0.1 results in ET estimates 150% greater than those calculated from a specific yield of 0.04. If a specific yield were 0.24, however, an increase of 0.06 would only be a 25% increase. Thus, precise and accurate knowledge of specific yield is critical to estimating ET from ground water levels, particularly when specific yield is low. Based on these results, use of diurnal ground water fluctuations for estimating ET in wetlands is limited to when ground water levels are sufficiently deep that standing water and changing soil moisture is not a source of water. Although this limits the use of the method in calculating a water budget, the method could provide accurate estimates of ET when ground water is the only source of water for the vegetation. These typically are times that water availability might limit ET in a wetland and actual ET deviates the most from true potential ET. These could also be times that water availability could be critical to the survival of certain wetland vegetation. To use this method, however, accurate values of specific yield are necessary.

Ground water levels and precipitation can also be used to estimate specific yield. By assuming all of the precipitation recharges the ground water, specific yield can be calculated by dividing the precipitation by the water level rise. This can only be done when no standing water is present. Specific yield calculated by this method (Figure 18) was similar to that estimated from ET (Figure 17), ranging from about 0.04 to 0.1. This relation is most evident at precipitation values greater than 0.015 m. For some of the precipitation events of less than 0.015, calculated specific yield was greater than 0.1. Calculated specific yield would be artificially high because part of the precipitation would replace the soil-moisture deficit, although it was accounted for as ground water recharge in the calculation. A rise in ground water levels could not be distinguished from diurnal cycles in 11 of 18 periods having 0.254 to 5.59 mm of precipitation (Figure 18).

Role of Ground Water at the Site

Westbrook (1994) indicated that ground water is recharged by wetlands and that ground water is not a significant source of water to wetlands. Long- and short-term fluctuations in ground water levels at the Ft. Lee created wetland, however, reflect a significant role of ground water to the hydrology of the site. The significance of ground water changes as depth of ground water changes. When ground water levels are at, or near, land surface at well FL2 (Figure 5), ground water levels also reflect the level of standing water in the wetlands because (1) the elevation of land surface around FL2 is only slightly greater than that of the adjacent wetland and (2) ground water and surface water are hydraulically interconnected.

When ground water levels are high and standing water is present in the wetland, both ground water and surface water are important to the hydrology of the site. At these times, ground water seeps are abundant on the slope between the wetland and the interstate. Ground water discharge also continues to supply water to the wetland through the four culverts under the interstate after storm-water runoff ceases. Thus, ground water discharge through these seeps and culvert inflows, as well as ground water flow through the aquifer, can be important sources of water to the wetland at these times.

Although surface flow from the site could not be measured, when rates of ET were low and ground water levels were high, ground water levels indicated some aspects of this flow (Figure 5). When ground water levels rose to near or above land surface in well FL2, ground water levels initially declined rapidly then declined at a much slower rate. The initial rapid declines probably resulted, in part, from surface flow across the broad lowland areas toward cabin creek. As water levels declined, surface water flowed through a more limited area causing water levels to decline more slowly.

When ground water levels declined to depths of about – 0.15 m at well FL2, standing water generally was minimally present in the wetland near the well. Ground water flow, soil moisture, and ET became the major components of the water budget at these times. When standing water was absent from the site, soil moisture and ground water were the major sources of water for discharge by ET. Much of the soil moisture was ground water that remained in the soil as ground water levels declined and the soil became unsaturated. As soil moisture decreased because of ET, water flowed from the water table through the soil to replace soil moisture.

The significance of ground water is further demonstrated quantitatively by information from the period July through September 1998. During this period, surface runoff was minimal, precipitation totaled 0.181 m and ET totaled 0.362 m. Ground water levels declined about 0.610 m. Based on a specific yield of 0.1, ground water storage supplied 0.061 m (about 0.025 m if the specific yield is 0.04) to ET (the 24-hr decline in diurnal ground water levels [Figure 6]). The remaining 0.119 m ($S\,y= 0.1$) to 0.156 m ($Sy = 0.04$) of discharge was supplied by a net ground water inflow to the site (the nighttime rise in diurnal ground water levels (Figure 6)). Consequently, ground water and precipitation each provided about 50% of the water for ET during this period. Of the 50% provided by ground water, about two-thirds (six-sevenths if the specific yield is 0.04) was provided by ground water inflow. A large part of the precipitation (especially when daily precipitation amounts were large) appears to have been temporarily stored as ground water (Figure 18). This storage as ground water is accounted for as precipitation, not as ground water, in this analysis.

By using this information, general estimates of the annual ground water contributions can be calculated. If annual estimates of the water budget are started in the winter when water levels are near or above land surface, the annual change in ground water storage is approximately zero; ground water inflow, therefore, is the only annual source of ground water to the site. The net monthly ground water inflow for July through September 1998 averaged 0.041 to 0.051 m, depending on the specific yield that is used. At this monthly rate, the annual net ground water inflow would be 0.477 to 0.622 m. Ground water inflow rates, however, would change as ground water levels change.

Based on Darcy's law, aquifer permeability, aquifer thickness, and horizontal water level gradients affect rates of lateral ground water flow. Horizontal water level gradients and aquifer thickness change as ground water levels change but aquifer permeability changes little. These changes would affect rates of net ground water inflow that discharges to the wetland. The net ground water inflow that discharges to the wetland is the difference between the ground water inflow and outflow. Changes in ground water inflow would be affected by changes in ground water levels between wells to the west of the wetland and wells along the west edge of the wetland. Changes in ground water outflow would be affected by changes in ground water levels between wells along the western and east edges of the wetland.

Changes in horizontal water level gradients from July 1998 to February 1999 indicate that the net ground water inflow is greater during periods of high water levels than during periods of low water levels. Horizontal water level gradients increased 12% to 80% from wells west of the wetland to wells along the west edge of the wetland from July 1998 to February 1999. Thus, based solely on horizontal water level gradients, the ground water flow to the wetland would have increased 12% to 80%. Additionally, horizontal water level gradients decreased 5% to 93% across the wetland from July 1998 to February 1999, indicating flow decreased across and from the wetland during this period.

The thickness of the aquifer increased in variable amounts across and west of the wetland from July 1998 to February 1999. The increased thickness averaged less than 0.61 m, however, and was of similar magnitude across and west of the wetland. Consequently, the rate of net ground water inflow to the site probably was significantly greater in February than in July. Thus, the calculated net annual inflow of 0.477 to 0.622 m is a lower limit of the net ground water inflow to the site. Ground water inflow during February would primarily discharge to the land surface in the wetland and contribute to the standing water in contrast to the uptake through ET in July.

Estimated Annual Water Budget

Precipitation (Table 2), surface water runoff additions (Figure 19), and ET losses (Figure 20) to/from the wetland were estimated as described in the Methods section. Surface water additions were particularly low due to the very dry year studied (Figure 19). Surface water losses could not be directly measured, however, because the Ft. Lee wetland does not have a water control structure, gaged channel, or other device to estimate the surface water outflow. Surface runoff usually occurs as both ditch and sheet discharge as discussed earlier. However, we were able to relate periods of these dispersed surface flow losses to relative water levels visually in the continuous recording well (FL2). By examining the well levels during the winter, an "onset of runoff" water level of 0.038 m below the soil surface was chosen. Well levels greater than 0.038 m thus indicate surface water outflow. Thus relative surface water outflow (Figure 21) was set to the amount of water above the "full" –0.038 m well reading 0 to – 0.038 m corrected for soil solids with $Sy = 0.1$).

Clearly, this estimate, as with other parameter estimates, likely has associated error. Depending on the "full" water level chosen and other corrections (e.g., assuming that all of the water above the full level leaves in one day), this estimate could vary greatly. The pattern of surface water outflow was consistent with what would be expected, with greater amounts in the winter and spring than during the peak of the growing season (Table 2, Figure 21).

Not knowing exact aquifer thickness and variations in specific yield for the wetland limited the ability to measure ground water inflow and outflow directly. Instead, we estimated the net ground water flux for each day by predicting the water level using the other parameters and comparing this to the actual well levels. By difference (and corrected for $Sy = 0.1$), the net ground water flux was estimated. From Table 2 and Figure 22 it is clear that ground water is an important source of water to the wetland. Net seepage from the wetland into the ground water is observed only in the winter and early spring. Since our ground water estimate is calculated by difference of all the other parameters, it also tends to accumulate the errors associated with all of the other estimates. Although we can conclude ground water is an important component of the water budget for the Ft. Lee wetland, quantitatively it may have intrinsic errors of estimation. However, we should point out that our overall net ground water estimate agrees well with the earlier USGS estimate discussed earlier, although it is somewhat higher than their reported conservative value.

The overall monthly water budget components for the period are presented graphically in Figure 23, and the overall annual estimated water budget is presented in Figure 24. On a net water flux basis, for the period monitored, the hydrology of the system is strongly controlled by net ground water additions coupled with surface water losses. ET exceeded precipitation in this very dry year, principally attributable to the fact that the ground water influx was such that ET did not become soil water limited for long periods. In a wetland without significant ground water additions, actual ET and surface water losses would likely have been much less.

Soil Hydrologic Studies

A complete summary of all soil, vegetation, and hydrologic investigations at Ft. Lee is given by Cummings (1999), including comparative soil properties over time. Additional analyses performed at two other VDOT mitigation sites are also described. The materials following in this section are limited to Cummings' study of soil-hydrologic interactions at Ft. Lee along a series of soil pits excavated along a well-defined wetness gradient (Figure 25).

Initial investigations of the Ft. Lee mitigation area revealed an obvious wetness gradient created during site construction. Well readings (Figure 26B) taken from July 1997 to January 1999 confirmed and detailed the wetness gradient. Moving east across the mitigation area, the site progressed from VPD to SWPD soils. The SWPD soils of the mitigation area occur along a highly compacted and elevated ridge created during construction. Soils of the VPD region were saturated within 0.30 m of the soil surface for 164 days (68% of the growing season) and saturated at or above the surface for 98 days (40% of the growing season). Soils of the PD region were saturated within 0.30 m of the soil surface for 123 days (51% of the growing season) and saturated from 0 to 0.15 m for 98 days (40% of the growing season). Soils of the SWPD ridge were never ponded, but saturated within 0.30 m for 70 consecutive days (30% of the growing season).

A similar wetness gradient existed in the reference area (Figure 26a) but was much more complex spatially. Regions further away from Cabin Creek were PD and saturated from 0 to 15 cm for 57 days (25% of the growing season), and soils contiguous to Cabin Creek tended to be VPD and were saturated at or above the soil surface for 70 days (30% of the growing season). VPD areas were saturated within 0.30 m of the soil surface for 85 days (35% of the growing season), and PD areas were saturated within 0.30 m of the soil surface for 70 days (30% of the growing season). SWPD soils were not found in the reference area due to the hydrologic characteristics of the area.

Mitigation and reference areas exhibited similar patterns in water table fluctuations during the monitoring period (Figure 27). Water tables were highest from November through May as a result of increased precipitation and decreased ET.

The occurrence of redoximorphic features was evaluated by drainage class at Ft. Lee. As discussed earlier, redox feature descriptions are largely qualitative since it is difficult to obtain accurate and repeatable quantitative estimates of relative occurrence, size, and distinctness. In a given horizon in a given pedon, redox features will vary from point to point laterally due to short-range changes in rooting, organic matter, texture, and internal drainage. This study attempted to make quantitative counts of redox features, specifically oxidized rhizospheres, noting location and size of features. The overall discussion below is drawn from a combination of quantitative data and qualitative synthesis of the features observed across and within the many pedons studied.

Numerous redoximorphic features were observed and counted, including Fe accumulations/depletions and Mn accumulations, but a greater emphasis was place on oxidized rhizospheres due to the disturbed state of the mitigation area. Oxidized rhizospheres are presumably active features indicative of current hydrologic conditions, whereas Fe and Mn accumulations/depletions could be relict features from a previous hydrologic regime. Oxidized rhizospheres were located mainly in surface horizons where roots were concentrated. They were associated with active root channels both on and within ped faces. In the PD and VPD areas, black Mn masses 0.005 to 0.01 m in diameter were observed within peds starting at a depth of 40 cm. Strong brown Fe masses were also noted in PD and VPD areas and were generally 0.25 to 0.01 m in diameter, associated with small pockets of sand. The Fe masses occurred higher in the profile, generally occurring between 0.10 and 0.30 m. In SWPD areas, no Mn masses were observed. Yellowish red to strong brown Fe masses were associated with ped faces. These features started at a depth of 0.20 m and continued throughout the profile.

Mitigation area soils in the VPD areas contained a greater quantity of active redox features (Figure 28) in the surface horizon than those soils in up slope, drier areas. Fewer active oxidized rhizospheres occurred in the SWPD soils and where present, were faint. Within a $0.01 m^2$ area of the surface horizon, 62% of roots formed oxidized rhizospheres in the VPD areas as compared with 31% in the SWPD areas. Redox feature prominence decreased as the degree of soil saturation decreased. Prominent features were observed in VPD areas, distinct features were observed in PD areas, and faint features were observed in SWPD areas. Oxidized rhizospheres in the PD areas were more abundant than those in the SWPD areas, but less prominent than those in the VPD areas. Forty-seven percent of roots in the PD areas contained oxidized rhizospheres as compared to 31% in the SWPD areas. The oxidized rhizospheres of the PD areas were described as distinct, whereas those of the VPD areas were described as prominent. Among the three transects within the mitigation area, the northern-most transect was coarser in texture than the other two transects and oxidized rhizospheres in this transect were not as prominent but still followed the general trend of occurrence discussed above.

In the reference area, redox features did not reflect the saturation gradient as distinctively as soils of the mitigation area (Figure 28). Oxidized rhizospheres in both VPD and PD areas were faint. PD areas contained fewer oxidized rhizospheres in surface horizons than VPD areas, as expected. Sixty-five percent of roots in VPD areas contained oxidized rhizospheres as compared with 37% in the PD areas. Oxidized rhizospheres (0.0025 to 0.005 m) were associated with active root channels in surface horizons, while larger Fe masses (0.01 to 0.02 m) were associated with pore linings above the water table.

Our detailed study of mitigation soils at Ft. Lee found that the occurrence of active redoximorphic features reflected the current hydrologic regime and that these features have apparently formed in less than 10 years. Stolt et al. (1998) investigated the time frame required for the formation of certain redoximorphic features at Ft. Lee in buried weathering bags. Redoximorphic features were observed within the interiors and exteriors of simulated peds within two years. Vepraskas et al. (1995) showed that redoximorphic features could be used as indicators of wetland hydrology in soils of constructed wetlands that are ponded or flooded for short periods of time (7 to 14 days). In another study, Vepraskas et al. (1999) found hydric soil field indicators formed by Fe-reduction developed over time in a constructed marsh, with full development of Fe-depleted matrices occurring five years after construction. Areas experiencing longer periods of saturation during the growing season contained higher quantities of prominent redox features than better drained areas. These results are in agreement with the results of this study.

The presence of redoximorphic features, particularly oxidized rhizospheres, increased with longer periods of saturation (Figure 28). For this site, jurisdictional areas were separated from non-jurisdictional areas by having greater than 35% relative abundance of oxidized rhizospheres in the surface. Soils in SWPD areas contained less the 35%. Trends in the occurrence of redox features with local changes in wetness or texture were not as pronounced in the reference area at Ft. Lee. Differences between drainage classes in the reference area were not as pronounced as in the mitigation area and soils were fairly uniform throughout the reference area. Well developed and deep A horizons coupled with very sandy textures probably worked in concert to mask prominence in surface horizon features in the Ft. Lee reference area. Coarser textured horizons in the Ft. Lee mitigation area displayed fewer redox features than clayey horizons of the same drainage class. This trend could be a result of water holding capacity and the effects of finer textured materials on gas exchange and reduction reactions.

Along the observed wetness gradient at Ft. Lee, oxidized rhizospheres in surface horizons were more abundant and more prominent in areas saturated at or above the surface for longer periods. Better drained areas had fewer oxidized rhizospheres, which were more faint. Areas of coarser textured materials possessed more faint features than finer textured materials in the same drainage class. Other features such as Fe/Mn concentrations/depletions were present, but emphasis was placed on oxidized rhizospheres in this study. Oxidized rhizospheres are associated with active root channels and have formed in less than 10 years under the current hydrologic conditions. Matrix colors in the mitigation area are dominantly relict features from a previous hydrologic regime and will require years of organic matter accumulation and soil saturation and reduction to become gleyed.

At Ft. Lee, SWPD areas were saturated within 0.30 m of the soil surface for 30% of the growing season, with seasonal high water tables never reaching the soil surface. PD areas were saturated within 0.30 m of the soil surface for 51% of the growing season, with almost 100 consecutive days between 0 and 0.15 m. VPD areas were saturated within 0.30 m of the soil surface for 68% of the growing season, with almost 100 consecutive days at or above the soil surface. At this site the relative occurrence of oxidized rhizospheres exhibits a direct relationship with the seasonal saturation interval and can be used as an indicator of wetland hydrology. According to the Corps of Engineers *Wetlands Delineation Manual* (Environmental Laboratory, 1987), VPD and PD areas of the Ft. Lee mitigation site meet the criteria for wetland hydrology, whereas SWPD areas may not meet the specified criteria. The manual outlines parameters for wetland hydrology that require that an area be seasonally saturated and/or inundated to the surface for a consecutive number of days for more than 12.5% of the growing season. Areas saturated to the surface between 5% and 12.5% of the growing season my or may not be wetlands (Environmental Laboratory, 1987). SWPD areas may be saturated for some time during the growing season, but are never inundated to the soil surface. Curiously, these SWPD areas clearly exceeded the soil wetness criteria for jurisdictional determination and contained redoximorphic features in near-surface horizons, but were clearly not jurisdictional with regard to botanical composition (Cummings, 1999). This may indicate that despite efforts to restore the appropriate hydrologic regime, other soil related factors such as compaction and a lack of soil organic matter are precluding the effective development of appropriate geochemical conditions for hydrophytic vegetation.

WATER BUDGET STUDIES AT MANASSAS

Our two earlier research reports (Daniels et al., 1996, 1998) focused primarily on our combined efforts to quantify water budget components at the Manassas wetland site. A final detailed report on that effort is given by Fomchenko (1998), and her major conclusions and estimated water budget are summarized here.

Site Description and Methodology

The wetland studied at Manassas was a natural system that was essentially perched in hydrologically tight Triassic "red bed" geology. The wetland graded from an open water/emergent type to drier shrub/scrub to forested wetland as one moved away from a perennial stream (Cockrell Branch) that brought substantial surface flow into the site. Non-wetland areas around the periphery of this approximately 10-ha jurisdictional wetland are currently being excavated to create new mitigation wetlands by VDOT. Beginning in 1996, Virginia Tech and USGS initiated an intensive water budget monitoring program at the site that focused primarily on accurately defining surface- and ground water regimes via a large network of ground water wells and piezometers and surface water gauging stations. Rainfall was measured on-site and ET was estimated via both the Thornthwaite and the diurnal water table flux methods.

In wetland mitigation, it is essential to estimate the amount of water available for potential storage in the wetland. This implies estimating the components of the wetland water budget. In this study, the water budget components, precipitation, runoff, ET, and ground water seepage were calculated on a monthly basis using the methods specified in the modified Pierce water budget model, and compared to on-site field measurements made over 10 months in 1996 and 1997 at a wetland in Manassas.

Results/Discussion

Comparison of monthly precipitation from the closest off-site weather station 32.2 km away (Dulles Airport) to onsite measurements indicated that precipitation off site differed by as much as 2.9 times the onsite precipitation.

The calculated runoff estimates using the SCS runoff method with an AMC II were very different from the runoff measured from hydrographs of actual stream discharge into the wetland during rainstorms. Percent differences ranged from 32% to 100%. Using AMC III instead of AMC II provided more accurate runoff estimates, probably because 1996 was a relatively wet year. These results demonstrated that the choice of AMC can greatly affect the water budget for the Manassas wetland. Runoff dominated the water available for potential storage at this site. The choice of AMC affected the runoff estimate for the Manassas wetland more than the use of offsite versus onsite precipitation data.

The diurnal cyclic changes of the water table taken in an observation well in the wetland were used to measure ET as proposed by White (1932). This method is applicable only during periods with no rain and when the water table is below the ground surface. It depends on accurate estimates of the specific yield of the soil and is very sensitive to errors in measuring specific yield. These results were compared to the calculated potential ET (PET) using the Thornthwaite method as specified for the modified Pierce model. The results indicated that the Thornthwaite PET underpredicted ET for some months and over-predicted ET for the other months. The largest differences from the diurnal cycle method were 0.0487 m higher in July and 0.0428 m lower in May. The effect of such differences on the water budget was usually negligible since stream inflow dominated water inputs, contributing as much as 3.57 m depth of water per month to the Manassas wetland. Ground water seepage loss (m/day) was estimated by the modified Pierce water budget model using Darcy's equation and a hydraulic gradient of 1.0. The net ground water seepage loss was estimated to be 0.86 mm/day (0.026 m/month). Similar loss estimates calculated using Darcy's equation, but with hydraulic head gradients measured with nested piezometers at the site ranged from 0.34 to 0.02 mm/day. A net ground water gain to the wetland of 0.003 cm/day was also observed for one set of hydraulic gradients. These ground water flow rates are all very slow and will add or remove relatively small amounts (0.010 m/month maximum) of water to the wetland. However, ground water estimates using a hydraulic gradient of 1.0 overestimated the loss of water from the wetland by ground water seepage and therefore provides the most conservative estimate for wetland design.

The potential storage of the Manassas wetland was obtained as the sum of inflows and outflows not including the base flow component of stream inflow, stream outflow, and ground water inflow. The potential storage calculated from onsite measurements and the modified Pierce model was dominated by runoff. However, the lower runoff values obtained using the modified Pierce model resulted in a relatively greater effect of the other water budget components on the modeled potential storage than on the measured values.

The overall water budget for a 10-month period at the Manassas wetland is given in Figure 29. As discussed previously, this system is dominated by surface water inputs and the tight underlying geology apparently limits ground water flux in the modeled portion of the wetland. However, it is important to note that detailed ground water studies in the drier shrub-scrub and forested portions of this wetland did indicate significant seasonal ground water inputs to those parts of the system.

The modified Pierce model underpredicted potential storage for every month of the study period. It indicated low or deficit potential storage, whereas the on-site measured potential storage consistently showed a surplus of water. These findings indicated that the modified Pierce water budget model was conservative for a relatively wet year. Therefore, a wetland design based on the modified Pierce water budget model may be more likely to maintain wet conditions due to the overall conservative estimates of the potential storage. However, if estimates are too conservative, a site suitable for wetland mitigation may not qualify due to an underestimated potential storage.

SUMMARY

Monthly estimates of ET varied greatly depending on whether estimates were calculated from the Bowen ratio, Thornthwaite, or Blaney-Criddle methods. Because the Bowen ratio method uses measured data and is not based on empirical relations, as are the Thornthwaite and Blaney-Criddle methods, estimates of ET based on the Bowen ratio method best represented actual rates of ET. Based on comparisons with calculations using the Bowen ratio method, calculation by the Thornthwaite method underestimated ET except during dry summer months when water availability limited actual ET. Consequently, the Thornthwaite method is not a good method for estimating either ET or potential ET at the site. Similarly, although estimates of annual ET by the Blaney-Criddle method were closer to estimates computed by the Bowen ratio method, the Blaney-Criddle method was not an accurate method for calculating monthly ET at the site.

Use of ET calculated by the Bowen-Ratio method and ground water levels to calculate specific yield of the aquifer indicates that the sources of water for ET change depending on the depth of the water table and the presence of standing water. When standing water is present and the water table is shallower than about - 0.15 m, both standing water and ground water are sources of water for ET. When the water table is deeper than about - 0.25 m, ground water is the principal source of water for ET. The specific yield of the aquifer appears to be between 0.04 and 0.1 when the water table is deeper than - 0.25 m. Because of the great influence that specific yield has on the estimate of ET from ground water fluctuations, a precise and accurate specific yield is necessary for estimating ET from ground water levels.

Both surface and ground water are important sources of water to the Ft. Lee created wetland. The relative importance of each changes seasonally and annually. Ground water flows to the east and north through the surficial aquifer beneath the site and discharges to Cabin Creek, similar to the direction of surface water flow. During periods of standing water in the wetland, ground water and surface water are hydraulically interconnected and changes in ground water levels reflect changes in the level of standing water. Ground water discharge appears to be a significant source of standing water in the wetland at these times. Both ground water and surface water are sources of water for discharge from the site through surface water flow and ET. As water levels and the area covered by standing water decrease, the role of surface water decreases and the role of the ground water increases. This typically occurs during the warm-weather months. From July through September 1998, for example, precipitation supplied about half of the 0.362 m of ET and ground water supplied the other half. Net ground water inflow (ground water discharge) averaged 0.041 to 0.051 m per month during this period, which equals 0.477 to 0.622 m. Based on horizontal water level gradients, rates of net ground water inflow are greater in the winter than in the summer, such that these estimates of annual ground water discharge are minimum likely values.

These combined results from detailed analyses of water budget components at Ft. Lee and Manassas reveal several important overall points. First, accurate onsite measurements of precipitation and ground water dynamics are critical to develop predictive water budgets. Ground water additions do play a major role in the water budgets of Virginia wetlands, particularly riparian Coastal Plain systems. Surface water additions as estimated by the SCS runoff curve approach are generally reliable, but are very sensitive to variations in the antecedent moisture parameters, which may need region- or site-specific study to correctly specify. ET estimates for a given month can vary widely based upon the method utilized, and that difference can be sufficient to influence overall wetlands design parameters. For sites with appropriate soil water levels and known values for soil specific yield, the diurnal water table flux method appears suitable for estimating on-site ET. When empirical approaches such as Blaney-Criddle or Thornthwaite are employed, their tendency to underpredict actual ET significantly must be recognized. Thus, any valid attempt to estimate the water budget for a given site is necessarily prone to a number of sources of error, and the best solution to this problem is the acquisition of detailed site-specific data sets.

Our specific studies at Ft. Lee clearly indicate that in a constructed mitigation site, the hydrologic regime can mimic that of the reference area very closely. Achieving this goal requires monitoring prior to site construction to accurately locate water table levels and very precise forward water budgeting procedures, or quite a bit of luck. In the Ft. Lee mitigation area a distinct wetness gradient exists, which transitions from VPD to SWPD areas with a relative elevation change of <0.5 m. This reinforces the commonly held belief that even minor variations in final mitigation site grade can have substantial effects on net soil wetness regime. Well records from the mitigation and reference area show similar trends in water table rise and fall, with the highest water tables occurring from November through May due to increased precipitation and decreased ET as expected. Somewhat poorly drained areas were saturated for the shortest amount of time at greater depths than VPD areas. Poorly drained areas were saturated to the surface for a shorter time during the growing season, but were saturated long enough near the surface to meet wetland hydrologic criteria. Very poorly drained areas remained saturated at or above the soil surface for the longest duration, easily meeting wetland hydrologic criteria. Varying degrees of saturation affected soil morphology within the mitigation/reference pair. The fact that distinct trends in oxidized rhizospheres were observable within a 5-year monitoring period at Ft. Lee is very important, and may provide a viable tool for assessing hydric soil development in Virginia mitigation wetlands.

Overall, the results of the Manassas site study show that the methods used to estimate each water budget component can have an effect on estimated potential storage or overall water supply for design purposes. For the Manassas wetland, this study shows that there is a suitable water supply to expand the existing size of the wetland to create new wetland areas as proposed by VDOT. However, changing the natural setting of the wetland could alter the water budget and create a different hydrological regime that may not support existing wetland functions. Such changes could occur from soil grading if the impermeable soils that prevent ground water losses are removed. In addition, overly conservative water level predictions can cause the wetland to remain at its maximum water level during wet years and this may be detrimental to some wetland species. Expanding these studies to other wetlands would also provide more confidence in extrapolating the results and findings on wetland water budgets.

Finally, our overall assessment of the Westbrook/Pierce approach to water budgeting for mitigation design in Virginia reveals that it is relatively straightforward to use and simple to implement. However, because ground water flux is largely ignored, we question its direct application to many wetland systems, particularly riparian Coastal Plain sites. In fairness, however, we should point out that Pierce (1993) clearly indicates that ground water additions can be used as part of his budgeting approach if sufficient on-site data are collected to justify such. This adds further support to our ground water monitoring conclusions as stated earlier. Because of its intrinsic methodology, this water budgeting approach is quite applicable to sites where net ground water flux is minimal, such as Manassas, and where the design intent is establishment of "wet" systems such as emergent or shrub scrub communities. The Westbrook/Pierce technique is also dependent upon surface water detention via berms or appropriate grading plans, and enough surface water plus precipitation must be detained on-site to support the wetland through summer droughts. This necessarily leads to a net annual hydroperiod in these types of mitigation wetlands that is very different from the cycle commonly observed (Genthner et al., 1998) in many forested wetlands in Virginia, particularly riparian Coastal Plain systems. It is our observation that use of this particular water budgeting approach leads to wetland designs that are "too wet" for their intended vegetation when it is implemented in areas where net ground water flux is positive. Conversely, if the bottom of the wetland site cannot be adequately sealed, and/or the net ground water flux is negative, application of this water budgeting approach leads to sites that are too dry. Again, this points out the critical importance of obtaining accurate ground water data before any mitigation site is designed.

CONCLUSIONS

- Use of the Pierce approach for developing mitigation wetland water budgets is prone to a number of errors in surface water charging estimates and ET estimates via Thornthwaite in addition to the ground water issues discussed above. Therefore, this approach should be viewed as a general purpose assessment tool rather than a site-specific design tool.

- The Pierce approach is most appropriate for estimating water budgets in surface water driven emergent/shrub-scrub systems with little ground water flux, and that rely upon berms or other water control structures to detain and pond water over impermeable soils or strata. This technique is particularly inappropriate for non-ponded forested systems that rely largely upon a combination of landscape position and ground water discharge for their hydric soil wetness regime. Unfortunately, a large portion of the wetlands that VDOT mitigates for in Virginia are forested wetlands of this type.

- Our data from Ft. Lee clearly indicate that the Thornthwaite ET technique significantly underestimates actual ET during the spring and fall seasons. Therefore, a conservative approach to ensure adequate wetness conditions would indicate that Thornthwaite ET estimates should be increased by approximately 35% during the cooler months.

- The diurnal water flux technique can generate a reasonably accurate and low cost ET estimate for a given site *if* the water table fluctuates at the appropriate depth below the soil surface and the specific yield of the soil/aquifer is known.

- The development of soil redox features, particularly the quantity and distinctness of oxidized rhizospheres, can be reliably used to interpret hydric soil development sequences in mitigation wetlands. For this technique to be effective, however, multiple observations must be made across documented wetness zones within a given site to establish site-specific criteria.

- Reestablishment of an appropriate mitigation site wetness regime to one that appears to meet jurisdictional wetness criteria will not always guarantee the success of desirable hydrophytic vegetation over time. Other soil related parameters such as compaction and organic matter content must be returned to appropriate condition as well.

RECOMMENDATIONS

1. *Obtain sufficient on-site ground water data to allow for determination of seasonal water level dynamics, local gradients, and the overall position of the mitigation site within its regional hydrologic regime.* This data set should be collected for a minimum of 1 year before site disturbance for mitigation sites, and the monitoring array should be maintained or reinstalled after site development. This would allow for both greatly improved water budgeting for mitigation site design and would subsequently allow VDOT to confirm earlier water budgeting estimates for net ground water flux, allowing and justifying postconstruction corrections where indicated. We understand that moving to a more intensive ground water monitoring regime such as this would increase the cost of mitigation site development. However, this incremental cost must be factored against the improved probability of permit approval, permit release, and overall mitigation success.

2. *Use the Pierce approach only as a general purpose assessment tool, not a site-specific design tool, for the development of mitigation wetland water balance budgets.* This technique is likely to underestimate the water loss attributable to ET significantly and therefore increases the chances of the wetland having insufficient water to support wetland plants.

3. *Increase ET estimates calculated using the Thornthwaite ET technique by approximately 35% during the spring and fall seasons.* This is a conservative approach to ensure that adequate wetness conditions exist despite this technique's propensity to underestimate ET during the cooler months of the year.

REFERENCES

Atkinson, R.B., W.L. Daniels, & J. Cairns, Jr. 1998. Hydric Soil Development in Depressional Wetlands: A Case Study from Surface Mined Landscapes. In S.K. Majumdar, E.W. Miller, & F.J. Brenner (ed.), *Ecology of Wetlands and Associated Systems.* The Pennsylvania Academy of Science, Easton.

Bouma, J. 1983. Hydrology and Soil Genesis of Soils with Aquic Moisture Regimes. In L.P. Wilding et al. (ed.), *Pedogenesis and Soil Taxonomy: I. Concepts and Interactions.* Elsevier Science Publishers, Amsterdam.

Buol, S.W. & R.A. Rebertus. 1988. Soil Formation Under Hydromorphic Conditions. In D.D. Hook et al. (ed.), *The Ecology and Management of Wetlands.* Vol. 1: Ecology of Wetlands. Timber Press, Portland, OR.

Cummings, A.R. 1999. *An Analysis of Palustrine Forested Wetlands in the Virginia Coastal Plain.* M.S. Thesis, Virginia Polytechnic Institute & State University, Blacksburg.

Daniels, R.B., E.E Gamble, & L.A Nelson. 1971. Relations Between Soil Morphology and Water Table Levels on a Dissected North Carolina Coastal Plain Surface. *Soil Science Society of America Proceedings*, 35:781-784.

Daniels, W.L., N. Persaud, N. Fomchenko, M. Focazio, & M. Fitch. 1996. *Wetlands Water Balance Studies: 1996 Research Report.* File Report. Department of Crop and Soil Environmental Sciences, Virginia Polytechnic Institute & State University, Blacksburg.

Daniels, W.L., N. Persaud, N. Fomchenko, G. Speiran, M. Focazio, & M. Fitch. 1998. *Wetlands Water Balance Studies: 1998 Research Report.* File Report, Department of Crop and Soil Environmental Sciences, Virginia Polytechnic Institute & State University, Blacksburg.

Dunne, T. & L.B. Leopold. 1978. *Water in Environmental Planning.* W.H. Freeman and Company, San Francisco.

Environmental Laboratory. 1987. *Corps of Engineers Wetland Delineation Manual.* Technical Report Y-87-1. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Faulkner, S.P. & W.H. Patrick. 1992. Redox Processes and Diagnostic Wetland Indicators in Bottomland Hardwood Forests. *Soil Science Society of America Journal,* 56:856-865.

Fomchenko, N.D. 1998. *Estimating the Components of a Wetland Water Budget.* M.S. Thesis, Virginia Polytechnic Institute and State University, Blacksburg.

Fretwell, J.D., J.S. Williams, & P.J. Redman. 1996. *National Water Summary of Wetland Resources.* U.S. Geological Survey Water-Supply Paper 2425.

Genthner, M.H., W.L. Daniels, R.L. Hodges, & P.J. Thomas. 1998. Redoximorphic Features and Seasonal Water Table Relations, Upper Coastal Plain, Virginia. In M.L. Rabenhorst et al. (ed.), *Quantifying Soil Hydromorphology.* Soil Science Society of America/American Society of Agronomy Special Publication. Soil Science Society of America, Madison, WI.

Megonigal, J.P., W.H. Patrick, and S.P. Faulkner. 1993. Wetland Identification in Seasonally Flooded Forest Foils: Soil Morphology and Redox Dynamics. *Soil Science Society of America Journal,* 57:140-149.

Mixon, R.B., C.R. Berquist Jr., W.L. Newell, G.H. Johnson. 1989. *Geologic Map and Generalized Cross Sections of the Coastal Plain and Adjacent Parts of the Piedmont, Virginia.* USGS Misc. Investigation Series, Map I-2033.

Munro, D.S. 1979. Daytime Energy Exchange and Evaporation from a Wooded Swamp. *Water Resources*, Vol. 15, No. 5, pp. 11259-11264.

National Technical Committee for Hydric Soils. 1995. Hydric soils of the United States. URL: http://www.statlab.iastate.edu/soils/hydric/national.html.

Pierce, G.J. 1993. *Planning Hydrology for Constructed Wetlands.* Wetland Training Institute Inc. Pub. WTI 93-2. Poolesville, MD.

Schelling, J. 1960. New Aspects of Soil Classification with Particular Reference to Reclaimed Hydromorphic Soils. *International Congress of Soil Science, Transactions* 7th. IV:218-224. Madison, WI.

Simonson, G.H. & L. Boersma. 1972. Soil Morphology and Water Table Relations: II. Correlation Between Annual Water Table Fluctuations and Profile Features. *Soil Science Society of America Proceedings,* 36:649-653.

Soil Conservation Service. 1985. *Soil Survey of Prince George County, VA.* USDA, Soil Conservation Service in cooperation with Virginia Polytechnic Institute and State University. U.S. Government Printing Office, Washington, DC.

Soil Survey Staff. 1994. *National Soil Survey Handbook.* USDA-Soil Conservation Service,. Washington, DC.

Stolt, M.H., M.H. Genthner, W.L. Daniels, V.A. Groover, & S. Nagle. 1998. Quantifying Fe, Mn, and Carbon Fluxes in Palustrine Wetlands. pp. 25-42. *In* M.L. Rabenhorst et al. (ed.), *Quantifying Soil Hydromorphology. Soil Science Society of America/American Society of Agronomy Special Publication.* Soil Science Society of America., Madison, WI.

Thornthwaite, C.W. 1948. An Approach Toward a Rational Classification of Climate. *Geographical Review,* 38: 55-94.

USDA-SCS, 1973. *A Method for Estimating Volume and Rate of Runoff in Small Watersheds.* SCS-TP-149. Government Printing Office, Washington, D.C.

Vepraskas, M.J., S.J. Teets, J.L. Richardson, & J.P. Tandarich. 1995. *Development of Redoximorphic Features in Constructed Wetland Soils. Technical Paper No. 5.* Wetlands Research, Inc. Chicago, IL.

Vepraskas, M.J., S.J. Teets, J.L. Richardson, & J.P. Tandarich. 1999. Dynamics of Hydric Soil Formation Across the Edge of a Created Deep Marsh. *Wetlands,* 19:78-89.

Walton, W.C. 1970. *Groundwater Resource Evaluation*: McGraw Hill Book Company, New York.

Westbrook, T.A. 1994. *Calculating a Water Budget for use in Construction of Wetlands.* U.S. Army Corps of Engineers, Norfolk District, Norfolk, Virginia.

White, W.N. 1932. *A Method of Estimating Ground Water Supplies Based on Discharge by Plants and Evapotranspiration from Soil: Escalante Valley, Utah in Contributions to the Hydrology of the United States, 1932*. U.S. Geological Survey Water-Supply Paper 659, pp. 1-105.

TABLES

Table 1.--Comparison of evapotranspiration (in centimeters) calculated by the Bowen Ratio, Thornthwaite, and Blaney-Criddle methods for May 1996 through May 1999 at the Fort Lee created wetland and evapotranspiration calculated for average conditions from 1961 through 1990 at Richmond International Airport.

Month	Average		1996			1997			1998			1999		
	Thornthwaite	Blaney-Criddle	Bowen Ratio	Thornthwaite	Blaney-Criddle	Bowen Ratio	Thornthwaite	Blaney-Criddle	Bowen Ratio	Thornthwaite	Blaney-Criddle	Bowen Ratio	Thornthwaite	Blaney-Criddle
January	0.23	0.91							2.41	1.19	1.57			
February	0.64	1.32							3.71	1.47	1.91	7.44	3.00	1.73
March	2.49	3.76							6.25	2.87	4.09	11.63	4.27	3.33
April	5.31	7.47				9.42	3.96	6.12	9.73	5.51	7.70	16.31	8.05	7.48
May	9.42	12.24	14.63	6.88	10.87	16.33	8.05	10.80	13.84	9.80	12.62	15.77	11.61	12.27
June	14.53	17.53	19.96	11.23	16.76	17.09	12.32	15.19	14.66	13.64	16.59			
July	15.39	18.90	16.54	11.68	17.53	13.92	14.48	17.91	15.24	14.96	18.44			
August	13.89	16.92	13.79	10.72	15.14	12.85	13.34	16.31	11.61	13.67	16.66			
September	9.83	11.48	10.13	9.35	11.33	7.77	10.13	11.79						
October	5.16	6.35	6.86	5.36	6.22									
November	2.36	3.51				2.79	1.40	2.62						
December	0.71	1.57				2.95	0.51	1.57						
Total	79.96	101.96	81.91	55.22	77.85	83.12	64.19	82.31	77.45	63.11	79.58	51.15	26.93	24.81

Table 2.--Monthly totals for each Fort Lee water budget component in centimeters of water.

Month	Precip.	Surface inflow	ET	Surface outflow	Groundwater inflow	Groundwater outflow	Groundwater (net)
May-98	9.96	0.00	-13.84	-20.45	26.06	-1.75	24.31
Jun-98	4.85	0.00	-14.66	0.00	12.12	-2.31	9.80
Jul-98	4.88	0.00	-15.24	0.00	13.72	-3.35	10.36
Aug-98	6.20	0.00	-11.61	0.00	10.29	-4.88	5.41
Sep-98	7.01	0.00	-9.58	0.00	7.85	-5.28	2.57
Oct-98	1.65	0.00	-6.35	0.00	5.72	-1.02	4.70
Nov-98	2.31	0.00	-3.51	0.00	2.92	-1.73	1.19
Dec-98	16.03	9.50	-1.57	-4.80	0.97	-20.12	-19.15
Jan-99	13.36	0.86	-1.17	-17.65	8.31	-3.68	4.62
Feb-99	3.71	0.00	-3.73	-0.05	2.82	-3.51	-0.69
Mar-99	9.02	0.00	-5.82	-35.43	32.89	-0.66	32.23
Apr-99	10.26	0.00	-10.29	-3.25	9.04	-5.79	3.25
total	**89.99**	**10.36**	**-97.33**	**-81.64**	**132.69**	**-54.08**	**78.61**

FIGURES

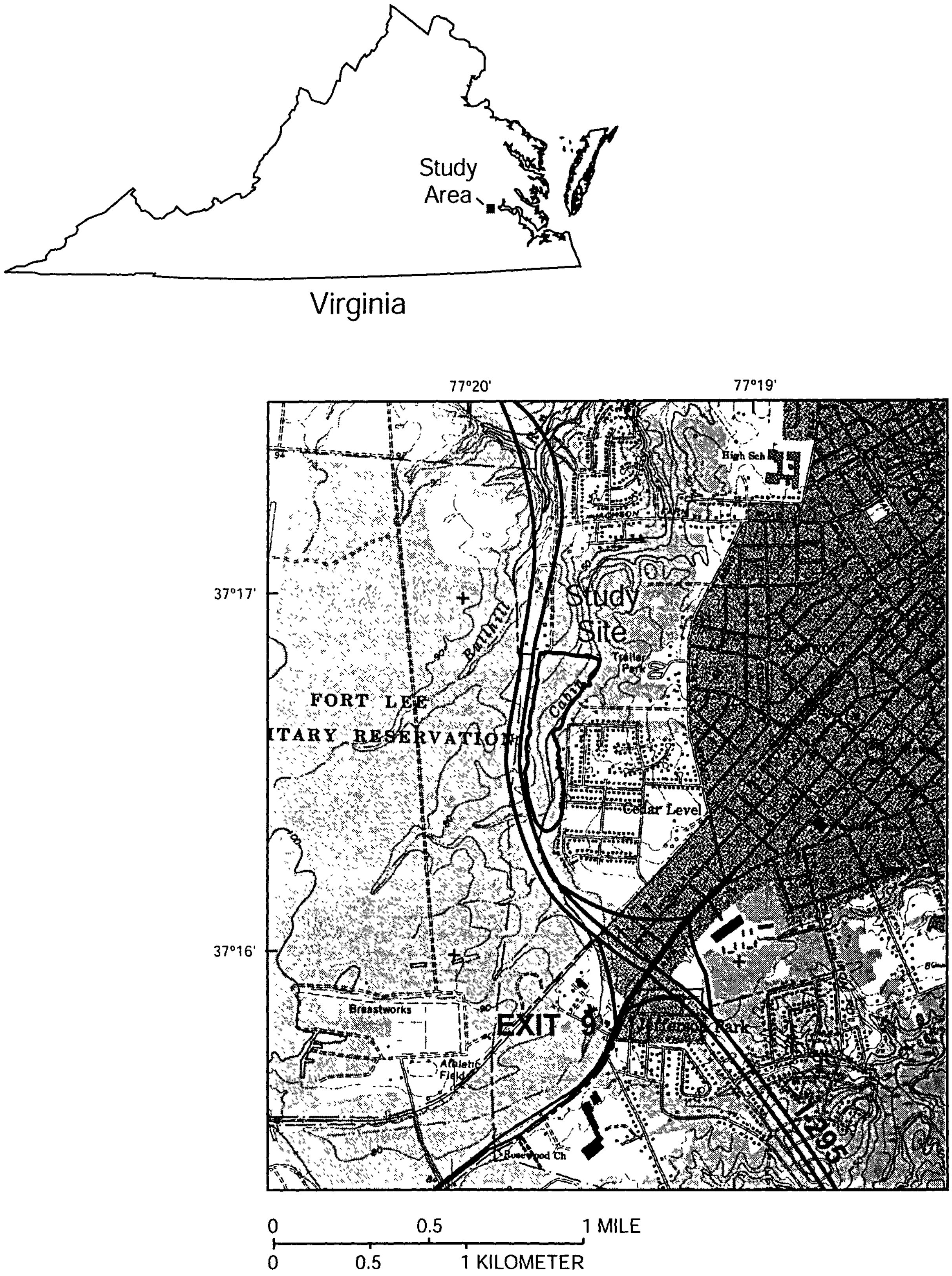


Figure 1. – Location of the study site.

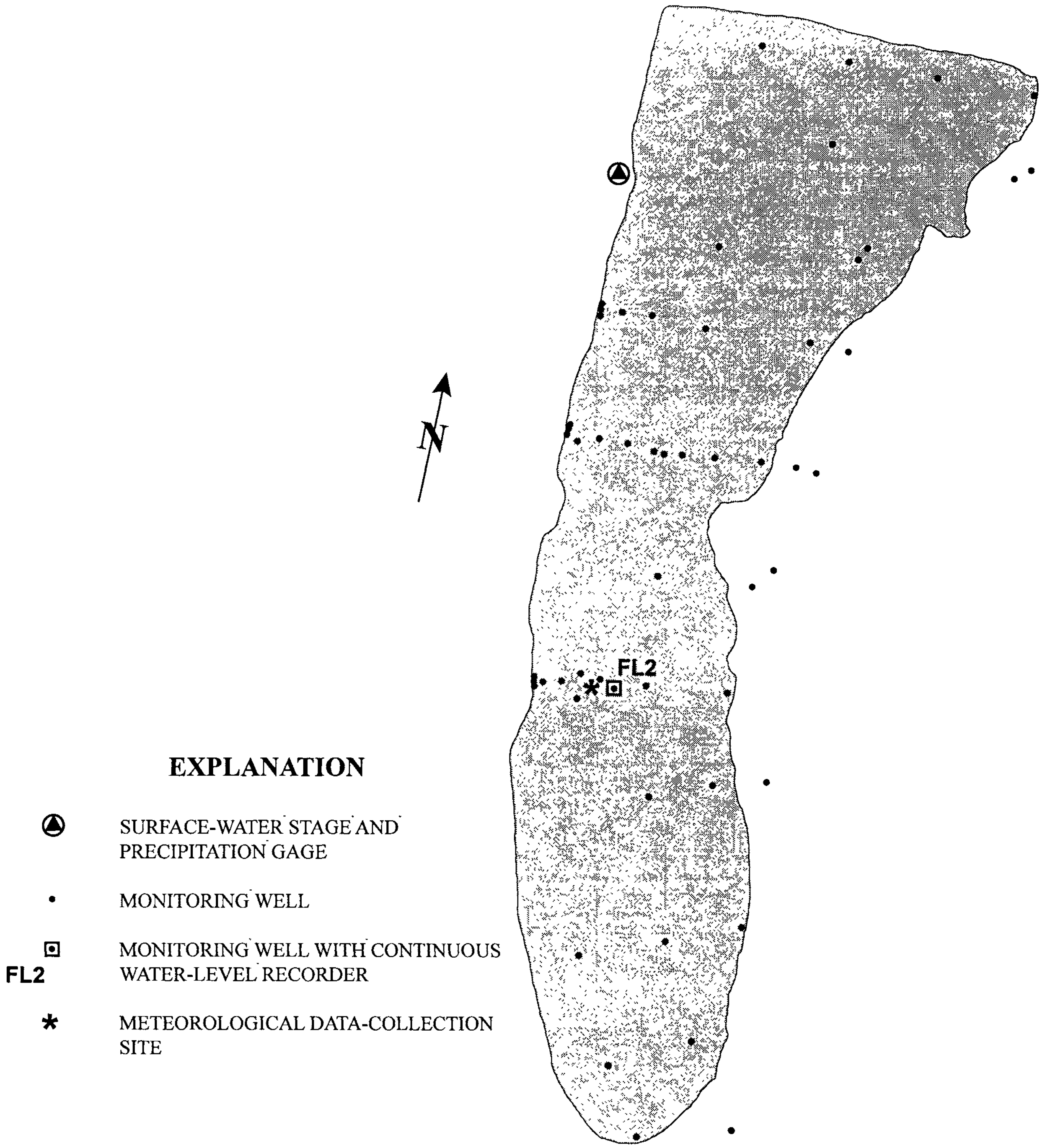


Figure 2. – Data-collection network.

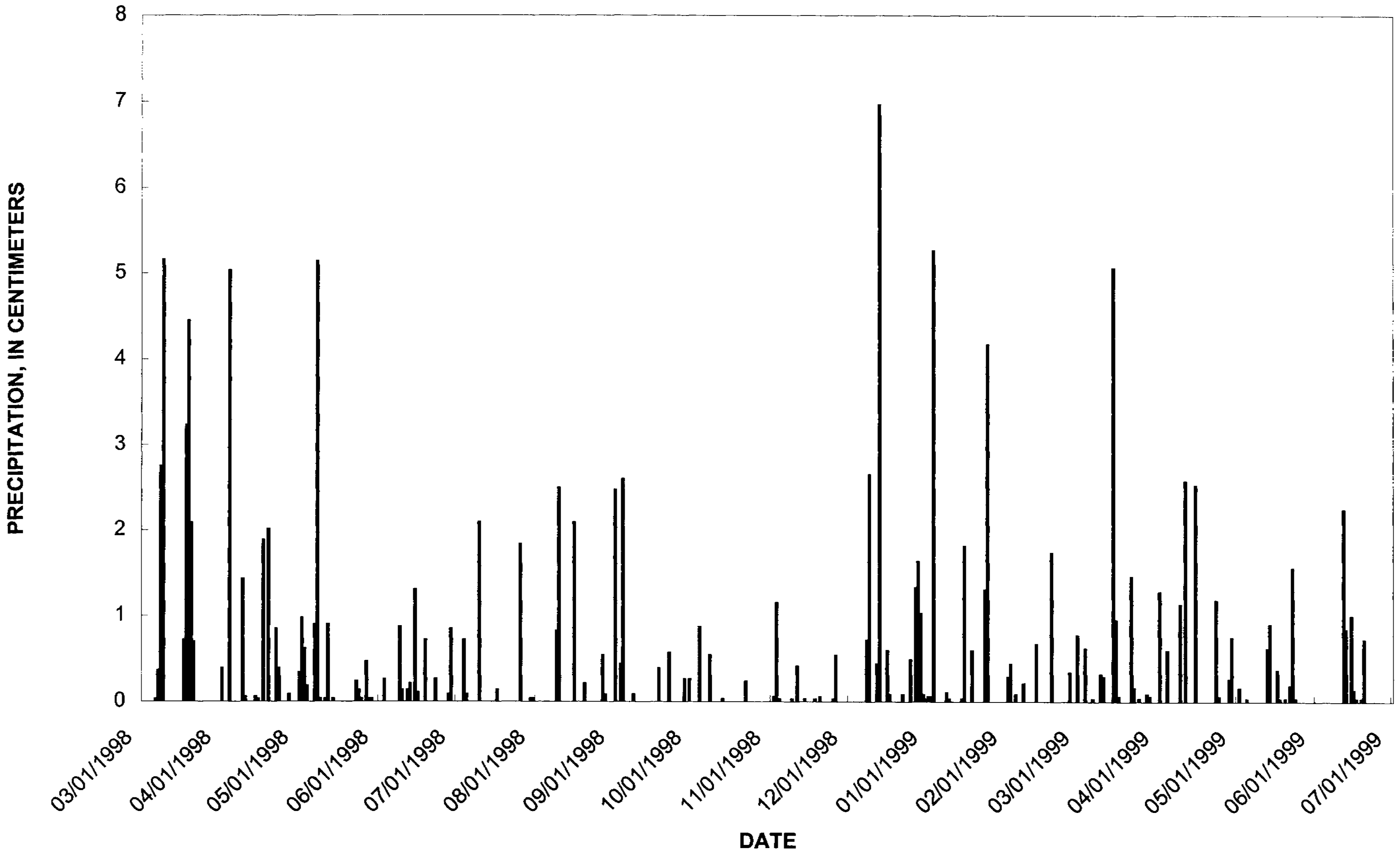


Figure 3. -- Daily precipitation at the Fort Lee created wetland, March 6, 1998, through June 20, 1999.

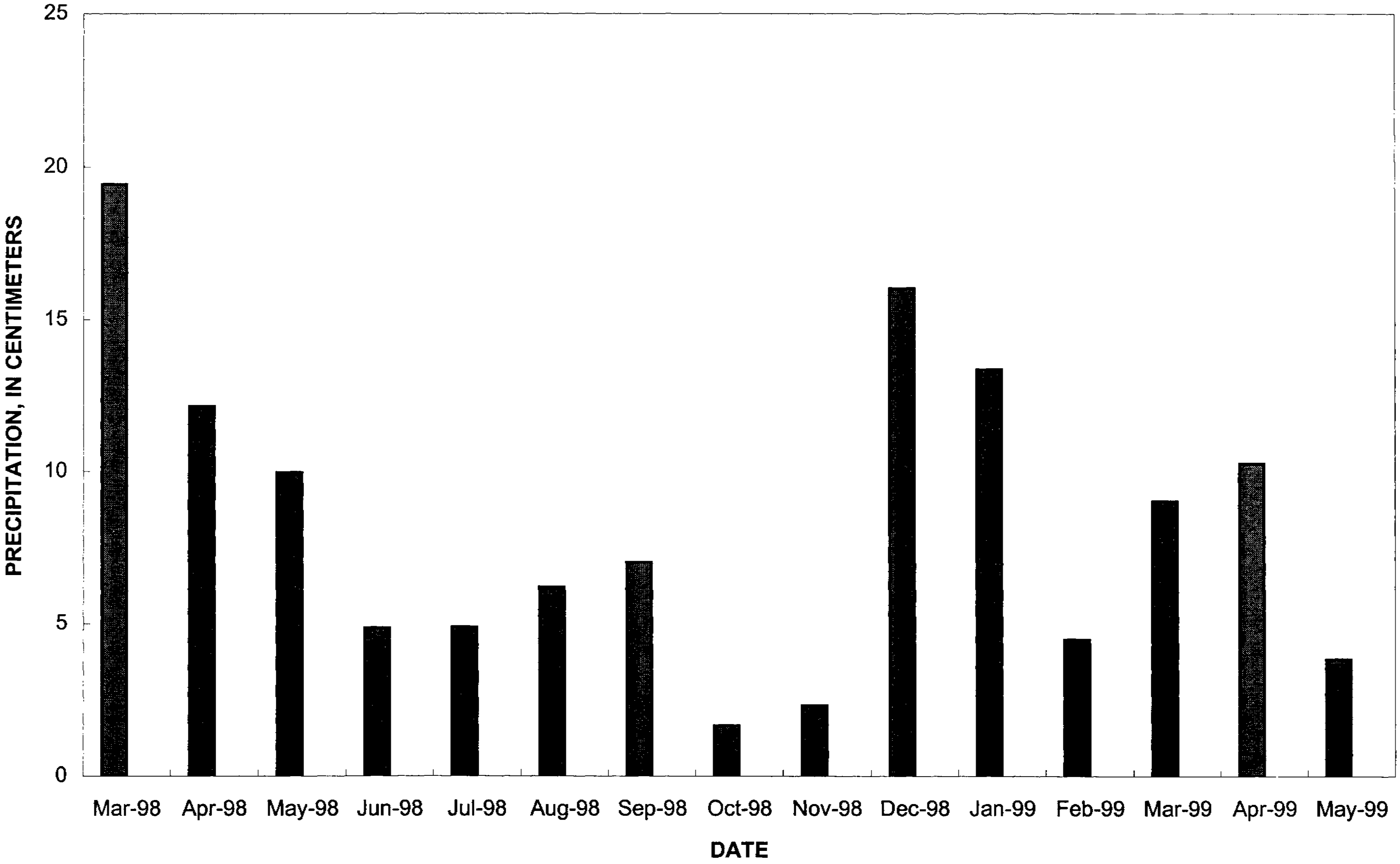


Figure 4.--Monthly precipitation at the Fort Lee created wetland, March 1998 through May 1999.

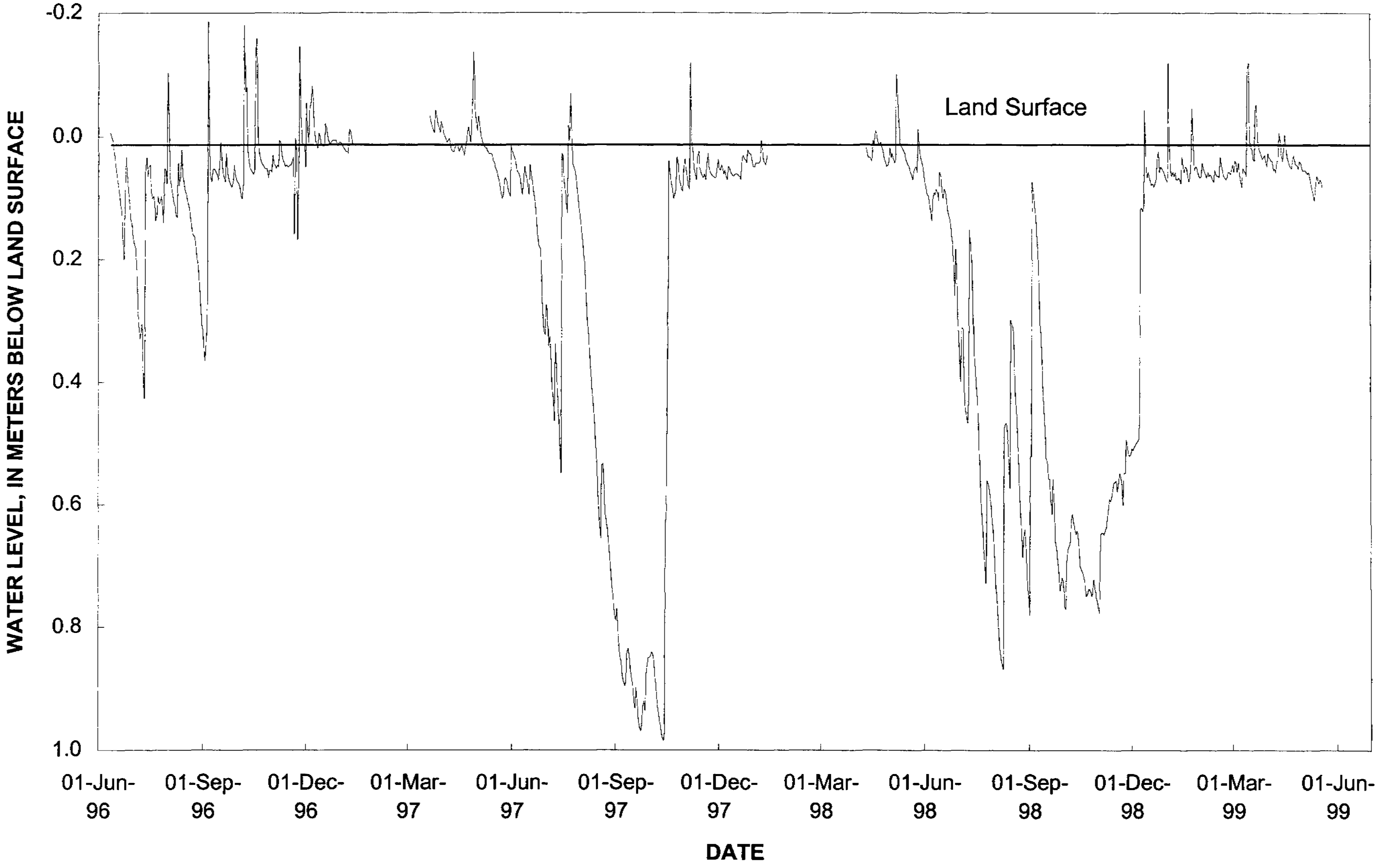


Figure 5.--Daily maximum ground-water levels in well FL 2 at the Fort Lee created wetland, June 1996 through May 1999.

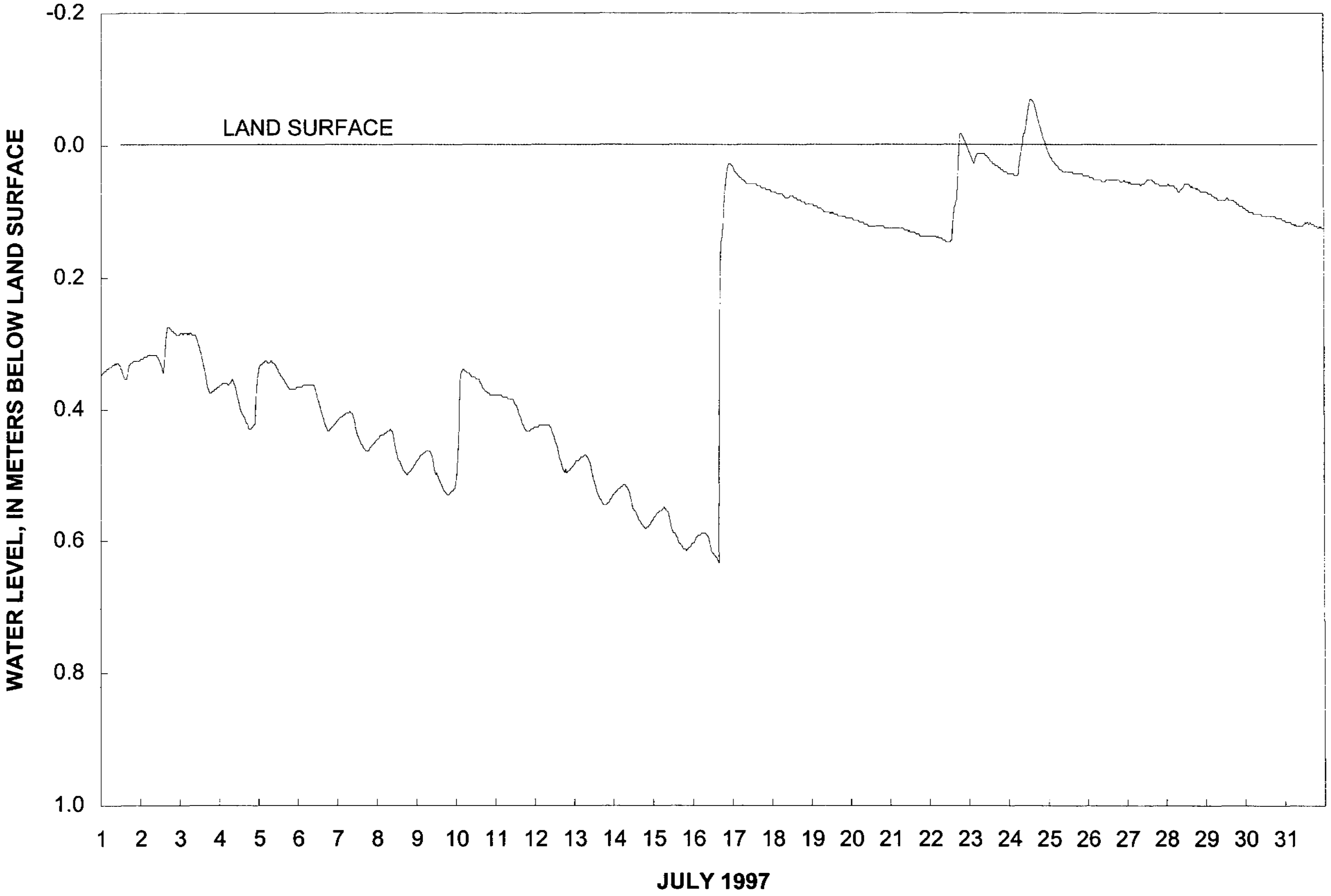


Figure 6. -- Diurnal cycles in ground-water levels in well FL2 at the Fort Lee created wetland, July 1997.

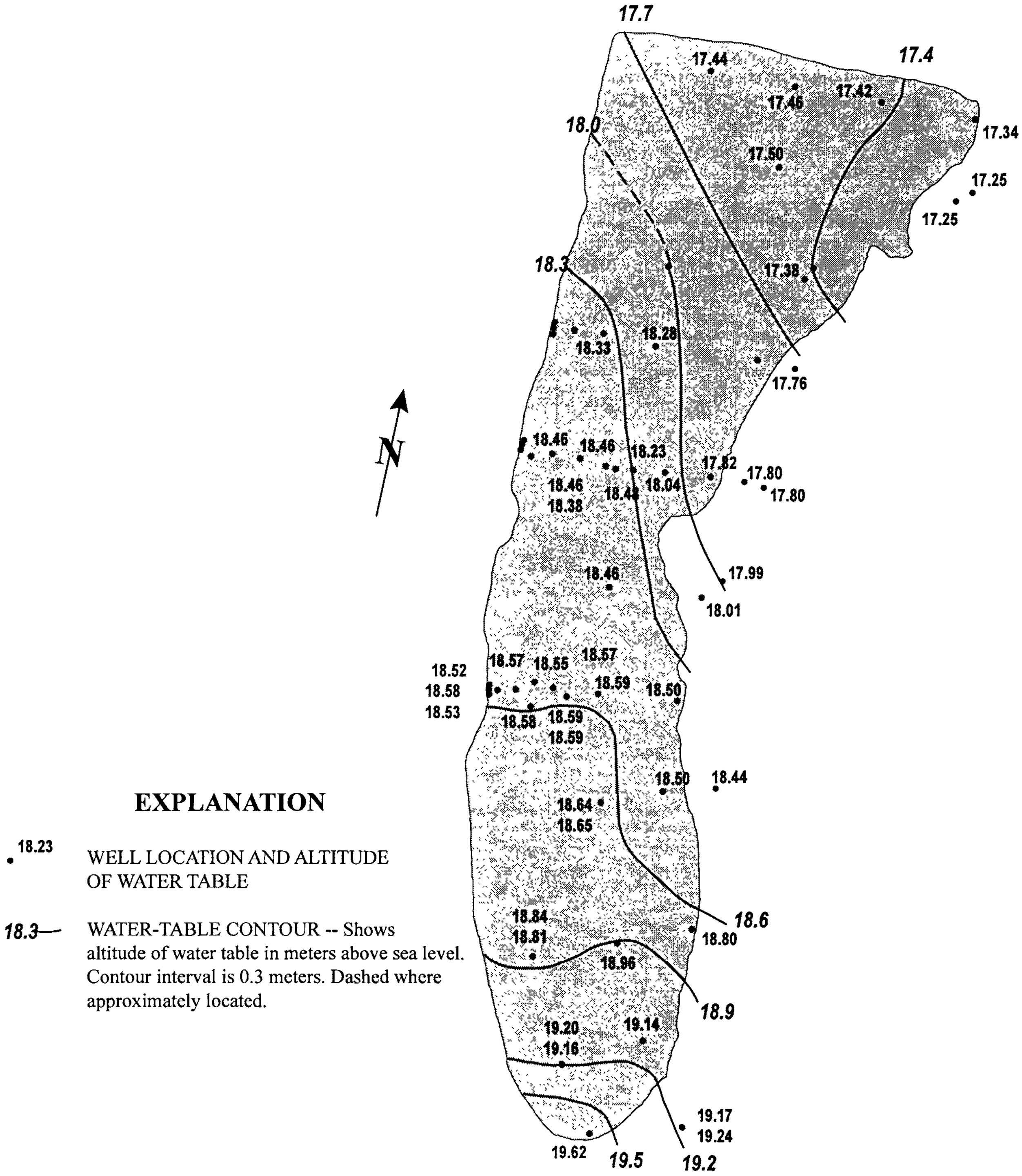
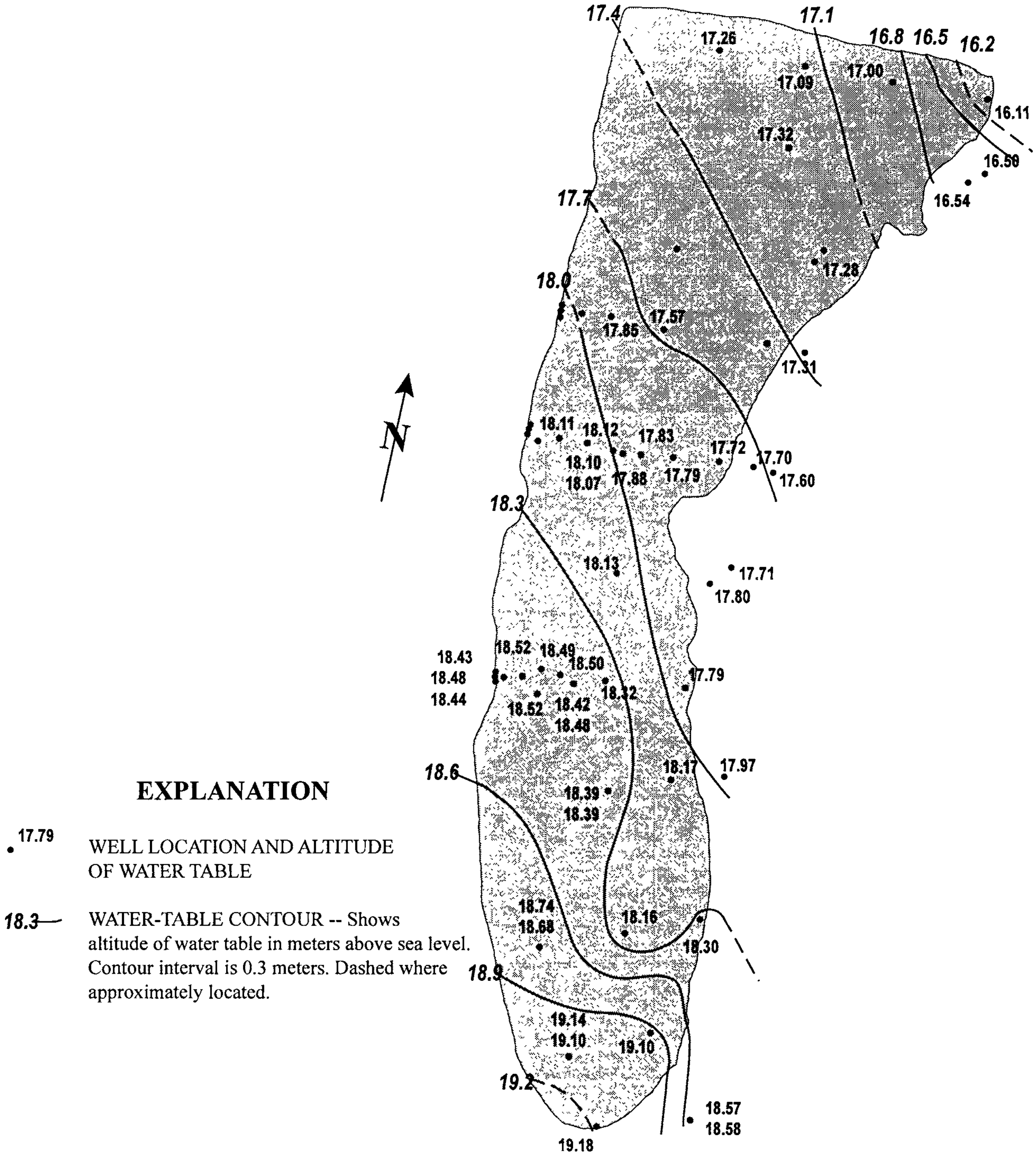


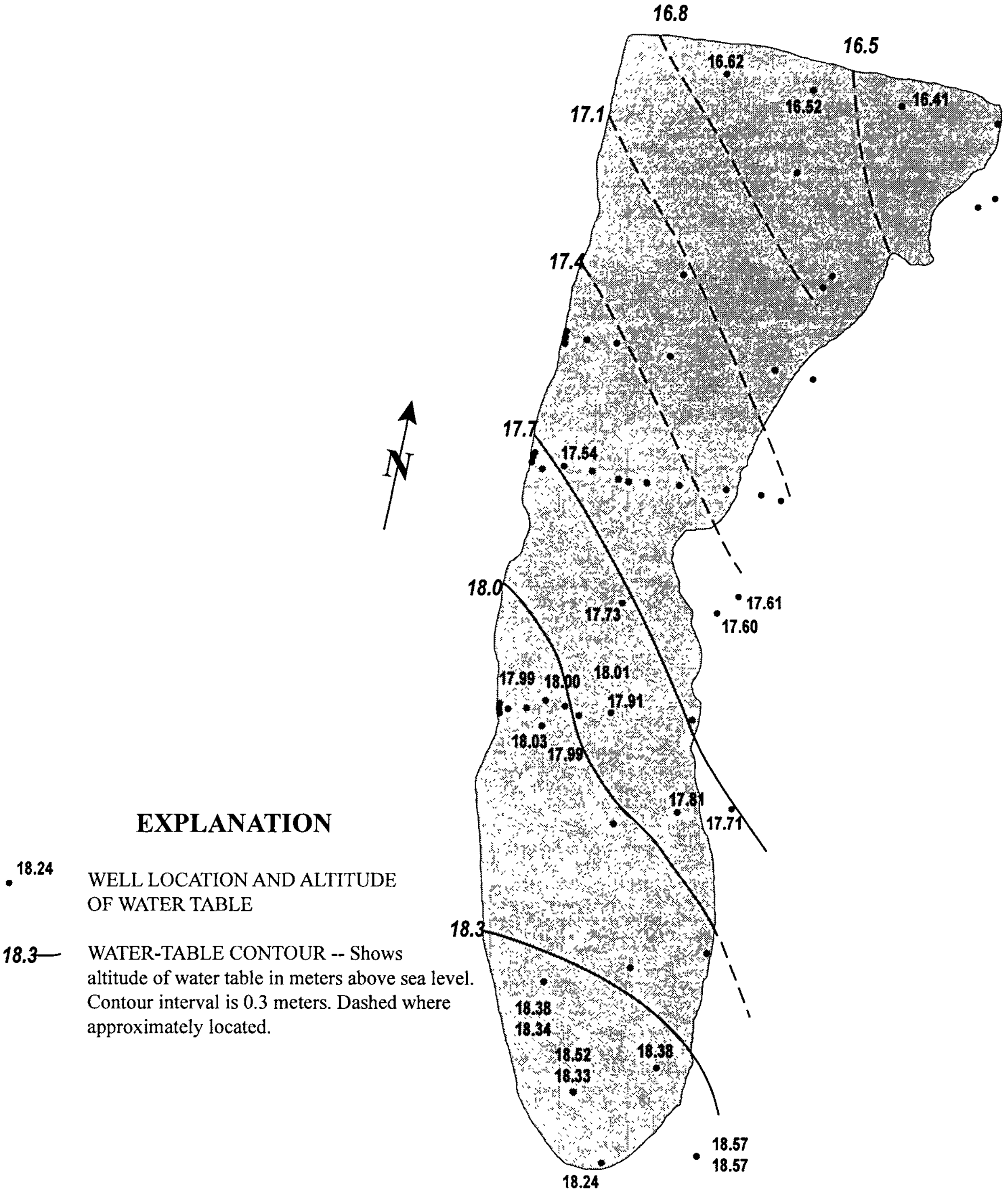
Figure 7. – Elevation of the water table at the Ft. Lee created wetland, February 19, 1998.



EXPLANATION

● 17.79	WELL LOCATION AND ALTITUDE OF WATER TABLE
18.3—	WATER-TABLE CONTOUR -- Shows altitude of water table in meters above sea level. Contour interval is 0.3 meters. Dashed where approximately located.

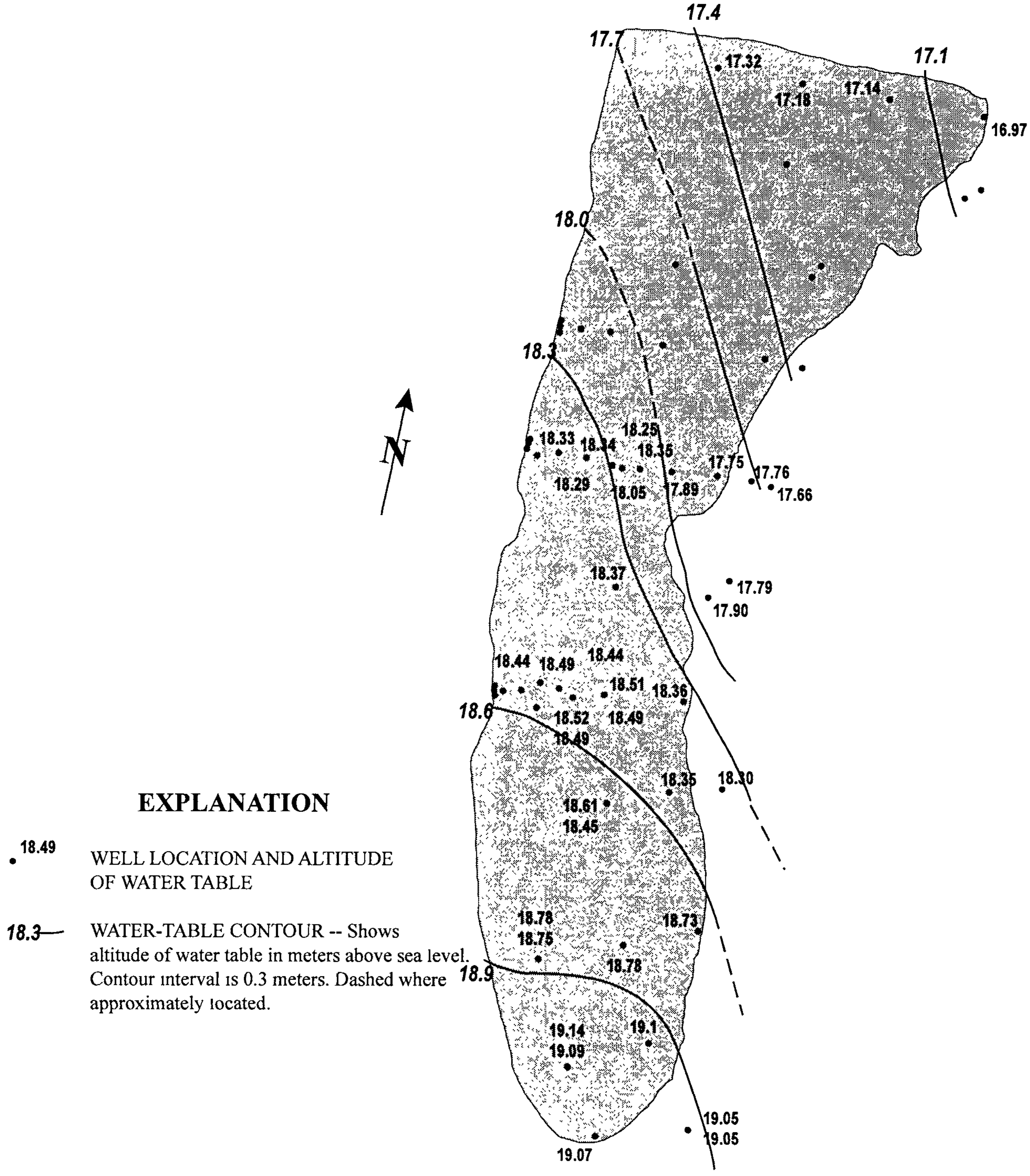
Figure 8. – Elevation of the water table at the Ft. Lee created wetland, June 15, 1998.



EXPLANATION

• 18.24	WELL LOCATION AND ALTITUDE OF WATER TABLE
18.3—	WATER-TABLE CONTOUR -- Shows altitude of water table in meters above sea level. Contour interval is 0.3 meters. Dashed where approximately located.

Figure 9. – Elevation of the water table at the Ft. Lee created wetland, November 18, 1998.



EXPLANATION

WELL LOCATION AND ALTITUDE OF WATER TABLE

WATER-TABLE CONTOUR -- Shows altitude of water table in meters above sea level. Contour interval is 0.3 meters. Dashed where approximately located.

Figure 10. – Elevation of the water table at the Ft. Lee created wetland, February 11, 1999.

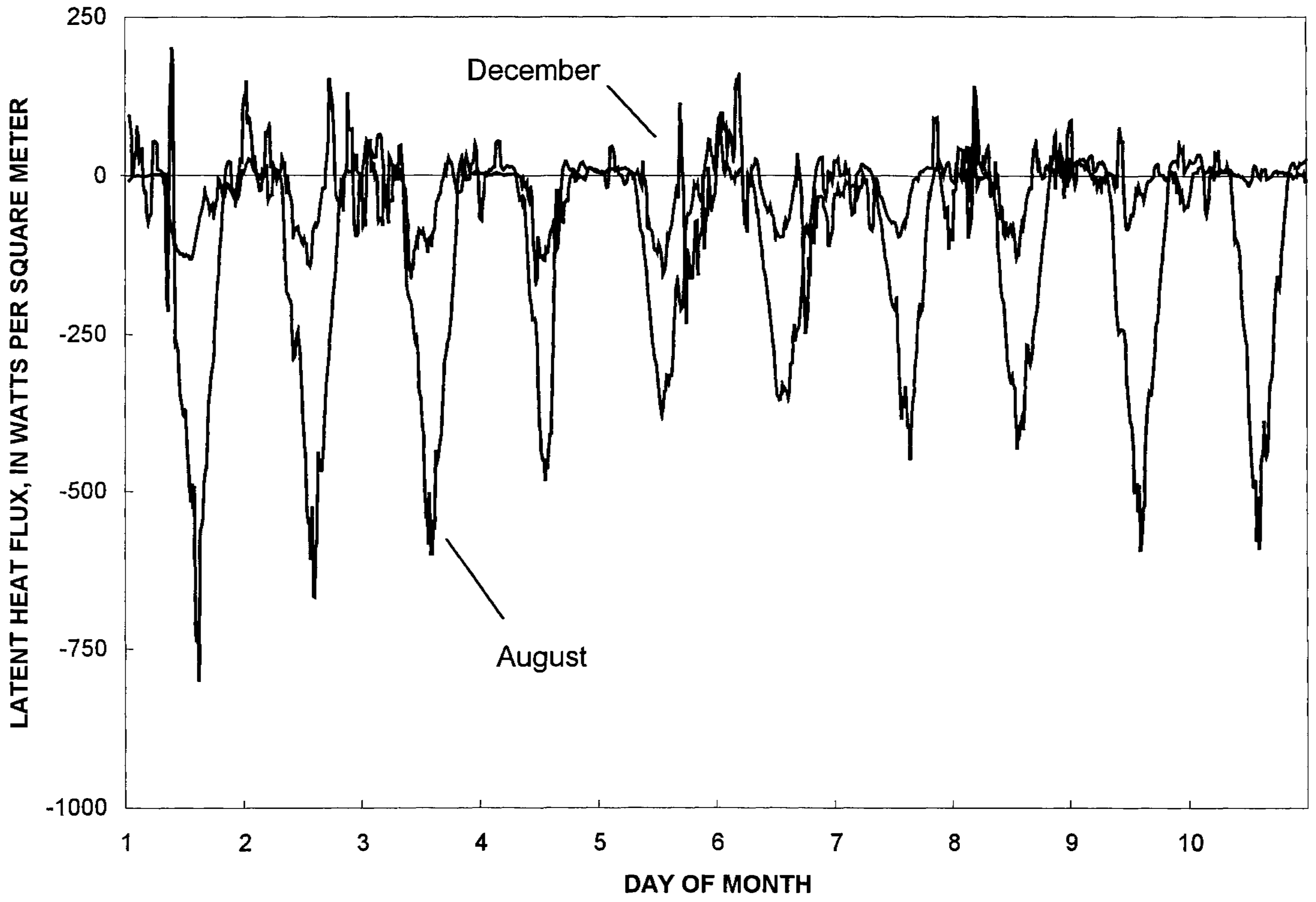


Figure 11. -- Running average (four, fifteen-minute values) of the latent heat flux (negative is toward land surface) at the Fort Lee created wetland, August 1 through 10, 1997, and December 1 through 10, 1997.

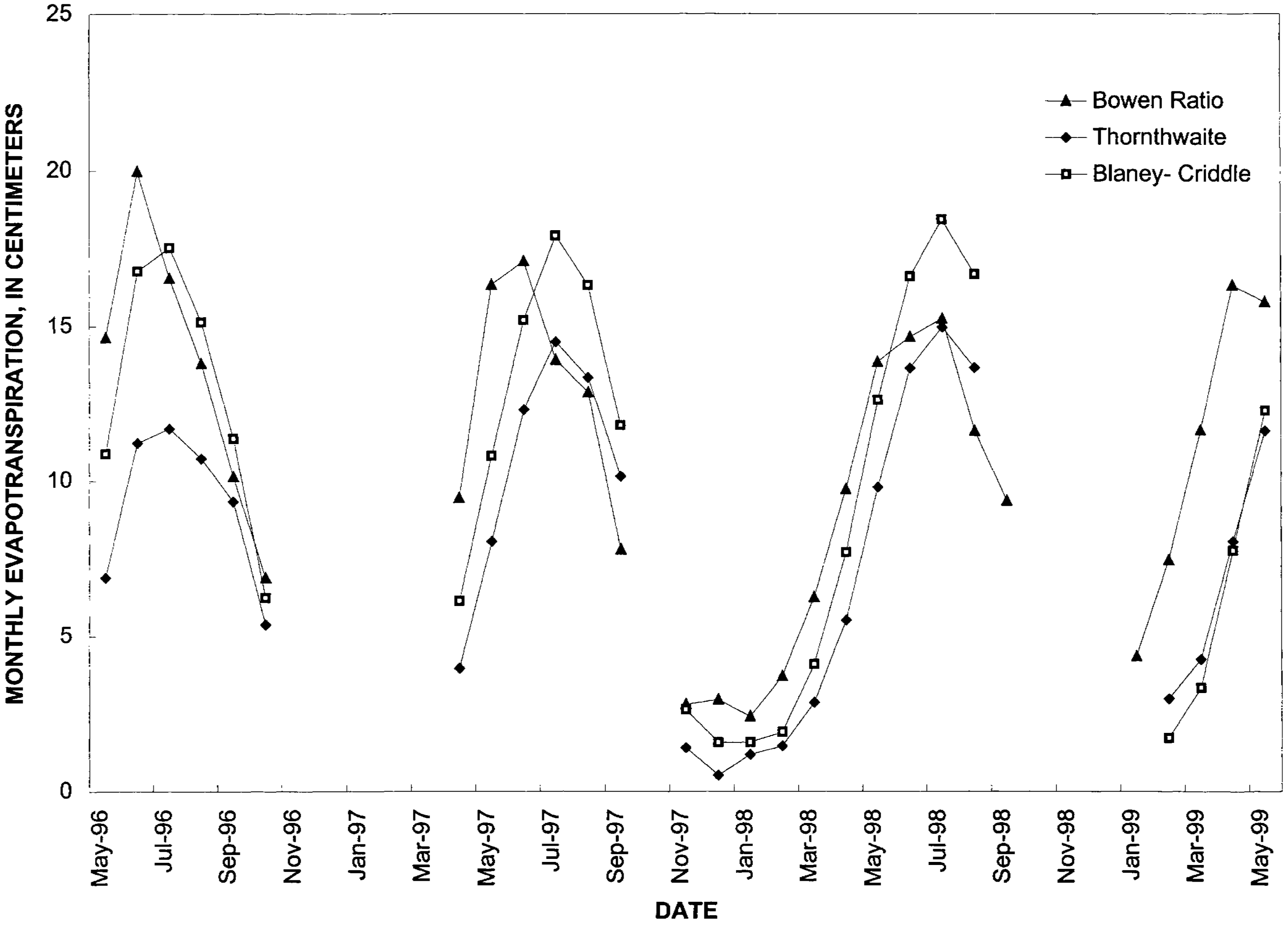


Figure 12.--Seasonal variations in monthly evapotranspiration calculated by the Bowen Ratio and potential evapotranspiration calculate by the Thornthwaite and Blainey-Criddle methods for the Fort Lee created wetland, May 1996 through May 1999.

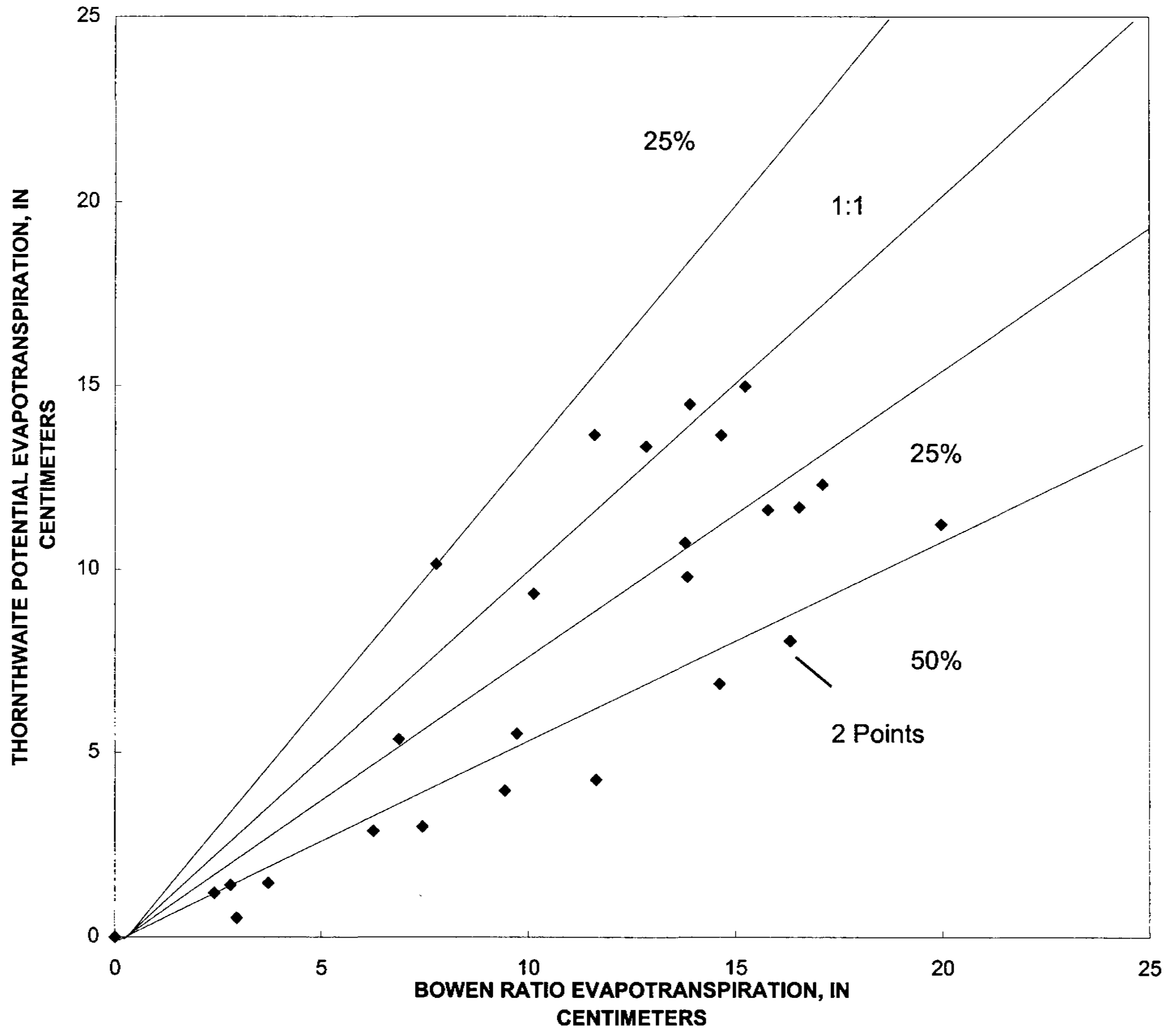


Figure 13.--Relation of monthly evapotranspiration calculated by the Bowen Ratio method and potential evapotranspiration calculated by the Thornthwaite method at the Fort Lee created wetland, May 1996 through May 1999.

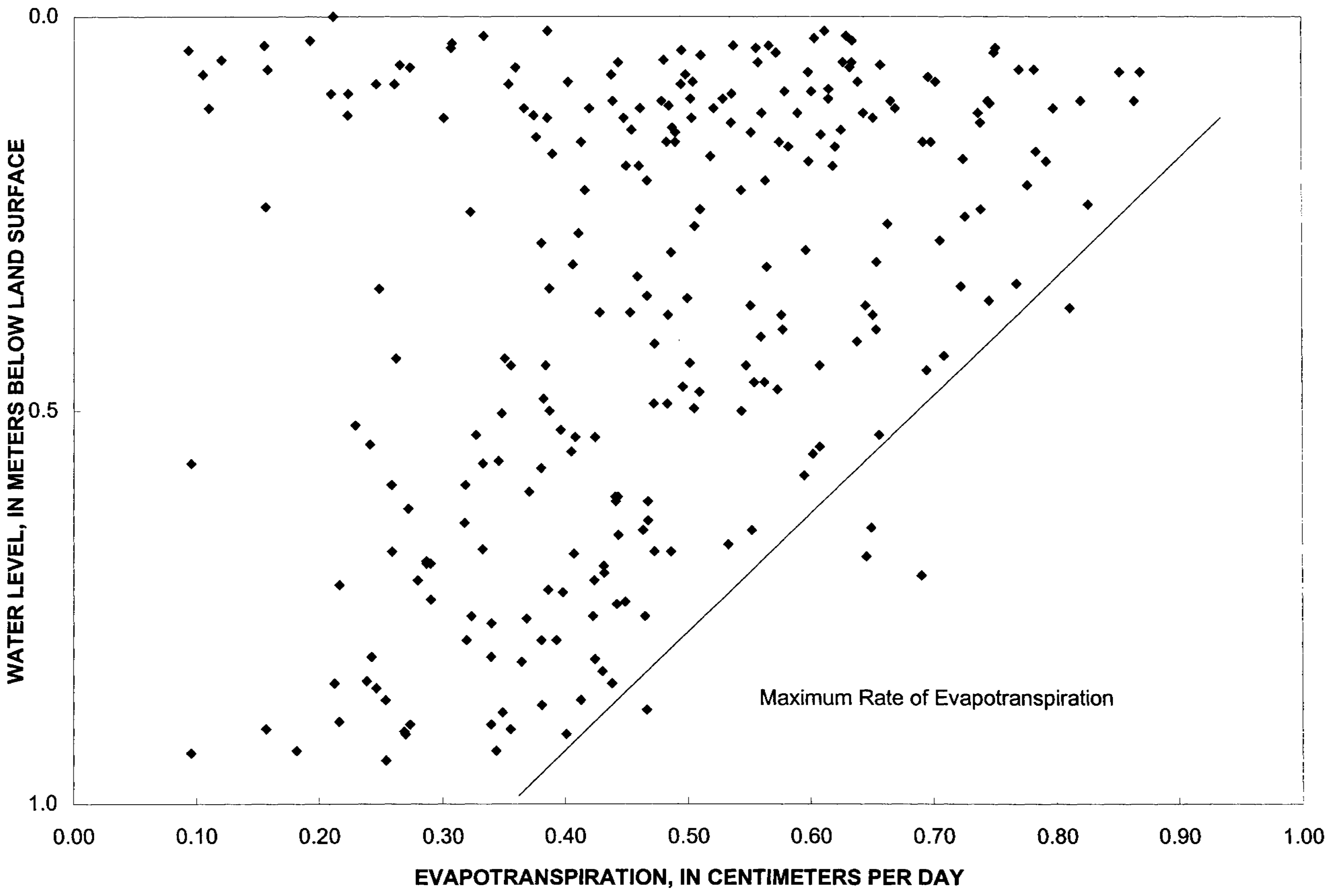


Figure 14. -- Relation of daily evapotranspiration calculated by the Bowen Ratio method and daily maximum ground-water levels when ground-water levels are below land surface in well FL 2 at the Fort Lee created wetland, 1996, 1997, and 1998.

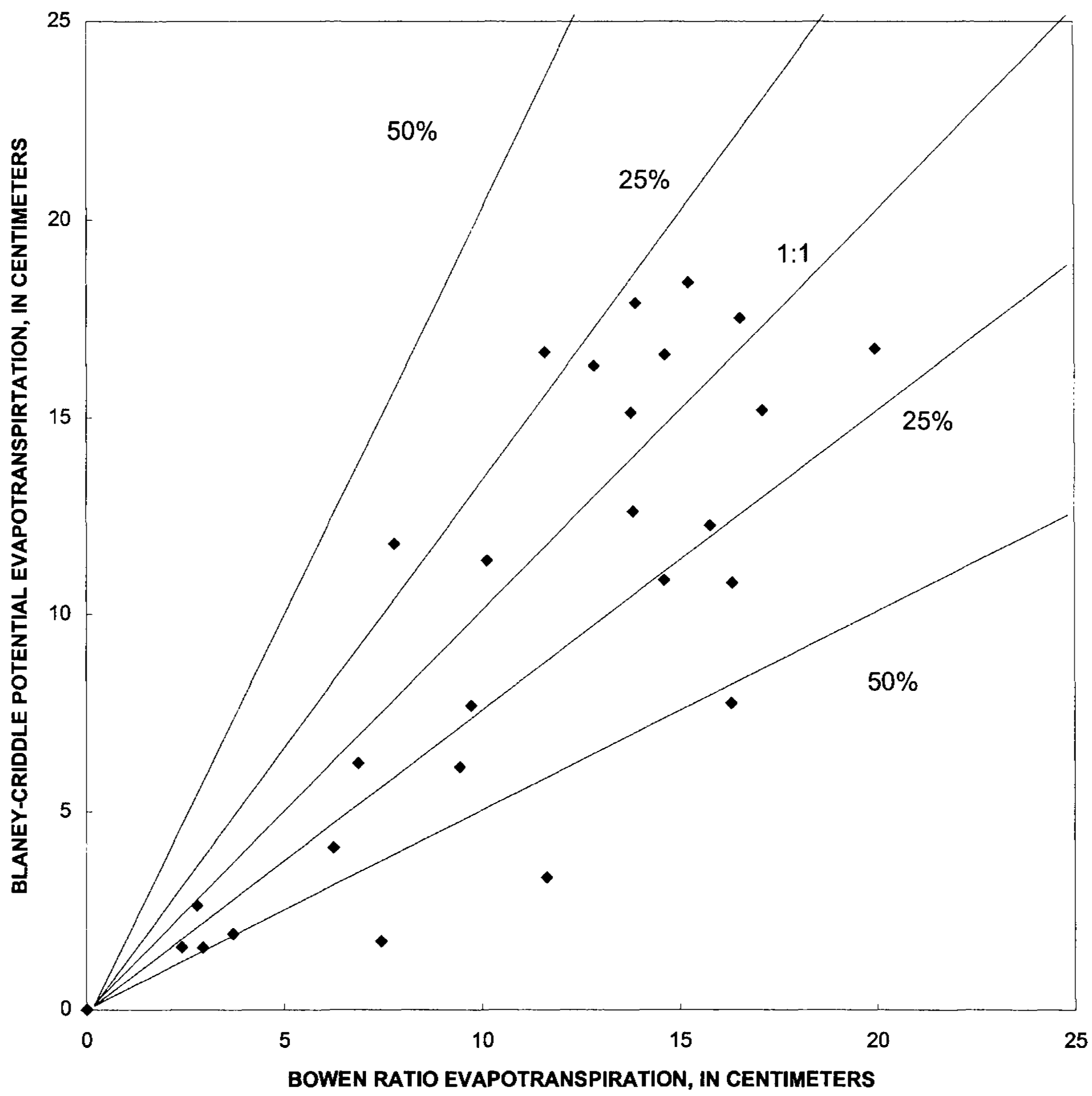


Figure 15.--Relation of monthly evapotranspiration calculated by the Bowen Ratio method and potential evapotranspiration calculated by the Blaney-Criddle method at the Fort Lee created wetland, May 1996 through May 1999.

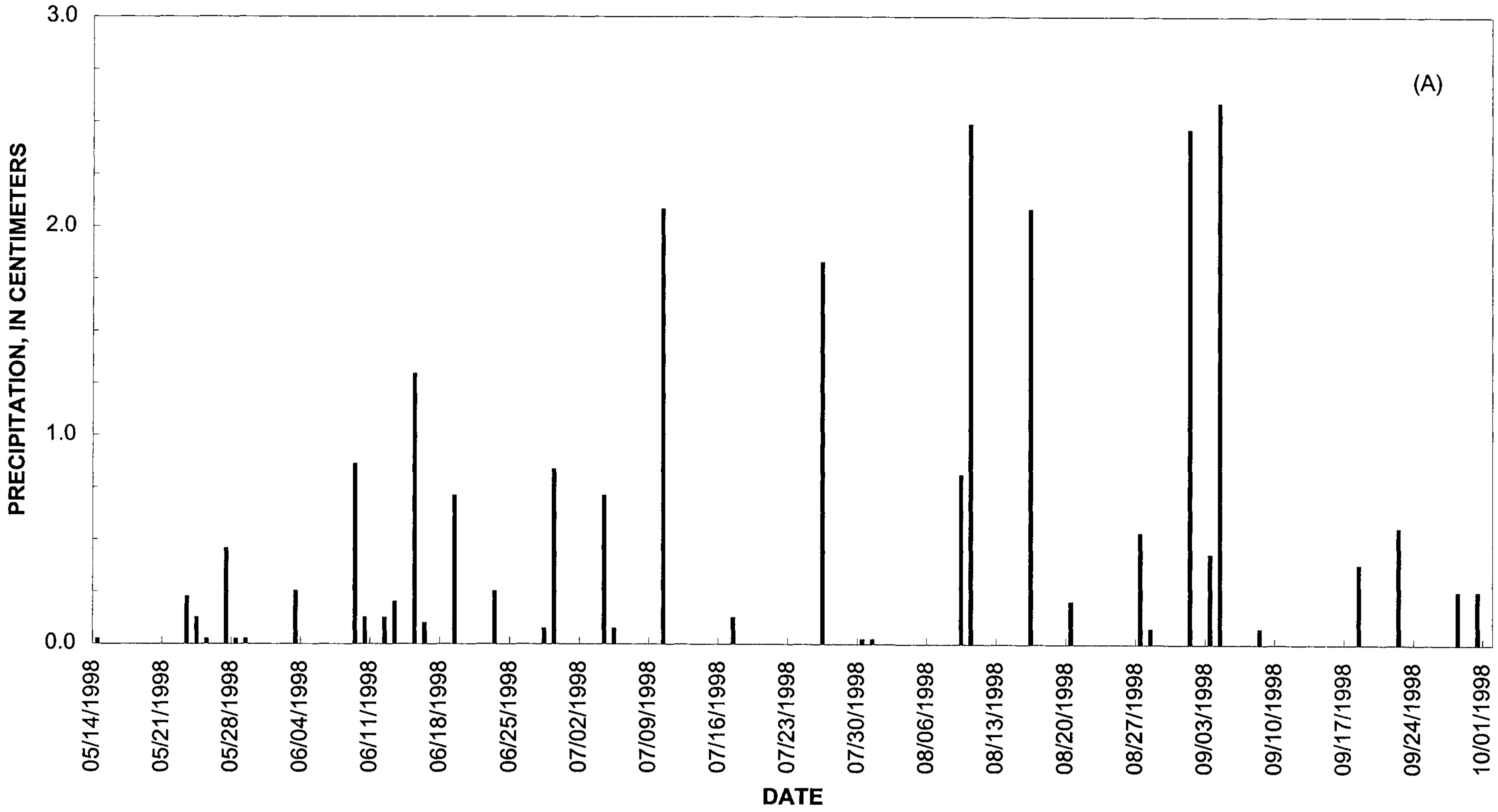


Figure 16a. -- Daily precipitation at the Fort Lee created wetland, May 14, 1998, through October 1, 1998.

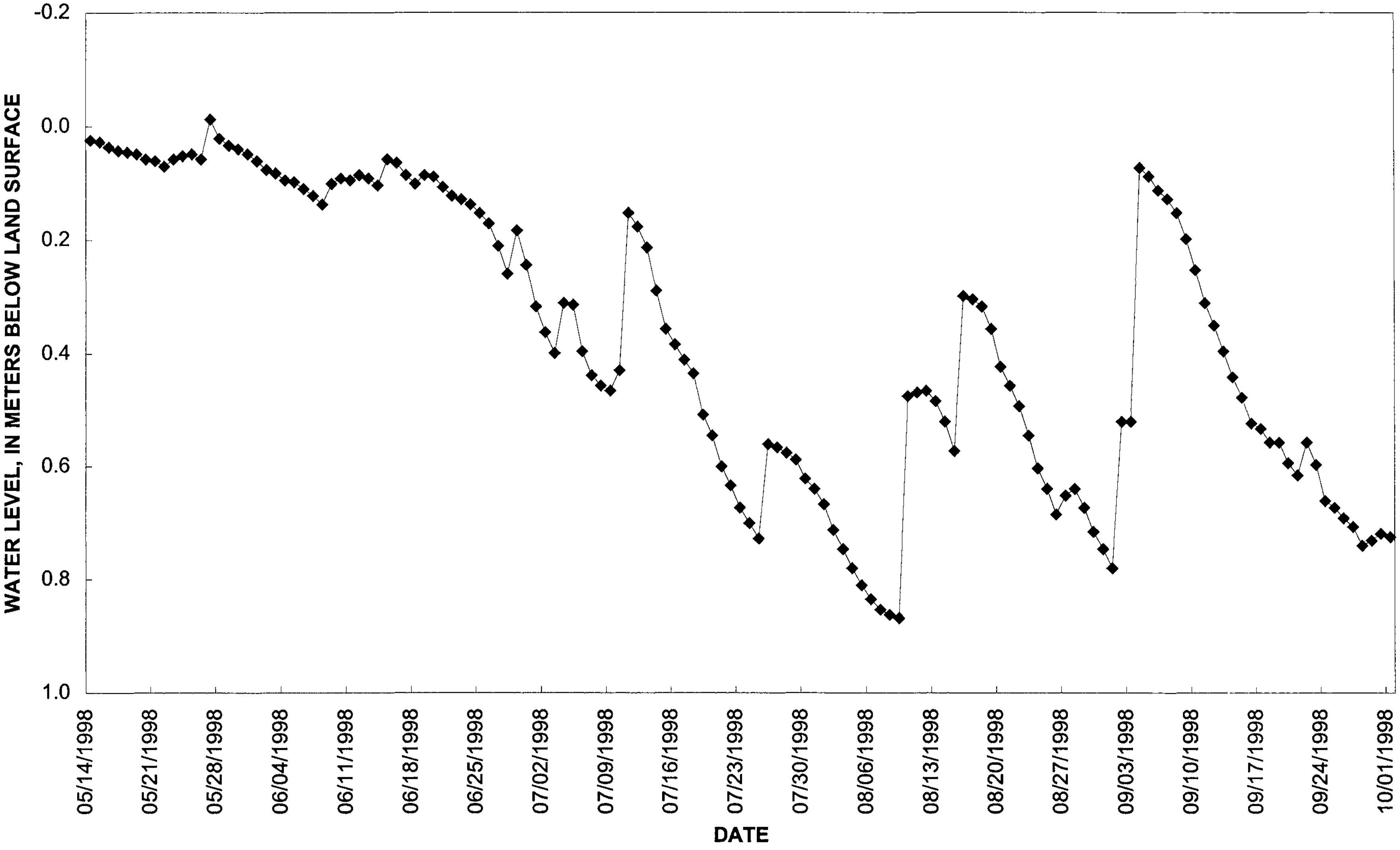


Figure 16b.--Daily maximum ground-water levels in well FL 2 at the Fort Lee created wetland, May 14, 1998, through October 1, 1998.

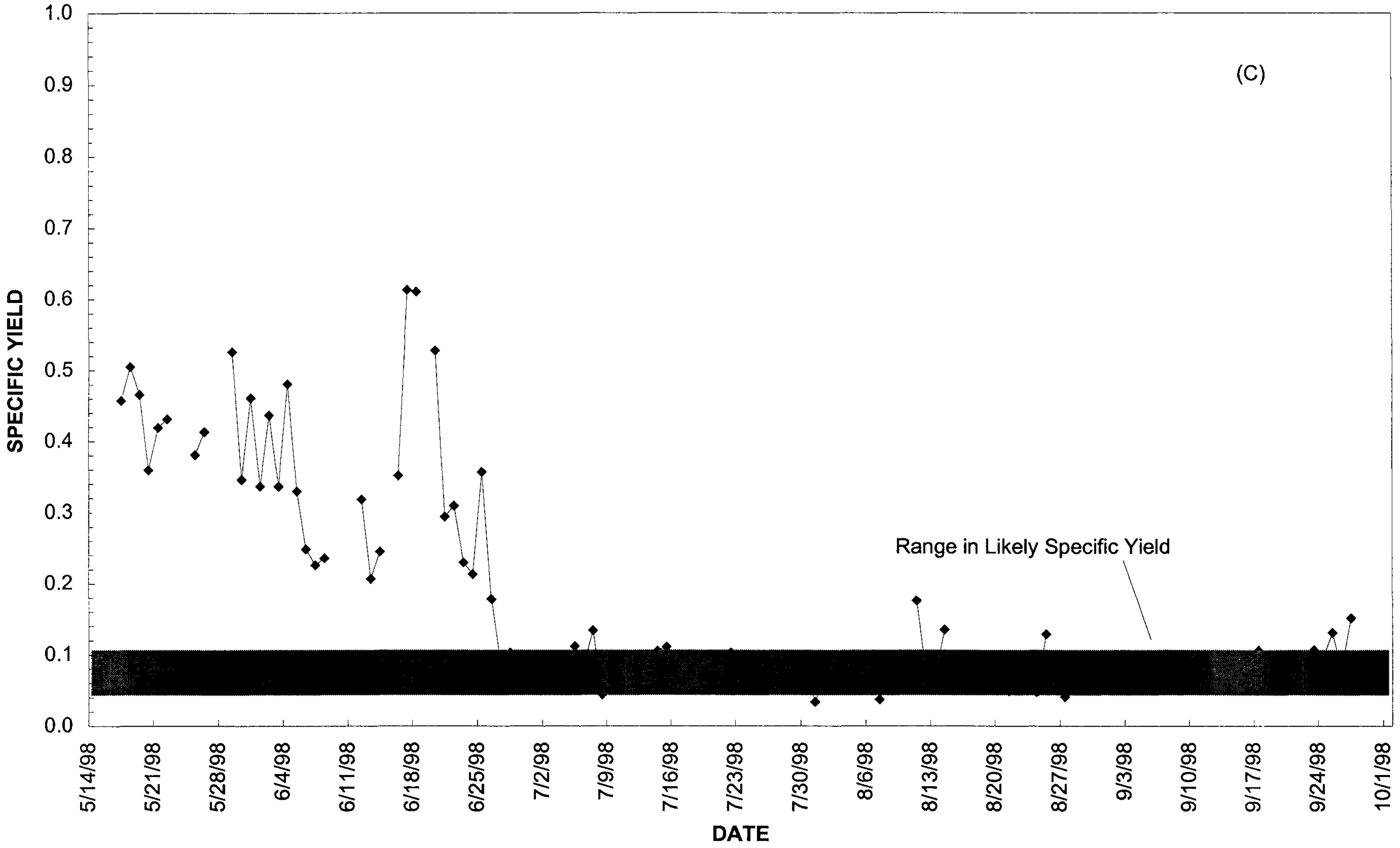


Figure 16c.--Specific Yield calculated from daily evapotranspiration calculated by the Bowen Ratio method and changes in ground-water levels at the Fort Lee created wetland, May 14, 1998, through October 1, 1998.

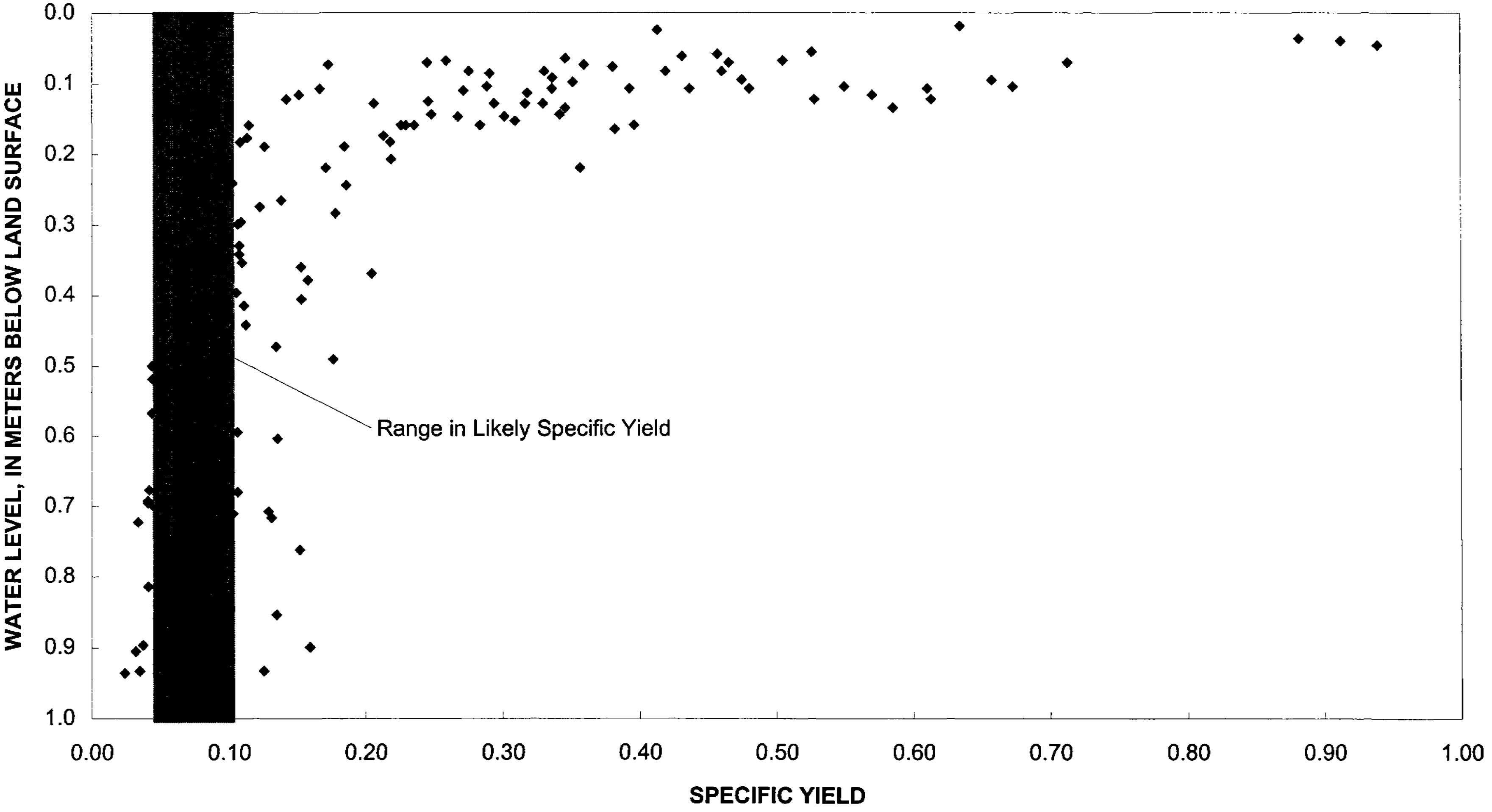


Figure 17. -- Relation of daily calculated specific yield and maximum ground-water levels at the Fort Lee created wetland, 1996, 1997, and 1998.

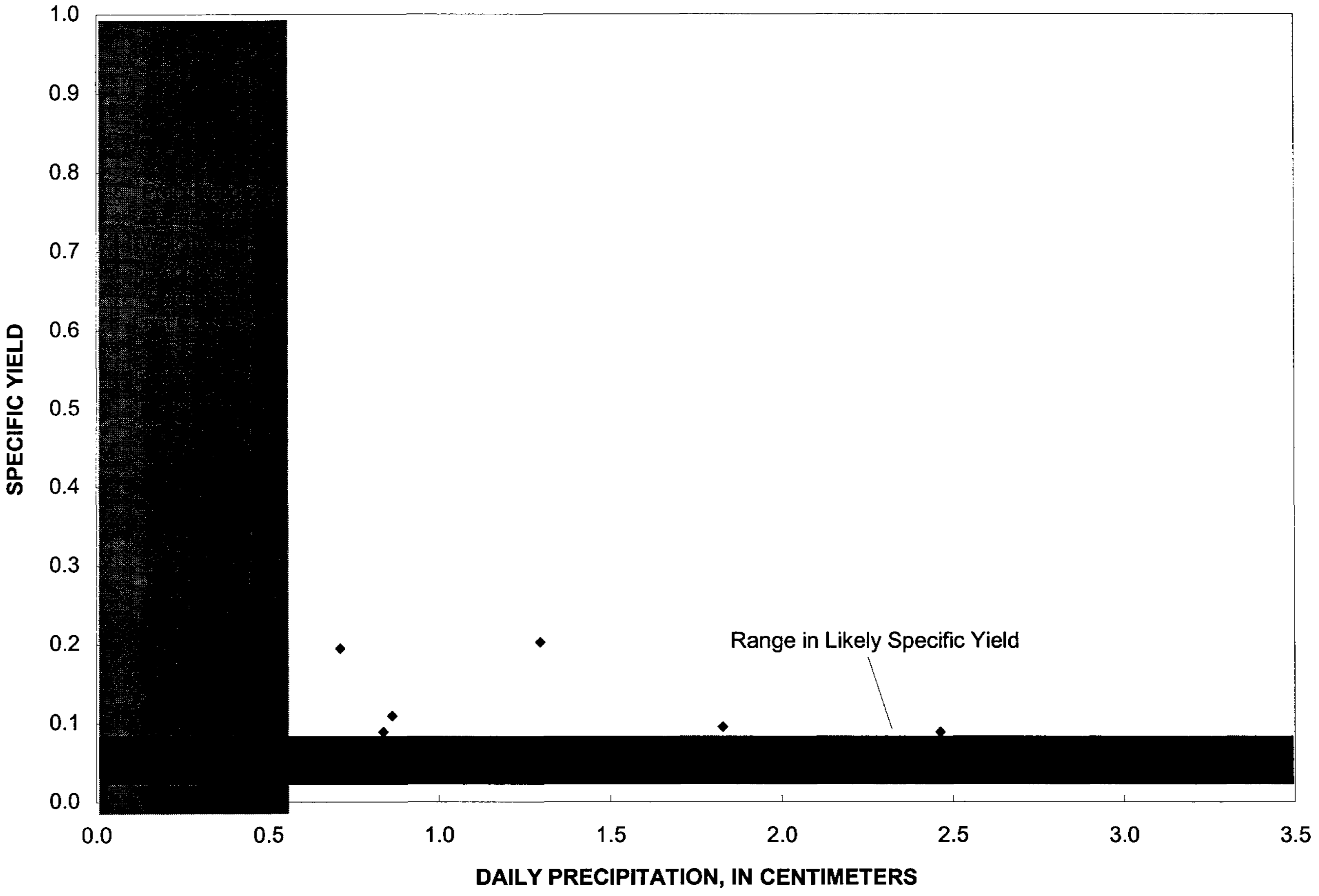


Figure 18. -- Relation between daily precipitation and specific yield calculated from the daily precipitation and daily rise in ground-water levels at the Fort Lee created wetland, June 15, 1998 through October 31, 1998.

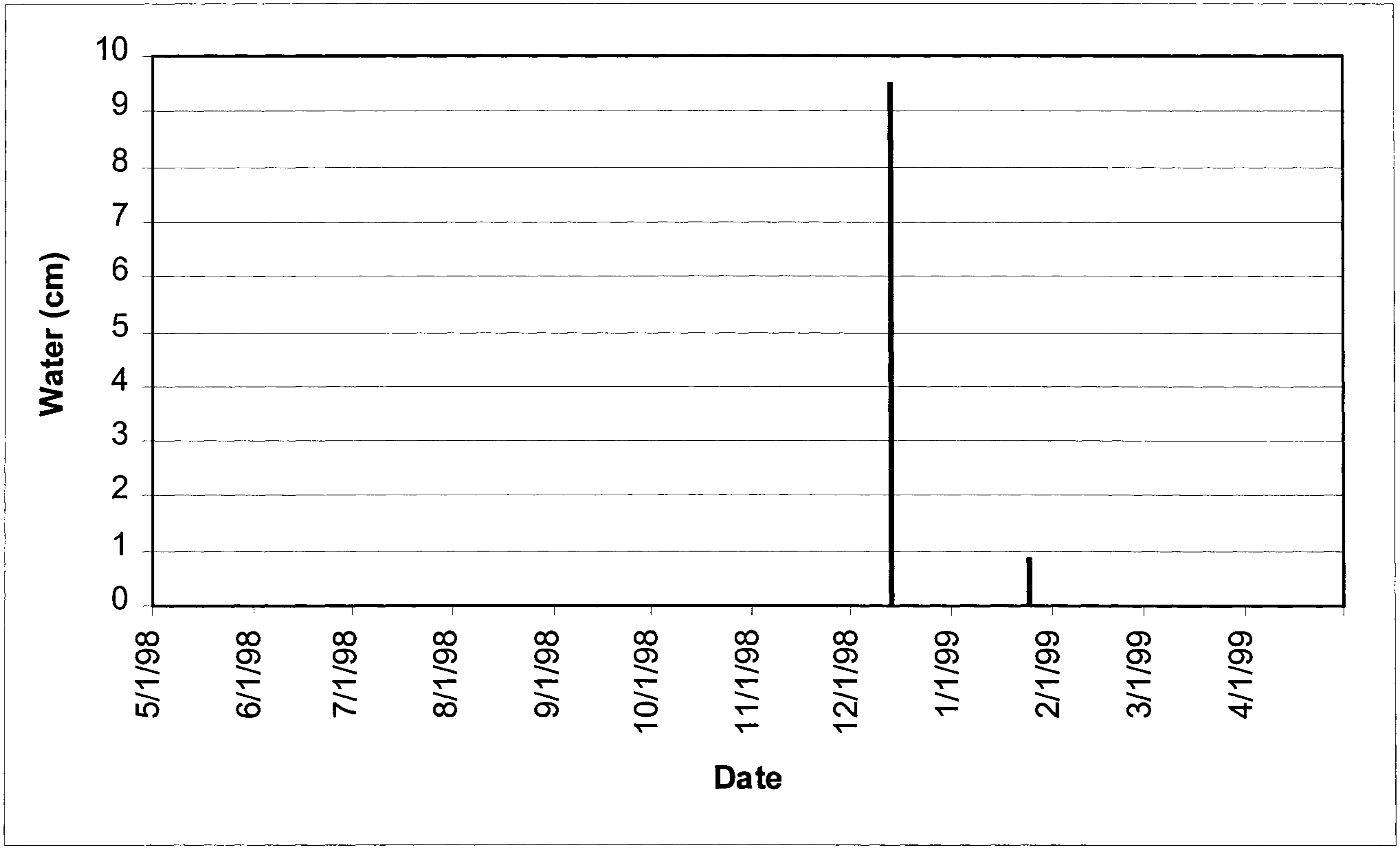


Figure 19.--Daily surface water inflow as estimated by the SCS Runoff Curve technique for the Fort Lee water budget between May 1, 1998 and April 30, 1999.

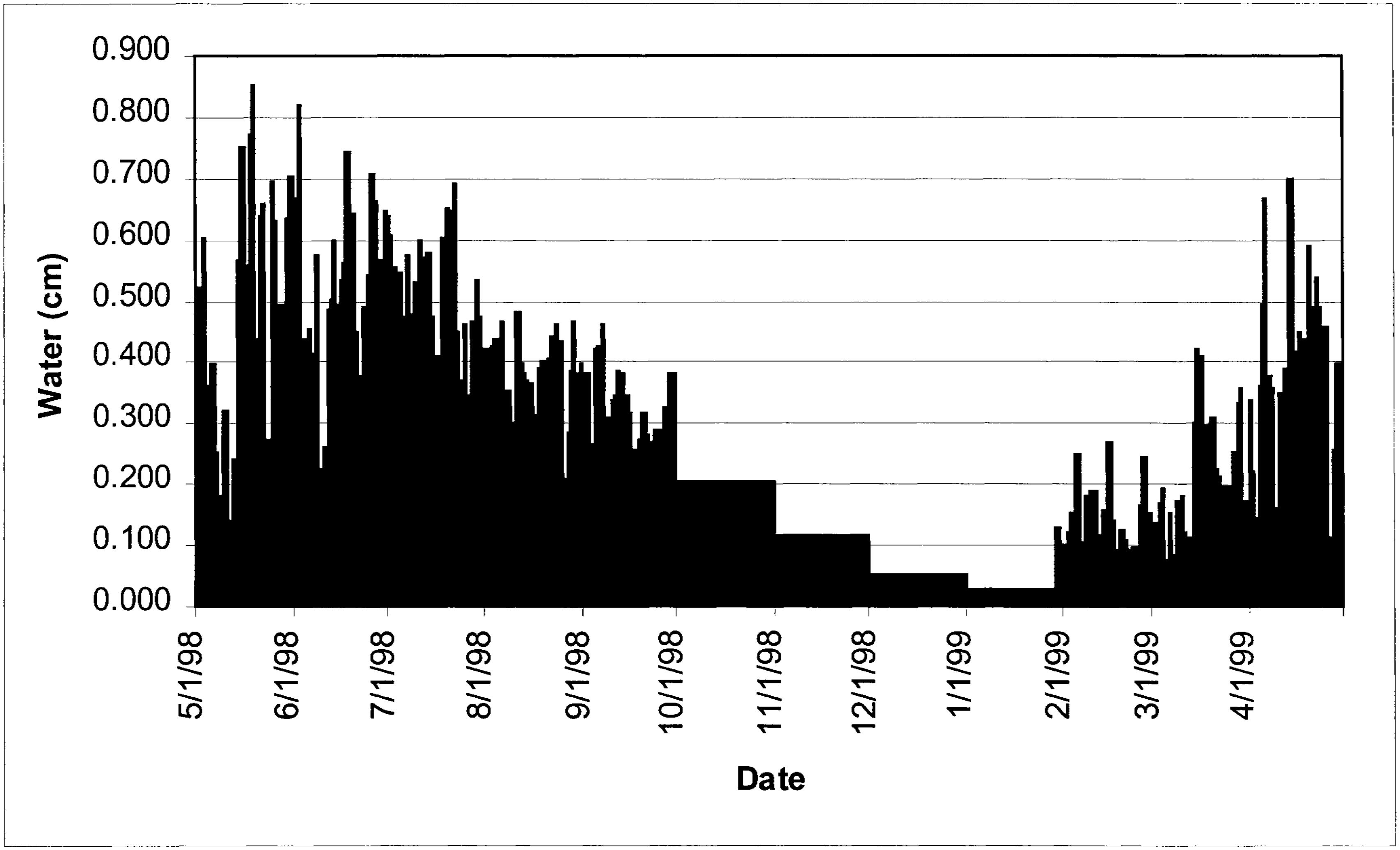


Figure 20.--Daily evapotranspiration losses from the Fort Lee water budget between May 1, 1998 and April 30, 1999. (Note: Average monthly Blaney Criddle estimate used for 9/28/98 to 1/28/99, all other values are from Bowen Ratio.)

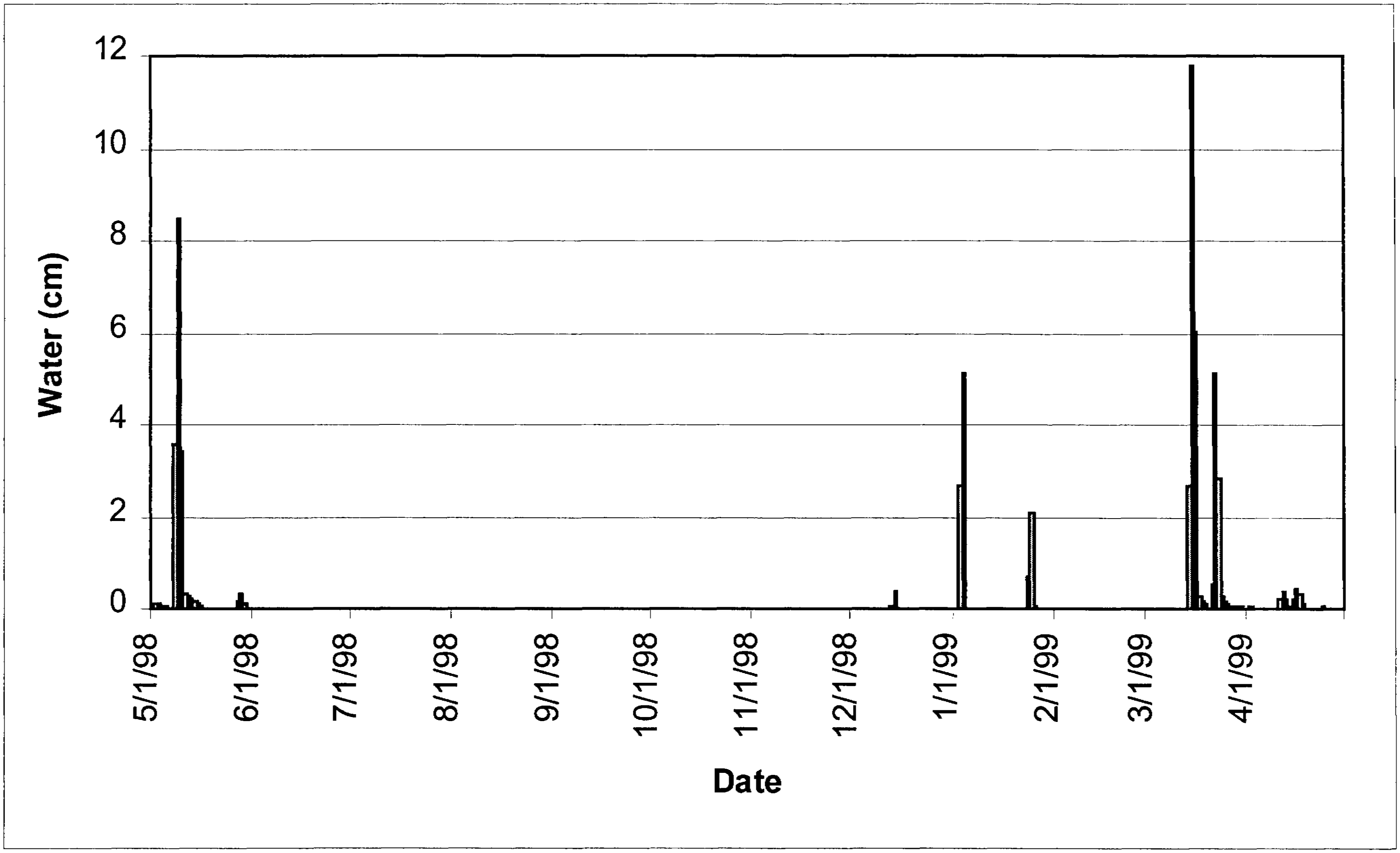


Figure 21.--Daily surface water outflow from the water budget between May 1, 1998 and April 30, 1999.

Figure 22.--Daily net groundwater inflows (positive) and outflows (negative) for the Fort Lee water budget between May 1, 1998 and April 30, 1999.

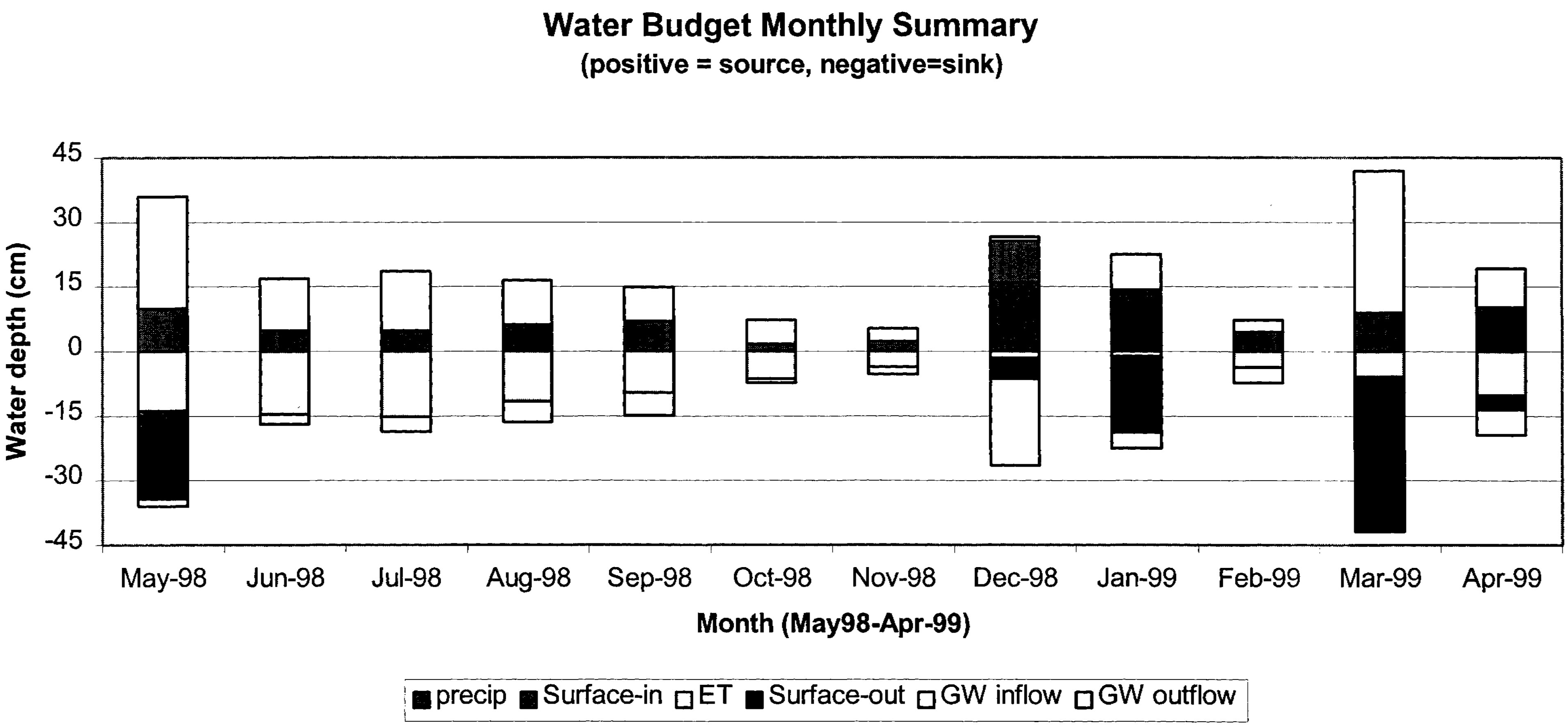


Figure 23.--Monthly total of each water budget parameter at Fort Lee during the year from May 1, 1998 to April 30, 1999. Negative values indicate losses (i.e. surface water outflow, ET, and net groundwater and soil water storage during periods of recharge) and positive values indicate sources (i.e. precipitation, surface water inflow, and net discharge of groundwater and soil water storage).

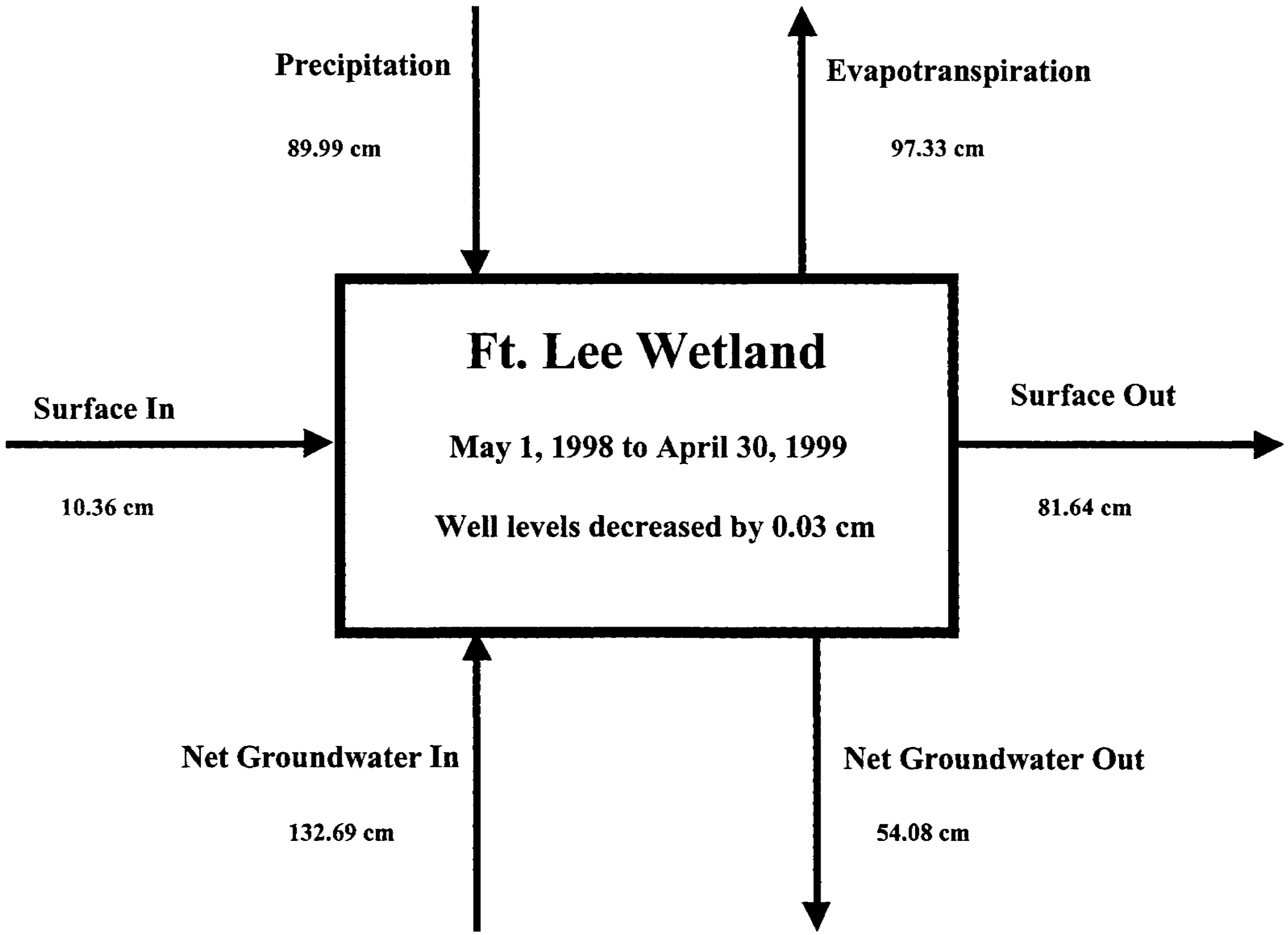


Figure 24.--Fort Lee Wetland water budget parameter totals for May 1, 1998 to April 30, 1999 based on net daily values.

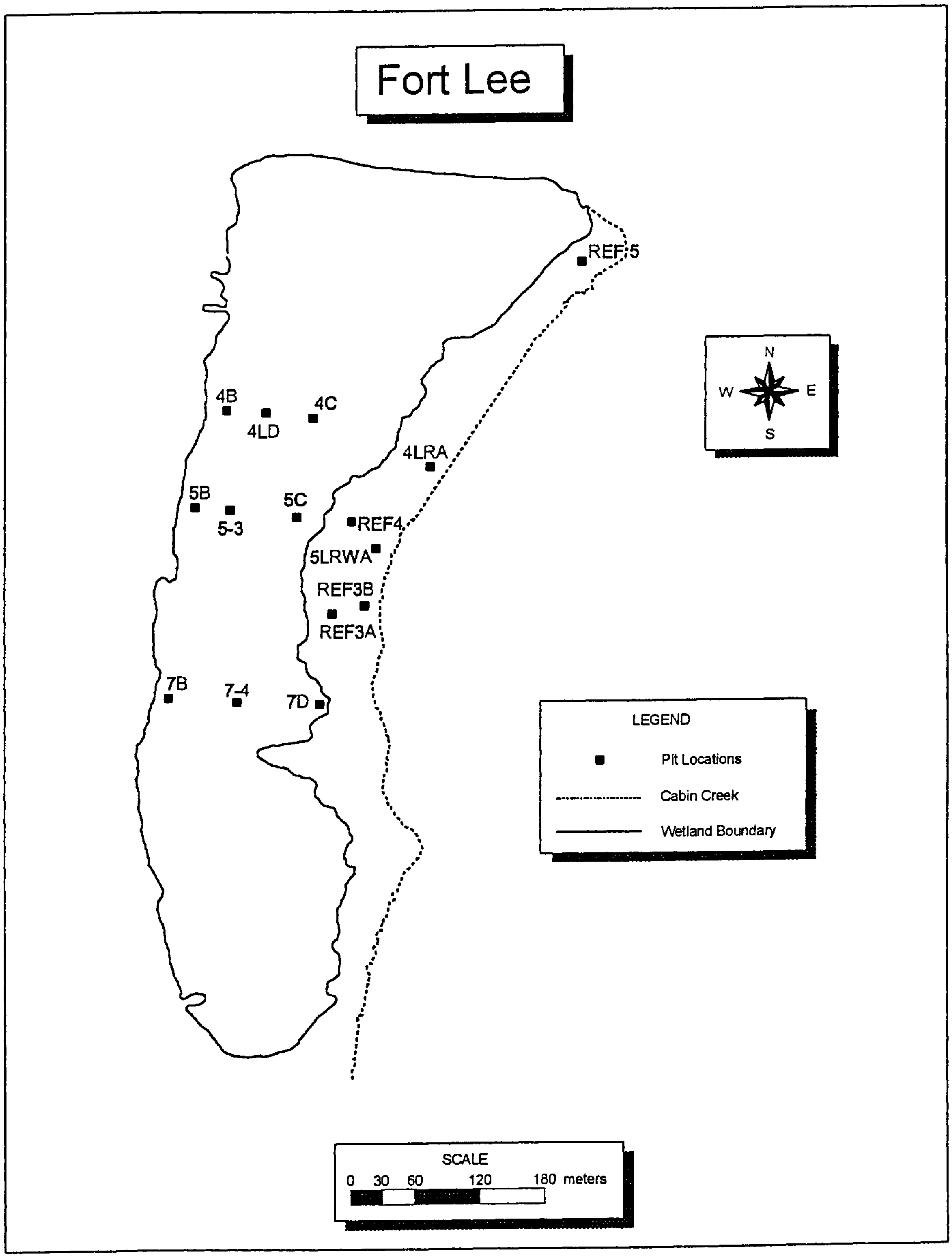


Figure 25. Fort Lee Pit Locations.

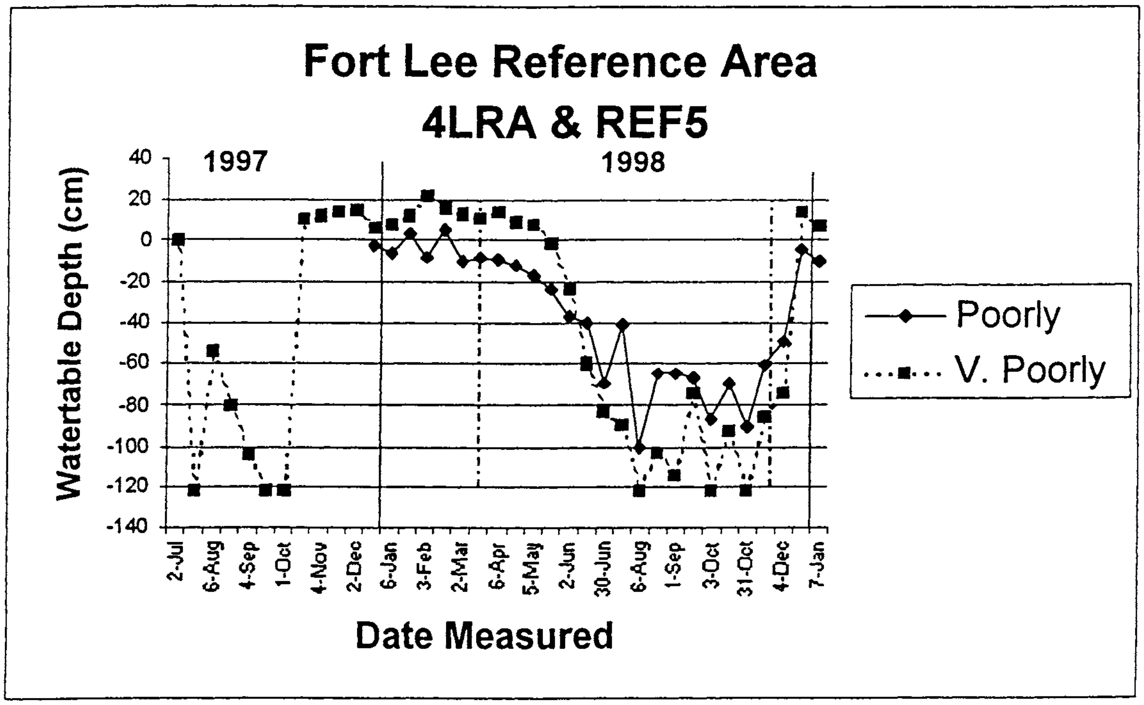


Figure 26a. Typical Fort Lee reference area hydrograph. Well readings between the dashed lines occurred during the growing season.

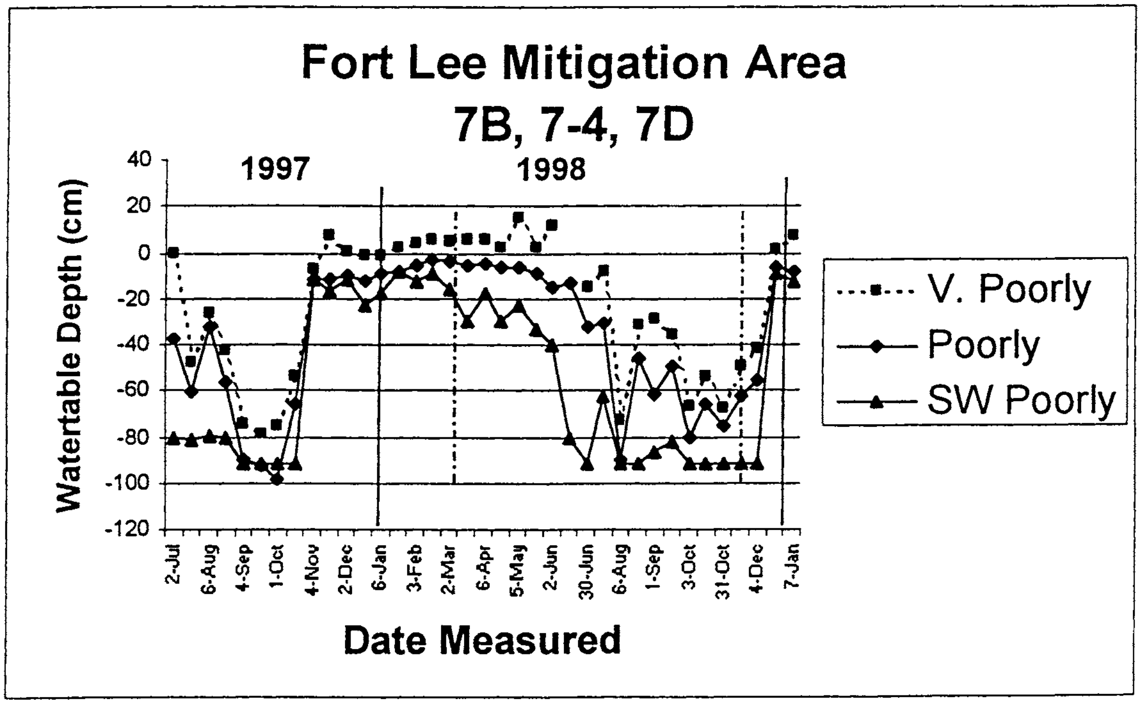


Figure 26b. Typical Fort Lee mitigation area hydrograph. Well readings between the dashed lines occurred during the growing season.

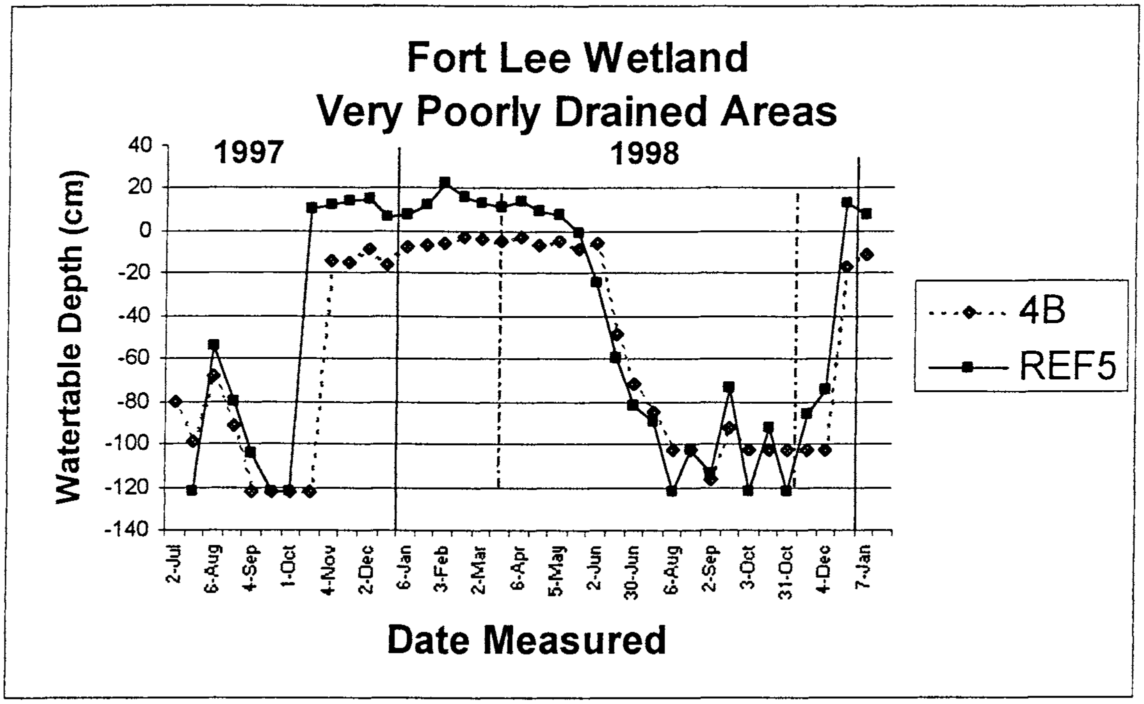


Figure 27a. Typical very poorly drained area hydrograph comparison. Well readings between the dashed lines occurred during the growing season.

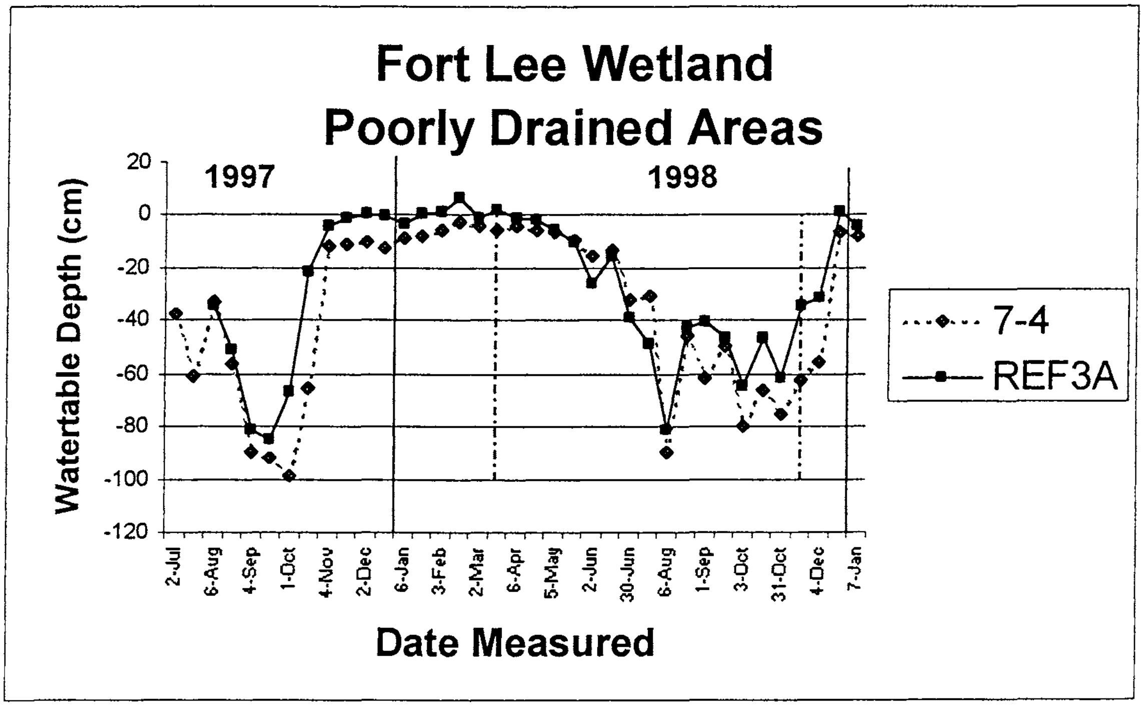


Figure 27b. Typical poorly drained area hydrograph comparison. Well readings between the dashed lines occurred during the growing season.

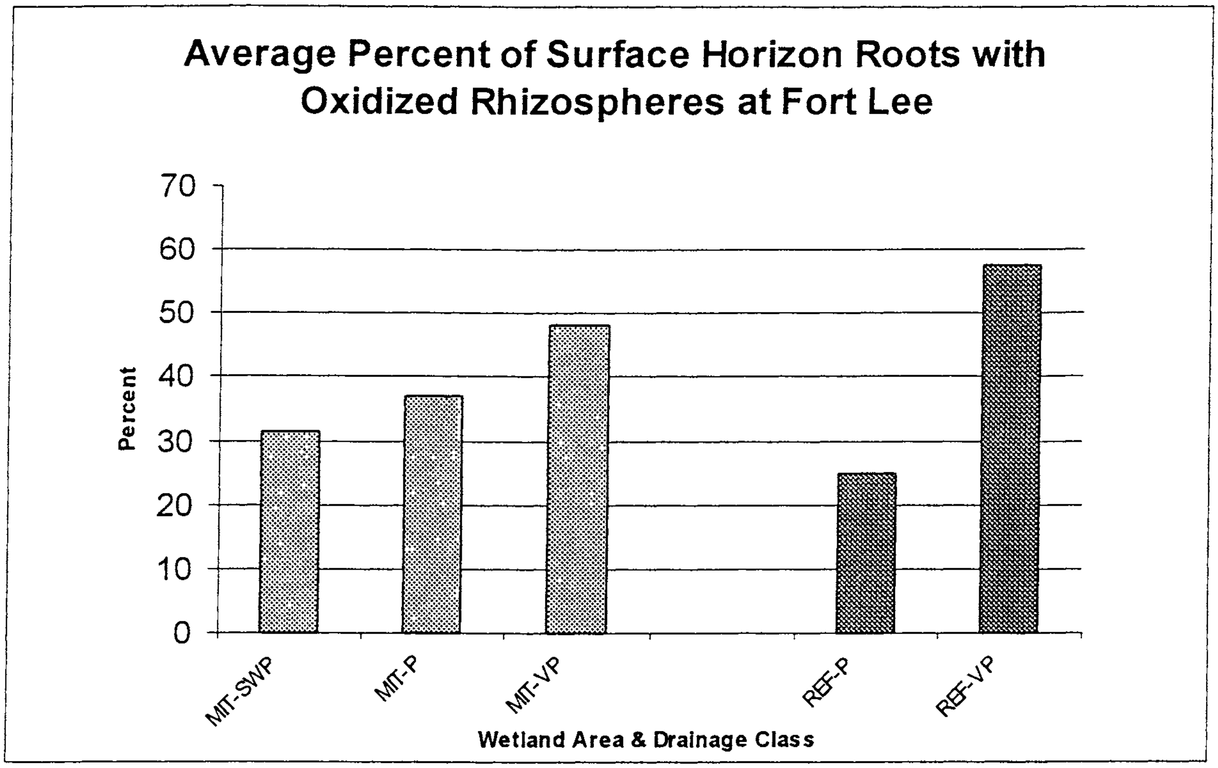


Figure 28. Average percent of surface horizon roots with oxidized rhizospheres at Fort Lee.

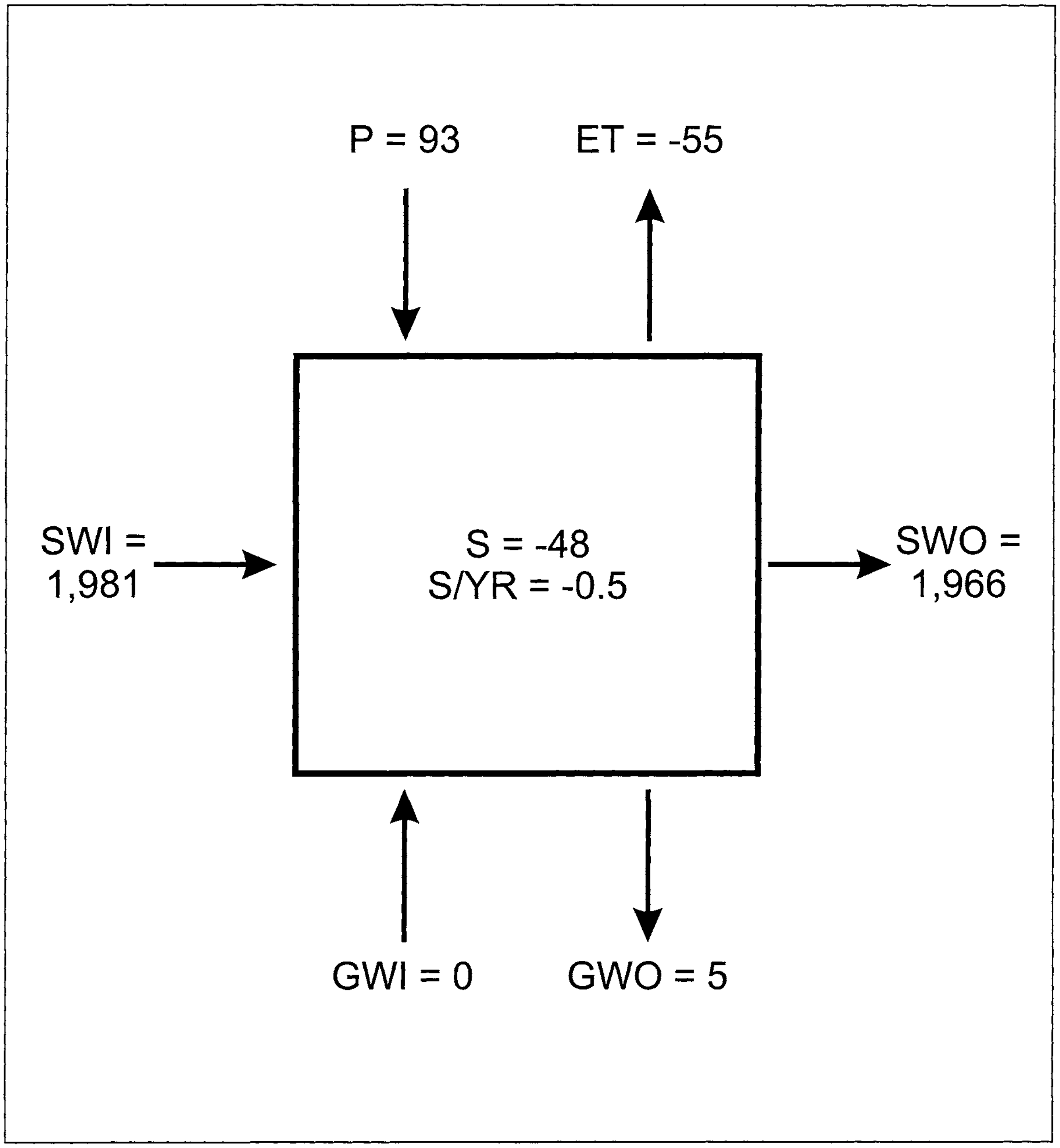


Figure 29. On-site measured water budget for the Manassas wetland. P = precipitation, ET = evapotranspiration, SWI = surface water inflow, SWO = surface water outflow, GWI = groundwater inflow, GWO = groundwater outflow, and S = change in storage. All values are expressed in cm/10 month period unless otherwise noted. Note: The months of May, June, July, January, and February did not include 9, 12, 3, 5, and 3 days of data, respectively.