CHAPTER V

HYDROLOGIC RESPONSE OF SOUTHEASTERN LOWER COASTAL PLAIN WET PINE FLATS TO HARVESTING AND SITE PREPARATION[1]

Abstract

The Southeastern Lower Coastal Plain includes over one million hectares of wet pine flats. These are economically, socially, and environmentally important to the region because of the high productivity and wetland functions and values. Understanding the hydrology of forested wetlands and adjacent non-wetlands is critical for their sustainable management and utilization. However, the hydrology of the forest ecosystem is not well quantified. These forests have been intensively managed for pine production for the past few decades. Harvesting and site preparation practices have become a concern among natural resource managers because of the perception that these practices can alter soil physical properties and site hydrology. The main objective of this study was to characterize and determine harvesting and site preparation effects on the site hydrology of wet pine flats; then, characterization of the water balance was attempted.

This study was done in an intensively managed loblolly pine (*Pinus taeda* L.) plantation in the lower coastal plain of South Carolina. Areas at the site were harvested in summer 1993 and winter 1994 under dry and wet conditions, respectively. Bedding and mole channel/bedding treatments were applied in fall 1995 in both the dry- and wet-harvested areas and replicated three times. An automated weather station and wells were used to collect climatic and surface water level data, respectively, from March 1996 onwards. Surface water levels were monitored monthly beginning in 1992 by 1-m deep wells installed on a 20 x 20 m grid in the study area. Piezometers were installed at high and low areas in each treatment plot to measure groundwater pressure heads.

Surface water levels frequently fluctuated during the growing season due to intense precipitation and high evapotranspiration demands. Total groundwater head in the study site was constantly higher than -25 cm throughout the study period, which caused groundwater seepage when surface water level was lower than the groundwater

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[1] Chapter V is prepared for submission to *Wetlands Journal*.

head. Frequent fluctuation of the surface water allowed adequate soil aeration, and constantly high groundwater and frequent precipitation provided abundant water supplies for plant growth. The results of annual water balance indicated that the annual surface soil water storage change was very small, and precipitation and evapotranspiration were approximately equal. Wet-weather harvesting increased surface water level and decreased the short-term surface water storage fluctuation that was an adverse condition for seedling growth, and bedding site preparation increased the surface water storage fluctuation and groundwater inflow, providing adequate soil aeration and water for seedling growth.

Introduction

Characterization of wetland hydrology is critically important in order to understand wetland functions, utilize the beneficial values, and manage and protect wetlands for future generations. Because wetland hydrology is the primary determining factor of wetland functions (Mitsch and Gosselink, 1993), it controls or modifies other abiotic factors, such as soil reduction-oxidation (redox) potential, soil pH, nutrient fluxes, and dissolved oxygen availability (Gosselink and Turner, 1978). These primary and secondary abiotic factors control biotic responses such as plant communities and wildlife habitats. However, understanding wetland hydrology is often troublesome because each wetland has complex and unique hydrology due to the variation of the water input and output patterns and hydroperiod (Mitsch and Gosselink, 1993). The combination of water input and output patterns and wetland physiography (including topography and soil) create unique hydroperiods (duration, fluctuation, and frequency of flooding or ponding water) within each wetland.

Most of the wet pine flats in the Southeastern Lower Coastal Plain are classified as headwater wetlands since they are located on broad hilltops and generally do not receive floodwater or stream discharge from adjacent areas (Figure V-1A). Therefore, the primary water source is precipitation. Saturated soil conditions in these wetlands are produced by slow runoff caused by the flat topography, slow vertical drainage (infiltration) and the clayey, impermeable subsurface layers (argillic horizons) which are common in the typical flatwood soils (Harms et al., 1998). Therefore, the primary water output is evapotranspiration.

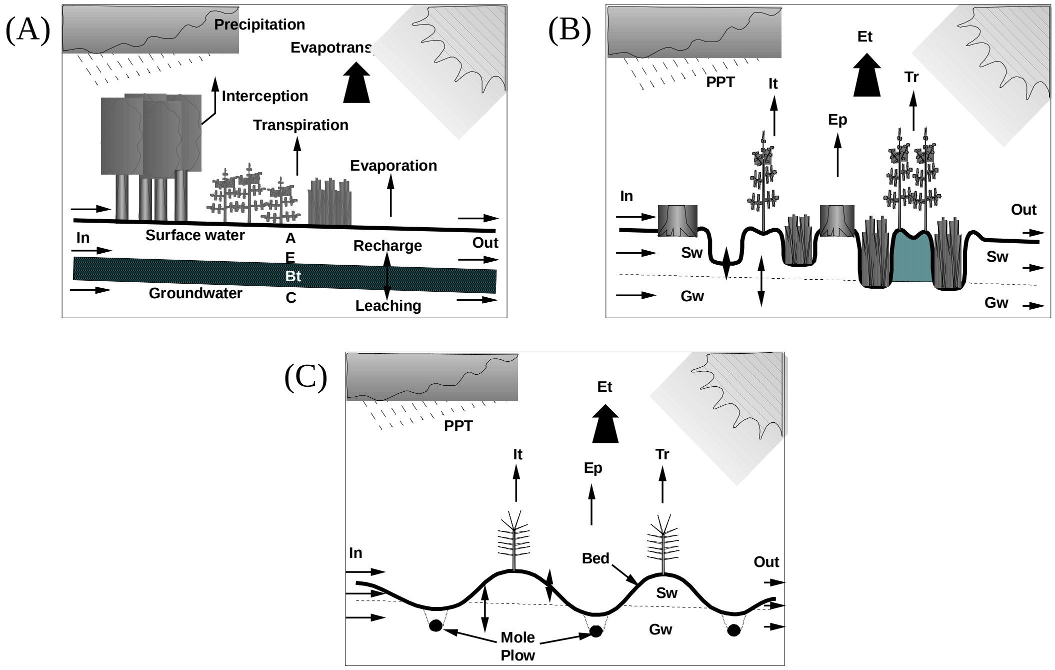

Figure V-1. Schematics of the hydrologic passway for wet pine flats under typical (A) undisturbed, (B) post-harvesting, and (C) post-site preparation conditions.

Common silvicultural practices have significant effects on hydrology (Figure V-1B). Forest harvesting, especially under wet conditions, creates soil disturbances such as compression tracks, shallow and deep ruts, smearing, and churning/puddling (Moehring and Rawls, 1970; Aust et al. 1995). These soil disturbances alter soil physical properties (Youngberg, 1959; Hatchell et al., 1970; Scheerer et al., 1994) and reduce lateral flow of surface water and near-surface groundwater (Aust et al., 1993). Consequently, the water table is increased (Aust et al., 1993, 1995, 1998a). Harvesting operations also sever the transpiring stems and remove the canopy, thereby reducing tree transpiration and interception. Although the same harvesting operations can increase soil evaporation and herbaceous transpiration and interception, such operations often increase the water table. Bedding, a common site preparation technique used in the lower coastal plain region to mitigate soil disturbance, increases soil water evaporation by exposing bare soil (Schultz, 1976) (Figure V-1C). Mole plowing (Spoor et al., 1982; Robinson et al., 1987) could redistribute ponded water to elevated areas during the dry period. This could increase soil water availability in the elevated dryer areas, while decreasing ponded water levels.

Understanding the hydrology of wet pine flats in the Southeastern Lower Coastal Plain is particularly important because (1) wet pine flats are very productive pine-dominated forests which have been extensively converted to industrial pine plantations (Allen and Campbell, 1988), and (2) they have a complex physiography that has been causing forest operational problems and environmental concerns (Harms et al., 1998). Many forest industries have invested tremendous capital in managing wet pine flats because they are one of the most productive forests (Allen and Campbell, 1988) due to the warm climate, long growing season, abundant water supply, and relatively fertile soils (Stout and Marion, 1993). Walker (1995) reported that relatively well-stocked forests (SI_{25} of 21 m with stocking of 1927 trees per ha) could produce over 5.5 m^3 ha^{-1} yr^{-1}. Because of their high productivity, over 1 million hectares of wet pine flats (including jurisdictional wetlands and non-wetlands) have been converted to intensively managed loblolly pine (*Pinus taeda* L.) plantations for fiber and timber productions (Aust, 1998).

The complex physiography of wet pine flats causes management and environmental concerns. Wet pine flats include some jurisdictional wetlands and a large area of marginal wetlands (Bengtson et all, 1991), and these wetlands and non-wetlands exist in mosaic patterns (Harms et al., 1998). Since plantation forests are usually harvested and site-prepared by management unit, not by natural boundaries, heavy equipment tends to disturb localized wet depressional areas or broader areas under wet-weather conditions. Many forest managers and environmentalists have been concerned about these problems because such disturbances may decrease long-term forest productivity (Powers et al., 1990).

In order to understand wetland hydrology, evaluation of surface water and groundwater is essential. Studies in an interior northern wetland indicated very active groundwater-surface water interactions (Roulet, 1990) and significant groundwater influence on watershed discharge (Verry and Boelter, 1978; Waddington et al., 1993; Devito et al., 1996) and on water chemistry (Hill, 1990; Devito and Dillon, 1993). In the Southeastern Lower Coastal Plain wet pine flats, these groundwater-surface water interactions are generally thought to be very small or negligible (Heath, 1975; Richardson, 1983; Rykiel, 1984; Skaggs et al.,1991). However, a previous study on a South Carolina wet pine flat showed relatively high groundwater tables during winter (unpublished data, Preston, 1994), which indicated that there could be groundwater-surface water interaction in these wetlands.

Characterization of the wetland hydrologic balance is equally important in order to understand and appreciate the unique wetland functions and values. The annual water balance of a Southeastern Lower Coastal Plain forested wetland was determined at the Okefenokee Swamp, Georgia (Rykiel, 1984), and a pocosin swamp in North Carolina (Richardson, 1983) (Table V-1). These studies showed that the water balance for these non-alluvial wetlands is dominated by the large amounts of precipitation (1170 to 1310 mm yr^{-1}), evapotranspiration (670 to 880 mm yr^{-1}), and surface water net outflow (390 to 490 mm yr^{-1}). Both the annual storage fluctuation ($\Delta V/\Delta t \cong 0$), and groundwater net outflow (10 to 40 mm yr^{-1}) were very small (Mitsch and Gosselink, 1993).

Studies in a Florida cypress pond/pine flat and North Carolina wet pine flat illustrated the range of precipitation and evapotranspiration values of forested wetlands (Table V-1). The Florida studies showed an annual precipitation range of 1070 to 1420 mm and an evapotranspiration range of 770 to 1310 mm; the highest precipitation was 1840 mm reported by Riekerk (1985). The North Carolina studies also showed a wide range of annual precipitation and evapotranspiration (1109 to 1870 mm and 782 to 1041 mm, respectively) (Amatya et al., 1996). These results showed that forested wetlands have different water balances, even when the forest system and the geographical region are similar. Water balances of mineral wet pine flats in the Southeastern Lower Coastal Plain have not been reported, and forest harvesting and site preparation effects on wet pine flat hydrology are not well understood.

Table V-1. Summary of the forested wetland water budget in the Southeastern Lower Coastal Plain of the United States.

Location	Ppt	Et	Surface Water Drainage	Net Groundwater	Reference
	----------------------	(mm yr^{-1})	----------------------		
Okefenokee Swamp Upland, GA	1310	-880†	-390	-40	Rykiel (1984)‡
Pocosin, NC	1170	-670	-490	-10	Richardson (1983)‡
Cypress Pond/Pine Flat, FL	1070	-1270	510	n/a	Heimburg (1976)§
Pine Flat, FL	1420	-770 to -1180	n/a	n/a	Heimburg (1984)¶
Cypress Pond/Pine Flat, FL	1280	-1310	n/a	n/a	Riekerk (1989)§
Cypress Pond/Pine Flat, FL	1140	-1130	n/a	n/a	Riekerk et al. (1995)§
Wet Pine Flat, NC	1243#	-1056	-218	n/a	McCarthy et al. (1991)
Wet Pine Flat, NC	1499††	-943	-387	n/a	Amatya et al. (1996)

† Negative sign indicates output source.

‡ As cited in Mitsch and Gosselink (1993).

§ As cited in Fares et al. (1996).

¶ As cited in Ewel and Smith (1992).

Values are mean of three sites.

†† Values are mean of three sites between 1988 and 1992.

Wet pine flats extend from north central coastal Florida to the Neuse River in North Carolina northward and to the Big Thicket area in southeastern Texas westward, except for the Mississippi River Delta (US Soil Conservation Service, 1981). These forests could encompass 2.6 million hectares (Cubbage and Flather, 1993), and approximately 1 million hectares of the area may be classified as jurisdictional wetlands (Harms et al. 1998). Because of the extent of wet pine flats and the common soil disturbance problems associated with intensive pine plantations, understanding the hydrologic functions and the effect of forest harvesting and site preparation on the hydrology is important. Therefore, the main objective of this study was to characterize and determine harvesting and site preparation effects on surface water flux and surface water-groundwater interaction of wet pine flats and to characterize the water balance.

Materials and Methods

This study was conducted as part of a long-term soil productivity (LTSP) study at a site located approximately 55 km west of Charleston, SC. The study site is in a typical wet pine flat. The soils within the study area are Argent (fine, mixed, thermic Typic Ochraqualfs), Santee (fine, mixed, thermic Typic Argiaquolls), Hobcaw (Fine-loamy, siliceous, thermic Typic Unbraquults) and Yemassee (fine-loamy, siliceous, thermic Aeric Ochraquults) (USDA Soil Conservation Service, 1982). These soils typically have a heavy clay argillic Bt horizon at a depth of 50-60 cm and an incipient E horizon just above the Bt. Drainage classes of these soils are poorly drained to very poorly drained, as indicated by ‘aquic’ suborder or subgroup taxonomic classes, and Argent, Santee, and Hobcaw are listed as hydric soils in the Hydric Soils of the United States (USDA Soil Conservation Service, 1991).

The average growing season, defined as the period during which the average surface soil temperature is above -2.2 °C with 5 years in 10 probability, is between March 14 and November 10, or 240 days. Average total precipitation at Walterboro, SC, located approximately 15 km northwest of the study site, is 1,120 mm annually and 897 mm during the growing season. Estimated potential evapotranspiration by the Thornthwaite equation (Thornthwaite and Mather, 1955) is 849 mm annually and 760 mm during the growing season.

The experimental site for this study consists of three 19.2-ha blocks, and each block is divided into six 3.2-ha treatment plots. The treatments are no-harvest (Control), dry-weather harvest/bed (Dry-Bed), dry-weather harvest/non-bed (Dry-Nonbed), wet-weather harvest/bed (Wet-Bed), wet-weather harvest/mole channel/bed (Wet-Mole-Bed), and wet-weather harvest/non-bed (Wet-Nonbed). These treatment combinations arrow us to evaluate effect of various silvicultural practices on wetland sire hydrology. The study site was established in 1991 for baseline data collection. Dry- and wet-weather harvesting treatments were applied in summer 1993 and winter 1994, respectively, and site preparation treatments were installed in fall 1995. Additional details of the study layout and project design are contained in Kelting et al. (1999).

Surface Soil Water Storage

The volume of water stored in the surface soil was calculated from surface water level, average surface soil depth, and average total porosity of surface soil. Surface water[2]

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[2] ’Surface water’ includes ’water above soil surface’ and ’near-surface unconfined groundwater’ since they are usually continuous in wet pine flats due to porous surface soils.

level was monitored by an automated digital recording well (WL40, Remote Data Systems, Whiteville, NC) with 4-hour intervals at each treatment plot and 1-meter long wells (perforated PVC pipe) installed in a 20 x 20 m grid pattern throughout the experimental site. In all, there were 1409 wells, and water levels in these wells were measured monthly beginning in March 1992. The data for the post-site preparation period (between February 1996 and February 1998) were used in this study. Surface soil depths (depth from surface to top of Bt horizon) were measured at each well location after the site preparation treatments were installed, and an average surface soil depth was determined. Average surface soil total porosity was determined from the soil physical characterization studies at the site (Burger, 1994).

The relation between surface water level and soil moisture content was developed from paired data collected by a prior study at the site (Burger, 1994). Burger (1994) took paired measures of surface water level and surface soil moisture content across the study site over time (n = 3233). Surface 30 cm soil moisture content (volumetric measurement) was measured by Time Domain Reflectometry (Trase System, Soilmoisture Equipment Co., Santa Barbara, CA) at each well location. Water table-soil moisture relation was determined by linear regression techniques:

$$\text{Soil Moisture}(\%) = a \times (\text{Water Table}) + b$$ **Equation 5.1**

All monthly surface water level data were converted to monthly soil moisture contents using Equation 5.1. Then, water storage volume of surface soil (in unit of depth) was calculated from the monthly soil moisture content, average total porosity, and average surface soil depth using the following relation:

$$\textbf{Soil Water Volume (mm)} = \frac{\textbf{Soil Moisture (\%)}}{100} \times \frac{\textbf{Total Porosity (\%)}}{\textbf{100}} \times \textbf{Surface Soil Depth (mm)}$$

Equation 5.2

Short-term surface soil water level fluctuations in wet pine flats can be dynamic, since these areas commonly have intense thunderstorms and relatively high evapotranspiration rates during the growing season. At the same time, these wetland systems appear to be relatively stable in terms of their annual water budget, as compared to alluvial forested wetlands that have hydroperiods which are affected by distant, off-site storm events (Rykiel, 1984; Richardson, 1983). Therefore, monthly soil water storage change (Δ Soil Water) is determined by the difference in soil water volume between two consecutive monthly measurements.

Surface Water-Groundwater Interaction

Two piezometer pairs were located in each plot, one pair at a higher elevation and one at a lower elevation. One piezometer in each pair was installed to a soil depth of approximately 400 cm, so that the piezometer tip was near the top of the marl layer, while the second piezometer was installed at a depth that was about 30 cm shallower than the first piezometer. These installations allowed the measurement of the pressure head at different depths and were used to estimate the total hydraulic head (Hillel 1982).

The total hydraulic head (H) is the sum of gravitational head (z) and fluid pressure head (h) as:

$$H = z + h$$ **Equation 5.3**

The total hydraulic head (H) at the tip of each piezometer is, therefore, given by the height of the water level of the piezometer (h) and relative elevation of the piezometer (z) with respect to an arbitrary datum.

The total hydraulic head of a confined aquifer (groundwater below Bt horizon) can be calculated from gravitational head and fluid pressure head of the piezometers (Hillel, 1982). Assuming water is incompressible (i.e., all potential changes are linear with respect to depth), the fluid pressure head gradient (h) could be expressed as a linear function of gravitational head, and the coefficients could be determined from water levels and depths of paired piezometers:

$$h = \frac{P}{\rho g} = a \times z + b$$ **Equation 5.4**

where $a = \frac{WT_d - WT_s}{D_d - D_s} - 1$

$$b = \frac{WT_s \times D_d - WT_d \times D_s}{D_d - D_s}$$

WT_d is the water level of the deep piezometer,

WT_s is the water level of the shallow piezometer,

D_d is the depth of the deep piezometer, and

D_s is the depth of the shallow piezometer.

When fluid pressure head is zero ($P = 0$), the total hydraulic head is equal to the gravitational head ($H = z$) (Equation 5.3); therefore, the total hydraulic head could be determined by solving for the fluid pressure head gradient (Equation 5.4) to the gravitational head (z). The calculated total hydraulic head was a point measurement of the groundwater relative to the surface (i.e., not corrected by relative elevation) because the purpose of this study was to evaluate surface soil water condition for plant growth.

Near-surface water and groundwater are often separated by an argillic horizon (Bt). When the Bt horizon is saturated, and when both surface water and groundwater exist, water can move upward or downward through the Bt from a zone of higher hydraulic potential to a zone of lower hydraulic potential. The vertical hydraulic gradient over Bt horizon (ΔH) is the difference between surface water and groundwater heads. Since saturated hydraulic conductivity (K_{sat}) and depth of Bt horizon(ΔL) were determined for each treatment plot, the rate and direction of water movement (q) in each treatment plot could be quantified by Darcy's Law (Equation 5.5):

$$q = K_{sat} \frac{\Delta H}{\Delta L} \qquad \textbf{Equation 5.5}$$

and the water movement expresses a surface water-groundwater interaction.

Water Balance

Precipitation, evapotranspiration, and surface water lateral flow were estimated to characterize overall water balance of the Southeastern Lower Coastal Plain wet pine flats.

Precipitation

Precipitation was measured continuously with an automated tipping bucket rain gage (Model CS-700, Campbell Scientific, Inc., Logan, UT) and recorded by a central control data logger unit (Model CR10X) in 10-minute intervals. The weather station was installed in the northeast corner of Block 1 during March 1996. Additionally, non-recording rain gages (PVC collecting funnel on a 2.5-liter bottle) were located in each block to correct for any differences between blocks caused by localized rain events such as commonly occur due to intense summer thunderstorms. The accumulated precipitation in these rain gages has been monitored monthly since July 1992. Furthermore, precipitation data of the regional national weather stations (National Climatic Data Center of National Oceanic and Atmospheric Administration) were used to evaluate adequacy of the on-site measured data.

Evapotranspiration

Evapotranspiration was obtained indirectly from meteorological estimates of potential evapotranspiration (PET). Potential evapotranspiration was estimated by several techniques: the Thornthwaite (Thornthwaite and Mather, 1955), Penman (1948), and Penman-Monteith (Monteith, 1965) equations. These methods require various climatic data (Table V-2).

Table V-2. Potential evapotranspiration estimation methods and inputs.

Method	Inputs
Thornthwaite	Mean monthly temperature
Penman	Mean daily temperature, net radiation, relative humidity, wind speed
Penman-Monteith	Mean daily temperature, net radiation, relative humidity, wind speed, stomatal conductance

The Penman-Monteith equation incorporates a stomatal conductance component to the Penman equation. Since stomatal conductance data was not available in this project, PET was calculated using a computer simulation model (Xu et al., 1998), which is a modification of the Penman-Monteith equation.

The meteorological elements used to calculate evapotranspiration were continuously monitored by the automated weather station at the study site and summarized hourly and daily. The sensor specifications for each meteorological element were wind speed (RM Young Wind Sentry Wind Set, Model 03001), solar radiation (LI-COR Silicon Pyranometer, Model LI200X), and air temperature and relative humidity (Vaisala 50Y temperature and relative humidity probe, Model CS500).

Surface Water Lateral Flow

Surface water lateral flow (drainage) was calculated using the differences between input, output, and soil water storage. Although surface water lateral flow was included as the residual of the water balance equation, it was assumed to be the major component of the residual, since all other factors in the equation were quantitatively determined or reasonably estimated.

Data Collection Period

The data collection period was between March 1996 and February 1998, and was divided into two annual hydroperiods, namely Hydroperiod 1, from March 1996 to February 1997, and Hydroperiod 2, from March 1997 to February 1998.

Results and Discussion

Surface Soil Water Storage

Surface water level in the study site fluctuated significantly due to the effects of precipitation and evapotranspiration. Automated well measurements and treatment plot means of monthly surface water level in control (Control), dry-weather harvesting/non-bedding (Dry-Nonbed), and wet-weather harvesting/mole channel/bedding (Wet-Mole-Bed) during the post-site preparation period are presented in Figure V-2. These data indicate significant surface water level increases caused by intense rainstorms and relatively fast water level decreases between the storms due to the high evapotranspiration rate. For example, significant amounts of rain (approximately 70 to 80 mm day^{-1}) in September and October 1998 (Figure V-2A) increased the surface water level over 60 cm in these treatment plots (Figures V-2B, 2C, 2D). However, a relatively dry period during September 1998 caused the water level to decrease over 70 cm. This decrease was contributed by an active high evapotranspiration. These types of fluctuations of surface water levels were observed frequently throughout the study period.

Seasonal surface water level fluctuations were also observed (Figure V-2). Although the total precipitation between November 1996 and March 1997 was significantly lower than the same period in 1997-1998 (Figure V-2A), surface water levels during both periods were near the surface in the Control, Dry-None, and Wet-Mole-Bed plots (Figures V-2B, 2C, 2D) because of the low evapotranspiration. Contrarily, the surface water level significantly fluctuated during the growing season (March through October) due to the high precipitation and evapotranspiration.

Surface water levels of the automated wells and treatment plot averages of monthly surface water level measurements were plotted for comparison (Figures V-2B, 2C, 2D). Although fluctuations in the treatment average water levels were not as high as fluctuations in the automated well measurements, both measurements generally followed a similar trend. Differences in the fluctuations were probably caused by variations in microtopography at each well point and timing of well measurements.

Minor treatment differences in plot average water level and automated water level measurements were observed (Figure V-2). The plot average water level measurements of the Control and Wet-Mole-Bed plots depicted relatively lower portion of the automated well measurement range (Figures V-2B, 2D), but the plot average water level measurements of the Dry-Nonbed plot depicted relatively higher portion of the automated well measurement range (Figure V-2C). This was probably caused by different evapotranspiration demands and drainage patterns among the treatment plots. More undisturbed vegetation was observed in the Control plot, and soils in the Wet-Mole-Bed plot were well drained.

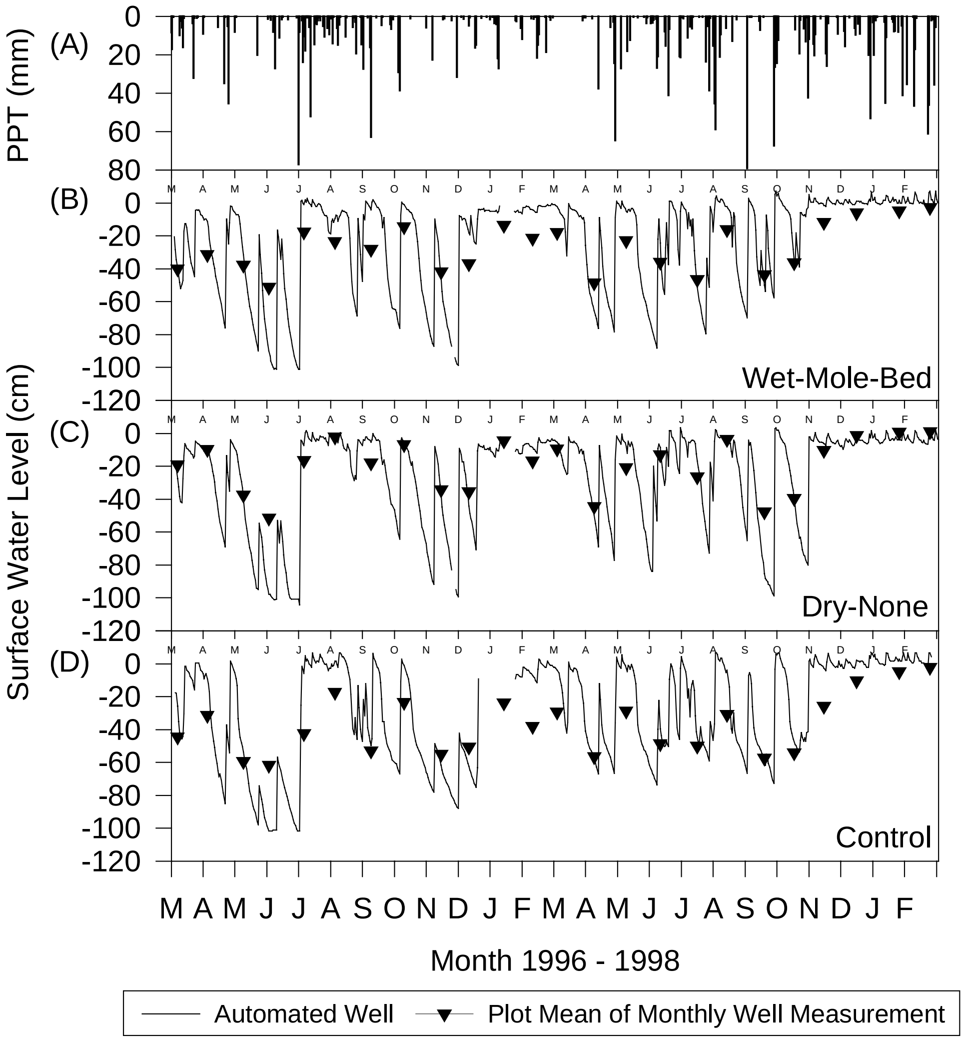

Figure V-2. Daily precipitation (A) and surface water level responses during post-site preparation period on (B) Wet-Mole-Bed, (C) Dry-Nonbed, and (D) Control plots.

Surface water levels were converted to soil water volume (depth) by using the average total porosity and average depth of surface soil (Equations 5.1, 5.2). Surface soil moisture gradients from the water table to the soil surface were caused by soil capillary suction. Although a few different soils were distributed in the study site, we assumed that soil texture and porosity of surface soils at the site were relatively homogeneous;

therefore, there was a constant capillary effect throughout the site, and the soil moisture gradient was equilibrated at the measurement time.

The surface water level-soil moisture relations are depicted by Equation 5.8.

$$\text{Soil Moisture} = 0.65 \times (\text{Surface Water Level}) + 61.86 \qquad \textbf{Equation 5.6}$$

where Surface Water Level was in cm, Soil Moisture was in percent, n = 3233, and $R^2 = 0.66$.

Average total porosity of the surface soil in the site was 50%, and average depth of the soil was estimated as 30 cm (Soil Conservation Service, 1982). Therefore, soil water volume was calculated as:

$$\textbf{Soil Water Volume} = \frac{\textbf{Soil Moisture(\%)}}{\textbf{100}} \times \frac{50\%}{100} \times \textbf{300} \qquad \textbf{Equation 5.7}$$

where Soil Water Volume was in mm. The range of soil water volume estimated by this equation was between 45 and 125 mm.

Monthly soil water storage change (Δ Soil Water) was determined by subtracting a monthly soil water volume from the prior month’s soil water volume (Figure V-3). The water storage change was significantly affected by precipitation and evapotranspiration. For instance, a large storm in July 1997 produced approximately 80 mm day^{-1} (Figure V-2A), which reversed the preceding month’s dry trend (Figures V-3A, 3B, 3C). The wetting trend was indicated by positive Δ Soil Water and increasing surface water levels in July 1997 (Figures V-2B, 2C, 2D), and the dry trend was indicated by negative Δ Soil Water and decreasing surface water levels during May and June 1997. These fluctuations of soil water storage were frequently observed throughout the study period. These results have very important implications for forest management because the short frequency of wet-dry fluctuation would provide abundant water supply and adequate soil aeration for plant growth, even though soils in the wet pine flats appeared to remain saturated throughout the year.

Different responses of surface soil water of the treatment plots among the blocks was probably caused by localized weather conditions and geological setting, including underlying geology, microtopography, drainage patterns, and soil of each block (Figure

V-3). Treatment differences of Δ Soil Water fluctuation were relatively small in the Block 1 and large in Block 3. These differences were significant among the blocks (P-value < 0.05).

Short-term wetting-drying fluctuations (positive and negative points of Δ Soil Water) occurred throughout the study period, but the fluctuations remained near the zero Δ Soil Water line (Figure V-3). This indicated that long-term soil water storage was relatively stable. This was also supported by the near-zero values of total soil water storage changes of each treatment, especially on non-bedded plots (Table V-3). These indicated that the annual soil water storage change of a wet pine flat was zero (ΔWater Volume/ΔTime = 0), as was also demonstrated by the other studies conducted in the Southeastern Coastal Plain forested wetlands (Heath, 1975; Richardson, 1983; Rykiel, 1984; Skaggs et al.,1991).

In order to evaluate the surface soil water volume change among the blocks and treatments, average fluctuations of Δ Soil Water (absolute values) were determined for each block and treatment plot. The statistical analysis results revealed that harvesting and site preparation treatments had significant effects on the fluctuations of Δ Soil Water (Figure V-3 and Table V-3). The fluctuations of Δ Soil Water in the Control plots had significantly greater fluctuations (27.46 mm) than the other treatment plots, with the exception of the Dry-Nonbed plots (P-value = 0.0208). The wet-weather harvesting plots including Wet/Nonbed, Wet-Bed, and Wet-Mole-Bed plots had significantly smaller fluctuations than the Control plots (Table V-3). The large Δ Soil Water fluctuations in the Control and Dry-Nonbed plots were probably caused by larger transpiration demand in these plots, as suggested by Xu et al. (1999a). Vegetation in the control plots consisted of a mature pine stand, and the Dry-Nonbed plots consisted of relatively undisturbed small vegetation.

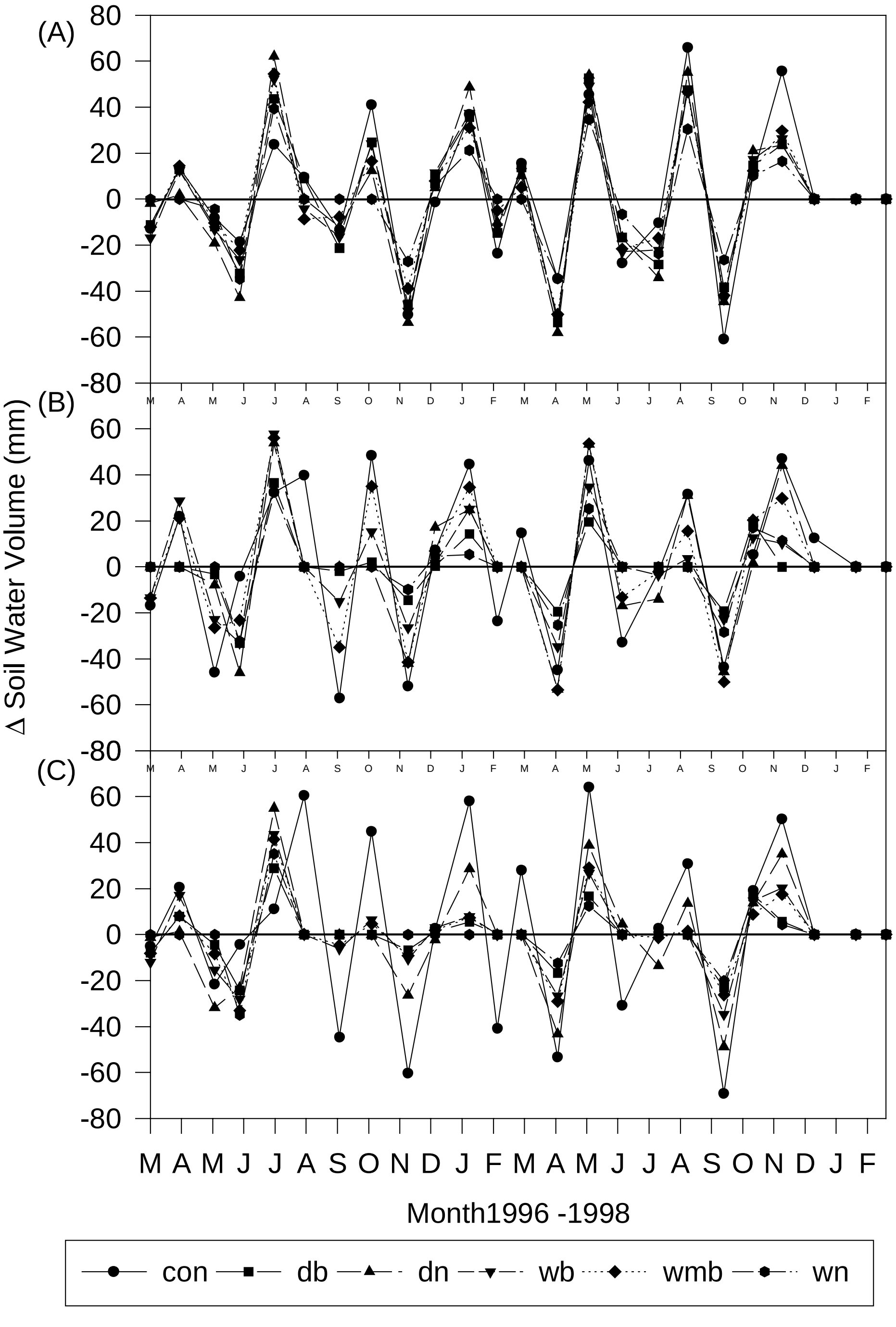

Figure V-3. Surface soil water volume change of Control (con), Dry-Bed (db), Dry-Nonbed (dn), Wet-Bed (wb), Wet-Mole-Bed (wmb), and Wet-Nonbed (wn) plots in (A) Block 1, (B) Block 2, and (C) Block 3 during post-site preparation period.

Table V-3. Total surface soil water storage change, average fluctuation of Δ Soil Water, and average surface water level of treatment plots during post-site preparation period.

Treatment	Total Soil Water Storage Change †	Average Δ Soil Water Fluctuation ‡	Average Surface Water Level §
	--------------------- (mm)	---------------------	(cm)
Control	46.98 a	27.46¶ a#	-39.0 a
Dry-Bed	4.36 b	12.68 bc	-18.3 b
Dry-Nonbed	0.00 b	19.73 ab	-19.8 b
Wet-Mole-Bed	12.72 b	17.61 b	-23.0 b
Wet-Bed	11.05 b	16.73 b	-21.2 b
Wet-Nonbed	0.00 b	8.93 c	-10.5 c

† Total soil water storage change is the summation of treatment plot.
‡ Average Δ Soil Water fluctuation is the treatment mean of the soil water volume change absolute values.
§ Average surface soil water level is the treatment mean of uncorrected monthly surface water level data.
¶ Values represent the mean of 3 blocks.
# Means followed by the same letter within a column are not significantly different at the 0.05 level.

Harvesting and site preparation treatments also affected the total (summation) soil water storage (Table V-3). After two years of measurement, the total soil water storage change in the Control plots (46.98 mm) was significantly larger than in the other harvesting plots, yet the average surface water level of the Control plots was significantly lower than in the other plots. This might indicate the surface water flow from the harvested area to the adjacent non-harvested area. Following harvesting and site preparation, the surface water level of the harvested plots increased due to the reduction of transpiration and soil disturbance; therefore, the average surface water levels of the harvested plots (> -23.0 cm) were significantly higher than those of the non-harvested plots (-39.0 cm) (Table V-3). This water table difference between the non-harvested and harvested plots could theoretically create a hydraulic gradient between the plots, and surface soil water could flow into the non-harvested plots.

In short, frequent fluctuations of the surface soil water level were caused by precipitation and evapotranspiration. Fluctuations of the Δ Soil Water were significantly different among the harvesting and site preparation treatments. Control and Dry-Nonbed plots showed larger Δ Soil Water than the other treatment plots because Control and Dry-Nonbed plots had higher evapotranspiration demands. The higher water demand of the Control plots caused a higher surface water gradient with the adjacent harvested plots, which might cause surface water flow from the harvested plots to the non-harvested plots.

Surface Water-Groundwater Interaction

Potential groundwater heads (calculated total hydraulic head of aquifer) were determined in an elevated and a low-lying area within each of the 18 treatment plots. These potential groundwater levels reflected some expected general seasonal patterns and some unexpected fluctuations (Figure V-4). The groundwater head was consistently between 0 and -25 cm from the soil surface throughout the study period, and the heads were generally highest during winter and early spring. Minor fluctuations of groundwater head occurred between late spring and fall. For example, minor decreases were observed in a majority of the piezometers during June and November 1996 and during June and September 1997 (Figure V-4). These groundwater head decreases might be associated with low precipitation in the previous month; precipitation in May and October of 1996 and May and August of 1998 was relatively low. These “lag” effects of precipitation suggests that the groundwater hydrology of the study site was at least partially affected by local recharges. However, unlike the surface water level, the groundwater level was less affected by precipitation and evapotranspiration, probably because the groundwater was separated from the climate by dense, thick clay layers (argillic horizons), and the groundwater was possibly affected by more stable, deeper aquifers. Potential groundwater heads showed unexpected increases in some months, and the cause of the increases was not certain. Treatment effects on the groundwater head were not significant.

Surface water and groundwater interactions were determined by interpretations of potential groundwater head (or total hydraulic head) and surface water level (monthly surface water well measurement) using Darcy’s Law. For Darcy’s Law (Equation 5.5), we assumed that the head differences (ΔH) equaled the difference between groundwater total hydraulic head and surface water table, the length of the porous column (ΔL) (thickness of Bt horizon) equaled 1520 mm (based on the soil profile descriptions) and average saturated hydraulic conductivity (K_{sat}) was assumed to be 5 mm day^{-1} (calculated from the soil profile study results by Miwa et al., 1998).

Results of the calculations indicated that the primary flow direction between groundwater and surface water was upward groundwater inflows/seepage (Figure V-5). Mean surface water levels of the treatment areas fluctuated between 0 and -60 cm during the study period (Figure V-2), whereas the groundwater total hydraulic head was between 0 and -25 cm during the same time (Figure V-4). Therefore, the groundwater inflows increased when the surface water levels were low (high hydraulic gradient) and decreased or reversed when the surface water levels were high (low or reversed hydraulic gradient) (Figure V-5).

Groundwater in- or outflow differences among the treatments were caused by the differences of surface water levels among treatments (Figure V-5). Groundwater inflows were highest in the Control (non-harvested) plots because the higher rates of evapotranspiration within the plots caused the surface water levels to be lower than in any harvested plots. The low surface water levels and the concurrent higher hydraulic gradients in the Control plots increased groundwater inflows. Among harvested plots, fluctuations of groundwater inflow rates were relatively low in Blocks 2 and 3, both of which were located at foots of hill slopes and on very gentle sideslopes that are almost indiscernible to the naked eye. In contrast, Block 1 was located on a relatively broad, flat hilltop. These subtle differences in topographic position and the associated physiography probably increased the surface water levels of Blocks 2 and 3 more than Block 1, and these differences explained why Blocks 2 and 3 had relatively lower groundwater inflows as compared to Block 1.

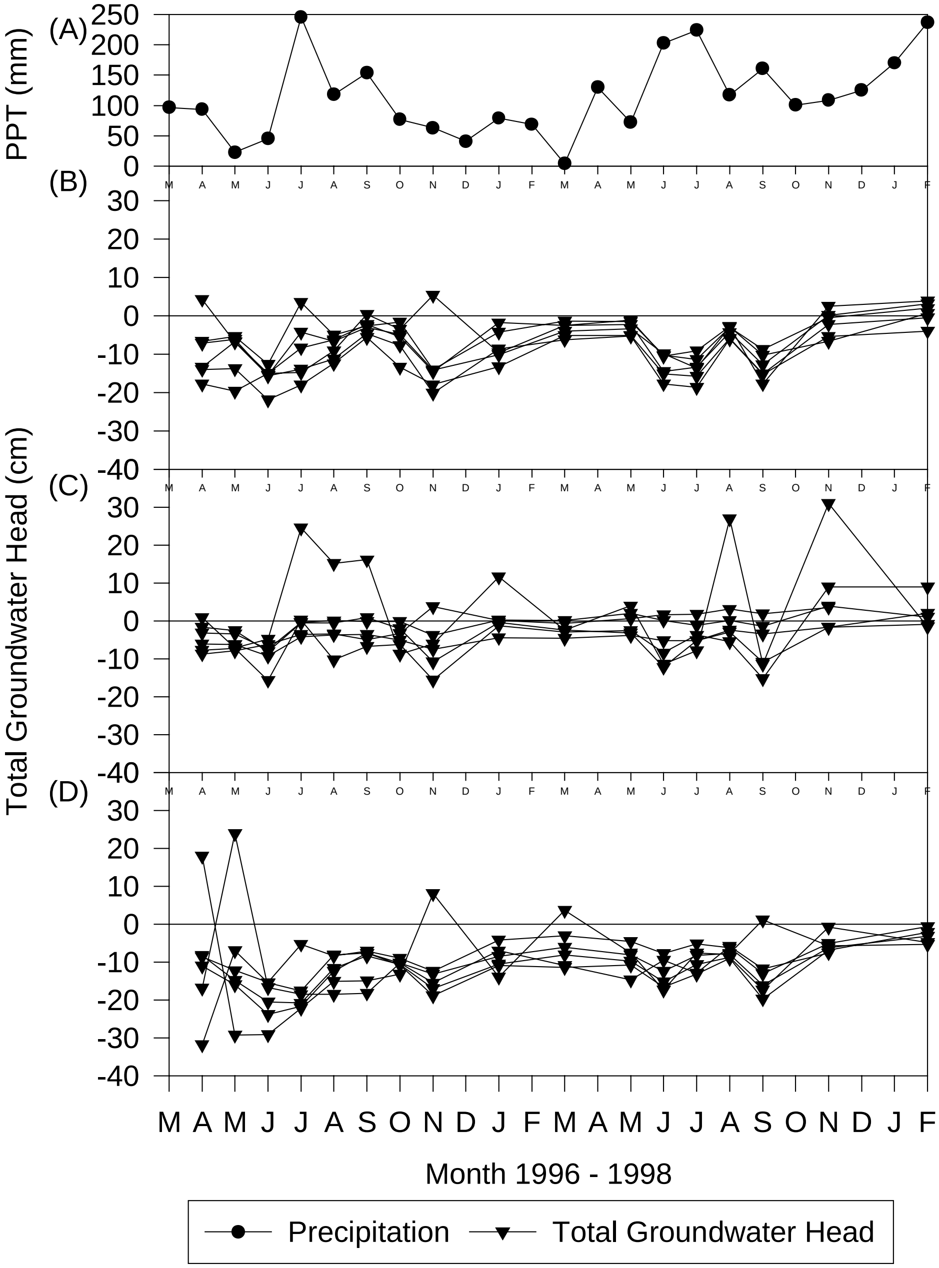

Figure V-4. Monthly precipitation(A) and plot average total groundwater head fluctuation of (B) Block 1, (C) Block 2, and (D) Block 3 during post-site preparation period.

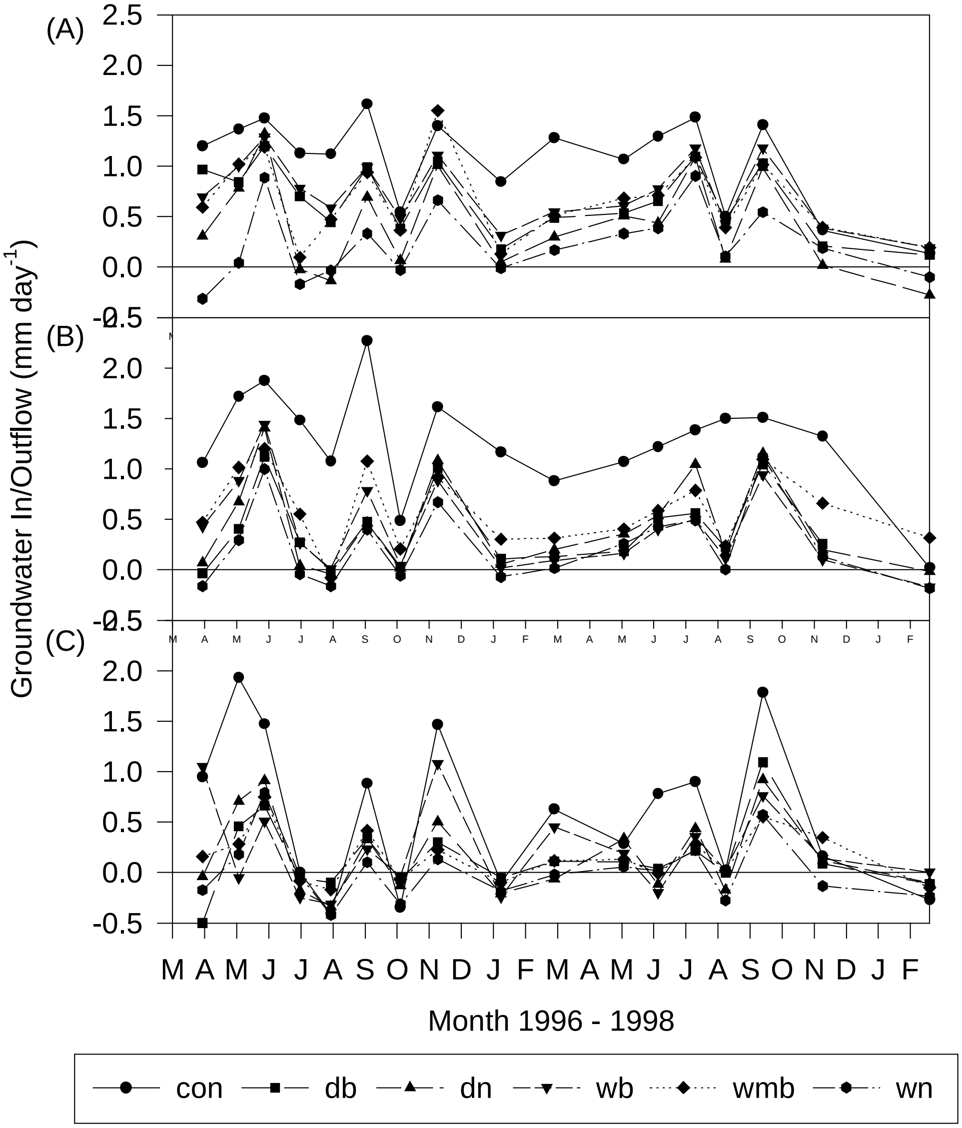

Figure V-5. Daily groundwater in- or outflow rate of Control (con), Dry-Bed (db), Dry-Nonbed (dn), Wet-Bed (wb), Wet-Mole-Bed (wmb), and Wet-Nonbed (wn) plots in (A) Block 1, (B) Block 2, and (C) Block 3 during post-site preparation period.

Although groundwater inflows and outflows have not received much attention in the flatwoods, this study indicated that upward groundwater fluxes could be a significant component of site hydrology. The range of groundwater flow rates was approximately between -0.5 and 2.5 mm day^{-1} (or -15 and 75 mm $month^{-1}$); therefore, monthly groundwater input or output volumes ranged between -480 and 2,400 m^3 (or metric ton) per treatment plot per month (or -150 and 750 m^3 ha^{-1} $month^{-1}$). Although these volumes were calculated based on the assumptions that the groundwater total hydraulic head was constant throughout a treatment plot, and that plot mean surface water levels were an adequate representative, the estimated groundwater flow rates represented a conservative estimate because parameters for Darcy's Law (thickness of the Bt horizon, saturated hydraulic conductivity, and total porosity of surface soils) were also conservative estimates. Additionally, extremely high groundwater inflow rates were omitted from the analyses.

Water Balance

Each wetland has a somewhat unique water balance because the physiography of each wetland is different. However, somewhat similar wetlands can be expected to have similar water balances. Since many human activities in and around wetlands have a significant effect on components of the water balance, characterization of water balance is important. This is particularly true today as the wetland regulatory agencies attempt to adopt the hydrogeomorphological system of wetland functional assessment, which heavily relies on "reference" sites (Brinson and Rheinhardt, 1998).

Precipitation

The results of precipitation showed annual and local variation in the region (Table V-4). Total precipitation measured by the tipping bucket gage was 1079.8 mm for Hydroperiod 1 and 1629.2 mm for Hydroperiod 2. Although the blocks in the study site were only separated by 1.6 km, the non-recording rain gage measurements were different among the blocks. Therefore, precipitation measured by the tipping bucket gage was adjusted for each block by fraction of each non-recording rain gage data for each measurement date, and overall average precipitation was determined by averaging the adjusted precipitation data. These results indicated that Hydroperiod 2 was relatively wet compared to Hydroperiod 1.

Table V-4. Annual precipitation of Hydroperiod 1 (Mar. 1996 - Feb. 1997) and Hydroperiod 2 (Mar. 1997 - Feb. 1998) measured by tipping bucket, the adjusted annual precipitation for each block, and overall average precipitation.

	Tipping Bucket	Adjusted Precipitation			Overall Average
Hydroperiod	**Gage Reading**	**Block 1**	**Block 2**	**Block 3**	**Precipitation**
	------------------------------------ (mm) ------------------------------------				
1	1079.8	1079.8	1093.3	1137.5	1103.5
2	1629.2	1629.2	1596.0	1726.3	1650.5

Annual precipitation variation at the study site agreed with regional precipitation data (Tables V-4, 5). Long-term precipitation records (1911-1994) in the region (Table V-5) showed that mean annual precipitation ranged from 1164 to 1315 mm, and the maximum and minimum records were 703 and 1943 mm, respectively. Since overall average annual precipitation results in the study site were 1103.5 mm for Hydroperiod 1 and 1650.5 mm for Hydroperiod 2 (Table V-4), the on-site measurement results were reasonable with respect to the regional long-term record. In addition, these data indicated that Hydroperiod 1 was a slightly dry period, since the annual average precipitation (1103.5 mm) was lower than the regional average annual precipitation (1254 mm), and Hydroperiod 2 was a relatively wet period, since the annual average precipitation (1650.5 mm) was higher than the regional average annual precipitation.

Table V-5. Annual average, minimum, and maximum precipitation in the selected National Weather Station sites in southeastern South Carolina.

	Average	Range	
Location	**PPT**	**Minimum**	**Maximum**
	-------------------- (mm) --------------------		
Charleston Airport, SC	1315	770	1854
Charleston City, SC	1164	732	1902
Summerville, SC	1284	703	1893
Walterboro, SC	1253	919	1943

The long-term trend (March 1996 to February 1998) of regional and study-site monthly precipitation was expressed by a double mass curve plot (Figure V-6). Precipitation data were averaged for the study site and region and accumulated for the study period. Cumulative site average precipitation during Hydroperiod 1 was lower than the long-term average of the regional precipitation, which was mainly caused by a low precipitation during May and July 1996 (Figure V-7). Precipitation during the first half of Hydroperiod 2 was nearer the average value because the plotted curve was parallel to the average line (Figure V-6). However, precipitation between November 1997 and February 1998 (the second half of Hydroperiod 2) was significantly high (Figure V-7), which was also indicated by an ascending trend of the plotted curve (Figure V-6), possibly because 1998 was an ‘El Nino’ year.

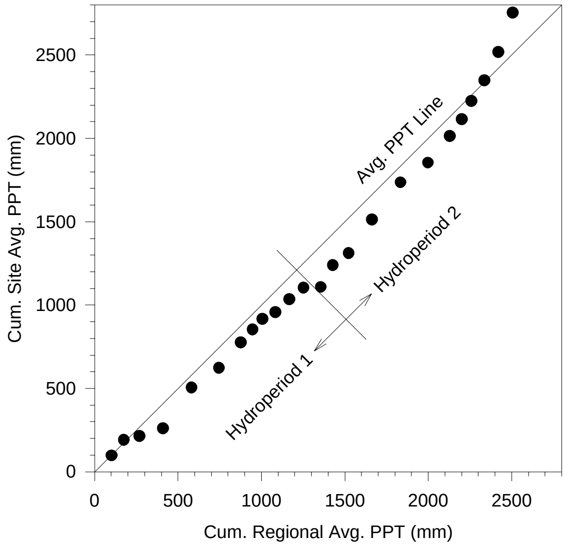

Figure V-6. A double mass curve plot of regional and study-site (adjusted and averaged) cumulative average precipitation.

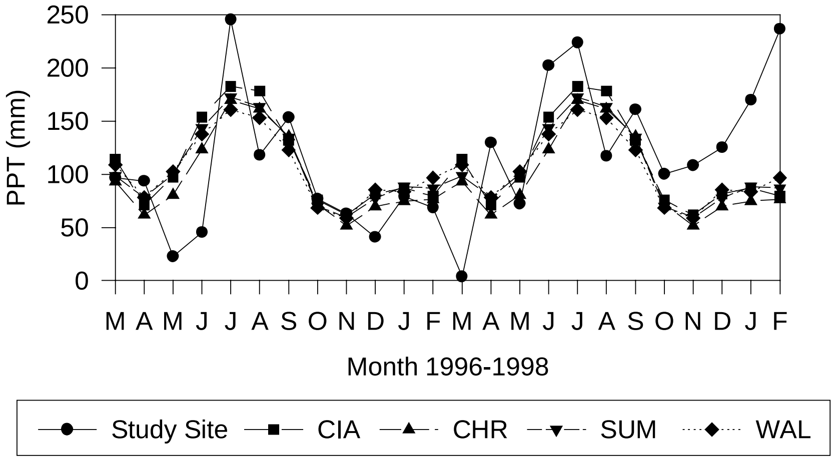

Figure V-7. Monthly total precipitation (PPT) at the study site (adjusted and averaged), Charleston International Airport, SC (CIA), Charleston, SC (CHR), Summerville, SC (SUM), and Walterboro, SC (WAL) during post-site preparation period.

Evapotranspiration

Estimated potential evapotranspiration (PET) varied widely among the methods (Table V-6). PET values were determined by the Thornthwaite procedure using both study site and regional monthly average air temperatures. These values were similar because the site and regional air temperature data were relatively similar. PET values, as estimated by the Penman equation, were higher than the Thornthwaite PET values and were as high as the pan evaporation values. These Penman PET values might not be accurate because of unavailability of certain parameter values. Coefficients of the net radiation and aerodynamic values that were specific for the Southeastern Lower Coastal Plain wet pine flats were not available in the literature. Pan coefficient for the Southeastern Lower Coastal Plain wet pine flat was also not available in a literature. Penman-Monteith PET values incorporated on-site daily weather conditions, and the values were midway between the Thornthwaite PET and Penman PET values; therefore, Penman-Monteith PET values were probably a conservative estimate of the actual evapotranspiration at the study site.

Table V-6. Estimated Potential Evapotranspiration of Hydroperiod 1 and 2 by Thornthwaite, Penman, and Penman-Monteith equations, and Pan Evaporation method.

	Study Site			Regional	
Hydroperiod	**Thornthwaite**	**Penman**	**Penman-Monteith**	**Thornthwaite**	**Pan Evaporation†**
	(mm)				
1	815.7	1506.3	1000.9‡	847.6	1522.5
2	807.1	1216.7	1001.7	838.3	1522.5

† Mean annual pan evaporation value between 1956 and 1970 at Charleston, SC (Farnsworth and Thompson, 1982).

‡ Xu et al., In preparation.

Comparison of monthly PET among Penman-Monteith and Thornthwaite equations and the pan evaporation data showed relatively similar annual trends (Figure V-8). Long-term average regional air temperature data were used for Thornthwaite PET estimation, and the pan evaporation data was also long-term average regional measurement data. The pan evaporation values were constantly 40 to 80 mm higher than the Thornthwaite PET values. Penman-Monteith PET values were intermediate between the Thornthwaite PET and pan evaporation values during the growing season. However, the Penman-Monteith PET and Thornthwaite PET values were similar during the winter (November to February), which might indicate that the Thornthwaite procedure did not accurately estimate active evapotranspiration of the lower coastal plain during summer.

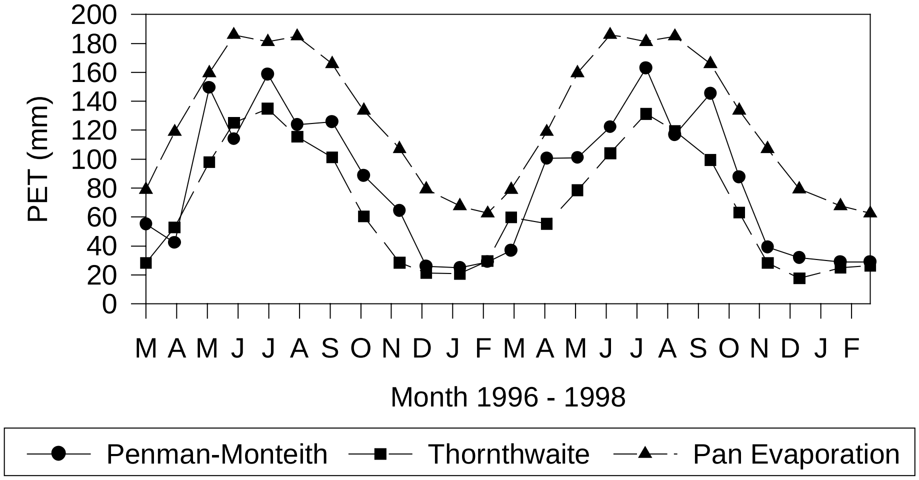

Figure V-8. Monthly total potential evapotranspiration estimated by Penman-Monteith and Thornthwatie equations and pan evaporation data.

Hydrologic Balance

The hydrologic balance of the study site was dynamic (Figures V-9, 10, 11). The study site received relatively high amounts of precipitation (Figures V-9A, 10A, 11A). Precipitation was especially high between late spring and early fall and was lowest during the winter months. This precipitation pattern is beneficial for plant growth because water was abundant when potential evapotranspiration demands were high (Figures V-9B, 10B, 11B). Although an occasional drying trend was observed as a sharp decrease of Δ Soil Water, frequent intense precipitation events replenished the soil water deficits, which are indicated by sharp increases of the Δ Soil Water (Figures V-9C, 10C, 11C). In general, soil water storage was relatively stable throughout the study period because of the short wetting-drying cycles.

These forest systems did not experience long-term wet or dry periods which could have major adverse effects on plant survival and growth. It is widely recognized that forest ecosystems that have frequent wetting and drying cycles have relatively high rates of net primary productivity (Conner, 1994), and the productivity of the study sites also supports this general finding. This relatively stable soil water storage might be supported by groundwater inflow (Figures V-9D, 10D, 11D). Groundwater heads in the study sites were relatively high throughout the year, and groundwater in/outflow was largely determined by the surface soil water level. When surface water level decreases, Δ Soil Water decreases, thus groundwater inflow increases. This was also shown by reverse pattern of the Δ Soil Water and groundwater in/outflow. Therefore, the groundwater in the study site appears to be functioning as a water reservoir to prevent the surface soil from experiencing drought conditions. Monthly cumulative residuals were determined from precipitation, evapotranspiration, surface soil water volume change, and groundwater in- or outflow (Figures V-9E, 10E, 11E). Residuals included surface water runoff and estimation errors.

The result of the water balance calculation indicated that large volumes of water were contributed by precipitation and were outputted by evapotranspiration. Surface soil moisture was constantly supported by groundwater inflow, and the groundwater might provide excessive water inputs. This agreed with the visually observed patterns of a drainage ditch flow during the growing season at the study site. Deep drainage ditches had constant water flow even during a extended dry period. However, quantification of the surface water runoff was not performed in this study because of the complex patterns of the existing ditch system, which included cross-road drainages and multiple ditches from very large areas.

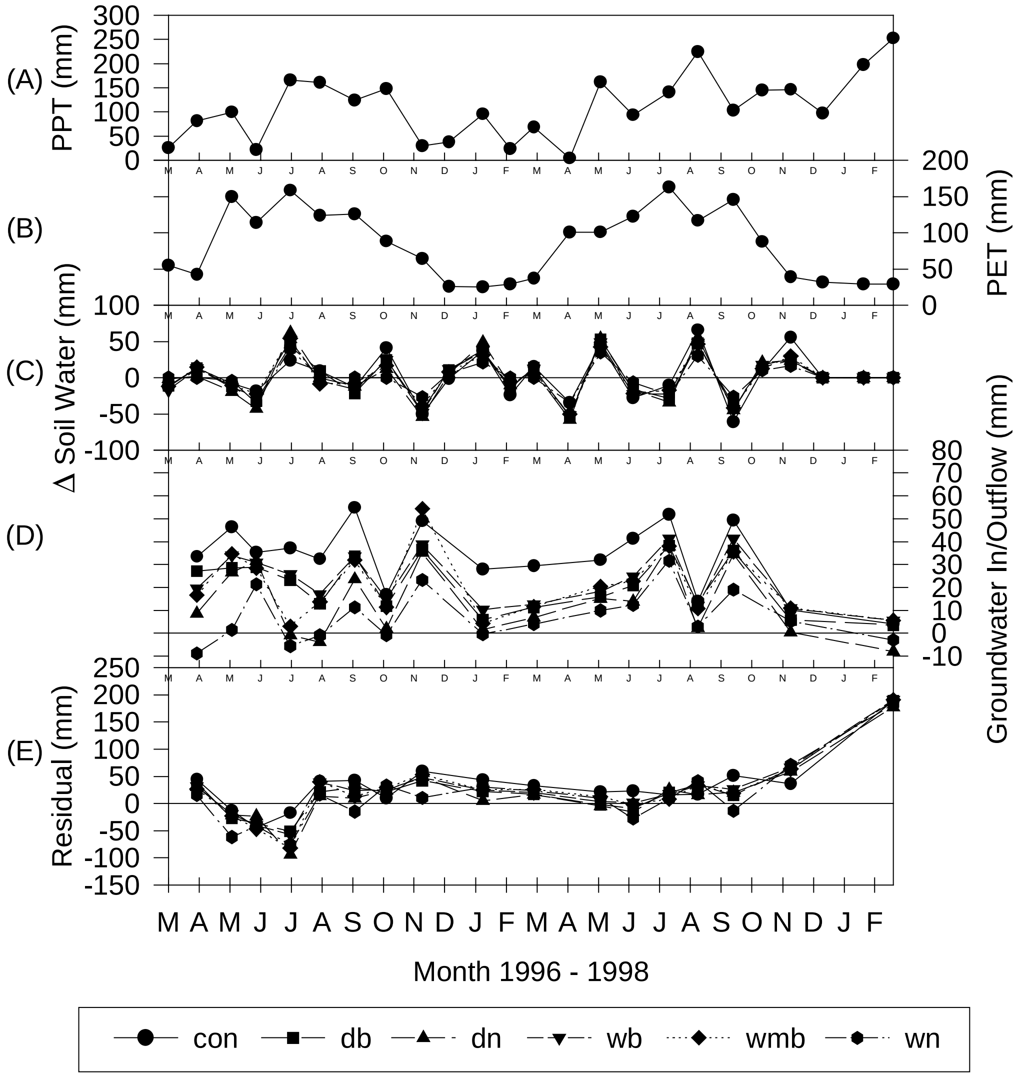

Figure V-9. Monthly change of (A) precipitation, (B) potential evapotranspiration, (C) surface soil water storage change, (D) groundwater in/outflow, and (E) residual in Block 1. The treatments include Control (con), Dry-Bed (db), Dry-Nonbed (dn), Wet-Bed (wb), Wet-Mole-Bed (wmb), and Wet-Nonbed (wn) plots.

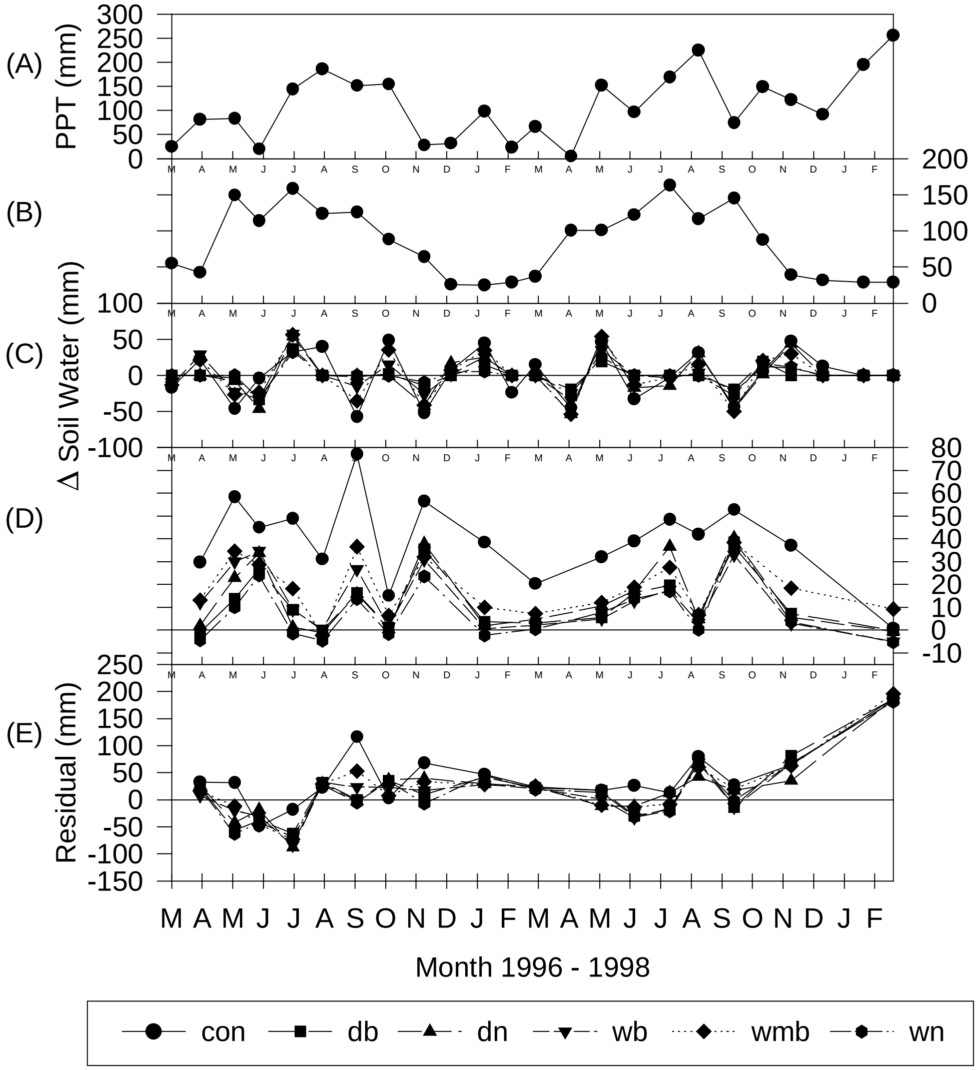

Figure V-10. Monthly change of (A) precipitation, (B) potential evapotranspiration, (C) surface soil water storage change, (D) groundwater in/outflow, and (E) residual in Block 2. The treatments include Control (con), Dry-Bed (db), Dry-Nonbed (dn), Wet-Bed (wb), Wet-Mole-Bed (wmb), and Wet-Nonbed (wn) plots.

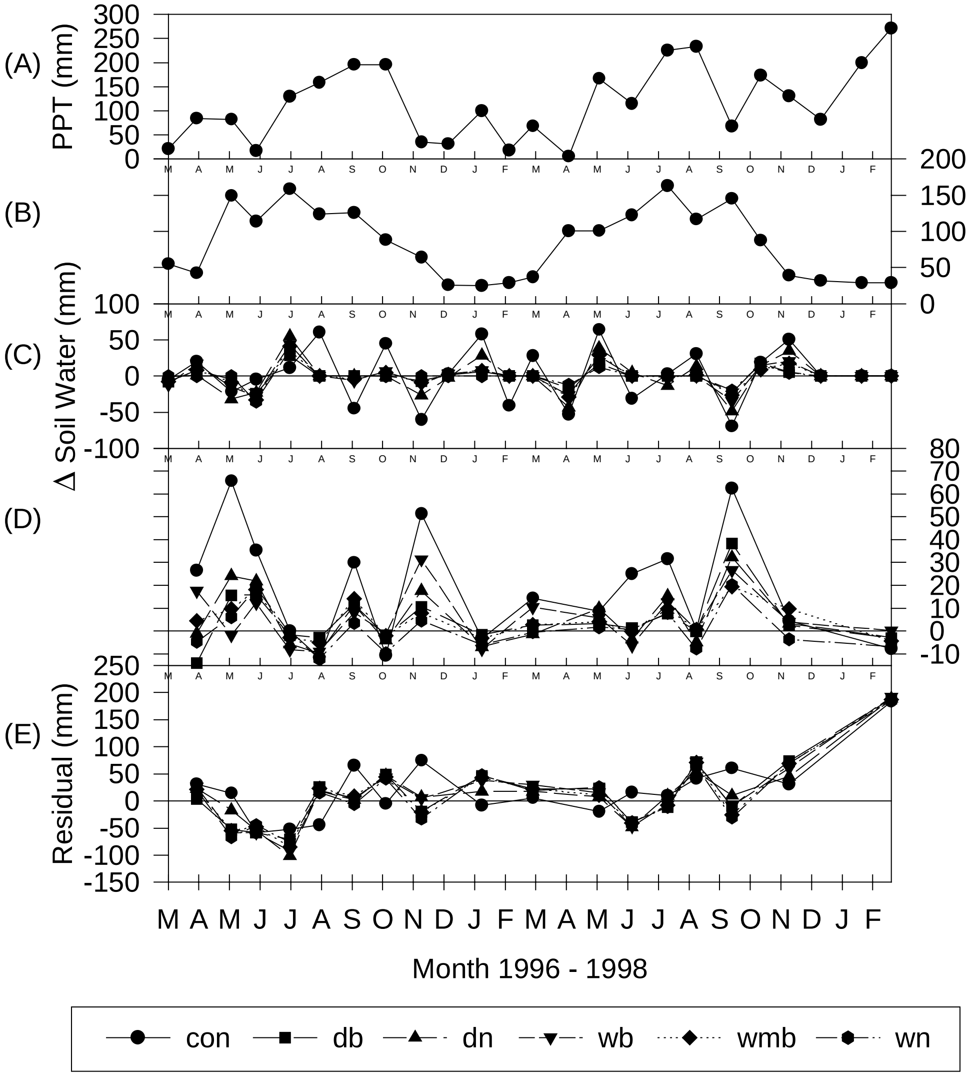

Figure V-11. Monthly change of (A) precipitation, (B) potential evapotranspiration, (C) surface soil water storage change, (D) groundwater in/outflow, and (E) residual in Block 3. The treatments include Control (con), Dry-Bed (db), Dry-Nonbed (dn), Wet-Bed (wb), Wet-Mole-Bed (wmb), and Wet-Nonbed (wn) plots.

The annual water balance of Blocks 1, 2 and 3 for Hydroperiod 1 and 2 was determined by summarizing monthly precipitation, evapotranspiration, soil water volume change, groundwater in/outflow, and residual (Figure V-12). These water balance results indicated that overall soil water storage of the study site was relatively stable. Annual soil water storage difference across the blocks and hydroperiods was less than 17 mm. These results agree with results of similar forested wetland water balance studies in the southeastern United States (Mitsch, 1979; Rykiel, 1984; Richardson, 1983). Precipitation and residual differences between Hydroperiods 1 and 2 in the Blocks were approximately equal (500 mm). This was caused by relatively constant values of groundwater inflow and stable surface soil water storage of each block. Groundwater inflow of Block 3 was relatively lower than that of Blocks 1 and 2. This might be caused by relatively small fluctuations of Block 3 soil water storage (Figure V-3). These results showed that annual water balance of wet pine flats could be different depending on the soil, topography, geology, and climatic setting of sites.

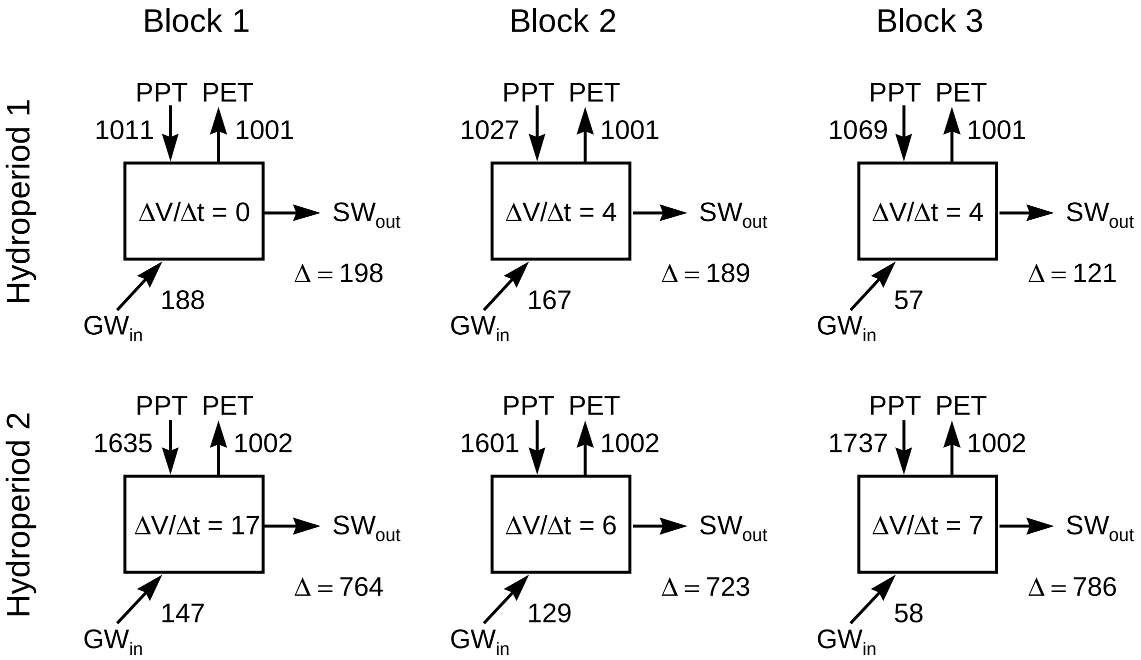

Figure V-12. Water balance (in mm yr^{-1}) of Blocks 1, 2, and 3 during Mar. 1996-Feb. 1997 (Hydroperiod 1) and Mar. 1997-Feb. 1998 (Hydroperiod 2). Legend includes precipitation (PPT), potential evapotranspiration (PET), groundwater inflow (GW_{in}), surface soil water storage change ($\Delta V/\Delta t$), surface water outflow (SW_{out}), and residual (Δ).

Harvesting and site preparation treatments had significant effects on water balance across the study site (Figure V-13). Control (non-harvested) plots had significantly high soil water storage change and groundwater inflow compared to the other harvested plots, which was probably caused by the high evapotranspiration demand of the mature pine stands. Average surface water levels of the Control plots were significantly lower than those of the surrounding harvested plots (Table V-3). This low surface water level created large hydraulic gradients to lateral and vertical water fluxes. In this study, evapotranspiration was estimated by the Penman-Monteith equation and was assumed to be constant throughout the study site; therefore, these PET values were probably not an accurate representation in this case. Actual evapotranspiration in Control plots could be higher than the estimated values because of multiple vegetation layers and tree canopy interception, and surface water outflow of Control plot could be lower than estimated. Groundwater inflows in Wet-Nonbed plots were significantly lower than in the other harvested plots. The low groundwater flow was caused by significantly high average surface water level and low fluctuation of Δ Soil Water (Table V-3). Relatively low groundwater inflows in Dry-Nonbed plots could be explained by the low total soil water storage change, relatively high average surface water level (Table V-3), and relatively small fluctuation of Δ Soil Water (Figure V-3). Annual water balance of bedded plots showed a relatively similar water balance.

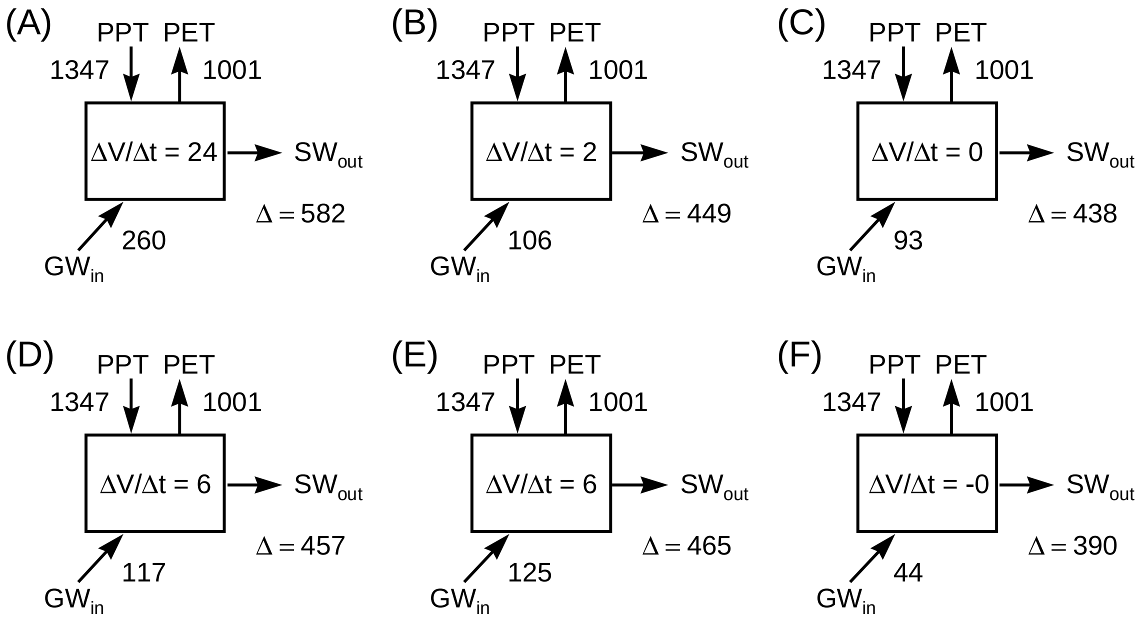

Figure V-13. Average annual water balance (in mm yr^{-1}) of (A) Control, (B) Dry-Bed, (C) Dry-Nonbed, (D) Wet-Bed, (E) Wet-Mole-Bed, and (F) Wet-Nonbed plots. Legend includes precipitation (PPT), potential evapotranspiration (PET), groundwater inflow (GW_{in}), surface soil water storage change ($\Delta V/\Delta t$), surface water outflow (SW_{out}), and residual (Δ).

Conclusion

Large fluctuations in the surface water and constantly high total groundwater head in the study site indicated that surface water and groundwater had strong interaction. High groundwater head often produced upward, strong hydraulic gradient, especially when surface water levels were low. Although surface water and groundwater were often separated by a thick, heavy clay, low conductive argillic (Bt) horizon, a significant amount of water could be supplied from groundwater to surface water because of the strong gradient. (When surface water levels were high, groundwater inflows decreased or reversed because the hydraulic gradient decreased or reversed.) These results indicated that the surface water level fluctuation determined groundwater inflow rate, and groundwater functioned as a reservoir for surface water. Therefore, surface water storage was not passively influenced by groundwater; rather, surface water storage controlled the groundwater influence. This surface water and groundwater interaction might explain the relatively high forest productivity of the study site, because the site was supported by an abundant water supply through groundwater and precipitation.

Forest harvesting and site preparation had significant effects on wet pine flat site hydrology. Bedded plots had larger surface water storage fluctuations than non-bedded plots; especially, wet-weather harvested and non-bedded plots showed the lowest fluctuations. These surface water storage changes affected groundwater in/outflow. Bedded plots had higher groundwater inflow rates than wet-weather harvested, non-bedded plots. These results suggested that wet-weather harvesting significantly altered the site hydrology of wet pine flats, and that bedding site preparation was an effective treatment in improving disturbed site hydrology.

The hydrology of this wet pine flat was relatively stable. The annual surface soil water storage change of the study site was very small. Total annual precipitation and potential evapotranspiration of southeastern South Carolina are typically 1200 to 1300 mm and 1000+ mm, respectively. These forests receive about 80% of total annual precipitation during the growing season, when the evapotranspiration demand is also high. The potential evapotranspiration demand during the growing season is about 90% of the total annual potential evapotranspiration. These seasonal precipitation and evapotranspiration patterns appear beneficial for plant growth because plants would receive abundant energy and water.

Slightly different annual water balances among the blocks indicated that the water balance of wet pine flats varies by physiographic setting. The groundwater inflow of Block 3 was significantly lower than those of Blocks 1 and 2. This was caused by the relatively high surface water levels and low groundwater heads of Block 3. The groundwater inflow of Block 1 was slightly higher than that of Block 2. Block 1 was located on top of a broad hill, and the average elevation was higher than the elevations of Blocks 2 and 3. Blocks 2 and 3 were located at the foot of a broad hill, and the average elevation of Block 3 was the lowest among the blocks.

Harvesting and site preparation methods for pine plantations had significant effects on the annual water balance. Bedded plots had significantly higher groundwater inflows than non-bedded plots. This was especially true in wet-weather harvested plots with non-bedding site preparation, which had significantly low groundwater inflows. These results were explained by fluctuations of soil water storage. Although the annual soil water storage change of all harvested plots was approximately equal, soil water storage of bedded plots had larger fluctuations than those of non-bedded plots. Additionally, soil water storage of bedded plots fluctuated more frequently than those of non-bedded plots. These repeated large fluctuations of soil water storage in the bedded plots indicated that surface soils in bedded plots dried and wetted frequently during the growing season, thereby providing good growing conditions for plant roots.

Significantly high soil water storage and groundwater inflow fluctuation in non-harvested (Control) plots indicated that mature forest stands had high evapotranspiration demands, and the high demands lowered the surface water level. This low surface water level produced high hydraulic gradients for lateral and vertical water movement. The annual soil water storage and groundwater inflow were significantly high. Apparently, a large amount of surface water flowed into non-harvested plots from adjacent harvested plots whose surface water levels were increased due to the low evapotranspiration demand.

These site hydrology results have important implications for wet pine flat forest management:

1. Wet-weather harvesting should be minimized in low-lying areas and at the feet of hill slopes where surface water of the surrounding area drains in. Severe surface soil disturbance in those areas significantly alters soil physical property and microsite hydrology, which increases surface water level (Aust et al., 1993, 1995).
2. These severely disturbed, poorly drained areas should be ameliorated to create plantable soil conditions. Bedding site preparation has been utilized to create an aerated surface soil in poorly drained areas.
3. Relatively elevated, dry areas may not need bedding site preparation because those areas are not disturbed and do not have prolonged soil saturation.
4. Dry-weather harvesting with no bedding site preparation would be an economical forest management practice in wet pine flats. Although this practice may not

maximize initial tree growth because of relatively high surface water level, frequent surface soil wetting-drying cycles provide adequate plant growing condition.

5. A significant hydraulic gradient produced by a mature forest stand could be utilized to draw excess surface water from an adjacent harvested area. Although the distance of this effect has not been quantified, this may be achieved by a narrow or irregularly shaped harvesting area.
6. Bedding site preparation is effective in accelerating soil evaporation rate by exposing the soil surface, but this effect could be detrimental at high-elevation, drier sites.