CHAPTER VI

SPATIAL CHARACTERIZATION OF WET FLAT PINE PLANTATION HYDROLOGIC RESPONSES TO HARVESTING AND SITE PREPARATION[1]

Abstract

Intensive forestry operations on wet sites may alter soil and hydrological properties, and these alterations could decrease seedling survival, growth, and future site productivity. Evaluations of site hydrology are particularly important for forested wetlands because hydrology controls many soil processes, such as pH, soil aeration, and nutrient availability. The objectives of this study were to characterize different harvesting and site preparation effects on site hydrology and to evaluate altered microsite hydrology with respect to the wetland hydrology criterion. This study was located in an intensively managed loblolly pine (*Pinus taeda* L.) plantation in the lower coastal plain of South Carolina. The site was harvested in summer 1993 and winter 1994 under dry and wet conditions, respectively. Bedding treatments were installed in both dry- and wet-harvested plots, and mole channel/bedding was installed in wet-harvested plots in fall 1995. Automated weather stations and wells were used to collect climatic and surface water level data beginning in 1995. Additionally, the surface water level was monitored monthly on a 20 x 20-m grid of 1-m wells beginning in 1992. Surface water hydraulic gradient evaluation and multivariate cluster analysis indicated that microsite hydrology and water flow patterns were significantly altered by wet-weather harvesting and bedding site preparation, but overall site hydrology was not altered. Evaluation of predicted surface water levels indicated that microtopography and precipitation patterns had significant influences on surface water levels during the site establishment period. These results revealed that the hydrologic components of wetland delineation were difficult in the wet pine flatwoods because it was significantly affected by microtopography, soil, and precipitation pattern.

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Introduction

Southeastern pine forests are some of the most productive forests in the United States because of the warm climate, long growing seasons, abundant water supplies, and relatively fertile soils in the region (Stout and Marion, 1993). Specifically, Southeastern Lower Coastal Plain pine plantations are some of the most intensively managed, productive forests in the United States (Allen and Campbell, 1988). Site indices of these forests often exceed 25 m in 25 years, and a 30-year-old intensively managed loblolly pine plantation often yields 10 m^3 ha^{-1} $year^{-1}$ (Baker and Langdon, 1990).

Wet pine flats of the Southeastern Lower Coastal Plain have little topographic relief and often have poor drainage (Stout and Marion, 1993). Typical soils in the area consist of a relatively coarse but organic matter-rich surface soil horizon (A or Ap) and an eluviated sandy albic horizon (E) over a fine textured argillic horizon (Bt) (Allen and Campbell, 1988). These subsurface soil horizons usually have extremely slow hydraulic conductivity that impedes the vertical flow of surface water. The flat topography and impermeable subsurface soils slow down the lateral flow of surface and near-surface water, which causes high surface water levels during the wet season.

The Southeastern Lower Coastal Plain wet pine flats consist of some jurisdictional wetlands and large areas of marginal wetlands. Bengtson et al. (1991) showed the effect of the gradual topography and impermeable subsurface soils on surface water levels on a typical wet pine flat in South Carolina and demonstrated the complexity of wetland delineation in the area. They found that 4% of the study area became jurisdictional wetlands according to the 1987 COE/EPA Wetland Manual Hydrology Criteria, which was: "inundated or reached to the surface soil saturation for more than 12.5% of the growing season." However, 81% of the area was included as jurisdictional wetlands according to the 1989 Federal Wetland Manual (Hydrology Criteria), which was: "inundated or reached to the saturation within 15-46 cm of soil depth for seven consecutive days" (Gaddis and Cubbage, 1998). These results showed that delineation of wetlands based on hydrological characteristics was complex and difficult. These results also indicated that the large area of wet pine flats had a relatively high surface water level during the growing season, and hydrology had a critical role in the wetland function.

Over one million hectares of wet pine flats in the Southeastern Lower Coastal

Plain are intensively managed, industrial forests (Aust, 1998). These areas are commonly managed for the production of loblolly pine (*Pinus taeda* L.), which may consist of road and ditch installations, secondary ditching, mechanized harvesting, bedding, planting of genetically selected pine seedlings, fertilization, and other silvicultural manipulations. These intensive silvicultural practices often cause severe soil disturbance and alteration of site hydrological characteristics (Allen and Campbell, 1988; Aust et al., 1993, 1995, 1998a 1998b). Tiarks and Haywood (1996) indicated that the alteration of soil physical properties and site hydrology altered subsequent soil chemical and biological processes that might have a critical role in long-term site productivity.

Soil disturbances created under wet-weather harvesting in wet pine flats include compression tracks, shallow and deep ruts, and churn/puddle, and these disturbances cause surface soil compaction, organic matter loss, increased surface water table, and site hydrology alteration (Aust et al., 1993, 1995, 1998). Many forest site productivity studies in the world (Krauss et al., 1939; Holmsgaard et al., 1961; Keeves, 1966; Wiedemann, 1935) showed the general trend of site productivity decrease caused by surface soil compaction by forest operations and soil organic matter loss and subsequent soil nutrient depletion (Powers et al., 1990). These study results have increased awareness of forest land managers in the southeastern United States for potential long-term site productivity decrease by soil disturbance. Additionally, since large areas of wet pine flats are jurisdictional wetlands (Aust, 1998), the soil, site, and hydrological disturbances associated with forest harvesting and site preparation operations have become the focus of environmental concerns.

Characterization of hydrologic responses to forest operations in these areas is necessary in order to determine the degree to which soil disturbances affect site hydrology and subsequent forest sustainability and long-term site productivity. However, not many studies have addressed the problems. This long-term soil productivity (LTSP) study was established in an intensively managed loblolly pine plantation in the Lower Coastal Plain of South Carolina to address those issues on an operational scale (Kelting et al., 1999). This LTSP study is somewhat unique because it has an intensive grid of water table wells that allows the use of spatial data analysis techniques. Also, the monthly measurement of the water tables from the pre-harvesting period to post-site preparation period allow determination of temporal changes of the water table caused by harvesting and site preparation. Most previous studies of wetland hydrology have relied upon much less data-intensive hydrologic measurements within a wetland at specific times and points, which were subsequently extrapolated to the entire site. Those results sometimes failed to present spatial and temporal characteristics of wetland function changes. The spatial data analysis techniques used in this study provide enhanced interpretation capabilities and allow visual characterization of site hydrology and microsite hydrological changes. The objectives of this study are to (1) characterize surface water[2] level change caused by harvesting and site preparation, (2) determine spatial characteristics of forest harvesting and site preparation effects on the site hydrological properties, and (3) evaluate microsite hydrology with respect to the wetland hydrology criterion.

Materials and Methods

This study was conducted as a part of a long-term site productivity study located approximately 55 km west of Charleston, SC. The area is in a typical wet pine flats. 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 horizon. Drainage classes of these soils are intermediate 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). Average growing season, which is defined as surface average soil temperature 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, 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.

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[2] Term 'surface water' used in this paper includes aboveground water, near-surface water, and perched water because they are continuous at the study site.

This study consisted of 3 19.2-ha blocks that have 6 treatment plots of equal size. The treatments are no-harvesting (Control), dry-weather harvesting with bedding (Dry-Bed), dry-weather harvesting with non-bedding (Dry-Nonbed), wet-weather harvesting with bedding (Wet-Bed), wet-weather harvesting with mole channeling and bedding (Wet-Mole-Bed), and wet-weather harvesting with non-bedding (Wet-Nonbed). The study site was established in 1991 for baseline data correction. Dry- and wet-weather harvesting were installed in summer 1993 and winter 1994, respectively, and site preparation was installed in fall 1995. Details of the study layout and project design are contained in Kelting et al. (1999).

One meter-long, surface water monitoring wells (nonrecording wells) were installed in a 20 x 20-m grid pattern throughout the study area (approximately 80 wells per treatment plot), and all 1409 wells were measured monthly between March 1992 and June 1993 (pre-harvesting), between July 1994 and July 1995 (post-harvesting), and between February 1996 and February 1998 (post-site preparation). One automated recording well (WL40, Remote Data Systems, Whiteville, NC) was installed in each treatment plot (18 points) for continuous surface water monitoring (every 4 hours), since surface water level is influenced by strong rain events, evapotranspiration, and surface water drainage (Freeze and Cherry, 1979). Each recording well was located beside a nonrecording well (reference well) which had been found to be highly correlated with the majority of the other nonrecording wells within a treatment plot. This continuous well measurement allowed estimation of the plot-wide daily water table fluctuation (temporal change) based on the regression analyses (Montgomery and Peck, 1992) between the nonrecording reference well and each nonrecording well. Relative elevations and surface soil depths (depth from surface to top of Bt horizon) were measured at each well point before and after harvesting and after site preparation. Disturbance class, which was a weighted average of qualitative soil disturbance levels within a 10-m radius of a well, was determined at each well point immediately after harvesting.

Overall effects of harvesting and site preparation on surface water level were analyzed by univariate (Steel and Torrie, 1980) and multivariate analyses (Johnson and Wichern, 1992). Statistical designs of univariate analysis used to test harvesting, site preparation, or harvesting/site preparation combination effects on measured variables were randomized complete block design, and 2 x 2 factorial with block design was used for evaluation of harvesting, site preparation, and harvesting × site preparation interaction effects.

Hydraulic gradient vectors and microtopography indices were calculated for each well point by using the relative hydraulic head difference between the well points. These values were used to evaluate harvesting and site preparation effect on microsite hydrology.

Multivariate explanatory analyses, including principal component analysis, factor analysis, and cluster analysis (Johnson and Wichern, 1992), were used to classify overall harvesting and site preparation effects on surface water level. New variables were generated from monthly surface water level measurement data to represent dynamic properties of site hydrology, and surface water level, site hydrology, soil, topography, and disturbance variables were included in the analyses.

Multiple linear regression techniques (Montgomery and Peck, 1992) were used to characterize spatial and temporal surface water dynamics in the study area. First, relationships between monthly surface water table and the temporal, spatial, and physical properties were established by multiple linear regression method. Then, daily surface water levels at each well point during 1996 and 1997 growing season were predicted based on the multiple linear regression equations. Finally, the predicted daily surface water levels were evaluated with respect to the wetland hydrology criterion (1991 Wetland Delineation Manual proposed revisions) to examine forest harvesting and site preparation effect on site hydrology.

Results and Discussion

Overall Characterization of Surface Water Level Change Caused by Forest Operations

Overall characterization of surface water level change caused by harvesting showed that wet- and dry-weather harvesting plots had significantly increased surface water levels compared to Control (non-harvested) plots (Table VI-1). This increase was probably caused by a combination of surface soil disturbance by the harvesting operation and decreased evapotranspiration. Although surface water levels on wet-weather harvested plots were slightly higher than those on dry-weather harvested plots, the differences were not significant. After site preparation, Control plots had the lowest average surface water level among the plots, and Wet-Nonbed plots had the highest average surface water level. Other harvesting-site preparation combinations were not significantly different from each other.

Table VI-1. Average surface water level of Control, Wet-Bed, Wet-Mole-Bed, Wet-Nonbed, Dry-Bed, and Dry-Nonbed treatment plots during pre-harvest (May 1992-Jun. 1993), post-harvest (Jul. 1994-Jul. 1995), and post-site preparation (Feb. 1996-Feb. 1998) periods.

Treatment Plot	Control	Wet-Bed	Wet-Mole-bed	Wet-Nonbed	Dry-Bed	Dry-Nonbed
	-- (cm) --					
Pre-Harvesting	-35.0† a‡	-34.9 a	-35.3 a	-30.8 a	-29.8 a	-34.1 a
		--------- Wet-Weather Harvesting ---------			Dry-Weather Harvesting	
Post-Harvesting	-40.5 a	-20.8 b	-25.1 b	-18.8 b	-23.5 b	-27.1 b
		Bedded	Mole-bed	Non-Bedded	Bedded	Non-Bedded
Post-Site Preparation	-39.0 a	-21.2 b	-23.0 b	-10.5 c	-18.3 b	-19.8 b

† Same treatment plots among the 3 blocks are pooled, and each plot included 80 measurement points.
‡ Means followed by the same letter within a row are not significantly different at the 0.05 level.

The univariate analysis did not elucidate the dynamic property of surface water level change. For instance, surface water level distributions in wet- and dry-weather harvesting plots were clearly different (Figure VI-1). The water levels in wet-weather harvesting plots were distributed closer to the soil surface than those in dry-weather harvesting plots, and the distribution ranges in wet-weather harvesting plots were narrower than those in dry-weather harvesting plots. Bedding site preparation (including mole-bedding), on the other hand, appeared to decrease overall surface water level and distribution range compared to non-bedded plots. These differences were probably caused by spatial variations within the study site and temporal variation of weather and soil natural recovery processes.

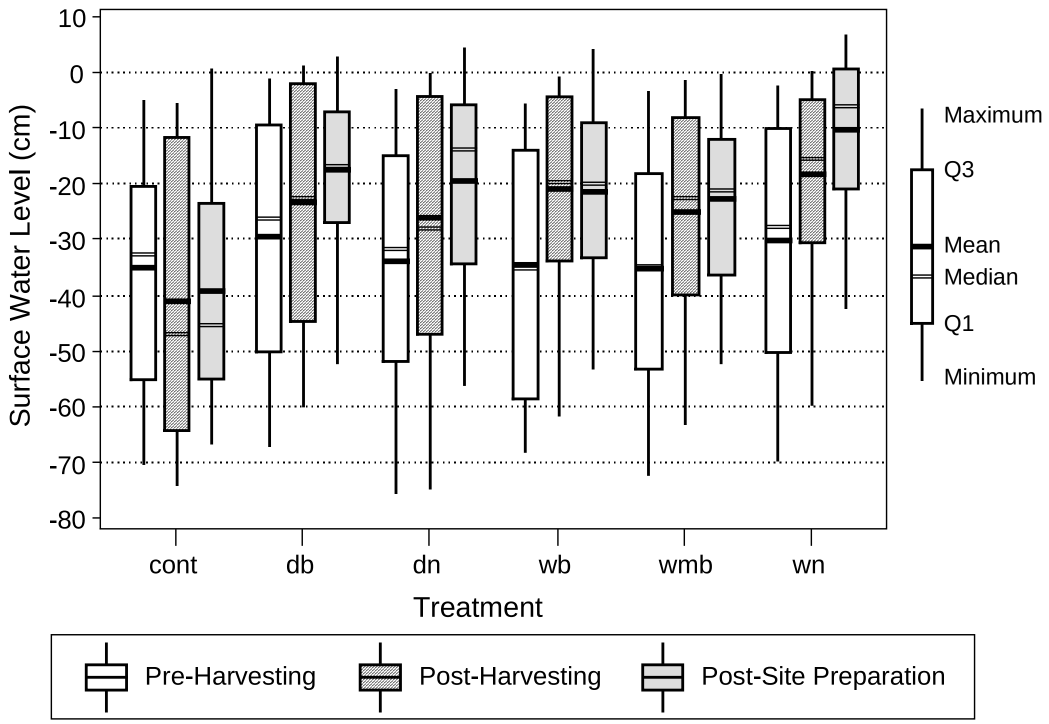

Figure VI-1. Mean surface water level distribution of Control (cont), Dry-Bed (db), Dry-Nonbed (dn), Wet-Bed (wb), Wet-Mole-Bed (wmb), and Wet-Nonbed (wn) treatment plots during pre-harvesting (May 1992-Jun. 1993), post-harvesting (Jul. 1994-Jul. 1995), and post-site preparation (Feb. 1996-Feb. 1998) periods.

Surface Water Flow Characterization

Topography of the study site is generally flat, but subtle relief and localized depressions, such as "gum ponds," are also present. These small topographic changes indicated that the surface water flow pattern in the study site was mosaic and complex; therefore, new variables which represent microsite hydrology and microtopography information were needed to evaluate surface water movement. Microsite hydrology would be expressed by microsite hydraulic gradient, and microtopography would be expressed by relative elevational differences between a point and the adjacent points.

Hydraulic Gradient Vector Determination

Water movement is driven by hydraulic potential from point to point, and water flows from a point of higher potential to a point of lower potential. Our hypotheses are that soil disturbance by harvesting created heterogeneous microtopography (i.e., surface water hydraulic gradient was altered), and site preparation ameliorated the microtopography change.

Hydraulic gradient between two points (Δh) was determined by Bernoulli's equation:

$$\Delta h = (z_1 + P_1/\rho g + v_1^2/2g) - (z_2 + P_2/\rho g + v_2^2/2g) \qquad \textbf{Equation 6.1}$$

where z was relative elevation, P was fluid pressure, ρ was fluid density, g was acceleration due to gravity, v was velocity of fluid, and subscripts indicate different locations. Our assumptions for this hydraulic gradient determination are: (1) the site topography is relatively smooth and gradual, so that the water movement is a slow, steady, mass flow; (2) surface soils (water conducting media) are of relatively uniform depth and homogeneous matrix, so that hydraulic conductivity is homogeneous and isotropic; and (3) fluid pressure is zero because surface water is unconfined, and water is practically incompressible. Using these assumptions, all pressure potentials and kinetic potentials become very small compared to gravitational potentials (elevation); therefore, hydraulic gradient could be determined from relative elevation differences between two points.

Hydraulic gradient vectors were determined at each well point to characterize spatial pattern of potential surface water movement. Since all surface water monitoring wells were installed in a 20 x 20-m grid pattern, hydraulic gradient differences in X and Y coordinate directions could be determined. Based on the X and Y coordinate hydraulic gradients, the vector angle (θ) and magnitude (L) were calculated for each point by the following equations:

$$\theta = \tan^{-1}(Y/X) \qquad \textbf{Equation 6.2}$$

$$L = (X^2 + Y^2)^{0.5} \qquad \textbf{Equation 6.3}$$

Microtopography index (MIC_TOPO) was also calculated by adding the relative elevation difference (hydraulic gradient difference) between a point and four adjacent points, shown by the following equation:

$$\begin{aligned} \text{MIC\_TOPO}_{(i,j)} = {} & [z_{(i,j)} - z_{(i-1,j)}] + [z_{(i,j)} - z_{(i+1,j)}] \\ & + [z_{(i,j)} - z_{(i,j-1)}] + [z_{(i,j)} - z_{(i,j+1)}] \end{aligned} \qquad \textbf{Equation 6.4}$$

where z was relative elevation and subscripts *i* and *j* were position indicators. Therefore, positive or negative value indicated convex or concave microtopography, respectively, and a value close to zero indicated plain microtopography.

Evaluation of Hydraulic Gradient Vector

Since hydraulic gradient vectors are solely a function of elevation difference among points, spatial distribution of the vectors can exhibit the direction and volume of potential surface water movement and the site hydrology alterations caused by the forest operations (Figure VI-2). For example, the pre-harvesting hydraulic gradient vector map of Block 1 depicted minor relief (Figure VI-2A); for example, a small ridge is observed in Wet-Bed plot, and localized depressions could be observed in middle section of the Dry-Nonbed plot and upper corner of the Dry-Bed plot. Contrarily, the post-site preparation hydraulic gradient vector map exhibited relatively large changes on surface water flow pattern (vector directions) and volume (vector length) in the Wet-Bed and Wet-Mole-Bed plots (Figure VI-2B). These results indicated that microtopography changes were produced by wet-weather harvesting and bedding site preparation that altered microsite hydrology.

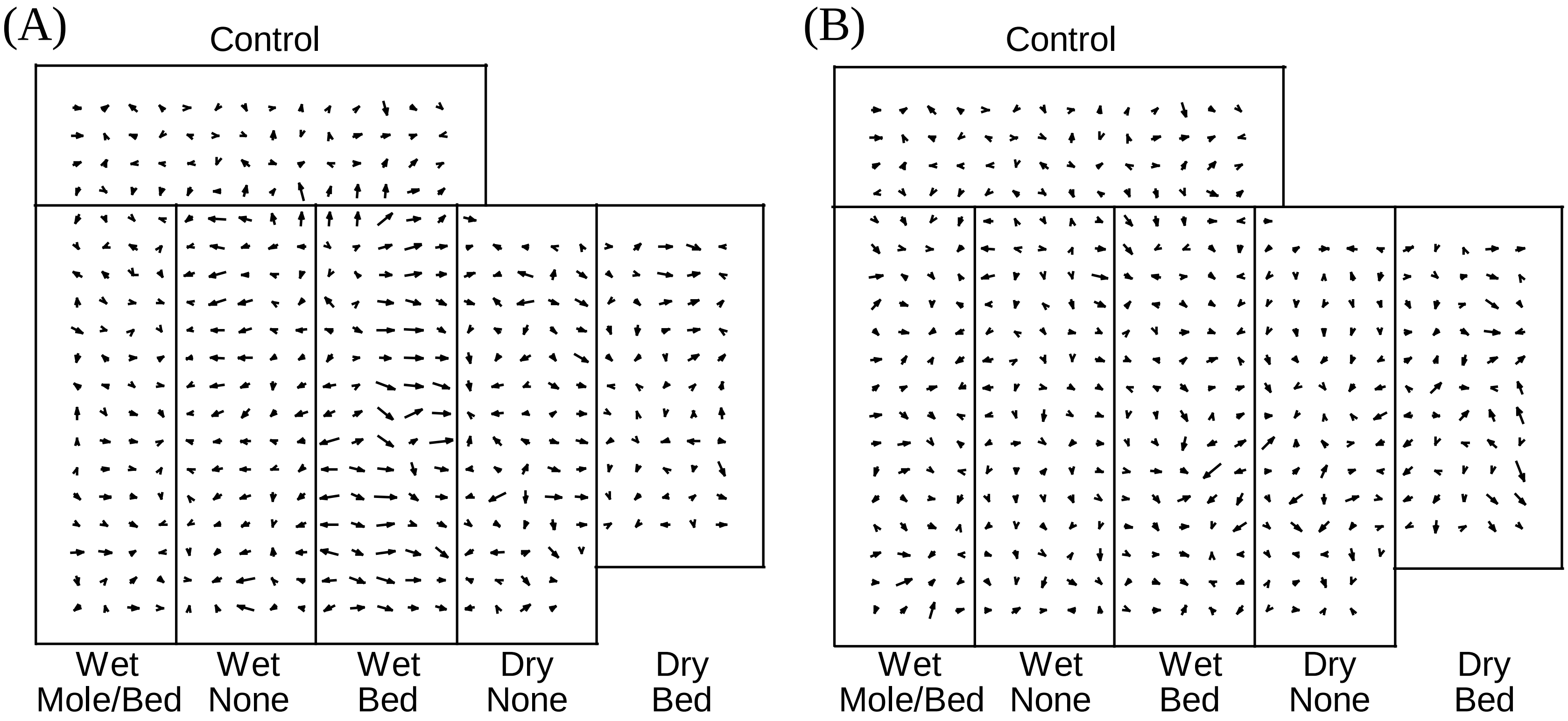

Figure VI-2. Surface water hydraulic gradient vector map of Block 1 for pre-harvesting (A) and post-site preparation (B) periods.

Hydraulic vector angle and magnitude changes among pre-harvesting, post-harvesting, and post-site preparation periods were evaluated to test significance of harvesting and site preparation effects on site hydrology (Table VI-2). Vector angle change was compared as the average of absolute differences between two periods at each point, since direction of vector angle change was not of interest. Vector magnitude change was calculated by subtracting post-treatment values from pre-treatment values at each point because positive or negative changes indicated decrease or increase of water flow, respectively. Wet- and dry-weather harvesting treatments for the post-harvesting to post-site preparation change was pooled across site preparation treatment because harvesting effect was not significant.

Vector angle change by wet- and dry-weather harvesting was significantly larger than the change in Control, and wet-weather harvesting change was significantly larger than dry-weather harvesting change (Table VI-2). Vector angle change by bedding site preparation (including Mole-Bed site preparation) was significantly larger than the change of no bedding plots. Furthermore, overall effect of harvesting and site preparation showed that both wet-weather harvesting and bedding site preparation changed vector angles significantly. These results indicated that microsite water flow pattern was significantly altered by wet-weather harvesting and bedding. However, vector magnitude (water flux) change was no different among the treatments and periods (Table VI-2). These results indicated that overall site hydrological characteristics might not be altered by harvesting and site preparation.

Table VI-2. Vector angle and magnitude change by wet- and dry-weather harvesting and bedding and non-bedding site preparation treatments among pre- and post-harvesting and post-site preparation periods.

	Vector Angle Change					**Vector Magnitude Change**				
	(°)					(Index)				
Pre-Harv. to	Wet		Dry		Cont.	Wet		Dry		Cont.
Post-Harv.	94.89† c‡		72.61 b		14.02 a	0.039§ a		0.032 a		0.006 a
Post-Harv. to	Bed		None		Cont.	Bed		None		Cont.
Post-Site Prep.	96.37 a		14.27 b		n/a	-0.016 a		-0.044 a		n/a
Pre-Harv. to Post-Site Prep.	Wet-Bed	Wet-Nonbed	Dry-Bed	Dry-Nonbed	Cont.	Wet-Bed	Wet-Nonbed	Dry-Bed	Dry-Nonbed	Cont.
	111.24 c	113.64 c	115.33 c	62.97 b	17.08 a	0.059 a	0.021 a	-0.026 a	-0.002 a	0.005 a

† Mean values of absolute differences at each point within a treatment between two periods.

‡ Same letter within a period and variable are not significantly different at the 0.05 level.

§ Mean values calculated by subtracting post-treatment value from pre-treatment value at each point.

Multivariate Characterization of Surface Water Level Change

Data

Surface water level change should be characterized with influencing environmental factors such as soil, topography, site hydrology, and human activity (harvesting and site preparation). Since common soils in the study site consisted of heavy clay argillic horizon, surface soil depth had a significant effect on surface water level. Additionally, surface soil depth was significantly affected by harvesting and site preparation operations, especially severe soil disturbance and bedding; therefore, surface soil depth measurement represented the soil influencing factor. Relative elevation and microtopography index at each well point was used to represent the topographical influencing factor. Hydraulic gradient vector angle and magnitude (determined in the previous section) represented micro-site hydrological influencing factor. Harvesting disturbance significantly altered surface soil depth and the soil physical properties. Soil disturbance class was visually determined at each well point after harvesting operation. Although the disturbance class was a qualitative, integer value, it was determined as area-weighted average of each disturbance class; therefore, disturbance class was expressed as a pseudo-quantitative continuous value, and was used to represent human activity influencing factor.

Few variables were generated from the surface water level measurement, besides overall mean surface water level, to represent various characteristics of surface water dynamics at the study site. Surface water at the study site could be separated into three categories. Category One was "true surface water level," which was above the argillic horizon. This category represented "wet soil condition." Category Two was low water level within the argillic horizon. This represented "moist soil condition" because soil water still existed in the argillic horizon but was held tightly by soil particles. Category Three was "out-of-range (no-water)" measurement, which represented relatively "dry soil condition" because water that remained in the argillic horizon was evaporated or drained due to prolonged dry condition. Based on the three categories, average values of ’true surface water level’ were calculated, and percent of ’out-of-range’ measurement days and ’true surface water’ measurement days over the total measurement days were calculated at each observation well to represent prolonged dry and wet periods, respectively.

These influencing factors and surface water variables, except disturbance class, were determined at each well point for each pre- and post-harvesting and post-site preparation period. Then, difference of each variable between pre-harvesting and post-harvesting, and post-harvesting and post-site preparation periods was calculated to evaluate harvesting and site preparation treatment effects.

Prior to multivariate analysis, non-significant variables were eliminated by Stepwise discriminant analysis (SAS Institute Inc., 1988) which evaluates significance of each variable to overall variance by partial F-test. The significant variables that would be used for multivariate analyses to evaluate harvesting effects were: disturbance class (DC), surface soil depth change (ΔDEPTH), relative elevation change (ΔELEV), microtopography index change (ΔMIC_TOPO), overall mean surface water level change (ΔMEAN_WT), ’true’ surface water level mean change (ΔTRUE_WT), percent ’dry’ days change (Δ%_DRY), and percent ’wet’ days change (Δ%_WET). The variables used to evaluate site preparation effects were: disturbance class (DC), relative elevation change (*d*ELEV), micro-topography index change (*d*MIC_TOPO), vector angle change (*d*V_ANGLE), overall surface water level mean change (*d*MEAN_WT), ’true’ surface water level mean change (*d*TRUE_WT), and percent ’dry’ day change (*d*%_DRY).

Principal Component Analysis and Factor Analysis

Harvesting Effect

Since many variables were included in the surface water level analysis, principal component analysis was used to reduce the number of variables, and factor analysis was used to improve interpretation of principal components (PCs) (Johnson and Wichern, 1992). Principal component analysis of harvesting effect showed that eigenvalues of PCs 1, 2, and 3 were relatively high, and the cumulative proportions explained 66% of the overall variation (Table VI-3); therefore, these PCs were important axes. PC 4 was a marginally important axis because the eigenvalue was slightly less than 1.0, which is a common cutoff value. Importance of each axis would be evaluated by factor analysis with respect to the interpretation of each axis. PC 1 consisted of relatively high loading of ΔMIC_TOPO, ΔMEAN_WT, and ΔTRUE_WT eigenvectors. PC 2 consisted of high loading of ΔDEPTH, ΔTRUE_WT, and Δ%_WET eigenvectors. PC 3 consisted of high loading of ΔELEV and Δ%_DRY eigenvectors. PC 4 consisted of high loading of DC and Δ%_DRY eigenvectors.

Table VI-3. Principal component analysis results of harvesting effect on surface water level change.

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8
Eigenvalue	2.2844	1.8895	1.1145	0.9859	0.7483	0.5037	0.3663	0.1074
Difference	0.3948	0.7750	0.1286	0.2376	0.2446	0.1374	0.2589	.
Proportion	0.2855	0.2362	0.1393	0.1232	0.0935	0.0630	0.0458	0.0134
Cumulative	0.2855	0.5217	0.6610	0.7843	0.8778	0.9408	0.9866	1.0000
Eigenvectors								
DC	0.231753	0.356199	-.031095	0.435051	-.741715	-.262471	-.096330	0.029397
ΔDEPTH	-.289107	0.536827	-.217616	-.003044	0.148637	-.201928	0.678122	-.241144
ΔELEV	-.284851	-.019237	0.688604	0.315015	0.253529	-.518504	-.104837	-.031070
ΔMIC_TOPO	-.452564	0.117009	0.321429	0.298162	-.194246	0.733851	0.099709	0.055380
ΔMEAN_WT	0.537823	0.145794	0.098111	0.360640	0.337003	0.262215	-.063198	-.602895
ΔTRUE_WT	0.415276	-.405775	0.279074	0.105155	-.101514	0.013777	0.705664	0.255922
Δ%_DRY	-.143677	-.236447	-.516810	0.692107	0.299004	-.047000	-.012323	0.292541
Δ%_WET	0.307249	0.573639	0.139939	-.049547	0.335377	0.108604	-.088495	0.649919

Factor analysis varimax rotation method (SAS Institute Inc., 1988) was used to maximize variance of variables along the principal component axes to improve interpretation of the principal components. Factor analysis was performed with four factors (PCs 1, 2, 3, and 4) and three factors (PCs 1, 2, and 3) to evaluate importance of fourth axis (FC 4) (Tables VI-4 and 5). Factor analysis with four factors showed that the

FC 4 consisted of high loading of Δ%_DRY (0.96). In factor analysis with three factors, however, Δ%_DRY showed moderately high loading in FC 1 (-0.53). These results indicated that the FC 4 could be included in FC 1.

Table VI-4. Variable loading for harvesting effect factors 1, 2, 3, and 4.

	FC 1	FC 2	FC 3	FC 4
DC	-0.11159	0.72783	-0.00136	0.08900
ΔDEPTH	-0.86730	0.16703	0.07975	-0.04220
ΔELEV	0.07534	-0.05000	0.89380	-0.07274
ΔMIC_TOPO	-0.35303	-0.12749	0.73636	0.11587
ΔMEAN_WT	0.40698	0.80029	-0.18034	-0.03554
ΔTRUE_WT	0.88486	0.11376	-0.07970	-0.02227
Δ%_DRY	-0.02488	-0.01191	-0.00947	0.96015
Δ%_WET	-0.24277	0.74048	-0.12201	-0.48941

Table VI-5. Variable loading for harvesting effect factors 1, 2, and 3.

	FC 1	FC 2	FC 3
DC	0.56766	-0.11876	-0.16482
ΔDEPTH	0.21017	-0.86186	0.03560
ΔELEV	-0.08370	0.01247	0.84104
ΔMIC_TOPO	-0.20960	-0.41940	0.62374
ΔMEAN_WT	0.67791	0.42224	-0.27167
ΔTRUE_WT	0.05815	0.88617	-0.05645
Δ%_DRY	-0.52456	-0.12172	-0.40060
Δ%_WET	0.90824	-0.18055	-0.04175

Interpretation of 3-factor and 4-factor factor analysis was similar (Tables VI-4 and 5):

- FC 1 axis of 4-factor factor analysis and FC 2 axis of 3-factor factor explained ’effect of surface soil depth and property changes on surface water level’ since these factors consisted of high loading (> 0.85) of ΔDEPTH and ΔTRUE_WT.
- FC 2 and 4 axis of 4-factor factor analysis and FC 1 axis of 3-factor factor analysis explained ’micro-site soil disturbance effect on overall surface water dynamics’ since these factors consisted of high loading of DC, ΔMEAN_WT, Δ%_DRY, and Δ%_WET.
- FC 3 axes of 4-factor and 3-factor factor analysis explained ’surface soil topography change’ since these factors consisted of high loading of ΔELEV and ΔMIC_TOPO.

These interpretations indicated that factor analysis with three factors sufficiently explained surface water level changes and the causes, and FC 4 did not add extra information. Interpretation of factors (FCs 1, 2, and 3) was slightly better than interpretation of principal components (PC 1, 2, and 3) because distribution of each variable loading for each factor was more polarized by factor analysis rotation (Table VI-3 and 5). The orthogonal transformation matrix used to convert the principal components to the factors follows:

$$T = \begin{bmatrix} 0.61708 & 0.63848 & -0.45995 \\ 0.73649 & -0.67445 & 0.05185 \\ 0.27711 & 0.37075 & 0.88643 \end{bmatrix}$$

Site Preparation Effect

Site preparation effect on surface water change was also examined through principal component analysis and factor analysis. Eigenvalue of principal components, and the proportions showed that PCs 1, 2, and 3 were important axes since they explained 68% of overall variation caused by site preparation (Table VI-6). PC 4 was a marginally important axis because the eigenvalue was slightly lower than the common cutoff value (1.0). PC 1 consisted of high loading of *d*ELEV, *d*MIC_TOPO, *d*MEAN_WT, and *d*TRUE_WT, PC 2 consisted of high loading of DC and *d*%_DRY, and PC 3 consisted of high loading of *d*V_ANGLE. PC 4 consisted of high loading of DC and *d*%_DRY that was the same composition as PC 2. This indicated that three principal components were sufficient to explain the overall variation.

Table VI-6. Principal component analysis results of site preparation effect on surface water level change.

	PC 1	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**	**PC 7**
Eigenvalue	2.6647	1.1262	0.9998	0.8786	0.6251	0.4775	0.2280
Difference	1.5385	0.1264	0.1212	0.2535	0.1476	0.2495	.
Proportion	0.3807	0.1609	0.1428	0.1255	0.0893	0.0682	0.0326
Cumulative	0.3807	0.5416	0.6844	0.8099	0.8992	0.9674	1.0000
Eigenvectors							
DC	0.040042	-.691769	-.176100	0.691285	0.086598	-.041798	-.041474
*d*ELEV	-.441414	0.097599	0.094525	0.029174	0.765411	-.441109	0.073557
*d*MIC_TOPO	-.485188	-.030070	-.025876	0.012844	0.217537	0.844933	-.040250
*d*V_ANGLE	0.007271	-.177220	0.976973	0.083066	-.071453	0.045139	0.004574
*d*MEAN_WT	0.514129	0.214583	0.051671	0.114311	0.418030	0.162330	-.687597
*d*TRUE_WT	0.534673	0.065066	0.015917	0.049560	0.370400	0.247687	0.713188
d%_DRY	-.133740	0.655240	0.044552	0.706177	-.205607	-.005196	0.099006

The factor analysis varimax rotation method was used to improve interpretation of principal components (Table VI-7). Orthogonal transformation matrix used to convert the principal components to the factors follows:

$$T = \begin{bmatrix} 0.99167 & 0.12827 & 0.01214 \\ 0.12849 & -0.97763 & -0.16653 \\ 0.00949 & -0.16670 & 0.98596 \end{bmatrix}$$

Rotation of PCs 1, 2, and 3 did not change variable-factor relations but shifted the loading distributions within variables to polarize weights for each factor. For example, FC 1 consisted of high loading of *d*ELEV, *d*MIC_TOPO, *d*MEAN_WT, and *d*TRUE_WT, which was the same variable composition as PC 1 (Table VI-6). However, the loadings of those variables in FC 1 were larger than those in PC 1, and the other variable loadings in FC 1 were smaller than those in PC 1. This indicated that interpretation of factor scores were clearer than those of principal component scores. Therefore, the factor analysis result was used for further analysis.

Table VI-7. Variable loading for site preparation effect factors 1, 2, and 3.

	FC 1	FC 2	FC 3
DC	-0.03118	0.75544	-0.05056
*d*ELEV	-0.70035	-0.20944	0.06719
*d*MIC_TOPO	-0.78977	-0.06608	-0.02981
*d*V_ANGLE	-0.00312	0.02254	0.99461
*d*MEAN_WT	0.86202	-0.12359	0.02321
*d*TRUE_WT	0.87455	0.04179	0.01479
d%_DRY	-0.12673	-0.71523	-0.07453

Interpretations of each factor for the site preparation effect were made based on variable loading of each factor:

- FC 1 axis was 'microsite topography and elevation change effect on surface water level' since FC 1 consisted of high loading of *d*ELEV, *d*MIC_TOPO, *d*MEAN_WT, and *d*TRUE_WT.
- FC 2 axis was 'residual subsurface soil disturbance effect on surface water level' because FC 2 consisted of high loading of DC and *d*%_DRY. Disturbance class (DC) in the site preparation effect analysis was probably expressing residual effect of harvesting soil disturbance such as subsurface soil compaction and churning (Miwa et

al., 1998).

- FC 3 axis was 'bedding effect on surface water flow' because *d*V_ANGLE was the only variable which had high loading in FC 3.

Factor Score Calculation

Based on the factor analysis results, new values (scores) were calculated for each observation using the selected factor loadings. At this point, FCs 1, 2, and 3 became new variables instead of actual variables, such as relative elevation, and observation scores became new values instead of actual measured values. Since rotation of axes were orthogonal transformations, actual relation among new observation score and actual observation values did not change. Example score calculation formula of FC 1 for site preparation effect at a well point (*i*) is shown below:

$$\begin{aligned} FC\ 1_{(i)} = {} & (-0.03118)(DC_i) + (-0.70035)(dELEV_i) + (-0.78977)(dMIC\_TOPO_i) \\ & + (-0.00312)(dV\_ANGLE_i) + 0.86202(dMEAN\_WT_i) \\ & + 0.87455(dTRUE\_WT_i) + (-0.12673)(d\%\_DRY_i) \end{aligned}$$ **Equation 6. 5**

Cluster Analysis

Observation scores of harvesting and site preparation effect factors were used for separate cluster analyses to classify harvesting and site preparation effects on surface water level change. Euclidean distance measure and McQuitty linking method were used in cluster analysis, and similarity value was used in dendrogram (MINITAB Inc., 1996).

Harvesting Effect

A dendrogram of harvesting effect cluster analysis showed four major groups at 70% similarity level, and the majority of observations within a group were joined by 90% similarity level (Figure VI-3). This indicated that each group's characteristics were somehow distinctive, and observations within each group were relatively homogeneous.

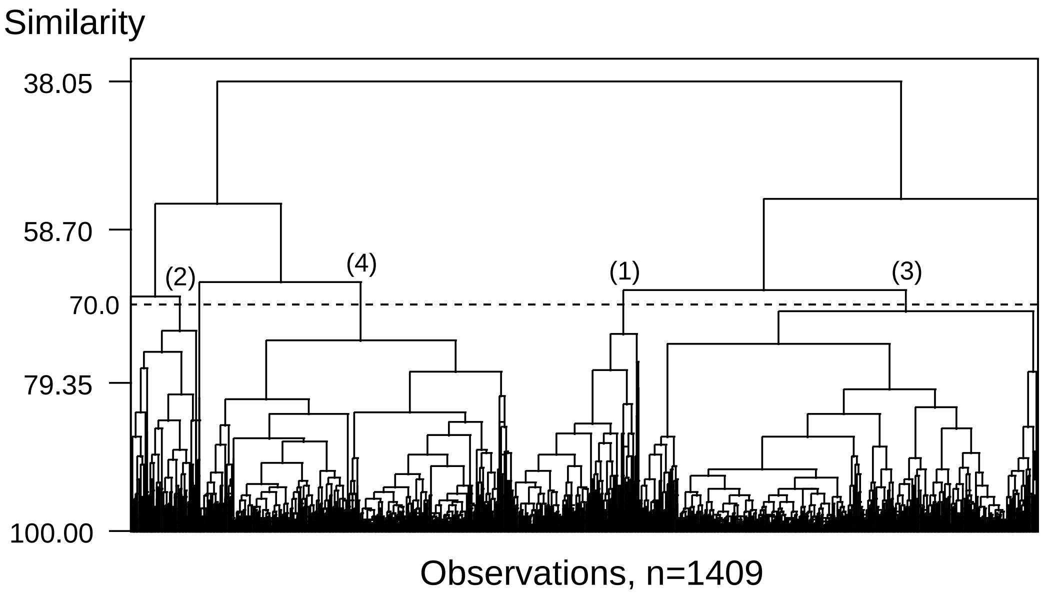

Figure VI-3. Cluster analysis dendrogram for harvesting effect on surface water level change and four major recognized groups (numbers in parentheses).

The centroid was determined for each group, and coordinates of a centroid on FC 1, 2, and 3 axes were examined to interpret characteristics of each group (Table VI-8). Coordinates of the Group 1 centroid were relatively high compared to the other groups' coordinates. The positive number of the FC 1 coordinate (0.9639) indicated that observations in Group 1 were located in a highly disturbed area, and the surface water levels were increased by the disturbance. The negative number of the FC 2 coordinate (-0.7079) and positive number of the FC 3 coordinate (0.8828) indicated increased surface soil depth, relative elevation, and microtopography. These results probably indicated small mounds created by surface soil disturbance. Therefore, interpretation of Group 1 was highly disturbed area, such as broad rutted area in wet-weather harvesting plots, with increased surface water level. FC 2 coordinate of the Group 2 centroid was significantly high compared to the other values. This indicated that the observations in Group 2 significantly decreased the surface soil depth and increased the surface water level. This might be indicating severely disturbed, deep rutted areas. The medium values of FC 1 and 3 coordinates of the Group 3 centroid indicated that the harvesting effect on these observations was probably minimal, and the surface water level was slightly decreased. FC 3 coordinate of the Group 4 centroid was a slightly larger negative value

(-0.7767). This indicated that the observations of the group slightly decreased relative elevation and increase of surface water level.

Table VI-8. Coordinates of group centroids for harvesting effect factor 1, 2, and 3.

Variable	Group 1	Group 2	Group 3	Group 4
FC 1	0.9639	0.5981	-0.5110	0.1284
FC 2	-0.7079	2.1426	0.1883	-0.3954
FC 3	0.8828	-0.5750	0.4524	-0.7767

Site Preparation Effect

A dendrogram of site preparation effect cluster analysis showed four major groups at 57% similarity level (Figure VI-4). These relatively low similarity values were the result of large observation variability in Groups 3 and 4. This large variability was probably caused by site preparation treatment, since bedding usually alters microtopography significantly. Control and Nonbed plots did not receive site preparation treatments; therefore, the observations in these plots probably showed low variability.

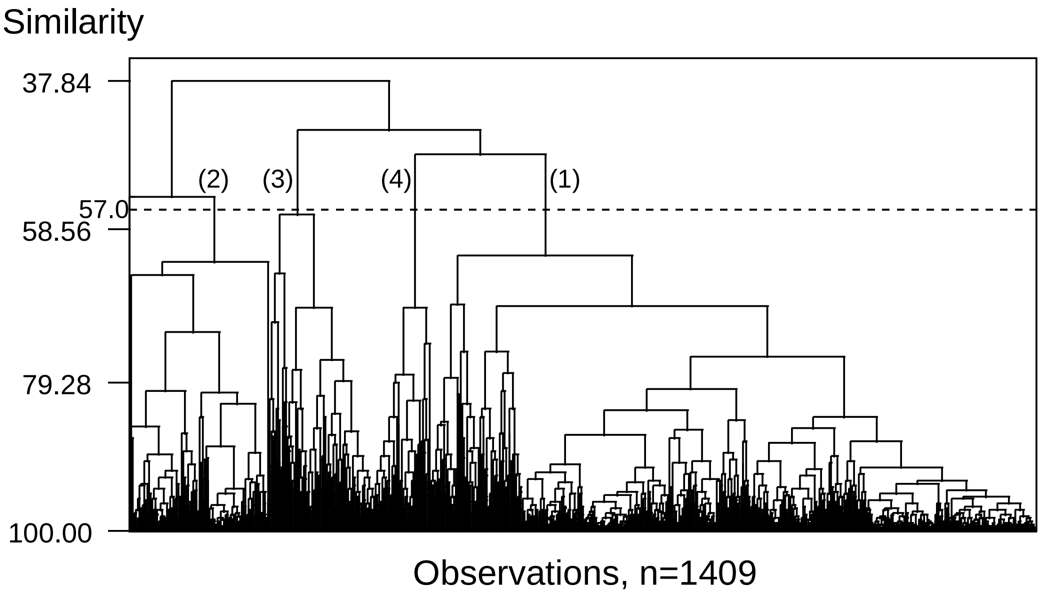

Figure VI-4. Cluster analysis dendrogram for site preparation effect on surface water level change and four major recognized groups (numbers in parentheses).

Centroid coordinates of each site preparation effect group explained the characteristics of the groups (Table VI-9). Group 1 was no-change locations because the coordinates were small. FC 2 coordinate of the Group 2 centroid showed a large negative value (-1.3922). Since FC 2 for site preparation effect explained the effect of microsite disturbance on surface water level, this low coordinate indicated a less disturbed, dryer area with a slightly lowered surface water level. FC 3 coordinate of the Group 3 centroid showed a large positive value (1.7319) that indicated that the observations in the group significantly changed the microtopography and surface water flow pattern by bedding. FC 1 coordinate of the Group 4 centroid showed a large positive value (2.1280), which indicated that the observations in the group significantly decreased surface soil depth and increased surface water level because FC 1 explained microsite topography change and the associated surface water level increase.

Table VI-9. Coordinates of group centroids for site preparation effect factors 1, 2, and 3.

Variable	Group 1	Group 2	Group 3	Group 4
FC 1	-0.1372	-0.4722	0.2883	2.1280
FC 2	0.2638	-1.3922	0.0840	0.4077
FC 3	-0.2883	0.1435	1.7319	-0.5155

In short, six classification groups were characterized by cluster analysis of harvesting and site preparation effects on surface water level change:

- First group was ’no change or slight surface water level decrease’ (Δ≅0 / WT↓) which included Group 3 of harvesting effect cluster analysis and Group 1 of site preparation effect cluster analysis.
- Second group was ’no change or small relative elevation decrease’ (Δ≅0 / ELEV↓) which was Group 4 of harvesting effect cluster analysis.
- Third group was ’highly disturbed area which significantly increased surface water level’ (DC / WT↑↑) which was Group 1 of harvesting effect cluster analysis.
- Fourth group was ’significant surface soil depth decrease which significantly increased surface water level’ (DEPTH↓↓ / WT↑↑) which included Group 2 of harvesting effect cluster analysis and Group 4 of site preparation effect cluster analysis.
- Fifth group was ’significant surface water level decrease’ (WT↓↓) which was Group 2 of site preparation effect cluster analysis.
- Sixth group was ’surface water flow pattern altered by bedding’ (BED / FLOW) which

was Group 3 of site preparation effect cluster analysis.

Spatial Characterization of Surface Water Change

Classification groups of harvesting and site preparation effects on surface water level change were plotted on a observation well map of the study site (Figure VI-5). These spatial maps showed that dry-weather harvesting plots consisted of many minor elevation-decreased areas (Δ≅0 / ELEV↓, ☐) which probably indicated compression tracks and a few disturbed and surface water level-increased areas (DC / WT↑↑, ∗ ; and DEPTH↓↓ / WT↑↑, +) (Figures VI-5A, 5C, and 5E). Contrarily, wet-weather harvesting plots consisted of many severely disturbed areas (DC / WT↑↑, ∗) and significant surface soil depth-decreased areas (DEPTH↓↓ / WT↑↑, +). This result indicated that dry-weather harvesting caused less surface soil disturbance than wet-weather harvesting. Although wet-weather harvesting plots consisted of many disturbed areas, these plots also included a number of less disturbed areas (Δ≅0 / WT↓, ○ ; and Δ≅0 / ELEV↓, ☐) which indicated that wet-weather harvesting plots had many different microsite conditions. This microsite variability probably caused no statistical difference in mean surface water level between dry- and wet-weather harvesting plots (Table VI-1).

Bedding (Bed and Mole-Bed plots) significantly decreased surface water level at some areas (WT↓↓, Δ) but at the same time significantly increased surface water level at other areas (DEPTH↓↓ / WT↑↑, +) (Figures VI-5B, 5D, and 5F). Additionally, bedding significantly changed microtopography and surface water flow patterns at another area (BED / FLOW, •). These results indicated that microsite hydrology was significantly altered by bedding site preparation. No area in non-site preparation plots (Control and Nonbed) showed a surface water level increase, which was further evidence of the surface water level increase associated with bedding site preparation, not other factors such as precipitation pattern. Bedding site preparation has been commonly suggested by many state forestry BMP manuals in order to ameliorate severe soil disturbance. However, this result indicated that bedding site preparation probably caused an increase in surface water level in low-lying areas; therefore, bedding did not appear to ameliorate site hydrology.

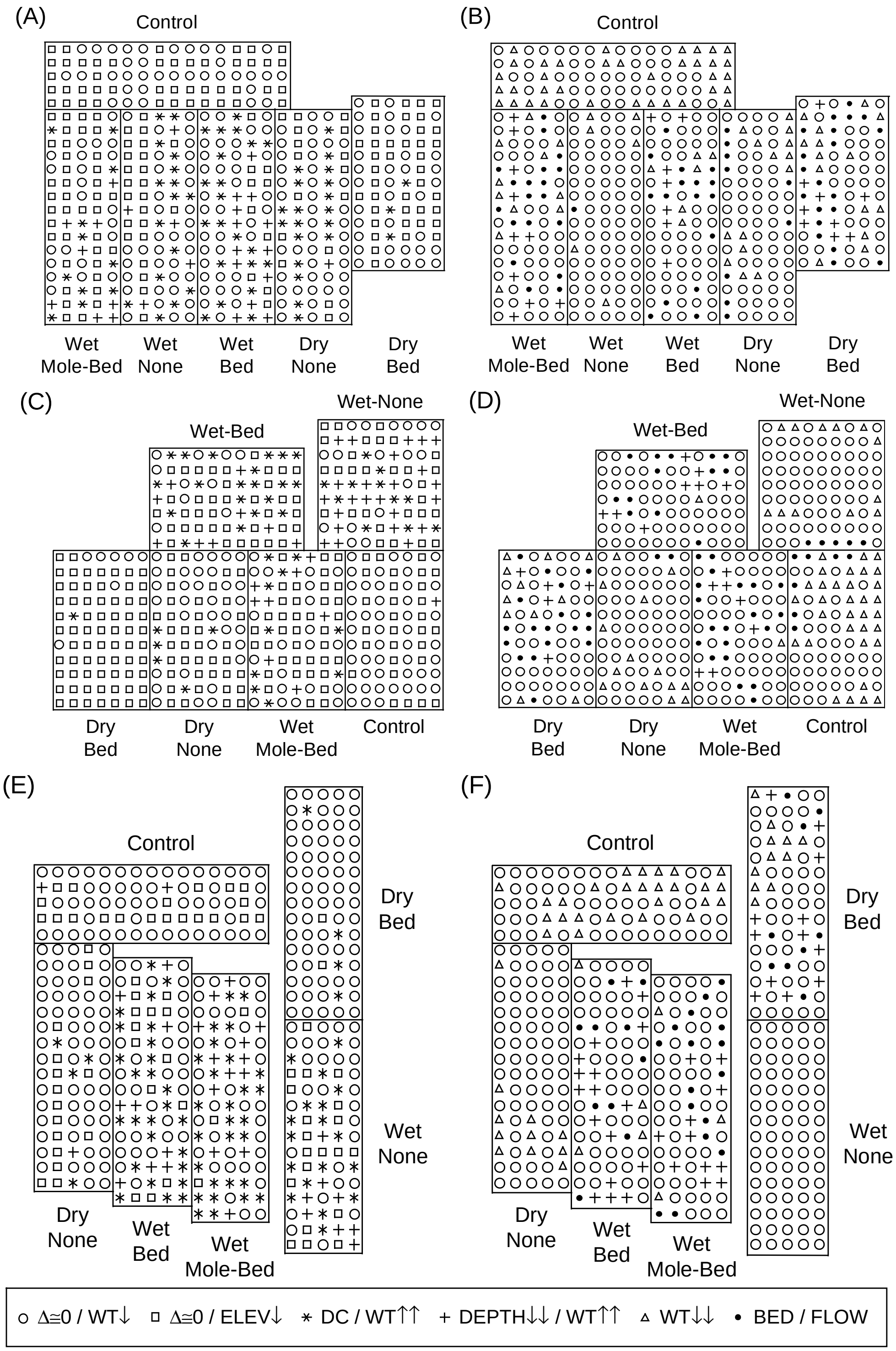

Figure VI-5. Spatial distribution of harvesting and site preparation effect classification groups on Block 1 (A and B, respectively), Block 2 (C and D, respectively), and Block 3 (E and F, respectively).

Prediction of Surface Water Level Change by Forest Operation

Surface Water Dynamics Characterization and Daily Water Table Prediction

Wetland hydrology is a dynamic system. In order to characterize surface water dynamics and the changes caused by treatments, surface water level should be expressed by function of temporal, spatial, and physical properties of the site. Multiple linear regression techniques were used to characterize monthly surface water level measurements. Continuous well measurements consisted of temporal dynamics of surface water level that was caused by precipitation and evapotranspiration. These measurements also included spatial characteristics of the site because surface water levels were affected by local surface runoff and lateral surface water movement. Spatial characteristics of the site could be explained by trend surface analysis, which includes X and Y coordinates of each point. Distance between a well and an automated well could be the other source of spatial variance. Therefore, X and Y coordinates and distance between a well and an automated well were included in the regression equation as a spatial property. Site physical properties included surface soil depth, disturbance class, and microtopography index.

Monthly surface water level measurements at each well during the post-site preparation period were correlated with all automated wells within the same block, then monthly water table data were sorted by the most correlated automated well. These sorted water table data (WT) were used for a response variable of the multiple linear regression. The general form of the regression equation was:

$$\begin{aligned} WT = \beta_0 + \beta_1(WT_{auto}) + \beta_2(DEPTH) + \beta_3(MIC\_TOPO) \\ + \beta_4(DC) + \beta_5(DIST) + \beta_6(X) + \beta_7(Y) \qquad \textbf{Equation 6.6} \end{aligned}$$

where WT_{auto} was the automated well data which corresponded with monthly well measurement date and time, DEPTH was surface soil depth, MIC_TOPO was micro-topography index, DC was soil disturbance class index, DIST was distance between a well and an automated well, and X and Y were well location coordinates. After multicollinearity diagnostics, highly influential observation detection, and regressor selection procedures, each regression equation showed significant overall p-values ($p\text{-value} < 0.05$), and the weighted block averages of adjusted R^2 were 0.67, 0.61, and 0.54 for Blocks 1, 2, and 3, respectively, which were adequate R^2 levels for this type of analysis. These results suggested that the regression equations were sufficient to predict surface water levels; therefore, daily surface water levels at each well point for the 1996 and 1997 growing seasons (March 14 through November 10) were calculated from the equations.

Wetland Hydrological Criteria Evaluation

Site hydrological alteration by treatment and site physical properties should be evaluated with respect to wetland hydrological criteria because many silvicultural, ecological, environmental, and social issues related to forested wetlands and intensive pine silviculture in the Lower Coastal Plain are partly based on hydrological properties. The wetland hydrology criteria used to evaluate the predicted daily surface water level in this study are the 1991 Wetland Delineation Manual proposed revisions, which state, “saturated to the surface 21 or more consecutive days” (Gaddis and Cubbage, 1998). This study focused on soil saturation criteria because surface soil saturation is more difficult to determine than soil inundation.

In order to evaluate the predicted daily surface water level with the wetland hydrology criteria, the soil-saturation equivalent water level has to be determined. This was determined from surface soil moisture (0-30 cm) and surface water level paired data (unpublished data, M.A. Burger, M.S. project, 1994). The linear regression analysis result was:

$$\text{(Water Table)} = -95.08 + 1.537\ \text{(Soil Moisture)} \qquad \textbf{Equation 6.7}$$

where $n = 3233$ and $R^2 = 0.66$. Soil saturation is defined as “a condition in which all voids (pores) between soil particles are filled with water" (USDA Soil Conservation Service, 1991). Therefore, the average total porosity of surface soil in the site (50%) was used as a saturated soil moisture value, and the equivalent water level during periods of soil saturation was estimated as -18.4 cm.

The predicted daily surface water levels were evaluated with wetland hydrological criteria: surface water level higher than -18.4 cm 21 or more days, and number of days which exceeded the criteria were determined at each point. Then, percent of ‘wet site’ was calculated for each treatment plot and each growing season, dividing the number of points which showed soil saturation by the number of total points in the plot. Adjusted cumulative days of 'wetland status' were also determined for each treatment plot and each growing season, adding the number of soil saturation days of each point for within the plot. (Cumulative days were adjusted since some plots had different numbers of well points.)

Test result of percent of wet site and adjusted cumulative days was no different among the treatments because of large variance (Table VI-10). This large variance indicated that some localized area might become wetter or dryer. Mean water table distribution box plot (Figure VI-1) and spatial distribution of harvesting and site preparation classification groups (Figure VI-5) also indicated that different micro-site showed different surface water level responses to harvesting and site preparation.

Table VI-10. Percent 'wet' area and adjusted cumulative 'wet' days based on predicted daily surface water level for 1996 and 1997 growing season.

Growing Season	Wet Bed	Wet Mole-Bed	Wet None	Dry Bed	Dry None	Control
Percent area						
	(%)					
1996	18.8†	25.8	31.1	26.0	22.4	36.6
1997	16.3	20.4	24.2	15.4	10.8	0.0
Adjusted cumulative days						
	(Days)					
1996	396[b]	480	804	793	228	482
1997	352	346	577	591	139	0

† Values are mean of three plots.

Distribution plot of 'wet set' with different 'wet day status' showed trends caused by micro- and mesotopography and precipitation pattern (Figure VI-6). Microtopography effects on site hydrology could be observed at the upper and lower sections of Wet-Mole-Bed and Wet-None plots in Block 1, middle section of Dry-None plot in Block 1 (Figures VI-6A and 6B), and upper and middle sections of Wet-Bed and Wet-Mole-Bed plots in Block 3 (Figures VI-6E and 6F). These 'wet site' patterns were associated with localized depression areas because both 1996 and 1997 growing season plots showed similar patterns.

Different wet site patterns between growing seasons which were observed at the Control and Dry-Bed plots in Block 3 indicated that surface water dynamics were also sensitive to annual precipitation patterns (Figures VI-6E and 6F). This could be explained by the 1996 and 1997 growing season hyetograph (Figure VI-7). Although cumulative precipitation during the 1997 growing season was more than that of 1996, the precipitation pattern of the 1996 growing season, especially between days 180 and 220, was more concentrated than the 1997 precipitation pattern. This concentrated precipitation pattern probably caused prolonged wet conditions in relatively low and flat areas such as Block 3, Control and Dry-Bed plots.

Mesotopography effects on site hydrology could be observed when comparing hydrological responses of each block. Blocks 1 and 3 showed some sensitivity to microtopography, and Block 3 showed some sensitivity to precipitation patterns, but Block 2 showed no response to either physiographical factor. This could be explained by soil differences in each block. Major soil series in Blocks 1 and 3 were Argent and Santee, which are poorly drained, slowly permeable, clay soils with 1-2% slopes (USDA Soil Conservation Service, 1982); therefore, surface water in the area drained into localized depressions, and drained water ponded the depression area prolonged time. Major soil series in Block 2 were Hobcaw and Yemassee, which are very poorly drained, moderately permeable loamy soils with 0-1% slopes (USDA Soil Conservation Service, 1982); therefore, surface water in the area slowly percolated into groundwater. These results suggested that micro- and mesotopography, soil, and precipitation patterns during the growing season have significant influences on wet pine flat site hydrology.

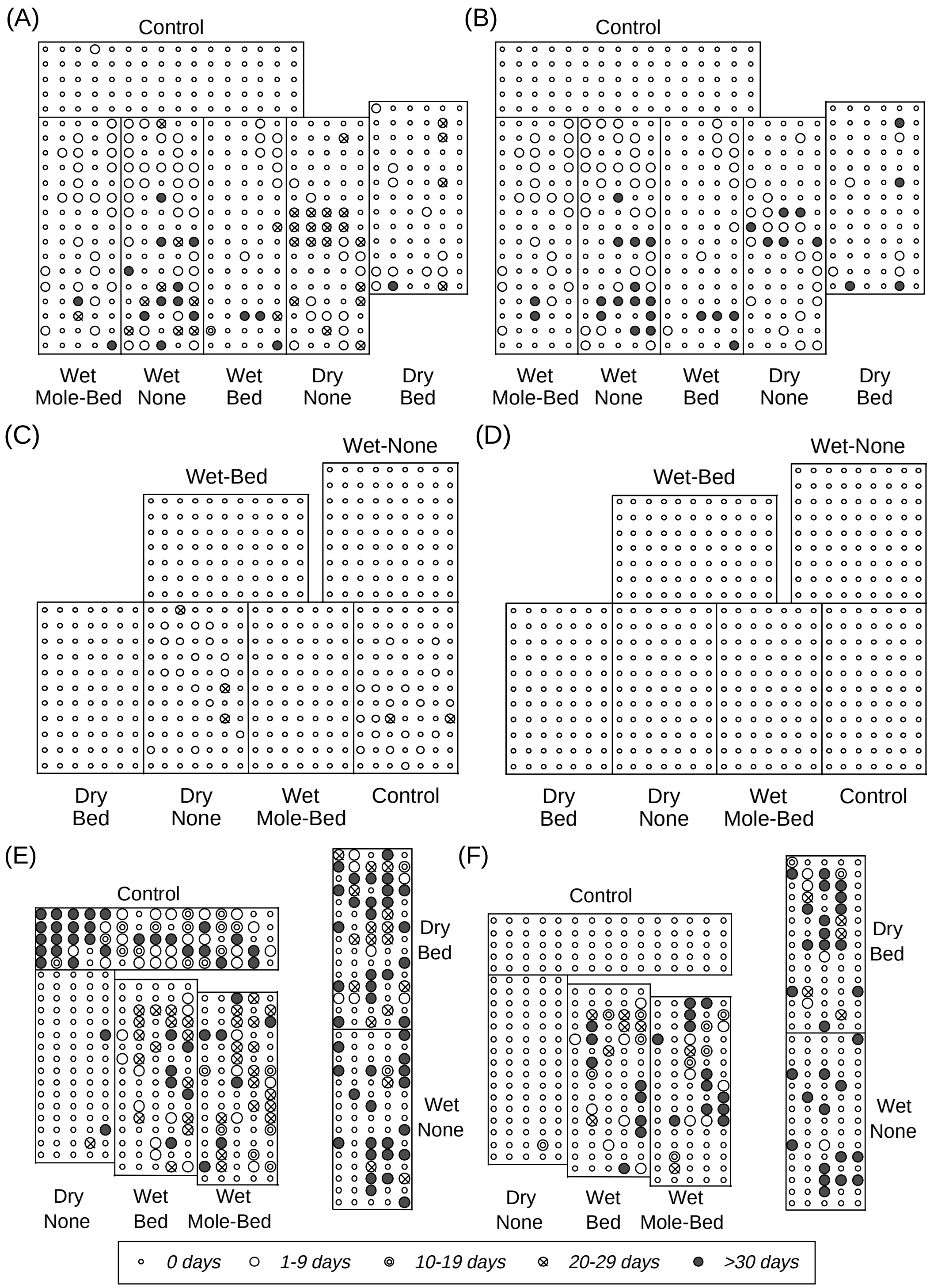

Figure VI-6. Spatial distribution of predicted 'Wet Site' and the cumulative 'Wet' days for Block 1, 1996 growing season (A) and 1997 growing season (B); Block 2, 1996 growing season (C) and 1997 growing season (D); and Block 3, 1996 growing season (E) and 1997 growing season (F).

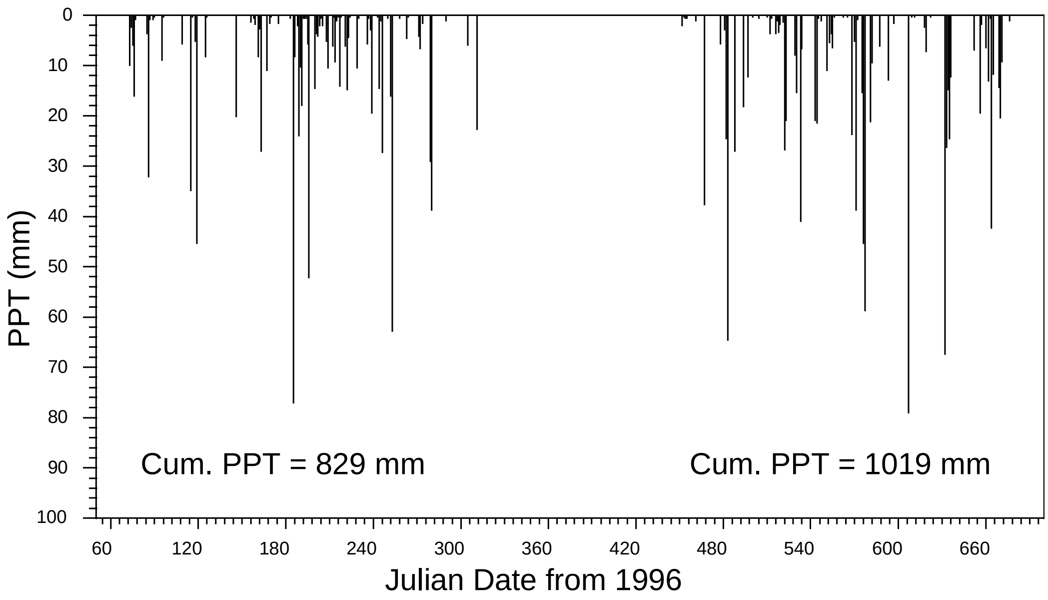

Figure VI-7. Hyetograph during 1996 and 1997 growing seasons at study site.

Conclusions

Wet pine flats in the Southeastern Lower Coastal Plain are generally considered to be relatively flat, homogeneous forest systems. However, the microsite hydrology was complex, and the different topographies and soils showed different responses to harvesting and site preparation operations. Both dry- and wet-weather harvesting plots increased overall mean surface water level compared to those of non-harvesting plots. This was mainly caused by low evapotranspiration rate in the harvested plots. The overall mean surface water level was not statistically different between dry- and wet-weather harvesting plots, but differences were observed in microsite. Dry-weather harvesting plots contained many undisturbed areas and compression tracks. Most of those areas did not show significant surface water level changes. Contrarily, wet-weather harvesting plots consisted of many disturbed areas whose surface water levels were significantly increased, as well as many less disturbed areas. This variation within wet-weather harvesting plots made it difficult to evaluate these disturbance effects on forest soils, and the microsite variation was often neglected by previous similar studies. The mole channeling-bedding treatment did not show any difference from the other bedding plots.

Multivariate cluster analysis and daily surface water level prediction showed that bedding lowered surface water level in high-elevation areas and increased surface water level in low-elevation areas. Hydraulic gradient characterization and multivariate cluster analysis indicated that bedding significantly altered surface water flow patterns within a harvested site; however, overall site hydrology might not be altered, since hydraulic gradient vector did not indicate significant outflow from the study site. These results indicated that the microsite variation of the surface water level differences was significantly influenced by minor elevational differences, and bedding site preparation accentuated the surface water level differences by altering microsite hydrology.

Bedding site preparation has been recommended by many BMPs in southeastern states to ameliorate severely disturbed wet sites (Aust, 1994). However, this site hydrology study did not show bedding amelioration effects on disturbed site hydrology. Miwa et al. (1998) also indicated that bedding site preparation did not ameliorate disturbed subsurface soils that might have significant effects on near-surface water flow. These indicated that the main benefit of bedding in wet sites was not soil amelioration, but increasing aerated soil volume to improve seedling survival and early growth.

Evaluation of predicted surface water levels indicated that micro- and mesotopography, soil, and precipitation pattern during growing season had significant influences on microsite hydrology. Evaluating these results using the 1991 Wetland Delineation Manual proposed revisions suggested that the wetland hydrology criteria were difficult to apply in wet pine flats because of the complex, subtle, mosaic pattern of site hydrology.

Overall, these results suggested the following major implications:

1. Wet-weather harvesting and bedding site preparation alter microsite hydrology, but overall site hydrology may not be affected. These results are important because the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency have expressed concern about whether forest harvesting and site preparation activities may alter the hydrology within jurisdictional wetlands. These findings support the maintenance of the exemption for forestry operations within wetland areas.
2. Local depressional areas may become wetter. Westvaco and other corporate land managers in the region have already recognized that up to 10% of the land areas

within these wet flat areas are localized depressions, known as “gum ponds.” Their current site preparation prescriptions are to avoid such areas and to allow natural regeneration to establish hardwood communities. As these depressional areas become wetter they will probably revert to wetter-site species such as swamp tupelo (*Nyssa aquatica* L.) and pond cypress (*Taxodium disticum* (L.) Rich.). These communities may be important for maintaining a diversity of habitat types across an area that is intensively managed for loblolly pine.

3. Wetland delineation requires determination of the hydrological criteria. This is very difficult during the stand establishment period because of the temporarily increased water table and microsite variability. The delineation process needs to be modified so that differences in evapotranspiration among different species and stand ages can be accounted for in the delineation process.
4. Yearly differences in hydroperiods within the same treatment area accentuate the difficulties of characterizing wetland hydrology for delineation purposes. The delineation process should be modified to include the use of long-term soil and surface water data for wetland determinations whenever the other two criteria are not clearly indicative of wetland status.

CHAPTER VII
SUMMARY AND CONCLUSIONS

This study was conducted to evaluate forest harvesting and site preparation effects on forest soils, site hydrology, and overall water balance of Southeastern Lower Coastal Plain wet pine flats. The results revealed that the hydrologic responses were site- and operation-specific, and that the hydrologic processes were complex.

Dry-weather harvesting had little effect on overall soil physical properties and surface water levels (partially failed to reject $H_0$1-1 and 2-1). Soil disturbance classification analysis indicated that dry-weather harvesting plots consisted primarily of undisturbed and compression track areas where water level changes were minimally affected by soil disturbances (partially failed to reject $H_0$3-1). Although surface water levels were generally higher at all harvesting sites because of the low transpiration rate, soil water storage characterization indicated that surface water storage of dry-weather harvesting sites has frequent fluctuations. These results suggested that if a site is not a localized low-lying flat area or "gum-pond," dry-weather harvesting with no bedding site preparation would be an economical forest management option for non-industrial, private forest owners. Although this method might not maximize plant growth because of relatively high average surface water level, the frequently aerated surface soil combined with abundant water could support adequate plant growth.

Wet-weather harvesting created widespread, highly disturbed areas and altered soil physical properties; consequently, site hydrology was altered (partially rejected $H_0$1-1, 2-1, and 3-1). Soil disturbance classification analysis and spatial characterization of the hydraulic gradient indicated that large areas of wet-weather harvesting plots were disturbed by harvesting due to the creation of rough surface topography, such as deep rutting and churning, in the plots. Severely disturbed layers in deep ruts (Ad horizons) had extremely low hydraulic conductivity; thus, the rough surface topography caused low infiltration, slow surface water drainage, and high surface water level.

Soil disturbance also altered subsurface soil physical properties (partially rejected $H_0$1-1). Soil profile descriptions of subsurface soil horizons showed that all disturbed soils consisted of compacted subsurface horizons (Bd) and/or structureless reduced subsurface horizons (Bdg). Macropores in the horizons were compressed and disconnected, structures of the horizons were severely disturbed, and hydraulic properties of the horizons were significantly decreased. These soil properties indicated that these horizons were an impermeable layer that caused high surface water levels (partially rejected $H_0$3-1). Continuously wet, disturbed soil is generally undesirable for plant growth. Therefore, wet-weather harvesting should be avoided, especially on low-lying areas and at the feet of hillslopes where surface water of the surrounding area drains.

Soil physical properties of the surface horizons (Ap) were not negatively altered by harvesting and site preparation because surface soil disturbance incorporated large amounts of organic matter and coarse organic debris in the horizon (partially failed to reject $H_0$1-1). This incorporation tended to offset the more negative aspects of trafficking.

Natural amelioration enhanced recovery of soil physical properties and site hydrology in the upper soil horizons because of frequent wet-dry cycle and higher biological activity (partially rejected $H_0$1-3). Soil profile descriptions and physical property analyses showed that disturbed surface soil layers in deep ruts (Ad horizon) were naturally ameliorated within two years of the disturbance. Amelioration was probably due to the wetting and drying cycles that caused the soil to shrink and swell and because of the cyclic aeration that provided suitable condition for aerobic and anaerobic biological activities. These results indicated that disturbed soil could be quickly ameliorated if the soils were exposed to frequent wet-dry cycles and aerated to enhance biological activities.

Disturbed subsurface horizons were not ameliorated by either natural processes or artificial ameliorative techniques (partially failed to reject $H_0$1-2 and 1-3). The disturbed subsurface horizons were saturated for extended periods; therefore, the process was slowed. Conventional site preparation techniques do not extend deep enough into the soil profile to reach the disturbed subsurface horizon; therefore, site preparation does little to alter physical properties of the deeper horizons. In fact, frequent traffic on the soil may induce soil compacting processes. These disturbed subsurface horizons might increase surface water level for a long period.

Bedding is a common site preparation technique for amelioration of severely disturbed, wet sites, and it has been widely recommended as an appropriate forestry BMP in many southeastern states. However, this study found that bedding had minimal direct effects on the surface soil physical properties, since the disturbed surface horizons were already mixed with organic matter, and bedding site preparation did not ameliorate subsurface soil physical properties (failed to reject $H_0$1-2). These results suggested that alternative site preparation techniques or deeper tillage (bedding) should be used to increase the aerated period and enhance natural amelioration processes.

Bedding site preparation was, however, effective in accelerating surface soil drying processes by increasing exposed soil surface areas, which increases evaporation from the soil surface (rejected $H_0$2-2 and 3-2). Characterization of surface water storage change showed repeated, large fluctuations of surface water storage in the bedded plots. This indicated that bedded surface soils provided good growing conditions for plants: large volumes of aerated soils and abundant water supplies during the growing season. Therefore, bedding site preparation is probably the best current solution for disturbed and wet-site preparation. Tall beds or mounding should be beneficial for wet-site preparation.

Harvesting and bedding site preparation significantly altered microsite hydrology (rejected $H_0$3-3 and 3-5), but overall site hydrology might not be affected (failed to reject $H_0$3-4 and 3-6). Hydraulic gradient characterization and multivariate cluster analysis indicated that harvesting and bedding significantly altered microtopography, surface water flow patterns, and microsite hydrology within the harvested and site-prepared sites. However, no significant differences of hydraulic gradient vector length and relatively small surface water outflow vectors indicated that overall site hydrology was minimally altered.

Although multivariate classification analysis showed significant wet-weather harvesting effects on microsite hydrology, the predicted surface water level evaluation did not show clear wet-weather harvesting effects on microsite wetland status (failed to reject $H_0$3-7). This was probably caused by other environmental effects, such as microtopography, landscape position, and precipitation pattern, which had stronger influences on site hydrology than harvesting. This suggested that forest managers may need to devote more attention to the microsite and landscape physical conditions of wet pine flats besides the operation timing and technique.

Multivariate classification analysis and predicted surface water level evaluation also showed bedding effects on microsite. Bedding decreased surface water level on elevated areas and increased surface water level within localized depressional areas (rejected $H_0$3-8). These results probably coincide with the significant alteration of site hydrology by bedding site preparation. Apparently, bedding quickly drained surface water from elevated areas, allowing it to quickly pond in depressional areas. These results suggested that an elevated and relatively dry area might lose more water with bedding site preparation. Therefore, these areas might not need bedding site preparation. Indeed, bedding in these areas may cause excessive drying, which could be detrimental for plant growth. On the other hand, severely disturbed, poorly drained areas should be site-prepared in order to create aerated soils, because these areas experience prolonged wet conditions.

In order to prevent negative bedding effects and maximize site productivity, different site preparation techniques could be utilized. Relatively elevated, drier areas could be site-prepared with low beds, small mounds, or disking. Slopes between elevated areas and low-lying areas could be site-prepared with contour bedding to prevent drainage effects. Depressional areas should be site-prepared with tall beds or mounding.

Overall hydrology characterization indicated that the water balance of wet pine flats was relatively stable. Annual surface soil water storage change of the study site was very small (failed to reject $H_0$2-4). Total annual precipitation and potential evapotranspiration in southeastern South Carolina were typically 1200 to 1300 mm and 1000+ mm, respectively. These forests received about 80% of their total annual precipitation during the growing season, when evapotranspiration demand was also high. These seasonal precipitation and evapotranspiration patterns were beneficial for plant growth because plants would receive abundant water and energy for their growth.

Slightly different annual water balance among blocks indicated that water balance of wet pine flats varied by location, and these differences were probably caused by topographical and geological settings. Harvesting and site preparation also had a significant effect on the annual water balance because wet-weather harvesting and bedding significantly altered surface water levels (rejected $H_0$3-1 and 3-2).

Surface water and groundwater were separated by a thick, heavy clay argillic (Bt) horizon. Groundwater head of the study site was constantly high during the study period, but surface water level fluctuated widely due to precipitation and evapotranspiration.

This study result indicated that groundwater in- or outflow rate was determined by surface water level, and a significant amount of water could be supplied from groundwater when surface water became low (rejected $H_0$2-3). This probably explains that relatively high forest productivity at the study site was supported by the abundant water supply through groundwater and precipitation.

High evapotranspiration demands of the mature forest caused significantly higher surface soil fluctuation and relatively low surface water level. This low water level increased groundwater inflow and lateral surface water movement. Apparently, large amounts of surface water flowed into non-harvested, mature stands from adjacent harvested areas because of high hydraulic gradient. This active pumping effect of the mature stand may be utilized to withdraw excess water from an adjacent harvested area to decrease the surface water table. Although the effective distance of the pumping effect has not been quantified, this may be achieved by small, narrow, and/or irregular shaped harvested areas. Additionally, bedding could be used to direct surface water toward adjacent forest stands, since bedding significantly alters the direction of surface water movement.

Determination of wetland hydrologic criteria during the stand establishment period was very difficult because evaluation of predicted surface water level indicated that site hydrology of wet pine flats was significantly affected by micro- and mesotopography, soil, and precipitation pattern during growing season. The delineation process needs to be modified so that differences in evapotranspiration among different species and stand ages, and precipitation pattern differences can be accounted for in the delineation process. Hydrologic characterization of the Southeastern Lower Coastal Plain loblolly pine plantation to forest harvesting and site preparation indicated that forest operations could have significant impacts on forest soils and site hydrology. Even though wet pine flats appear to be flat and homogeneous, forest operation impacts vary by spatial variation of a site. Additionally, those soil and hydrologic alterations are affected by more dynamic, long-term natural changes. Although it is difficult to predict the effects of a long-term shift of wet pine flat soil and hydrology, this short-term study suggested that the increased surface water level will be decreased, disturbed soil structure will be ameliorated, and altered site hydrology will be stabilized over time. Evapotranspiration of mature stands exhibited high water demand, and the demand decreased the surface water level. This indicated that the increased surface water level of the harvested sites will be lowered as planted trees grow and start demanding more water. As surface water level decreases, subsurface soils will be aerated more frequently and increase biological activity, including root growth and micro- and macrofauna. Disturbed subsurface soil structure and site hydrology would be ameliorated by these processes.

Sandy surface soil, clayey subsurface soil, flat topography, relatively high precipitation and evapotranspiration rates during the growing season are common features of the Southeastern Lower Coastal Plain wet pine flat forests. Therefore, these study results would be applicable for a wide range of wet pine flat forests because similar soil physical and hydrological processes occur.

Although wet pine flats appear to be highly resilient systems, the forests should be managed with the best possible management practices to sustain long-term site productivity. Many studies have shown that organic matter losses and soil compaction that are induced by intensive forestry practices cause decreases in site productivity. Certainly, severe soil disturbances which have been observed in the region have caused stand establishment failures and slow recovery of disturbed soils. These research results strongly suggest that forest managers should minimize soil disturbances and should use site preparation to enhance seedling survival and growth.

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VITA: Masato Miwa

The author was born in Tokyo, Japan, in 1962. He grew up in Kokubunji, Tokyo, and Iruma, Saitama, where he graduated from Hanno High School in March 1980. He came to the United States on October 12, 1986, and completed the Intensive English Language Program at the University of Arkansas at Little Rock on August, 1987. He received the Associate of Arts degree in General Education from Central Baptist College, Conway, Arkansas, in May 1989, the Bachelor of Science degree in Forestry from the University of Arkansas at Monticello in May 1991, and the Master of Science degree in Forestry from Mississippi State University in December 1993, with emphasis on soils and bottomland hardwood regeneration. In August 1999, he received a Ph.D. in Forestry from Virginia Polytechnic Institute and State University, with emphasis on wetland hydrology and soils. He is a member of the Soil Science Society of America, Society of Wetland Scientists, and Society of American Foresters. He is currently employed by the Department of Forestry, Virginia Polytechnic Institute and State University, as a Postdoctoral Associate, and is investigating hydrologic processes and functions of various lower coastal plain wetland systems.