

WATERSHED RESPONSE TO LONGLEAF PINE RESTORATION— APPLICATION OF PAIRED WATERSHEDS ON THE SANTEE EXPERIMENTAL FOREST

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Abstract—Restoration of longleaf pine (LLP) is a prominent land management objective throughout the Southeastern United States. Several recent tree- and plot-scale studies suggest that water yield from LLP-dominated landscapes may increase relative to loblolly or mixed pine hardwoods due to differences in stand structure and the higher water use efficiency of LLP. Here we present a new long-term, watershed scale study to test those hypotheses, whereby a watershed dominated by loblolly pine is being restored to LLP using operational silvicultural treatments. We are using a paired watershed approach at the Santee Experimental Forest in South Carolina. Hydrologic responses are being measured using established and new stations for monitoring rainfall, climate, water table, soil moisture, stream flow, and water quality. Vegetation and soil responses will be determined through longitudinal assessment of established inventory plots. Simulation models are being used to guide field data collection and projecting long term hydrological responses under multiple scenarios. This study was implemented in 2018 with the baseline assessment, and the treatments will be installed in 2019-2020.

INTRODUCTION

Restoration of longleaf pine (*Pinus palustris*) ecosystems is a prominent land management objective throughout the Southeastern United States, and it is the principal goal described in the recently approved Forest Plan for the Francis Marion National Forest. While there have been numerous studies regarding the longleaf pine (LLP) ecology, silviculture, and the associated responses of ecosystem services (Samuelson and others 2012), there are major uncertainties regarding the effects of watershed-scale restoration on the hydrology and carbon balance (Brantley and others 2018). The linkage between watershed-scale LLP restoration and hydrologic and biogeochemical processes is particularly important as regional considerations on water resource management and carbon sequestration expand (Brantley and others 2018). In contrast to loblolly pine (*Pinus taeda* L.) stands, LLP stands have a much lower stocking with the understory generally dominated by grasses and sedges, potentially influencing on both soil moisture and water uptake as well as above- and below-ground carbon balance. As a result of these differences in stand structure and composition, it may be expected that LLP stands will exhibit less rainfall canopy interception loss and more infiltration of precipitation. Additionally, studies examining the water use of LLP stands

suggest that they consume less water through transpiration than loblolly due to both the lower stocking and reduced water use to support its metabolic functions (Ford and others 2004, Gonzalez-Benecke and others 2011, McLaughlin and others 2013, Vose and others 2003). Based on leaf physiological traits from a 1-year study comparing longleaf to loblolly and slash pine forest stands in a lower Mississippi valley site, Samuelson and others (2012) concluded that their results do not support the contention that LLP has a more conservative leaf water use strategy than the other two pine species. However, those studies have been done on individual trees or small field plots, hence there is considerable uncertainty scaling those responses to a watershed, due in large part to the spatial heterogeneity of soil conditions, micro-topography, interactions between overstory and understory vegetation in water use competition. Watershed hydrological responses to forest disturbances such as fires and thinning, are scale dependent (Hallema and others 2018; Liu and others 2018). Nonetheless, Lockaby and others (2013) suggested restoring LLP could be a management strategy to increase water yield from forested landscapes.

Paired watershed studies provide the basis to assess hydrologic responses to land management treatments. The paired watershed approach, where two neighboring

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watersheds (one reference and one treatment) are monitored concurrently during calibration (pre-treatment) and post-treatment periods (Clausen and Spooner 1993, Jayakaran and others 2014, Loftis and others 2001, Ssegane and others 2013), has been extensively used to assess effects of silvicultural practices on water yield, other hydrologic variables and ecosystem services (Bliss and Comerford 2002, Bosch and Hewlett 1982, Brown and others 2005, Tomer and Schilling 2009). This approach is used primarily on 1st order watersheds (Bren and Lane 2014) although its applicability for predicting effects on flood events on larger systems has been challenged (Alila and others 2009).

Our objective is to implement a watershed-scale study that incorporates silvicultural treatments for restoring LLP that are typical of the lower coastal plain to address important questions regarding the effects on water resources, forest carbon stocks, and ecosystem services. The principal hypothesis guiding this study is that LLP restoration will result in an increase in water yield from the watershed. The approach for this study is to utilize the paired watershed monitoring complemented by modeling on the Santee Experimental Forest, which is located within the Francis Marion National Forest, near Charleston, SC. The following is an overview of the new study that was initiated in 2018.

EXPERIMENTAL APPROACH

The Watersheds

Paired watersheds on the Santee Experimental Forest (SEF) that have been gauged since the 1960s are used in this study. The treatment watershed (WS-77) is a 155 ha 1st order watershed, that is paired with a 160 ha reference watershed (WS-80). These are parts of the headwaters of Huger Creek, a 4th order stream (fig. 1), which is a major tributary of East Branch of Cooper River that drains into to Charleston Harbor. This low-gradient watershed with elevations ranging from about 9.75 m towards the northwest to about 5.79 m at the outlet drains into Fox Gulley Creek via 1.26 km long stream further down to Turkey Creek, a tributary of Huger Creek. The vegetation on WS-77 is dominated by loblolly pine, a result of the earlier silvicultural research in the late 1970s. In contrast the vegetation on WS-80 is a mixed hardwood-pine forest, a result of natural regeneration following the large-scale blow-down of the forest during Hurricane Hugo (September, 1989). Soils on the watersheds are poorly to moderately-well drained sandy clay loam surface soil overlaying clay that are typified by the Wahee and Craven soil series in the uplands and the Megget and Betheera soils in the riparian zones (fig. 2). The climate is warm-humid temperate, with average daily temperature of 17.8 °C and annual rainfall

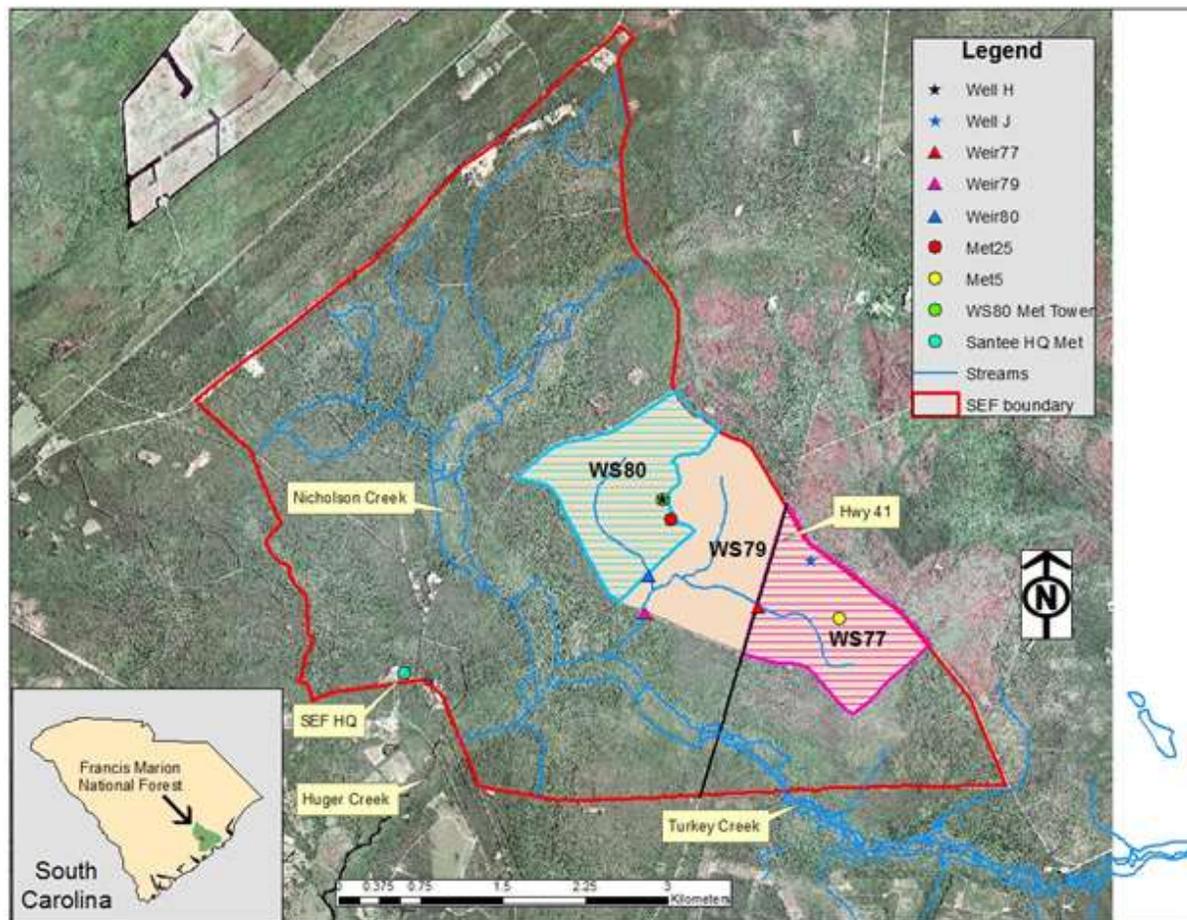


Figure 1—Location and layout of Santee Experimental Forest showing the experimental watersheds WS77 (study site) with the control WS80 in the paired system, SC.

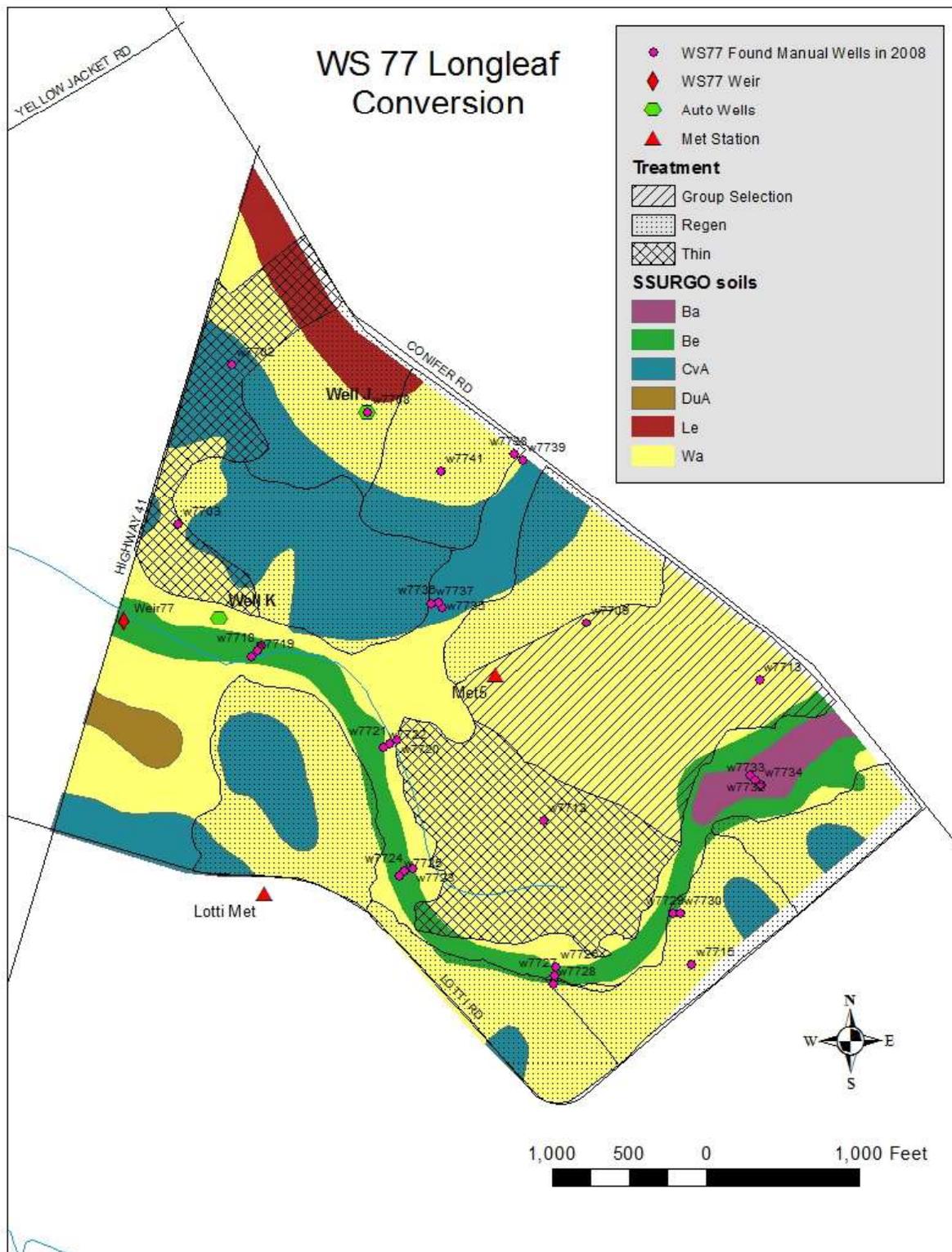


Figure 2—Distribution of soil types and existing vegetation shown together with proposed treatments for longleaf pine regeneration on WS77. Shown also are various monitoring stations on the watershed.

of about 1370 mm. More details on the watersheds are described by Harder and others (2007), Amoah and others (2012), and Dai and others (2013).

An attribute of this study is that the WS-77 and WS-80 have been used for paired watershed analyses since the late 1960s. Accordingly, there's a long-term record to support the comparative analyses for this study. During early calibration (1969-1976), a statistically significant relationship between monthly flow was established between control and treatment watersheds (Binstock 1978) to evaluate effects of partial prescribed burning from 1976-1980 (Richter and others 1983). That relationship reversed for 10 years following Hurricane Hugo, in 1989, in response to the significant stand damage (Hook and others 1991), and then returned to the pre-hurricane disturbance pattern by 2004, following stand recovery (Jayakaran and others 2014).

A recent summary of measured annual rainfall and streamflow for the watersheds WS-77 and WS-80 is presented in table 1, in addition to annual Penman-Monteith (P-M) potential evapotranspiration (PET) estimated for WS-80 using data

from the tower weather station (fig. 1) for 2011 to 2017. The mean runoff of coefficient values observed in recent period (table 1) are similar to those reported for the historic period before Hurricane Hugo (Amatya and others 2006). The relationship between the WS-77 and WS-80 are shown in figure 3. For: (A) storm event outflow for pre- and Post-Hugo periods, (B) post-Hugo regression of daily flows (red line) compared against the pre-Hugo (dashed blue line) period for the same frequencies, and (C) monthly streamflow for the 2004-2017 post-Hugo period. Both the event outflow and daily flow (figs. 3A and 3B) indicate that the post-Hugo relationships with data from 2004-2013 are quite similar with no significant difference with the 1969-1978 pre-Hugo relationship, indicating a full hydrologic recovery. Therefore, the post-Hugo monthly relationship between the paired watersheds obtained with daily data extended through 2017 shown in figure 2C is proposed to be used as pre-treatment relationship to examine the watershed-scale effects on monthly water yield. The effect will be evaluated by comparing the mean measured monthly flow from WS-77 with the mean of expected monthly values from the treatment, had it not been disturbed.

Table 1—Measured annual rainfall, streamflow and runoff coefficient (ROC for Watershed 77, 80, and estimated annual Penman-Monteith potential evapotranspiration (P-M PET) for 2011-2017

Year	Watershed 80			Watershed 77			P-M PET <i>mm</i>
	Rainfall <i>mm</i>	Flow <i>mm</i>	ROC	Rainfall <i>mm</i>	Flow <i>mm</i>	ROC	
2011	934	31	0.03	977	58	0.06	1351
2012	1174	28	0.02	1148	59	0.05	1239
2013	1433	219	0.15	1502	350	0.23	1017
2014	1375	199	0.14	1340	305	0.23	1123
2015	2171	967	0.44	2146	948	0.44	1098
2016	1743	556	0.32	1709	590	0.34	1197
2017	1443	217	0.15	1555	421	0.27	1254

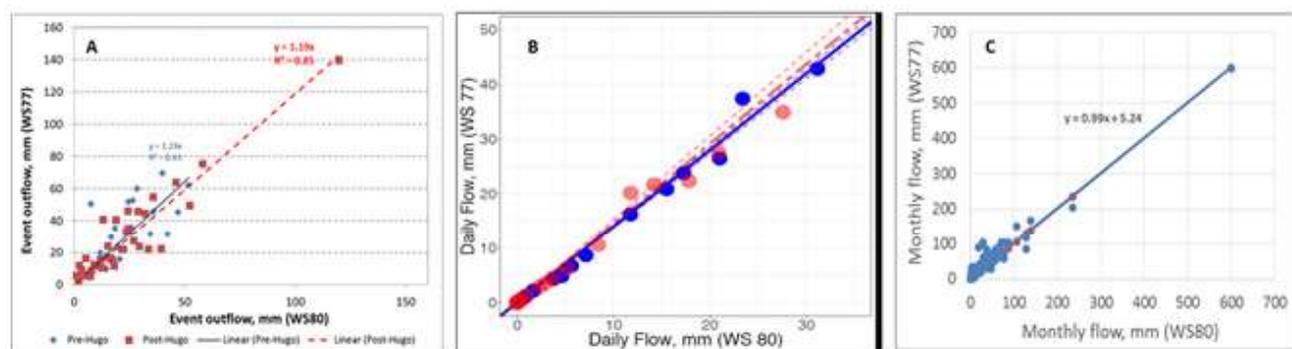


Figure 3—Relationships between the treatment (WS77) and the reference (WS80) for (A) storm event outflow for pre- and post-Hugo periods, (B) post-Hugo regression of daily flows (red line) compared against the pre-Hugo (dashed blue line) period for the same frequencies, and (C) monthly streamflow for the 2004-2017 post-Hugo period.

Treatment Design

Utilization of operational silvicultural practices of the Francis Marion National Forest is implicit to the objective of this study. Accordingly, three practices are routinely considered to initiate changes in the forest composition and structure to establish a LLP forest, (a) clear-cut followed by replanting (i.e., regeneration), (b) thinning, and (c) group selection.

(a) Regeneration cut: This treatment is used where there isn't a basis for natural regeneration of LLP. Existing forest stands are clear-cut (approximately 56 ha), followed by flat planting LLP seedlings on 3 x 3 m grid. (b) Thinning: In stands that have some LLP present (approximately 65 ha), thinning provides the capability to retain an overstory canopy and foraging trees for the red cockaded woodpecker (*Picoides borealis*), while providing conditions that are favorable for LLP regeneration. The stocking of the current stand is reduced to approximately 15 m² ha⁻¹ (60 square feet per acre) of basal area. (c) Group Selection: This is a hybrid approach suited to areas without LLP; in this system the small openings are clear-cut with the balance of the forest thinned (approximately 20 ha). Accordingly, the thinned stand is reduced to a basal area of 15 m² ha⁻¹ (60 square feet per acre) and the clear-cut patches are planted on a 3 x 3 m spacing.

These three treatments were allocated to WS-77 based on the composition of the existing forest, resulting in about 73 percent of the watershed being manipulated (fig. 2), resulting in the watershed being a mosaic of young LLP, mature loblolly pine, and bottomland hardwoods. South Carolina Best Management Practices were used in the treatment layout; as a result the riparian zones are not harvested and remain as bottomland hardwoods. To prepare the watershed for harvesting, a prescribed fire was conducted in March, 2018. Following the harvest, which will occur in 2019-2020, another prescribed fire will be used to reduce logging residue. The site will be planted during the winter following the post-harvest fire.

Experimental Design and Analyses

The paired watershed approach provides the design framework for this study for addressing the hydrological responses associated with LLP restoration of WS-77 with respect to the short- and long-term effects on seasonal and annual water yield, flow frequency duration, and storm event hydrograph parameters. We will utilize the 2004-2018 as the baseline calibration period for comparing watershed responses. The relationships from this long-term baseline should provide a sensitive basis for detecting changes in WS-77 relative to the reference watershed. It is also important to note that this baseline period includes several extreme precipitation events that occurred in the region in October 2015 and 2016 and September 2017, and also dry periods of 2007, 2011, and 2012, thereby providing a robust basis for accommodating the influences of extreme events during the treatment assessment period.

Quantification of the watershed-scale assessment of effects of restoration on water and carbon yield on the treatment watershed (WS-77) will be conducted by constructing seasonal and annual budgets for pre- and post-treatment conditions based on measurements of hydro-meteorological variables and nutrients, dissolved organic carbon (DOC), soil C, and biomass.

Since long-term continuous monitoring is resource restricted, we also intend to use validated hydrologic models to further understand process interactions and evaluate impacts of various management treatments. Earlier studies using the process-based MIKE SHE (DHI 2005) model that simulates ET, infiltration, unsaturated flow, saturated flow, and overland flow for predictions of water table depth and streamflow on the watersheds at Santee Experimental Forest (SEF) within the Francis Marion National Forest (FMNF) were found more satisfactory (Dai and others 2010, 2013) than the quasi-physically based DRAINMOD (Skaggs 1978) model WS-80 (Harder and others 2007) and WS-77 (Amoah and others 2012). MIKE SHE will be used to test the sensitivity of various management and climate scenarios beyond the treatments implemented in WS-77. The modeling will be able to project for short term and long term (full stand rotation) effects of conversions to LLP. We expect that it may take at least 20 years before the watershed-scale effects of the LLP restoration on the water budget can be affirmed experimentally. However, during that time data will be used to validate and advance the application of simulation models for characterizing the response to the restoration treatments.

Monitoring and Measurements

Hydro-meteorologic monitoring—The established hydrology and climate monitoring stations on the SEF will be used to support the monitoring for this study. Those stations include a full meteorological station at the SEF headquarters (approximately 2 km from WS-77), an above-canopy meteorological station on WS-80, and three field precipitation stations within the watersheds that also include air and soil temperature. Stream flow is measured at the outlet weirs, and water quality samples are obtained using flow proportional sampling. Water table depth within the watersheds are monitored in wells selected to represent the network of manual wells that were established in 1991 (fig. 4). Those wells are being augmented to provide measurements of the restoration treatments on the dominant soils (e.g., Wahee, Craven). For details on the historic rainfall, streamflow, water quality, and weather data collected on the paired watersheds since 1964 see descriptions by Binstock (1978), Richter (1983), Amatya and others (2006), Dai and others (2013).

Vegetation and soil monitoring—Both WS-77 and WS-80 have a network of forest inventory plots (0.04 ha) that were systematically distributed across the watersheds in 1991. A subset of those plots have been selected to provide a basis for assessing the stand treatment effects on the two major soil types (Wahee and Craven) (fig. 4). On each of those plots tree and ground layer vegetation were measured in May-July,

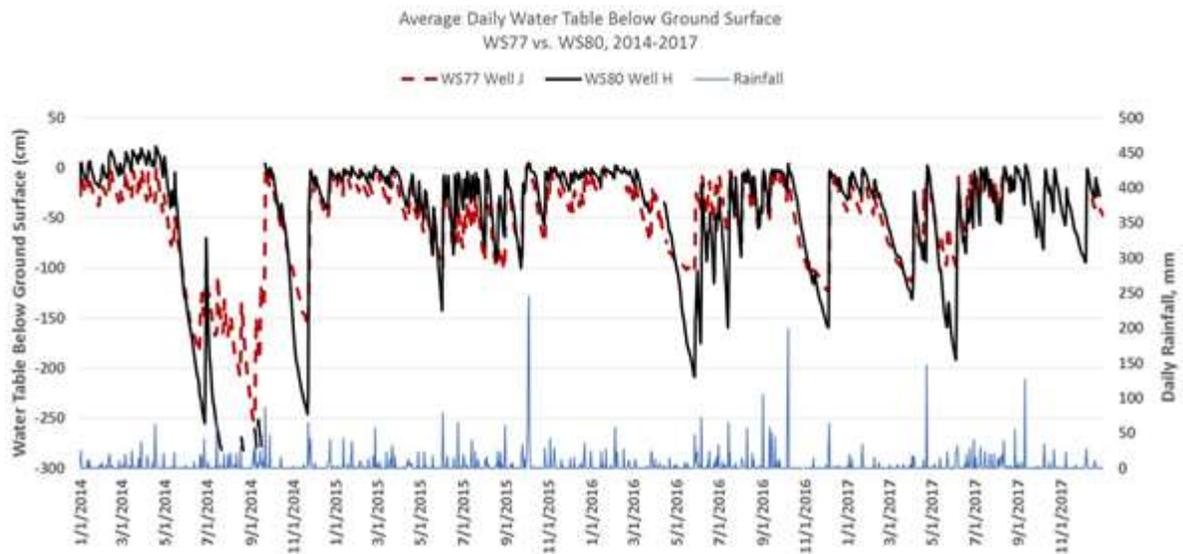


Figure 4—Water table depth below soil surface on the treatment (WS-77) and reference (WS-80) watersheds, and rainfall for 2014-2017.

2018, to provide a baseline on the forest structure and species composition. Soils were also objectively sampled on each plot to a depth of 1 m to provide a baseline on physical and chemical properties. The intent is to utilize these plots as a basis for assessing changes in vegetation and soil properties associated with the conversion process and subsequent stand development.

Change in soil water storage is a major factor in determining whether LLP affects the stand water balance and hydrologic response to storm events. To support the associated assessments, shallow ground water wells (2.5-3.0 m) and soil moisture monitoring stations are being installed on the stand treatments and major soil types. Where practical, existing wells are being utilized, however several new wells have been installed. Each of the wells is instrumented with a WL-16 water level logger. Each of those sites will also be instrumented with a Stevens Hydra soil moisture monitoring station, configured to measure 3 depths (30, 60, 90 cm) at two locations within a 20 m radius of the station.

Leaf area index (LAI) is another parameter that is closely associated with plant water use and carbon dynamics. While the SEF does not routinely monitor LAI of the watersheds, plans are to collect a 12 month pretreatment baseline using a Licor LAI2000, and then maintain monthly measurements through the conversion process in order to characterize the redistribution of LAI across the watershed as a result of the treatments and the subsequent stand development.

Data Analyses

Climatic and streamflow data together with the soil moisture data will be analyzed to quantify the water balance on both watersheds. All climatic data will be processed for estimating daily/monthly, and annual Penman-Monteith (P-M) potential evapotranspiration (PET) for a forest reference. Water table

data together with soil drainable porosity will also be used to assess changes in soil water storage. Seasonal rainfall-runoff relationships will be established to examine seasonal runoff coefficient (ROC-as percentage of rainfall that leaves the watershed as streamflow), and water balance for pre- and post-treatment years will be analyzed for detecting seasonal changes in water yield and evapotranspiration (ET), if any. Event-based analyses will consider the conversion treatment's effects on storm runoff and its characteristics.

The watershed water budget for a period of interest will be constructed as follows:

$$\pm\Delta S = P - O - ET \quad (1)$$

where

ΔS = change in soil water storage (mm) for a given period

P = total precipitation (mm) for the period

O = total streamflow (mm) for the period

ET = evapotranspiration (mm) for the period.

For the selected periods when water table is at or very near surface at the beginning and the ending period ΔS can be assumed negligible (zero), leaving the ET for the period as

$$ET = P - O \quad (2)$$

Since ET is generally near the potential ET (PET) for saturated conditions with water table near the surface, the ET calculated by equation 2 will be verified against the estimated

PET also, besides verifying with ET calculated by equation 1 where ΔS is calculated as average soil moisture measured on replicated stands/soils.

Daily stand level ET will be estimated using equation 1 where ΔS is obtained from the soil moisture and water table data. The estimate will also be checked following the method of Fisher and others (2005) that uses estimated PET, soil field capacity (FC) determined from soil water retention data to be obtained from laboratory analysis of undisturbed field soil core samples, and measured soil moisture (SM). The method assumes daily ET approximating PET when the SM equals or exceeds the FC otherwise ET is reduced by the ratio of SM/FC. In the absence of soil moisture data for any period, change in soil water storage may also be approximated using volume drained versus water table depth relationship also to be obtained using soil water retention data and saturated hydraulic conductivity measured in the field or laboratory (Harder and others 2007).

Seasonal regression relationships of streamflow (water yield) between the watersheds using long-term pre-treatment data (2004-2018) will be established as discussed above. For the initial hydrologic response analyses that reflects the stand conversion step, regression parameters of relationship will be compared against the one to be obtained from streamflow data soon after treatment (2019-21). Similarly storm hydrograph and water table responses will be assessed during the conversion process.

Model Applications

A key component of this study is model applications. The empirically based findings assessing ecosystem responses to the LLP restoration may not be mature for at least two decades. Hence the application of hydrologic and ecosystem models afford the opportunity to (a) simulate responses based on anticipated conditions of the restored LLP forest, and (b) test the applicability of models to describe the conversion process. The opportunities for modeling applications on the SEF are particularly rich given the long-term data record on the watersheds and existing simulation results from previous studies (Dai and others 2013).

The initial phase of modeling will focus on the application of the MIKESHE model to simulate the hydrologic response during the conversion processes and the anticipated changes when the LLP is well established (e.g., > 20 years). The pre-stand conversion portion of that simulation will be validated with pre-treatment (2004 - 2018) water table and streamflow data. Subsequent monitoring (e.g., 2019-2021) will be used to validate the watershed-scale hydrologic responses during the conversion process. A multi-criterion validation will be used with distributed soil moisture and water table data to affirm confidence on the model's internal structure and capability to predict hydrology on a distributed watershed-scale. Such a validated model then can be applied to assess the long-term effects of LLP restoration on watershed hydrology of the study watershed and larger similar watersheds

within the region. We will also encourage the application of other watershed hydrologic models to provide a basis of comparison.

Spatially distributed daily water table information is needed to simulate the carbon and greenhouse gas dynamics of these forested watersheds that are characterized by low relief and a significant proportion of wetlands (Dai and others 2011). Accordingly, our intent will be to use Forest DNDC, a process based forest biogeochemical model, in a linked modeling framework with the simulated hydrology to predict changes in forest and soil carbon stocks and greenhouse gas fluxes. As noted for the hydrologic modeling, we will encourage applications of other forest biogeochemical models including DRAINMOD-Forest (Tian and others 2012).

PERSPECTIVES

Paired watershed studies have been used for decades to assess the cumulative effects of forest stand management practices on hydrologic processes and the associated interactions with soils and vegetation. Accordingly, it is the most suitable approach, when a stable and statistically significant relationship (Ssegane and others 2013) exists, to assess how the myriad factors that cumulatively affect water yield will manifest at the watershed scale. While the basic question regarding water yield will be answered through the stream discharge measurements, the real value of this study will be realized through analyses of the regulating factors, particularly the soil moisture, so that the response can be interpreted mechanistically. Accordingly, careful consideration of ET from the tree canopy layer and ground vegetation layer is fundamental.

The initial decade of this study will address the stand conversion phase of the restoration treatment, which is analogous to many other hydrologic response studies that have been conducted over the past 50 years. Accordingly, it presents the opportunity to thoroughly validate simulation tools for assessing hydrologic, vegetation, and soil responses, which should then provide a robust basis for applications in other areas of the Southeastern United States.

The value afforded by this long-term study will not be realized without a strong collaboration. There are a host of science and management related questions, driven by either measurements or modeling, which could be addressed through the application of the LLP restoration treatments, so we hope that this paper will help increase awareness of the opportunities potentially available for partners interested in this subject

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