EVALUATING WATERSHED-SCALE EFFECTS OF LONGLEAF PINE RESTORATION ON WATER YIELD USING A PAIRED WATERSHED AND MODELING APPROACHES

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EXTENDED ABSTRACT

Restoration of longleaf pine (LLP) (*Pinus palustris* Mill.) ecosystems is a public land management objective throughout the Southeastern United States, including the Francis Marion National Forest in South Carolina. While there have been numerous plot or stand-scale studies regarding LLP ecology, silviculture, and other ecosystem services (Samuelson and others 2012), there are uncertainties regarding the watershed-scale effects of re-establishing LLP forests due to the spatial heterogeneity of soil conditions, micro-topography, slope, and understory vegetation. In contrast to loblolly pine (*Pinus taeda* L.) (LP) stands managed for timber production, LLP stands managed for open canopy conditions with frequent prescribed fire have a much lower stocking, a longer period of open canopy, a sparse midstory, and an understory generally dominated by grasses and sedges, potentially influencing soil moisture and transpiration (Brantley and others 2018). As a result of these differences in stand structure and composition, it may be expected that the LLP stands will exhibit lower leaf area index (LAI), therefore, reduced interception loss and evapotranspiration (ET), and more infiltration of precipitation recharging groundwater and thus increasing water yield than LP stands managed for timber production. Thus, a careful examination of spatial characteristics of the watershed, including stand vegetation LAI, root depth, and albedo is fundamental for an accurate interpretation of the water yield (WY), as part of the LLP restoration experiment (Trettin and others 2019), which is using a paired watershed approach, where one control and one treatment are monitored concurrently during calibration (pre-treatment) and post-treatment periods (Amatya and others 2021, Jayakaran and others 2014, Loftis and others 2001, Ssegane and others 2013), backed also by a modeling approach (Amatya and others 2022) to assess effects of silvicultural practices on hydrology and WY.

The key objective of this study is to develop a calibration relationship between monthly WY of paired headwater watersheds [155-ha WS77 (treatment) and 160-ha WS80 (control)] that is statistically significant ($\alpha = 0.05$) with a predictive capability, in anticipation of a later study to assess the hydrologic response [WY and soil moisture (SM)] to restoring the LLP using the relationship backed by a watershed hydrologic modeling on Forest

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Service, U.S. Department of Agriculture, Santee Experimental Forest (SEF) in coastal South Carolina. (fig. 1A). The watersheds impacted by Hurricane Hugo in 1989 (Hook and others 1991) and regenerated since then was reported to start a full recovery from 2004 (Jayakaran and others 2014). The regenerated vegetation on WS77 and WS80 is dominated by LP and mixed hardwood-pine stands on WS80, respectively. Soils on the watersheds are poorly- to moderately-well drained sandy clay loam overlaying clay in the uplands and relatively wetter soils in the riparian zones (fig. 1B). The climate is warm-humid temperate, with average daily temperature of 17.8 °C and annual rainfall of about 1370 mm (Dai and others 2013). Daily rainfall, streamflow (runoff), and water table (WT), as a proxy of SM, measured on both the watersheds only from 2011 until 2019, as a pre-treatment period covering extreme wet and dry periods, were used for the analysis of paired annual difference in WY and monthly WY relationship, which was also compared with an earlier reported study (2004-2011 post-hurricane recovery periods) (Jayakaran and others 2014). Data has also been recently used for calibration of MIKE SHE hydrologic model (Amatya and others 2022). Both the historic and current hydrology and meteorology data for the WS77 and WS80 study sites are reported by Amatya and Trettin (2019) and Amatya and Trettin (2021), respectively.

Results showed annual runoff responses (flow and runoff coefficient [flow/rainfall]) with WS77 > WS80 in 2011-2019 with average annual WS80 ET > WS77 ET, as expected (table 1). Note the average annual ET of the WS80 (control) was very close to the PET, indicating no SM limitation. Similarly, the mean monthly runoff difference (WS80-WS77) of -6.80 mm was not significantly different ($p = 0.54$) from -3.89 mm for the 2004-2011 period, possibly indicating ongoing post-Hugo recovery (Amatya and others 2021). Monthly streamflow calibration relationship (WS77 = 1.15*WS80 + 3.70; $R^2 = 0.87$; $p < 0.0001$), excluding the extreme October 2015 event, for the 2011-2019 was highly significant and not different from the WS77 = 1.14*WS80 + 1.70 ($R^2 = 0.87$) for the 2004-2011 period. The model predicted monthly runoff which agreed well ($R^2 = 0.96$; Nash-Sutcliffe efficiency = 0.95 for all data and $R^2 = 0.89$; NSE = 0.82 after deleting two extreme events of October 2015 and 2016) with observed data (Amatya and others 2022). However, the daily WT predictions at a single well were not as satisfactory, especially in dry summer months with high ET demands. So, the model is also being tested with data from additional wells to test the possible heterogeneity-related discrepancies in soil hydraulic properties used from the adjacent control site (Dai and others 2010) (fig. 1A).

This study is important because it is the first to re-evaluate the paired watershed flow calibrations after a major natural disturbance. While the basic question regarding WY will be answered through the runoff measurements, the value of this study will be realized through analyses of the factors regulating the hydrologic responses, especially the SM of dominant soil types as well as the WT on them (Trettin and others 2019). Accordingly, SM sensors near WT wells are also being deployed on all treatments being implemented following the silvicultural treatments for LLP restoration (fig. 1B), which include regeneration cut (56 ha) retaining an overstory canopy and foraging trees for red cockaded woodpecker (*Picoides borealis)*, thinning (65 ha), and group selection (24 ha)—a hybrid approach suited to areas without LLP (fig. 1B). A 3m x 3m planting in early 2023 soon after a second prescribed burning is proposed (Trettin and others 2019). While 2020-2023 data will be used to examine post-treatment WY response and test the MIKE SHE model calibrated with pre-treatment data (Amatya and others 2021), the model will also be applied to simulate the hydrologic effects of restored LLP stands (reduced basal area/LAI) using future climatic projections for this region. However, lack of LAI, root depth, and albedo data for the LLP stands may likely influence the model predictions.

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Table 1—Measured annual rainfall, flow, runoff coefficient for the WS77 and WS80 watersheds

Year	WS80 Rainfall	WS80 Flow	WS80 ROC	WS80 ET	WS77 Rainfall	WS77 Flow	WS77 ROC	WS77 ET	WS80-Forest P-M PET
	mm	*mm*			*mm*	*mm*			*mm*
2011	934	31	0.03	903	977	58	0.06	920	1351
2012	1174	28	0.02	1146	1148	56	0.05	1092	1239
2013	1433	219	0.15	1214	1502	334	0.22	1168	1017
2014	1375	199	0.14	1176	1340	293	0.22	1047	1123
2015	2171	967	0.45	1204	2146	950	0.44	1196	1098
2016	1743	556	0.32	1187	1709	579	0.34	1131	1197
2017	1443	217	0.15	1226	1555	392	0.25	1163	1177
2018	1633	361	0.22	1272	1661	474	0.29	1187	1146
2019	1381	201	0.15	1180	1429	334	0.23	1095	1200
Average	**1476**	**309**	**0.19**	**1168**	**1496**	**385**	**0.23**	**1111**	**1172**
Standard deviation	351	294	0	105	339	272	0	87	94
COV	0.24	0.95	0.71	0.09	0.23	0.71	0.53	0.08	0.08

ROC = rainfall/flow; ET = rainfall–flow; COV = Coefficient of variance.
Penman-Monteith based PET for forest on WS80 is included (Amatya and Harrison 2016).

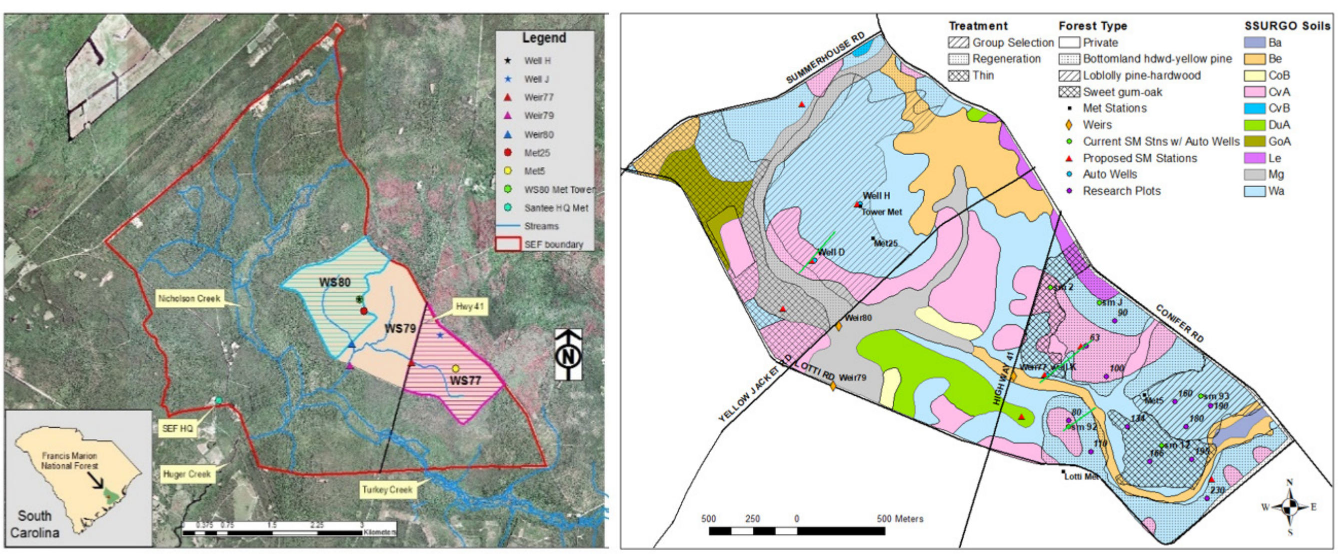

Figure 1—(A) Site map of Santee Experimental Forest with paired watersheds (WS77-treatment and WS80-control) in South Carolina, and (B) SSURGO Soil and forest vegetation types on WS77 and WS80 with locations of weirs (gauging stations), automatic (Auto) wells, and weather (Met) stations.

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