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Quantifying the Role of State and Private Forest Lands in Providing Surface Drinking Water Supply for the Southern United States

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ABSTRACT

Forests provide the most stable and highest quality water supplies among all land uses. The Southern United States is heavily forested, and most of the forests are owned and managed by State and private entities, thus it is critical to understand the role of forest lands in providing water across the region, the fastest growing in the Nation. We quantified surface water supply originating on State and private forest (SPF) lands in the 13 Southern States at the 12-digit Hydrologic Unit Code watershed scale, using the Water Supply Stress Index (WaSSI) hydrologic model. Water originating on seven forest ownership types was tracked through the river network and linked to a database of surface drinking water intakes to quantify the population served by water from SPF lands across the South. We found that the area of SPF lands was 44.2 percent of the total land area and that SPF lands contributed 44.3 percent of the 836 billion $\text{m}^3 \text{yr}^{-1}$ total available surface water supply in the region. Of the 7,582 surface drinking water intakes in the study area, 6,897 (91.0 percent) received some portion of their water from SPF lands, with 4,526 (65.6 percent) receiving >20 percent of their water from SPF lands. Approximately 55.3 million people in the South and 1.8 million people outside the 13 Southern States derived some portion of their surface water supply from SPF lands. These results highlight the importance of southern State and private forests in providing drinking water to downstream communities.

Keywords: Drinking water, hydrologic modeling, State and private forest lands, WaSSI, water supply, water yield.

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INTRODUCTION

Forests are known to provide the most stable and clean supply of water among all land uses (Brown and others 2008, 2016; Caldwell and others 2014; Vose 2019). Twenty-six percent of the total U.S. land area is forest land which contributes 46 percent of the total available water supply (Brown and others 2016). For more than a century, studies using paired watersheds and mathematical and modeling methods (Wei and others 2018, Zhang and others 2008, Zhao and others 2010) have demonstrated that losses in forest cover commonly result in increased water yield, while forest cover gains generally result in a decreased water yield (Caldwell and others 2016, Elliott and others 2017, Ford and others 2011) due to greater evapotranspiration (ET) rates in forests than other vegetation types and land covers (Sun and others 2011a). Results vary depending on the spatial scale, climate, forest type, and hydrological regime (Evaristo and McDonnell 2019, Filoso and others 2017, Zhang and others 2017). In addition to decreasing water yield (Brown and others 2005, Sun and others 2006, Zhao and others 2010), afforestation or reforestation can increase groundwater recharge, soil infiltration capacity, and water quality (Filoso and others 2017, Price and others 2010, Zhang and others 2008). Though forests transpire more water, they may increase baseflows in the dry season due to greater soil water storage (Krishnaswamy and others 2013, Price and others 2011). Research also shows that watersheds with greater forest coverage produce better water quality than watersheds with lesser forest coverage (Sun and others 2004, Tu 2013). Forest conversion to residential, commercial, and agricultural lands results in greater concentrations and exports of suspended sediments, nutrients, pesticides, and other toxins (Jackson and others 2017, Webster and others 2018). These water quality changes, along with increased summer temperatures, diminish aquatic species diversity (Frisch and others 2016). Given the many water-related benefits of forest lands, many water supply authorities seek to maintain forest lands in their contributing watersheds to protect water quality and minimize water treatment costs (Warziniack and others 2017).

Water availability influences local economies and human well-being, but population growth and climate change may upset the balance of water supply and demand in the future. The U.S. population doubled

DEFINITIONS

Water yield is the amount of excess water leaving a watershed as streamflow after accounting for losses that include changes in water storage in the soil, evaporation, and transpiration from vegetation. In this study, water yield is the depth to which a watershed (HUC12) would be covered if all of the streamflow were uniformly distributed over it. The unit of water yield is mm yr^{-1} .

Water supply is calculated by accumulating the water volume generated from each land cover type in the entire river system upstream of a location of interest along the river network. The unit of water supply is $\text{m}^3 \text{yr}^{-1}$.

between 1950 and 2008 (U.S. Census Bureau 2010), leading to a significant increase in water use. Total water withdrawal in the United States increased from about 300 billion $\text{m}^3 \text{yr}^{-1}$ in 1950 to 580 billion $\text{m}^3 \text{yr}^{-1}$ in 2010 (Dieter and Maupin 2015). If the current trend continues, the U.S. population will reach 383 million by 2040. South Carolina, North Carolina, Georgia, Texas, and Florida—5 of the top 10 fastest growing U.S. States—are among the 13 Southern States of the U.S. Department of Agriculture Forest Service Region 8, which also includes Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Oklahoma, Tennessee, and Virginia (hereafter the South). For example, the populations in Texas and Florida are predicted to increase by > 50 percent by 2040 relative to 2010 (University of Virginia Weldon Cooper Center 2018). If per capita water consumption remains constant, water demand will grow with the population, and water withdrawals will continue to increase. Apart from increasing water demand, population growth will also affect the quantity and quality of water supply by changing land use from forests to developed land uses. Across the United States, forest cover declined from 4.14 million km^2 (46 percent of total land area) in 1630 to 3.10 million km^2 (33 percent of land area) in 2012 (Oswalt and others 2014). In the Southern United States, about 10 000 km^2 of forest were lost to urban development between 1992 and 1997 (Alig and others 2010), and forest land is predicted to decline by up to 13 percent from 1997 to 2060 due to urbanization (Wear 2013). Water stress is commonly reported in the Western United States because of the dry climate. However, with rapid population growth and climate change, water stress is predicted to increase even in

the historically water-rich Southern United States (Lockaby and others 2013, Missimer and others 2014, Sun and others 2008).

Forest ownership patterns differ between eastern and western regions of the United States. While the Federal Government owns 2.59 million km² of forest in the United States, most of it (75 percent) lies in the 11 western contiguous States. In contrast, most of the forest land in the Eastern United States is privately owned. Across the South, forests owned by State and local governments, corporations, families, and other private entities (hereafter State and private forest; SPF) account for about 90 percent of the total forest land area. Family-owned forests are the majority of privately owned forest lands in the South (55 percent), followed by corporately owned forests (26 percent). Most of this family-owned forest is used for the aesthetics that forests provide, as habitat for wildlife, and as part of a family legacy, while corporations that own forest land with wood-processing facilities traditionally have been a major source of U.S. timber production (Oswalt and others 2014). The ideal condition is to keep as much existing forest land as possible in forest cover to maintain the high-quality and stable supply of water in the South; however, privately owned forests are vulnerable to urban development (McNulty and others 2013), which is likely to affect both water quantity and water quality.

For more than a century, U.S. legislation has emphasized the importance of protecting forests and water resources. The Organic Act of 1897, the Weeks Act of 1911, the Sustained Yield Forest Management Act of 1944, and the National Forest Management Act of 1976 all sought to safeguard our Nation's forests and water resources. The Forest Service upholds this legislation and is dedicated to the future improvement of water resources through restoration and enhancement of forested landscapes. The State and Private Forestry branch of the Forest Service provides technical and financial assistance to States, Tribes, communities, nonindustrial private landowners, and other resource managers to help sustain and manage non-Federal forests for timber production, recreation, wildlife, and other ecosystem services while protecting

soil and water resources. The Southern Group of State Foresters (SGSF) is a nonprofit organization consisting of State Foresters from across the South, who provide leadership in sustaining the economic, environmental, and social benefits of the South's forests, and work to identify and address existing and emerging issues and challenges that are important to southern forests and citizens. The SGSF and Forest Service State and Private Forestry work in partnership to help sustain the South's forests and the ecosystem services they provide, including the provisioning of clean, reliable water supplies.

Previous work has attempted to link SPF and water at various scales in the United States but not in sufficient detail to provide resource managers with the information needed to demonstrate importance of specific SPF lands for specific drinking water supplies. Caldwell and others (2014) showed that SPF across the South in total contributed 32.4 percent of the water supply and provided water to 6,188 communities serving a total population of 48.7 million but did not provide detail at the State level, identify specific communities and populations served by water from SPF, or quantify the relative contribution of different ownership types within SPF. Brown and others (2016) quantified the water yield provided by SPF in the United States at the State level but did not quantify water supply by SPF ownership type or link this water supply to specific communities and populations served by that water. Understanding the contribution of specific SPF lands to drinking water supply for specific downstream communities is critical for forest management and source water protection on SPF lands.

This study aims to quantify the contribution of SPF lands to drinking water supply systems in the 13 Southern States. As such, the available water and origin of that water at each public surface drinking water intake was estimated using a water balance model. Our objectives were to: 1) estimate how much fresh surface water supply originated from SPF lands across the region and by State; and 2) quantify the contribution of SPF lands to specific drinking water supplies.

METHODS

Extent and Scale of Analysis

This study focused on surface water supply and surface drinking water intakes in the 13 Southern States of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia. The term “water supply” used in the following text is surface water supply. We quantified the proportion of the available surface water to a given public surface drinking water intake that originated on forest land across the South and by State in the South (fig. 1). In calculating these proportions, we accounted for the water supply that originated in areas that are located outside of the South but drain to the South through the river network, including the Missouri, Upper Mississippi, Ohio, and Rio Grande Rivers. Likewise, we included surface drinking water intakes in our analysis that are located outside the region or a given State but receive water from the region/State. The spatial resolution of our analysis was the 12-digit, or sixth-level, Hydrologic Unit Code (HUC12) watershed scale. The South covers approximately 23,000 HUC12 watersheds with a mean size of about 900 km². The relative contribution of forests to the total water supply

was calculated for any point along a stream network, such as the location of a surface drinking water intake, by tracking water yield from forest lands through the river network.

The WaSSI Model

The Water Supply Stress Index (WaSSI) hydrologic model was developed to assess the impacts of climate change, land use change, and population growth on water supply stress, river flows, and ecosystem productivity across the conterminous United States (Caldwell and others 2011, 2012; Sun and others 2011b). WaSSI has been tested, validated, and used in climate change assessments across the conterminous United States (Caldwell and others 2015; Lockaby and others 2013; Marion and others 2013; Sun and others 2015a, 2016; Tavernia and others 2013), in examining the water-energy nexus at the national scale (Averyt and others 2011), in quantifying surface water supplied by national forests (Caldwell and others 2014), and in studying the impacts of historical drought on national forests and grasslands (Sun and others 2015b).

WaSSI is an integrated monthly model that simulates the full hydrologic cycle. WaSSI is parameterized using readily available national-scale soil, land

Forest Service Region 8, land areas by forest ownership, and upstream river basins

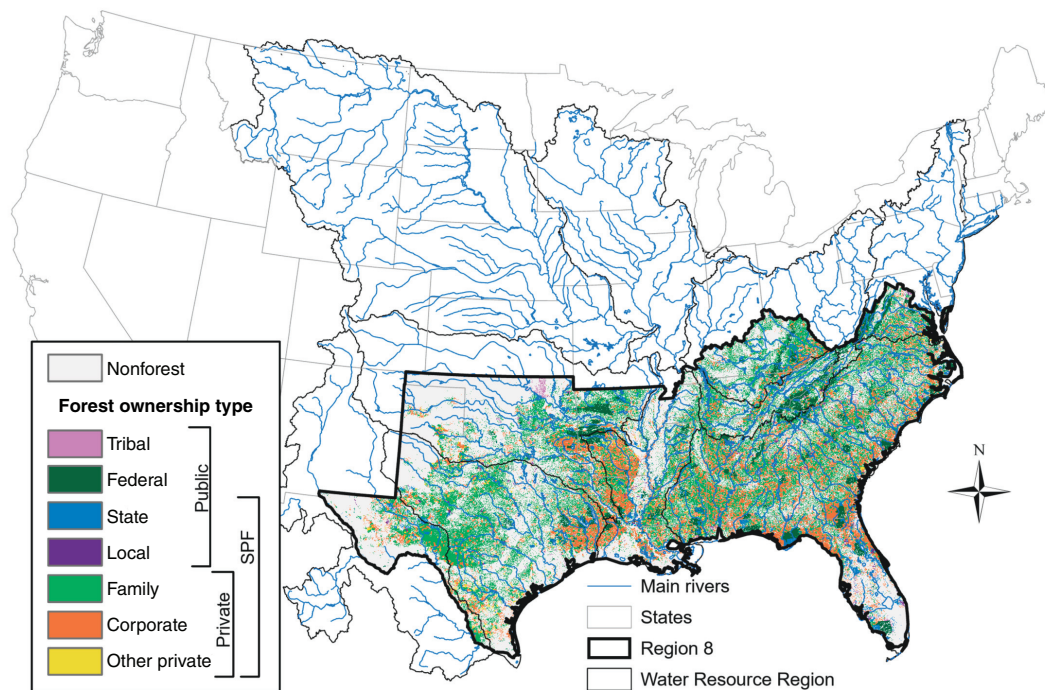


Figure 1—Nonforest land and forest lands by ownership ca. 2014 (Hewes and others 2017) in the South (Region 8), plus upstream contributing river basins used in modeling and the amount of water supply originating on State and private forest (SPF) lands serving surface drinking water intakes in the South.

cover, and climate databases (table 1). To match the scale of analysis (HUC12 watershed scale), all input data sets were spatially rescaled using an area-weighted averaging scheme. In WaSSI, precipitation is partitioned into rain and snow using an air temperature-based conceptual snow accumulation and melt model (McCabe and Wolock 1999). The WaSSI model calculates monthly infiltration, surface runoff, soil moisture, and baseflow processes for each HUC12 watershed land cover type using algorithms of the Sacramento Soil Moisture Accounting Model (SAC-SMA) (Burnash 1995, Burnash and others 1973). The soil profile is divided into a relatively thin upper layer and a much thicker lower layer which supplies moisture to meet ET demands (Koren and others

2003). Each layer consists of tension water storage (i.e., between soil water tensions of field capacity and the plant wilting point) and free water storage (i.e., soil water tension greater than field capacity) that interact to generate surface runoff, lateral water movement from the upper soil layer to the stream (interflow), percolation from the upper soil layer to the lower soil layer, and lateral water movement from the lower soil layer to the stream (baseflow). Monthly ET is calculated as a function of potential ET (Hamon 1963), precipitation, and leaf area index (LAI) using empirical relationships derived from multisite eddy covariance measurements (Sun and others 2011a, 2011b). Storage and ET for impervious cover in each HUC12 are assumed to be negligible, thus all precipitation falling

Table 1—Data inputs for the Water Supply Stress Index (WaSSI) model

Data/database	Source	Resolution	Time period
Soil properties	State Soil Geographic (STATSGO)-based Sacramento Soil Moisture Accounting Model Soil Parameters NOAA-National Weather Service, Office of Hydrologic Development, Hydrology Laboratory	1- x 1-km grid	N/A
Impervious cover	National Land Cover Database (NLCD) 2011 Percent Developed Imperviousness (CONUS) for the conterminous United States (https://www.mrlc.gov/data/nlcd-2011-percent-developed-imperviousness-conus-0) Global Man-made Impervious Surface (GMIS) Dataset from Landsat, v1 (2010) for HUCs outside the United States (https://sedac.ciesin.columbia.edu/data/set/ulandsat-gmis-v1/data-download)	30- x 30-m grid	2011
Forest ownership	Forest Ownership in the Conterminous United States circa 2014: Distribution of Seven Ownership Types - Geospatial Dataset (https://www.fs.usda.gov/rds/archive/Product/RDS-2017-0007)	250- x 250-m grid	2014
Monthly mean leaf area index (LAI) by land cover	Moderate Resolution Imaging Spectroradiometer (MODIS) (https://modis.gsfc.nasa.gov/)	1- x 1-km grid	2001–2010
Climate (monthly precipitation and temperature) for the conterminous United States	PRISM Climate Group (http://www.prism.oregonstate.edu/)	4- x 4-km grid	2001–2010
Climate (monthly precipitation and temperature) for the HUCs outside the United States	Daymet (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1345)	1- x 1-km grid	2001–2010
River network	National Hydrography Dataset (NHD) (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/national-hydrography-dataset)	1:100,000	N/A
Watershed boundaries	Watershed Boundary Dataset (WBD) (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/watershed-boundary-dataset)	HUC12 (~90 km ²)	N/A

HUC = Hydrologic Unit Code; NOAA = National Oceanic and Atmospheric Administration; PRISM = Parameter-elevation Regression on Independent Slopes Model.

on the impervious portion of a watershed is assumed to be runoff and is routed directly to the watershed outlet. Water yield is calculated for each land cover type in a given HUC12 as the sum of surface runoff from pervious and impervious surfaces, interflow, and baseflow after accounting for losses that include changes in water storage in the soil, evaporation, and transpiration from vegetation. Water yield for each HUC12 is then calculated as the sum of the area-weighted averages of water yield of each land cover type present and expressed in mm yr^{-1} . Water yield for each HUC12 is then routed and accumulated from upstream to downstream HUC12s along the river network to estimate the total water supply at the outlet of each respective HUC12. The water supply is the sum of the water yield generated in all HUC12s upstream of a given location on the river network expressed in $\text{m}^3 \text{yr}^{-1}$. While some applications of WaSSI have included the effects of anthropogenic water use, no anthropogenic water use was considered in this study.

Forest Ownership

In this study, forests in seven ownership types (Federal, Tribal, State, local, corporate, family, and other private [the last two also referred to together as nonindustrial private forest, or NIPF]) were derived from a dataset of conterminous U.S. forest ownership circa 2014 (Hewes and others 2017) (table 1). Corporate ownership lands include forest land owned by forest industry as well as other corporate entities such as Timber Investment Management Organizations and Real Estate Investment Trusts (TIMOs and REITs, respectively). This dataset was interpolated from forest ownership point data, collected as part of the Forest Service Forest Inventory and Analysis (FIA) program using the Thiessen polygon method. The overall accuracy in correctly categorizing SPF land was > 90 percent. However, the accuracy in identifying each forest ownership type varied according to the training size (Butler and others 2014). The amount of forest land in this dataset may differ from that of other published land cover datasets due to differences in the definition of forest land as well as conceptual differences between “land use” and “land cover.” For example, the 2006 National Land Cover Database (NLCD), which was used by Caldwell and others (2014), describes “land cover” and defines forest land as a canopy > 5 m tall; young trees in early succession or trees stunted by environmental conditions would be considered shrubland cover (Homer and others 2015).

The forest ownership dataset we used describes “land use” and defines forest as land at least 36.6 m wide and 0.4 ha in size with at least 10-percent cover by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated.

For this analysis, we overlaid the SPF ownership raster on the HUC12 boundaries and the Moderate Resolution Imaging Spectroradiometer (MODIS) LAI model inputs to derive the inputs for each of the seven forest ownership types as well as nonforest land. We revised the WaSSI flow routing algorithm to track water flow from each land cover type through the river network (fig.1). In addition to the HUC12 watersheds in the conterminous United States, we also included the areas in Canada and Mexico that contribute water to watersheds in Forest Service Region 8 in order to accurately estimate the total flow (table 1). The WaSSI model was run at the monthly time step from 2001 to 2010 over the HUC12 watersheds in and upstream of Region 8. The years 2001 and 2010 were selected because they roughly corresponded to the time periods of the land cover and LAI input databases, as well as the drinking water population-served estimates (discussed below). The mean annual water supply and the fraction of mean annual water supply originating on SPF land in the South were quantified for each HUC12.

Linking Water Yield from Forests to Surface Drinking Water Intakes

We employed the methods detailed in Caldwell and others (2014) to link water yield from forests to surface drinking water intakes and briefly summarize those methods here.

Population served by each surface drinking water intake is derived from the U.S. Environmental Protection Agency’s (EPA) Safe Drinking Water Information System (SDWIS) database (EPA 2017), which contains information on water systems such as location, population served, and system type (residential or other). Self-supplied groundwater wells, such as those serving single-family homes, are not included in the database; thus, our estimates of the population served by SPF lands are conservative as these wells are likely getting a portion of their water from forest lands. Public water systems in the EPA database were screened for those located in the

South, serving a population of at least 25 people, and whose source was denoted as “surface water” and “groundwater under the influence of surface water.” No systems or intakes in the SDWIS whose source was identified as strictly “groundwater” were included in our analysis because we could not be certain of the origin of groundwater supplies (i.e., forest land vs. nonforest land) for any given well at such large scale. The population served in the SDWIS is attributed to the water system as opposed to specific intakes within a system. Where there were multiple intakes with different locations in a given water system, we assumed that the total population served by the water system was divided equally among the intakes in that system. As a result, our representations of population served differ spatially from local data in some instances. The final database used in this analysis included 7,440 surface drinking water intakes inside the South (fig. 2) serving a total population of 56.6 million people (49 percent of the nearly 114 million people in the South [EPA 2017]) and 142 surface drinking water intakes outside the region serving a total population of another 1.8 million people.

We overlaid the surface drinking water intakes on the HUC12 watershed boundaries and assumed that the WaSSI-estimated proportion of water from forest lands at the outlet of the HUC12 watershed in which a given intake was located was representative of the intake location. This might not be accurate for any intake located on a tributary and not on the HUC’s main stem, but this assumption was necessary because, like other semi-distributed hydrologic models, WaSSI estimates water supply at the outlet of each modeling unit (in this case, HUC12 watersheds) in the river network but cannot resolve the amount of water provided by forest land for specific locations within each modeling unit. In some cases, intakes were located in coves off the main stem of water supply reservoirs; thus, the proportion of water from forest lands on the reservoir main stem was more representative than that of the inundated tributary in which the intake was located. We assumed that these intakes were receiving source water with the same proportion of water from forest land as that of the first HUC12 watershed downstream and on the main stem of the water supply reservoir.

Surface drinking water intakes in Region 8

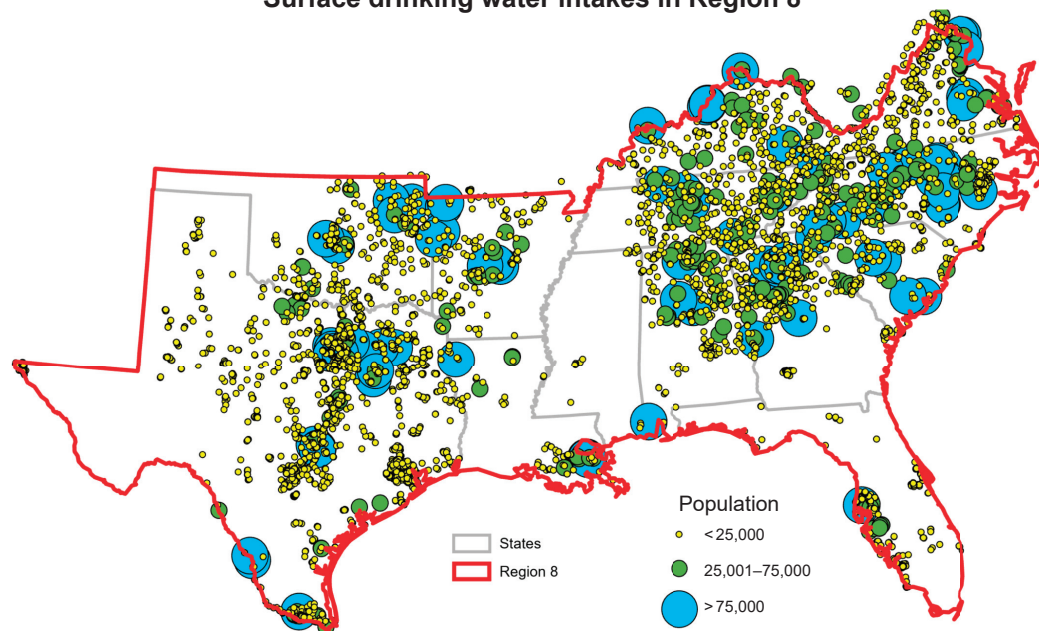


Figure 2—The 7,582 surface drinking water intakes used in the study area. Intakes are sized and colored according to the population that depends on water from these intakes.

RESULTS

Water Supply and Water Yield from State and Private Forest Land

Mean annual (2001–2010) water supply was spatially variable, reflecting the influences of climate and upstream drainage area (fig. 3). The mean annual water supply ranged from near zero in watersheds in arid western Texas to about 710 billion $\text{m}^3 \text{yr}^{-1}$ at the outlet of the Mississippi River. Water yield was highest in areas with high precipitation and low ET (e.g., mountainous areas or at high latitude, or both) and lowest in areas with low precipitation and high potential ET (e.g., the arid high plains of the United States) (fig. 4). Mean annual water yield ranged from $< 200 \text{ mm yr}^{-1}$ in the western portions of the study area to $> 1000 \text{ mm yr}^{-1}$ in the high-elevation Southern Appalachian Mountains.

Water supply originating on SPF lands in the 13 Southern States made significant and disproportionate contributions to the total water supply across the region in comparison with other land cover and ownership types (figs. 5 and 6). State and private forest land area in the 13 Southern States was 44.2 percent of the total land area, but SPF lands contributed 44.3 percent of the 836 billion $\text{m}^3 \text{yr}^{-1}$ total available

water supply generated. Within SPF, the majority of the land area (63.6 percent) was NIPF which contributed 61.2 percent of the water supply, followed by corporate private forests (29.2 percent of the land area and 31.0 percent of the water supply) (fig. 5). In general, areas with a high proportion (> 75 percent) of water supply from SPF (fig. 6) have a dominant percentage of SPF lands, such as southwestern Texas, southern Arkansas, northern Louisiana, southern Mississippi, and western Alabama (fig. 1).

At the State level, the contribution of water supply from SPF varied by local forest ownership patterns. Unsurprisingly, Texas (the largest of the 13 Southern States) had the greatest total water supply with about 118 billion $\text{m}^3 \text{yr}^{-1}$, followed by Louisiana and Florida (fig. 7A). However, the majority of water supply in Texas originated on nonforest lands (~ 60 percent) (fig. 7B). Most of the SPF lands in Texas are in the western south-central part of the State. For example, the Llano River, one of the upstream water supply rivers of the city of Austin, had > 75 percent water supply originating on SPF (fig. 6). For the 13 Southern States, Alabama had the greatest amount (~ 40 billion $\text{m}^3 \text{yr}^{-1}$) and the highest percentage (~ 60 percent) of water supply from SPF, which included ~ 40 percent of the total water supply from NIPF. More than 40 percent of Alabama's HUC12s had > 75 percent of

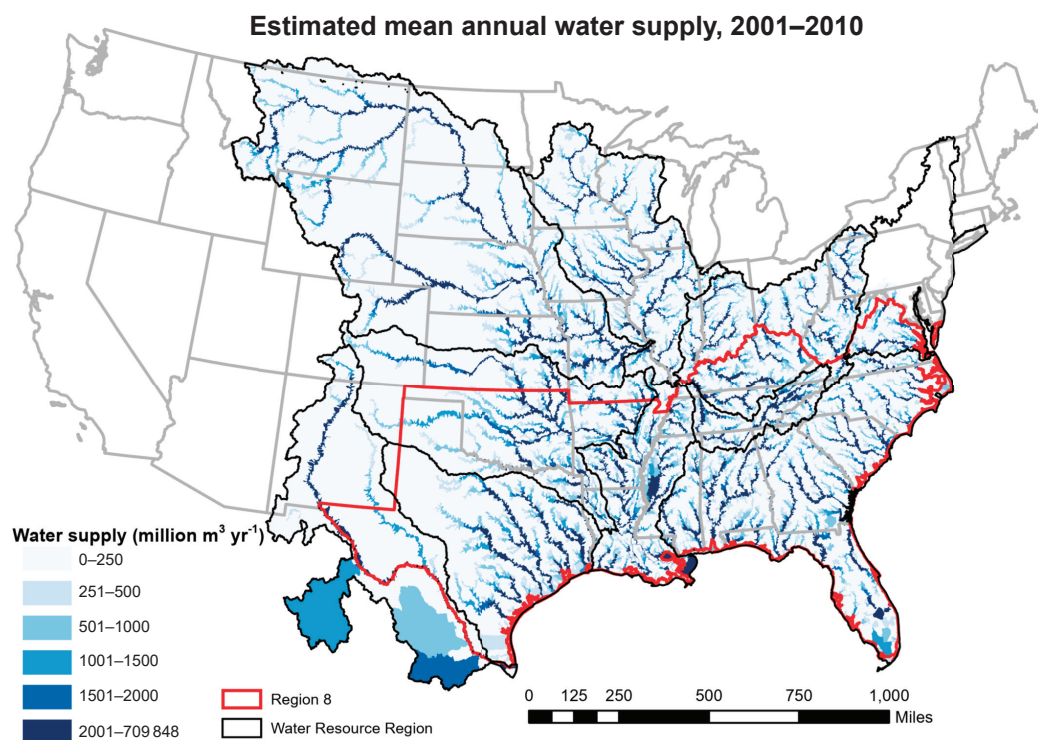


Figure 3—Estimated 2001–2010 mean annual water supply in millions of $\text{m}^3 \text{yr}^{-1}$ by 12-digit (sixth-level) Hydrologic Unit Code (HUC12) watershed for those watersheds supplying water to the South. HUCs are colored by the magnitude of available water supply at the HUC outlet.

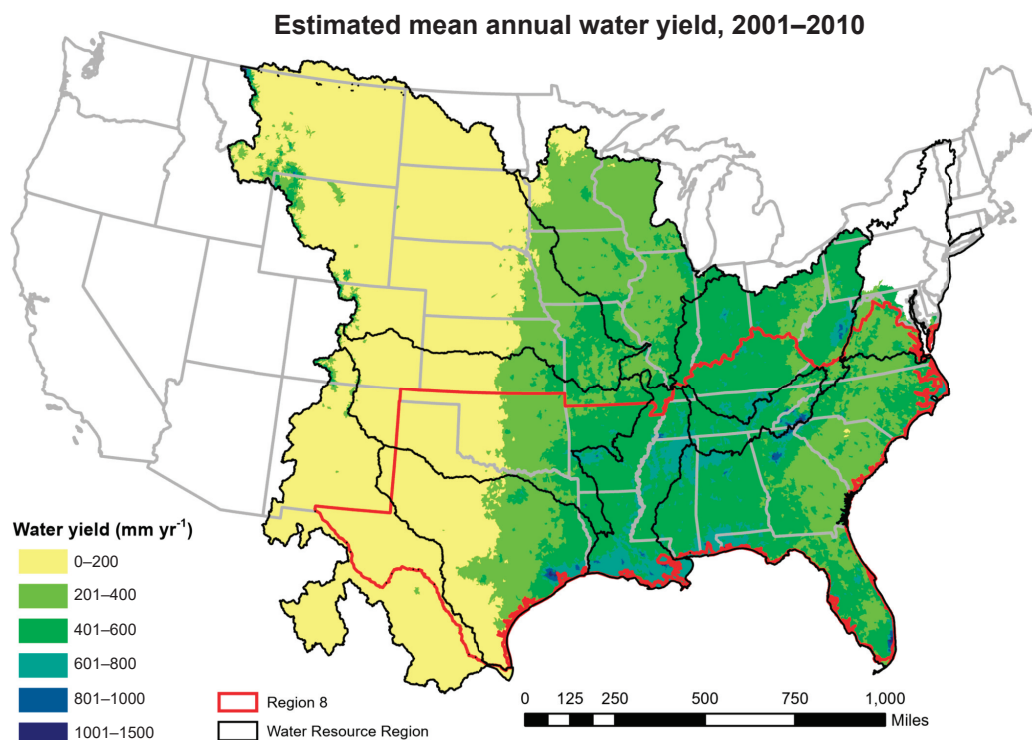


Figure 4—Estimated 2001–2010 mean annual water yield in mm yr⁻¹ by 12-digit (sixth-level) Hydrologic Unit Code (HUC) watershed for those watersheds supplying water to the South. HUCs are colored by the magnitude of the long-term mean annual water yield of each HUC area-weighted by land cover types.

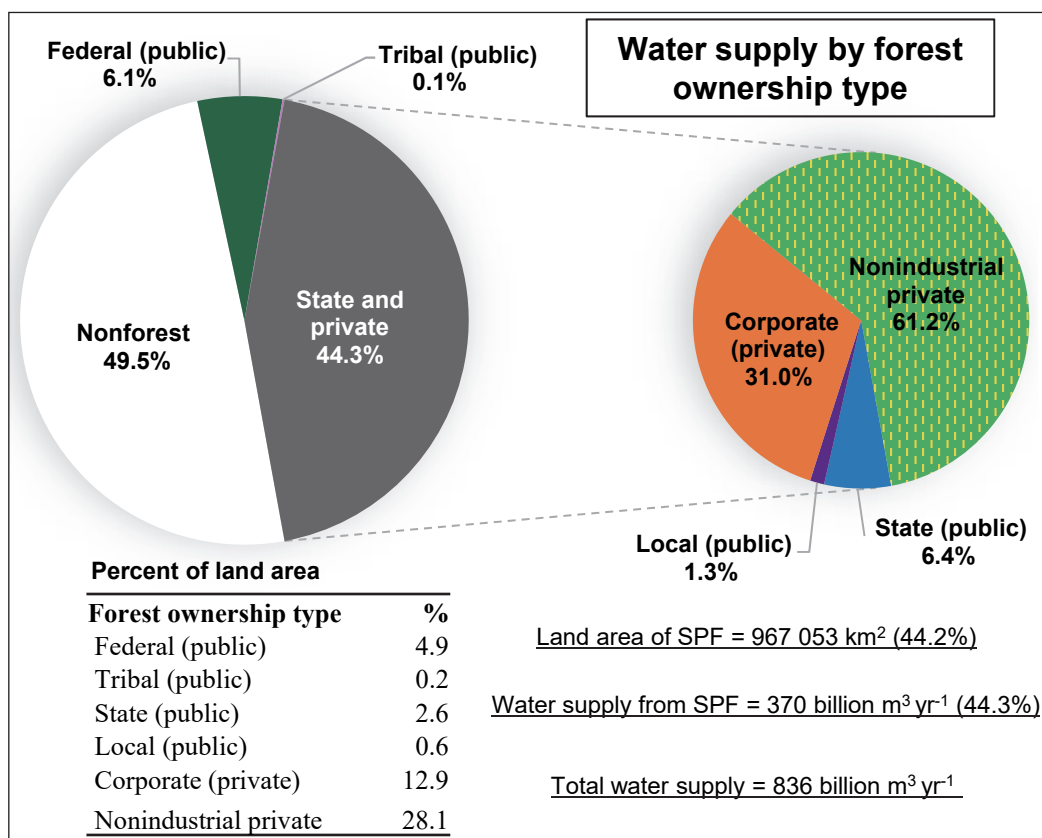


Figure 5—Summary of water supply from and land area of State and private forest (SPF) lands serving surface drinking water intakes in the South.

Streams by proportion of water from State and private forest lands in Region 8

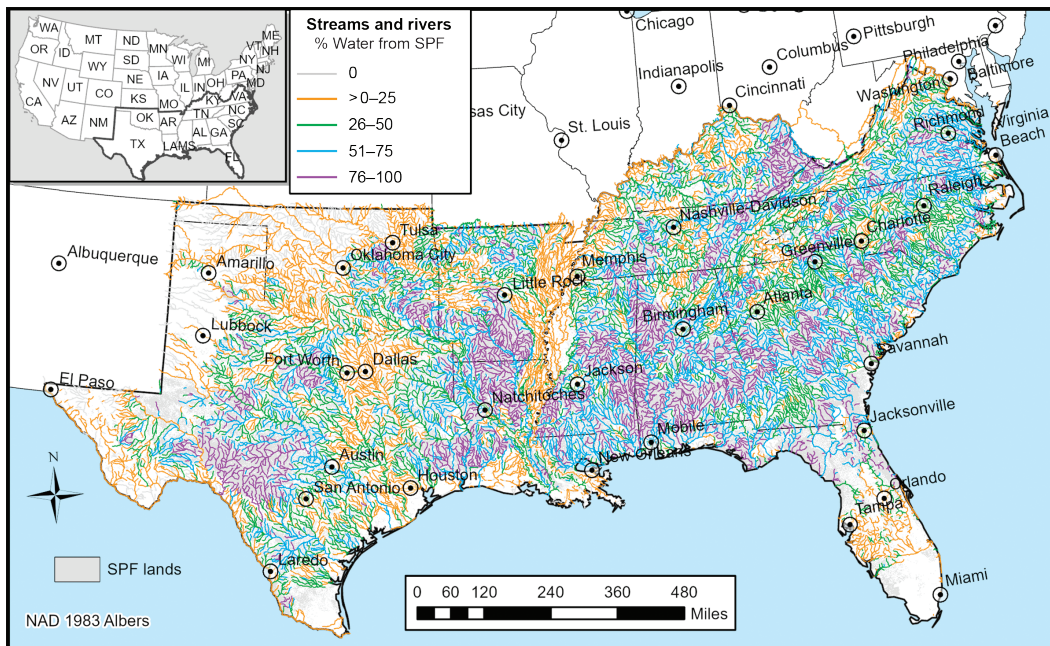


Figure 6—Percentage of the total 2001–2010 mean annual water supply that originated on State and private forest (SPF) lands by Hydrologic Unit Code (HUC) watersheds' streamlines. Water supply is the total amount of surface water available at the outlet of each HUC watershed, including flow accumulated from HUCs upstream. Streamlines of 12-digit (sixth-level) HUC watersheds are colored according to the fraction of total water supply at the watershed outlet that originated on SPF lands.

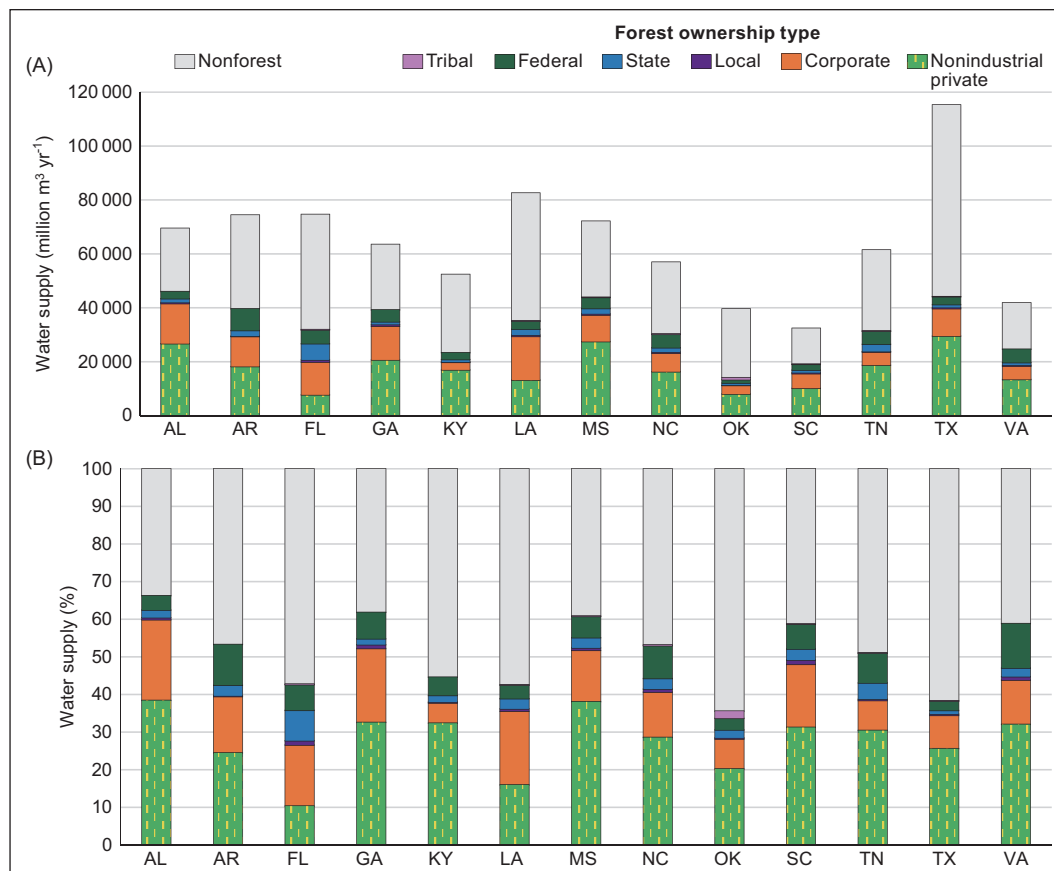


Figure 7—Mean annual water supply in millions of $\text{m}^3 \text{yr}^{-1}$ (A) and percentage of water supply (B) originating on each forest ownership type for each State.

their water supply originating on SPF. Overall, NIPF was the dominant source of water supply from SPF for 11 of the 13 Southern States (the exceptions being Florida and Louisiana), followed by corporate forest (fig. 7B). In Kentucky, NIPF contributed >80 percent of water supply originating on SPF, while >70 percent of water supply originating on SPF was from State and corporate forest in Florida.

Relationship between Forest Cover and Water Supply

About half of the land area in the South is forested, with forests occupying between 20 and 70 percent of land area by State. Overall, forest land area in the South and the proportion of water supply originated on forest lands were closely linked at the State level (fig. 8). The consistent relationship between forest coverage and water supply suggests that different forest ownership types had similar water yield in the Southern United States (fig. 9A). Some exceptions were notable, however. For example, federally owned forests in North Carolina had much higher water yield than did SPF in the State, likely because of the higher precipitation in the mountainous western part of the

State where most federally owned forests are located. In addition, nonforest land tended to have a greater ratio of precipitation that ended up as streamflow (i.e., runoff coefficient) than forest land, while different forest ownership types had very similar runoff coefficients (fig. 9B). Only in Texas and Oklahoma did nonforest lands have a lower runoff coefficient than forest lands, suggesting that precipitation in these nonforest land areas was too low to support forests (fig. 9A).

Population and Communities Served by Water from Forest Lands

Approximately 55 million people in the South derived some portion of their drinking water from SPF lands. This represents 49 percent of the total population in the region (fig. 10). In addition, approximately 1.8 million people outside the 13 Southern States received some portion of their drinking water (>0 percent of the total supply) from SPF in the South (fig. 6). The population in the South was served by water from forests to different extents depending on the size of the communities (as represented by their public drinking water systems) and their proximity to forest lands

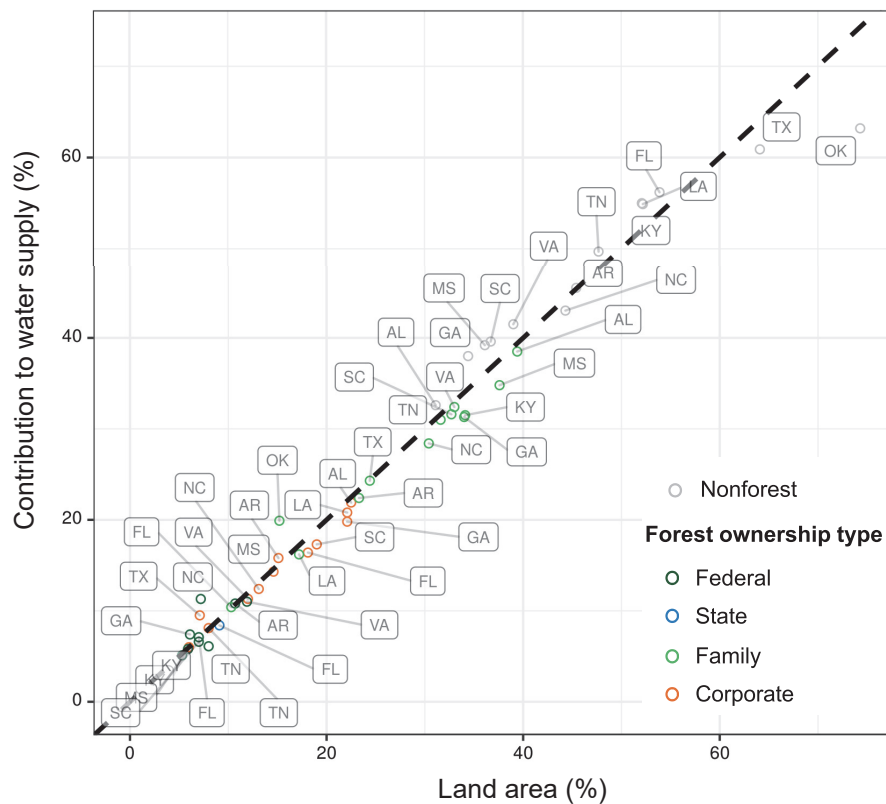


Figure 8—The relationship between forest ownership types as a percentage of the land area (percent) and their contribution to water supply (percent) for the 13 Southern States. Only forest ownership categories >5 percent of the total area in each State are shown.

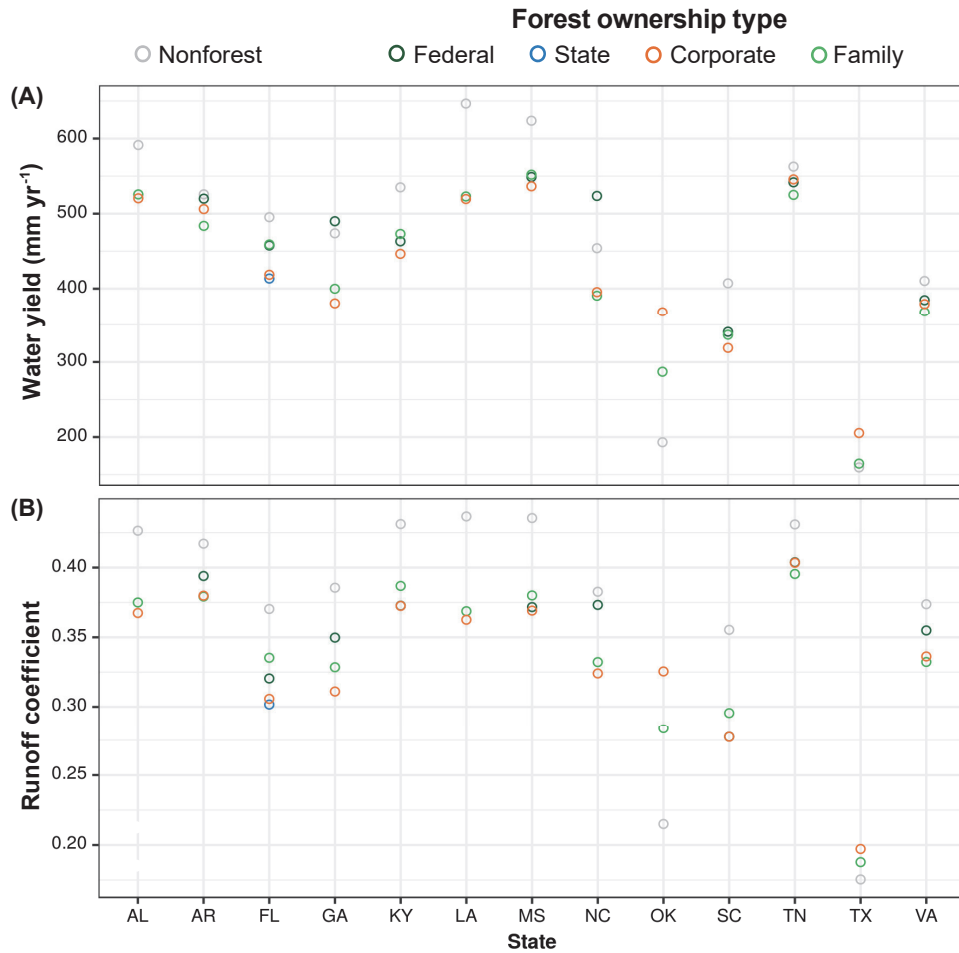


Figure 9—The averaged water yield (A) and runoff coefficient (B) of different forest ownership types in each State. Only forest ownership categories > 5 percent of the total area in each State are shown.

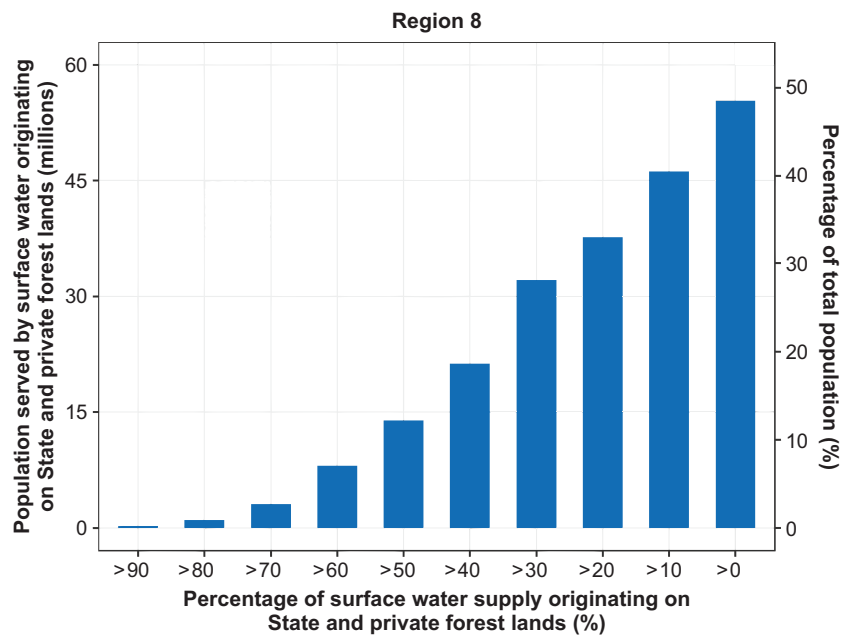


Figure 10—Cumulative frequency of population served according to percentage of water coming from State and private forest (SPF) lands in the South.

(figs. 10 and 11). Approximately 14 million people in the South received > 50 percent of their drinking water from SPF lands. Of the 7,582 surface drinking water intakes in the study area, 6,897 (91.0 percent) received some portion of their source water from SPF lands, with 4,526 receiving > 20 percent of the source water from SPF lands. For the 13 Southern States, SPF served the largest population in Texas: 16.7 million people (59.0 percent of the total population) derived some of their drinking water supply from SPF. Less than 10 percent of the population in Texas received the majority (> 50 percent) of their water from SPF, however. In contrast, about 3.4 million people in

Alabama got water from SPF lands, with 30.3 percent receiving at least half of their water supply from SPF. In Oklahoma, Louisiana, and Florida, < 5 percent of the total population received the majority of their drinking water supply from SPF.

Some surface drinking water intakes serve large populations and receive > 20 percent of their water supply from SPF lands. Examples include Birmingham, AL; Atlanta (proper), GA; Natchitoches, LA; Charlotte, NC; Raleigh, NC; Greenville, SC; Nashville, TN; Richmond, VA; and Austin, TX.

Surface drinking water intakes receiving water from SPF lands aggregated to HUC12 in Region 8

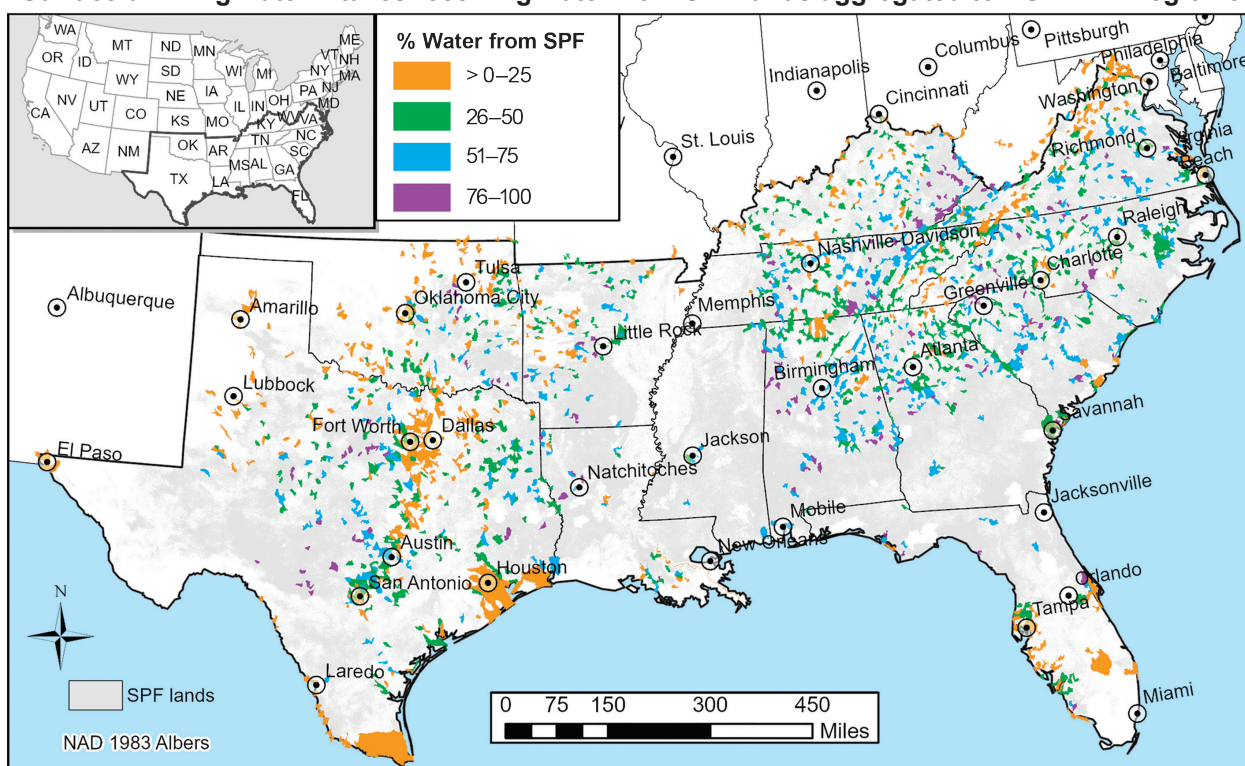


Figure 11—Intakes aggregated in HUC12 watersheds where some amount of source water originated on State and private forest (SPF) lands. HUC12 watersheds are colored by the percentage of surface water from SPF in the South.

CASE STUDY: CITY OF AUSTIN

We selected Austin as an example to demonstrate how SPF contributed to the drinking water supply for the community, as this city has an especially high population receiving > 50 percent of its water from SPF lands. Austin lies near the outlet of the Colorado River Basin in Texas, which has its headwaters originating in southeastern New Mexico. The Colorado River Basin is 103 599 km² in area, and forest covers 49.5 percent of the total area. Ninety-nine percent of the forest is SPF. The dominant ownership is family forest, which accounts for about 40 percent of the total land area and contributes to 52 percent of the surface water (fig. 12). Corporately owned forests contribute 7 percent of surface water and account for 6.1 percent of the total land area. There are three intakes for the city of Austin, which served almost 1 million people. Those three intakes received an average of 62.4 percent of their surface drinking water from SPF. One of three intakes is located at the Mansfield Dam, serving about 324,446 people in Austin. The reservoir also provides surface water for another 23,000 people in Travis County. Another two intakes are located northwest of Austin, in Lake Austin, serving 648,892 more people.

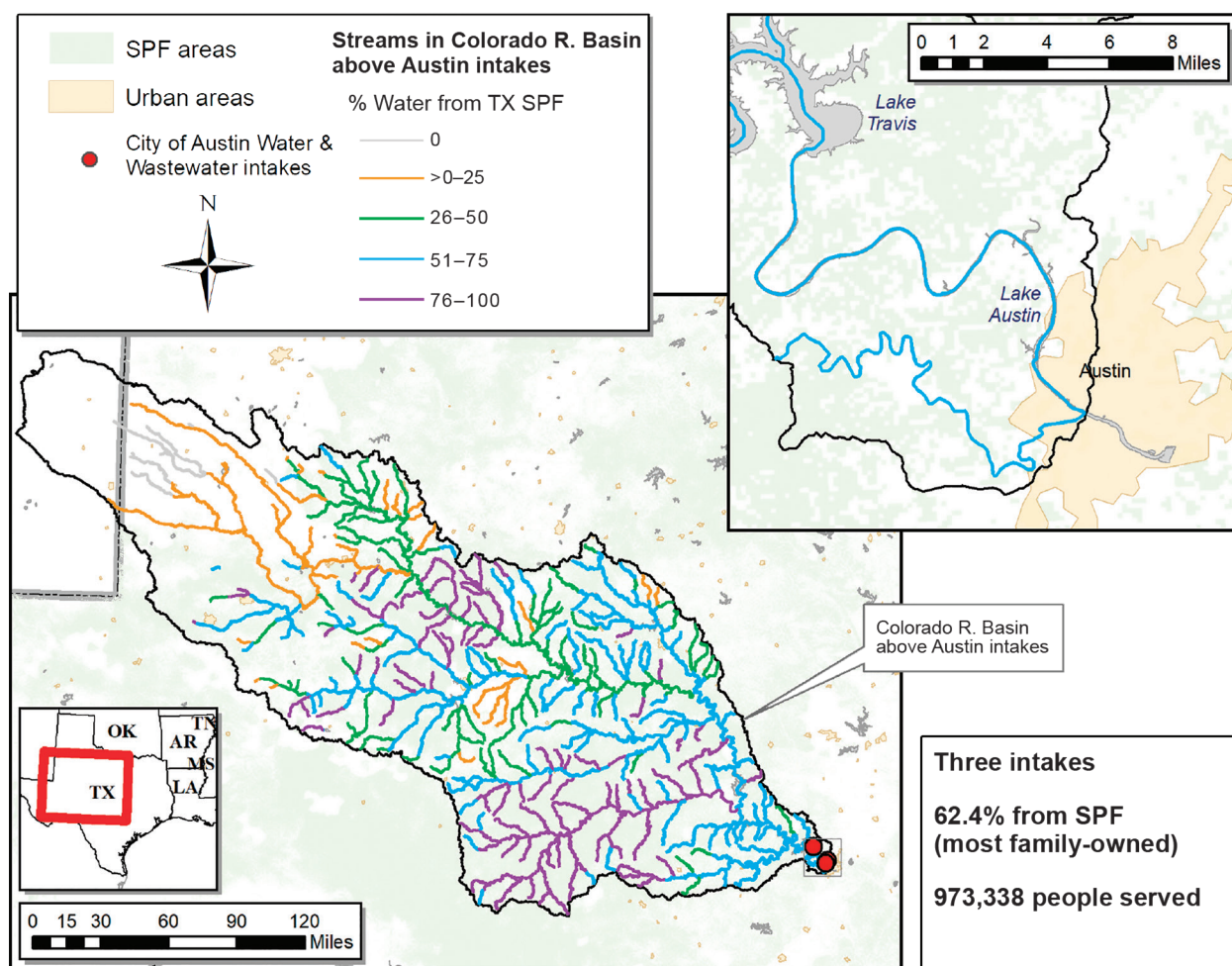


Figure 12—Case study of the City of Austin Water & Wastewater, Austin, TX.

DISCUSSION

In this study, we quantified the water supply derived from SPF lands in the 13 Southern States and these lands' contributions to surface drinking water intakes and populations served. State and private forest lands provided almost half of the total surface water in the study area, and thus played an essential role in supplying drinking water to communities. More than 10 percent of the population in the South received > 50 percent of their drinking water from SPF lands. We found that water supply from private forest lands dominated the water supply that came from forest lands, while public (Federal, Tribal, State, and local) forests supplied < 10 percent of surface water. In an earlier study, Caldwell and others (2014) reported that National Forest System lands contributed 3.4 percent of the total water supply in the Southern States and that SPF lands provided 32.6 percent of total water supply. In contrast, we found that the SPF lands contributed about 44.3 percent of the water supply, a difference of 11.7 percent. The differences in the estimates are related to the different input databases used for forest cover and ownership in the two studies. As stated previously, Caldwell and others (2014) used the 2006 National Land Cover Database, in which SPF lands made up 27.1 percent of the total land area in the 13 Southern States. In contrast, the 2014 forest ownership dataset used in the present study (table 1) indicates that SPF lands represent about 44.2 percent of the total land area (967 053 km²) (fig. 5), which is similar to some previous reports (Huggett and others 2013).

Water Yield from Forests is Closely Tied to Forest Area and Precipitation Patterns across the South

The considerable difference in water supply from different forest ownerships reflected the abundance and spatial distribution of forests in relation to the spatial patterns of precipitation (fig. 6). Apart from water yield, the proportion of precipitation that ends up as streamflow (i.e., the runoff coefficient) is strongly related to precipitation because most of the South is not water-limited (Renner and Bernhofer 2012) in Budyko's framework (Budyko and others 1974). Overall, the contribution of each forest ownership type to water supply closely reflected forest area for each type, at least at the State level (fig. 8). This suggests

that different forest ownership types tend to have similar water yields in most of the States (fig. 9A). In each State, differences in water yield and runoff coefficient between different forest ownerships were small, because the annual precipitation was quite similar among those forest ownership types. However, Federal forests showed much higher water yield in Georgia and North Carolina than other forest lands (fig. 9A) because most of Federal forests in these two States are located within the Appalachian Mountains where the highest annual precipitation in the South is found.

In contrast, nonforest lands tended to have a higher respective percentage of water supply than their percentage of total land. This is due to the fact that nonforest lands generally had greater water yield and runoff coefficients than forest lands (fig. 9). The exceptions to this were the nonforest lands in Texas and Oklahoma (fig. 9). In Oklahoma, the average water yields in the forest and the nonforest lands were 350 mm yr⁻¹ and 200 mm yr⁻¹, respectively (fig. 4). Moreover, the runoff coefficient was much lower in nonforest lands (~0.20) than forest lands (~0.30) (fig. 9B). The large difference in water yield between forest and nonforest in these two States was a result of the difference in rainfall amounts in the western areas of Texas and Oklahoma compared to the eastern parts of those States. Across the South, moving from east to west, the annual rainfall decreased from more than 1300 mm yr⁻¹ in the Appalachian Mountains to < 700 mm yr⁻¹ in the western portion of the region.

Climate Change and Population Growth Might Exacerbate Water Stress Conditions

Water stress, or the ratio of water demand to water supply (Averyt and others 2013, Duan and others 2019, Lockaby and others 2013, Sun and others 2008), in general is concentrated in the Western United States due to the dry climate there. Although water supply is generally high in the South because of the high precipitation, high water demand due to large populations has resulted in water stress in some urban areas, such as Atlanta (Jeong and others 2015) and Raleigh (Hester and Larson 2016). Water supply is also expected to continue to decrease due to climate change, which will increase surface temperature and increase the frequency and severity of droughts. The South is forecast to experience warming for the duration of

the 21st century, while varied changes in precipitation are predicted to occur in the same period (McNulty and others 2013). Higher air temperatures will likely increase water loss by ET (Lockaby and others 2013). Moreover, under the current warming trend, drought is expected to occur more frequently. Drought and climate change have already resulted in a dramatic reduction of water available to ecosystems and to the public across the United States (Creed and others 2014, Sun and others 2015b). For example, Sun and others (2015b) found that droughts in the 2000s resulted in up to a 54-percent reduction in precipitation, which led to streamflow decreases from forest lands of up to 90 percent. Sun and Vose (2016) predicted that streamflow in 48 percent of HUC12 watersheds is projected to decrease by 2031–2060 from the baseline period of 1979–2007 across the United States.

Concurrent with reductions in water supply, water demand may increase in the 21st century due to rising population. Population in the 13 Southern States is projected to increase by 36.2–67.9 million by 2060 (34–65 percent from the 2010 level), with Texas and Florida increasing > 50 percent and Georgia and North Carolina > 30 percent by 2040 in comparison with 2010 (University of Virginia Weldon Cooper Center 2018). Per capita water use in U.S. cities has been declining steadily over the past few decades as a result of conservation policies (Rockaway and others 2011). For instance, Dieter and Maupin (2015) reported national domestic water use per capita decreased from an average of 122 m³ yr⁻¹ in 2010 to 113 m³ yr⁻¹ in 2015. However, population growth may further increase water demand in the South. With continued climate change, larger deficits between water supply and demand will likely occur in the South (Brown and others 2019, Naumann and others 2018), and more people may be subject to water stress (Gosling and Arnell 2016).

Land Cover Change, Water Supply, and Water Quality

Land cover change might also affect water stress (Lockaby and others 2013). Forest conversion to urban use in some areas might relieve water stress conditions locally by increasing water yield (Suttles and others 2018); however, transformation of forests to cropland would exacerbate water stress due to high water demand from irrigation (Lockaby and others

2013). Alternatively, afforestation or reforestation and forest protection can significantly enhance terrestrial ecosystem services, increasing ecosystem productivity (Zhang and others 2014), reducing soil erosion and other water pollutants (Gao and others 2016), and enhancing biodiversity (Fuchs and others 2015, Ouyang and others 2016). However, there is a tradeoff between water yield and other ecosystem services provided by afforestation in some areas (Farley and others 2005, Jackson 2005), especially in arid regions (Liang and others 2015, Zhang and others 2017, Zhou and others 2015). Indeed, Wei and others (2018) found that change in vegetation cover explained 30.7 ± 22.5 percent of global average variation in annual runoff. Therefore, effective forest management will need to comprehensively consider tradeoffs among all ecosystem services including those directly affecting public water supply (Ellison and others 2012, Sun and Vose 2016).

Although nonforest lands generally have higher water yield than forest lands and deforestation might increase water yield and late summer/early fall baseflow (Evaristo and McDonnell 2019, Suttles and others 2018, Swank and Webster 2014), water quality from forest land is much higher than other lands (Sun and others 2004, Tu 2013). Forest land cover in water supply areas can reduce the cost of treating water by improving water quality at the intake (Tu 2013, Warziniack and others 2017). Watersheds with more forest cover tend to have lower concentrations of some water quality indicators such as nutrients, organic carbon, and sediment than watersheds with less forest cover (Swank and others 2001, Tu 2013, Warziniack and others 2017). Forest loss could lead to an increase in sediment and nutrient yields in streams (Arthur and others 1998, Riekerk 1985, Swank and others 2001). Lockaby and others (2013) predicted that urbanization by 2060 in the Appalachians, Piedmont, and Coastal Plain would increase imperviousness and further reduce water quality in the headwaters of several major river basins. Further, future climate change might amplify the impacts of forest loss on water quality by increasing water temperature (Karl and others 2009). The combination of urbanization and climate change could affect both water quantity and quality; therefore, an important next step will be understanding how forest ownerships affect water quality in the Southern United States.

SUMMARY AND CONCLUSION

In this analysis, we used a hydrologic model and a database of surface drinking water intakes to quantify the extent to which people depend on water from SPF lands in the South. We estimated that SPF lands, which account for 44.2 percent of the total area in the 13 Southern States, contribute 44.3 percent of the approximately 836 billion $\text{m}^3 \text{ yr}^{-1}$ of total water supply in the region. Of the public surface drinking water intakes in the South, 6,897 (91.0 percent) receive some surface water from SPF lands in the region and serve 55.3 million people, and 4,526 of these receive >20 percent of their water from SPF lands and serve 37.8 million people. State and private forest lands in the South provide more than half of the water supply for 14.0 million people in the region and beyond. Nonindustrial private forest land is the largest contributor to water supply among all forest ownerships (27.1 percent of total) and SPF (61.2 percent of SPF). State and private forest lands not only benefit people living in the local catchments but often provide surface water and other ecosystem services for people downstream. This study provides a systematic assessment of the interactions among water, forests, and people highlighting the deep connection between SPF and water supply in the South. Conservation and sound forest management are needed to ensure clean and stable water supplies for southern communities now and in the future.

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Liu, Ning; Dobbs, G. Rebecca; Caldwell, Peter V.; Miniati, Chelcy Ford; Bolstad, Paul V.; Nelson, Stacy; and Sun, Ge. 2020. Quantifying the role of State and private forest lands in providing surface drinking water supply for the Southern United States. Gen. Tech. Rep. SRS-248. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 405 p. <https://doi.org/10.2737/SRS-GTR-248>.

Forests provide the most stable and highest quality water supplies among all land uses. The Southern United States is heavily forested, and most of the forests are owned and managed by State and private entities, thus it is critical to understand the role of forest lands in providing water across the region, the fastest growing in the Nation. We quantified surface water supply originating on State and private forest (SPF) lands in the 13 southern States at the 12-digit Hydrologic Unit Code watershed scale, using the Water Supply Stress Index (WaSSI) hydrologic model. Water originating on seven forest ownership types was tracked through the river network and linked to a database of surface drinking water intakes to quantify the population served by water from SPF lands across the South. We found that SPF lands comprised 44.2 percent of the total land area and contributed 44.3 percent of the 836 billion m³ yr⁻¹ total available surface water supply in the region. Of the 7,582 surface drinking water intakes in the study area, 6,897 (91.0 percent) received some portion of their water from SPF lands, with 4,526 (65.6 percent) receiving >20 percent of their water from SPF lands. Approximately 55.3 million people in the South and 1.8 million people outside the 13 southern States derived some portion of their surface water supply from SPF lands. These results highlight the importance of southern State and private forests in providing drinking water to downstream communities.

Keywords: Drinking water, hydrologic modeling, State and private forest lands, WaSSI, water supply, water yield.



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