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A novel method for increasing water-yields, pine forests of the Northern Gulf of Mexico, USA

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Abstract. This study introduces a new method to identify, prioritize, and select areas for pine basal area reduction to maximize water-yields in pine forests along the Northern Gulf of Mexico, USA. Using this method, the Apalachicola Region of Northwest Florida, an area covered by dense vegetation and pine plantation forests, demonstrated to experience a shortage of freshwater due to increased upstream water demand, climate change, and past forest management practices. Potential initial water-yield gains were: 1) 469 m^3 d^{-1} if all pine basal areas were reduced from current to a maximum of 18 m^2 ha^{-1}, and 53,400 m^3 d^{-1} if pine basal areas were reduced from current to a maximum of 7 m^2 ha^{-1} for the Apalachicola Region. The method identifies watersheds mainly along the Apalachicola and other rivers near the Gulf coast that have the greatest potential to increase water-yields. Increasing forest water yields translates to increased freshwater availability and improved forest and soil health, water quality, and ecosystem function, services, and resilience, as well as socioeconomic outcomes for communities and people who rely on ecotourism and fisheries for their livelihoods. This method will empower forest managers to focus scarce resources in targeted areas to maximize water-resource benefits per resource investment. Although demonstrated in the Apalachicola Region, the method is transferable, repeatable, and scalable,throughout other pine forests of the Northern Gulf Coast Region. This method is also easily upgraded and adapted to increasingly higher resolution datasets as they become available or as relationships between forest metrics, evapotranspiration, and water yields are improved.

Keywords: basal area, forests, geospatial, land cover, water yield

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1 Introduction

1.1 Southeastern Pine Forests

Native longleaf pine forests (*P. palustris Mill.*) once covered 38 million ha in the Southeastern United States, or nearly 90 percent of the land ranging from Virginia to Texas and from the southern Appalachian Region to the Gulf and Atlantic Coasts and central Florida. Mature upland longleaf pine forests undergo frequent natural fire and have low basal areas, an open canopy, a sparse mid-story, and a diverse uninterrupted herbaceous layer (Walker and Peet 1985; Platt 1999; Kirkman et al., 2001; McIntye 2012). Over most the last century in the Apalachicola Region, longleaf forests were often replaced with dense, fast-growing slash pine (*Pinus elliottii)* plantations managed for timber production, agricultural and other non-forest uses, with some tracts also being lost from fire suppression. By 1995, longleaf pine occupied only 1.2 million ha in the Southeastern U.S. (Rauscher and Johnson, 2004). Less than 3% of the original longleaf forests remain scattered and patchy in the Southeastern U.S. today (Brockway et al., 2005; McConnaughey, 2020; Rauscher and Johnson, 2004).

Longleaf pine forests support ecosystems ranging from wet Flatwoods and xeric Sandhills to rocky mountainous ridges and provide critical habitat to the greatest diversity of species outside of the tropics (Brockway et al., 2005).; Up to 900 plant species were found only in longleaf forest ecosystems (Rauscher and Johnson, 2004). One goal of longleaf forest restoration is to produce multi-age forest stand structure that adds complexity, diversity, and maintains ecosystem services and long-term economic value (Mitchell et al., 2006). Longleaf pine forest restoration in the Southeastern Gulf Coastal Region will also enhance water resources. Longleaf pine reforestation is a critical component to achieve long-term increases in freshwater yield in Gulf coastal pine forests. By decreasing pine basal areas in the densely spaced, high evapotranspiration (ET), slash pine and pine plantation forests and reforesting with the slower growing, lower ET, longleaf pine and regular understory removal, significant water-yield increases can be realized and maintained over time (Brantley et al., 2017). This project aims to assist land managers to identify, prioritize, and select areas for pine basal area reduction followed by longleaf pine reforestation to maximize the potential benefits of increased freshwater availability in the region (Brantley et al., 2017).

1.2 Evapotranspiration, Water-yield, and Water demand

Harper (1956) observed that changes in land use since the beginning of European settlement had major impacts on ET, changing the water balance and presenting a potential path for mitigating water scarcity (Brantley et al., 2017). Water yields and therefore potential water-yield increases contribute to multiple pools within a water budget including stream flow, groundwater recharge, soil water and storage. Forests play a critical role in regulating hydrological processes, including moderating the timing and magnitude of streamflow (Elliott et al., 2017). However, these processes are particularly sensitive to leaf area index and ET (Aranda et al., 2012; Hanson et al., 2019; Brantley et al., 2017).

Because forests are critical sources of clean and abundant water, forest management is an essential tool for managing water resources in the Southeast (Neary et al., 2009; Lockaby et al., 2013; Caldwell et al., 2014; Marion et al., 2014). Evapotranspiration, largely by plants, is the second largest component in the annual water flux cycle in terrestrial ecosystem

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water-balance, after precipitation (Jasechko et al., 2013; Good et al., 2015). Evapotranspiration consumes water, returning it directly to the atmosphere, and therefore prone to change with changes in land cover and land use. Changes in vegetation may affect water availability at all scales, including direct effects on water yield. Water yield, defined as the difference between precipitation and ET, contributes directly to streamflow, groundwater recharge, and soil water storage (Filoso et al., 2017). Annual water yields, subject to change on from intra-annual precipitation variability, are a conservative process and generally shows little variation over time if vegetation and precipitation are relatively stable (Oishi et al., 2010). However, if land cover—i.e., vegetation types and/or percent cover amounts, are changed ET may be significantly increased, affecting the terrestrial water balance and therefore water yields.

Large-scale conversion of current slash and mixed pine forests in the Southeastern USA to frequently burned, open-canopy, lower density, longleaf pine forests would benefit water resources by reducing ET, increase water yields, streamflow, and groundwater recharge, and mitigates against droughts (Brantley et al., 2017). Brantley et al. (2017) report that longleaf pine/wiregrass forest clusters have annual ET rates of approximately 489 mm y^{-1} in mesic soils (less in Sandhills). Powel et al. (2005) reports an average ET rate of 754 mm y^{-1} (range 594-816 mm y^{-1}) in Florida and southwestern Georgia in mixed, mature, low-density, stands of slash and longleaf pine, where longleaf pine is dominant or codominant (Whelan et al., 2015). They conclude that mature open-canopy longleaf pine forests maintained by fire have lower annual ET rates compared to mixed longleaf and slash pine or solely slash pine forests. Full implementation could produce an approximate potential water-yield gain of 18-40 percent depending on replacement levels and management decisions (Ford et al., 2008; McLaughlin et al., 2013; Novick et al., 2014; Whelan et al., 2015; Brantley et al., 2017). As longleaf pines age, ET rates generally decrease inversely with time since restoration, presenting opportunities to study water yield changes in restoration areas in future studies (Filisio et al., 2017).

Restored longleaf pine forests provide ideal land cover for increasing forest water yields. Longleaf forests, with their characteristic low stand densities and sapwood area, lowering leaf area index, have lower ET rates (Brantley et al., 2017). Other factors that increase ET and therefore water consumption in southeastern pine forests include excessive mid- and under-story forest growth and forest-floor litter. Mid- and understory vegetation increase the overall forest ET water demand and forest-floor litter which intercepts precipitation, increases ET, lowering water yields. Mid- and understory vegetation and floor litter must be reduced and eliminated using prescribed burns on a regular basis within restored longleaf forests to maintain long-term water-yield gains (McIntye, 2012; Hamada et al., 2004; Powell et al., 2005; Brantley et al., 2013).

Restored longleaf pine forests provide ideal land cover for improving ecosystems, wildlife habitat, and water quality by increasing water yields (Brantley et al., 2017). Increasing available annual freshwater availability increases forest resilience to drought by reducing water stress on remaining trees (McDowell and Allen 2015; Brantley et al., 2017; Bosch and Hewlett 1983; Brown et al., 2005; Sun et al., 2015; McLaughlin et al., 2013). Greater water yields and restored longleaf forest ecosystems will improve water quality by reducing runoff and therefore soil erosion and adding more water for dilution, enhancing terrestrial and aquatic habitat, and increasing carbon sequestration (Sun et al., 2006). Mature longleaf pine forests

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maintained with prescribed fire at basal areas ranging from 7 to 18 m2 ha^{-1} provide optimal wildlife habitat and maximize ecosystem services, function, and resilience.

1.3 Ecohydrologic Restoration

Forests have a multitude of complicating factors influencing hydrologic responses from initial basal area reduction and longleaf restoration, including land-use history, soil and ecological conditions, tree species, forest management decisions, restoration methods used to restore forest cover, and climate change (Filisio et al., 2017). Large-scale restoration projects may enhance local precipitation effects, intensifying the local water cycle and increasing local freshwater availability, but they may not result in higher water yields regionally. A physiological response from forest restoration may include reduced transpiration rates from higher overall water-use efficiency (the rate of growth per amount of water used) and increased carbon dioxide and temperatures within forests with greater water availability. Large-scale hydrologic studies following longleaf reforestation projects are rare (Filisio et al., 2017).

Over the last few decades, hydrologic/ecological restoration projects have been successful in re-establishing hydrologic characteristics and ecosystem function, services and sustainability in two projects in Florida and many projects in the Western U.S. Generally, western ecological restoration efforts have been implemented over relatively small areas (i.e., less than 30 square km) or within single watersheds and the focus has been on restoring critical habitat for a single or specific group of at risk species. In Florida, large-scale ecohydrologic restoration projects have been implemented in the Lower Kissimmee (Cairns, 1995)--a regional watershed and in the Tate's Hell State Forest in the Apalachicola Region (Coates and Lewis, 2010a and 2010b). These ecohydrological restoration projects, implemented to improve and potentially restore critical habitat and freshwater availability for many federally listed, threatened, or endangered species in altered and/or damaged areas. Projects provided restoration plans and methods for accomplishing their goals.

The historic Kissimmee River and Floodplain Hydrologic Restoration Project in Central Florida, implemented in the early to mid-1980s, was primarily a hydrologic restoration project to restore ecological services, function, resilience, and critical habitat along the Lower Kissimmee River and Floodplain—a regional river basin. The objectives were to restore historic natural hydrologic characteristics of flow, timing, levels, flood intervals, specific flooded areas, and quantity. The plan, if implemented and successful, would ensure the full restoration of ecological function, service, resilience, and critical habitat in the river, riparian zone, floodplain, and adjacent wetlands and the re-population of many federally listed, endangered, or threatened species, and make local fisherman happy (Cairns, 1995; USFWS, 2016). The Kissimmee River restoration team implored a hydrologic model and weighted indices scheme to define "natural" characteristics of flow and test and identify processes and features of the channel and floodplain that could be "adjusted" to accomplish their goals. Ultimately, the project used a combination of channel restoration, levee and canal refilling, and scheduled upstream dam water releases to re-establish natural hydrologic characteristics in the lower basin. Following hydrologic restoration, native vegetation were replanted in and along the channel, floodplain and wetlands (Cairns, 1995). The fully implemented restoration project continues to provide benefits in the Lower Kissimmee Basin including increased freshwater supply at natural intervals and quantities, improved

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water quality, aquatic habitat, species richness, abundance, and diversity, and ecosystem function, services, and resilience today (Cairns, 1995). The project is considered to be an overwhelmingly success by scientists and the public and so, is considered an excellent blueprint for the types of tools that can be used in ecohydrologic restorations today (Cairns, 1995).

Within the Apalachicola Region, the State of Florida commissioned the Northwest Florida Water Management District to develop and administer a hydrologic restoration plan and contract projects in Tate's Hell State Forest — an area previously managed for timber production (pine plantations) over most of the last century (Coates and Lewis, 2010a). The goal of the restoration is to increase freshwater discharge to the Apalachicola River, Bay, and Estuary to improve and increase critical habitat for federally listed threatened or endangered species in the region. The current process, developed using systematic scoring and weighted indices, is used to select and prioritize areas for hydrologic restoration activities. Index scores are based on: 1) proximity to Apalachicola River, Bay, and Estuary--closer basins are rated more highly; 2) total critical habitat area in potential basin--number of federally listed threatened or endangered species recorded in the proposed area within the past 10 years; and 3) the feasibility of the restoration—least changed from historic conditions--less costly restorations, rated more highly (Coates and Lewis, 2010a). Sub-regional watersheds with the highest scores draining into the Apalachicola River, Bay, or Estuary were selected for initial restoration projects (Coates and Lewis, 2010b). Restoration activities include forest road removal, canal and ditch infilling, culverts and bridge replacement with gravel-hardened low-water crossings, and total basal area reduction and removal through prescribed fire and physical means and replanting cleared areas with longleaf pine at lower basal areas (Coates and Lewis, 2010b). The projects, once fully implemented, will increase water quantity and critical habitat in and near the Apalachicola River, Bay, and Estuary and improve critical habitat, and ecosystem services, function, and resilience, hopefully increasing populations of native occupying species (Coates and Lewis, 2010a).

2.1 The Apalachicola Region

The Apalachicola study area of Northwest Florida consists of a contiguous area of mostly pine forested watersheds discharging into the Apalachicola River, Estuary, or Bay including the lower Apalachicola-Chattahoochee-Flint (ACF) contributing area (in Florida) as well other local drainages from east of Panama City to the eastern boundary of the Aucilla-Wascissa River basin (figure 1 and figure 6). Most of these areas contribute directly or indirectly to the Apalachicola River, Bay, and Estuary, St. Joseph Bay, the Ochlockonee River basin, or Apalachee Bay. The pilot area includes the greater Apalachicola Region, and St. Vincent, Little St. George, St. George, and Dog Islands. The Region, designated as one of top 5 biodiversity "Hot Spots" in North America (Stein et al. 2000), provides rich and diverse habitat and the bulk of freshwater originating in Florida discharging to the Apalachicola River, Bay, and Estuary.

Over most of the last century, the Apalachicola Region was managed for intensive timber production using slash pine (*pinus elliotti)* plantation management practices (Rauscher and Johnson, 2004); currently, more than 80 percent of the Apalachicola study area has pine present in the canopy (mostly slash, or a mixture of slash and longleaf and others in pine plantations). Thousands of miles of roads, including ditches, culverts, and bridges were constructed and many wetlands and swamps were drained and/or filled to facilitate timber harvests. For example, over 800 miles of roads run through Tate's Hell

State Forest alone (Coates and Lewis, 2010a). Runoff and interflows were re-directed to the nearest downslope ditch and quickly routed to culverts; draining not necessarily the watershed of origin.

Roads and their associated ditches bisect watersheds cutting lower basins off from headwater flows, increasing flow velocities causing erosion, cause out-of-basin flows, and decrease critical habitat and total wetland area causing many species to become federally listed, threatened, or endangered.

Past management policies such as fire-suppression, have allowed mid- and understory vegetation to become excessive and water intensive invasive and exotic species have gained footholds in the region. Fire suppression was practiced until relatively recently (1970s), allowing excessive forest-floor litter and mid- and understory vegetation to build up increasing the total basal area and ET water demand. The excess vegetation and litter made for super-heated fires when they did occur, damaging forest soils and even fire tolerant vegetation (Hodges 1995; Rauscher and Johnson, 2004). Upstream urban and agricultural water demand and climate change have combined to limit freshwater availability in the Apalachicola Region (Light et al, 1995; Leitman et al, 2016; Aavudai et al., 2018). Light et al. (1995) estimates that there is approximately a 20 percent decline in discharge at low flow coming down to the Apalachicola River from upstream basins over the last 50 years. The loss of regular fire and dense water hungry vegetation combined with greater upstream water demand and climate change have created a freshwater deficit in the Apalachicola Region. The loss of freshwater availability, especially during drought periods, have driven the State of Florida to Federally List multiple species as species of concern by under the Federal Endangered Species Act (USFWS, 2017). Currently listed species include the frosted Flatwoods salamander, red-cockaded woodpecker, striped newt, and gopher tortoise, and flora such as Harper's beauty, Florida skullcap, white-birds-in-a-nest and Godfrey's butterwort (ARSA, 2016) and many other species populations are in decline https://www.longleafalliance.org/study_area accessed 10/23/2020; USFWS, 2017). Today's forest managers strive to restore and maintain natural longleaf pine forests in the Apalachicola region by funding this study to increase forest water yields by decreasing pine basal areas and replant and maintain longleaf pine at near optimal densities. Current pine basal area reduction and replanting and maintaining longleaf pine forests at optimal basal areas will increase freshwater availability and improve federally listed species populations abundance and reproductive success as well as increase community diversity and richness and the critical habitat needed for the survival of many species (Nordman, 2016).

This study proposes a new method for identifying, prioritizing, and selecting areas for pine basal area reduction to maximize initial water yield gains in forests across the Northern Gulf Coast. Output from this method guides forest managers in developing plans for projects that, if implemented, provide the greatest potential for increasing water availability benefits per resource investment from current to lower pine basal areas. Demonstrated net long-term water-yield gains of 18-40 percent are possible, in properly maintained longleaf forests. Successful regional pine basal area reduction and longleaf reforestation and maintenance will increase freshwater availability to soil, streams, and groundwater, and critical habitat and improve water quality, and ecosystem services, function, and resilience to climate change, and improve socioeconomic conditions for local residents and communities.

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2 Research Objectives

Objectives of this study are:

1. Demonstrate a method for identifying, prioritizing, and selecting areas for pine basal area reduction to maximize water-yield gains by quantifying potential freshwater-yield increases within relevant boundaries--watersheds and forest management compartments, at two selected relevant basal area levels—a maximum of 18 m2 ha^{-1} and a maximum of 7 m2 ha^{-1}.
2. Demonstrate the use of the Getis-Ord Gi* Hot-Spot cluster analysis for identifying, prioritizing, and selecting statistically significant individual forest stands within relevant sub-regional boundaries for pine basal area reduction to maximize water yields per resource investment.

3 Methods

3.1 General

Several relationships linking water yield to basal area, developed in Cohen et al. (2018) for pine forests in north and central Florida, facilitated the selection of areas with significant water-yield increase potential. Their study measured geologic, soil, climate, groundwater, and forest metrics such as basal area, leaf area index, tree density, rooting depths, and other parameters over a 2-year period to identify and parameterize relationships between pine forest water yield and forest metrics at 6 instrumented pine-forest plots located in Northwest to Central Florida. Their study plots ranged from young to mature and open-canopy longleaf pine forests to pine plantations forests (Cohen et al., 2018). Their general linear model related water yield to leaf area index (derived from basal area), depth to shallow groundwater, and the aridity—the ratio of potential evapotranspiration to normal--mean annual, precipitation (Cohen et al., 2018). Leaf area index, estimated from basal area, calculated using Eq. (1) below, had an r-squared of 0.65 (Cohen et al., 2018). Equation (2), the general linear model for water yield has an r-squared of 0.93.

(1) $LAI = 0.073 * BA + 0.2671,$ (R-squared = 0.6493),

where *LAI* = Leaf Area Index and *BA* = Basal Area (Cohen et al., 2018).

(2) $WY = 393.20 - 335.16 * \left(\frac{PET}{MAP}\right) - 1.95 * (WT) - 7.97 * (LAI),$
(R-squared = 0.93; Standard Deviation = 11.64245),

where: *WY* = water yield in cm y^{-1}, $((PET)\ (MAP)^{-1})$ = ratio of potential annual ET to Mean Annual Precipitation, *WT* = depth the shallow groundwater in cm, and *LAI* = Leaf Area Index ($m^2\ m^{-2}$) (Cohen et al., 2018).

3.2 Relevant Steps for Identifying, Prioritizing, and Selecting Areas

The first step in identifying and selecting areas for pine basal area reduction to maximize water-yield increases: obtain the best available necessary datasets. Geospatial datasets used to calculate water yields include basal area—to calculate leaf area index, pine percent land cover including specific location and quantity information, depth-to-shallow groundwater or datasets needed to derive the information and estimates of the aridity ratio. A recently published, high resolution (1 m) basal area raster dataset (post Hurricane Michael) became available in 2019 for the Apalachicola study area (St. Peter et al., 2019; St. Peter et al. 2020). Processing included resampling to upscale the raster grid to a 10 m resolution, clipping, and snapping the raster to occupy an aligned identical 10 X10 m grid for use with all datasets over the Apalachicola study area. This study used Global Coordinate System--USA North America, UTM 16N, NAD 1983 meters for the analysis. Total basal area, derived from remotely sensed (Sentinel 2) and field plots (38 m by 38 m) resolution (St. Peter et al., 2019; St. Peter et al. 2020), has a RMSE of 2.81 m^2 ha^{-1} (12.24 ft^2 ac^{-1}). Pine percent land cover, with a 10 m resolution error 15.2% error in predicted broad class probabilities for identifying species (Hogland et al., 2017; St. Peter et al., 2018), was processed to align the raster grid to occupy identical space and corner locations.

Other necessary datasets for calculating water-yield datasets include depth-to-shallow groundwater depth and the aridity. Depth-to-shallow groundwater data, was derived by taking the difference between two datasets: the elevation of the surface of the surficial aquifer system (resolution of 9.14 m) (FDEP, 2015; Bush and Johnston, 1988) and a 2015 Laser light Detection And Range (LiDAR) derived digital elevation model of land surface elevation. The aridity ratio—the ratio of annual potential evapotranspiration (PET) to normal mean annual precipitation (MAP) was set to 0.92 for this study. This value, based on measured and estimated (PET) $(MAP)^{-1}$ values from two studies in pine forests throughout Florida (Douglas et al., 2009; Cohen et al., 2018); is an approximate median of the observed range in values from their studies (0.84—0.98).

The water yield and water-yield gain scenario generation process, described below, proceeded as follows. Potential water yields, for each pine basal area dataset, were generated employing equation (1)--to estimate leaf area index, followed by equation (2)--to estimate potential water yields. Three water-yield datasets, generated for each pine basal area, were current, a maximum of 18 m^2 ha^{-1}, and a maximum of 7 m^2 ha^{-1}. Water-yields, likely to increase if pine basal areas are reduced from higher to lower levels, were calculated by taking the differences between water-yields calculated for each basal area level. Gains were evaluated using the three reduction scenarios: pine basal area scenarios are pine basal areas are reduced from: 1) current to a maximum of 18 m2 ha^{-1}, 2) from a maximum of 18 m2 ha^{-1} to a maximum of 7 m2 ha^{-1}, and 3) from current to a maximum of 7 m2 ha^{-1}.

Zonal statistics identify areas with the highest potential to increase water yields, were calculated using two relevant boundary datasets--The sub-regional U.S. Geological Survey High Resolution National Hydrography Dataset--Watershed Boundary Divide dataset, Hydrologic Unit level 12 (HUC12) (Moore et al., 2019) (https://apps.nationalmap.gov/viewer/, accessed 01/15/2020), and the Forest Management Compartment boundary dataset. Watersheds, relevant due to the need to increase freshwater to the Apalachicola River, Bay, and Estuary and Management compartments are relevant because forest

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activities are planned and scheduled using forest management compartments—providing potential opportunities to piggy-back onto other previously scheduled activities within the ANF. Watersheds and forest compartments, selected for pine basal-area reduction based on maximizing water-yield increases, optimize water-yield gains per resource investment. Zonal statistics, computed for each water-yield-gain scenario, were summed by HUC12 watershed within the Apalachicola region. The top twenty-five watersheds in terms of greatest total water-yield gain potential, highlighted in Fig. 6 and listed in Table 3, show watersheds that could undergo basal area reduction to produce greatest water-yield gains.

Following zonal statistics with relevant boundary datasets, the authors determined that a refinement method was necessary to identify significant areas within relevant boundaries, allowing forest managers to hone scarce resources for maximum effect at a tree stand or a small forest cluster level. The Getis-Ord G Hot-Spot cluster analysis highlights statistically significant areas within larger datasets; Significant tree stands and forest clusters, identified by the Getis-Ord Gi* analysis, for water-yield gain data from scenario 3 within the Little Owl Creek (LOC) basin. The analysis may be used only within sub-regions, such as HUC12 watersheds or forest compartments, because of the intensive computational time and memory requirements. Other analyses may also be appropriate and/or used to identify significant areas of water-yield gain.

4 Results and Discussion

Estimated total basal area for all vegetation types in the Apalachicola study area ranged from 0.0 to 96.9 m2 ha^{-1} with a mean of 16.0 m2 ha^{-1} (St. Peter et al., 2019, St. Peter et al., 2020). Current pine basal area, calculated by multiplying current total basal area by the fractional percent of pine area on a grid-cell by cell basis, ranged from 0.0 to 57.5 m2 ha^{-1} with a mean of 2.5 m2 ha^{-1} (table 1 and Fig. 2). Leaf area indices, generated using pine basal area datasets and Equation (2), ranged from 0.27 m^2 m^{-2} (the intercept for the equation) to 4.5 m^2 m^{-2} for the Apalachicola study area; with a mean of 0.5 m^2 m^{-2} for the current pine basal area dataset. This range falls squarely within the expected range of expected LAI values for pine forests in Florida (Table 1) (Cohen et al, 2018).

Water yield potential ranged from -11,000 and 82.0 m^3 y^{-1} over the greater Apalachicola study area. Positive water yields indicate that precipitation exceeds water demand from ET on an annual basis so that the potential exists for “excess” precipitation to become runoff or infiltrate into the soil as water yield. Negative water yield values indicate that the ET water demand exceeds the average annual precipitation, sometimes by large amounts (-11,000 m^3 y^{-1}). Annual precipitation variability in timing, amounts, and location may result in years where soil water yield varies from negative to positive.
The large range in calculated water yields prompted this study to perform a sensitivity analysis of the effects of LAI, depth-to-water, and aridity on water yields. Using observed ranges in LAI (0.3 to 7.3 m^2 m^{-2} for all basal areas), depth to water (0.0 to 10,000 cm, encompassing the range of observed values), and aridity (0.80 to 0.98), it was found that when depth to water was 10 cm or less, water yield values were positive over the entire range of aridity and LAI values. Water depths of 0 to 40 cm produced variable water yields ranging from positive to negative values. At depth-to-water values greater than 40 cm negative water yields are produced over the entire range of expected LAI and aridity values; indicating that the depth to water

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is great enough that any precipitation that might manage to get past ET and infiltrate would likely be evaporated in the soil before becoming a positive water yield. Note, depths-to-water water range from 0 to less than 2 m throughout the southeastern quadrant of the study area, the coastal region, and in the northwest corner of the study area where the Floridan aquifer system outcrops (Fig. 4). In the southeastern coastal region, swamps, swales, wetlands, intermittent ponds, lakes, and streams are relatively common (Fig. 4). Annual water yields, primarily controlled by annual precipitation and ET, are significantly affected by depth-to-water--a function of the geology and soils—aquifer and soil properties such as depth and confinement properties; affecting whether or not potential "excess" water would become runoff and flow to nearby streams or infiltrate into soils and potentially become groundwater.

Water-yield gains ranged from 0.0 to 29.4 m^3 y^{-1} per cell for the study area and all scenarios (Table 2). As one would expect, the maximum water-yield gain per cell (29.4 m^3 y^{-1}) occurs under scenario 3 (Table 2). Mean water-yield gains were generally low for individual cells--0.0, 0.1, and 0.1 m^3 y^{-1} per cell for scenarios 1, 2, and 3, respectively; however, total potential water-yield gain over the study area ranged from 469 m^3 y^{-1} (scenario 1), to 53,400 m^3 y^{-1} (scenario 3). Notably, most water-yield gains were identified for areas with pine basal areas of a maximum of 18 m^2 ha^{-1} to a maximum of 7 m^2 ha^{-1} (Table 2); This result is not unexpected considering less than 10 percent of cells have pine basal areas exceeding 9.5 m^2 ha^{-1}. Potential water-yield gains under scenario 3, demonstrated using the Little Owl Creek basin (Fig. 5a), show small clusters of high-water-yield gain areas, however, it is difficult to synthesize the information in a meaningful way for identification and selection for maximizing water-yield gains within specific areas. Water-yield gain datasets, aggregated over meaningful sub-regional boundaries help focus resources toward specific areas that have the potential to produce maximum water-yield gains, such as watersheds, forest compartments, or other relevant boundary information.

Water-yield gain datasets were aggregated by USGS HUC12 (Moore et al., 2019) watershed and forest stand management compartment boundary data using zonal statistics to quantify, identify, prioritize, and select areas for pine basal area reduction that could, if treated, produce the maximum water-yield gains. Watershed boundaries are relevant because of the regional goal to increase freshwater discharge to the Apalachicola River, Bay, and Estuary. Selecting specific watersheds draining directly or nearly directly to the Apalachicola River, Bay, or Estuary for treatments could maximize water-yield increases the area that needs it most, significantly benefiting this system.

Many of the top 25 basins for water-yield gain contribute directly or nearly directly to Apalachicola River, Bay, or Estuary, the Gulf of Mexico (Fig. 6a and 6b). The Lower Wascissa (92.8 and 3,594 m^3 d^{-1}, respectively), Brothers River (30.2 and 2,194 m^3 d^{-1}, respectively), and Apalachicola River, Bay, and Estuary (23.8 and 1,314 m^3 d^{-1}, respectively) were the three potentially highest-gaining watersheds under scenarios 1 and 3 (Figure 6a and b; Table 3). Scenarios 1 showed a slightly different set of top gaining basins than scenario 3 (Fig. 6a and b; Table 3); this was due to the uneven distribution of pine basal areas, generally below 18 m^2 ha^{-1} levels within the study area. Total initial water-yield gains if pine basal areas are reduced from current to a maximum of 7 m^2 ha^{-1} in the top 25 basins could be as high as 26,258 m^3 d^{-1}, providing increased flows in streams throughout the region. Rounding out the top 10 watersheds for water-yield gains using scenario 3 include: Little Owl Creek (1,125 m2 ha-1), Juniper Cove Swamp (1,005 m^3 d^{-1}), Kennedy Creek (1,232 m^3 d^{-1}), Big Gully Creek (940 m^3 d^{-1}), Upper Juniper Creek-New River-New River (1,138 m^3 d^{-1}), and Womack Creek Swamp (1,035 m^3 d^{-1}) (Table 3 and figure 6 a). Other basins with significant gain potential include the Wakulla River, the Middle Sopchoppy River, and the Lower West bank of the Ochlockonee River basin (Table 3 and Fig. 6a). Many of these watersheds contribute directly to the Apalachicola River, Bay, and Estuary, Ochlockonee River, or drain directly to the Gulf of Mexico and are vital oyster production areas. The USDA Forest Service uses forest management compartments to assign and schedule forest activities such as timber clearing and fire. Compartments with scheduled clearing and/or prescribed fire activities scheduled that have great water-yield gain potential should be selected for pine basal area reduction—taking advantage of the synergy to maximize water-yields producing increased benefits for forest health and critical habitat areas. Water-yield gain aggregated by ANF forest timber management compartment using scenarios 1 and 3 datasets, identified forest compartments that, if treated, have the potential to produce the greatest water-yield gains (Fig. 7a and 7b. Under scenario 1, forest compartments 335, 98, 38, 112, and 106 show the greatest initial water-yield gain potential *(note that compartment 999 indicates private ownership and is not part of the USFS forest management activities).* Under scenario 3, compartments 86, 55, 91, 61, 20, 66, 335, and 38 show the greatest potential water-yield gains. Forest managers can use this information along with scheduled activities to maximize water-yield increases per resource investment.

A demonstration of the technique of aggregating water-yield gain datasets using relevant boundaries such as HUC12 watershed or forest compartments in selecting areas for pine basal area reduction is useful; however, this study demonstrates the need to refine the selection process further. The Getis-Ord Gi* Hot-Spot analysis identifies statistically significant areas "clusters" at the tree stand and small forest cluster level for basal area reduction. This tool allows managers to targeting specific tree stands or clusters within selected a watershed or forest compartment for reduction, focusing scarce resources and returning the greatest benefit in water-yield gain. Scenario 3 water-yield gains in the Little Owl Creek basin selected to demonstrate the usefulness of the Getis-Ord Gi* "Hot-Spot" analysis for identifying tree stands and small forest clusters within a larger area (Fig. 5b). The Little Owl Creek basin was chosen to demonstrate the use of the Getis-Ord Gi* analysis because of its location, fully within the ANF, its relatively high water-yield gain potential under scenario 3, and the existence of a related ongoing water-quality study investigating the effects of culverts on water quality. The Hot-Spot analysis revealed several tree stands in the eastern half of the watershed that were statistically significant, meaning they have the greatest water-yield gain potential if pine basal areas are reduced within the watershed (Fig. 5b). This analysis is especially useful for targeting specific tree stands within greater areas for pine basal area reduction, maximizing water-yield gains per resource expenditures.

5 Conclusions

This study presents a novel method for assisting forest managers in the USA Gulf Coast region in identifying, prioritizing, and selecting areas for pine basal area reduction with a goal of maximizing potential water-yield gains. The method, demonstrated in the Apalachicola Region of Northwest Florida, uses processes and techniques that allow forest managers to focus scarce resources to achieve the maximum water-yield increase at multiple scales and at selected pine basal area levels. Pine basal area

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reduction levels were set to longleaf optimal basal area levels: from current to a maximum 18 m^2 ha^{-1} and from current to a maximum of 7 m^2 ha^{-1}. Water yields, formulated using a general linear model, were calculated using leaf area index (derived from basal area), depth to shallow groundwater, and aridity (Cohen et al., 2018). This study, advantaged by recently published, high resolution land cover type and forest metric dataset used percent pine land cover (Hogland et al., 2017; St. Peter et al., 2018), post-Hurricane Michael total basal area (St. Peter et al., 2019; St. Peter et al., 2020), LiDAR surface elevation and elevation of shallow groundwater (FDEP, 2015; Bush and Johnston, 1988) to derive depth-to-shallow groundwater, and published estimates of evapotranspiration and normal precipitation, to estimate water-yields for each pine basal area dataset. Water-yield gains, calculated by taking the difference between water yield datasets calculated for each pine basal area, identify areas where potential water-yield gain can be maximized if pine basal area reduction occurs. Zonal statistics aggregated water-yield gains over relevant boundary areas such as watershed or forest management compartment. Areas with the greatest total water-yield gain can be identified and selected for basal area reduction. Zonal statistics demonstrated using HUC12 watersheds and ANF forest management compartments, identify watersheds and compartments with the greatest water-yield gain potential if treated. Statistically significant tree clusters or forest stands within greater boundaries, such as watersheds or forest compartments, may be identified using the Getis-Ord Gi* "Hot-Spot" analysis. The Hot-Spot analysis allows managers to select statistically significant tree stands within larger areas for treatment, allowing managers to focus scarce resources on maximizing water-yield gains per resource expenditures within selected larger areas. Increasing freshwater availability in pine forests of the Gulf coast region will increase freshwater availability, improving and increasing soil water-yields and ecosystem service, function, and resilience, water quality, and recharge to streams and groundwater. Increasing freshwater and ecosystem services, function, and resilience will result in significant socioeconomic benefits for communities and residents in the Apalachicola Region, an area that relies on fisheries and ecotourism for their livelihoods.

Water-yield gains, estimated using the method describe in this study, represent a gross estimate of the initial potential to increase water-yields if the pine basal areas are reduced at selected levels. Calculated water-yield gains in this study represent potential initial water-yield increases following pine basal area reduction at the proposed level. Any actual gains made by basal area reduction will be quickly undone if early successional vegetation and litter is allowed to resume and grow unchecked. Real long-term water-yield gains may only be realized when longleaf pine reforestation with regularly scheduled prescribed fire to keep mid- and under-story species and forest-floor litter cleared out. Natural longleaf forests have some of the lowest ET rates among southeastern land cover types and are absolutely the best cover for increasing water yield, and improving ecosystem services, function, and resilience while improving and maintaining water quality in the region (Brantley et al., 2017).

Recommendations for future research include establishing stronger, localized, species specific relationships between basal area and leaf area index. A thorough understanding of the mechanisms and consequences of vegetation changes on ET, and water yield in reforested longleaf forests should also be explored (Wang et al., 2018). Follow-up studies could take advantage of treatment recommendations and project implementation from this study in the Apalachicola Region to test the premise that pine basal area reduction followed by longleaf pine reforestation with maintenance will increase regional freshwater availability. Relationships between pine basal area, density, water yields, and longleaf reforestation, and/or other forest compositions scenarios should be quantified. Additionally, the relationship between leaf area index and water yield, while strong (r-squared of 0.93), uses the relationship between leaf area index and basal area (r-squared 0.65), and so, final water-yield estimates are not as strong as the r-squared for the relationship indicates. This study creates a baseline from which future studies can improve the relationship between pine basal area and leaf area index. Relationships for southern pine forests and ET are also relatively underdeveloped compared to ET estimates for agricultural crops, especially for mixed pines (various species), hardwoods, shrubs, and grass species. The relationships and estimates are ripe for further exploration and development, especially with the treasure trove of newer high resolution, remotely sensed satellite climate and land cover imagery and derived products becoming available.

Other recommendations include, this method should be scripted into a flexible, robust decision-making support tool to facilitate use by those without extensive GIS processing and programming knowledge. A very basic Python script was written during this project's development, but it needs to be taken to the next level for widespread use. Finally, a robust error analysis is essential for every geospatial dataset and project. Basal area, percent pine fraction, and depth to shallow groundwater datasets all have associated error estimates. An attempt to characterize error using bootstrapping techniques was made however, it failed. Raster datasets used in the demonstration area have a 10-m resolution so that each dataset has roughly 425,772,025 cells, bootstrapping. These datasets are considered "Big Data" and appropriate computing resources and techniques for assessing error must be identified and developed. Newer methods for processing "Big Data" have become available lately such as the "Bag of Little Bootstraps" method (Kleiner et al., 2012). This method may be best way to generate unbiased nonparametric error estimates and confidence intervals for the large Regional datasets. Follow-up studies should be pursued to provide error estimates and confidence intervals for water-yield estimates produced by this study.

Author contribution: Christy Crandall developed the method, performed all GIS dataset preparation and analyses to calculate water yield and water-yield gain datasets, and in addition, wrote the manuscript. Joseph St. Peter provided the original basal area and pine percent land cover datasets. Jason Drake and Paul Medley provided invaluable editing suggestions as well as data analysis and figures critiques. Jordan Vernon provided the LiDAR land surface elevation dataset used to derive the depth to water dataset. Victor Ibeanusi, Charles Jagoe, and Gang Chen provided scientific guidance on the study and editorial suggestion for the manuscript.

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Table 1. Summary statistics for study area subregions in hectares, subregional percent of total area, percent of area where percent per cell is greater than zero; and cell summary statistics of percent pine, pine basal area (m^2 ha^{-1}) (St. Peter et al., 2019, St. Peter et al., 2020), and pine Leaf Area Index (LAI) (m^2 m^{-2}) (Hogland et al., 2017; St. Peter et al, 2018).

Study Area	Greater Apalachicola	Dog Island	St. George	Little St. George	St. Vincent
Area in Hectares	1,892,933	591	2,116	884	4,928
Percent of Total Area	99.6	0.03	0.1	0.05%	0.26%
Pine land-cover by sub-region					
Percent of cells pine land-cover > 0.0	87	48	39	68	83
Percent pine by cell and sub-region					
Minimum	0	0	0	0	0
Mean	15	3.9	4.9	10	6.3
Maximum	83	37	49	75	67
Standard Deviation	10	3.9	4.8	9.4	5.0
Pine basal area by sub-region					
Minimum	0	0	0	0	0
Mean	2.5	0.3	0.3	0.9	0.7
Maximum	57.5	18.2	31.8	39.9	34.2
Standard Deviation	2.8	0.7	1.0	1.9	1.0
Pine leaf area index (m^2 m^{-2})					
Minimum*	027*	0.27*	0.27*	0.27*	0.27*
Mean	0.50	0.27*	0.27*	0.27*	0.27*
Maximum	4.5	1.6	2.6	3.2	2.8
Standard Deviation	0.2	0.1	0.1	0.1	0.1

**equation intercept*

Table 2. Estimated water yield gains per cell for pine basal area reduction scenarios: 1 current to less than or equal to 18 m2 ha-1, 2 a maximum of 18 to 7 m2 ha-1, and 3 current to less than or equal to 7 m2 ha-1 summarized for the Apalachicola study area.

Scenario number	Pine basal area reduction level	Minimum (m^3 y^{-1})	Mean (m^3 y^{-1})	Maximum (m^3 y^{-1})	Standard Deviation (m^3 y^{-1})	Total Water Yield Gain (m^3 d^{-1})

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1)	Current to a maximum 18 (m2 ha-1)	0.0	0.0	23.0	0.1	469
2)	18 to a maximum 7 (m2 ha-1)	0.0	0.1	6.4	0.5	52,931
3)	Current to a maximum 7 (m2 ha-1)	0.0	0.1	29.4	0.5	53,400

615 **Table 3. The top 25 watersheds that, if treated, could produce the greatest water-yield gains ($m^3\ d^{-1}$); by HUC12 watershed number, watershed name, and water-yield gain ($m^3\ d^{-1}$), for scenarios 1 and 3 -- if pine basal areas are reduced from current to a maximum of 18 $m^2\ ha^{-1}$ and from current to a maximum of 7 $m^2\ ha^{-1}$.**

HUC12	Watershed Name	Scenario 1 Water Yield Gain ($m^3\ d^{-1}$)	Scenario 3 Water Yield Gain ($m^3\ d^{-1}$)
031101030504	Lower Wacissa River	92.8	3,594
031300110803	Brothers River	30.2	2,194
031300110804	East River-Apalachicola River Frontal	23.8	1,314
031200030902	Whitehead Lake		1,294
031300110604	Kennedy Creek	4.2	1,232
031300130401	Upper Juniper Creek-New River		1,138
031300110801	Little Owl Creek		1,125
031200030903	Hitchcock Lake	2.0	1,115
031200030901	Highlog Lake		1,067
031200031202	Womack Creek Swamp		1,035
031300110802	Juniper Cove Swamp	15.6	1,005
031300110602	Big Gully Creek	2.0	940
031300130202	Cat Branch-New River	1.0	850
031300130103	Lindsay Bay		779
031402030604	Carlisle Lake	5.5	774
031300130502	Whiskey George Creek	19.6	738
031300130402	Lower Juniper Creek-New River	1.0	714
031200011103	Pinhook River	2.0	704
031300130404	Cat Creek	13.2	690
031200011001	Wakulla River	5.5	686
031200030301	Lake Jackson	6.4	675
031101030502	Upper Wacissa River	2.0	662

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031200030805	Reedy Creek	2.0	660
031200010802	Middle Lost Creek	1.0	644
031300130403	Gator Creek-New River	1.0	629
031101030501	Welaunee Creek	10.7	
031200010503	Chicken Branch	10.0	
031300130503	Tates Hell Swamp-Cash Creek	8.5	
031300120606	Douglas Slough	6.5	
031200010203	Lake Miccosukee	6.0	
031300130501	North Tates Hell Swamp	5.6	
031200010401	Lake Killarney	5.5	
031200030105	Lake Iamonia	5.3	
031300130504	Blounts Bay Frontal	5.2	
031300110705	Lake Wimico	5.2	
031300110501	Sutton Creek	4.7	
031300130301	Thousand Yard Bay	4.6	
031200010901	Springs Creek	4.2	
031300120502	Lower Tenmile Creek	4.2	
031200010602	Black Swamp-Lake Munson	3.9	
	Total =	307	26,258

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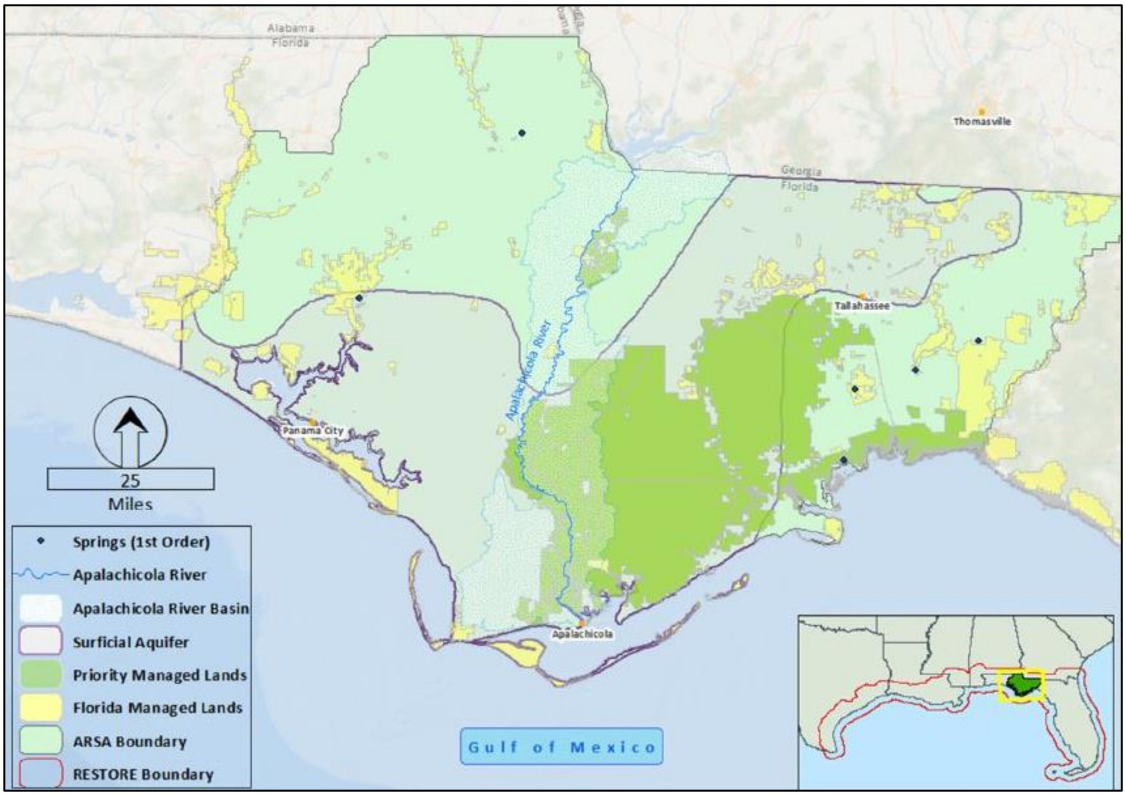

Figure 1. The Study Area (Apalachicola Regional Study Area boundary, Northern Gulf of Mexico, Northwest Florida, USA.

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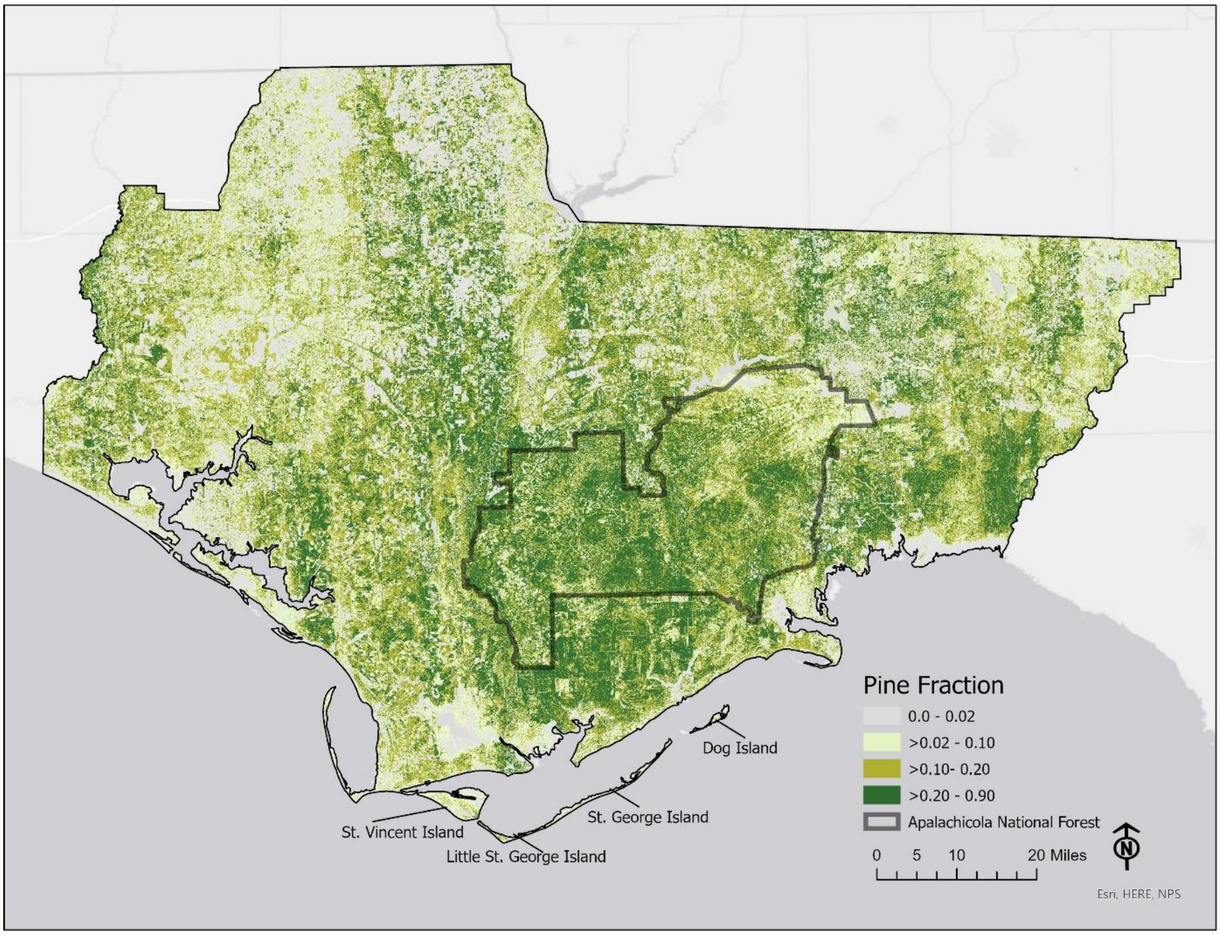

Figure 2. Fraction of cell area in pine (Hogland et al., 2017, St. Peter et al., 2018).

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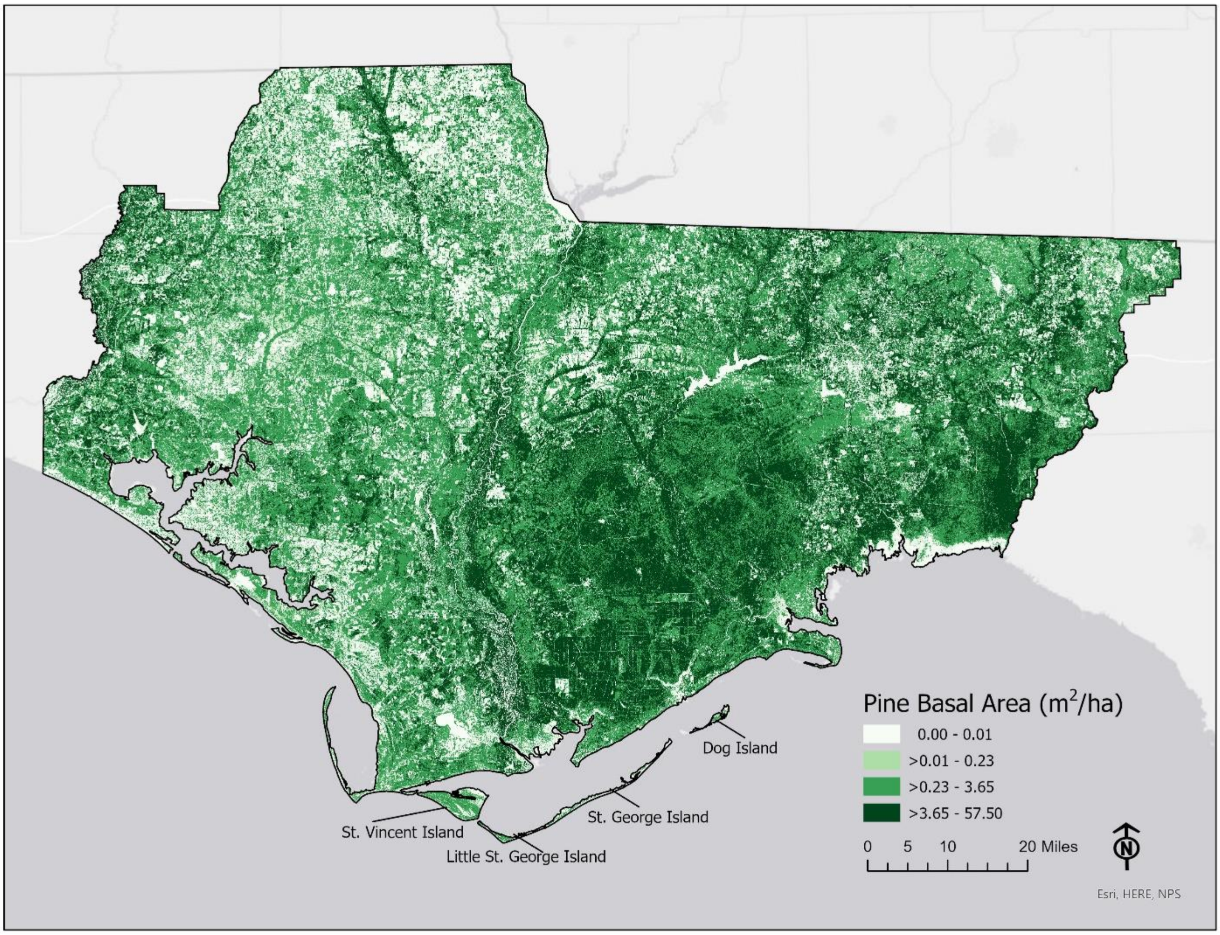

Figure 3. Pine basal area (m2 ha-1) within the study area post-Hurricane Michael (St. Peter et al., 2019, St. Peter et al., 2020).

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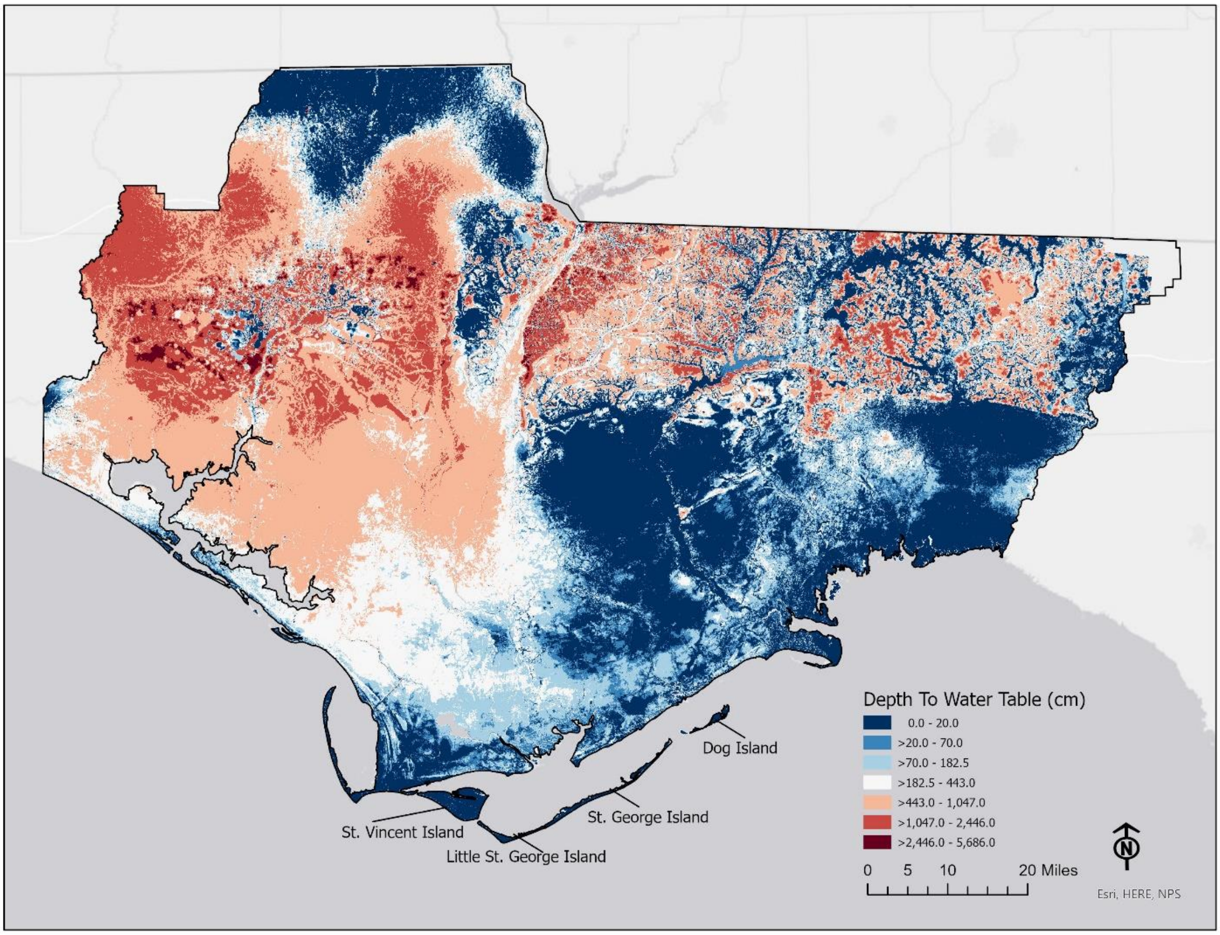

Figure 4. Depth to water for the water-table aquifer (surficial and unconfined Floridan aquifers) in cm in Northwest Florida (FDEP, 2015; Bush and Johnston, 1988).

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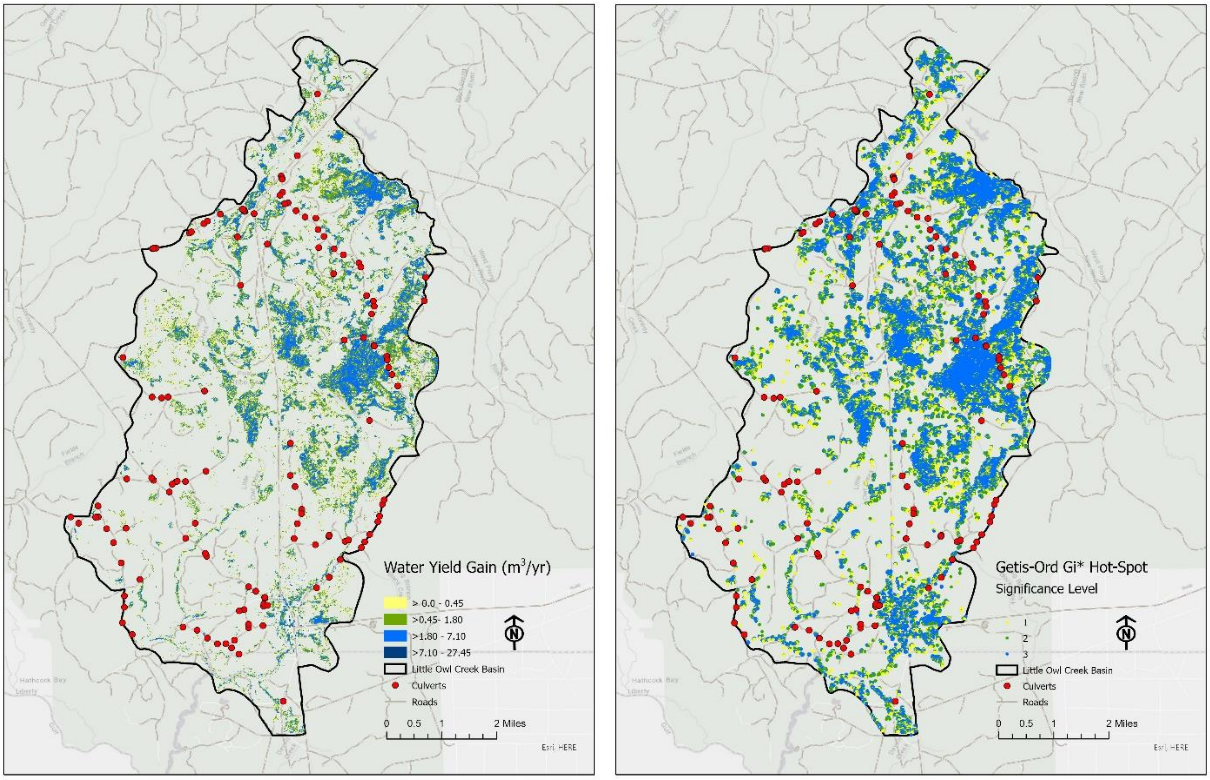
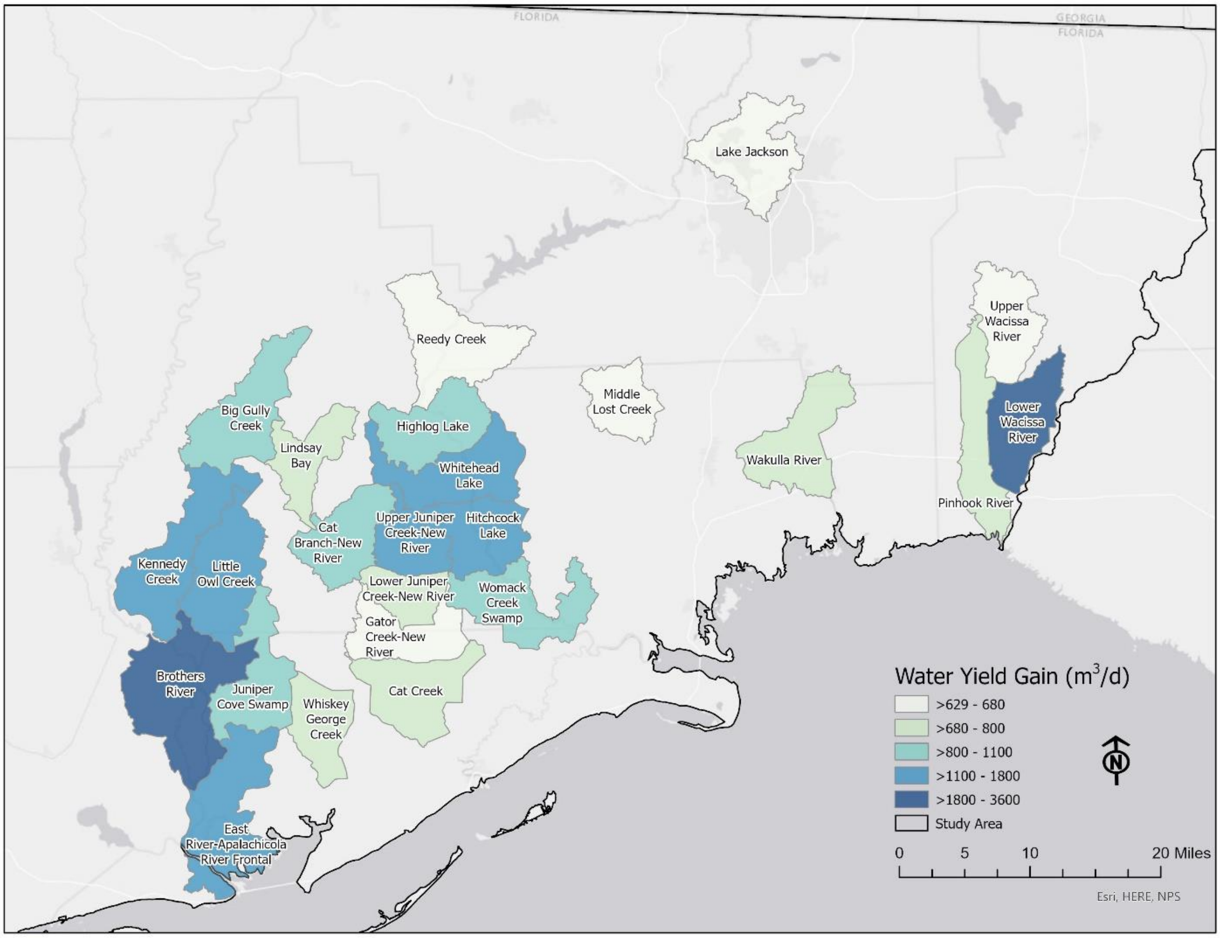


(a) *(b)*

635 **Figures 5 a and b. (a) Estimated water yield gain in m^3 y^{-1} per cell if pine basal areas are reduced from current to less than or equal to 7 m^2 ha^{-1} in the Little Owl Creek basin, culvert locations, and ANF Forest Compartments; (b). Significant Getis-Ord Gi* Hot-Spots within the Little Owl Creek basin—cluster areas where water yield gains are statistically significant if pine basal areas are reduced**


Lake Jackson
Reedy Creek
Upper Wacissa River
Middle Lost Creek
Big Gully Creek
Lindsay Bay
Highlog Lake
Lower Wacissa River
Wakulla River
Whitehead Lake
Pinhook River
Cat Branch-New River
Upper Juniper Creek-New River
Hitchcock Lake
Kennedy Creek
Little Owl Creek
Lower Juniper Creek-New River
Womack Creek Swamp
Gator Creek-New River
Brothers River
Juniper Cove Swamp
Whiskey George Creek
Cat Creek
East River-Apalachicola River Frontal
Water Yield Gain (m³/d)
>629 - 680
>680 - 800
>800 - 1100
>1100 - 1800
>1800 - 3600
Study Area
0
5
10
20 Miles
Esri, HERE, NPS

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(a)

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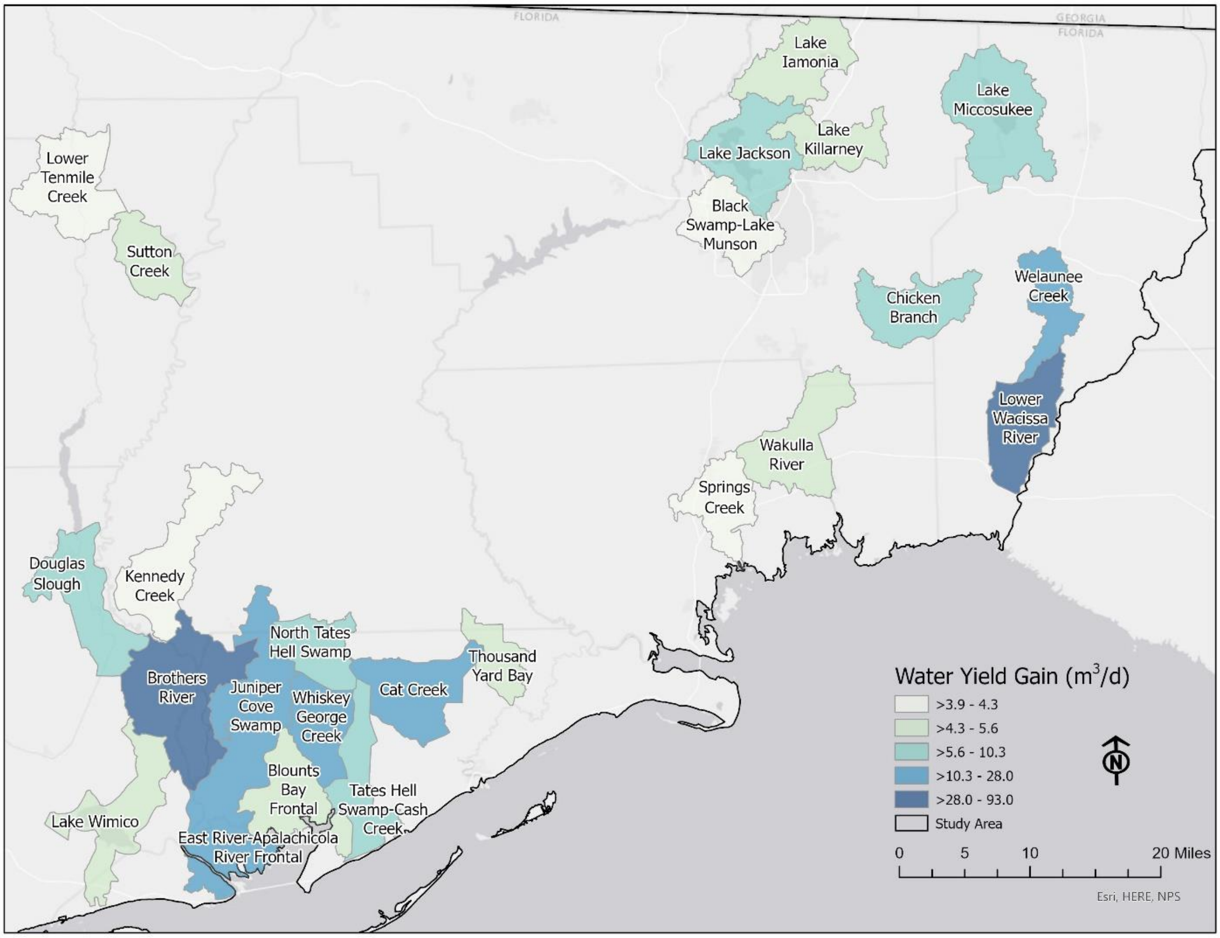

(b)

645 **Figures 6 a and b. Twenty-four of the top twenty-five HUC12 watersheds with the potential to produce the greatest water-yield gains if (a) pine basal areas are reduced from current to a maximum of 7 m^2 ha^{-1} and (b) pine basal areas are reduced from current to a maximum of 18 m^2 ha^{-1}.**

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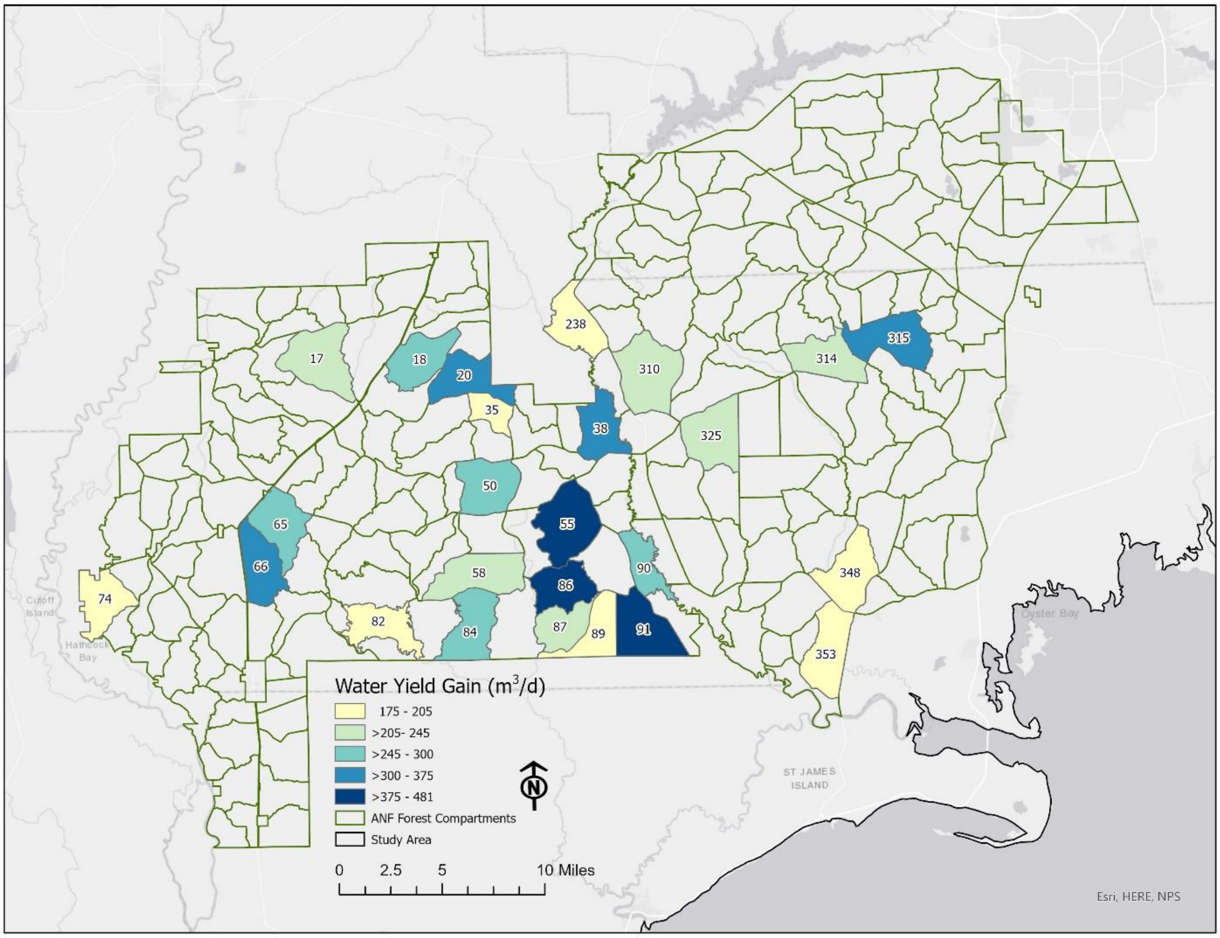

650 *(a)*

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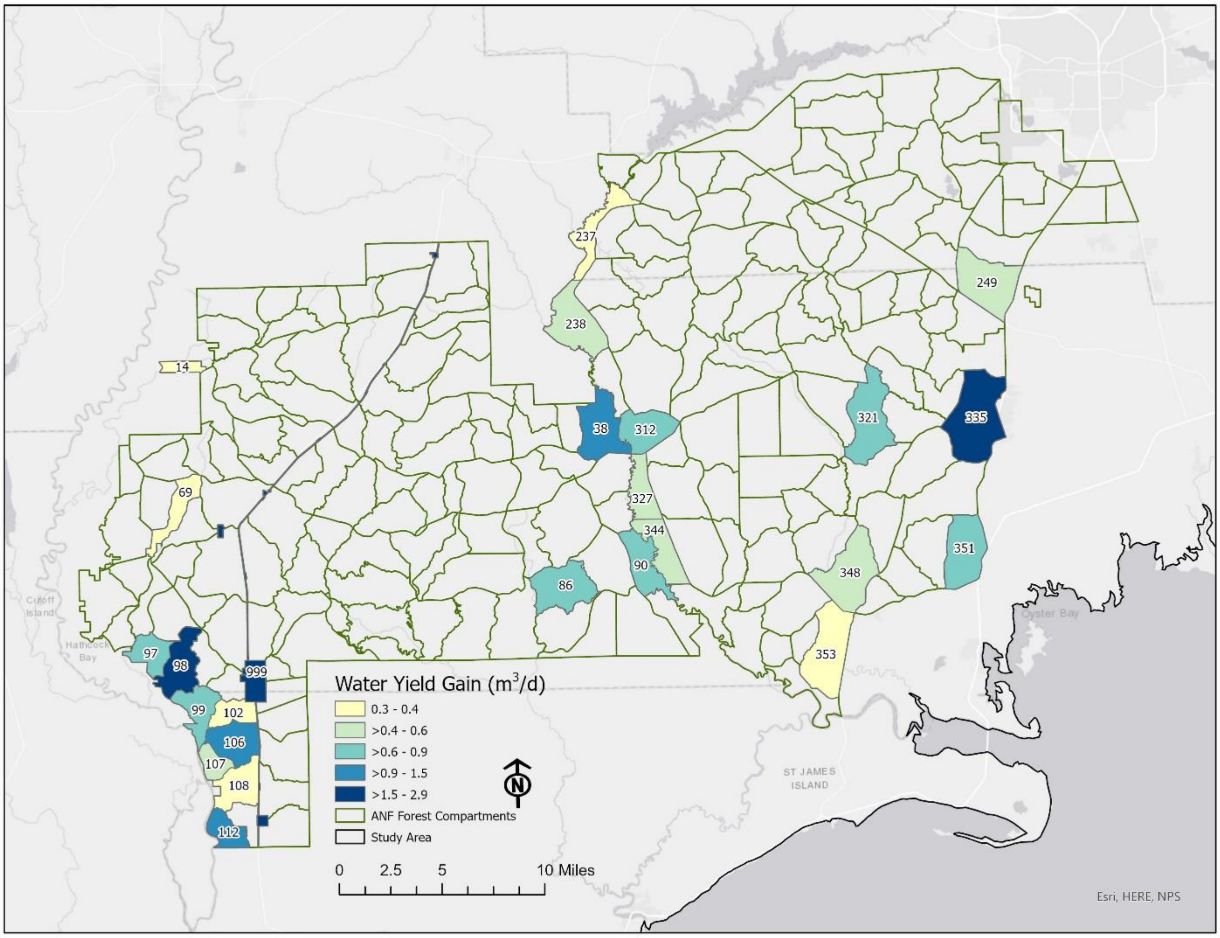

655 **Figures 7 a and b. Forest timber management compartments within the Apalachicola National Forest with the potential to produce the greatest water-yield gains if pine basal areas are reduced from using scenario 1 from current to a maximum of 18 m^2 ha^{-1} and (b) from current to a maximum of 7 m^2 ha^{-1}.**