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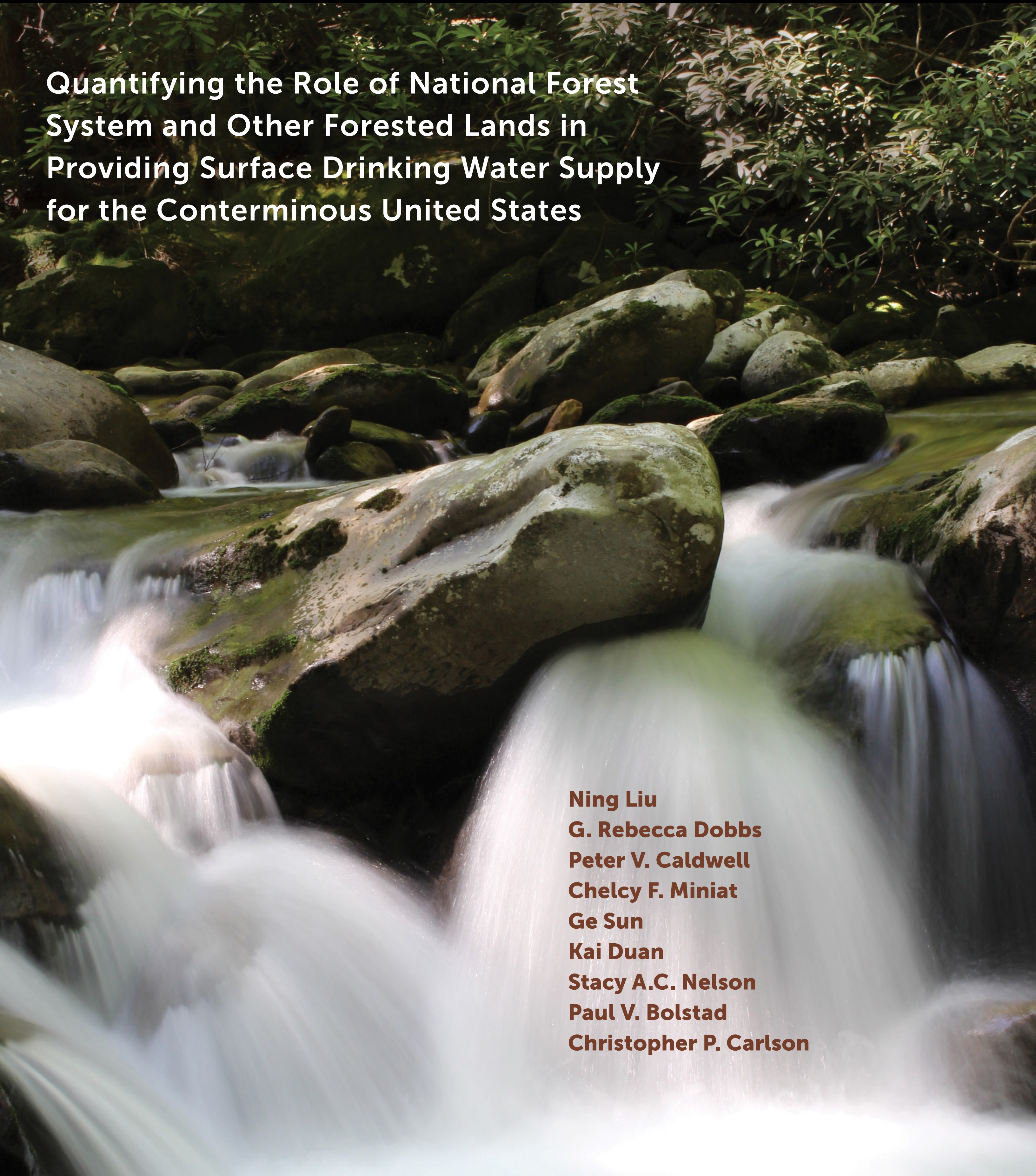

Quantifying the Role of National Forest System and Other Forested Lands in Providing Surface Drinking Water Supply for the Conterminous United States

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ABSTRACT

The U.S. Department of Agriculture's Forest Service manages more than 779,000 km^2 (193 million acres) of national forests and grasslands (collectively, National Forest System [NFS] lands) that play a significant role in providing clean, fresh water for local ecosystems and economies. This water is sometimes transferred hundreds of kilometers away to also serve big cities through inter-basin transfers (IBTs).

The contribution of NFS lands to surface drinking water supplies for public water systems has not been assessed at the national scale while accounting for IBTs. The Forest Service Water Supply Stress Index (WaSSI) model was modified to provide estimates of 2001–2015 mean annual surface water supply and the proportion of mean surface water supply originating on 172 NFS land units and other forested lands at the 12-digit hydrologic unit code scale across the conterminous United States (CONUS) while accounting for water transfer through IBTs. Predictions of the proportion of surface water supply originating on NFS and other forested lands were linked to specific downstream communities and populations, using surface drinking water intake information from the U.S. Environmental Protection Agency Safe Drinking Water Information System database of public water systems.

A new database of 594 IBTs was compiled for this study, ranging from 0.01 million $m^3\ yr^{-1}$ to 8,900 million $m^3\ yr^{-1}$, for a total transferred volume of 116,894 million $m^3\ yr^{-1}$. Overall, NFS lands comprised 9.2 percent of the total CONUS land area but contributed 12.8 percent of the surface water supply. In the West, NFS lands comprised 19.2 percent of the total land area but contributed 46.3 percent of the 478.7 billion $m^3\ yr^{-1}$ surface water supply; in the East, NFS lands comprised about 2.8 percent of the total land area and 3.8 percent (66.6 billion $m^3\ yr^{-1}$) of the surface water supply. In total across the CONUS, NFS and other forested lands comprised 28.7 percent of the total land area but contributed 46.0 percent of the surface water supply. Approximately 45.8 million people derived >10 percent of their surface drinking water supply from NFS lands, and 22.6 million people received >50 percent of their surface drinking water supply from NFS lands. Approximately 125.5 million people, about 39 percent of the total population in the CONUS in 2017, derived >10 percent of their surface drinking water supply from NFS and other forested lands, with 83.1 million people receiving >50 percent of their surface drinking water supply from NFS and other forested lands.

In addition to those populations receiving surface drinking water supply from their local public surface drinking water intakes, 12.6 million people were served by public water systems that purchased surface drinking water supply from other public water systems deriving >10 percent of their surface drinking water supply from NFS lands. This study provides a systematic accounting of NFS and other forested lands for surface drinking water supply. Our results can aid water resource and forest managers in developing integrated watershed management plans at a time when climate change, population growth, and land development threaten water supplies.

Keywords: Drinking water, inter-basin transfers, National Forest System, WaSSI, water supply, water yield.

CONTENTS

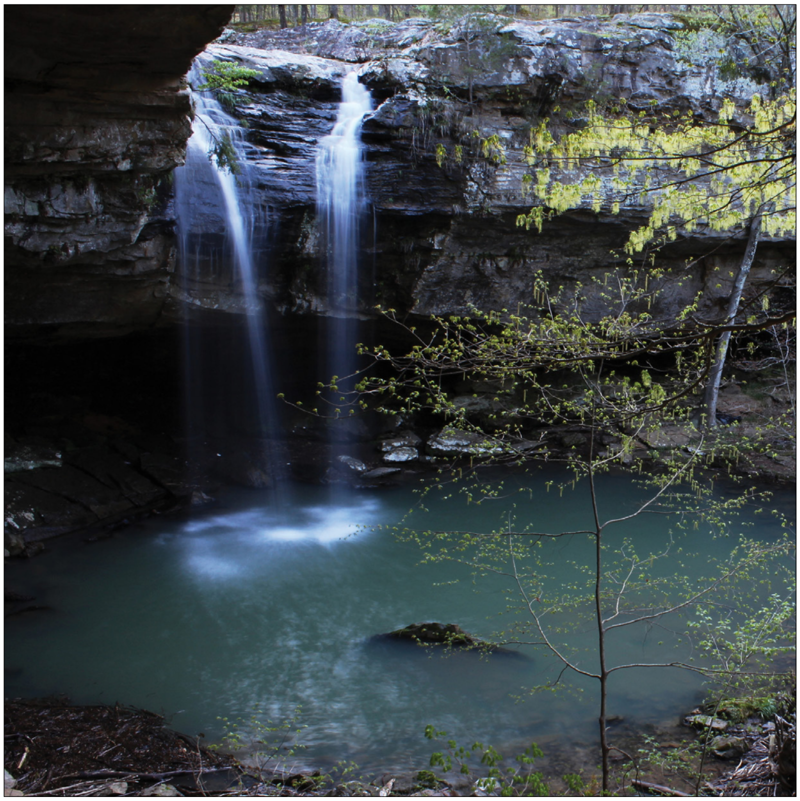
DEFINITIONS

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}.

Surface water supply is calculated by accumulating the total volume of water yield generated over a region, or in the entire river system upstream of a location of interest along the river network (e.g., watershed outlet) and including surface water supply from inter-basin transfers, both assuming that water losses to ground water are negligible. The unit of surface water supply is m^3 yr^{-1}.

Surface drinking water supply is the surface water supply available to a given public water system intake at the location of that intake.

INTRODUCTION



For more than a century, U.S. legislation has emphasized the importance of protecting forests and water resources. Early policymakers in the United States recognized this linkage, writing in the Organic Administration Act of 1897, "No National Forest shall be established, except to improve and protect the forest within the boundaries, or for the purpose of securing favorable conditions of water flows…." Initially, the U.S. Department of the Interior was responsible for identifying and managing these forests, but in 1905 President Theodore Roosevelt transferred this responsibility to the USDA Forest Service. Later, the Weeks Act of 1911, Clarke-McNary Act of 1924, and Bankhead-Jones Farm Tenant Act of 1937 provided the Forest Service with the authority to acquire lands not in the public domain. All three of these acts had water-related objectives and were based on the original purposes outlined in the Organic Act: securing favorable conditions of flow. Similarly, 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. In all of this enabling legislation, the Forest Service has been charged with sustaining and improving water resources through protection, restoration, and enhancement of forested landscapes. The Forest Service currently manages 779,000 km^2 (193 million acres) of public lands in the National Forest System (NFS) across the conterminous United States (CONUS), Alaska, and Puerto Rico, which includes 155 national forests, 20 national grasslands, 20 national recreation areas, 1 national tallgrass prairie, 6 national monuments, and 6 land utilization projects. In addition, the Forest Service cooperates with States, other Federal agencies, Tribes, and private landowners to sustain the Nation's other forests and grasslands.

In addition to generally establishing national forests to improve the condition of water resources, the Organic Act specified that, “Waters within National Forest boundaries may be used for domestic, mining, milling or irrigation purposes, as governed by state or federal law,” suggesting that Congress was concerned about drinking water supply when setting the framework for managing NFS lands. Since then, a century of research has demonstrated unequivocally that forested lands provide the cleanest and most stable water supply compared to other land types (Brogna and others 2018, Dudley and Stolton 2003, Fiquepron and others 2013, Giri and Qiu 2016, Jackson and others 2004, Lockaby and others 2013, Nagy and others 2012). Forested lands have been shown to make significant and disproportionate contributions to the total water supply for downstream communities (Brown and others 2008, 2016; Caldwell and others 2014; Creed and others 2019; Liu and others 2020; Sun and others 2015b; Vose 2019).

Given the many water-related benefits of forested lands (Brunette and Germain 2003, Seattle Public Utilities 2011, Taylor 2018), drinking water utilities are increasingly seeking ways to maintain forested lands to protect water quality and sustain water supply (Warziniack and others 2017). Water stress is a growing concern in the United States (Sun and others 2008) and elsewhere (Gosling and Arnell 2016, Vörösmarty and others 2000). Already common in the arid U.S. West, water stress is predicted to increase even in the water-rich U.S. South with rapid population growth and climate change (Brown and others 2019). Annual total water withdrawal in the United States increased from about 300 billion m^3 in 1950 to 580 billion m^3 in 2010 (Dieter and Maupin 2017), coinciding with a doubling of the U.S. population (U.S. Census Bureau 2010). Even though per capita and total water consumption have decreased since 1980 in the CONUS (Dieter and Maupin 2017), water demand is projected to grow with population, and water withdrawals are expected to continue to increase (Brown and other 2013), except in areas where water supply is already overallocated.

Apart from increasing water demand, population growth will also affect the quality of water supply as forests are converted to developed areas (Tu 2013). Exurban growth (i.e., the increase in population and associated land development near the edges of existing developed land) is the most persistent and permanent land use change threatening water quality even at low development densities (Stein and others 2009). This type of development increased considerably over the past 4 decades, with increasing development beyond the suburban fringe (Homer and others 2020, Radeloff and others 2005, Theobald 2005). About one-third of the land in the United States is now covered by forests, after declining from an estimated 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 2019). Although the total amount of forest area in the CONUS has stabilized in recent decades (D’Annunzio and others 2015), forested lands are predicted to decline as the population grows (Wear and others 2013). Consequently, improving water supplies has been recognized as one of the important goals in forest and water management (Sun and Vose 2016). Managing forests for water resources under land development pressure and climate change is a major challenge in natural resource management in the 21st century (Haddeland and others 2014, National Research Council 2008, Vose 2019).

Although the basic forest and water relationship is well documented, quantifying forest water resources at a national level is rarely done due to the complexity of climate, hydrologic processes, forest structure, land use/land cover, and water use. Water yield from forests is generated when precipitation is more than sufficient to meet evapotranspiration (ET) needs, resulting in downstream surface water supply that supports ecosystems and people (Sun and others 2002). Forest removal commonly results in short-term increased water yield due to reduced ET, in proportion to the percentage of the watershed cut or forest basal area removed (Andréassian 2004, Bosch and Hewlett 1982, Sun and others 2005), while afforestation generally decreases water yield (Andréassian 2004, Farley and others 2005, Filoso and others 2017) due to greater ET rates in forests compared to other vegetation types.

The spatial distribution of forest and land cover and land use change is expected to affect surface water supply for downstream communities (Greene and others 2013). Forest conversion to residential, commercial, and agricultural uses reduces water quality (Mapulanga and Naito 2019, Moore and others 2005) and increases runoff and flood risk (Li and others 2020). Privately owned forests are increasingly vulnerable to urban development (McNulty and others 2013), which will have implications for both water quantity and water quality (Li and others 2020, Martinuzzi and others 2014). Decades of research has shown that, in general, the greater the forest coverage in a watershed, the higher the water quality (Giri and Qiu 2016, Tu 2013).

Forest management, which can differ considerably based upon forest ownership, can affect surface water supply via changes in the magnitude and timing of water yield as well as the quality of that water (Sun and Vose 2016). Forest ownership patterns differ between the eastern and western regions of the United States, with implications for surface water supply and watershed management. While the Federal Government owns 1.7 million km^2 of forested land in the CONUS, most of it (89 percent) lies in the 11 Western contiguous States. In contrast, most of the forested land in the Eastern United States is privately owned. For example, State and private forests—forests owned by State and local governments, corporations, families, and other private entities—account for about 90 percent of the total forested land area across the South. Federally owned forests are managed for multiple uses including timber production, habitat, and other ecosystem services, while corporately owned forests (26 percent of the total forested land in the South) are generally managed to maximize timber production.

Natural watershed hydrology is not only affected by forest management but also by water diversion and human-made hydraulic structures. Water from forested lands can be transferred to other regions through inter-basin transfers (IBTs) to meet demand where supply is scarce or where raw water quality is paramount (McDonald and others 2014). New York City, for example, imports approximately 90 percent of its water from the Catskill and Delaware watersheds (NYC Environmental Protection 2017), while Los Angeles obtains >90 percent of its water from multiple sources hundreds of kilometers away (Ashoori and others 2015). Dickson and Dzombak (2017) identified 2,161 IBTs crossing 6-digit hydrologic unit code (HUC6) watershed boundaries in the United States using the U.S. Department of the Interior, U.S. Geological Survey (USGS) National Hydrography Database (NHD) (Moore and Dewald 2016), with about 300 IBTs driven by city water use. However, the volumes of water transferred by each identified IBT were not quantified. Without considering these IBTs, the magnitude and spatial extent of forest influence on surface drinking water supplies are misrepresented (Emanuel and others 2015). Clearly, a detailed, spatially explicit, national-scale IBT database is needed to accurately assess the contribution of water originating on forested lands to surface drinking water supplies.

This study aims to quantify the contribution of NFS and other forested lands to surface drinking water supply systems in the CONUS. As such, we (the researchers and authors of this report) estimated the surface water supply and the origin of that water at each public surface drinking water intake using a water balance model while accounting for natural water drainage throughout the river network as well as water transferred through IBTs. Our objectives were to: (1) estimate how much surface water supply originated from NFS and other forested lands across the CONUS; and (2) estimate how many people and which communities receive this surface drinking water supply, both with and without IBTs. Results presented here supersede those presented in Caldwell and others (2014) for NFS and other forested lands in the South and are complementary to those in Liu and others (2020) that provide detailed information on surface drinking water supply from southern forested lands by ownership type. This study is the first attempt to evaluate benefits of NFS and other forested lands to public surface drinking water intakes across the CONUS while accounting for IBTs.

METHODS

Extent and Scale of Analysis

This study focused on surface water supply originating on 151 national forests, 20 national grasslands, and 1 national recreation area (hereafter collectively referred to as NFS land) as well as other forested lands, and how that water contributes to surface drinking water supply at public surface drinking water intakes across the CONUS. We focused on surface water supplies because we could not be certain of the origin (i.e., forested land versus nonforested land) of ground water for any given water supply well at this large scale. Depending on local factors such as well depth, elevation gradients, and aquifer characteristics, ground water may originate from near where it is withdrawn or from some distance away. We quantified the proportion of surface drinking water supply serving a given public surface drinking water intake that originated on each NFS unit and other forested lands (fig. 1). The boundaries of the 172 units of NFS lands were derived from the Forest Service Basic Ownership dataset (table 1). Similar to Caldwell and others (2014), other forested lands not part of NFS lands were defined by the 2006 National Land Cover Database (NLCD) (table 1) and include deciduous, evergreen, and mixed forest.

The spatial resolution of our analysis was the 12-digit, or sixth-level, hydrologic unit code (HUC12) watershed scale. There are approximately 82,000 HUC12s in the CONUS, with a mean area of 100 km². In addition to the HUC12s in the CONUS, watersheds in Canada and Mexico that drain to the CONUS were included so that the total flow volumes and proportion of flow originating on NFS and other forested lands near international borders could be properly estimated. The NFS lands include approximately 15,352

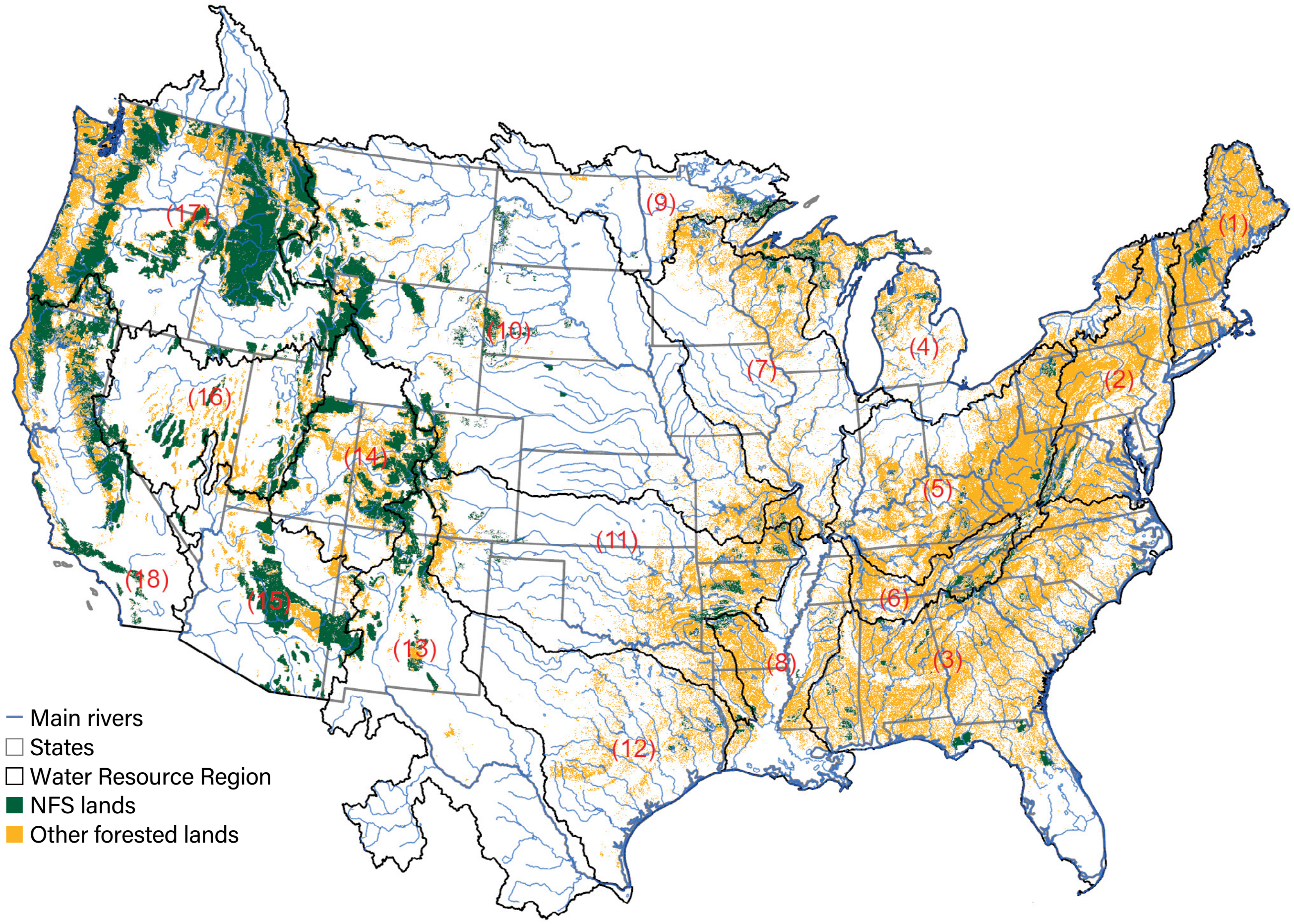


Figure 1—National Forest System (NFS) lands, other forested lands, and the land area simulated to estimate total surface water supply and the amount of that water supply originating on NFS and other forested lands serving public surface drinking water intakes in the conterminous United States. Labels on the map are Water Resource Regions, including: 1 (New England), 2 (Mid-Atlantic), 3 (South Atlantic-Gulf), 4 (Great Lakes), 5 (Ohio), 6 (Tennessee), 7 (Upper Mississippi), 8 (Lower Mississippi), 9 (Souris-Red-Rainy), 10 (Missouri), 11 (Arkansas-White-Red), 12 (Texas-Gulf), 13 (Rio Grande), 14 (Upper Colorado), 15 (Lower Colorado), 16 (Great Basin), 17 (Pacific Northwest), and 18 (California). Source: Liu and others 2022.

HUC12 watersheds, and there are about 16,162 watersheds downstream of those NFS lands. The relative contribution of NFS and other forested lands to the surface water supply was calculated for every HUC12 through each river network.

Estimating Surface Water Supply From National Forest System and Other Forested Lands

The surface water supply from each land cover type in a HUC12 was estimated using the Water Supply Stress Index (WaSSI) hydrologic model (Caldwell and others 2011, 2012; Sun and others 2011a). The WaSSI model has been tested, validated, and compared to other water balance models (Caldwell and others 2012, 2015, 2020; Li and others 2020; Schwalm and others 2015; Sun and others 2011a, 2011b; Sun and others 2015a). It has been used in several regional- and national-scale water resource assessments (Duan and others 2018, 2019; Li and others 2020; Lockaby and others 2013; Marion and others 2013; Sun and others 2015b, 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 State and private forest lands (Liu and others 2020) in the South, and in studying the impacts of historical drought on national forests and grasslands (Sun and others 2015b) across the CONUS.

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 (SAC-SMA) soil parameters National Oceanic and Atmospheric Administration, National Weather Service, Office of Hydrologic Development, Hydrology Laboratory	1- x 1-km grid	N/A
Impervious cover for the conterminous United States	National Land Cover Database (NLCD) 2006 Percent Developed Imperviousness (CONUS) (https://www.mrlc.gov/data/nlcd-2006-percent-developed-imperviousness-conus)	30- x 30-m grid	2006
Impervious cover for areas outside the United States	Global Man-made Impervious Surface (GMIS) Dataset from Landsat, v1 (2010) (https://sedac.ciesin.columbia.edu/data/set/ulandsat-gmis-v1/data-download)	30- x 30-m grid	2010
National Forest System	U.S. Department of Agriculture, Forest Service, Automated Lands Program Land Status Record System surface ownership parcels (Basic Ownership dataset) (https://data.fs.usda.gov/geodata/edw/edw_resources/meta/S_USA.BasicOwnership.xml)	Parcel	2013
Land cover	National Land Cover Database (NLCD) 2006 (CONUS) (https://www.mrlc.gov/data/nlcd-2006-land-cover-conus)	30- x 30-m grid	2006
Monthly mean leaf area index (LAI) by land cover	Moderate Resolution Imaging Spectroradiometer (MODIS) (https://modis.gsfc.nasa.gov/)	1- x 1-km grid	2001–2012
Climate (monthly precipitation and temperature) for the conterminous United States	PRISM Climate Group (http://www.prism.oregonstate.edu/)	4- x 4-km grid	2001–2015
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	2001–2015
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.

The WaSSI model is parameterized using readily available national-scale soil, land cover, and climate data (table 1). All input datasets were spatially rescaled using an area-weighted averaging scheme to match the scale of analysis (i.e., HUC12 watershed scale). 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 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 that 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 on the impervious portion of a watershed is assumed to be runoff and is routed directly to the watershed outlet. While this assumption may overestimate the effect of impervious cover on water yield in some locations, it was necessary because we could not be certain about the amount of water storage on impervious surfaces or their connectivity to surface water at the national scale. 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 surface water supply at the outlet of each respective HUC12. The surface water supply is the sum of the water yield generated in all HUC12s upstream of a given location on the river network and expressed in m^3 yr^{-1}.

For this analysis, we overlaid the ca. 2013 NFS land ownership parcels on NFS administrative boundaries, the HUC12 boundaries, the NLCD, and the Moderate Resolution Imaging Spectroradiometer (MODIS) LAI model inputs to make a unique land cover category for NFS lands. The NFS land ownership parcels differ from NFS administrative forest boundaries in that NFS land ownership parcels contain only those parcels owned by the NFS, whereas the land in the NFS administrative boundaries includes all lands within the boundary regardless of whether the NFS owns the land. For example, the administrative boundary for the Nantahala National Forest includes the town of Franklin, NC, but the NFS does not own the land in the town. We also quantified the contribution of other (non-NFS) forested lands to surface water supply. Similar to Caldwell and others (2014), forested lands in the NLCD including deciduous, evergreen, and mixed forest were aggregated to represent other forests that are not part of NFS lands. We present our water supply results for three categories: (1) NFS lands alone, (2) NFS lands and other forested lands, and (3) other lands that are neither NFS lands nor forested land as described by the NLCD (e.g., crop land, developed land, etc.). It should be noted that the NFS lands evaluated in this study include both national forests and national grasslands (though the latter comprise only 2.3 percent of all NFS lands) as well as one national recreation area. In addition, the other forested lands based on the NLCD do not include woody wetlands or areas with young trees in early succession or trees stunted by environmental conditions, which would be classified as shrubland in the NLCD (Homer and others 2015). We revised the WaSSI flow routing algorithm to track surface water supply from NFS lands, NFS and other forested lands, and other lands through the river network (fig.1) at the monthly time step from 2001 through 2015 over all HUC12 watersheds. The years 2001 and 2015 were selected because they roughly corresponded to the drinking water population-served estimates and IBT database (discussed below). The mean annual surface water supply and the fraction of mean annual surface water supply originating on NFS and other forested lands were quantified for each HUC12 watershed. In addition to a CONUS-wide assessment, we quantified the surface water supply originating on each individual national forest, national grassland, and national recreation area in isolation.

Linking Water Yield From Forested Lands to Public Surface Drinking Water Intakes

The surface water supply originating on NFS and other forested lands was linked to communities and populations served using the 2017 Quarter 3 version of the U.S. Environmental Protection Agency (EPA) Safe Drinking Water Information System (SDWIS) database of public water systems (U.S. EPA 2017), which contains information on those water systems such as intake locations, population served, water source, and system type (residential or other). Public water system (PWS) surface drinking water intakes in the SDWIS database were screened for obvious locational errors, and only those facilities meeting the following criteria were included in the analysis: (1) facilities associated with a PWS serving a population of at least 25 people, (2) facilities associated with a PWS whose primary source was denoted as "surface water" or "ground water under the influence of surface water," and (3) facilities whose facility-level water type was denoted as "surface water" or "ground water under the influence of surface water."

Many PWSs that depend on surface water do not have public surface drinking water intakes of their own but rather purchase their surface water supply from other PWSs. We also identified those PWSs purchasing surface water supply directly from a selling PWS that obtained some of their surface water supply from NFS and other forested lands. We could not quantify the proportion of surface water supply from forested lands for these purchasing PWSs because the water volume of the purchases is not available at the scale of this study. Instead, we identified those PWSs that purchase water from a selling PWS that receives some portion (i.e., ≥0.01 percent) and >10 percent of their surface drinking water supply from NFS and other forested lands. Criteria for inclusion of a purchasing PWS were (1) a selling PWS was identified, (2) the purchasing PWS's primary source was denoted as "surface water" or "ground water under the influence of surface water," (3) the purchasing PWS's facility-level water type was denoted as "surface water" or "ground water under the influence of surface water," and (4) the purchasing PWS did not have their own surface water facilities and thus were not already in our database of PWSs.

The population served in the SDWIS database is attributed to the PWS as opposed to specific intakes within a system. When calculating population served by water from NFS and other forested lands, we aggregated the surface drinking water supply across all intakes for each PWS by calculating the total available surface drinking water supply and the total surface drinking water supply from NFS and other forested lands across all intakes for the PWS. When intakes were displayed on maps (e.g., fig. 2), we divided the total population served by the PWS equally among the intakes for that system. As a result, our representations of population served differ spatially from local data in some instances and may overrepresent or underrepresent the proportion of the population served for a given intake.

The final database used in this analysis included 8,910 public surface drinking water intakes across 5,041 PWSs (fig. 2) serving a total population of 137.9 million people (43 percent of the approximately 323 million people living in the CONUS in 2017 [U.S. EPA 2017]). Most of the remainder of the CONUS population obtains drinking water supplies from ground water sources or purchased surface water supplies from other PWSs. In total, there were 8,412 PWSs that purchase surface water supply from other PWSs through 12,290 consecutive connection or nonpiped facilities serving 73.2 million people in the CONUS. We overlaid the public surface drinking water intakes on the HUC12 watershed boundaries and assumed that the WaSSI-estimated proportion of water from NFS and other forested lands at the outlet of the HUC12 watershed in which a given intake was located was representative of the intake location. This assumption might not be accurate for those intakes located on a tributary and not on the HUC main stem but was necessary because, like other semi-distributed hydrologic models, WaSSI estimates surface 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 NFS and other forested lands 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 surface water supply from NFS and other forested 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 NFS and other forested lands as that of the first HUC12 watershed on the main stem downstream of the water supply reservoir.

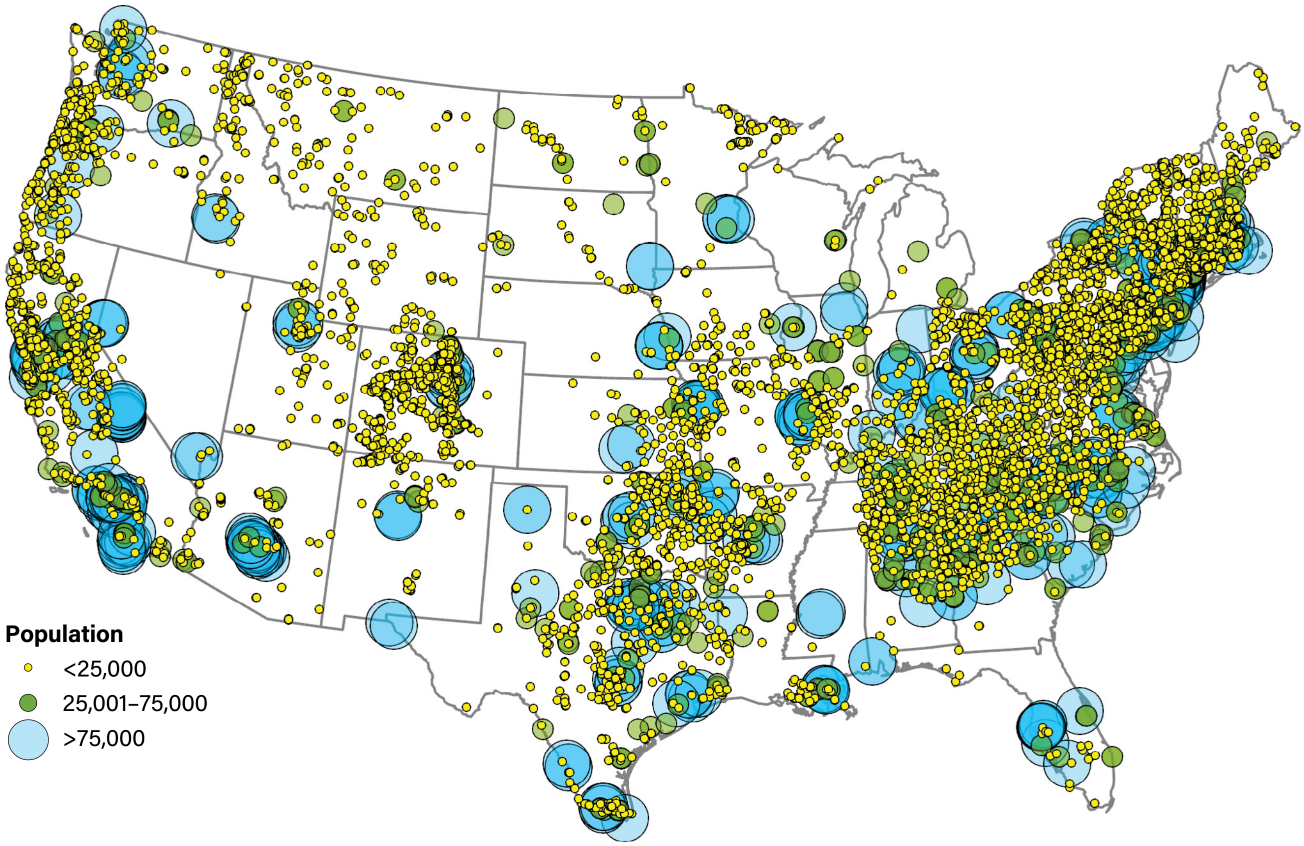


Figure 2—The 8,910 public surface drinking water intakes in the study area based on the U.S. Environmental Protection Agency Safe Drinking Water Information System database of public water systems. Intakes are sized and colored according to the populations that receive water from these intakes. These intakes collectively serve 137.9 million people or 43 percent of the total population in the conterminous United States.

Inter-Basin Surface Water Transfers

The most comprehensive national-scale database of IBTs in the CONUS was compiled in the 1980s by the USGS (Mooty and Jeffcoat 1986, Petsch 1985). This database was generated from survey questionnaires at the State level and considered all IBTs that crossed HUC6 boundaries, while identifying source and destination basins at the 8-digit hydrologic unit code (HUC8) scale. In all, there were 256 IBTs in this inventory with annual transfer flow volumes based on estimates from 1973 through 1982. While dated, this database has been widely used for national-scale water resource assessments (e.g., Brown and others 2019, Duan and others 2019, Emanuel and others 2015). More recently, Dickson and Dzombak (2017) created a CONUS-wide database of 2,161 potential IBT locations at the HUC6 level by identifying artificial connections in the NHD that crossed HUC6 boundaries but did not estimate transfer flow volumes for these potential IBTs. For the present study, it was necessary to identify source and destination watersheds at a much finer spatial resolution than HUC6 in some areas due to the numerous transfers from sometimes small watersheds that divert surface water supply from forested watersheds to municipal drinking water utilities. In addition, more contemporary IBT flow volumes were desired that are reflective of current surface water supply magnitudes and water uses. To meet this need, we compiled a new IBT database for the CONUS informed by previous inventories and the SDWIS but with updated transfer flow volumes and added spatial resolution where needed as described below.

The process of building the IBT database began with researching anthropogenic water movement in a given area in order to understand the spatial parameters and interconnectivity of transfers. From this, we determined what volumetric data we needed to acquire, after which we approached the numerous agencies managing the relevant data (table 2). After acquiring data, we processed it as needed for consistency of units and time, and for fit into the transfer steps we previously identified. Units of measurement in the IBT database are million m^3 for transfer volume and an annual time step, covering the 30 years from 1986 through 2015 whenever possible.

In the Upper Colorado Region (Water Resource Region [WRR] 14), where water transfers are ubiquitous and vary greatly in spatial and volumetric scope (Mooty and Jeffcoat 1986, Petsch 1985), we recognized an IBT when water was made to cross the boundaries of HUC12s. That is, if surface water was transferred from one HUC12 to another, the transfer was considered an IBT and was included in the database. In the remainder of the CONUS, we generally did not consider transfers as IBTs unless they crossed HUC8s because IBTs outside of the Upper Colorado River Basin tend to draw from larger water sources; exceptions occur where important systems cannot be understood without resorting to a HUC12 scale for defining IBTs, such as the Atlanta, GA, area and parts of the California Region (WRR 18). In all cases, regardless of IBT definition scale, we identified HUC12s as the origins and destinations of IBTs. We further defined IBTs as ending when water reached its treatment plant (for municipal and industrial uses) or the apparent end of irrigation infrastructure in the case of agricultural uses. As such, our IBT database is not intended for full water budget work. Irrigation transfers were generally included only when prominent and/or integrated within a complex system that included drinking water supplies. Because our main interest was in drinking water supply and the populations intertwined with it, outside of the Upper Colorado Region (WRR 14), we filtered potential systems incorporating IBTs by population served, using a threshold of 200,000 people served based on the 2017 EPA SDWIS data on public surface drinking water intakes. Using this approach, some IBTs that transfer water originating on NFS and other forested lands to public surface drinking water intakes may not be included in our database. However, this level of screening for potential IBTs was necessary to balance our investigation effort with providing a reasonable representation of the movement of water from NFS lands by IBTs.

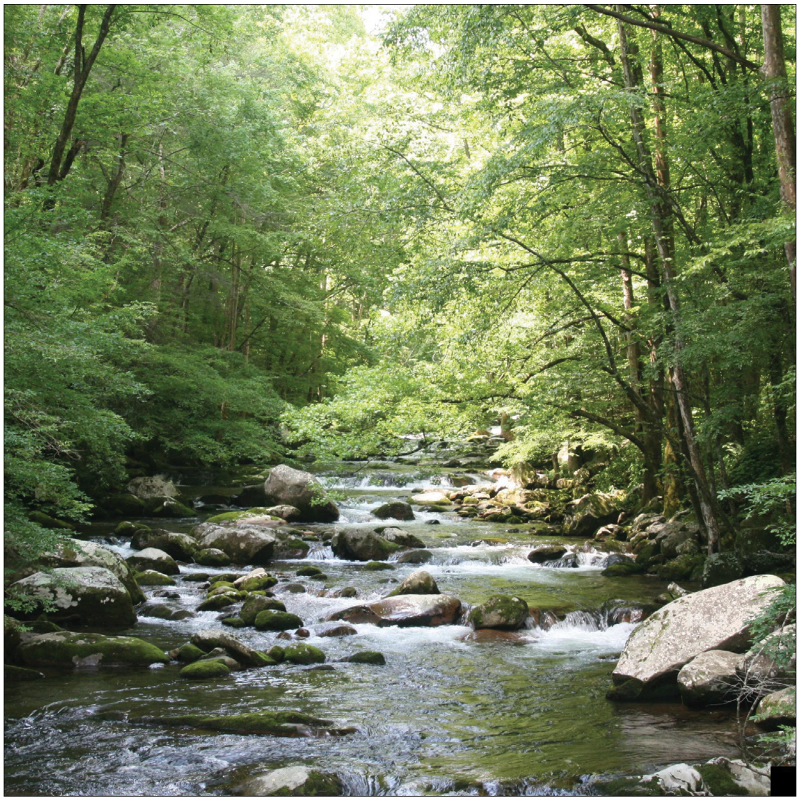
We modified the WaSSI model to account for surface water transfer through IBTs by incorporating the transfer from the source to the destination HUC12 for all IBTs in the flow accumulation calculations. In this way, the surface water supply from NFS and other forested lands of all HUCs affected by a given IBT was updated based on the amount of surface water transferred through the IBT in the source and destination HUC12 as well as those downstream.

Table 2—Data sources for inter-basin transfer volumes

Agency name	Level	Accessed via
Alabama Office of Water Resources	State	Request
Arizona Department of Water Resources	State	Online report documents
Aurora (CO) Water	Municipal	Request
California State Water Project	State	Online report documents
Central Arizona Project	Regional	Request
Central Arkansas Water (in/serving Little Rock, AR)	Municipal	Request
Charlotte (NC) Water	Municipal	Request
City of Sacramento (CA)	Municipal	Request
Coachella Valley (CA) Water District	Regional	Online report documents
Colorado Decision Support Systems	State	Online public data server
Colorado Springs (CO) Utilities	Municipal	Request
Denver (CO) Water	Municipal	Online report documents; request
Des Moines (IA) Water Works	Municipal	Request
East Bay Metropolitan Utilities Department (CA)	Regional	Request
Georgia Environmental Protection Division	State	Request
Greater Cincinnati (OH) Water Works	Municipal	Request
Los Angeles (CA) Department of Water and Power	Municipal	Request
Massachusetts Water Resources	State	Request
Metropolitan District Commission (CT)	Regional	Request
Metropolitan Utility District of Omaha (NE)	Municipal	Request
Metropolitan Water District of Southern California (in/serving parts of Greater Los Angeles, CA)	Regional	Request
New Mexico Office of State Engineer	State	Online public data server
New York City (NY) Open Records[a]	Municipal	Request
Northern Water (CO)	Regional	Request
Oklahoma Water Resources Board	State	Request
Sabine River Authority of Louisiana	Regional	Request
San Francisco (CA) Public Utilities Commission	Municipal	Request
South Carolina Department of Health and Environmental Control	State	Request
Texas Water Development Board	State	Request
U.S. Department of the Interior, Bureau of Reclamation[b]	Federal	Online public data server; online report documents; request
U.S. Department of the Interior, U.S. Geological Survey	Federal	Online public data server; online report documents
Utah Division of Water Rights	State	Online public data server
Virginia Department of Environmental Quality	State	Request
Wyoming State Engineer's Office	State	Online report documents

[a] Some New York City data are also from U.S. Geological Survey, including historical reports.
[b] Multiple Bureau of Reclamation offices and projects.

RESULTS



Water Yield and Surface Water Supply From National Forest System and Other Forested Lands

Mean annual (2001–2015) water yield showed clear spatial patterns between the 11 Western States (West) and the 37 Eastern States (East) (fig. 3A). The predicted mean annual water yield in the East ranged from <200 mm yr^{-1} in the Great Plains to >1,000 mm yr^{-1} in the high-elevation Appalachian Mountains; in the West, it was generally <200 mm yr^{-1}, except in the Northwest Coast and a few other high-precipitation areas (fig. 3A). The annual surface water supply ranged from zero in watersheds in arid and semi-arid areas to about 28.9 billion m^3 yr^{-1} at the outlet of the Colorado River in the West and to about 801.4 billion m^3 yr^{-1} at the outlet of the Mississippi River in the East (fig. 3B).

In comparison with other land cover types, NFS and other forested lands produce disproportionate contributions to the surface water supply across the CONUS (table 3 and figs. 3 and 4). National Forest System and other forested lands comprised 28.7 percent of the total CONUS land area but contributed 46.0 percent of the surface water supply. Alone, NFS lands comprised 9.2 percent of the total CONUS land area and provided 12.8 percent of the surface water supply.

National Forest System lands are the main water resource in the West, while other forested lands dominate the water supply in the East. In the West, NFS lands accounted for 19.2 percent of the total land area and contributed 46.3 percent of the 478.7 billion m^3 yr^{-1} surface water supply generated there. In contrast, in the East, >90 percent of forested lands are other forested lands, which provided 35.0

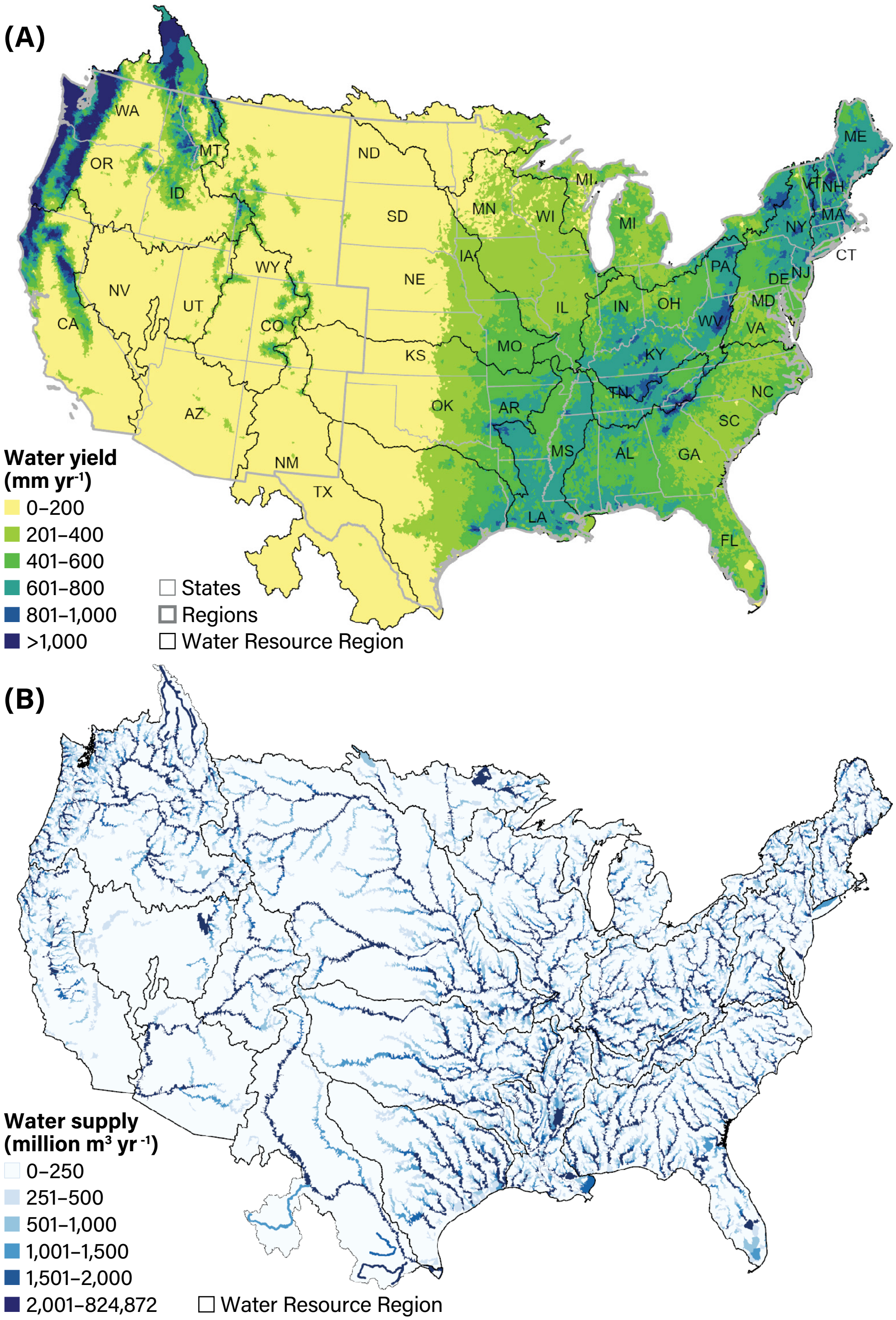


Figure 3—(A) Estimated 2001–2015 mean annual water yield in mm yr^{-1} and (B) surface water supply in millions of m^3 yr^{-1} by 12-digit (sixth-level) hydrologic unit code (HUC12) watersheds. The HUCs in (B) are colored by the magnitude of available water supply at the watershed outlet.

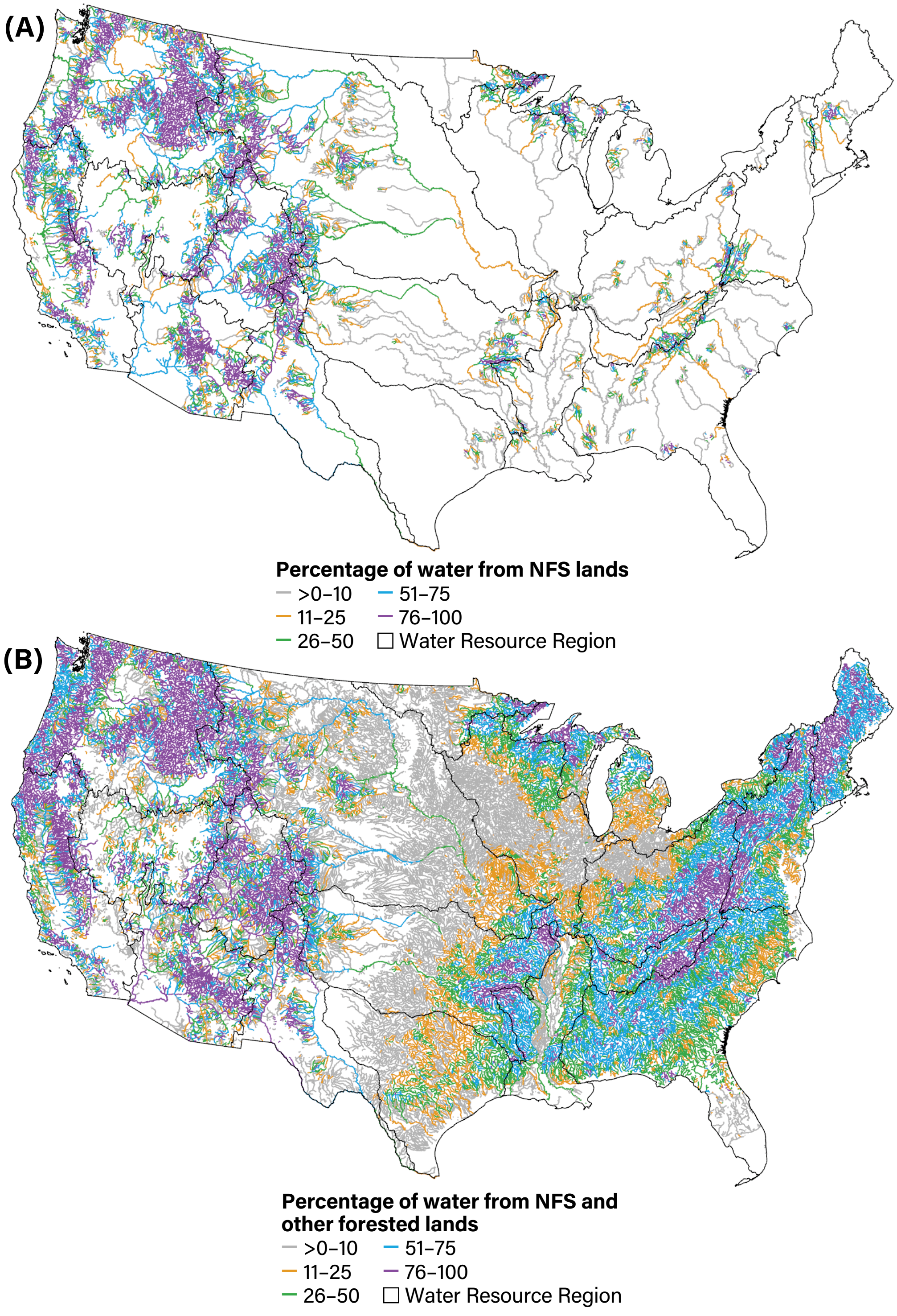


Figure 4—Percentage of the total 2001–2015 mean annual surface water supply that originated on (A) National Forest System (NFS) lands and (B) NFS and other forested lands by hydrologic unit code (HUC) watershed streamlines. Surface water supply is the total amount of surface water available at the outlet of each HUC watershed, including flow accumulated from HUCs upstream after accounting for inter-basin transfers. Streamlines of HUC12 (12-digit [sixth-level]) watersheds are colored according to the fraction of total water supply at the watershed outlet that originated on (A) NFS lands and (B) NFS and other forested lands. Source for (B): Liu and others 2022.

Table 3—Summary of water supply from National Forest System (NFS) and other forested lands in the conterminous United States (CONUS)

	West[a]	East[b]	CONUS
Total land area (million km^2)[c]	3.1	4.7	7.8
Total land area in NFS lands (million km^2) (percentage of the total)	0.6 (19.2%)	0.1 (2.8%)	0.7 (9.2%)
Total land area in NFS and other forested lands (million km^2) (percentage of the total)	0.9 (29.7%)	1.3 (28.1%)	2.2 (28.7%)
Mean total annual water supply (billion m^3 yr^{-1})[c]	478.7	1,769.4	2,248.1
Mean total annual water supply originating on NFS lands (billion m^3 yr^{-1}) (percentage of the total)	221.4 (46.3%)	66.6 (3.8%)	288.1 (12.8%)
Mean total annual water supply originating on NFS and other forested lands (billion m^3 yr^{-1}) (percentage of the total)	347.2 (72.5%)	687.3 (38.8%)	1,034.6 (46.0%)

[a] Includes 11 Western U.S. States (Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming).

[b] Includes 37 Eastern U.S. States (Alabama, Arkansas, Connecticut, Delaware, Florida, Georgia, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Nebraska, New Hampshire, New Jersey, New York, North Carolina, North Dakota, Ohio, Oklahoma, Pennsylvania, Rhode Island, South Carolina, South Dakota, Tennessee, Texas, Vermont, Virginia, West Virginia, and Wisconsin).

[c] Including water bodies.

percent of the 1,769.4 billion m^3 yr^{-1} surface water supply generated in the East.

Forest area distribution and surface water supply varied by WRR within the CONUS (WRRs shown in fig. 1). The South Atlantic-Gulf Region (WRR 3) (fig. 5A) had the greatest surface water supply from all lands with about 333.1 billion m^3 yr^{-1}, followed by the Pacific Northwest (WRR 17) and Ohio (WRR 5) Regions. However, the contribution of NFS and other forested lands to surface water supply was much higher in the Pacific Northwest Region (WRR 17) than in the South Atlantic-Gulf Region (WRR 3) (fig. 5B). The Upper Colorado Region (WRR 14) had the highest percentage (83.2 percent) of surface water supply from NFS and other forested lands, followed by the Pacific Northwest (WRR 17) and California (WRR 18) Regions. Areas with a high proportion (>40 percent) of surface water supply from NFS lands are predominantly distributed in the western WRRs (13–18). The Pacific Northwest Region (WRR 17) had the greatest surface water supply from NFS lands with about 133.7 billion m^3 yr^{-1}, followed by the California (WRR 18) and Missouri (WRR 10) Regions. In contrast, the Upper Colorado Region (WRR 14) had the highest percentage (69.7 percent) of its surface water supply from NFS lands, which accounts for 18.9 percent of the total land area. In the East, NFS lands comprised about 2.8 percent of the total land area and 3.8 percent of surface water supply (66.6 billion m^3 yr^{-1}). Overall, in the central and western WRRs (9–18), NFS and other forested lands contributed a much higher percentage of surface water supply than other lands, while in the eastern WRRs (1–8), NFS land area and the proportion of surface water supply that originated on NFS lands were closely linked (<5-percent difference in percentage of NFS forest coverage and surface water supply).

Water Transferred by IBTs

There are 594 IBTs in the database we compiled for this study, transferring from 0.01 million m^3 yr^{-1} to 8,900 million m^3 yr^{-1}, based on average transfer volumes from 2001 through 2015 (fig. 6). The IBTs transferred a total water volume of 116,894 million m^3 yr^{-1} over a total distance of 36,339 km. More than half of those IBTs (386 of 594) are transferring water from HUC12s where >50 percent of their water originated on NFS and other forested lands, with most of those IBTs located in the Western United States (Colorado and California Regions [WRRs 14, 15, and 18]). Those IBTs generally related to supplying urban areas, such as Los Angeles, CA; San Francisco, CA; Denver, CO; Las Vegas, NV; and Phoenix, AZ; in the West, and New York City, NY; and Atlanta, GA; in the East.

Inter-basin transfers moved surface water supply both within and across WRRs. Notably,

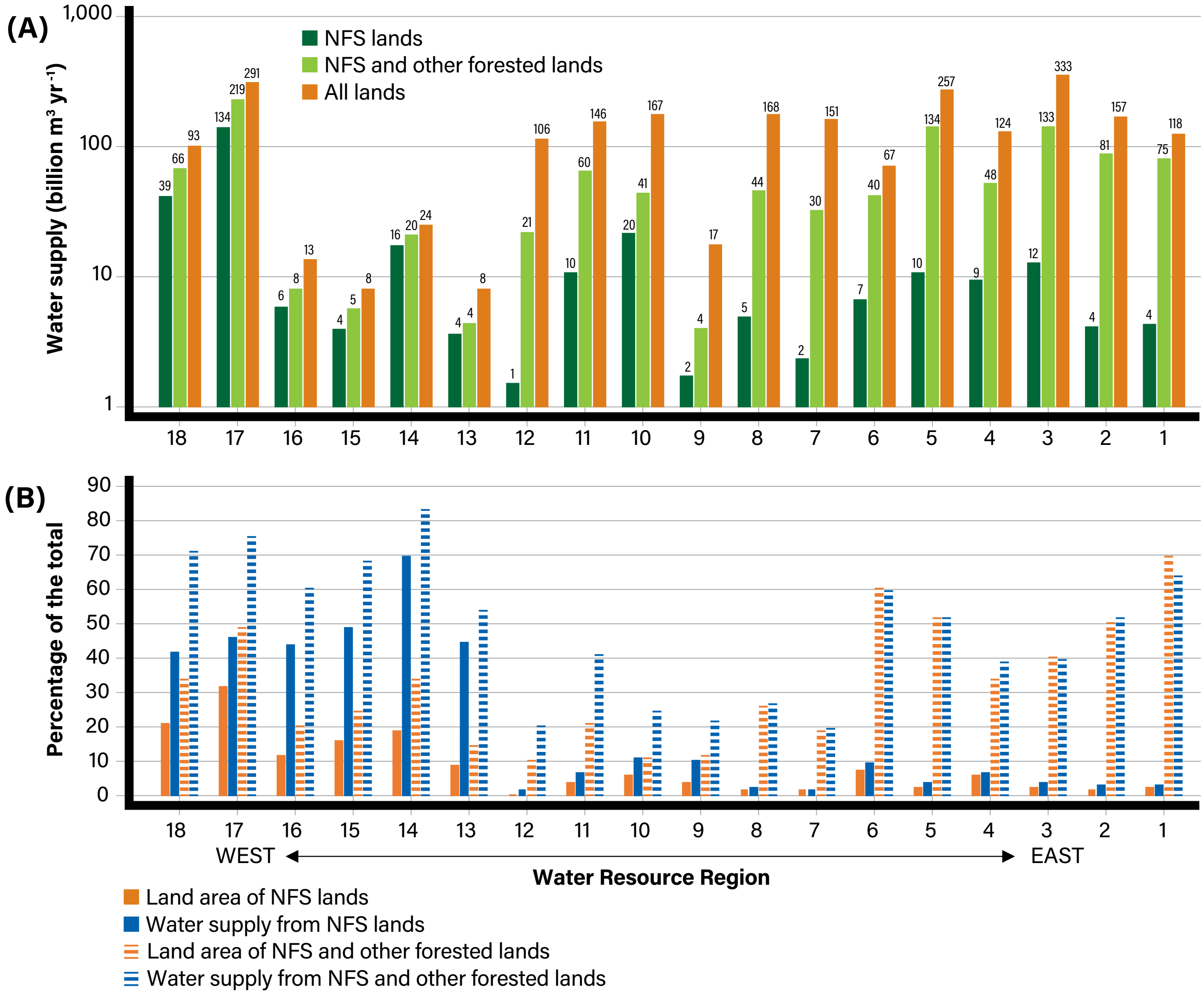


Figure 5—(A) Mean annual water supply originating on National Forest System (NFS) lands, NFS and other forested lands, and all lands in billions of m^3 yr^{-1}; and (B) percentage of water supply originating on and land area of NFS and other forested lands for each Water Resource Region (WRR). The WRRs are shown in figure 1.

multiple IBTs transferred a total of 873.5 million m^3 yr^{-1} of surface water supply from the Upper Colorado Region (WRR 14) to adjacent WRRs 10, 11, 13, and 16 (fig. 7). Based on 2001–2015 average values, 459.6 million m^3 of surface water supply was transferred from the Upper Colorado Region (WRR 14) to the Missouri Region (WRR 10), with 38.3 percent of that coming from the Arapaho National Forest, 18.8 percent from the White River National Forest, and another 21.6 percent from other forested lands. Four major (and several smaller) IBT projects carry this surface water supply, including: (a) Hoosier Pass Tunnel, which transfers water from the Blue River headwaters into the Missouri Region (WRR 10), where it enters the Blue River Pipeline owned by and serving Colorado Springs, CO; (b) headwater collection systems on the Blue and Fraser Rivers, channeling water to the Roberts and Moffat Tunnels (City of Denver), respectively, thence into various South Platte River tributaries for use downstream in metro Denver, CO; (c) the U.S. Department of the Interior, Bureau of Reclamation's Windy Gap and Colorado-Big Thompson Projects, which gather surface water supply from the uppermost reaches of the

Inter-basin surface water transfers by origin and destination HUC12s

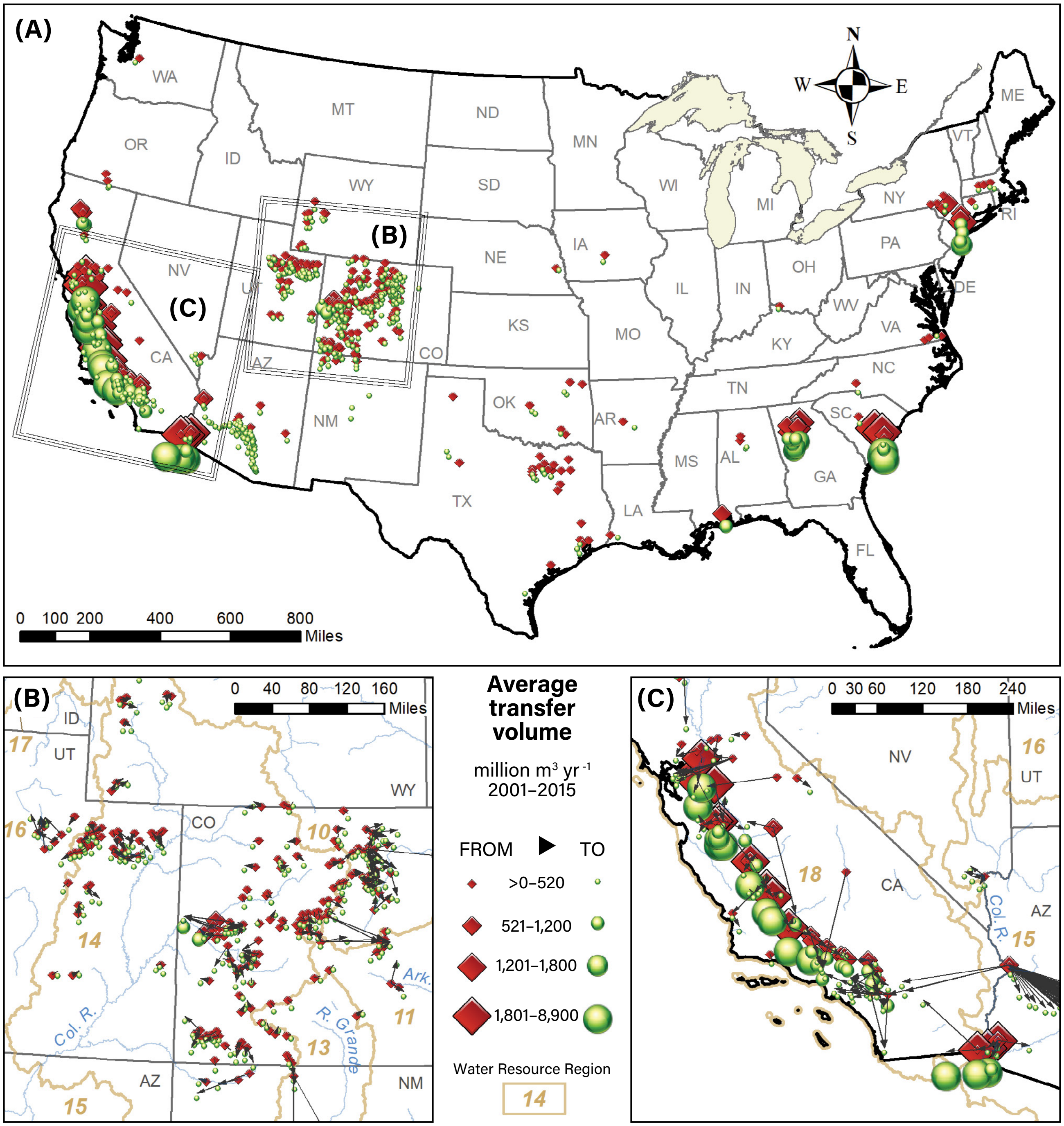


Figure 6—Inter-basin transfers (IBTs) in the (A) conterminous United States, (B) Upper Colorado Region (Water Resource Region [WRR] 14) and (C) California Region (WRR 18) from 2001 through 2015. Red diamond and green circle symbols represent mean annual transfer volume (million m³ yr⁻¹) and direction of IBTs between 12-digit (sixth-level) hydrologic unit code (HUC12) watersheds (red = transferred from HUC12; green = transferred to HUC12). The green symbols are spatially offset to make red symbols visible where there is spatial coincidence. Source: Liu and others 2022.

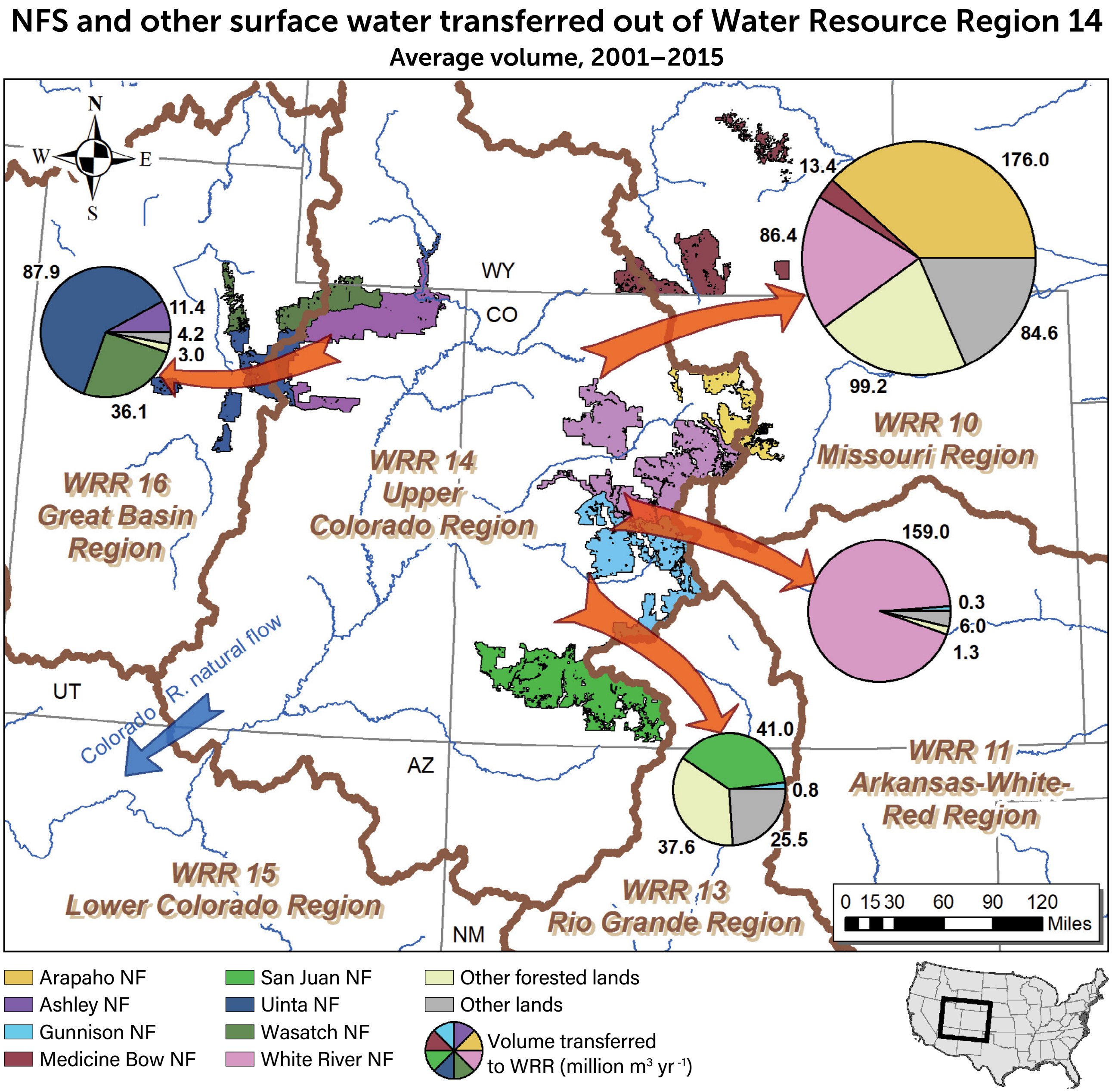


Figure 7—Mean annual surface water (million m^3 yr^{-1}) transferred out of the Upper Colorado Region (Water Resource Region [WRR] 14) from National Forest System (NFS) lands, other forested lands, and other lands through inter-basin transfers from 2001 through 2015. Source: Liu and others 2022.

Colorado River and pump it through the Adams Tunnel, after which it is distributed throughout the northern Colorado Front Range, from Boulder to Fort Collins; and (d) water from the headwaters of Little Snake River that is transferred into the North Platte watershed, as replacement for water that Cheyenne, WY, extracts from other parts of the North Platte watershed.

Most of the surface water supply transferred from the Upper Colorado Region (WRR 14) to the Arkansas-White-Red Region (WRR 11) (95.5 percent) originated from the White River National Forest, gathered from headwaters of Colorado River tributary systems on the Eagle River where the collection system in the Homestake Creek watershed (the Homestake Project) is co-owned by Aurora, CO, and Colorado Springs, while the Bureau of Reclamation's Fryingpan-Arkansas Project collects from headwaters of Fryingpan and Roaring Fork Rivers. Homestake Project water travels through Homestake Tunnel and then flows into the upper reaches of the Arkansas River while Fryingpan-Arkansas Project water travels through several different tunnels to eventually reach the Arkansas River. Water partly made up of these transfers is extracted from the Arkansas River downstream by two major (and some smaller) systems. At the Otero Pump Station, water from the river is diverted for transfer to the Missouri Region (WRR 10), some into South Platte tributaries, later extracted by Aurora, and some into Homestake Pipeline to Colorado Springs (back in the Arkansas-White-Red Region [WRR 11]). The other main Arkansas River extraction tied into these IBT systems takes water from the on-river Pueblo Reservoir further downstream and pipes it to Colorado Springs and nearby communities without entering WRR 10.

The main water transferred from the Upper Colorado Region (WRR 14) to the Rio Grande Region (WRR 13) is via the San Juan-Chama Project (Bureau of Reclamation). Surface water is collected from headwaters of the San Juan River, some originating in the San Juan National Forest, and is tunneled to a small Rio Grande tributary. The transferred water serves the Jicarilla Apache near the tunnel outfall, the cities of Albuquerque (78.9 percent from NFS land) and Santa Fe, NM (78.3 percent from NFS land), and downstream communities on the Rio Grande.

While there are several small water transfers between the Upper Colorado (WRR 14) and Great Basin (WRR 16) Regions, the two largest transfers are part of two different Bureau of Reclamation projects. The first diverts surface water from the upper reaches of the Duchesne River in the Wasatch National Forest and channels it through the Duchesne Tunnel as part of the Provo River Project. The second, called the Strawberry Valley Project, involves a complex collection system within the Duchesne watershed, with surface water originating in the Wasatch, Uinta, and Ashley National Forests. Collected water is channeled through the Strawberry Tunnel, after which it follows natural flow toward the broader Salt Lake City, UT, urban area (61.6 percent from NFS land in total).

Population and Communities Served by Water From Forested Lands

From National Forest System lands only—Many people receive surface drinking water supply from NFS lands through intakes managed by their PWS. Including surface water supply from IBTs, we found that:

- Approximately 79.6 million people obtained some portion (≥0.01 percent) of their surface drinking water supply from NFS lands through intakes managed by their PWS.
- Approximately 45.8 million people obtained >10 percent of their surface drinking water supply from NFS lands through intakes managed by their PWS. This represents 14.2 percent of the total CONUS population (323 million people) and 33 percent of the 138 million people served by public surface drinking water intakes in 2017.
- Approximately 22.6 million people received >50 percent of surface drinking water supply from NFS lands (figs. 8A and 9).

Without incorporating IBTs, we found that:

- Approximately 43.8 million people would have derived >10 percent of their surface drinking water supply from NFS lands.

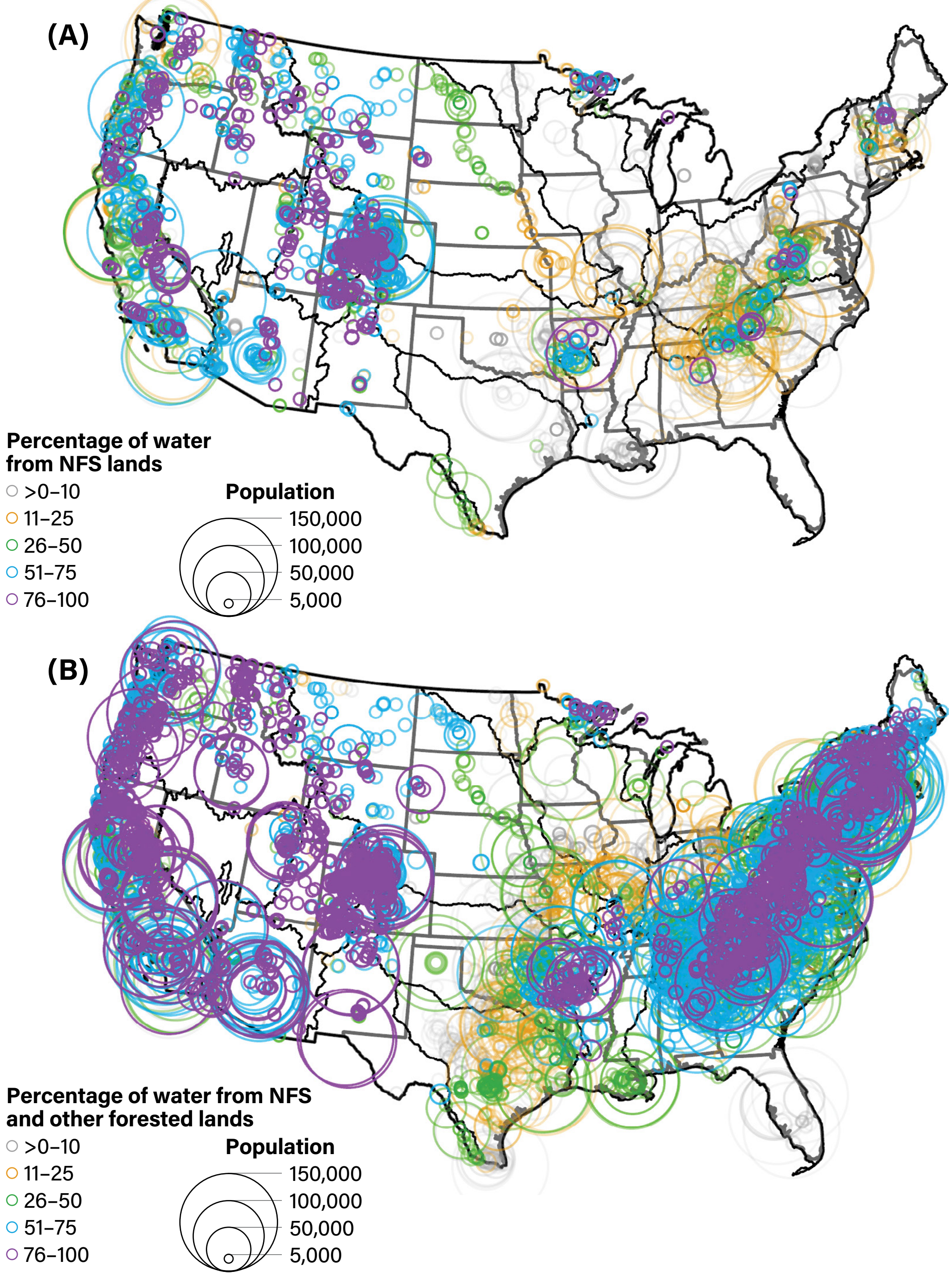


Figure 8—Public surface drinking water intakes where some amount of source water originated on (A) National Forest System (NFS) lands and (B) NFS and other forested lands. Circles representing intakes are colored by the percentage of surface drinking water from (A) NFS lands and (B) NFS and other forested lands after accounting for inter-basin transfers and sized by the population served. Source for (B): Liu and others 2022.

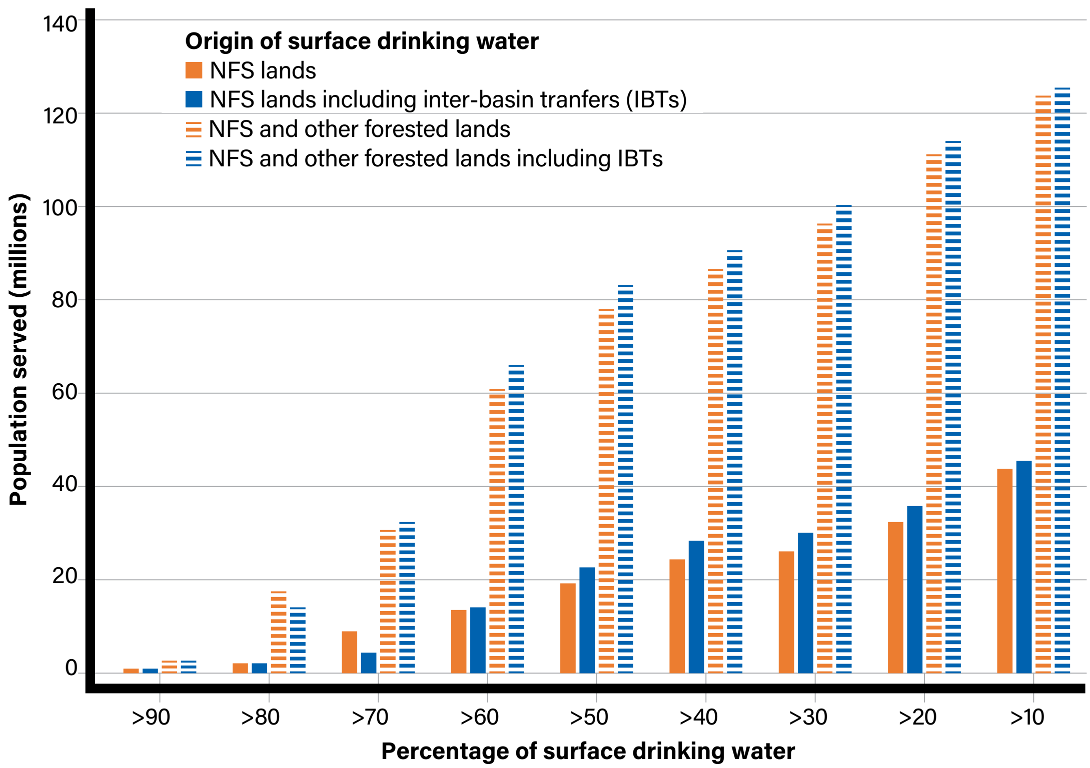


Figure 9—Cumulative frequency of population served according to percentage of surface drinking water originating on National Forest System (NFS) lands and NFS and other forested lands.

- Approximately 19.6 million people would have derived >50 percent of their surface drinking water supply from NFS lands.

Of the 2,725 public surface drinking water intakes receiving >10 percent of water from NFS lands, whether as natural downstream flow or via IBTs, 1,531 intakes (56.2 percent) received >50 percent of their surface drinking water supply from NFS lands (fig. 8A). Of the 2,653 public surface drinking water intakes located downstream of NFS lands and receiving >10 percent of surface drinking water supply from those NFS lands through natural flow, 1,466 (55.3 percent) received >50 percent of their surface drinking water supply from NFS lands. The City of Asheville, NC, PWS, for example, serves a population of 124,300; 46.7 percent of this surface water originates on NFS lands upstream of Asheville, with 0 percent received through IBTs.

There were 62 public surface drinking water intakes that obtained all of their NFS-origin surface drinking water supply through IBTs; 23 of these received >50 percent of surface drinking water supply from NFS lands. For example, the City of Calexico, CA, serving 40,211 people, received 65.3 percent of its surface drinking water supply from NFS lands, 100 percent of which is received through IBTs (via the All-American Canal from the Lower Colorado River).

Many PWSs receive water from NFS lands through a mixture of natural downstream flow and IBTs. Examples include Colorado Springs Utilities, which serves 424,171 people with 62.5 percent of the surface drinking water supply coming from NFS lands overall, including 4.6 percent from several IBTs; and the City of San Diego, CA, which serves 1.3 million people with 53.3 percent of the water coming from NFS lands overall, including 29.7 percent from IBTs, notably through the Metropolitan Water District of Southern California and Bureau of Reclamation. In some cases, the IBT influx decreases instead of increases the percentage of water from NFS lands, either because the transferred water has a lower portion of NFS surface drinking water supply than the downstream water, or because an outgoing IBT upstream of the public surface drinking water intakes removes NFS water and delivers it elsewhere. An example of this situation is found in Palmdale Water District, CA, which serves 116,183 people with 47.7 percent of the surface drinking water supply coming from NFS lands. However, before IBT water is mixed in, the portion of surface drinking water supply from NFS lands is 83.1 percent.

From National Forest System and other forested lands—Many more people receive surface drinking water supply from NFS and other forested lands through intakes managed by their PWS. Including surface water supply from IBTs, we found that:

- Approximately 136.7 million people obtained some portion (≥0.01 percent) of their surface drinking water supply from NFS and other forested lands through intakes managed by 4,994 PWSs.
- Approximately 125.5 million people, around 39 percent of the total population in the CONUS in 2017, derived >10 percent of their surface drinking water supply from NFS and other forested lands (fig. 9).
- Approximately 83.1 million people received >50 percent of their surface drinking water supply from NFS and other forested lands.

Without incorporating IBTs, we found that:

- Approximately 123.7 million people would have derived >10 percent of their surface drinking water supply from NFS and other forested lands.
- Approximately 78.0 million people would have received >50 percent of their surface drinking water supply from NFS and other forested lands.

Of the 8,910 public surface drinking water intakes in 5,041 PWSs in the CONUS, 7,891 intakes (88.6 percent) serving 4,621 PWSs received >10 percent of their surface drinking water supply from NFS and other forested lands, with 5,073 intakes in 3,107 PWSs receiving >50 percent of their surface drinking water supply from NFS and other forested lands (fig. 8B).

Inter-basin transfers help redistribute water from NFS and other forested lands to people in other locations, especially in dry urban areas in the West. With the help of IBTs, many dry cities get a large portion of their surface drinking water supply from NFS and other forested lands that lie in other regions (fig. 10). For example, the Los Angeles-Long Beach-Riverside-San Bernardino, CA, area, serving 7.1 million people, received 68.7 percent of its surface drinking water supply from NFS and other forested lands in the Colorado and California Regions (WRRs 14, 15, and 18) through several IBTs: the Los Angeles Aqueduct (and Second Los Angeles Aqueduct) owned by the Los Angeles Department of Water and Power and carrying water from Mono Lake and Owens River; the Colorado River Aqueduct, owned by the Metropolitan Water District of Southern California and carrying lower Colorado River content; and both the West Branch and the East Branch of the California Aqueduct (California State Water Project). Similarly, the Las Vegas-Henderson, NV, area, with 1.6 million people served, received about 81.5 percent of its surface drinking water supply from NFS and other forested lands in the Upper Colorado Region (WRR 14) through the Griffith Project, drawing water from Lake Mead, formed by construction of the Hoover Dam (both Bureau of Reclamation projects). The Greater Phoenix, AZ, area, with 3.4 million people served, received 82.0 percent of its surface drinking water supply from NFS and other forested lands in the Colorado Regions (WRRs 14 and 15) through the Central Arizona Project and the Salt River Project, both currently private, though the Bureau of Reclamation built some of their infrastructure.

Water purchased from other public water systems—In addition to those PWSs and populations receiving surface drinking water supply from forested lands through intakes managed by their PWS, there were numerous PWSs that purchased surface drinking water supply from another PWS, including:

- 1,566 PWSs serving 12.6 million people that purchased surface drinking water supply from another PWS that received >10 percent of their surface drinking water supply from NFS lands
- 2,660 PWSs serving 24.6 million people that purchased surface drinking water supply directly from another PWS receiving some portion (≥0.01 percent) of their surface drinking water supply from NFS lands after accounting for IBTs

NFS and other surface water supplying key arid cities

Average volume, 2001–2015

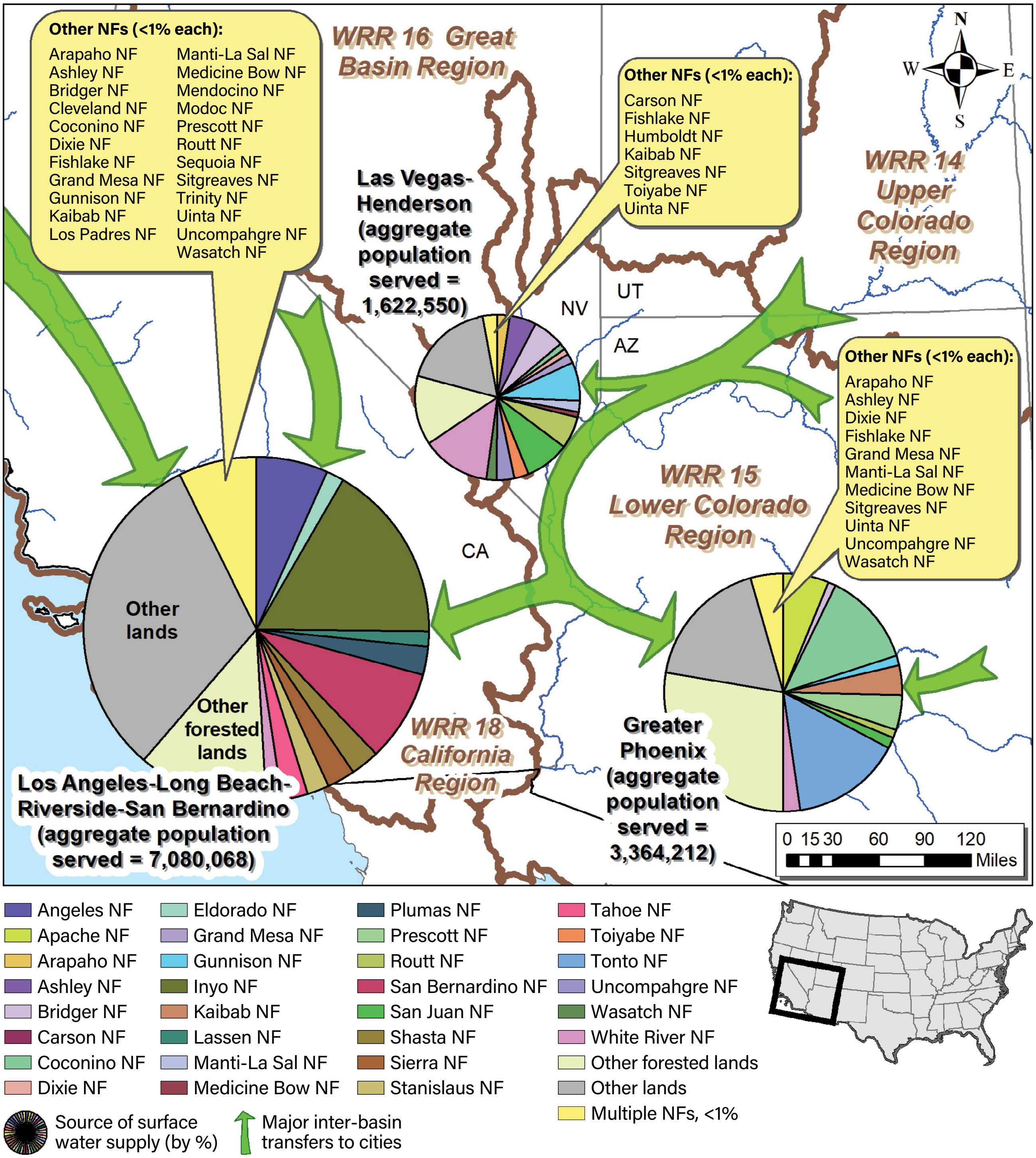


Figure 10—The contribution of National Forest System (NFS) lands, other forested lands, and other lands to surface water supply in key cities in the arid Southwestern United States. WRR = Water Resource Region.

- 4,683 PWSs serving 38.3 million people that purchased surface drinking water supply from another PWS that received >10 percent of their surface drinking water supply from NFS and other forested lands
- 5,329 PWSs serving 41.9 million people that purchased surface drinking water supply from another PWS receiving some portion (≥0.01 percent) of their surface water supply from NFS and other forested lands after accounting for IBTs

These estimates of the population served by PWSs purchasing surface drinking water supply from another PWS receiving >10 percent of their surface drinking water supply from forested lands may not reflect the actual proportion of surface drinking water supply from forested lands for these purchasing PWSs because the water volume of the purchases is not available at the scale of this study.

From individual National Forest System units—In addition to evaluating the contribution of surface water supply from all NFS and other forested lands collectively, we evaluated the individual contribution for each of 151 national forests, 20 national grasslands, and 1 national recreation area. To accomplish this objective, we created unique model input databases, performed the surface water supply simulation with the WaSSI model including IBTs, and linked the surface water supply outputs to the EPA SDWIS database of public surface drinking water intakes to estimate the population and communities served by each individual NFS unit. Results of the analyses for each national forest, grassland, and recreation area are provided in a supplemental information document that accompanies this report (https://doi.org/10.2737/WO-GTR-100-Sup1) and an online database (https://doi.org/10.2737/RDS-2021-0098). In a case study presented here, we highlight one of the national forests—the Pike National Forest—which, among all national forests, served the largest population receiving >50 percent of its surface drinking water supply from NFS lands.

CASE STUDY: PIKE NATIONAL FOREST

We selected the Pike National Forest in Colorado to demonstrate how NFS lands contribute to the surface drinking water supply for downstream communities as well as those in other river basins through IBTs. In total, the Pike National Forest served the largest population (1.2 million people) receiving >50 percent of its surface drinking water supply from NFS lands among all national forests. The Pike National Forest encompasses approximately 4,435 km^2 (1.1 million acres) in the Front Range of Colorado (just east of the Continental Divide) and includes the headwaters of the Arkansas and South Platte Rivers (in WRRs 11 and 10, respectively). Water from the Pike National Forest makes its way east to communities in Nebraska, Missouri, Kansas, Oklahoma, Tennessee, and Arkansas, and down the Mississippi River to Louisiana (fig. 11).

Downstream of the Pike National Forest, we estimated that 53 PWSs receive >10 percent of their surface drinking water supply from the Pike National Forest and serve approximately 1.74 million people. Around 1.2 million people receive >50 percent of their surface drinking water supply from the Pike National Forest, mainly from public surface drinking water intakes located in close proximity to the Forest. For example, two of four intakes of the Denver Water Board, CO, each received about 67 percent of their surface drinking water supply from the Pike National Forest; over the entire PWS, 56.0 percent of water originated from the Pike National Forest with 1 million people served (figs. 11 and 12). Thirteen of 26 intakes of Colorado Springs Utilities, CO, received >50 percent of their surface drinking water supply from Pike National Forest; over the entire PWS, 8.9 percent of water originated from the Pike National Forest with 424,171 people served. In addition to those PWSs receiving surface water supply from the Pike National Forest through their own intakes, there were 206 PWSs serving 1.6 million people that purchased surface water from PWSs receiving some portion of their surface water supply from Pike National Forest and 47 PWSs serving 0.6 million people that purchase surface water from PWSs receiving >10 percent of their surface water from Pike National Forest. For example, the Denver Water Board, CO, sells surface water to 37 other PWSs across the greater Denver area serving an additional 0.57 million people.

In addition, 25 PWSs received some of their surface drinking water supply from the Pike National Forest through IBTs. For example, one of four public surface drinking water intakes of the Denver Water Board received 15.3 percent of its surface drinking water supply from the Pike National Forest through IBTs. Two of 23 intakes of the City of Aurora, CO, together received an average of 45.9 percent of their surface drinking water supply from the Pike National Forest through IBTs, with 325,000 people served over the entire PWS (fig. 11). In both of these examples, the transferred water is withdrawn from Strontia Springs Reservoir, which received both natural downstream flow of South Platte River tributaries within Pike National Forest and water transferred into the South Platte system from the Arkansas-White-Red and Upper Colorado Regions (WRRs 11 and 14), much of it from the White River National Forest that lies across the Continental Divide from the Pike National Forest.

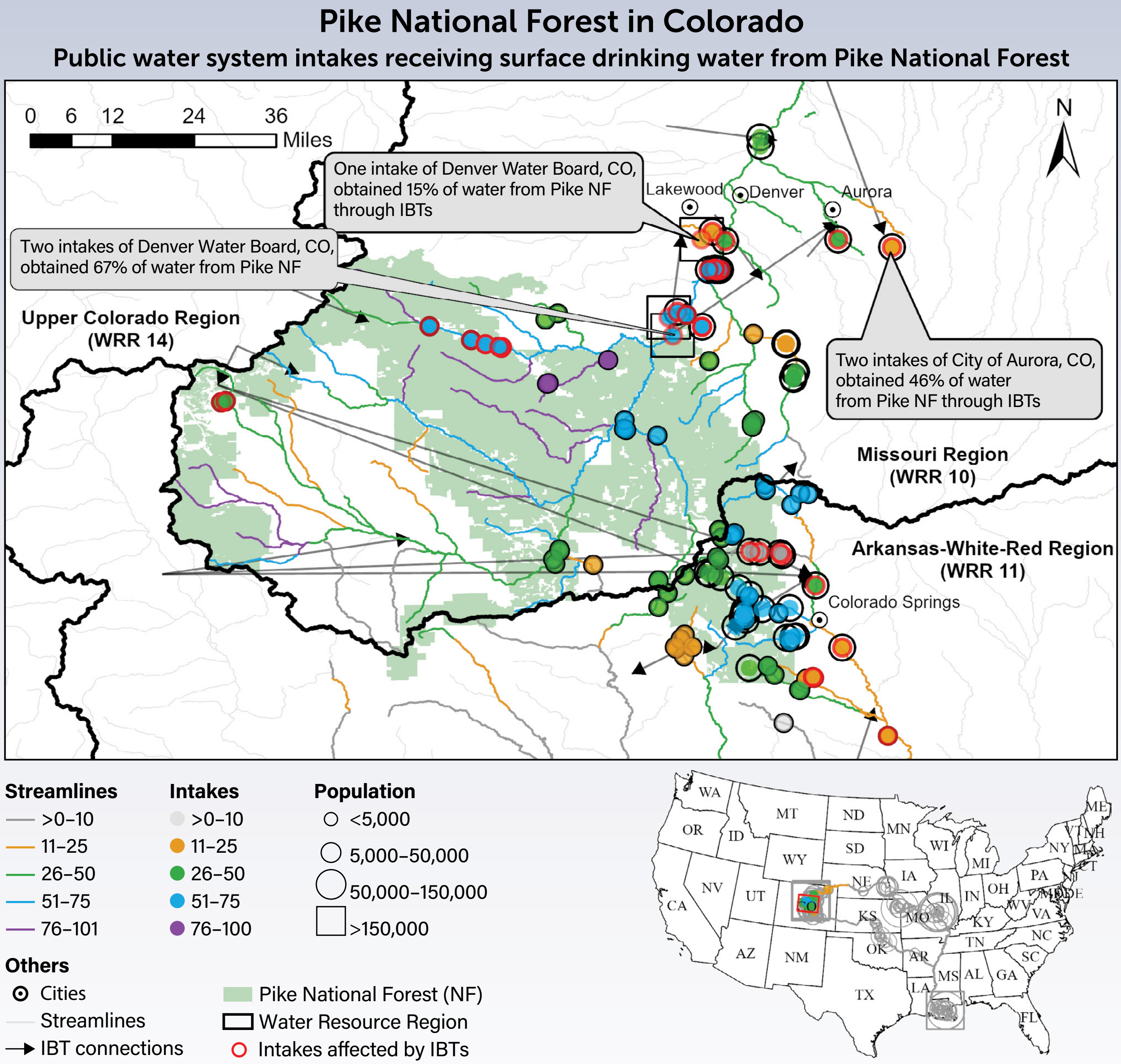


Figure 11—Case study of public surface drinking water intakes receiving surface water from the Pike National Forest, CO. IBT = inter-basin transfer.

SUMMARY OF PUBLIC WATER SYSTEMS AND POPULATIONS RECEIVING SURFACE DRINKING WATER SUPPLY FROM NATIONAL FOREST SYSTEM LANDS

Supplemental information for General Technical Report WO-100 (https://doi.org/10.2737/WO-GTR-100)

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REGION 2: ROCKY MOUNTAIN REGION

Pike and San Isabel National Forests

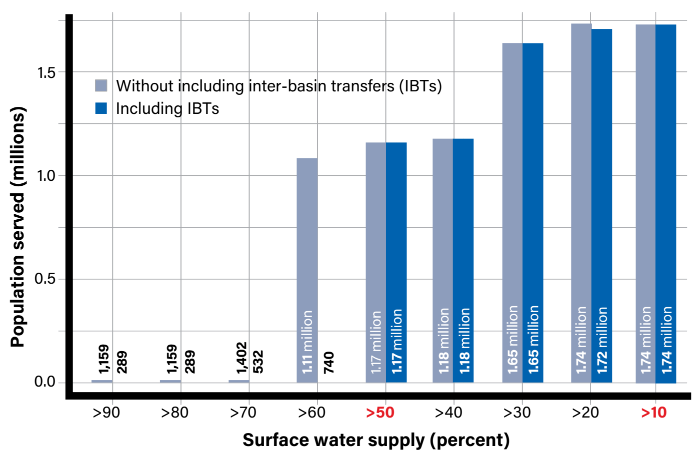
Pike National Forest

~1.1 million acres (4,435 km²) in Colorado

BETWEEN 2001 AND 2015:

- **Average surface water supply from Pike National Forest was 604.8 million gallons per day (835.6 million m^3 yr^{-1}).**
- **Fifty-three public water systems (PWSs) serving a total population of approximately 1.7 million people received >10 percent of their surface drinking water supply from Pike National Forest whether inter-basin transfers were included or not.**
- **Twenty-three PWSs serving 1.2 million people received >50 percent of their surface drinking water supply from Pike National Forest.**
- **Forty-seven additional PWSs serving 586,580 people purchased surface water from other PWSs that received >10 percent of their surface water from Pike National Forest.**

Cumulative frequency of population served according to the percentage of water coming from Pike National Forest (not including those served through surface water purchases)



Example public water systems (PWSs) getting surface drinking water supply from Pike National Forest accounting for inter-basin transfers

PWS ID	PWS name	Number of intakes	Population served in 2017	Percentage of total surface water
CO0116001	DENVER WATER BOARD	4	1,000,000	56.0
CO0103005	AURORA CITY OF	23	325,000	36.8
CO0101150	THORNTON CITY OF	3	136,977	36.2
CO0118015	CENTENNIAL WSD	7	96,394	57.2
CO0118010	CASTLE ROCK TOWN OF	9	59,362	25.0
CO0103045	ENGLEWOOD CITY OF	3	46,541	50.4
CO0138045	STERLING CITY OF	1	15,100	16.7
CO0118055	ROXBOROUGH PARK WSD	1	10,622	57.5
CO0121950	WOODMOOR WSD	3	8,741	51.3
CO0160900	WOODLAND PARK CITY OF	2	8,500	29.9

Source: Liu, N.; Dobbs, G.R.; Caldwell, P.V. [and others]. 2022. Public water systems and populations receiving surface drinking water supply from National Forest System lands. 2d ed. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2021-0098-2.

Figure 12—Summary of public water systems and populations receiving surface drinking water supply from the Pike National Forest. This summary and others for all National Forest System units can be found in a supplemental information document that accompanies this report.

DISCUSSION

This is the first national-scale study to account for IBTs in the linkage between water originating on NFS and other forested lands and the PWSs and populations they serve, both through the intakes managed by their local PWSs and through purchases from other PWSs. We combined a hydrologic model, a database of public surface drinking water intakes for PWSs, and an IBT database to determine the role of NFS and other forested lands in providing surface drinking water supply to public surface drinking water intakes in the CONUS. We found that NFS and other forested lands provide almost half (46.0 percent) of the surface water supply, providing some surface drinking water supply for 136.7 million people—nearly half of the total population. More importantly, many people get the majority of their surface drinking water supply from NFS and other forested lands with the help of IBTs.

Forested Lands as the Dominant Drinking Water Source in Arid Areas

National Forest System and other forested lands in the western arid areas tend to provide a much higher proportion of surface water supply than what would be expected from their percentage of total land (fig. 5). Although NFS and other forested lands make up only 28.7 percent of total land in the CONUS, they provide almost half of the total surface water supply (46.0 percent). This result is very close to previous studies regarding the amount of water supply originating on forested lands (Brown and other 2016, Luce and others 2017). The higher water yield in forested lands than other lands resulted in this disproportionate contribution of forested lands on surface water supply in the arid areas. However, this does not mean that forests use less water than nonforests; on the contrary, water use by forests through evapotranspiration is generally much higher than on nonforested lands (Zhang and others 2016). The large difference in water yield between forested and other lands in arid areas (fig. 3A) was a result of the difference in precipitation amounts across the regions (Daly and others 1997). The annual precipitation was 972 ± 678 mm yr^{-1} and 358 ± 275 mm yr^{-1} for forested lands and nonforested lands in the West, respectively. On the one hand, forests can only exist in relatively high-precipitation areas; on the other hand, forested lands enhance precipitation by maintaining atmospheric moisture (Spracklen and others 2012). In contrast, in the relatively wet Eastern United States, the contribution of NFS and other forested lands to surface water supply closely reflected their land area (fig. 4) (Liu and others 2020) because precipitation and water yield were similar across land cover types (fig. 3A), and most of this region is not water-limited (Renner and Bernhofer 2012).

A much higher percentage of people living in the West get the majority (>50 percent) of their surface drinking water supply from NFS and other forested lands than do people living in the East (fig. 8). Our results showed that about 29.5 million people, or 39.3 percent of the total population in the West, get >50 percent of their surface drinking water supply from NFS and other forested lands, while about 53.6 million people, or 21.6 percent of the total population in the East, get >50 percent of their surface drinking water supply from NFS and other forested lands. Previously, Liu and others (2020) reported that around 25.3 percent of people in the 13 Southern States get >50 percent of their surface drinking water supply from non-Federal forested lands, which make up 90 percent of the total forested land area. Similarly, Caldwell and others (2014) found that around 20 percent of people get >50 percent of their surface drinking water supply from non-Federal forested lands in the South. While there are fewer IBTs in the Eastern United States, neglecting their role in water delivery to water utilities could result in an underestimation of the contribution of forested lands to surface drinking water supply in those studies.

Role of IBTs in Distributing Water From Forested Lands to People

For people who obtain the majority (>50 percent) of their surface drinking water supply from NFS and other forested lands across the CONUS, 19.4 million, or 6.0 percent of total population, obtained some of this water through IBTs. Inter-basin transfers are critical in the arid West where 15.2 million people obtained some of their surface drinking water supply through IBTs, which represents 52 percent of the total population in the West who obtain the majority of their water from NFS and other forested lands. Despite the recognition that forests are critical for reliable and high-quality water supplies for downstream communities (Creed and van Noordwijk 2018), this study demonstrates the role of forested lands in surface drinking water supply for people living outside of forested basins. Although the contributions of surface drinking water supply from forests to urban areas through certain water resources management programs have been reported previously, such as by New York City (NYC Environmental Protection 2017), Los Angeles (Ashoori and others 2015), and Seattle (Seattle Public Utilities 2011), no previous national-scale studies were able to link each NFS unit to the population served and accurately represent the water transfers from these NFS lands across WRRs. Therefore, the importance of forested lands to surface drinking water supply would have been underestimated by previous studies (Barnes and others 2009, Caldwell and others 2014, Liu and others 2020). Our IBT database can help fill this gap in future hydrologic modelling to more accurately account for the human-mediated water transfers between basins, which have generally been ignored in past studies because of data limitations (Dickson and others 2020).

Purchased Surface Drinking Water Supply

Many PWSs that depend on surface water do not have public surface drinking water intakes of their own but rather purchase their surface drinking water supply from other PWSs. Connections between purchasing and selling PWSs can be complex. For example, some PWSs that sell surface drinking water supply to other PWSs also purchase water from one or more other PWSs themselves. Further, the volumes of surface drinking water purchases between sellers and purchasers are not available at the national scale. Accurately quantifying the proportion of surface drinking water supply from forested lands for these purchasing PWSs requires knowledge of purchase volumes, their other sources of surface drinking water supply and the corresponding volumes, and all of the connections between PWSs. This level of analysis was beyond the scope of the current study; however, we did identify those PWSs that purchase surface drinking water supply from selling PWSs that obtained some portion (≥0.01 percent) and >10 percent of their surface drinking water supply from forested lands, along with populations served. In generating these estimates, we included the first water transaction among purchasing and selling PWSs but did not account for additional transactions when selling PWSs also purchase water from other PWSs. As a result, our estimates of the PWSs and populations served by surface water originating on forested lands through water purchases may be conservative.

If it were assumed that purchasing PWSs serve surface drinking water supply from forested lands at the same proportion as that obtained by the selling PWSs through their intakes, the population served by these purchasing PWSs could be added to the population served by PWSs through the intakes they manage that obtain a given proportion of surface drinking water supply from forested land. For example, under this assumption, with 45.8 million people receiving >10 percent of their surface drinking water supply from NFS lands through their PWS intakes and 12.6 million people receiving surface drinking water supply from a PWS that purchases water from another PWS that receives >10 percent of their surface drinking water supply from NFS land, a total of 58.4 million people would obtain >10 percent of their surface drinking water supply from NFS lands. Similarly, a total of 163.8 million people would obtain >10 percent of their surface drinking water supply from NFS and other forested lands. Estimating the total population getting >10 percent of their surface drinking water supply from forested lands under this assumption may be uncertain and could lead to an overestimation of the population served in some cases; the estimated proportion of the total surface water supply originating on forested land that is available to these purchasing PWSs may not reflect the actual proportion because the volume of water purchased from various PWSs is not known. On the other hand, we could reasonably estimate the total population receiving some portion (≥0.01 percent) of their surface drinking water supply from forested lands under this assumption because this approach only requires knowledge of which PWSs are connected through these water purchases but does not require knowledge of the volume of water purchased. Under this assumption, a total of 104.2 million people would obtain some of their surface drinking water supply from NFS lands, and 178.6 million people would obtain some of their surface drinking water supply from NFS and other forested lands.

Dependence on Water From Forests

Various estimates of populations that use surface water supply from forested lands have been developed over the years and are used widely in publicly available literature today. For example, a 2007 Forest Service briefing states, “180 million people…rely on forested lands to capture and filter their drinking water” (USDA Forest Service 2007). This estimate can be traced back to Stein and others (2005), which references a personal communication with Dr. James Sedell in 2005, stating, “According to Forest Service estimates, some 180 million people depend on forests for their drinking water.” A report by Sedell and others (2000) is sometimes referenced for information about the population dependent on surface drinking water supply originating on NFS lands; this report mentions a 1999 EPA study that showed about 60 million people live in communities located in watersheds containing NFS lands. These earlier, coarse estimates are consistent with our estimates of populations receiving any portion (≥0.01 percent) of their surface drinking water supply from forests either through their public surface drinking water intakes or through their PWS purchasing from another PWS, i.e., 104.2 million people receiving surface drinking water supply from NFS lands and approximately 178.6 million people receiving surface drinking water supply from NFS and other forested lands. Clearly, many of these communities receive substantial quantities of surface drinking water supply from other forested and nonforested lands as well.

In this study, we present results for communities and populations that receive >10 percent of their surface drinking water supply from forested lands, but we show all public surface drinking water intakes that receive any portion of their water from forested lands to illustrate upstream/downstream relationships between forests and PWSs. Fifty percent of surface drinking water supply originating on forested lands is an upper threshold that highlights communities which rely on forested land for most of their water. The relative importance of any quantity depends on several local factors including the total available raw surface water supply at an intake location, frequency and severity of drought, population and per capita domestic water use, water use by other sectors, and downstream water rights and environmental flow requirements. Therefore, it would be misleading to suggest that amounts above or below an arbitrary threshold are equivalent in terms of public value across all locations. Displaying the population served information as a function of percentage of surface drinking water supply from forested land (e.g., fig. 9) allows readers to assess importance using use their own judgement and experience. We suggest readers carefully consider what threshold is appropriate for their watershed and PWS.

Population Growth, Climate Change, Water Supply, and Water Quality

Our study has shown the importance of NFS and other forested lands in providing surface drinking water supply for communities during the period of 2001–2015. However, climate change is expected to increase surface temperature and increase the frequency and severity of droughts, both of which will likely reduce surface water supply (Creed and others 2014, Duan and others 2017, Sun and others 2015b). The high contribution of surface water supply from forested lands suggests that protecting forested lands from development (Brown and others 2019) and maintaining healthy forests can improve water resource sustainability.

Although per capita water use in U.S. cities has been declining steadily over the past few decades (Dieter and Maupin 2017, Rockaway and others 2011), population growth is expected to increase total water demand, especially in urban areas (Brown and others 2019, Yigzaw and Hossain 2016). Population growth will also indirectly further increase water demand across the United States by raising the water demand of agricultural and landscape irrigation, which may be exacerbated by climate change (Brown and others 2019, Creed and others 2014). Drought and warming have already resulted in a dramatic reduction of water available to ecosystems and to the public across the United States (Sun and others 2015b). With continued climate change, larger deficits between water supply and demand will likely occur in the central and southern Great Plains States, the Southwestern States and Intermountain and Rocky Mountain States, and California, and even in the relatively wet Southeastern States (Brown and others 2019, Naumann and others 2018, Sun and Vose 2016), suggesting more people may be subject to water stress (Duan and others 2019, Gosling and Arnell 2016). The increase in population and urbanization in some parts of the country will increase demand for clean water while putting more emphasis on minimizing development of existing forested lands (Brown and others 2019). While some areas located at climate margins that currently support forests may not be able to do so under climate change (Guo and others 2018), maintaining natural land cover in these areas (e.g., grassland, shrubland) could help maintain downstream water quality.

Apart from providing a disproportionate amount of the Nation's public surface water supply, larger areas of forest cover also result in higher water quality, thereby lowering the raw water treatment costs for public drinking water and providing numerous other ecosystem services such as habitat for aquatic biota (Abildtrup and others 2013, Lopes and others 2019, Warziniack and others 2017). Watersheds with more forest cover tend

Table 4—Comparison among studies that quantified the contribution of National Forest System (NFS) and other forested lands to water supply in the conterminous United States

	Brown and others 2008	Brown and others 2016[a]	Luce and others 2017	This study
Hydrologic model	**Advection-Aridity model** (Brutsaert and Stricker 1979) **Zhang model** (Zhang and others 2001)	**VIC** (Mahat and others 2017)	**VIC** (Livneh and others 2013)	**WaSSI** (Caldwell and others 2012, Sun and others 2011b)
Model spatial resolution	5 x 5 km	~12 x 12 km	~6 x 6 km	HUC12 (~100 km^2)
Model temporal resolution	Monthly/mean annual	Daily	Daily	Monthly
Product temporal resolution	Mean annual	Mean annual	Mean annual + mean summer	Mean annual
Time period	1953–1994	1981–2010	1915–2011	2001–2015
NFS boundaries	Proclamation	Ownership and proclamation	Proclamation	Ownership
Total land area (thousand km^2)	7,691	7,700	NR	7,776
NFS land area (thousand km^2) (percentage of total)	846 (11%)	693 (9%)	846 (11%)	719 (9%)
All forested land area (thousand km^2) (percentage of total)	2,230 (29%)	1,987 (26%)	NR	2,235 (29%)
Total water supply (billion m^3)	1,769	1,922	NR	2,248
NFS water supply (billion m^3) (percentage of total)	326 (18%)	280 (15%)	NR (18%)	288 (13%)
All forested land water supply (billion m^3) (percentage of total)	931 (53%)	884 (46%)	NR	1,035 (46%)
All forested land representation[b]	1992 NLCD classes 41, 42, 43	2006 NLCD classes 41, 42, 43	NR	NFS ownership parcels and remaining 2006 NLCD classes 41, 42, 43

HUC = hydrologic unit code; NLCD = National Land Cover Database; NR = not reported; VIC = Variable Infiltration Capacity; WaSSI = Water Supply Stress Index.
[a] NFS land area and water yield data shown are based on estimates for NFS ownership parcels.
[b] NLCD land cover classes 41, 42, and 43 include deciduous, evergreen, and mixed forest, respectively.

to have lower concentrations of nutrients and sediment than watersheds with less forest cover (Swank and others 2001, Tu 2013, Warziniack and others 2017). However, these forest-based ecosystem services are increasingly threatened by land use change (Curtis and others 2018) and climate change and its cascading direct (e.g., increase in evaporative potential and drought severity, increased stream temperature) (Hoegh-Guldberg and others 2018, Isaak and others 2017) and indirect (tree species shift, wildland fires, outbreak of insects and diseases, altered flood magnitudes) impacts (Hallema and others 2018, Hultine and others 2010). Forest loss could lead to an increase in sediment and nutrient loads in streams (Arthur and others 1998, Goode and others 2012, Riekerk 1985, Swank and others 2001). By 2060, it is predicted that the population of the United States will be around 500 million people (under Shared Socioeconomic Pathway Scenarios 5; Riahi and others 2017), which could result in a >35-percent increase of the developed land in comparison with 2010 (U.S. EPA 2020). Moreover, private forests would be most vulnerable to the development (Liu and others 2021). Forest conversion to urban use in some areas might relieve water stress conditions locally by increasing water yield (Suttles and others 2018); however, dispersed development on private forested lands might elevate stormflow and flood risk and degrade water quality through increased sediment delivery associated both with development and with a densification of road networks (Stein and others 2009). Therefore, protecting existing forests from fragmentation and addressing other environmental threats become even more critical for surface water supplies that depends on privately owned forests.

Comparison to Previous Studies

Several studies have estimated water supply and the proportion of water supply originating on NFS and other forested lands across the CONUS (table 4). These studies differ in their modeling approaches, spatial and temporal resolution, modeling time period, and representation of NFS and other forested lands. For example, Brown and others (2008) used a multimodeling approach to predict mean annual water supply over the 1953–1994 time period, land cover based on the 1992 NLCD, and NFS lands based on proclamation boundaries. Our study used the monthly WaSSI hydrologic model over the 2001–2015 time period, land cover based on the 2006 NLCD, and NFS lands based on ownership parcels. The NFS ownership parcels differ from NFS proclamation boundaries in that NFS ownership parcels contain only those parcels owned by the NFS, whereas the NFS proclamation boundaries include all lands regardless of whether NFS owns the land. As a result of differences in NFS boundaries used, Brown and others (2008) and Luce and others (2017) report larger percentages of NFS land in the CONUS (11 percent) than in our study and Brown and others (2016) (9 percent), as well as larger proportions of water supply from NFS lands (18 percent) compared to Brown and others (2016) (15 percent) and our study (13 percent). Similarly, differences in the representation of all forested lands resulted in differences in reported land area and water supply from all forests. To represent all forests, Brown and others (2008) used 1992 NLCD land cover classes 41, 42, and 43 (deciduous, evergreen, and mixed forest, respectively), and Brown and others (2016) used the 2006 NLCD classes 41, 42, and 43. Our study used the NFS ownership parcels and 2006 NLCD classes 41, 42, and 43 for remaining lands to represent all forested lands. Due in part to the differences in time period of land cover data, Brown and others (2016) reported lower forested land area (26 percent) than Brown and others (2008) (29 percent), which contributed to a lower proportion of water supply from forested land (46 percent versus 53 percent, respectively). Similarly, because our study used NFS lands, including both national forests and national grasslands, as part of all forested land, we report higher forested land area (29 percent) than Brown and others (2016) (26 percent) yet similar water supply from all forested lands (46 percent). In addition to differences in forested area, differences in modeling time period will affect water supply predictions due to differences in climate over those time periods. For example, precipitation increased approximately 4 percent from 1901–2015 across the CONUS and was generally greater in the East and lower in the West from 1986 through 2015 compared to 1901–1960 (Easterling and others 2017). These differences in precipitation over time may partly explain why our study and Brown and others (2016) predicted greater total water supply than Brown and others (2008). Despite differences in predicted magnitudes of water supply, the proportions of water supply from NFS lands and other forested lands are very consistent across studies when considering the differences in representation of forested land area discussed above. In all, results of this study are consistent with previous work when considering differences in modeling approaches, spatial and temporal resolution, modeling time period, and representation of NFS and other forested lands.

SUMMARY

Overall, NFS lands comprise 9.2 percent of the total CONUS land area but contributed 12.8 percent of the total surface water supply. When incorporating IBTs, approximately 45.8 million people obtained >10 percent of their surface drinking water supply from NFS lands, and 22.6 million people received >50 percent of surface drinking water supply from NFS lands. In addition to those populations receiving surface drinking water supply from their local public surface drinking water intakes, 12.6 million people were served by PWSs that purchased surface drinking water from other PWSs deriving >10 percent of their surface drinking water supply from NFS lands.

Although NFS and other forested lands make up 28.7 percent of the total CONUS land area, they provide 46.0 percent of the surface water supply. About 125.5 million people, or 38.9 percent of the total population in the CONUS in 2017, derived >10 percent of their surface drinking water supply from NFS and other forested lands from the intakes managed by their PWSs, including those receiving water through IBTs. Around 83.1 million people, or 25.7 percent of the total population in the CONUS, receive the majority (>50 percent) of their surface drinking water supply from NFS and other forested lands. In addition to those populations receiving surface drinking water supply from their local public surface drinking water intakes, 38.3 million people were served by PWSs that purchased surface drinking water from other PWSs deriving >10 percent of their surface drinking water supply from NFS and other forested lands.

NFS and other forested lands are the dominant surface water supply source in the West. Inter-basin transfers played a critical role in providing surface drinking water supply from NFS and other forested lands to urban areas, especially in the arid West. Our study developed benchmark high-resolution data for water supply, identified surface water sources and withdrawal locations for public surface drinking water supplies, and highlights the water-related benefits of NFS and other forested lands to downstream communities and people living in other areas through IBTs.

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The U.S. Department of Agriculture's Forest Service manages more than 779,000 km^2 (193 million acres) of national forests and grasslands (collectively, National Forest System [NFS] lands) that play a significant role in providing clean, fresh water for local ecosystems and economies. This water is sometimes transferred hundreds of kilometers away to also serve big cities through inter-basin transfers (IBTs). The contribution of NFS lands to surface drinking water supplies for public water systems has not been assessed at the national scale while accounting for IBTs. The Forest Service Water Supply Stress Index (WaSSI) model was modified to provide estimates of 2001–2015 mean annual surface water supply and the proportion of mean surface water supply originating on 172 NFS land units and other forested lands at the 12-digit hydrologic unit code scale across the conterminous United States (CONUS) while accounting for water transfer through IBTs. Predictions of the proportion of surface water supply originating on NFS and other forested lands were linked to specific downstream communities and populations, using surface drinking water intake information from the U.S. Environmental Protection Agency Safe Drinking Water Information System database of public water systems. A new database of 594 IBTs was compiled for this study, ranging from 0.01 million $m^3\ yr^{-1}$ to 8,900 million $m^3\ yr^{-1}$, for a total transferred volume of 116,894 million $m^3\ yr^{-1}$. Overall, NFS lands comprised 9.2 percent of the total CONUS land area but contributed 12.8 percent of the surface water supply. In the West, NFS lands comprised 19.2 percent of the total land area but contributed 46.3 percent of the 478.7 billion $m^3\ yr^{-1}$ surface water supply; in the East, NFS lands comprised about 2.8 percent of the total land area and 3.8 percent (66.6 billion $m^3\ yr^{-1}$) of the surface water supply. In total across the CONUS, NFS and other forested lands comprised 28.7 percent of the total land area but contributed 46.0 percent of the surface water supply. Approximately 45.8 million people derived >10 percent of their surface drinking water supply from NFS lands, and 22.6 million people received >50 percent of their surface drinking water supply from NFS lands. Approximately 125.5 million people, about 39 percent of the total population in the CONUS in 2017, derived >10 percent of their surface drinking water supply from NFS and other forested lands, with 83.1 million people receiving >50 percent of their surface drinking water supply from NFS and other forested lands. In addition to those populations receiving surface drinking water supply from their local public surface drinking water intakes, 12.6 million people were served by public water systems that purchased surface drinking water supply from other public water systems deriving >10 percent of their surface drinking water supply from NFS lands. This study provides a systematic accounting of NFS and other forested lands for surface drinking water supply. Our results can aid water resource and forest managers in developing integrated watershed management plans at a time when climate change, population growth, and land development threaten water supplies.

Keywords: Drinking water, inter-basin transfers, National Forest System, WaSSI, water supply, water yield.