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Inter-Basin Transfers Extend the Benefits of Water From Forests to Population Centers Across the Conterminous U.S.

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Key Points:

- National Forest System and other forested lands comprised 28.7% of the total land area but contributed 46.0% of the total water yield
- Approximately 125.5 million and 83.1 million people received more than 10% and 50% of their surface drinking water supply from forested lands, respectively
- Without considering inter-basin transfer, benefits of forests to water supply would be underestimated

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Abstract Clean water from forests is commonly used to supply drinking water to communities both within and outside basin boundaries through inter-basin transfers (IBTs). Here, we modified the Water Supply Stress Index (WaSSI) model to provide estimates of mean water yield and the proportion of mean flow originating on forested lands at the 12-Digit Hydrologic Unit Code scale across the conterminous United States (CONUS). We accounted for the benefits of forests for drinking water supply and receiving populations through IBTs by incorporating a new IBT database, surface intake location information for public drinking water systems, and modeled water yield from forests. We compiled the new database of 594 IBTs 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}. According to our results, forested lands comprised 28.7% of the total land area across CONUS, but contributed 46% of the total surface water yield. Approximately 125.5 million people derived more than 10% of their surface drinking water supply from forested lands, and 83.1 million people received more than 50% of their surface drinking water supply from forested lands. Of those 83.1 million people receiving more than 50% of their surface drinking water supply from forested lands, 19.4 million people obtained some (≥0.01%) of that water through IBTs. We conclude that accounting for IBTs is critical to accurately assess the contribution of forested watersheds for surface drinking water supply. Hydrologic models for assessment and decision making must include IBTs to fully account for the effects of climate change and human population dynamics on water resource availability at watershed to regional scales. Results from this study can aid water resource and forest managers in developing integrated watershed management plans at a time when climate change, population growth, and land use change threaten water supplies.

1. Introduction

Fresh water shortage to meet human and ecosystem needs is recognized globally (Gosling & Arnell, 2016; Vörösmarty et al., 2000). Water stress is already common in the dry western United States (U.S.; Milly & Dunne, 2020). With rapid population growth and climate change, water stress is predicted to increase even in the water-rich southeastern U.S (Brown et al., 2019; G. Sun et al., 2008). Annual total water withdrawal in the U.S. increased from about 300 billion m^3 in 1950 to 580 billion m^3 in 2010 (Dieter & Maupin, 2017), coinciding with a doubling of the U.S. population (U.S. Census Bureau, 2010). Even though total water consumption per capita has decreased since 1980 in the conterminous United States (CONUS; Dieter & Maupin, 2017), water demand is projected to grow with population, and water withdrawals are projected to increase (Brown et al., 2013) except in areas where water supply is already overallocated. Exurban growth, as the most persistent and permanent land use change, increased considerably over the past four decades (Homer et al., 2020; Radeloff et al., 2005; Stein et al., 2009; Theobald, 2005), threatening water supply in many population centers in the U.S.

Globally, forested watersheds provide 75% of accessible freshwater resources (Millennium Ecosystem Assessment, 2005). A century of research has demonstrated unequivocally that forested lands provide the cleanest and most stable water supply compared to other land cover types (Brogna et al., 2018; Creed & van Noordwijk, 2018;

Dudley & Stolton, 2003; Fiquepron et al., 2013; Giri & Qiu, 2016; Jackson et al., 2004; Lockaby et al., 2013). Although the total amount of forest area has stabilized in recent decades in the U.S. (D'Annunzio et al., 2015) after earlier considerable decline (Oswalt et al., 2019), forested lands are predicted to decline again in the future as the population grows (Wear et al., 2013). Given the many water-related benefits of forested lands (Brunette & Germain, 2003; Taylor, 2018; Warziniack et al., 2017), drinking water utilities are protecting their source forested watersheds for high water quality and sustain water supply (NYC Environmental Protection, 2017; Seattle Public Utilities, 2011). Consequently, improving water supplies has been recognized as one of the important goals in forest management (FAO et al., 2021; Sun & 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 et al., 2014; National Research Council, 2008; Vose, 2019).

For more than a century, U.S. legislation has emphasized the importance of protecting forests and water resources. Since the late 1800s, certain acts have been passed to safeguard our Nation's forests and water resources. In this legislation, the U.S. Department of Agriculture (USDA) Forest Service has been charged with sustaining and improving water resources through protection, restoration, and enhancement of forested landscapes. 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 national forest lands.

The spatial distribution of forested lands affects the surface water supply for downstream communities (Greene et al., 2013). Forested lands contribute disproportionately to the total water supply for downstream communities in the U.S (Brown et al., 2008, 2016; Caldwell et al., 2014; Creed et al., 2019; Liu et al., 2020, 2021; Vose, 2019). Our previous study shows that over half of the U.S. population benefits from water originating from forested lands because forests are often found in areas with high precipitation and are regarded as "water towers" (Liu et al., 2021). Although water supply has been recognized as a critical factor for National Forest management, privately owned forests are the most vulnerable to future land use change and associated water supply impacts (Liu et al., 2021). Most of the public forests lie in the 11 contiguous western states, while privately owned forests are the dominant forested lands in the eastern U.S. For example, forests owned by corporations, families, and other private entities account for about 80% of the total forested land area across the South (Liu et al., 2020). Federally owned forests are managed for multiple uses, including timber production, habitat, and other ecosystem services, while corporately owned forests (26% of the total forested land in the South) are generally managed to maximize timber production.

Human water supply is affected not only by natural hydrology and land cover but also by human-made water diversions and hydraulic structures. Water can be transferred thousands of kilometers away to other regions through inter-basin transfers (IBTs) to meet demand where supply is scarce or where raw water quality is problematic (McDonald et al., 2014). Distant watersheds that produce high-quality water are often preferred over nearby watersheds producing lower quality water to reduce treatment cost. For example, the New York City imports approximately 90% of its surface drinking water from the Catskill and Delaware watersheds (NYC Environmental Protection, 2017). Los Angeles obtains more than 90% of its water from multiple sources outside the city (Ashoori et al., 2015). These donor watersheds are often protected areas with high forest coverage. Previously, the most comprehensive national-scale database of IBTs in the CONUS was compiled in the 1980s by the USGS (Mooty & Jeffcoat, 1986; Petsch, 1985). This database was generated from survey questionnaires at the State level and considered all IBTs that crossed 6-digit hydrologic unit code (HUC6) watershed boundaries, while identifying source and destination basins at the 8-digit (fourth level) hydrologic unit code (HUC8) scale. In all, there were 256 IBTs in this inventory with annual transfer flow volumes based on estimates from 1973 to 1982. While dated, this database has been widely used for national-scale water resource assessments (e.g., Brown et al., 2019; Duan et al., 2019; Emanuel et al., 2015). More recently, Dickson and Dzombak (2017) estimated that there are 2,161 IBTs crossing HUC6 watershed boundaries in the U.S., by utilizing the U.S. Department of the Interior, U.S. Geological Survey (USGS) National Hydrography Database (NHD; Moore & Dewald, 2016), with about 300 IBTs driven by city water use. However, while the potential locations of IBT conveyances were identified, transfer volumes for these IBTs were not quantified. For this present study, we have compiled a new database of IBTs that represents the most complete accounting and updated information on water transfers for public drinking water, including high-resolution spatial location of donor and receiving watersheds as well as water transfer volumes. Without considering these IBTs, the magnitude and spatial extent of forest influence on surface drinking water supplies are misrepresented (Emanuel et al., 2015).

This study aims to quantify the contribution of forested lands to surface drinking water supply systems in the CONUS, including those watersheds receiving water via IBTs. As such, the available water and the origin of that water by land cover at each public surface drinking water intake were estimated using a water balance model by accounting for natural water drainage throughout the river network as well as water transferred through IBTs. Our objectives were to: (a) estimate how much fresh surface water supply originated from forested lands across the CONUS; and (b) estimate how many people and which communities receive this water supply, both with and without IBTs. This study is the first attempt to evaluate the contributions of forested lands to public surface drinking water intakes across the CONUS while accounting for IBTs.

2. Materials and Methods

2.1. Extent and Scale of Analysis

This study focused on water yield originating on forested lands, and how that water contributes to surface drinking water supply at public water systems across the CONUS. We focused on surface water supplies because we could not be certain of the origin (i.e., forested land vs. nonforested land) of water for any given groundwater supply well at this large scale. Depending on local factors such as well depth, pumping rates, elevation gradients, and aquifer characteristics, groundwater may originate near where it is withdrawn or from some distance away.

We quantified the proportion of the surface water supply available to a given public surface drinking water intake that originated on forested lands. Forested lands in this study include 172 National Forest System (NFS) units and other forested lands (Figure 1). Similar to Caldwell et al. (2014), other non-NFS forested lands were defined by 2006 National Land Cover Database (NLCD; Table 1), including deciduous, evergreen, and mixed forest. The boundaries of the 172 units of NFS lands were derived from the Basic Ownership data set developed by the U.S. Department of Agriculture Forest Service (USFS; Table 1).

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 about 100 km^2. In addition to the HUC12s in the CONUS, watersheds in Canada and Mexico that drain to the CONUS were included so that total flow volumes and proportion of flow originating on forested lands near international borders could be properly estimated. The relative contribution of forested lands to the total water supply was calculated for every HUC12 through each river network.

2.2. Estimating Surface Water Supply From Forested Lands

The water supply from each land cover type in a HUC12 was estimated using the Water Supply Stress Index (WaSSI) hydrologic model (Caldwell et al., 2011, 2012; G. Sun et al., 2011). The WaSSI model has been tested, validated, and compared to other water balance models (Caldwell et al., 2012, 2015, 2020; Li et al., 2020; Schwalm et al., 2015; G. Sun et al., 2011). It has been used in several regional and national scale water resource assessments (Duan et al., 2018, 2019; Li et al., 2020; Lockaby et al., 2013; Marion et al., 2013; S. Sun et al., 2016; Tavernia et al., 2013), in examining the water-energy nexus at the national scale (Averyt et al., 2011), in quantifying surface water supplied by National Forests (Caldwell et al., 2014) and State and private forests in the South (Liu et al., 2020) and across the CONUS (Liu et al., 2021), and in studying the impacts of historical drought on National Forests and Grasslands across the CONUS (S. Sun et al., 2015a, 2015b).

The WaSSI model is parameterized using readily available national-scale soil, land cover, and climate data (Table 1). All input data sets 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 & Wolock, 1999). The WaSSI model calculates monthly infiltration, surface runoff, soil moisture, and baseflow for each HUC12 land cover type using algorithms of the Sacramento Soil Moisture Accounting Model (SAC-SMA; Burnash, 1995; Burnash et al., 1973). The soil profile is divided into a relatively thin upper layer and a much thicker lower layer that supplies moisture to meet evapotranspiration (ET) demands (Koren et al., 2003). Each layer consists of tension

Table 1
Data Inputs for the Water Supply Stress Index (WaSSI) Model

Data/database	Source	Resolution	Time period
Soil properties	State Soil Geographic (STATSGO)-based Sacramento Soil Moisture Accounting Model Soil Parameters National Oceanic and Atmospheric Administration National Weather Service, Office of Hydrologic Development, Hydrology Laboratory	1- × 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- × 30-m grid	2006
Impervious cover for areas outside the United States	Global Man-made Impervious Surface (GMIS) Data Set from Landsat, v1 (2010) (https://sedac.ciesin.columbia.edu/data/set/ulandsat-gmis-v1/data-download)		2010
National Forest System	USFS Automated Lands Program Land Status Record System surface ownership parcels (basic ownership) (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- × 30-m grid	2006
Monthly mean leaf area index (LAI) by land cover	Moderate Resolution Imaging Spectroradiometer (MODIS) (https://modis.gsfc.nasa.gov/)	1- × 1-km grid	2001–2012
Climate (monthly precipitation and temperature) for the conterminous United States	PRISM Climate Group (http://www.prism.oregonstate.edu/)	4- × 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- × 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
Surface drinking water Intake	Safe Drinking Water Information System (SDWIS) database (https://www.epa.gov/ground-water-and-drinking-water/safe-drinking-water-information-system-sdwis-federal-reporting)	Points	2017Q3

Note. HUC = Hydrologic Unit Code.

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 streams (interflow), percolation from the upper soil layer to the lower soil layer, and lateral water movement from the lower soil layer to streams (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 (G. Sun et al., 2011). Storage and ET in each HUC12 for impervious cover 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. Water yield is calculated for each land cover type in a given HUC12 as the sum of surface runoff from pervious and impervious surfaces, interflow, and baseflow after accounting for losses that include changes in water storage in the soil, evaporation, and transpiration from vegetation. Water yield for each HUC12 is then calculated as the sum of the area-weighted averages of water yield of each land cover type present and expressed in mm yr^{-1}. Water yield for each HUC12 is then routed and accumulated from upstream to downstream HUC12s along the river network to estimate the total water supply at the outlet of each respective HUC12. In this study, the 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 federal NFS land ownership parcels on 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. We also quantified the contribution of non-NFS forested lands to surface water supply. The NFS lands evaluated in this study include both National Forests and National Grasslands, with

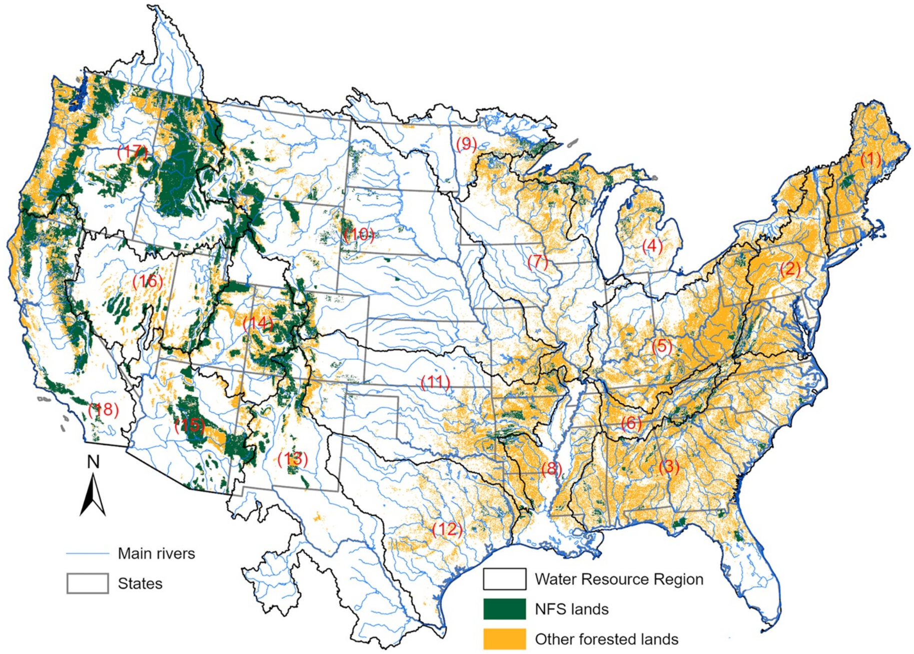

Figure 1. Distribution of National Forest System (NFS) lands and other forested lands for estimating water supply originating on forested lands serving public surface drinking water in the CONUS. Water resource regions (WRR) in the National Hydrography Data set (NHD) are: 1 (New England), 2 (Mid-Atlantic), 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).

the latter comprising only 2.3% of all NFS lands. Therefore, results for NFS lands are considered to be from forests on those lands. In addition, the other forested lands based on the NLCD do not include woody wetlands, areas with young trees in early succession, or trees stunted by environmental conditions, that are classified as shrubland in the NLCD (Homer et al., 2015).

The WaSSI flow routing algorithm tracks water flow from forested lands and other lands through the river network (Figure 1) 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 water supply and the fraction of water supply originating on forested lands were quantified for each HUC12 watershed.

2.3. Linking Water Yield From Forested Lands to Public Water Systems

The surface water supply originating on forested lands was linked to communities and populations served using the 2017Q3 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 intakes in the SDWIS database were screened for obvious locational errors, and only those facilities meeting the following criteria were included in the analysis: (a) facilities associated with a public water system serving a population of at least 25 people, (b) facilities associated with a public water system whose primary source was denoted as "surface water" or "ground water under the influence of surface water," and (c) facilities whose facility-level water type was denoted as "surface water" or "ground water under the influence of surface water."

The population served in the SDWIS database is attributed to the water system as opposed to specific intakes within a system. When calculating the population served by water from forested lands, we aggregated the surface drinking water supply across all intakes for each public water system by calculating the total available surface drinking water supply and the total surface drinking water supply from forested lands across all intakes for the public water system. When intakes were displayed on maps (Figures 7 and 9), we divided the total population served by the public water system 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 public water systems serving a total population of 137.9 million people [43% 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 supply from another public water system. We overlaid the public surface drinking water intakes on the HUC12 watershed boundaries and assumed that the WaSSI-estimated proportion of water from forested lands at the outlet of the HUC12 watershed in which a given intake was located was representative of the intake location.

2.4. Inter-Basin Surface Water Transfers

In this study, we compiled a new IBT database for CONUS at the HUC12 scale. Of the 626 IBTs in the database, this study incorporates the 594 that transfer water from or to areas downstream of forested lands. This study used the average volume transferred between 2001 and 2015 from the IBT database. Irrigation transfers were generally included only when prominent and/or integrated within a complex system that included drinking water supplies. In the Upper Colorado Region (Water Resource Region, WRR, 14), where water transfers are ubiquitous and vary greatly in spatial and volumetric scope (Mooty & Jeffcoat, 1986; Petsch, 1985), an IBT was recognized 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 remainder of CONUS, IBTs were included when they crossed HUC8s and also served more than 200,000 people based on the 2017 EPA SDWIS data on public surface drinking water systems, because our main interest was in drinking water supply and the populations intertwined with it. Using this approach, some IBTs that transfer water originating on forested lands to public surface drinking water intakes may not be included in our database. However, this level of screening potential IBTs was necessary to balance the investigation effort with providing a reasonable representation of the movement of water from forested lands by IBTs.

We modified the WaSSI model to account for water transfers through IBTs by incorporating the water transferred from the source to the destination HUC12 for all IBTs in the flow accumulation calculations. Thus, the available water supply from forested lands of each HUC12 reflected the amount of surface water transferred across HUC12s through the IBTs upstream.

3. Results

3.1. Water Yield From Forested Lands

Forested lands contributed disproportionately more water yields to the total surface water supply in comparison with other land cover types at the CONUS scale (Table 2). Forested lands comprised 28.7% of the total land area but contributed 46.0% of the total available water supply. Alone, NFS lands comprised 9.2% of the total land area and provided 12.8% of the total available surface water supply. NFS lands are the main source of water from forested lands in the West, while non-NFS lands dominate the water supply from forested lands in the East. In the West, forested lands comprised 29.7% of the total land area and contributed 347.2 billion $m^3\ yr^{-1}$, or 72.5% of the total available water supply generated there. In contrast, in the East, forested lands comprised 28.1% of the total land area and provided 687.3 billion $m^3\ yr^{-1}$, or 38.8% of the total available water supply generated in the East.

In general, areas with a high proportion (>75%) of water supply from forested lands (Figure 2) had a large percentage of forested lands upstream (Figure 1), such as most of the forested headwaters in the West and Appalachian mountains in the East. In the East, the proportion of water supply from forested lands gradually decreased with distance downstream and was less than the proportion of the upstream area that was forested. For example, the percentage of surface water supply from forested lands in the Ohio Region (WRR 5) was lower than the

Table 2
Summary of Water Supply From Forested Lands From 2001 Through 2015

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

[a]West of CONUS, including western 11 states—Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming. [b]East of CONUS, including eastern 37 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]Aggregated from the watershed boundaries, including water bodies.

percentage of forested lands in the total contributing area along the mainstream (Figure 3a). It declined from >70% of water from forested lands in the headwaters to about 50% at the confluence of the Ohio River and the Mississippi River, while the percentage of forested lands declined only slightly from about 85% to about 78%. In contrast, many rivers in the West still had more than 75% of their water supply from forested lands at great distances downstream while the amount of forest upstream declined significantly. For example, the percentage of surface water supply from forested lands in the Colorado Regions (WRR 14 and 15) was much higher than the percentage of forested lands in the total contributing area along the mainstream (Figure 3b). Although the percentage of forested lands in the total land area substantially decreased from around 100% of the forested

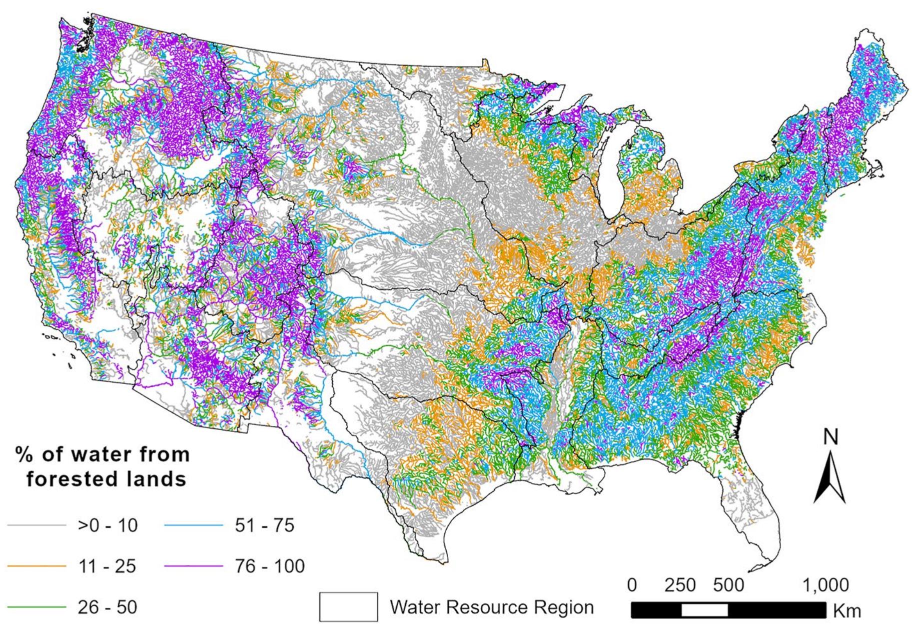

Figure 2. Percentage of the total 2001–2015 mean annual water yield that originates on forested lands after incorporating IBTs by 12-digit (sixth-level) Hydrologic Unit Code (HUC12) watersheds streamlines. Surface water supply is defined as the total amount of flow volume at the outlet of each HUC watershed, including flow accumulated from HUCs upstream. Streamlines of HUC12 watersheds are colored according to the fraction of total water supply at the watershed outlet that originated on forested lands.

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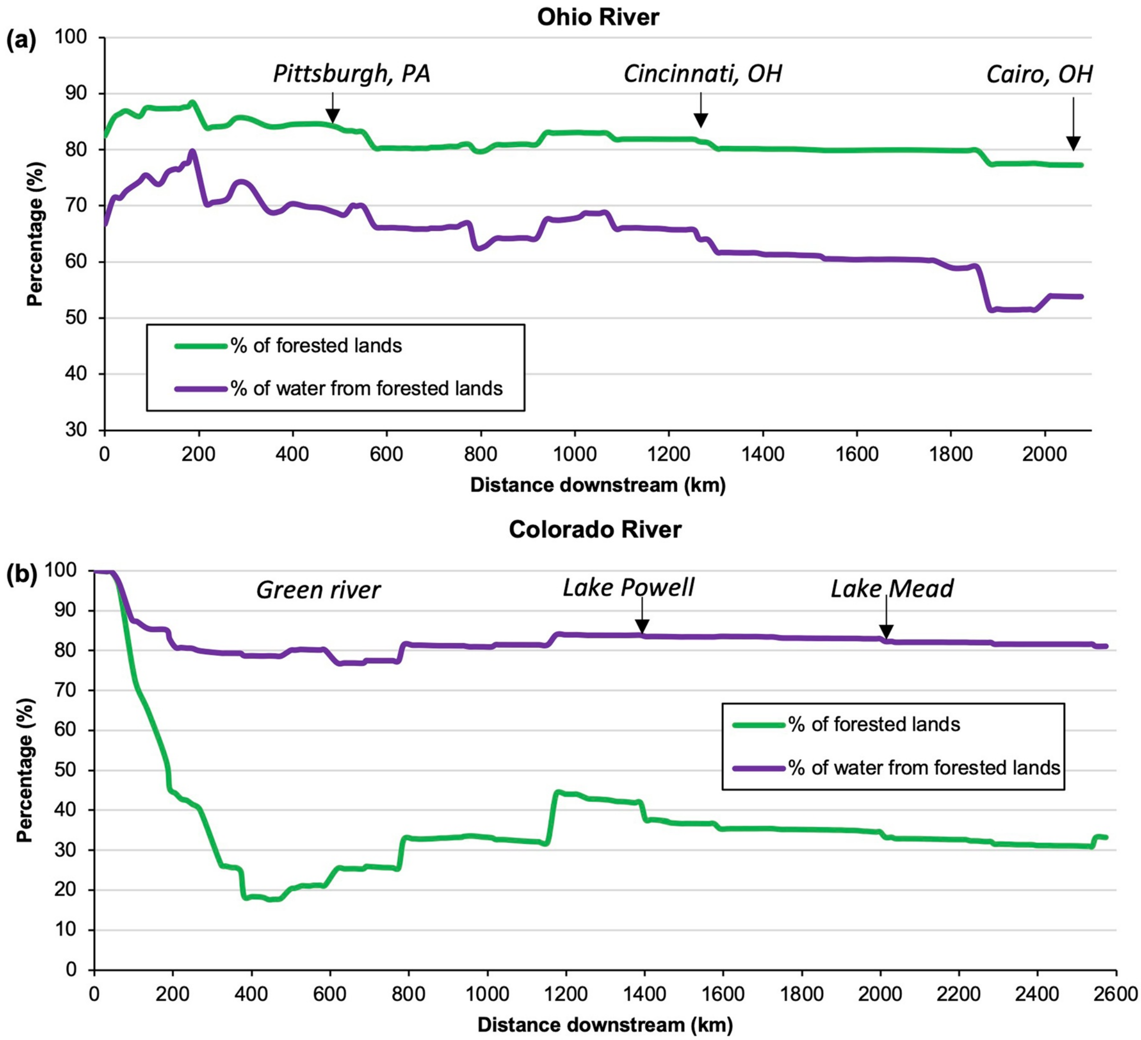

Figure 3. Percentage of forested lands in the contributing land area and the proportion of surface water supply that originates on forested lands along the mainstream of the Ohio River in the East (a) and the Colorado River in the West (b) of the CONUS.

headwaters to less than 20% approximately 400 km downstream of the headwaters, the percentage of surface water supply from forested lands was consistently high (about 80%).

3.2. Water Transferred by IBTs

Those 594 IBTs used in this study, transferring from 0.01 million m^3 yr^{-1} to 8,900 million m^3 yr^{-1}, based on the average of transfer volumes from 2001 through 2015 (Figure 4), 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 out of 594) are transferring water from HUC12s where >50% of their water originated on forested lands, with most of those IBTs located in the Western United States (Colorado and California Regions). This group of 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.

The IBTs considerably altered the total available water in downstream river reaches (Figure 5). The IBTs on average increased total available water by more than 10% for 2,987 HUC12s downstream of those 594 IBTs. There are almost the same number of HUC12s that lose water as a result of IBTs transfers. Around 400 HUC12s gained more than 50% of their accumulated water through large IBTs; these HUCs are mainly located in urban areas such as Los Angeles, CA and Phoenix, AZ (Figure 5b), Denver, CO (Figure 5c), and New York City, NY (Figure 5d).

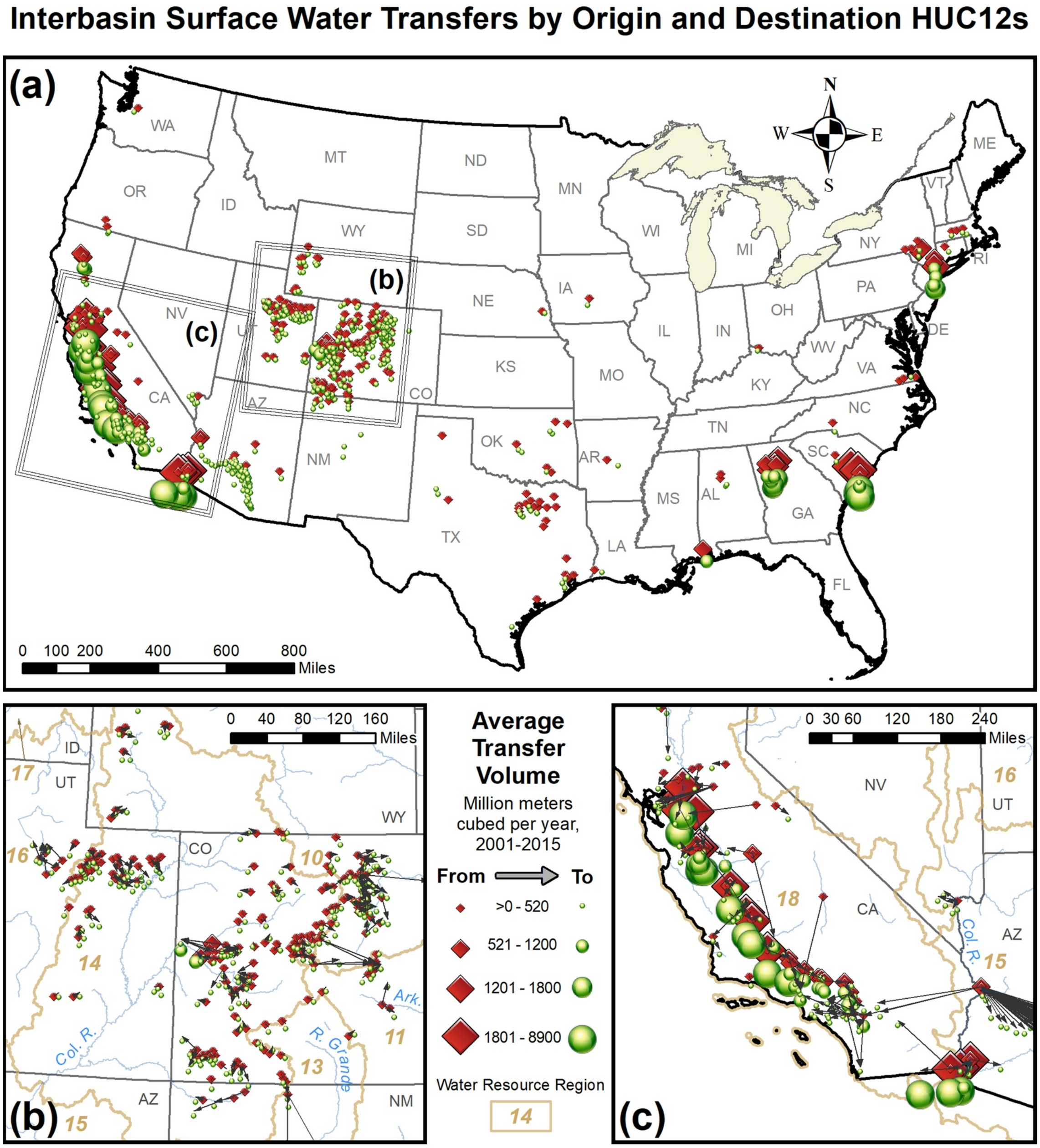

Figure 4. Inter-basin transfers (IBTs) in the conterminous United States from 2001 to 2015. Colors show the direction of IBTs and size represents mean annual transfer magnitudes between 12-digit Hydrologic Unit Code watersheds (HUC12s).

Due to those large IBT transfers, 63 HUC12s lost more than 50% of their total available water and were mostly located in upstream forested lands. Almost 30% of water at the mouth of Colorado River was lost due to the IBTs to other regions (Figure 5b).

IBTs moved water originating on forested lands both within and across water resource regions. Notably, multiple IBTs transferred a total of 873.5 million m^3 yr^{-1} of surface water from the Upper Colorado Region (WRR 14) to adjacent Water Resource Regions 10, 11, 13, and 16 (Figure 6). Based on 2001–2015 average values, 459.6 million m^3 of surface water was transferred from Upper Colorado Region (WRR 14) to Missouri Region (WRR 10; 82.4% from forested lands), 166.5 million m^3 to Arkansas-White-Red Region (WRR 11; 96.4% from forested lands), 104.9 million m^3 to Rio Grande Region (WRR 13; 75.7% from forested lands), and 142.6 million m^3 to Great Basin Region (WRR 16; 97.0% from forested lands).

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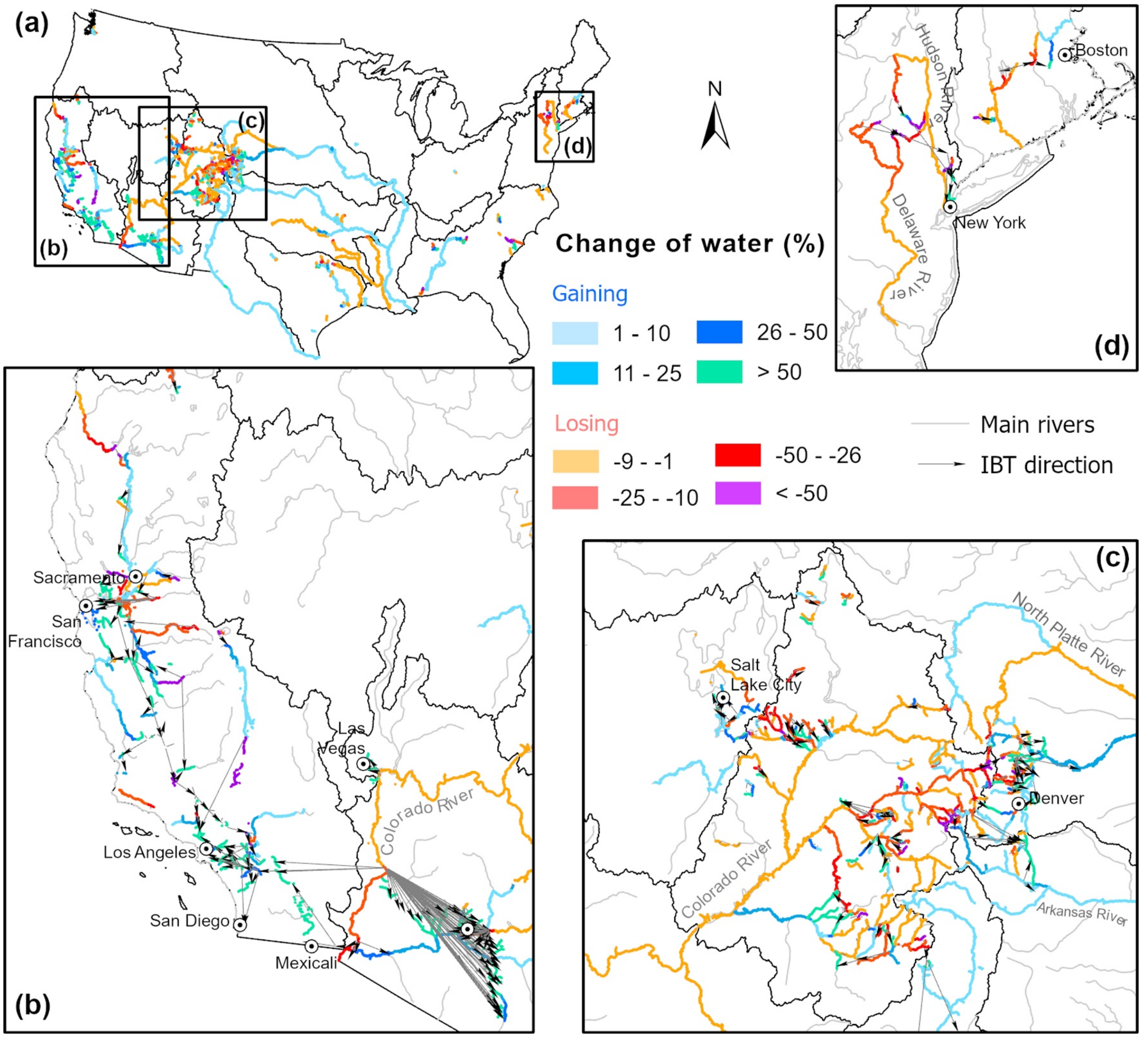

Figure 5. Impacts of inter-basin transfers on downstream flows averaged over the years 2001–2015. Net impacts shown for HUC12s within the conterminous United States (a). For three major areas, the California Region and lower Colorado River Region (b), the upper Colorado River Region (c), and the New York area (d).

3.3. Population and Communities Served by Water From Forested Lands

Approximately 125.5 million people, around 40% of the total population in the CONUS in 2017, derived >10% of their surface drinking water supply from forested lands. Approximately 83.1 million people received >50% of their surface drinking water supply from forested lands. Of the 8910 public surface drinking water intakes in 5,041 communities in CONUS, 7,891 intakes (88.6%) serving 4,621 communities received >10% of their surface drinking water supply from forested lands, with 5,073 intakes in 3,107 communities receiving >50% of their surface drinking water supply from forested lands (Figure 7). There are 4,994 public water systems that received some portion (≥0.01%) of their surface drinking water supply from forested lands incorporating IBTs, serving approximately 136.7 million people in the CONUS. Without incorporating IBTs, approximately 123.7 million people would have derived >10% of their surface drinking water supply from forested lands, and 78.0 million would have received >50% of their surface drinking water supply from forested lands (Figure 8).

IBTs helped redistribute water from forested lands to people in other locations, especially in dry urban areas in the West (Figures 4 and 9). For example, the Los Angeles-Long Beach-Riverside-San Bernardino, CA, area, serving 7.1 million people, received 68.7% of its surface drinking water from forested lands in the Colorado and California Regions (WRR 14, 15, and 18) through several IBTs (Figure 5b): 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

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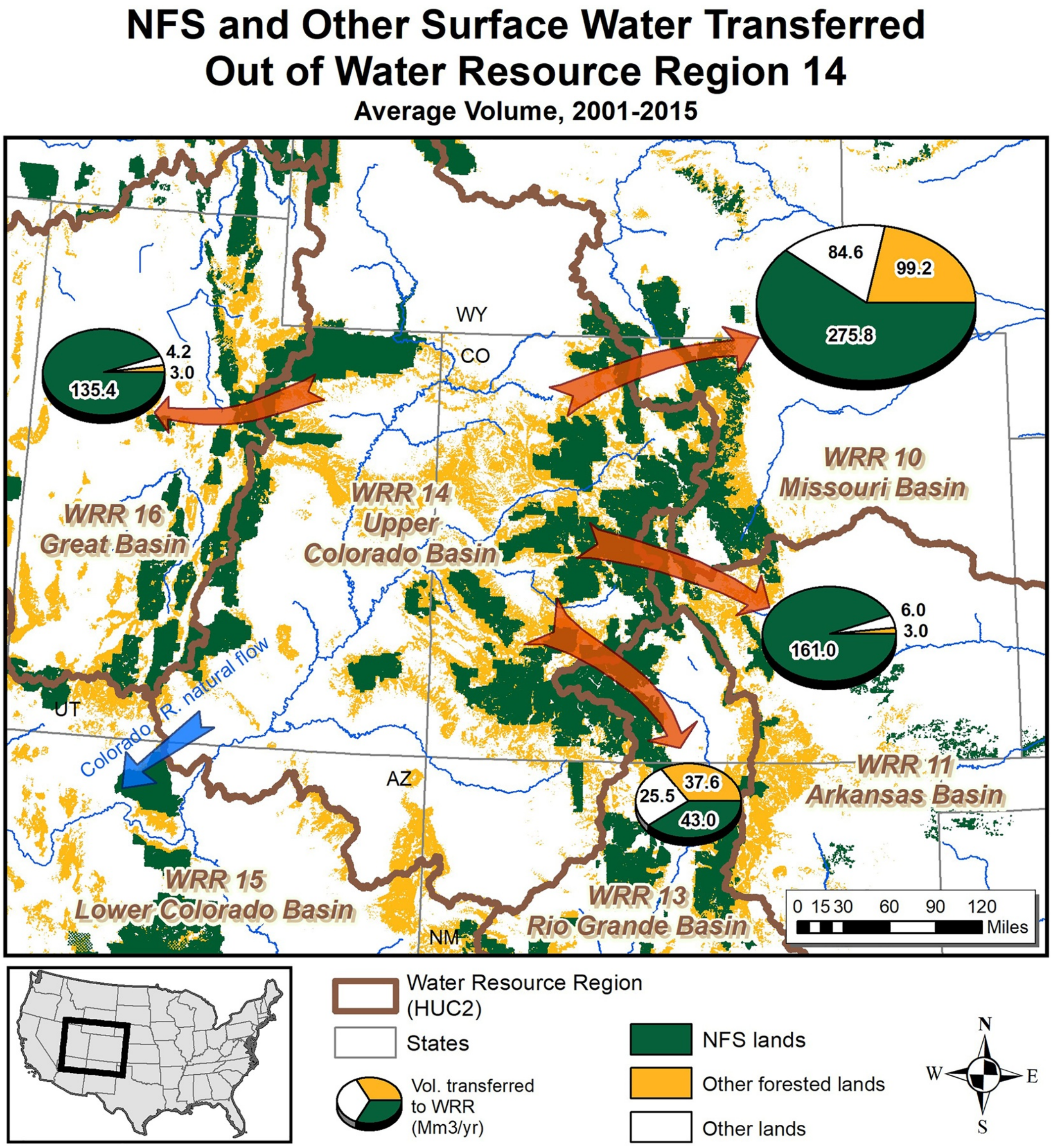

Figure 6. Mean annual surface water transferred out of the Upper Colorado Basin (WRR 14) from forested lands (NFS and other forested lands), and other lands through IBTs from 2001 to 2015.

Southern California and carrying lower Colorado River water; 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 81.5% of its surface drinking water from forested lands in the Upper Colorado River basin (WRR 14) through the Griffith Project, drawing water from Lake Mead, formed by the construction of the Hoover Dam (both Bureau of Reclamation projects). The greater Phoenix, AZ, area, with 3.4 million people served, received 82.0% of its surface drinking water from forested lands in the upper and lower Colorado Regions (WRR 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 infrastructures.

4. Discussion

We combined a hydrologic model, a database of public surface drinking water intakes for public water systems, and an IBT database to determine the role of forested lands in supplying surface drinking water to public surface drinking water intakes in the CONUS. We found that forested lands generate almost half of the surface

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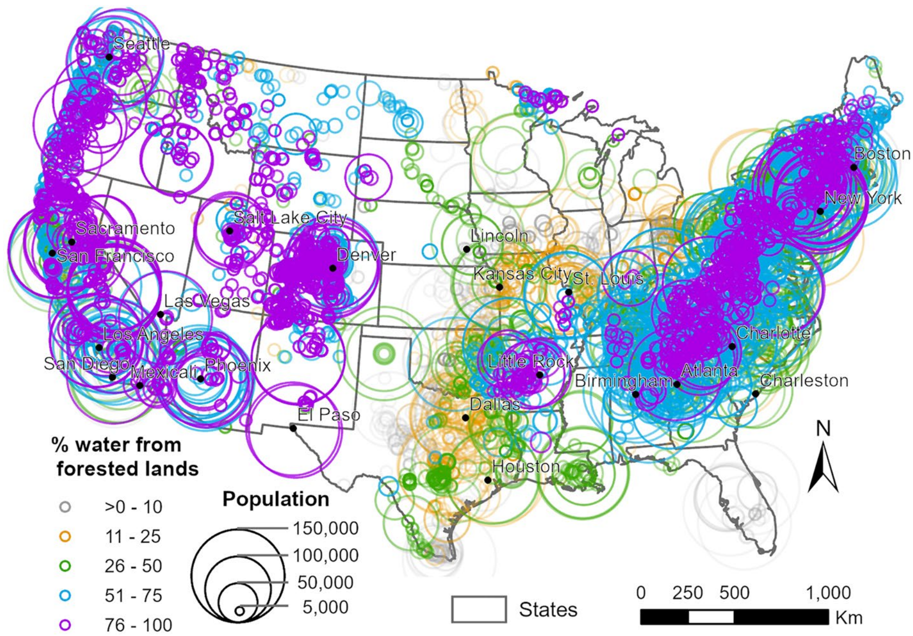

Figure 7. Population served at public surface drinking water intakes and the amount (%) of source water originating on forested lands (NFS and other forests) after accounting for IBTs. Intakes are colored by the percentage of surface drinking water from forested lands and the size of the circles indicates population size.

water supply, and approximately 137 million people received some portion (≥0.01%) of their surface drinking water supply from forested lands. The IBTs considerably decreased the total available water in watersheds downstream of the withdrawals. Conversely, many people get the majority of their surface drinking water supply from NFS and other forested lands with the help of IBTs. This study is the first national-scale study to

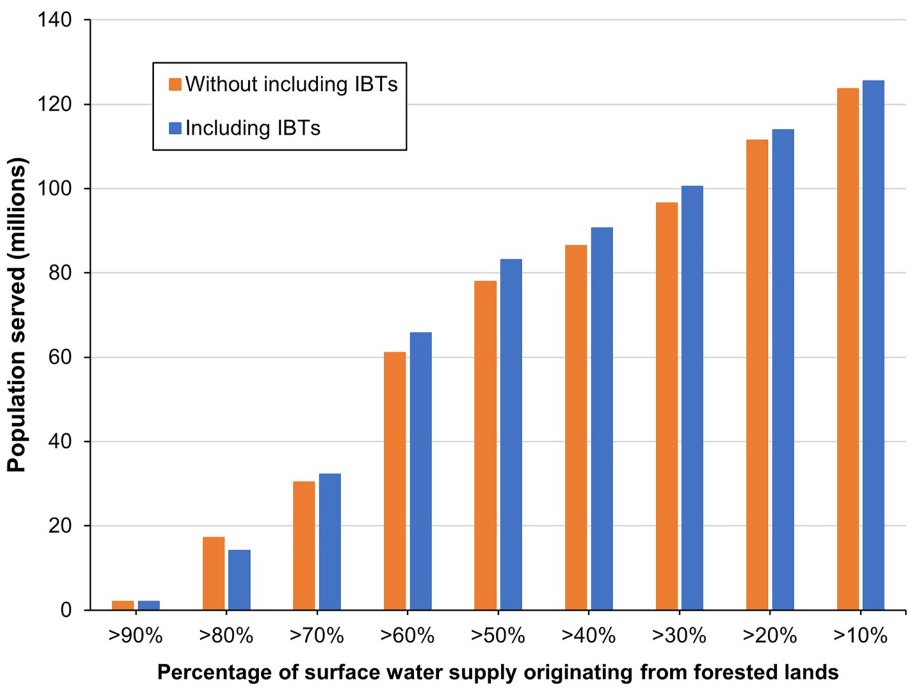

Figure 8. Cumulative frequency of population served according to percentage of surface drinking water coming from forested lands with and without incorporating IBTs.

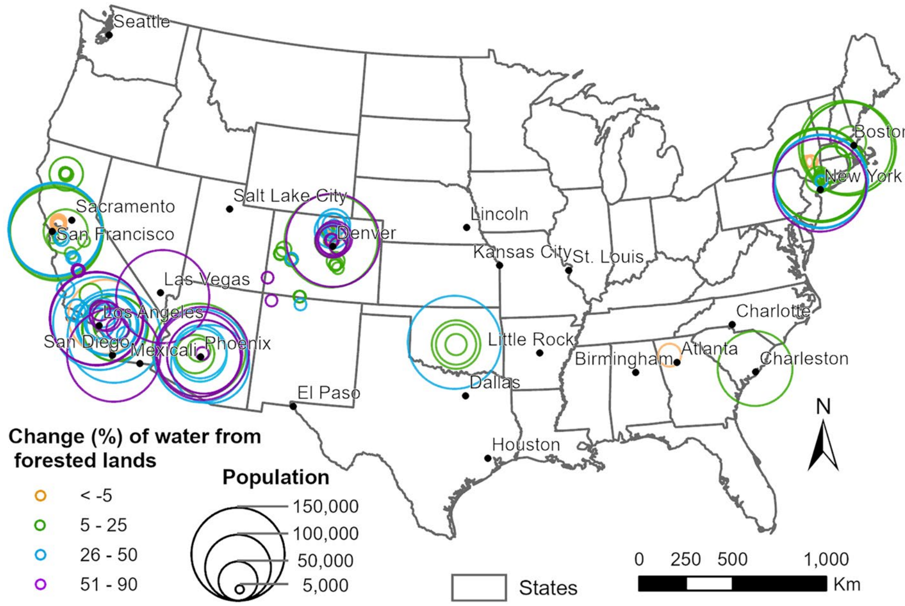

Figure 9. Surface drinking water supply and population affected by IBTs. Intakes are colored by the change of the percentage of surface drinking water from all forested lands (NFS and other forested lands) after incorporating IBTs and the size of the circles indicates population size.

account for IBTs in the linkage between water originating on forested lands and the public water systems and populations they serve.

4.1. 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 (e.g., Brown et al., 2008, 2016). These studies differ in their modeling approaches, spatial and temporal resolution, study time periods, and representation of NFS and other forested lands. We compared previous studies to our results (Table 3).

Brown et al. (2008) and Brown et al. (2016) used a multi-modeling approach to predict mean annual water yield. Brown et al. (2008) modeled over the 1953–1994 time period with land cover based on the 1992 NLCD, and NFS lands based on proclamation boundaries. Brown et al. (2016) modeled over the 1981–2010 time period with land cover based on the 2006 NLCD, and NFS lands based on ownership and 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 boundaries. Differences in the representation of all forested lands resulted in differences in reported land area and water yield from all forests. To represent all forests, our study and those of Brown et al. (2008, 2016) all used land cover classes 41, 42, and 43, but as defined differently in 1992 (Brown et al., 2008) and 2006 (our study and Brown et al., 2016). Due in part to the differences in time period of land cover data, Brown et al. (2016) reported lower forested land area (26%) than Brown et al. (2008) (29%), which contributed to a lower proportion of water yield from forested land (46% vs. 53%, 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%) than Brown et al. (2016) (26%), yet similar water yield from all forested lands (46%).

In addition to differences in forested area, differences in modeling time period will affect water yield predictions due to differences in climate over those time periods. For example, precipitation increased approximately 4% from 1901 to 2015 across CONUS, and was generally greater in the East and lower in the West from 1986 to 2015 compared to 1901 to 1960 (Easterling et al., 2017). These differences in precipitation over time may partly explain why our study and Brown et al. (2016) predicted greater total water yield than Brown et al. (2008). Despite differences in predicted magnitudes of water yield, the proportions of water yield from NFS lands and

Table 3
Comparison Among Studies That Quantified the Contribution of NFS and Other Forested Lands to Water Supply in the Conterminous United States

	Brown et al. (2008)	Brown et al. (2016)[a]	Luce et al. (2017)	This study
Hydrologic Model	Advection-Aridity model (Brutsaert & Stricker, 1979 Zhang model (L. Zhang et al., 2001)	VIC (Mahat et al., 2017)	VIC (Livneh et al., 2013)	WaSSI (Caldwell et al., 2012; G. Sun et al., 2011)
Model spatial resolution	5 × 5 km	~12 × 12 km	~6 × 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 (% of total))	846 (11%)	693 (9%)	846 (11%)	719 (9%)
All forested land area (thousand km^2 (% 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 (% of total))	326 (18%)	280 (15%)	NR (18%)	288 (13%)
All forested land water supply (billion m^3 (% 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

Note. HUC = Hydrologic Unit Code; NFS = National Forest System; 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.

other forested lands are 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.

4.2. Forested Lands Are the Dominant Water Source in Dry Areas

A much higher percentage of people living in the West get the majority (more than 50%) of their surface drinking water from forested lands than people living in the East (Figure 7). Our results showed that about 29.5 million people, or 39.3% of the total population in the West, get more than 50% of their surface drinking water from forested lands, while about 53.6 million people, or 21.6% of the total population in the East, get more than 50% of their surface drinking water from forested lands. Previously, Liu et al. (2020) reported that around 25% of people in the 13 Southern States get more than 50% of their water from non-federal forested lands, which make up 90% of the total forested land area. Similarly, Caldwell et al. (2014) found that around 20% of people get more than 50% of their water 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 (Figure 9).

4.3. IBTs Help Distribute Water From Forested Lands to People

For people who obtain the majority (>50%) of their surface drinking water supply from forested lands across the CONUS, 19.4 million, or 6.0% of total population, obtained some of this water through IBTs. IBTs are critical in the arid West, where 15.2 million people obtained some of their surface drinking water supply through

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IBTs, which represents 52% of the total population in the West who obtain the majority of their water from forested lands (Figure 9). Despite the longstanding recognition that forests are critical for reliable and high-quality water supplies for downstream communities (Creed & van Noordwijk, 2018), this study demonstrates the role of forested lands in surface drinking water supply for people living outside of forested watersheds. Although the contribution of water from forests to urban areas through certain water resources management programs has been reported previously, such as by the New York City (NYC Environmental Protection, 2017), Los Angeles (Ashoori et al., 2015), and Seattle (Seattle Public Utilities, 2011), no previous national-scale studies were able to link each NFS unit to the population served and quantitatively represent the water transfers from these NFS lands across WRRs with a high spatial resolution. Therefore, the importance of forested lands to surface drinking water supply might have been underestimated by previous studies that did not account for IBTs (Barnes et al., 2009; Caldwell et al., 2014; Liu et al., 2020, 2021). Future hydrologic modeling should include IBTs to more accurately account for the human-mediated water transfers between basins (Dickson et al., 2020).

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

We examined the importance of forested lands and IBTs in providing surface drinking water for communities during the historical period of 2001–2015. However, several factors are likely to increase the uncertainty of findings from this study.

The per capita water use in U.S. cities has been declining steadily over the past few decades as a result of conservation practices (Dieter & Maupin, 2017; Rockaway et al., 2011), but population growth is expected to increase total water demand, especially in urban areas (Brown et al., 2019; Yigzaw & Hossain, 2016). Population growth will also indirectly further increase water demand across the U.S. by raising the water demand for agricultural and landscape irrigation, which may be exacerbated by climate change (Brown et al., 2019; Creed et al., 2014). Drought and warming have already resulted in a dramatic reduction of available water to ecosystems across the U.S (S. Sun et al., 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 et al., 2019; Naumann et al., 2018; Sun & Vose, 2016), suggesting more people may be subject to water stress in the future (Duan et al., 2019; Gosling & Arnell, 2016). IBTs are more likely to be constructed when the water stress increases (Dickson & Dzombak, 2017). However, climate change is expected to increase surface temperature and increase the frequency and severity of droughts, both of which will likely reduce water supply (Creed et al., 2014; Duan et al., 2017; Heidari et al., 2021; S. Sun et al., 2015a).

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 (Abildtrup et al., 2013; Lopes et al., 2019; Warziniack et al., 2017). Watersheds with more forest cover tend to have lower concentrations of nutrients and sediment than watersheds with less forest cover (Swank et al., 2001; Tu, 2013; Warziniack et al., 2017). Therefore, the increase in population and urbanization in some parts of the country might increase the demand for high-quality water from forested lands (Brown et al., 2019). The high contribution of water supply from forested lands suggests that protecting forested lands from conversion to developed lands and maintaining healthy forests can improve water resource sustainability.

5. Conclusions

Although forested (NFS and other forested) lands make up 28.7% of the total CONUS land area, they provide 46.0% of the total surface water supply. About 125.5 million people, or 38.9% of the total population in the CONUS in 2017, derived more than 10% of their surface drinking water supply from forested lands, including those receiving water through IBTs. Around 83.1 million people, or 25.7% of the total population in the CONUS, receive the majority (>50%) of their surface drinking water supply from forested lands.

The IBTs as incorporated in our modeling considerably altered the total available water in downstream river reaches.Out of 2,987 HUC12s receiving flow from those 594 IBTs, 389 HUC12s gained more than 50% of their total available water through IBTs.

Forested lands are the dominant water source in the West. IBTs played a critical role in providing surface drinking water supply from forested lands to urban areas, especially in the dry West. Our study developed benchmark high-resolution data for water yield, identified surface water sources and withdrawal locations for public surface drinking water, and highlighted the water-related benefits of forested lands to downstream communities and people living in other areas due to IBTs. Hydrological models for decision-making must include IBTs to fully account for the effects of forests on water resource availability at watershed to regional scales. This becomes more important with water shortage under climate change and rise in human water demands in the future.

Data Availability Statement

Data sets used for this study were obtained from several sources as described in Table 1.

Acknowledgments
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