Environmental Science & Technology

Article

pubs.acs.org/est

Freshwater Vulnerability beyond Local Water Stress: Heterogeneous Effects of Water-Electricity Nexus Across the Continental United States

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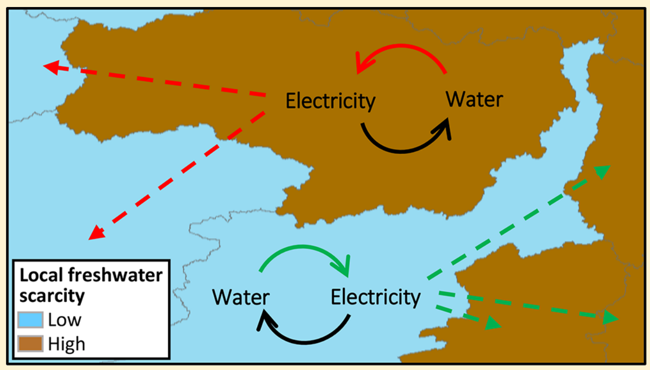
Supporting Information



ABSTRACT: Human health and economic prosperity are vulnerable to freshwater shortage in many parts of the world. Despite a growing literature that examines the freshwater vulnerability in various spatiotemporal contexts, existing knowledge has been conventionally constrained by a territorial perspective. On the basis of spatial analyses of monthly water and electricity flows across 2110 watersheds and three interconnected power systems, this study investigates the water-electricity nexus (WEN)'s transboundary effects on freshwater vulnerability in the continental United States in 2014. The effects are shown to be considerable and heterogeneous across time and space. For at least one month a year, 58 million people living in water-abundant watersheds were exposed to additional freshwater vulnerability by relying on electricity generated by freshwater-cooled thermal energy conversion cycles in highly stressed watersheds; for 72 million people living in highly stressed watersheds, their freshwater vulnerability was mitigated by using imported electricity generated in water-abundant watersheds or power plants running dry cooling or using nonfreshwater for cooling purposes. On the country scale, the mitigation effects were the most significant during September and October, while the additional freshwater vulnerability was more significant in February, March, and December. Due to the WEN's transboundary effects, overall, the freshwater vulnerability was slightly worsened within the Eastern Interconnection, substantially improved within the Western Interconnection, and least affected within the ERCOT Interconnection.

1. INTRODUCTION

Freshwater stress can severely impair human health and economic prosperity.[1] Properly identifying and evaluating the underlying stressors of such vulnerability is key to effectively mitigating current and future challenges. Existing literature suggest, besides natural processes (e.g., climate change[2]), new and continuing human activities, such as population growth,[2−5] industrialization and increases of living standards,[6] and infrastructure investments[7] are the primary drivers of freshwater vulnerability experienced or anticipated in many parts of the world. Despite a growing literature that investigated the freshwater vulnerability in various spatiotemporal contexts (e.g., refs 2,8−18), existing understanding of the anthropogenic stressors has been conventionally constrained by a territorial perspective, considering water availability, demand, and infrastructures within a watershed, city, region, or country. In a modern society, however, a large quantity of human water needs in one area is met by freshwater originated from other areas by consuming imported food, clothing, electricity, and other consumer goods and services.[19−21] As such, the freshwater vulnerability of consuming areas is beyond local freshwater stress but also influenced by the freshwater requirements of all relevant producing sectors and the freshwater stress of the producing areas.

The effects of sectoral and spatial connectedness of modern production and consumption systems on freshwater vulnerability (i.e., a relatively new driver) have not been fully considered.[22,23] By simulating counterfactual scenarios of economic localization, researchers have recently quantified the effects of regional and global trade of products and services on local freshwater stress. Mixed effects (i.e., alleviation or

Received: April 13, 2017
Revised: July 23, 2017
Accepted: July 26, 2017
Published: July 26, 2017

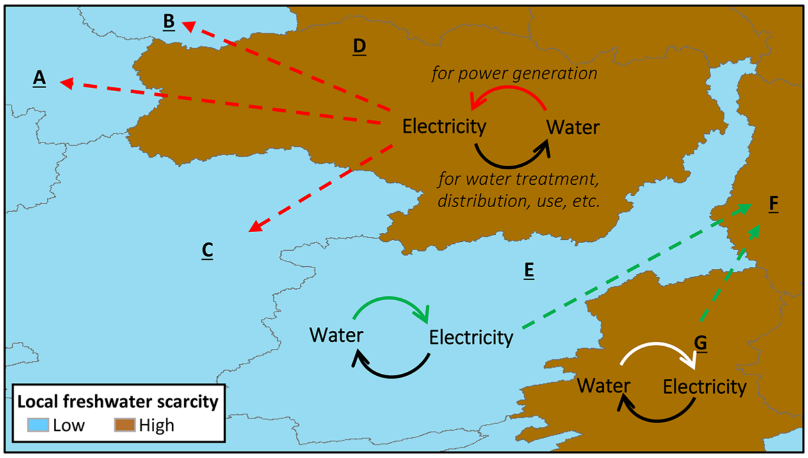


Figure 1. Freshwater vulnerability effects of the sectorally and spatially connected water and energy systems. 1) Watersheds A to G are delineated by gray lines; 2) Solid arrows illustrate the sectoral connections: the colored arrows (red or green) indicate water requirements for electricity generation (i.e., a critical focus of existing water-electricity nexus literature); the white arrow indicates electricity is generated relying on dry cooling or nonfreshwater resources (e.g., saline or reclaimed water) for cooling purposes; the black arrows (→) indicate electricity as an input for treating, distributing, and utilizing water (i.e., another critical research stream of the nexus) (e.g., in refs 55−58), 3) Dashed arrows illustrate the spatial connections (i.e., that electricity is commonly generated in one region and transmitted along with the cooling water embedded to another region): red dashed arrow indicates additional freshwater vulnerability propagated through the regional electricity transmission grid when people living in watersheds of low water stress depend on electricity generated from watersheds experiencing high water stress; green dashed arrow indicates by importing electricity generated from water-abundant watersheds or without freshwater cooling, the freshwater vulnerability of people living in highly stressed locations is mitigated; 4) The colored and white arrows illustrate the focus of this analysis (i.e., the WEN's transboundary effects on freshwater vulnerability), which are beyond thermoelectric cooling's direct effects on local water stress.

aggravation of local freshwater stress by affecting freshwater extractions) were found across basins and regions.[19,24−27] At the global scale, economic globalization was shown to have mitigated human water use and thus freshwater stress.[19,25,28,29] Not based on the rather extreme counterfactuals, prior studies traced freshwater consumption along existing supply chains and revealed the additional freshwater risks Jordan and the UK were exposed to by relying on food products imported from water-scarce countries.[30,31] However, little is known about how freshwater vulnerability is affected by the water-electricity nexus − the sectoral and spatial linkages whose importance for water and energy sustainability and economic security has been acknowledged in various research and policy agendas.[32−35]

The water-electricity nexus (WEN) characterizes the interdependencies of the production and consumption of water and electricity (Figure 1). The sectoral linkages, especially the cooling water demand of power generation, has been a critical focus of existing WEN literature.[34,36−39] In the United States, over half of the ∼4 billion MWh of electricity generated in 2014 was produced by freshwater-cooled thermal energy conversion cycles.[40,41] According to the latest estimates from 2010,[42] thermoelectric power generation accounted for ∼40% of the country's annual freshwater withdrawal and ∼3% of freshwater consumption. Studies have quantified the freshwater withdrawal and consumption rates of various fuel types, generation technologies, cooling systems, geographic locations, and regional grids (e.g.[38,43−45]). Regarding WEN's effects on freshwater stress, high water stress directly posed by existing thermoelectric cooling needs in the U.S. was only found in 23 watersheds and minimal from a national perspective.[46] However, hydro-climatological conditions, such as droughts and heat waves, could reduce generating capacity,[47−49] leading to substantial increases of electricity price.[48,50] Increasingly, the effect of freshwater availability on electric power generation and transmission are simulated at a high spatiotemporal resolution, under contemporary and future conditions of the hydro-climatological systems.[10,11,27,37,45,47,51−54] These efforts aim to gain insight on complex system phenomena and influence power plant and transmission grid investments.

Beyond thermoelectric cooling's direct effects on local water stress, the WEN's transboundary effects on freshwater vulnerability (as illustrated by colored and white arrows in Figure 1) have not been systematically assessed. These effects arise from a critical distinction between water and electricity issues: the relevant spatial scales. While water resources and usage are generally bound by watersheds, electricity is generated at the point or local scale, transmitted broadly through suitable infrastructure, and used in other places.[59] Specifically in the U.S., the electricity was transmitted within one of three interconnected power systems: the Western Interconnection, Eastern Interconnection, and Electric Reliability Council of Texas (ERCOT) Interconnection.[60] Given the widespread reliance on electricity for nearly all of the socioeconomic activities in modern societies and electricity's low substitutability by other commodities, consumers can be exposed to freshwater vulnerability in the form of, for instance, curtailed power supply or sharply increased spot market prices,[61] if they depend on electricity generated from locations experiencing high water stress. On the other hand, by importing electricity generated from water-abundant locations or without freshwater cooling, the freshwater vulnerability of highly stressed locations can be mitigated. These effects involve a multitude of natural, engineering, and human systems that vary significantly across time and space. As a result, in comparison to the effects that conventional anthropogenic stressors directly impose on local freshwater stress, WEN's transboundary effects on freshwater vulnerability can be more complex and less visible.

This study aims to investigate WEN's transboundary effects on freshwater vulnerability in the continental United States. This analysis uses detailed and recent estimates available for

DOI: 10.1021/acs.est.7b01942
Environ. Sci. Technol. 2017, 51, 9899−9910

freshwater withdrawal and consumption, renewable freshwater resources, electricity generation, electricity consumption, and population in the U.S. The multiscale data sets are harmonized to the watershed scale, and spatial analyses are performed at a monthly time step for 2110 watersheds covering the continental U.S. Previously, water-electricity nexus studies that integrated freshwater availability at the utility or interconnection level focused on either the West U.S. (i.e., the Western Interconnection)[11,37] or Texas (i.e., the ERCOT Interconnection).[45,54] By expanding to all three interconnections, this study provides consistent and comparable regional results, revealing that the conventionally neglected transboundary freshwater vulnerability effects of WEN are considerable yet distinct across the three interconnections. Using monthly rather than annual average values, this study also better captures the often-great temporal variations of electricity and water flows, which are key to assessing the two systems, their contemporaneous interactions, and the WEN's transboundary effects on freshwater vulnerability. The study also quantifies the monthly freshwater withdrawal and consumption rates per unit electricity generation, with stress levels of the cooling water sources distinguished. To validate the results, uncertainty and sensitivity analyses were conducted for varying water availability estimates and grid delineations. This refined knowledge of freshwater vulnerability by considering the sectoral and spatial connections of the WEN features two influential frameworks of systems integration (i.e., resource nexuses and telecoupling). Results of this study point to a clear need for more comprehensive assessments of the human-nature feedbacks, including the spatial feedbacks, in freshwater vulnerability analyses. The refined knowledge is critical to developing successful strategies and regulatory interventions regarding the upgrades of and investments in power production and transmission systems to mitigate the impacts of freshwater vulnerability.

2. METHODS AND DATA SOURCES

2.1. Processing Spatial Data in a Geographical Information System. The basic unit of this analysis is a watershed, a most fundamental unit of water resource analyses and the accounting unit commonly adopted in recent WEN literature (e.g., refs 39, 46, 48, and 62). The watershed boundaries are defined by the 8-digit Hydrologic Unit Code (HUC-8), based on the late 2016 Watershed Boundary Dataset from the Natural Resources Conservation Services.[63] The dataset divides the United States into 2303 watersheds, some of which extend to neighboring countries. For this analysis, watershed area that is non-U.S. territory was cut off based on the 2014 U.S. county boundary obtained from the U.S. Census.[64] A nationwide geographical information system (GIS) was developed to convert data collected from various sources, originally available at different scales (see Table 1) to the watersheds. The grid-, county-, and state-based data were first converted to 0.05° × 0.05° grids and then matched to the watersheds, assuming even distribution within a grid, county, state, and watershed. Data/information on individual power plants were spatially matched to the watersheds based on the coordinates of each power plant reported by the U.S. EIA.[65]

The target year of the analysis was 2014, for which all statistics were available and up-to-date except for water withdrawal. The most up-to-date water withdrawal data in the United States were for the year 2010. As such, negligible water withdrawal changes from 2010 to 2014 were assumed in this study, which is consistent with the historical trends.[67] Given both water withdrawal and population data were only available on an annual basis, the study also assumed an even distribution of freshwater withdrawals throughout 2014 and negligible intra-annual population migration. 2110 Watersheds covering the 48 continental states, where data were available for all variables in Table 1, were chosen as the spatial boundary of this analysis. The GIS system and assumptions resulted in consistent country-level estimates when compared with the originally reported national values. For validation purposes, the sums of watershed-level values of each variable (i.e., total area, population, freshwater withdrawal, electricity generation, and freshwater withdrawal by power generation of the 2110 watersheds) reached 91−98% of the national estimates reported for the United States (Table S1). On the basis of the GIS system, monthly freshwater stress, electricity transmission and outsourcing, and population affected by water stress due to the WEN were then assessed at the watershed scale.

Table 1. Data/Information Collected for This Analysis and Their Sources

data	year	source[a]	description
runoff	2014	NLDAS (NOAH model)[66]	kg/m^2/month, 0.125° × 0.125°
population	2014	U.S. Census Bureau[64]	people per county
freshwater withdrawal	2010	USGS[42]	gallons per day per county
power plant location	2014	U.S. EIA[65]	coordinates
electricity generation	2014	U.S. EIA[40,65]	MWh/month per generator
cooling water withdrawal and consumption	2014	U.S. EIA[40,65]	gallons/min per generator
electricity sales	2014	U.S. EIA[41]	MWh/month per state
watershed boundary	2016	NRCS[63]	2303 watersheds

[a]NLDAS, North American Land Data Assimilation System; USGS, U.S. Geological Survey; US EIA, U.S. Energy Information Administration; NRCS, Natural Resources Conservation Service.

2.2. Quantifying Monthly Water Stress for Watersheds throughout the Continental U.S. The freshwater withdrawal to availability (w.t.a.) ratio was used to measure the freshwater stress experienced at a watershed. As a conventional water stress indicator,[68] the w.t.a. ratio measures the amount of pressure water users, including municipalities, industries, power plants, and agricultural activities, directly put on water resources and aquatic ecosystems.[3,69] As water availability and demand distribute unevenly over time and space, estimates of the w.t.a ratio and similar water stress indicators depend on the spatial and temporal scales selected. Water stress levels tend to be underestimated by annual or country-level assessments.[70,71] The grid-cell level likely overestimates water stress because water transfers between grid cells are large in reality.[2]

To better account for the spatial variations in water demand and the climate-induced spatial and intra-annual variability of freshwater availability, this analysis quantified the freshwater stress for the 2110 watersheds at a monthly time step for the year 2014 (eq 1):

$$\text{w.t.a.}_{i,j} = \frac{\text{WW}_{i,j}}{\text{IRWR}_{i,j}} \quad (1)$$

DOI: 10.1021/acs.est.7b01942
Environ. Sci. Technol. 2017, 51, 9899−9910

Freshwater withdrawal in watershed i, during month j (i.e., $WW_{i,j}$) was converted from county-level freshwater withdrawal estimates assuming constant monthly water demand (as discussed above). Freshwater availability was quantified as the internal renewable water resources (IRWR) available for watershed i, during month j. $IRWR_{i,j}$ was estimated as the sum of monthly "surface runoff (non-filtrating)" and "subsurface runoff (baseflow)" obtained from the NLDAS-2 Noah monthly dataset.[66] As such, $IRWR_{i,j}$ provides a conservative estimate of the sustainable water supply to which local human populations have access,[72] assuming water from upstream cannot be reused at downstream because of consumptive use or water pollution. Unlike other literature (e.g., refs 73 and 74), the effects of artificial reservoirs on reducing temporary shortages were not accounted in this analysis, mainly due to the lack of recent reservoir operation data in the United States. This omission could lead to an overestimation of the monthly variations of freshwater availability.

As a validation check, the estimate of freshwater availability was compared with literature estimates and measurements of the long-term internal renewable water resources in the United States. This study estimated that 2382 km^3 internal renewable freshwater resources were available in the U.S. in 2014, well within the reported range of 1928 km^3 to 2900 km^3 in previous studies.[75−77] In addition, a sensitivity analysis was carried out in which the monthly freshwater availability estimates were varied by ±50%. Consistent with existing literature,[4,68,71] the severity of freshwater stress is ranked as no stress (w.t.a. < 0.1), low stress (0.1 ≤ w.t.a. < 0.2), moderate stress (0.2 ≤ w.t.a. < 0.4), severe stress (0.4 ≤ w.t.a. < 1), and extreme stress (w.t.a. > 1); w.t.a. ≥ 0.4 is considered as high water stress.

2.3. Assessing Electricity Deficiency and Surplus.

2.3.1. Mapping the Watershed Boundaries to the Electricity Grids. As Figure S1 shows, the continental United States is served by three interconnected power systems: the Western Interconnection, Eastern Interconnection, and Electric Reliability Council of Texas (ERCOT) Interconnection.[60] There are few connections and little energy transfer between them.[78] The three interconnections are further divided into eight subregions overseen by the North American Electric Reliability Corporation (NERC).[60] While NERC supplies a map of the three interconnections and eight subregions, definitive boundaries do not exist and the NERC map may suggest (sub)region assignments that are different in reality.[44] In this analysis, the 2110 watersheds were assigned to one of the eight NERC subregions and then one of the three interconnections (see Figure S2) using available information from multiple sources (i.e., the coordinates of over 7000 power plants,[65] NERC affiliation of each power plant,[65] the shapefiles of eGRID regions released by the U.S. EPA,[79] and the concordances between NERC and eGRID regions). Note, for watersheds with multiple power plants that belong to more than one interconnection or NERC subregions, the watersheds were assigned according to the power plant with the highest net annual electricity generation.

2.3.2. Electricity Balance within the Interconnections. Within each interconnection, monthly electricity generation ($E_{g,j}$) and monthly electricity use ($E_{u,j}$) was assumed to balance (eq 2). Electricity generation of each interconnection was obtained by summing the monthly net electricity generation of power plants within it. Then, the monthly per capita electricity use in each watershed ($e_{u,i,j}$) was calculated based on the demand-supply balance:

$$E_{u,j} = E_{g,j} = \sum \text{pop}_i \times e_{u,i,j} = \sum \text{pop}_i \times (e_{u,j} \times \alpha_{i,j}) \tag{2}$$

pop_i is the number of population living in watershed i. The heterogeneity of monthly electricity use rate within each interconnection was accounted through $e_{u,j} \times \alpha_{i,j}$ in eq 2. By construction, $e_{u,j}$ represents the base per capita electricity use in month j of each interconnection. For each watershed within an interconnection, the ratio $\alpha_{i,j}$ captures its relative monthly electricity use rate in comparison to the base level. Specifically, $\alpha_{i,j}$ was estimated from state-level monthly electricity sales data,[41] representing the relative monthly electricity use variations for people living within the same interconnection but different states. Estimates of county-level or more spatially refined monthly electricity use were not available.

2.3.3. Electricity Deficiency of the Watersheds. If $e_{g,i,j} < e_{u,i,j}$, the electricity deficiency rate in watershed i during month j ($\text{def}_{i,j}$) was calculated as the difference between electricity generation and use as a fraction of electricity use (eq 3). With regard to the WEN's transboundary effects on freshwater vulnerability, electricity deficiency experienced in watershed i with low to no water stress (w.t.a. < 0.2), denoted by $def_{i,j}*$, is one of the two necessary conditions to result in additional freshwater vulnerability in the watershed. Similarly, electricity deficiency experienced in watershed i under severe to extreme water stress (w.t.a. > 0.4), denoted by $\text{def}_{i,j}**$, is necessary to result in mitigated freshwater vulnerability in the watershed.

$$\text{def}_{i,j} = (e_{u,i,j} - e_{g,i,j})/e_{u,i,j} \tag{3}$$

2.3.4. Electricity Outflows of the Interconnections. Besides electricity deficiency, WEN's transboundary effects of additional or mitigated freshwater vulnerability in watershed i also relies on the characteristics of imported electricity outflows, specifically, the water stress status of cooling water sources and the cooling water requirements. Within each interconnection, electricity surplus of each watershed ($e_{g,i,j}$ - $e_{u,i,j}$, where $e_{g,i,j} > e_{u,i,j}$) makes up the electricity outflows to the watersheds with electricity deficiency (where $e_{g,i,j} < e_{u,i,j}$). The electricity surpluses are assumed to be well-mixed within each interconnection. The effects of this assumption were tested and are discussed in section 4.3.

For each interconnection in month j, eq 4 calculates the fraction of electricity outflows generated using freshwater (i.e., for cooling purposes) in highly stressed watersheds k (w.t.a. > 0.4), corresponding to the second necessary condition for WEN's transboundary effects of additional freshwater vulnerability. $\beta_{k,j}$ is the percentage of electricity generated using cooling water in watershed k and month j.

$$\text{out}_j* = \sum [(e_{g,k,j} - e_{u,k,j}) \times \beta_{k,j}]/\sum (e_{g,i,j} - e_{u,i,j}) \tag{4}$$

Given only power plants with a nameplate capacity of 100 MW or more are required to report monthly cooling water usage to the U.S. EIA,[40,65] the numerator neglects electricity outflows generated by small power plants (<100 MW) that also relied on scarce water for cooling purposes. In 2014, 874 power plants reported cooling water usage to the U.S. EIA. Throughout the year, 486−515 of those plants reported nonzero monthly freshwater cooling and contributed 51%−56% of the monthly electricity generation of the continental U.S. Hydropower, accounting for 5−8% of the total electricity generation, is mainly constrained by upstream freshwater availability and was thus not accounted in the numerator

DOI: 10.1021/acs.est.7b01942
Environ. Sci. Technol. 2017, 51, 9899−9910

either. As such, eq 4 provides a conservative estimate of the amount of electricity imports vulnerable to local freshwater stress.

The second necessary condition for WEN's transboundary effects of mitigated freshwater vulnerability is represented by eq 5. WEN mitigates the freshwater vulnerability in highly stressed watersheds when electricity deficiency in these areas are met by outsourcing electricity from water-abundant watersheds m (w.t.a. < 0.2) or power plants running dry cooling or using nonfreshwater resources for cooling purposes. $\beta_{m,j}$ is the percentage of electricity generated using freshwater cooling in watershed m and month j.

$$\text{out}_j^{**} = \sum [(e_{g,m,j} - e_{u,m,j}) \times \beta_{m,j} + (e_{g,j}^0 - e_{u,j}^0)] / \sum (e_{g,i,j} - e_{u,i,j}) \quad (5)$$

$(e_{g,j}{}^0 - e_{u,j}{}^0)$ represents the electricity surplus that, according to the cooling water usage reported to U.S. EIA,[57,67] was generated without extracting freshwater for cooling purposes. In 2014, 302 of the 874 power plants with ≥100 MW nameplate capacity relied completely on dry cooling or nonfreshwater resources (e.g., saline or reclaimed water) for cooling purposes, supplying about 30% of the monthly electricity generation in the continental U.S. Not accounting for electricity outflows from small power plants (<100 MW) or hydropower, eq 5 provides a conservative estimate of electricity imports not vulnerable to local freshwater stress.

2.4. Assessing WEN's Transboundary Effects on Freshwater Vulnerability.

On the basis of the above indicators of electricity deficiency and surplus, eq 6 calculates the number of people that lived in water-abundant watersheds (w.t.a. < 0.2) but were vulnerable to freshwater stress in water-stressed watersheds (w.t.a. > 0.4) by relying on electricity generated from there:

$$\text{pop}_{i,j}^* = \text{pop}_i \times \text{def}_{i,j}^* \times \text{out}_j^* \quad (6)$$

It is critical to note that the multiplication of the watershed population (pop_i) with $\text{def}_{i,j}*$ assumes that, within each watershed, the deficiencies were concentrated to a smaller population rather than dispersed among the entire population. The following multiplication with out_j* assumes, within each interconnection, electricity outsourced from highly stressed areas was used by a small group of people rather than being distributed among all of those experiencing deficiency. As such, $\text{pop}_{i,j}*$ calculated by eq 6 gives a conservative estimate of the additional freshwater vulnerability caused by the WEN.

Eq 7 calculates the population that lived in water-stressed watersheds (w.t.a. < 0.2) where the freshwater vulnerability was mitigated by outsourcing electricity from water-abundant watersheds (w.t.a. < 0.2) or power plants running dry cooling or using nonfreshwater resources for cooling. Similarly to $\text{pop}_{i,j}*$, $\text{pop}_{i,j}**$ gives a conservative estimate of the mitigated freshwater vulnerability by the WEN.

$$\text{pop}_{i,j}^{**} = \text{pop}_{i,j}^{**} \times \text{def}_{i,j}^{**} \times \text{out}_j^{**} \quad (7)$$

3. RESULTS

3.1. Monthly Freshwater Stress by Watershed.

Spatiotemporal variability is critical for assessing and understanding freshwater stress in the continental U.S. (Figure 2; Table 2). Although less than 20% of the 2400 km^3 freshwater available within the United States in 2014 was withdrawn for anthropogenic activities, the monthly assessments at the watershed scale suggest 32% (May) to 59% (September) of the U.S. population lived in severely or extremely stressed watersheds, while 24% (75 million, September) to 57% (175 million, May) of the population lived in watersheds of low to no stress. Given freshwater withdrawals were assumed to be evenly distributed throughout the year due to data availability, the temporal variability in freshwater stress were due to the high temporal variability of freshwater availability. Nationally, the available freshwater resources ranged widely from 114 (November) to 313 km^3 (April).

Figure 2 further highlighted the very heterogeneous temporal characteristics across the country. Consistent with previous studies (e.g., ref 3, 16, and 46), freshwater stress was high and persistent in the Western U.S. (especially in California and Arizona) and the Great Plains. However, the monthly results revealed that the Eastern states were not completely exempt from freshwater stress (see Figure 2 and Figure S3). A large portion of the watersheds along the Lower Mississippi River and the Ohio River were under high water stress from August through December. Freshwater stress was also high in the Northeastern coastal states during the Fall months.

3.2. Electricity Deficiency and Outsourcing.

The prevalent power deficiencies by month and interconnection are illustrated by Figure 3. With small monthly variations, about 75%, 81%, and 73% of the watersheds within the Eastern, Western, and the ERCOT Interconnection sourced electricity from other watersheds within the same interconnection, respectively. The figure also reveals the distinct water stress profiles of the electricity-deficient watersheds across the three interconnections. Within the Eastern and the Western Interconnection, they were dominated by those under no to low stress and severe to extreme stress, respectively. For the ERCOT Interconnection, the electricity-deficient watersheds were predominantly under high (low) stress levels from December to April (May to November). These patterns correspond well with the temporal and spatial variations of water stress levels observed within each interconnection (see Figure 2). From the perspective of freshwater availability, the figure indicates there are considerable potentials, especially within the Eastern Interconnection, of generating more electricity in water-abundant areas to reduce the electricity generation and outsourcing from water-stressed areas.

Further, as Figure 4A and Figure S4 illustrate the monthly deficiencies within these electricity-deficient watersheds were overall high for all three interconnections (i.e., 87−92%). The high watershed deficiency rates are attributable to the uneven distribution of power plants within each interconnection and the highly skewed power generation among the power plants (see Figure 4 and Figure S4). In 2014, about 5700 power plants (individual nameplate capacity ≥ 1MW) located in about 1200 watersheds (or 59% of the 2110 watersheds) contributed net positive electricity supplies to the aggregated U.S. electricity grid. People living in the rest of the watersheds thus relied completely on electricity generated by power plants in other watersheds. Among the active power plants, about 80% of the electricity was generated by less than 10% of the plants every month. As such, watersheds with smaller power plants are also likely to rely, to a varying degree, on outsourced electricity. The observations further confirm the critical "scale" distinction between water and energy use: while water resources and usage are generally bound by watersheds, electricity used within one watershed is often transmitted from other watersheds.

DOI: 10.1021/acs.est.7b01942
Environ. Sci. Technol. 2017, 51, 9899−9910

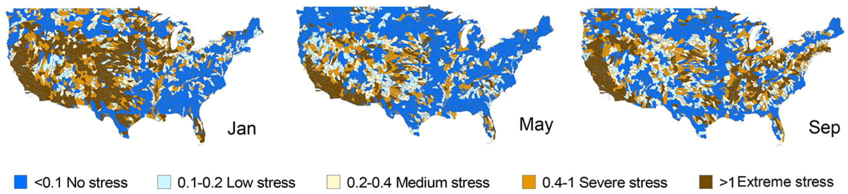


Figure 2. Monthly (January, May, and September) water stress levels of the 2110 watersheds in the continental United States in 2014. Water stress levels are measured as the monthly freshwater withdrawal to freshwater availability (i.e., w.t.a. ratios). Full monthly results are provided in Figure S3.

Table 2. Population Living in Watersheds of Various Freshwater Stress in 2014[a]

	severe to extreme (w.t.a. ≥ 0.4)		moderate (0.2 ≤ w.t.a. < 0.4)		low to no stress (w.t.a. < 0.2)	
Jan	1.4×10^{08}	(47.0%)	3.2×10^{07}	(10.4%)	1.3×10^{08}	(41.8%)
Feb	1.3×10^{08}	(41.5%)	4.8×10^{07}	(15.7%)	1.3×10^{08}	(41.9%)
Mar	1.2×10^{08}	(39.4%)	4.3×10^{07}	(13.9%)	1.4×10^{08}	(45.9%)
Apr	1.1×10^{08}	(35.6%)	3.1×10^{07}	(10.1%)	1.6×10^{08}	(53.4%)
May	9.9×10^{07}	(32.2%)	3.1×10^{07}	(10.0%)	1.8×10^{08}	(57.0%)
Jun	1.1×10^{08}	(37.0%)	5.1×10^{07}	(16.6%)	1.4×10^{08}	(45.5%)
Jul	1.4×10^{08}	(46.0%)	4.9×10^{07}	(16.1%)	1.1×10^{08}	(37.2%)
Aug	1.7×10^{08}	(53.6%)	4.8×10^{07}	(15.5%)	9.2×10^{07}	(30.0%)
Sep	1.8×10^{08}	(59.1%)	4.9×10^{07}	(15.8%)	7.5×10^{07}	(24.3%)
Oct	1.8×10^{08}	(58.4%)	4.3×10^{07}	(13.9%)	8.3×10^{07}	(26.9%)
Nov	1.8×10^{08}	(58.0%)	4.1×10^{07}	(13.4%)	8.6×10^{07}	(27.8%)
Dec	1.4×10^{08}	(45.6%)	4.1×10^{07}	(13.2%)	1.2×10^{08}	(40.4%)

[a]Per class, population is given in number of people and the corresponding fraction of total population in the United States (%).

3.3. Water Stress Profiles of the Electricity outflows. In 2014, 34−38% of the monthly electricity was generated using freshwater cooling and transmitted outside of the watershed boundary. As shown by Figure 5, the electricity outflows demonstrate considerable regional heterogeneity in terms of cooling water usage. A much higher fraction of the outsourced electricity (i.e., 53−66%) was generated without freshwater cooling within the Western Interconnection. In comparison, only 24−37% of the power transmissions were generated without freshwater cooling within the other two interconnections. This discrepancy can be largely explained by the Western Interconnection's significant hydropower supply (∼23%) and considerable solar and wind power supply (∼9%). In comparison, the total nonthermal power supply (i.e., hydro, solar, and wind power) accounted only for ∼7% and ∼11% in the Eastern and ERCOT Interconnections, respectively.

Due to the spatial and temporal heterogeneity of the freshwater stress, the electricity outflows within each interconnection demonstrate varying water stress profiles. As Figure 5 shows, of the total electricity transmitted from one watershed to another within the Eastern, Western, and ERCOT Interconnections, 20−50% (7−28%), 10−30% (8−18%), and 40−65% (0−15%) were sourced from watersheds under severe to extreme stress (no to low stress), respectively. Note that although freshwater stress is known to be more severe in areas within the Western Interconnection than those within the Eastern Interconnection, electricity transmissions within the former appears to have considerably lower water stress implications than the latter, mainly because the majority of the electricity outflows generated in the West U.S. were based on dry cooling or nonfreshwater cooling resources. This could reflect the physical limitations of freshwater resources and/or the historical awareness and thus consideration of the severe water stress condition in infrastructure planning and development in the West. In contrast, electricity outflows within the ERCOT Interconnection, which overlaps with another drought-prone region in the U.S., demonstrate the highest freshwater vulnerability associated with the electricity transmission. The vulnerability is especially high given both severe groundwater depletion and load shedding were recorded in Texas during the one-year drought in 2011,[80] and multiyear droughts are expected across the state in the late 21st century.[81]

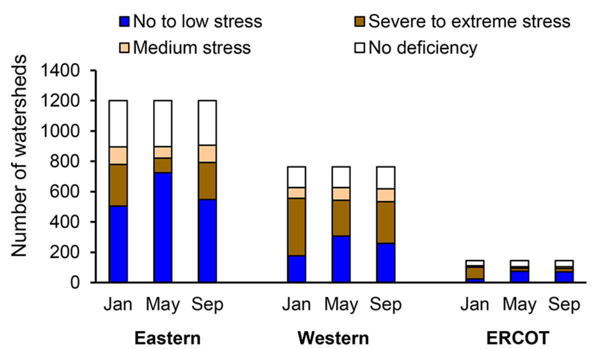


Figure 3. Monthly (January, May, and September) electricity-deficient watersheds (solid bars, distinguishing water stress conditions) and self-sufficient watersheds with each interconnection.

Despite the spatial variations, among those power plants that reported freshwater cooling, it is common that much more of the electricity outflows were generated from areas experiencing high water stress rather than those under no to low water stress.

3.4. WEN's Effects on Freshwater Vulnerability. On the basis of the results above and eqs 6 and 7, WEN's transboundary effects on freshwater vulnerability were quantified. Overall, WEN resulted in significant freshwater vulnerability implications across the continental U.S. For at least one month in 2014, 58 million population living in watersheds of low to no freshwater stress were exposed to additional freshwater vulnerability by relying on electricity generated in severely or extremely stressed watersheds. One the

DOI: 10.1021/acs.est.7b01942
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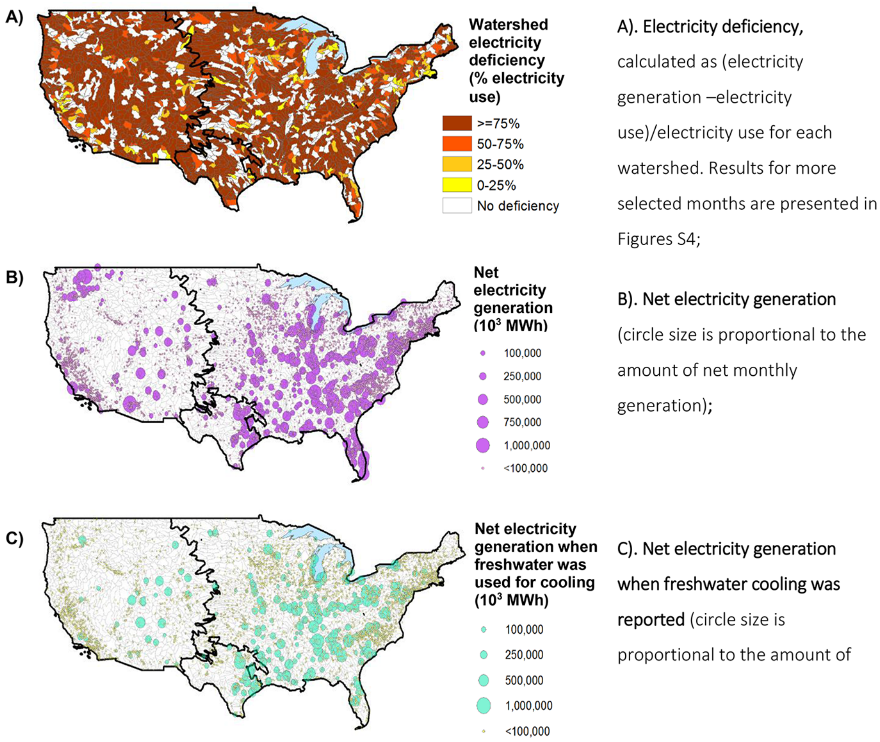

Figure 4. Electricity generation and deficiency at the watersheds in May, 2014. (A) Electricity deficiency, calculated as (electricity generation−electricity use)/electricity use for each watershed. Results for more selected months are presented in Figures S4; (B) net electricity generation (circle size is proportional to the amount of net monthly generation); and (C) net electricity generation when freshwater cooling was reported (circle size is proportional to the amount of net monthly generation).

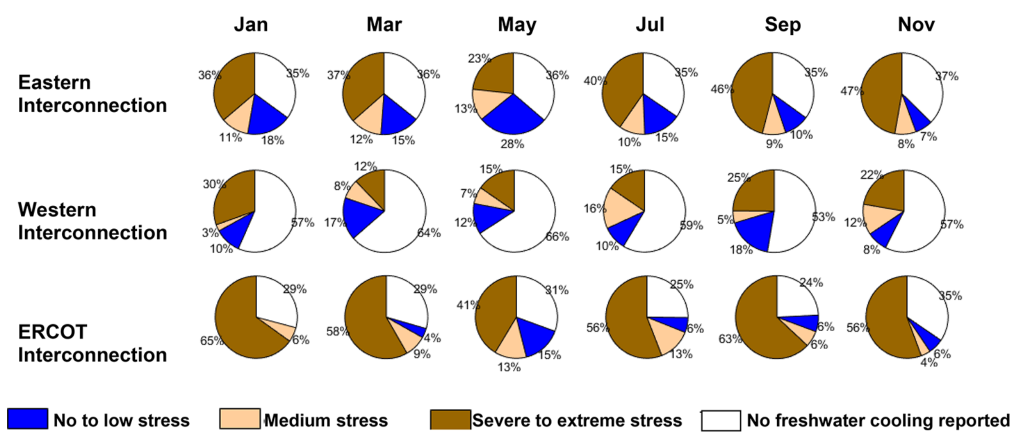

Figure 5. Monthly electricity outflows by cooling water requirement and freshwater stress level.

other hand, for 72 million population living in highly stressed watersheds, their freshwater vulnerability was mitigated by using imported electricity generated in watersheds of low to no stress (31 million) or power plants running drying cooling or using nonfreshwater for cooling purposes (41 million) for at least one month in 2014.

As shown in Figure 6a, the WEN's additional or mitigation effects on freshwater vulnerability are heterogeneous across time and space. The additional freshwater vulnerability affected 22 million (September) to 32 million (February) people living in watersheds of low to no freshwater stress. Freshwater vulnerability was mitigated for 25 million (May) to 41 million (September) people living in watersheds of severe to extreme water stress. At the country scale, the mitigation effects were the most significant during the fall months, especially September and October, while the additional freshwater vulnerability effects were more significant in February, March, and December.

As Figure 6b shows, the WEN's transboundary effects affected the freshwater vulnerability of the three interconnections differently. Distinct from conventional perceptions that water stress impacts are low in the Eastern U.S. (e.g., refs 3, 16, and 46), these results highlight the additional freshwater vulnerability impacts mainly affected people living in the East. About 50 million people living in the Eastern Interconnection were affected by the additional freshwater vulnerability for at least one month in 2014, accounting for 85% of the impacted population assessed for the continental U.S. In comparison, only about 8% and 6% of the impacted population were from the Western and ERCOT Interconnections, respectively. With

DOI: 10.1021/acs.est.7b01942
Environ. Sci. Technol. 2017, 51, 9899−9910

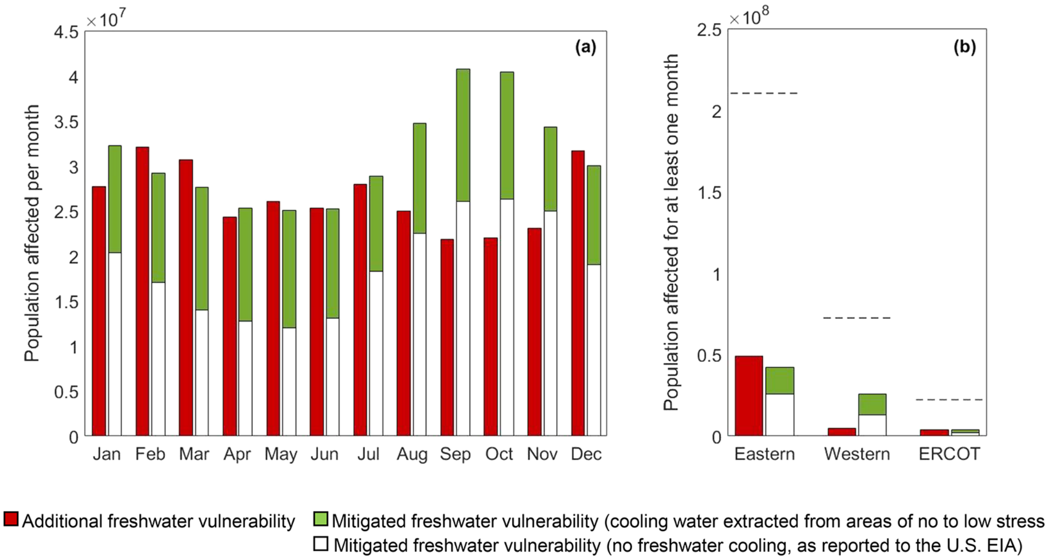

Figure 6. WEN's transboundary effects on freshwater vulnerability are heterogeneous across time and space: (a) people affected throughout the months in 2014 and (b) people affected for at least one month in 2014 (dashed lines indicate the total population living within each interconnection).

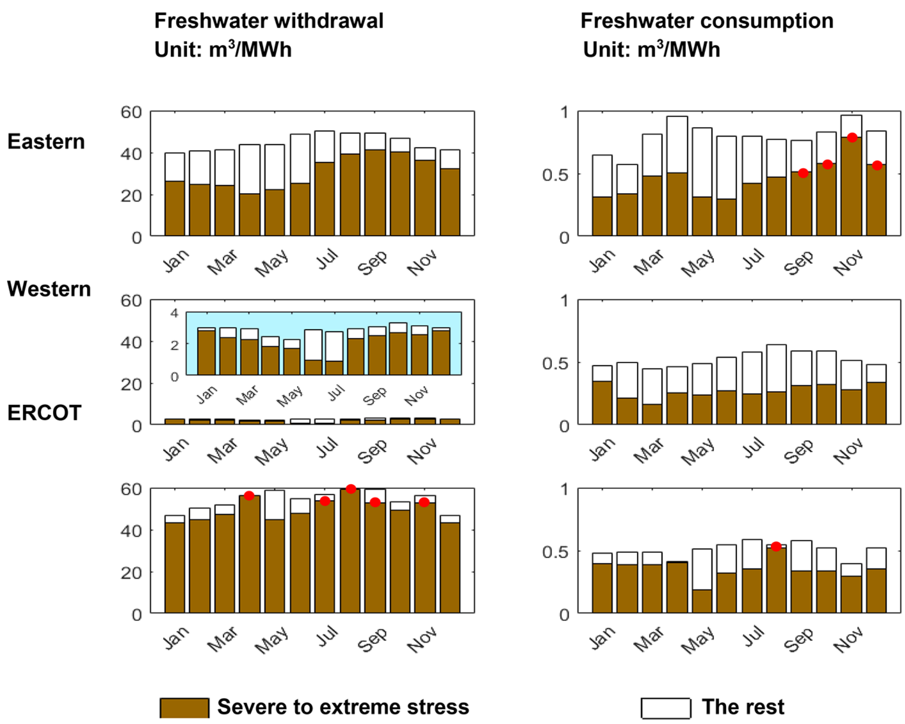

Figure 7. Cooling water usage per unit electricity generation, distinguishing water stress levels of the cooling water sources. Shaded bars represent cooling water sourced from watersheds under severe to extreme water stress, hollow bars represent the rest freshwater usage; red ● denote the top five monthly scarce water withdrawal and scarce water consumption rates across the three interconnections).

regard to the benefits of mitigated freshwater vulnerability, 59%, 36%, and 5% of the population affected for at least one month in 2014 were from the Eastern, Western, and ERCOT Interconnections, respectively. On the basis of the accounts of the affected population in Figure 6b, due to the WEN's transboundary effects, freshwater vulnerability was slightly worsened within the Eastern Interconnection, substantially improved within the Western Interconnection, and least affected within the ERCOT Interconnection.

4. DISCUSSION

4.1. Assessing Freshwater Vulnerability from a Systems Perspective. Addressing complex interconnections through systems integration, such as the resource nexuses and telecoupling that tie different issues and distant places together, respectively, is essential for solving the myriad sustainable challenges.[33] To holistically assess freshwater vulnerability, results of this study highlight the need to consider the interactions between the water and the electricity systems both within and outside of the conventional territorial boundaries of

DOI: 10.1021/acs.est.7b01942
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water resources. As a consequence, this study also highlights the need to revisit the nuances of using conventional water stress metrics for assessing and managing freshwater vulnerability. For example, the water crowding index (i.e., the number of people living on a given unit of water resources or water resources available per capita)[2,4,82] relates local water resources to the local water demand of population and measures the ultimate territorial water security. The ratio of local water withdrawal to availability (w.t.a.) represents the immediate anthropogenic pressures on local freshwater environments. However, as shown by this study, these two widely-adopted metrics become a less relevant measure for water sufficiency or stress when goods and services people consume are increasingly produced remotely.

Focusing on the water-electricity nexus, this study refined the knowledge of freshwater vulnerability in the continental United States, providing new insights for potential upgrades and investments of power systems. Surprisingly, the traditionally unaccounted for freshwater vulnerability impacts were predominant in the Eastern U.S., where water stress risks have been conventionally perceived to be low and water-energy nexus has been least studied. Previously, research showed the water needs of thermoelectric power plants are predominant in the eastern U.S.[46] However, by focusing on the direct impacts on local water stress and neglecting the intra-annual variations of water availability, the water stress implications of thermoelectric water needs were concluded as localized and minimal on the national scale.[46] It is also critical to note that water stress' impacts on power generation appear to be much lower in reality due to the reservoir storage at thermoelectric power plants, current regulatory regime that focuses on thermal effluent discharges rather than real-time environmental or minimum flows, and the provisional variances approval granted at extreme conditions.[49,83] Despite this, under high water stress, thermoelectric power generation remains vulnerable to competitions with other critical water users (e.g., municipal demands) and new regulatory regimes that limit cooling water abstractions based on environmental flows. Revealing that a considerable amount of electricity outflow was generated using cooling water extracted from highly stressed watersheds (Figure 5) and there are considerable potentials of generating more electricity in water-abundant areas (Figure 4), this study indicates opportunities to further optimize power generation and transmission, mitigating the vulnerability to reallocations of water use, hydro-climatological constraints and regulatory arrangements.

4.2. Water Stress Profiles of Electricity. Prior WEN studies quantified the freshwater withdrawal and consumption rates of electricity generation, distinguishing fuel types, generation technologies, cooling systems, geographic locations, and regional grids (e.g., refs 38, 43−45). While quantifying the freshwater rates (only accounting for cooling water use) based on monthly water and electricity data, this study further specified the water stress conditions of the cooling water sources (Figure 7). Overall, for a given unit of electricity generated, freshwater withdrawal was the highest in the ERCOT (47−60 m^3/MWh) and freshwater consumption in the Eastern (0.58−0.96 m^3/MWh) Interconnection. While almost all of the cooling water withdrawals (80−100%) can be traced to watersheds of high stress levels (i.e., w.t.a. > 0.4) within the ERCOT Interconnection, about 40−85% of the cooling water consumption within the Eastern Interconnection was extracted from highly stressed watersheds. Within the Western Interconnection, the freshwater cooling withdrawals were significantly lower (i.e., ∼3 m^3/MWh) than the other two interconnections while the cooling water consumption was comparable, although also the lowest of the three. Of interest, a recent study indicates considerations on fuel and technology costs, policy drivers and the topology of electricity demand within the Western Interconnection, rather than water availability, will likely lead to implementation of distributed, low-water electric power generation.[11]

If only considering the freshwater extracted from highly stressed watersheds (i.e., the scarce water), the peak cooling water withdrawal rates all occurred within the ERCOT interconnection, specifically (in descending order) in August, April, July, September, and November (>50 m^3/MWh). For cooling water consumption, the peak rates of scarce water consumed for thermoelectric cooling occurred during September to November in the Eastern Interconnection and during August in the ERCOT Interconnection (>0.51 m^3/MWh). Within the ERCOT Interconnection, previous research showed water consumption intensities of electricity output are the highest when electricity demand is the lowest since the baseload coal-fired generators are the most water-intensive.[45] In response to recent environmental regulations on emission reduction there, the retirement of coal-fired power plants and the expansion of natural gas-fired capacity may effectively reduce the water intensive energy generation units,[54] thus mitigating the peak water and scarce water intensities of electric power generation. However, more stringent restrictions at ERCOT power plants on CO_2 emissions (e.g., > 75% below BAU) would likely increase water withdrawals by 64% when coal-fired power plants are replaced by nuclear generation.[85,86]

4.3. Caveats, Uncertainties, and Call for Future Research. To avoid misinterpretation of the results, three primary limitations deserve mention. First, the study only provided conservative estimates of the WEN's transboundary effects on freshwater vulnerability. It is possible that more people were affected through the WEN, for example, considering the water constraints on hydropower generation. Hydropower contributes to ∼6% of electricity generation in the U.S.[41] but makes a much higher contribution (17%) to the global electricity supply.[47] A recent study showed that hydropower's current and increasing water demands impose pressure on available freshwater resources and aggravate the water stress levels in China.[88] It is also critical to note that the present analysis focuses on water use for electricity generation. In the U.S., water use for the fuel cycle and power plant manufacturing can reach up to 26% of electricity's total life cycle water consumption; in the western U.S., fuel cycle and manufacturing water consumption can even exceed operational demands.[84] In order to systematically mitigate water stress, a life cycle approach needs to be taken in investment decisions about power infrastructures.

The second limitation of this study is related to quantification of the local freshwater stress using the w.t.a. (withdrawal to availability) ratio. Like some literature (e.g., 4, 68, and 71), this study used freshwater withdrawal as the numerator and adopted the stress threshold accordingly. However, others (e.g., 16 and 89) preferred using freshwater consumption, given a significant fraction of water withdrawals may return to its source and become available for further use over a relatively short time period. As for the denominator of the w.t.a. raio (i.e. water availability), this study did not account for environmental requirements, which may underestimate the water stress levels. Mainly due to the lack of data, the effects of

DOI: 10.1021/acs.est.7b01942
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artificial reservoirs or upstream inflows were also neglected in the estimates of water availability, which could potentially cause overestimates of the stress levels. Further, throughout this study, freshwater resources refer to the fresh surface and groundwater, also known as the blue water.[70,90,91] The availability and usage of green water (i.e., moisture in the unsaturated zone of soil and available for plants)[87] is not accounted in the assessments of freshwater stress. To understand the uncertainties associated with the water stress assessed, sensitivity analyses (SA) that varied monthly freshwater availability by ±50% were performed. The SA results indicate that, for at least one month in 2014, 54−55 million people and 69−73 million people were affected with additional and mitigated vulnerability, respectively, demonstrate the robustness of the study's main findings in light of wide ranges of water availability variations.

Third, electricity transmission was not modeled based on realistic data of the grids. The overall structure of the electrical grids was modeled after governmental reports suggesting there is minimal electricity transmission across the three interconnections.[78] Without access to detailed transmission data, this analysis assumes electricity feeding into each interconnection is well mixed. However, some literature have adopted the classification of eight NERC subregions (e.g., refs 44, 92, and 93) modeling the electricity transmissions within each subregion. To test the effects of different grid delineation and the possibilities that electricity feeding into each interconnection may not be well mixed, the same analyses were conducted based on NERC classification. Consistent results were generated: for example, 55 million and 72 million population were estimated for the additional and mitigated vulnerability effects for at least one month in 2014, respectively. Often based on electricity transmission optimized for system-wide least cost, recent literature (e.g., refs 27, 54, and 94) have greatly improved the spatiotemporal resolutions of electricity transmission models. Without doubt, understanding of the WEN's freshwater vulnerability implications can be further improved by future research that adopts detailed power flow model developed from realistic grid transmission data. The significant and unexpected results from this study also indicate the need to further understand the implications of sectoral and spatial connectedness other than the WEN on freshwater vulnerability.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b01942.

> Detailed description of the Methods; (Table S1) main variables used and their national coverage; (Figure S1) map of NERC interconnections; (Figure S2) NERC interconnections mapped in the GIS system developed in this study; (Figure S3) monthly water stress levels of the 2110 watersheds in the continental United States in 2014; (Figure S4) electricity generation and deficiency at the watersheds; and brief statement in nonsentence format listing the contents of the material supplied (PDF)

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Notes

The authors declare no competing financial interest.

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