

1 **Title Page**

2 **Title:**

3 **Freshwater vulnerability beyond local water stress: the heterogeneous effects of**
4 **water-electricity nexus across the continental United States**

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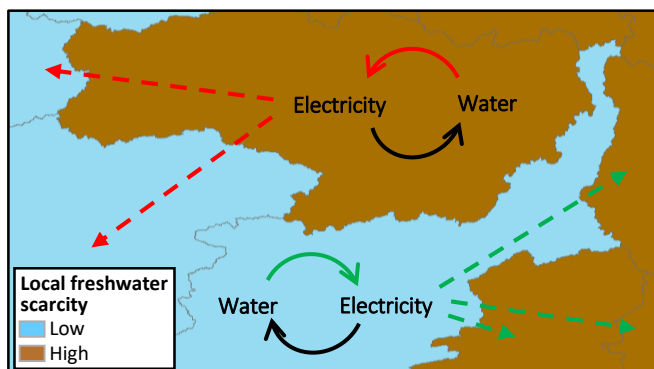
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21 **Abstract**

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

39 TOC:



40 1. Introduction

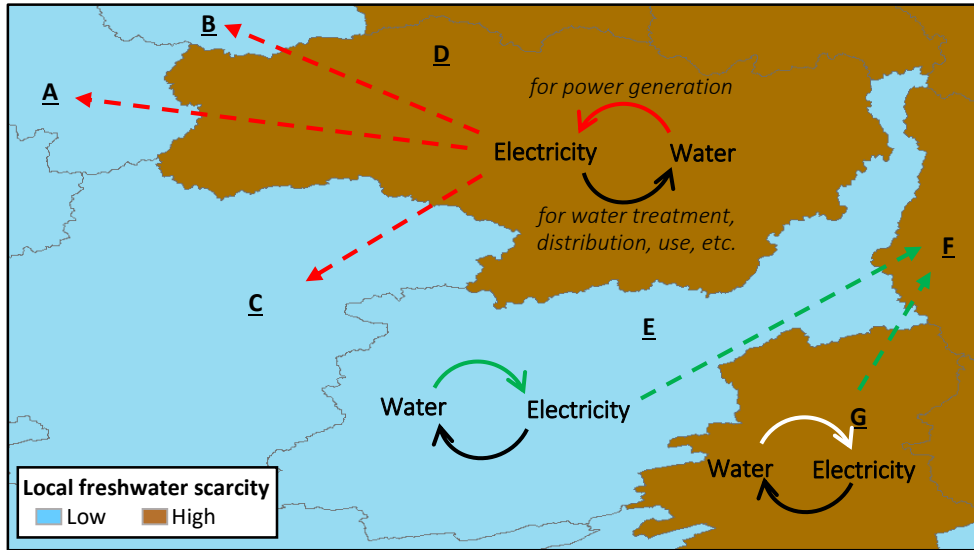
41 Freshwater stress can severely impair human health and economic prosperity.¹ Properly identifying and
42 evaluating the underlying stressors of such vulnerability is key to effectively mitigating current and future
43 challenges. Existing literature suggest, besides natural processes (e.g. climate change²), new and
44 continuing human activities, such as population growth²⁻⁵, industrialization and increases of living
45 standards, and infrastructure investments are the primary drivers of freshwater vulnerability experienced
46 or anticipated in many parts of the world. Despite a growing literature that investigated the freshwater
47 vulnerability in various spatiotemporal contexts (e.g.^{2, 6-16}), existing understanding of the anthropogenic
48 stressors has been conventionally constrained by a territorial perspective, considering water availability,
49 demand, and in-place infrastructures within a watershed, city, region or country. In a modern society,
50 however, a large quantity of human water needs in one area is met by freshwater originated from other
51 areas by consuming imported food, clothing, electricity, and other consumer goods and services.¹⁷⁻¹⁹ As
52 such, the freshwater vulnerability of consuming areas is beyond local freshwater stress but also
53 influenced by the freshwater requirements of all relevant producing sectors and the freshwater stress of
54 the producing areas.

55

56 The effects of sectoral and spatial connectedness of modern production and consumption systems on
57 freshwater vulnerability, i.e. a relatively new driver, have not been fully considered.^{20, 21} By simulating
58 counterfactual scenarios of economic localization, researchers have recently quantified the effects of
59 regional and global trade of products and services on local freshwater stress. Mixed effects, i.e.
60 alleviation or aggravation of local freshwater stress by affecting freshwater extractions were found across
61 basins and regions.^{17, 22-25} At the global scale, economic globalization was shown to have mitigated human
62 water use and thus freshwater stress.^{17, 23, 26, 27} Not based on the rather extreme counterfactuals, prior
63 studies traced freshwater consumption along existing supply chains and revealed the additional

64 freshwater risks Jordan and the UK were exposed to by relying on food products imported from water-
65 scarce countries.^{28, 29} However, little is known about how freshwater vulnerability is affected by the
66 water-electricity nexus –the sectoral and spatial linkages whose importance for water and energy
67 sustainability and economic security has been acknowledged in various research and policy agendas.³⁰⁻³³
68
69 The water-electricity nexus (WEN) characterizes the interdependencies of the production and
70 consumption of water and electricity (Figure 1). The sectoral linkages, especially the cooling water
71 demand of power generation, has been a critical focus of existing WEN literature.^{32, 34-37} In the United
72 States, over half of the ~4 billion MWh of electricity generated in 2014 was produced by freshwater-
73 cooled thermal energy conversion cycles.^{38, 39} According to the latest estimates from 2010,⁴⁰
74 thermoelectric power generation accounted for ~40% of the country’s annual freshwater withdrawal and
75 ~3% of freshwater consumption. Studies have quantified the freshwater withdrawal and consumption
76 rates of various fuel types, generation technologies, cooling systems, geographic locations, and regional
77 grids (e.g.^{36, 41-43}). Regarding WEN’s effects on freshwater stress, high water stress directly posed by
78 existing thermoelectric cooling needs in the U.S. was only found in 23 watersheds and minimal from a
79 national perspective⁴⁴. However, hydro-climatological conditions, such as droughts and heat waves, could
80 reduce generating capacity⁴⁵⁻⁴⁷ leading to substantial increases of electricity price^{46, 48}. Increasingly, the
81 effect of freshwater availability on electric power generation and transmission are simulated at a high
82 spatiotemporal resolution, under contemporary and future conditions of the hydro-climatological
83 systems.^{8, 9, 25, 35, 43, 45, 49-52} These efforts aim to gain insight on complex system phenomena and influence
84 power plant and transmission grid investments.

85



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87

88 **Figure 1 Freshwater vulnerability effects of the sectorally and spatially connected water and energy systems.**

- 89 1) Watersheds A to G are delineated by gray lines;
- 90 2) Solid arrows illustrate the sectoral connections: the colored arrows (→ or →) indicates water requirements for
 91 electricity generation, i.e., a critical focus of existing water-electricity nexus literature; the black arrows (→)
 92 indicates electricity as an input for treating, distributing, and utilizing water, i.e., another critical research
 93 stream of the nexus, e.g. in refs. ⁵³⁻⁵⁶; the white arrow indicates electricity is generated relying on dry cooling or
 94 non-freshwater resources (e.g. saline or reclaimed water) for cooling purposes;
- 95 3) Dashed arrows illustrate the spatial connections, i.e. that electricity is commonly generated in one region and
 96 transmitted along with the cooling water embedded to another region: --→ indicates additional freshwater
 97 vulnerability propagated through the regional electricity transmission grid when people living in watersheds of
 98 low water stress depend on electricity generated from watersheds experiencing high water stress; --→
 99 indicates by importing electricity generated from water-abundant watersheds or without freshwater cooling,
 100 the freshwater vulnerability of people living in highly-stressed locations is mitigated;
- 101 4) The colored arrows illustrate the focus of this analysis, i.e. the WEN's transboundary effects on freshwater
 102 vulnerability, which are beyond thermoelectric cooling's direct effects on local water stress.

103

104 Beyond thermoelectric cooling's direct effects on local water stress, the WEN's transboundary effects on
 105 freshwater vulnerability (as illustrated by colored arrows in Figure 1) have not been systematically
 106 assessed. These effects arise from a critical distinction between water and electricity issues – the
 107 relevant spatial scales. While water resources and usage are generally bound by watersheds, electricity is
 108 generated at the point or local scale, transmitted broadly through suitable infrastructure, and used in
 109 other places.⁵⁷ Specifically in the U.S., the electricity was transmitted within one of three interconnected
 110 power systems: the Western Interconnection, Eastern Interconnection, and Electric Reliability Council of

111 Texas (ERCOT) Interconnection.⁵⁸ Given the widespread reliance on electricity for nearly all of the
112 socioeconomic activities in modern societies and electricity's low substitutability by other commodities,
113 consumers can be exposed to freshwater vulnerability in the form of, for instance, curtailed power supply
114 or sharply increased spot market prices,⁵⁹ if they depend on electricity generated from locations
115 experiencing high water stress. On the other hand, by importing electricity generated from water-
116 abundant locations or without freshwater cooling, the freshwater vulnerability of highly-stressed
117 locations can be mitigated. These effects involve a multitude of natural, engineering, and human systems
118 that vary significantly across time and space. As a result, in comparison to the effects that conventional
119 anthropogenic stressors directly impose on local freshwater stress, WEN's transboundary effects on
120 freshwater vulnerability can be more complex and less visible.

121

122 This study aims to investigate WEN's transboundary effects on freshwater vulnerability in the continental
123 United States. This analysis uses detailed and recent estimates available for freshwater withdrawal and
124 consumption, renewable freshwater resources, electricity generation, electricity consumption, and
125 population in the U.S. The multi-scale datasets are harmonized to the watershed scale, and spatial
126 analyses are performed at a monthly time step for 2,110 watersheds covering the continental U.S.
127 Previously, water-electricity nexus studies that integrated freshwater availability at the utility or
128 interconnection level focused on either the West U.S. (i.e. the Western Interconnection)^{9, 35} or Texas (i.e.
129 the ERCOT Interconnection).^{43, 52} By expanding to all three interconnections, this study provides
130 consistent and comparable regional results, revealing that the conventionally-neglected transboundary
131 freshwater vulnerability effects of WEN are considerable yet distinct across the three interconnections.
132 Using monthly rather than annual average values, this study also better captures the often-great
133 temporal variations of electricity and water flows, which are key to assessing the two systems, their
134 contemporaneous interactions, and the WEN's transboundary effects on freshwater vulnerability. The

135 study also quantifies the monthly freshwater withdrawal and consumption rates per unit electricity
136 generation, with stress levels of the cooling water sources distinguished. To validate the results,
137 uncertainty and sensitivity analyses were conducted for varying water availability estimates and grid
138 delineations. This refined knowledge of freshwater vulnerability by considering the sectoral and spatial
139 connections of the WEN features two influential frameworks of systems integration, i.e. resource nexuses
140 and telecoupling. Results of this study point to a clear need for more comprehensive assessments of the
141 human-nature feedbacks, including the spatial feedbacks, in freshwater vulnerability analyses. The
142 refined knowledge is critical to developing successful strategies and regulatory interventions regarding
143 the upgrades of and investments in power production and transmission systems to mitigate the impacts
144 of freshwater vulnerability.

145

146 **2. Methods and Data Sources**

147 **2.1 Processing spatial data in a geographical information system**

148 The basic unit of this analysis is a watershed, a most fundamental unit of water resource analyses and the
149 accounting unit commonly adopted in recent WEN literature (e.g.^{37, 44, 46, 60}). The watershed boundaries
150 are defined by the 8-digit Hydrologic Unit Code (HUC-8), based on the late 2016 Watershed Boundary
151 Dataset from the Natural Resources Conservation Services.⁶¹ The dataset divides the United States into
152 2303 watersheds, some of which extend to neighboring countries. For this analysis, watershed area that
153 is non-U.S. territory was cut off based on the 2014 U.S. county boundary obtained from the U.S. Census.⁶²
154 A nationwide geographical information system (GIS) was developed to convert data collected from
155 various sources, originally available at different scales (see Table 1), to the watersheds. The grid-, county-,
156 and state-based data were first converted to $0.05^\circ \times 0.05^\circ$ grids and then matched to the watersheds,
157 assuming even distribution within a grid, county, state, and watershed. Data/information of individual

158 power plants were spatially matched to the watersheds based on the coordinates of each power plant
 159 reported by the U.S. EIA.⁶³

160

161 **Table 1 Data/information collected for this analysis and their sources**

Data	Year	Source*	Description
Runoff	2014	NLDAS (NOAH model) ⁶⁴	kg/m ² /month, 0.125°×0.125°
Population	2014	US Census Bureau ⁶²	People per county
Freshwater withdrawal	2010	USGS ⁴⁰	Gallons per day per county
Power plant location	2014	US EIA ⁶³	Coordinates
Electricity generation	2014	US EIA ^{38, 63}	MWh/month per generator
Cooling water withdrawal and consumption	2014	US EIA ^{38, 63}	Gallons/minute per generator
Electricity sales	2014	US EIA ³⁹	MWh/month per state
Watershed boundary	2016	NRCS ⁶¹	2303 watersheds

162 *NLDAS: North American Land Data Assimilation System

163 USGS: U.S. Geological Survey

164 US EIA: U.S. Energy Information Administration

165 NRCS: Natural Resources Conservation Service

166

167 The target year of the analysis was 2014, for which all statistics were available and up-to-date except for
 168 water withdrawal. The most up-to-date water withdrawal data in the United States were for the year
 169 2010. As such, negligible water withdrawal changes from 2010 to 2014 were assumed in this study 2014,
 170 which is consistent with the historical trends⁶⁵. Given both water withdrawal and population data were
 171 only available on an annual basis, the study also assumed an even distribution of freshwater withdrawals
 172 throughout 2014 and negligible intra-annual population migration. 2,110 watersheds covering the 48
 173 continental states, where data were available for all variables in Table 1, were chosen as the spatial
 174 boundary of this analysis. The GIS system and assumptions resulted in consistent country-level estimates
 175 when compared with the originally reported national values. For validation purposes, the sums of

176 watershed-level values of each variable, i.e. total area, population, freshwater withdrawal, electricity
177 generation, and freshwater withdrawal by power generation of the 2,110 watersheds, reached 91-98% of
178 the national estimates reported for the United States (Table S1). Based on the GIS system, monthly
179 freshwater stress, electricity transmission and outsourcing, and population affected by water stress due
180 to the WEN were then assessed at the watershed scale.

181

182 2.2 Quantifying water stress experienced at the watersheds

183 The freshwater withdrawal to availability (*w.t.a.*) ratio was used to measure the freshwater stress
184 experienced at a watershed. As a conventional water stress indicator,⁶⁶ the *w.t.a.* ratio measures the
185 amount of pressure water users, including municipalities, industries, power plants, and agricultural
186 activities, directly put on water resources and aquatic ecosystems.^{3,67} As water availability and demand
187 distribute unevenly over time and space, estimates of the *w.t.a* ratio and similar water stress indicators
188 depend on the spatial and temporal scales selected. Water stress levels tend to be underestimated by
189 annual or country-level assessments.^{68,69} The grid-cell level likely overestimates water stress because
190 water transfers between grid cells are large in reality.²

191

192 To better account for the spatial variations in water demand and the climate-induced spatial and intra-
193 annual variability of freshwater availability, this analysis quantified the freshwater stress for the 2,110
194 watersheds at a monthly time step for the year 2014 (Eq. 1):

$$195 \quad w.t.a._{i,j} = \frac{WW_{i,j}}{IRWR_{i,j}} \quad \text{Eq. 1}$$

196 Freshwater withdrawal in watershed *i*, during month *j*, i.e. $WW_{i,j}$, was converted from county-level
197 freshwater withdrawal estimates assuming constant monthly water demand (as discussed above).

198 Freshwater availability was quantified as the internal renewable water resources (*IRWR*) available for

199 watershed i , during month j . $IRWR_{i,j}$ was estimated as the sum of monthly “surface runoff (non-filtrating)”
200 and “subsurface runoff (baseflow)” obtained from the NLDAS-2 Noah monthly dataset.⁶⁴ As such, $IRWR_{i,j}$
201 provides a conservative estimate of the sustainable water supply to which local human populations have
202 access,⁷⁰ assuming water from upstream cannot be reused at downstream because of consumptive use
203 or water pollution. Unlike other literature (e.g.^{71, 72}), the effects of artificial reservoirs on reducing
204 temporary shortages were not accounted in this analysis, mainly due to the lack of recent reservoir
205 operation data in the United States. This omission could lead to an overestimation of the monthly
206 variations of freshwater availability.

207
208 As a validation check, the estimate of freshwater availability was compared with literature estimates and
209 measurements of the long-term internal renewable water resources in the United States. This study
210 estimated that 2,382 km³ internal renewable freshwater resources were available in the U.S. in 2014, well
211 within the reported range of 1,928 km³ to 2,900 km³ in previous studies.⁷³⁻⁷⁵ In addition, a sensitivity
212 analysis was carried out in which the monthly freshwater availability estimates were varied by $\pm 50\%$.
213 Consistent with existing literature^{4, 66, 69}, the severity of freshwater stress is ranked as: no stress
214 ($w.t.a. < 0.1$), low stress ($0.1 \leq w.t.a. < 0.2$), moderate stress ($0.2 \leq w.t.a. < 0.4$), severe stress ($0.4 \leq w.t.a. < 1$),
215 and extreme stress ($w.t.a. > 1$); $w.t.a. \geq 0.4$ is considered as high water stress.

216

217 **2.3 Assessing electricity deficiency and surplus**

218 ***2.3.1 Mapping the watershed boundaries to the electricity grids***

219 As Figure S1 shows, the continental United States is served by three interconnected power systems: the
220 Western Interconnection, Eastern Interconnection, and Electric Reliability Council of Texas (ERCOT)
221 Interconnection.⁵⁸ There are few connections and little energy transfer between them.⁷⁶ The three
222 interconnections are further divided into eight sub-regions overseen by the North American Electric

223 Reliability Corporation (NERC).⁵⁸ While NERC supplies a map of the three interconnections and eight sub-
224 regions, definitive boundaries do not exist and the NERC map may suggest (sub-)region assignments that
225 are different in reality.⁴² In this analysis, the 2,110 watersheds were assigned to one of the eight NERC
226 sub-regions and then one of the three interconnections (see Figure S2) using available information from
227 multiple sources, i.e. the coordinates of over 7000 power plants,⁶³ NERC affiliation of each power plant,⁶³
228 the shapefiles of eGRID regions released by the U.S. EPA,⁷⁷ and the concordances between NERC and
229 eGRID regions. Note, for watersheds with multiple power plants that belong to more than one
230 interconnection or NERC sub-regions, the watersheds were assigned according to the power plant with
231 the highest net annual electricity generation.

232 *2.3.2 Electricity balance within the interconnections*

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

$$237 \quad E_{u,j} = E_{g,j} = \sum \text{pop}_i \times e_{u,i,j} = \sum \text{pop}_i \times (e_{u,j} \times \alpha_{i,j}) \quad \text{Eq. 2}$$

238 pop_i is the number of population living in watershed i . The heterogeneity of monthly electricity use rate
239 within each interconnection was accounted through $e_{u,j} \times \alpha_{i,j}$ in Eq. 2. By construction, $e_{u,j}$ represents the
240 base per capita electricity use in month j of each interconnection. For each watershed within an
241 interconnection, the ratio $\alpha_{i,j}$ captures its relative monthly electricity use rate in comparison to the base
242 level. Specifically, $\alpha_{i,j}$ was estimated from state-level monthly electricity sales data³⁹, representing the
243 relative monthly electricity use variations for people living within the same interconnection but different
244 states. Estimates of county-level or more spatially-refined monthly electricity use were not available.

245 **2.3.3 Electricity deficiency of the watersheds**

246 If $e_{g,i,j} < e_{u,i,j}$, the electricity deficiency rate in watershed i during month j ($def_{i,j}$) was calculated as the
247 difference between electricity generation and use as a fraction of electricity use (Eq. 3). Regarding the
248 WEN's transboundary effects on freshwater vulnerability, electricity deficiency experienced in watershed
249 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
250 result in additional freshwater vulnerability in the watershed. Similarly, electricity deficiency experienced
251 in watershed i under severe to extreme water stress ($w.t.a. > 0.4$), denoted by $def_{i,j}^{**}$, is necessary to result
252 in mitigated freshwater vulnerability in the watershed.

253
$$def_{i,j} = (e_{u,i,j} - e_{g,i,j}) / e_{u,i,j} \quad \text{Eq. 3}$$

254 **2.3.4 Electricity outflows of the interconnections**

255 Besides electricity deficiency, WEN's transboundary effects of additional or mitigated freshwater
256 vulnerability in watershed i also relies on the characteristics of imported electricity outflows, specifically,
257 the water stress status of cooling water sources and the cooling water requirements. Within each
258 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
259 electricity outflows to the watersheds with electricity deficiency (where $e_{g,i,j} < e_{u,i,j}$). The electricity
260 surpluses are assumed to be well-mixed within each interconnection. The effects of this assumption was
261 tested and is discussed in Section 4.3.

262

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

267
$$out_j^* = \sum[(e_{g,k,j} - e_{u,k,j}) \times \beta_{k,j}] / \sum(e_{g,i,j} - e_{u,i,j}) \quad \text{Eq. 4}$$

268 Given only power plants with a nameplate capacity of 100 MW or more are required to report monthly
 269 cooling water usage to the U.S. EIA ^{38, 63}, the numerator neglects electricity outflows generated by small
 270 power plants (<100 MW) that also relied on scarce water for cooling purposes. In 2014, 874 power plants
 271 reported cooling water usage to the U.S. EIA. Throughout the year, 486-515 of those plants reported
 272 nonzero monthly freshwater cooling and contributed 51%-56% of the monthly electricity generation of
 273 the continental U.S. Hydropower, accounting for 5-8% of the total electricity generation, is mainly
 274 constrained by upstream freshwater availability and was thus not accounted in the numerator, either. As
 275 such, Eq. 4 provides a conservative estimate of the amount of electricity imports vulnerable to local
 276 freshwater stress.

277

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

284
$$out_j^{**} = \sum[(e_{g,m,j} - e_{u,m,j}) \times \beta_{m,j} + (e_{g,j}^0 - e_{u,j}^0)] / \sum(e_{g,i,j} - e_{u,i,j}) \quad \text{Eq. 5}$$

285 $(e_{g,j}^0 - e_{u,j}^0)$ represents the electricity surplus that, according to the cooling water usage reported to U.S.
 286 EIA, ^{55, 65} was generated without extracting freshwater for cooling purposes. In 2014, 302 of the 874
 287 power plants with ≥ 100 MW nameplate capacity relied completely on dry cooling or non-freshwater
 288 resources (e.g. saline or reclaimed water) for cooling purposes, supplying about 30% of the monthly
 289 electricity generation in the continental U.S. Not accounting for electricity outflows from small power

290 plants (<100 MW) or hydropower, Eq. 5 provides a conservative estimate of electricity imports not
291 vulnerable to local freshwater stress.

292

293 2.4 Assessing WEN's transboundary effects on freshwater vulnerability

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

$$297 \quad pop_{i,j}^* = pop_i \times def_{i,j}^* \times out_j^* \quad \text{Eq. 6}$$

298 It is critical to note that the multiplication of the watershed population pop_i with $def_{i,j}^*$ assumes that,
299 within each watershed, the deficiencies were concentrated to a smaller population rather than dispersed
300 among the entire population. The following multiplication with out_j^* assumes, within each
301 interconnection, electricity outsourced from highly-stressed areas was used by a small group of people
302 rather than being distributed among all of those experiencing deficiency. As such, $pop_{i,j}^*$ calculated by Eq.
303 6 gives a conservative estimate of the additional freshwater vulnerability caused by the WEN.

304

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

$$309 \quad pop_{i,j}^{**} = pop_i \times def_{i,j}^{**} \times out_j^{**} \quad \text{Eq. 7}$$

310 **3. Results**

311 **3.1 Monthly freshwater stress by watershed**

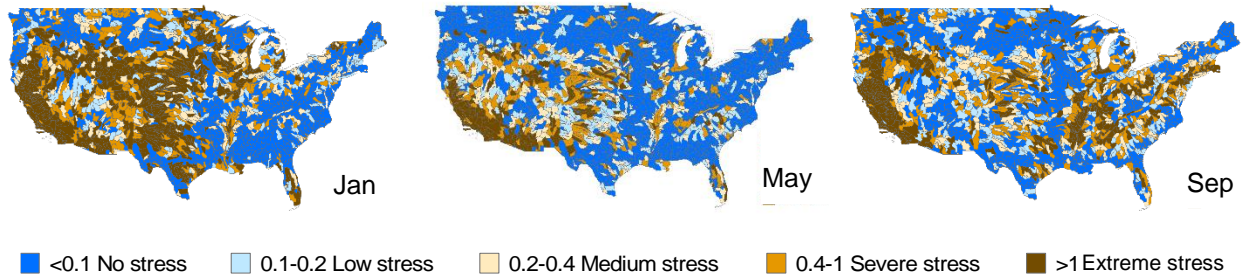
312 Spatiotemporal variability is critical for assessing and understanding freshwater stress in the continental
 313 U.S. (Figure 2; Table 2). Although less than 20% of the 2,400 km³ freshwater available within the United
 314 States in 2014 was withdrawn for anthropogenic activities, the monthly assessments at the watershed
 315 scale suggest 32% (May) to 59% (September) of the U.S. population lived in severely or extremely
 316 stressed watersheds, while 24% (75 million, September) to 57% (175 million, May) of the population lived
 317 in watersheds of low to no stress. Given freshwater withdrawals were assumed to be evenly distributed
 318 throughout the year due to data availability, the temporal variability in freshwater stress were due to the
 319 high temporal variability of freshwater availability. Nationally, the available freshwater resources ranged
 320 widely from 114 (November) to 313 km³ (April).

321 **Table 2. Population living in watersheds of various freshwater stress in 2014. Per class, population is given in number**
 322 **of people and the corresponding fraction of total population in the United States (%).**

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

323
 324 Figure 2 further highlighted the very heterogeneous temporal characteristics across the country.
 325 Consistent with previous studies (e.g.^{3, 14, 44}), freshwater stress was high and persistent in the Western
 326 U.S. (especially in California and Arizona) and the Great Plains. However, the monthly results revealed

327 that the Eastern states were not completely exempt from freshwater stress (see Figures 2 and S3). A
328 large portion of the watersheds along the Lower Mississippi River and the Ohio River were under high
329 water stress from August through December. Freshwater stress was also high in the Northeastern coastal
330 states during the Fall months.
331



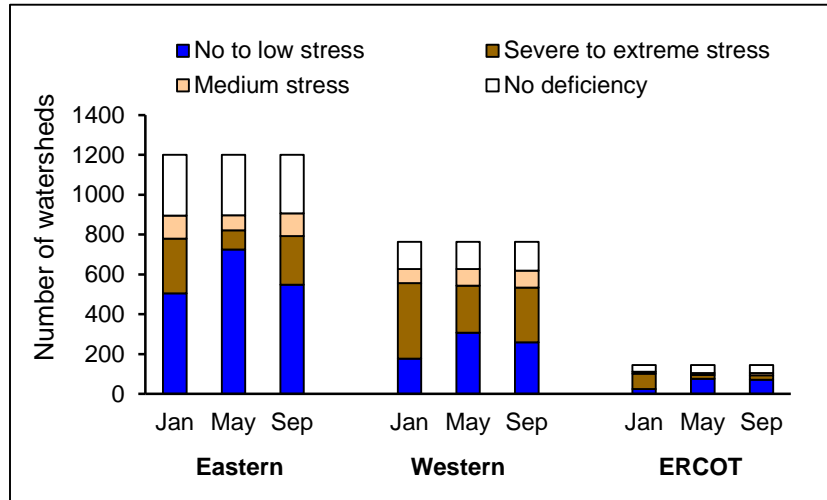
332
333 **Figure 2. Monthly (January, May, and September) water stress levels of the 2,110 watersheds in the continental**
334 **United States in 2014.** Water stress levels are measured as the monthly freshwater withdrawal to freshwater
335 availability, i.e. *w.t.a.* ratios. Full monthly results are provided in Figure S3 in the Supporting Information (SI).

336

337 3.2 Electricity deficiency and outsourcing

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

348 within the Eastern Interconnection, of generating more electricity in water-abundant areas to reduce the
 349 electricity generation and outsourcing from water-stressed areas.
 350



351
 352 **Figure 3. Monthly (January, May, and September) electricity-deficient watersheds (solid bars, distinguishing water**
 353 **stress conditions) and self-sufficient watersheds with each interconnection.**

354 Further, as Figures 4A and S4 illustrate, the monthly deficiencies within these electricity-deficient
 355 watersheds were overall high for all three interconnections (i.e., 87-92%). The high watershed deficiency
 356 rates are attributable to the uneven distribution of power plants within each interconnection and the
 357 highly skewed power generation among the power plants (see Figure 4 and S4). In 2014, about 5,700
 358 power plants (individual nameplate capacity ≥ 1 MW) located in about 1,200 watersheds (or 59% of the
 359 2,110 watersheds) contributed net positive electricity supplies to the aggregated U.S. electricity grid.
 360 People living in the rest of the watersheds thus relied completely on electricity generated by power plants
 361 in other watersheds. Among the active power plants, about 80% of the electricity was generated by less
 362 than 10% of the plants every month. As such, watersheds with smaller power plants are also likely to
 363 rely, to a varying degree, on outsourced electricity. The observations further confirm the critical “scale”
 364 distinction between water and energy use: while water resources and usage are generally bound by
 365 watersheds, electricity used within one water shed is often transmitted from other watersheds.

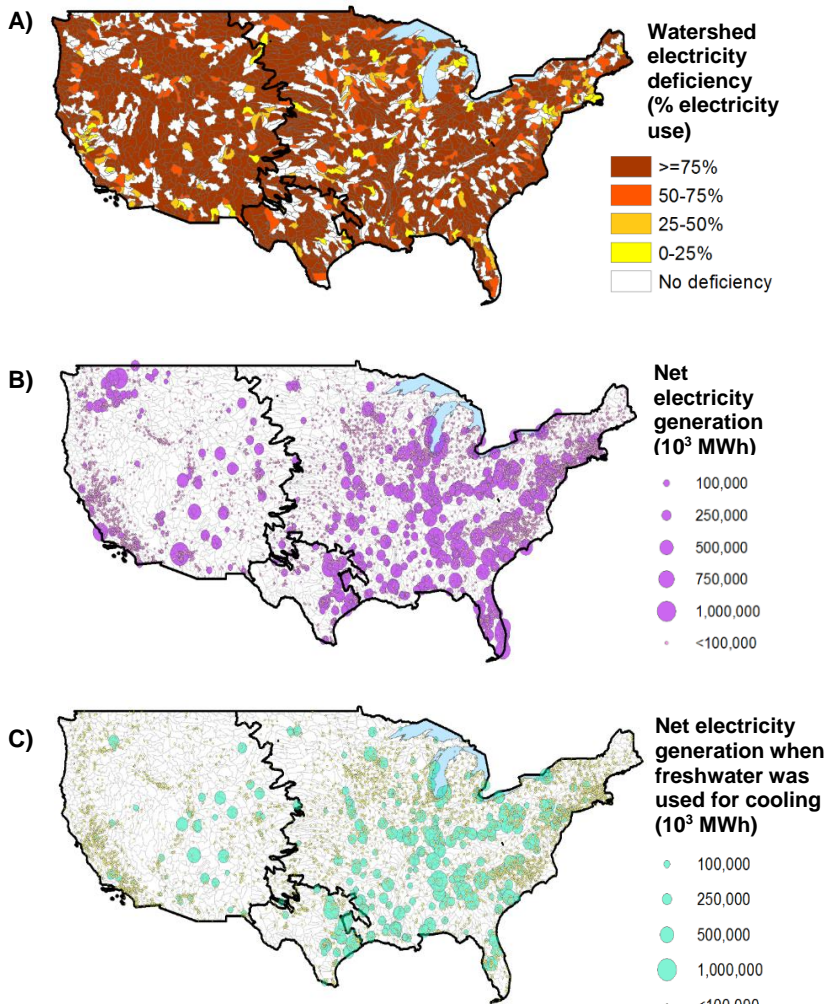


Figure 4 Electricity generation and deficiency at the watersheds in May, 2014.

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);

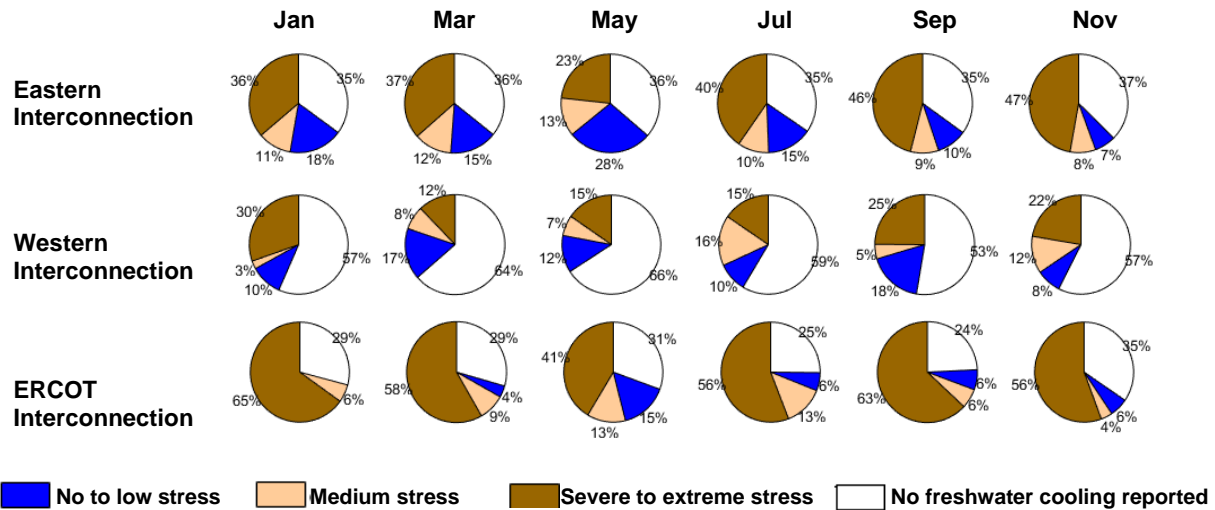
C). Net electricity generation when freshwater cooling was reported (circle size is proportional to the amount of

366

367 3.3 Water stress profiles of the electricity outflows

368 In 2014, 34-38% of the monthly electricity was generated using freshwater cooling and transmitted
 369 outside of the watershed boundary. As shown by Figure 5, the electricity outflows demonstrate
 370 considerable regional heterogeneity in terms of cooling water usage. A much higher fraction of the
 371 outsourced electricity, i.e. 53-66%, was generated without freshwater cooling within the Western
 372 Interconnection. In comparison, only 24-37% of the power transmissions were generated without
 373 freshwater cooling within the other two interconnections. This discrepancy can be largely explained by
 374 the Western Interconnection’s significant hydropower supply (~23%) and considerable solar and wind

375 power supply (~9%). In comparison, the total non-thermal power supply (i.e. hydro, solar, and wind
 376 power) accounted only for ~7% and ~11% in the Eastern and ERCOT Interconnections, respectively.



377 **No to low stress** **Medium stress** **Severe to extreme stress** **No freshwater cooling reported**

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

379

380 Due to the spatial and temporal heterogeneity of the freshwater stress, the electricity outflows within
 381 each interconnection demonstrate varying water stress profiles. As Figure 5 shows, of the total electricity
 382 transmitted from one watershed to another within the Eastern, Western, and ERCOT Interconnections,
 383 20-50% (7-28%), 10-30% (8-18%), and 40-65% (0-15%) were sourced from watersheds under severe to
 384 extreme stress (no to low stress), respectively. Note that although freshwater stress is known to be more
 385 severe in areas within the Western Interconnection than those within the Eastern Interconnection,
 386 electricity transmissions within the former appears to have considerably lower water stress implications
 387 than the latter, mainly because the majority of the electricity outflows generated in the West U.S. were
 388 based on dry cooling or non-freshwater cooling resources. This could reflect the physical limitations of
 389 freshwater resources and/or the historical awareness and thus consideration of the severe water stress
 390 condition in infrastructure planning and development in the West. In contrast, electricity outflows within
 391 the ERCOT Interconnection, which overlaps with another drought-prone region in the U.S., demonstrate
 392 the highest freshwater vulnerability associated with the electricity transmission. The vulnerability is

393 especially high given both severe groundwater depletion and load shedding were recorded in Texas
394 during the one-year drought in 2011⁷⁸ and multi-year droughts are expected across the state in the late
395 21st century.⁷⁹ Despite the spatial variations, among those power plants that reported freshwater
396 cooling, it is common that much more of the electricity outflows were generated from areas experiencing
397 high water stress rather than those under no to low water stress.

398

399 **3.4 WEN's effects on freshwater vulnerability**

400 Based on the results above and Eqs. 6-7, WEN's transboundary effects on freshwater vulnerability were
401 quantified. Overall, WEN resulted in significant freshwater vulnerability implications across the
402 continental U.S. For at least one month in 2014, 58 million population living in watersheds of low to no
403 freshwater stress were exposed to additional freshwater vulnerability by relying on electricity generated
404 in severely or extremely stressed watersheds. On the other hand, for 72 million population living in
405 highly-stressed watersheds, their freshwater vulnerability was mitigated by using imported electricity
406 generated in watersheds of low to no stress (31 million) or power plants running dry cooling or using
407 non-freshwater for cooling purposes (41 million) for at least one month in 2014.

408

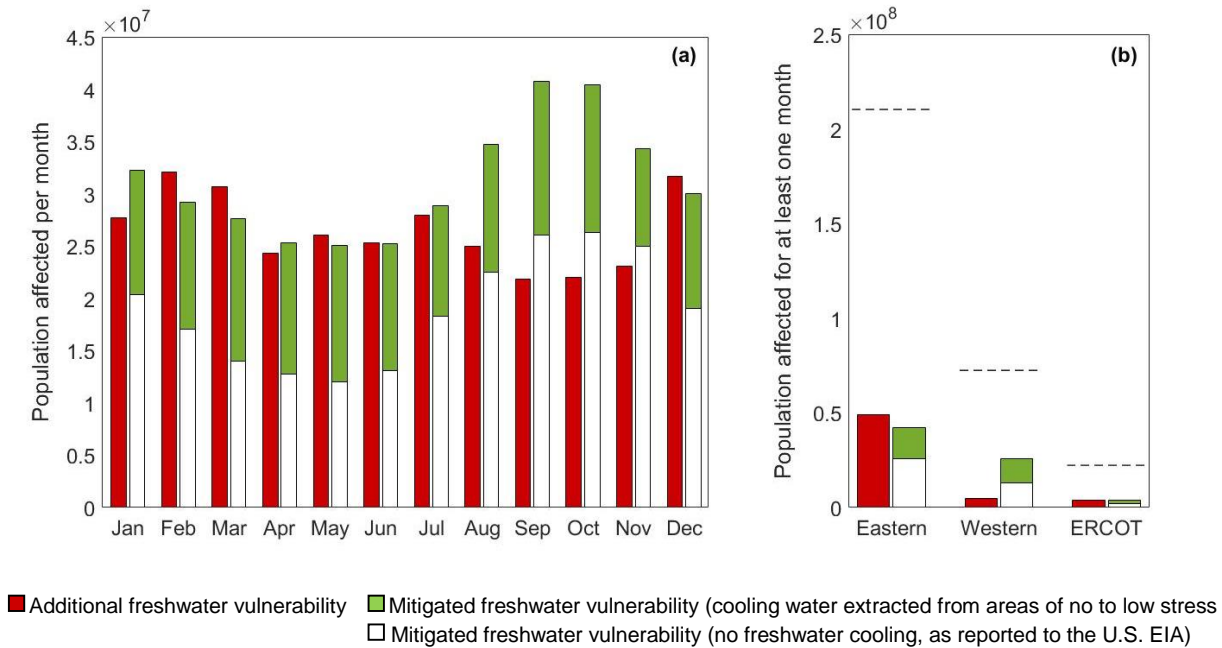
409 As shown in Figure 5a, the WEN's additional or mitigation effects on freshwater vulnerability are
410 heterogeneous across time and space. The additional freshwater vulnerability affected 22 million
411 (September) to 32 million (February) people living in watersheds of low to no freshwater stress.
412 Freshwater vulnerability was mitigated for 25 million (May) to 41 million (September) people living in
413 watersheds of severe to extreme water stress. At the country scale, the mitigation effects were the most

414 significant during the fall months, especially September and October, while the additional freshwater
 415 vulnerability effects were more significant in February, March, and December.

416 **Figure 6 WEN’s transboundary effects on freshwater vulnerability are heterogeneous across time and space: (a).**

417 people affected throughout the months in 2014; **b)** people affected for at least one month in 2014 (dashed lines

418 indicate the total population living within each interconnection).



419
 420 As Figure 6b shows, the WEN’s transboundary effects affected the freshwater vulnerability of the three
 421 interconnections differently. Distinct from conventional perceptions that water stress impacts are low in
 422 the Eastern U.S. (e.g.^{3, 14, 44}), these results highlight the additional freshwater vulnerability impacts mainly
 423 affected people living in the East. About 50 million people living in the Eastern Interconnection were
 424 affected by the additional freshwater vulnerability for at least one month in 2014, accounting for 85% of
 425 the impacted population assessed for the continental U.S. In comparison, only about 8% and 6% of the
 426 impacted population were from the Western and ERCOT Interconnections, respectively. Regarding the
 427 benefits of mitigated freshwater vulnerability, 59%, 36%, and 5% of the population affected for at least
 428 one month in 2014 were from the Eastern, Western, and ERCOT Interconnections, respectively. Based on

429 the accounts of affected population in Figure 6b, due to the WEN's transboundary effects, freshwater
430 vulnerability was slightly worsened within the Eastern Interconnection, substantially improved within the
431 Western Interconnection, and least affected within the ERCOT Interconnection.

432

433 4. Discussion

434 4.1 Assessing freshwater vulnerability from a systems perspective

435 Addressing complex interconnections through systems integration, such as the resource nexuses and
436 telecoupling that tie different issues and distant places together, respectively, is essential for solving the
437 myriad sustainable challenges.³¹ To holistically assess freshwater vulnerability, results of this study
438 highlight the need to consider the interactions between the water and the electricity systems both within
439 and outside of the conventional territorial boundaries of water resources. As a consequence, this study
440 also highlights the need to revisit the nuances of using conventional water stress metrics for assessing
441 and managing freshwater vulnerability. For example, the water crowding index, i.e. the number of people
442 living on a given unit of water resources or water resources available per capita^{2, 4, 80}, relates local water
443 resources to the local water demand of population and measures the ultimate territorial water security.
444 The ratio of local water withdrawal to availability (*w.t.a.*) represents the immediate anthropogenic
445 pressures on local freshwater environments. However, as shown by this study, these two widely-adopted
446 metrics become a less relevant measure for water sufficiency or stress when goods and services people
447 consume are increasingly produced remotely.

448

449 Focusing on the water-electricity nexus, this study refined the knowledge of freshwater vulnerability in
450 the continental United States, providing new insights for potential upgrades and investments of power
451 systems. Surprisingly, the traditionally unaccounted-for freshwater vulnerability impacts were

452 predominant in the Eastern U.S., where water stress risks have been conventionally perceived to be low
453 and water-energy nexus has been least studied. Previously, research showed the water needs of
454 thermoelectric power plants are predominant in the eastern U.S.⁴⁴ However, by focusing on the direct
455 impacts on local water stress and neglecting the intra-annual variations of water availability, the water
456 stress implications of thermoelectric water needs were concluded as localized and minimal on the
457 national scale.⁴⁴ It is also critical to note that water stress' impacts on power generation appear to be
458 much lower in reality due to the reservoir storage at thermoelectric power plants, current regulatory
459 regime that focuses on thermal effluent discharges rather than real-time environmental or minimum
460 flows, and the provisional variances approval granted at extreme conditions.^{47, 81} Despite this, under high
461 water stress, thermoelectric power generation remains vulnerable to competitions with other critical
462 water users (e.g. municipal demands) and new regulatory regimes that limit cooling water abstractions
463 based on environmental flows. Revealing that a considerable amount of electricity outflow was
464 generated using cooling water extracted from highly-stressed watersheds (Figure 5) and there are
465 considerable potentials of generating more electricity in water-abundant areas (Figure 4), this study
466 indicates opportunities to further optimize power generation and transmission, mitigating the
467 vulnerability to re-allocations of water use, hydro-climatological constraints and regulatory arrangements.

468

469 **4.2 Water stress profiles of electricity**

470 Prior WEN studies quantified the freshwater withdrawal and consumption rates of electricity generation,
471 distinguishing fuel types, generation technologies, cooling systems, geographic locations, and regional
472 grids (e.g.^{36, 41-43}). While quantifying the freshwater rates (only accounting for cooling water use) based
473 on monthly water and electricity data, this study further specified the water stress conditions of the
474 cooling water sources (Figure 7). Overall, for a given unit of electricity generated, freshwater withdrawal
475 was the highest in the ERCOT (47-60 m³/MWh) and freshwater consumption in the Eastern (0.58-0.96

476 m³/MWh) Interconnection. While almost all of the cooling water withdrawals (80-100%) can be traced to
 477 watersheds of high stress levels (i.e. *w.t.a.*>0.4) within the ERCOT Interconnection, about 40-85% of the
 478 cooling water consumption within the Eastern Interconnection was extracted from highly-stressed
 479 watersheds. Within the Western Interconnection, the freshwater cooling withdrawals were significantly
 480 lower (i.e. ~3 m³/MWh) than the other two interconnections while the cooling water consumption was
 481 comparable, although also the lowest of the three. Of interest, a recent study indicates considerations on
 482 fuel and technology costs, policy drivers and the topology of electricity demand within the Western
 483 Interconnection, rather than water availability, will likely lead to implementation of distributed, low-water
 484 electric power generation.⁹

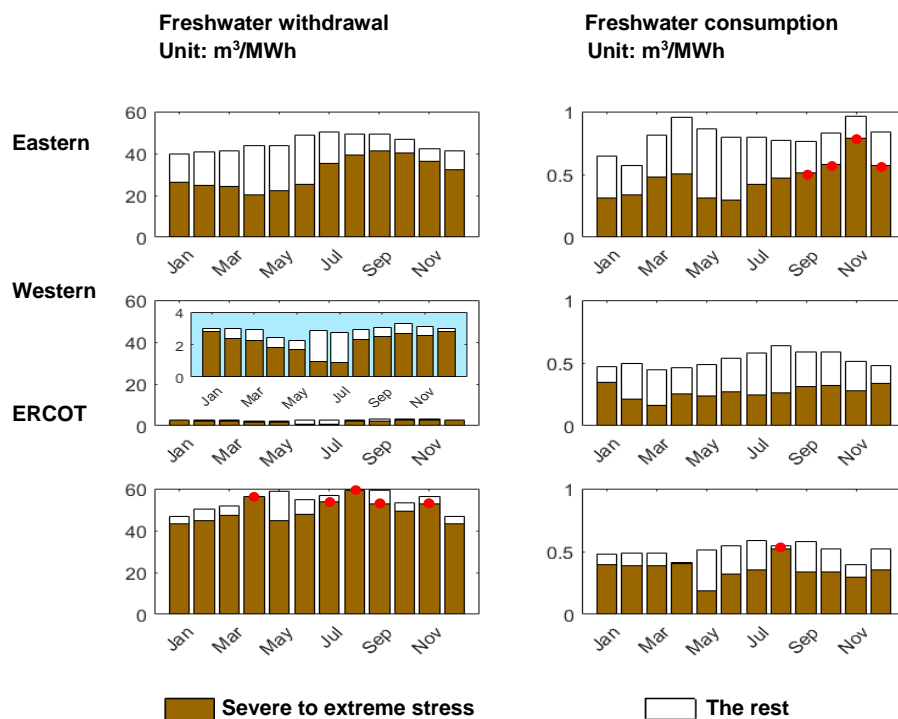


Figure 7. Cooling water usage per unit electricity generation, distinguishing water stress levels of the cooling water sources.

Shaded bars represent cooling water sourced from watersheds under severe to extreme water stress, hollow bars represent the rest freshwater usage; red dots denote the top five monthly scarce water withdrawal and scarce water consumption rates across the three interconnections)

485
486

487 If only considering the freshwater extracted from highly-stressed watersheds, i.e. the scarce water, the
 488 peak cooling water withdrawal rates all occurred within the ERCOT interconnection, specifically (in
 489 descending order) in August, April, July, September, and November (>50 m³/MWh). For cooling water
 490 consumption, the peak rates of scarce water consumed for thermoelectric cooling occurred during

491 September to November in the Eastern Interconnection and during August in the ERCOT Interconnection
492 ($>0.51 \text{ m}^3/\text{MWh}$). Within the ERCOT Interconnection, previous research showed water consumption
493 intensities of electricity output are the highest when electricity demand is the lowest since the baseload
494 coal-fired generators are the most water-intensive.⁴³ In response to recent environmental regulations on
495 emission reduction there, the retirement of coal-fired power plants and the expansion of natural gas-fired
496 capacity may effectively reduce the water intensive energy generation units,⁵² thus mitigating the peak
497 water and scarce water intensities of electric power generation. However, more stringent restrictions at
498 ERCOT power plants on CO_2 emissions (e.g. $>75\%$ below BAU) would likely increase water withdrawals by
499 64% when coal-fired power plants are replaced by nuclear generation.⁸³

500 **4.3 Caveats, uncertainties and call for future research**

501 To avoid misinterpretation of the results, three primary limitations deserve mention. First, the study only
502 provided conservative estimates of the WEN's transboundary effects on freshwater vulnerability. It is
503 possible that more people were affected through the WEN, for example, considering the water
504 constraints on hydropower generation. Hydropower contributes to $\sim 6\%$ of electricity generation in the
505 U.S.³⁹ but makes a much higher contribution (17%) to the global electricity supply.⁴⁵ A recent study
506 showed that hydropower's current and increasing water demands impose pressure on available
507 freshwater resources and aggravate the water stress levels in China.⁸⁶ It is also critical to note that the
508 present analysis focuses on water use for electricity generation. In the U.S., water use for the fuel cycle
509 and power plant manufacturing can reach up to 26% of electricity's total life cycle water consumption; in
510 the western U.S., fuel cycle and manufacturing water consumption can even exceed operational
511 demands.⁸² In order to systematically mitigate water stress, a life cycle approach needs to be taken in
512 investment decisions about power infrastructures.

513

514 The second limitation of this study is related to quantification of the local freshwater stress using the
515 *w.t.a.* (withdrawal to availability) ratio. Like some literature (e.g. ^{4, 66, 69}), this study used freshwater
516 withdrawal as the numerator and adopted the stress threshold accordingly. However, others (e.g. ^{14, 87})
517 preferred using freshwater consumption, given a significant fraction of water withdrawals may return to
518 its source and become available for further use over a relatively short time period. As for the
519 denominator of the *w.t.a.* ratio, i.e. water availability, this study did not account for environmental
520 requirements, which may underestimate the water stress levels. Mainly due to the lack of data, the
521 effects of artificial reservoirs or upstream inflows were also neglected in the estimates of water
522 availability, which could potentially cause overestimates of the stress levels. Further, throughout this
523 study, freshwater resources refer to the fresh surface and ground water, also known as the blue water.⁶⁸
524 ^{88, 89} The availability and usage of green water, i.e. moisture in the unsaturated zone of soil and available
525 for plants,⁸⁵ is not accounted in the assessments of freshwater stress. To understand the uncertainties
526 associated with the water stress assessed, sensitivity analyses (SA) that varied monthly freshwater
527 availability by $\pm 50\%$ were performed. The SA results indicate that, for at least one month in 2014, 54-55
528 million people and 69-73 million people were affected with additional and mitigated vulnerability,
529 respectively, demonstrate the robustness of the study's main findings in light of wide ranges of water
530 availability variations.

531

532 Third, electricity transmission was not modeled based on realistic data of the grids. The overall structure
533 of the electrical grids was modeled after governmental reports suggesting there is minimal electricity
534 transmission across the three interconnections⁷⁶. Without access to detailed transmission data, this
535 analysis assumes electricity feeding into each interconnection is well mixed. However, some literature
536 have adopted the classification of eight NERC sub-regions, e.g. ^{42, 90, 91}, modeling the electricity
537 transmissions within each sub-regions. To test the effects of different grid delineation and the

538 possibilities that electricity feeding into each interconnection may not be well mixed, the same analyses
539 were conducted based on NERC classification. Consistent results were generated: for example, 55 million
540 and 72 million population were estimated for the additional and mitigated vulnerability effects for at least
541 one month in 2014, respectively. Often based on electricity transmission optimized for system-wide least
542 cost, recent literature (e.g.^{25, 52, 92}) have greatly improved the spatiotemporal resolutions of electricity
543 transmission models. Without doubt, understanding of the WEN's freshwater vulnerability implications
544 can be further improved by future research that adopts detailed power flow model developed from
545 realistic grid transmission data. The significant and unexpected results from this study also indicate the
546 need to further understand the implications of sectoral and spatial connectedness other than the WEN on
547 freshwater vulnerability.

548

549 **Supporting Information (SI)**

550 *Included in the SI are:*

- 551 • A detailed description of the Methods
- 552 • Table 1. Main variables used in this study and their national coverage
- 553 • Figure S1. Map of NERC interconnections
- 554 • Figure S2. NERC interconnections mapped in the GIS system developed in this study
- 555 • Figure S3. Monthly water stress levels of the 2,110 watersheds in the continental United States
556 in 2014.

- 557 •
- 558 • Brief statement in nonsentence format listing the contents of the material supplied as
- 559 Supporting Information.
- 560

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