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Monthly virtual water transfers on the U.S. electric grid

Jenni Nugent[1], Christopher M Chini[2], Rebecca A M Peer[3] and Ashlynn S Stillwell[1,*]

[1] Department of Civil and Environmental Engineering, University of Illinois Urbana-Champaign, 205 N Mathews Ave, Urbana, IL 61801, United States of America
[2] Department of Systems Engineering and Management, Air Force Institute of Technology, 2950 Hobson Way, WPAFB, OH 45433, United States of America
[3] Department of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand
[*] Author to whom any correspondence should be addressed.

E-mail: ashlynn@illinois.edu

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Abstract

Water consumed by power plants is transferred virtually from producers to consumers on the electric grid. This network of virtual transfers varies spatially and temporally on a sub-annual scale. In this study, we focused on cooling water consumed by thermoelectric power plants and water evaporated from hydropower reservoirs. We analyzed blue and grey virtual water flows between balancing authorities in the United States electric grid from 2016 to 2021. Transfers were calculated using thermoelectric water consumption volumes reported in Form EIA-923, power plant data from Form EIA-860, water consumption factors from literature, and electricity transfer data from Form EIA-930. The results indicate that virtual water transfers follow seasonal trends. Virtual blue water transfers are dominated by evaporation from hydropower reservoirs in high evaporation regions and peak around November. Virtual grey watertransfers reach a maximum peak during the summer months and a smaller peak during the winter. Notable virtual blue water transfers occur between Arizona and California as well as surrounding regions in the Southwest. Virtual grey water transfers are greatest in the Eastern United States where older, once-through cooling systems are still in operation. Understanding the spatial and temporal transfer of water resources has important policy, water management, and equity implications for understanding burden shifts between regions.

1. Introduction

In 2022, 60.2% of utility-scale electricity in the United States was generated by fossil fuels, 18.2% by nuclear, and 6.2% by hydropower [1]. Water scarcity and quality challenges threaten the availability and reliability of these electricity supplies [2]. Therefore, it is important to quantify and benchmark the consumption of water in the generation of electricity, including virtual water as the water required to produce a product. The concept was introduced by Allan in the late 1990s as a partial solution to water scarcity challenges in the Middle East [3, 4]. Ecological footprints were also introduced in the early 1990s and account for ecological impacts in terms of land area [5]. Building on this concept, Hoekstra and Hung [6] introduced the concept of water footprints in 2002 as a metric for analyzing freshwater consumption.

The water stress impact of thermoelectric power generation is both regional and seasonal [7–9], and thermoelectric cooling water demand exacerbates water stress [9–11]. Rising water stress threatens electricity production [12, 13]. Falling water source levels, rising surface water temperatures, and thermal regulations designed to protect aquatic ecosystems decrease cooling system efficiency and increase the likelihood of power plant curtailment or shutdown [14–16]. Climate change impacts also threaten hydropower productivity by increasing reservoir evaporation and decreasing precipitation and streamflows [17, 18]. One study predicted a thermoelectric power plant summer capacity decrease of 4.4%–16% for 2031–2060 in the United States, along with extreme capacity reductions increasing by a factor of three [17]. Increased

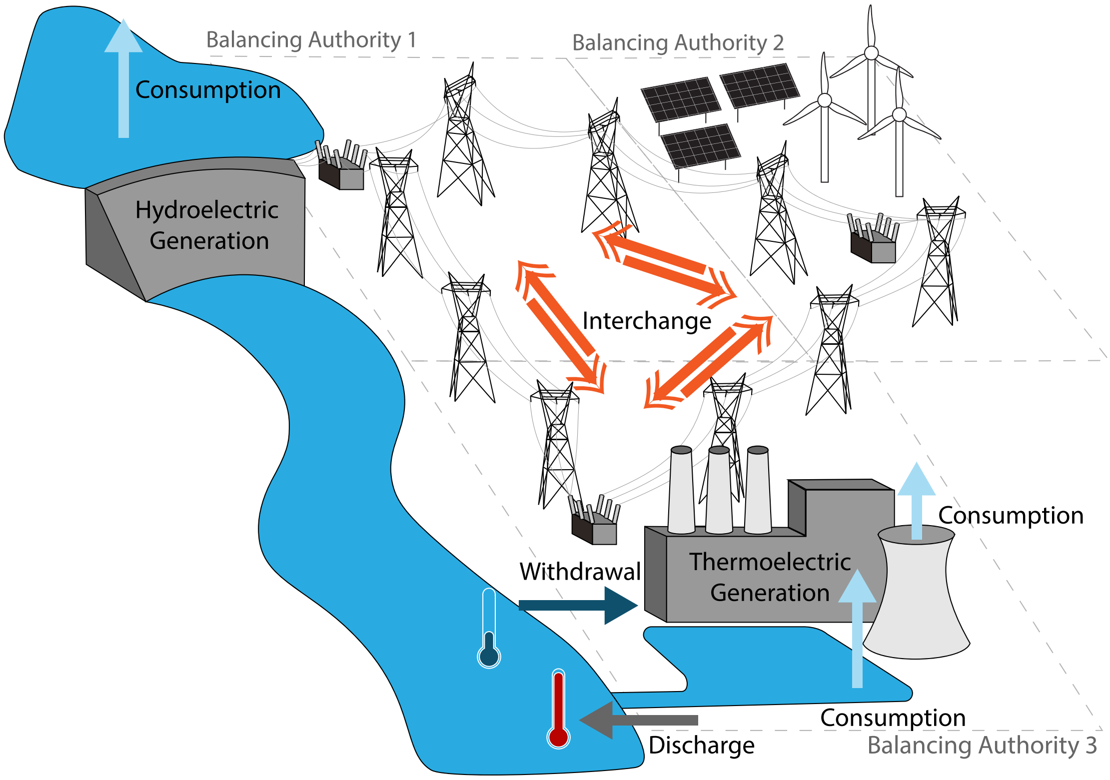

Figure 1. Water consumed during electricity generation is transferred virtually between balancing authorities through the electric grid.

penetration of renewable electricity generation, such as photovoltaic solar and wind, may decrease operational water demands for electricity [19, 20].

Water is consumed in the process of generating electricity at both hydropower and thermoelectric power plants. This water is then transferred virtually with the electricity as it is transmitted and distributed to end users. All electricity consumed by various sectors has local or distant water impacts depending on where the electricity was generated. Understanding this network of virtual water transfers allows regulators and planners to identify the burden shift between consumers and producers. The virtual water trade of energy is an established focus in the literature [21–29]. Figure 1 provides an illustration of the sources of virtual water of electricity and depicts how this water is transferred to end users, sometimes significant distances, within and between balancing authorities.

A review of energy virtual water trade literature found many limitations in existing studies including exclusion of hydropower footprints, varying methods, and analyzing trade at an annual scale, thus ignoring seasonal variability [30]. Few studies have analyzed the virtual water transfers on a sub-annual scale [31–33]. This scale of study is important because water footprints for electricity generation are not constant throughout the year [25, 34], as electricity demands, fuel mix for electricity generation, air and water temperatures, weather, and thermodynamic cooling requirements vary seasonally [35]. Identifying the spatial and temporal variations of virtual water transfers is vital for understanding the burden shift of electricity generation from consumers to producers.

We analyze the spatial and temporal relationship of virtual water transfers on the electric grid of the contiguous United States. In this study, we focus on blue and grey water footprints. A blue water footprint is the quantity of water consumed from ground and surface water sources. This quantity is relevant for hydroelectric (reservoir evaporation) and thermoelectric (cooling) power plants. The grey water footprint is the volume of water necessary to dilute a pollutant to meet water quality regulations [36]. In this analysis, the pollutant is waste heat in the cooling water effluent from thermoelectric power plants. We quantified monthly blue and grey water footprints for each balancing authority (BA) from 2016 to 2021. We used these footprints and total BA electricity generation to develop monthly water footprint factors (m^3 of water MWh^{-1}), which were then multiplied by electricity interchange between balancing authorities to determine monthly virtual water transfers.

2. Background

A review of virtual water for energy trade literature from 2007 to 2021 found only three papers that analyzed virtual water transfers on a sub-annual scale: two analyzed the virtual water on the European electric grid [31, 32], and one quantified inter-provincial transfers in China [33]. The United States faces notable seasonal weather patterns, frequent droughts, and water stress across the country, particularly in the West. Therefore, understanding the seasonal water impacts of electricity generation and how the burden shifts between consuming regions and producing regions is vital to both water and energy policy decisions.

To accurately understand this burden shift, the water consumption from hydropower reservoirs also needs consideration. Hydropower water footprints have been shown to have notable contributions to virtual water transfers [37, 38], yet these footprints are often neglected from virtual water analyses [30].

2.1. Water footprint of electricity

2.1.1. Water withdrawal vs. consumption

Water withdrawal is the total volume of water removed from a water source and may or may not be returned to the same water source. Water consumption is the volume of water that is evaporated, transpired, or incorporated into products or crops. Thermoelectric power plants (e.g. coal, natural gas, nuclear) use steam to spin turbines that drive generators to produce electricity. Most power plants use either once-through or recirculating cooling water systems to condense this steam back into boiler feed water so it can be reused. Once-through cooling systems withdraw large volumes of water to absorb waste heat, and then discharge this water back into the environment. Cooling water intake structures negatively affect aquatic organisms by trapping them against screens [39], and heated effluent is harmful to organisms and the environment [40, 41]. Recirculating cooling water systems use towers, canals, or ponds to dissipate heat through evaporation, rather than returning the water to the environment. This approach reduces water withdrawals compared to once-through cooling, but increases water consumption. Hydropower generation also consumes water through evaporation and seepage from the reservoir impounded by the dam, although seepage is more likely to stay within the river basin and is generally considered to be small [42, 43]. In this study, consistent with the definitions and formulations of water footprint, we evaluate consumptive water of electricity generation.

2.1.2. Water footprints

Water footprints include three different consumptive components: blue, green, and grey water [6, 44]. Blue water footprints refer to the volume of water consumed from ground or surface sources. In terms of electricity generation, blue water footprints include water evaporated from cooling towers or from the surface of cooling ponds at thermoelectric power plants, water evaporated from hydroelectric reservoirs, and water used for washing photovoltaic solar panels. Hydroelectric power plays a substantial role in the blue water footprint of electricity, but is often excluded from studies as the consumption, occurring through evaporation from reservoirs, is not reported to the EIA [37, 38, 42, 45]. Green water footprints refer to water use from precipitation and would come into consideration when analyzing the agricultural water demand of growing biofuels or biomass. The scope of this study is limited to the operational water demand for electricity production; therefore, green water footprints are not considered.

Grey water footprints are the estimated volume of water required to dilute a given amount of pollution to below water quality standard thresholds. For most types of pollution in the United States, such as chemical or biological waste, grey water footprints fall short as a metric because these types of pollution are managed through water treatment and not through dilution. However, the concept of grey water can be used to represent the impacts of thermal pollution from thermoelectric generators [46]. The grey water footprint from thermal pollution in the form of heated cooling water discharge is substantial for thermoelectric power plants [34]. Grey water calculations are based on state and regional thermal effluent policies that are themselves based on an absolute temperature limit or a net change in temperature [34].

2.1.3. Water footprint of hydropower generation

There is debate as to how hydropower water consumption should be calculated and how the hydropower water footprint should be allocated in multi-purpose reservoirs [42, 43]. Hydropower water consumption estimates have a large range of uncertainty due to the various methods of calculation [43]. The major debates surround gross versus net evaporation, and how to allocate evaporation to different reservoir uses. Previous estimates of water consumption by hydropower based on gross evaporation greatly overestimated the consumptive impact of hydroelectric dams [43, 47–51]. Gross evaporation is the rate of total evaporation from the reservoir, while net evaporation is the change in evaporation with respect to the state of the region before the reservoir was inundated. Models of hydroelectric water consumption based on multiple allocation scenarios by Grubert [42] improve upon out-dated gross evaporation estimates cited in Macknick *et al* [47–49].

There is not a consistent method for allocating water consumption to different reservoir purposes [42, 43, 52]. While it is clear that allocating all evaporation to hydropower is an overestimate, there are drawbacks to allocating based on reported primary purpose, weighting based on reported purposes, and assigned monetary values [42]. Dams and reservoirs can serve more functions than exclusively hydroelectric power generation. Purposes reported in the National Inventory of Dams (NID) for hydroelectric dams also include irrigation, water supply, flood risk reduction, navigation, recreation, debris control, fish and wildlife pond, 'fire protection, stock, or small farm pond', and other [53]. The NID lists the primary purpose and all other purposes of a given dam. This classification is dependent on the local, state, or federal employee tasked with recording or updating the dam information in the NID database, which is not always representative of the dam and reservoirs' function and can change over time as the NID is updated. The NID does not currently provide an archive of annual updates to the database. Multiple hydroelectric dams, including Grand Coulee, American Falls, and Tiber Dam, are not currently listed as having the purpose of 'Hydroelectric' in the NID despite their high production of electricity. This ambiguous categorization makes allocating evaporative consumption to different purposes difficult, not only because different uses do not necessarily have the same environmental impacts, but reported purposes are not necessarily consistent or all-inclusive.

Evaporation from reservoirs is also highly dependent on regional variables, so applying a single factor across the United States will likely overestimate consumption in some regions and underestimate in others. For example, applying a non-regional consumption factor (in terms of water volume per unit energy) in the Pacific Northwest will likely overestimate consumption because hydroelectric generation is large but evaporation is relatively low. Conversely, applying a non-regional factor in the Southwestern United States will underestimate consumption where evaporation from desert reservoirs is high. Similarly, applying a static value based on generation will reflect when hydropower generation is high (typically spring time), rather than when net evaporation is highest. To accurately understand how the water footprint of hydropower influences virtual water transfer estimates, evaporation from reservoirs needs to be estimated on a sub-annual scale based on regional characteristics.

2.2. The United States interconnections

The power grid in the contiguous United States is comprised of three grids: the Eastern Interconnection, the Western Interconnection, and ERCOT (Electric Reliability Council of Texas). The dividing line between the Eastern and Western Interconnections runs through the center of the country, just east of the Rocky Mountains, roughly. These grids have direct current (DC) ties that connect them, but transfers between them are limited. Transfers within these grids are managed by BAs, formerly referred to as Control Areas. BAs are entities responsible for balancing the supply and demand of electricity by managing generation and BA-to-BA transfers [54]. BAs vary in size, both in terms of generation/demand and geographical area, and have poorly defined boundaries with overlap, which makes mapping difficult [55]. According to Form EIA-930, there are currently 64 U.S. BAs, along with 7 Canadian BAs and 2 Mexican BAs tied to the U.S. grids [54]. Virtual water transfers with the Canadian and Mexican BAs are excluded from this study. The number of balancing authorities has varied over time, with 5 BAs retired since 2015 and 3 activated since 2017.

A review of 69 studies of the virtual water trade of energy (published between 2007 and 2021) found 61 articles that included electricity [30]. As previously alluded to, most were multi-year and single year studies, and only three focused on sub-annual timescales scale [31–33]. Additionally, most studies investigated virtual water for energy trade in China, and only 9 investigated virtual water transfers associated with energy trade in the United States [21–29]. Of these 9 studies, only 8 investigate virtual water for electricity trade and most focus on a limited region in the United States. Only one study investigates the network of virtual water transfers for electricity across the entire contiguous United States, and this analysis expands upon that work to investigate at a sub-annual timescale and include the impacts of hydropower generation.

3. Methods

Monthly blue and grey water footprints (m^3 of water) were calculated for each BA using power plant data from Form EIA-930 and EIA-860 and dam and reservoir data from the National Inventory of Dams (NID) [53, 56, 57]. Grey water footprints were calculated based on cooling water inlet and outlet temperatures to account for thermal pollution caused by thermoelectric power plants.

3.1. Data availability

Form EIA-923, 'Power Plant Operations Report', collects generator- and plant-level monthly fuel consumption and electricity generation data for plants with a total generator nameplate capacity of 1 MW or greater, along with monthly plant- or cooling-system level water usage data [56]. Form EIA-923 Schedule 8D collects water withdrawal, consumption, discharge, and diversion rates and volumes, along with average and maximum intake and discharge temperatures for 'thermoelectric power plants (organically fueled, nuclear, and combined-cycle) with a total steam capacity of 100 MW or greater' [58]. The Form-923 instructions define consumption as water evaporated in cooling towers or cooling ponds [58]. Discharge is defined as water that is returned to a natural body of water or to multi-use reservoir. The Form-923 Instructions include an appendix with diagrams clarifying these water usage definitions for each of the different cooling technologies [58].

Form EIA-860 'Schedule 2, Plant Data' provides power plant location data, including BA assignment beginning in 2013 [57] Prior to 2013, only NERC (North American Electric Reliability Corporation) region and ISO/RTO (independent system operator/regional transmission organization) Code were reported.

This analysis used the Penman–Monteith model to estimate monthly evapotranspiration volumes in hydropower [42]. The evapotranspiration rates are calculated using multiple inputs including wind speed, pressure, cloud cover fraction, solar radiation, and temperatures (air, wet bulb, and water). Reservoir data including primary purpose, all purposes, reservoir normal storage, and reservoir surface area can be found in the NID [53]. The NID is maintained by the U.S. Army Corps of Engineers in collaboration with the Federal Emergency Management Agency (FEMA) and state and federal dam regulatory agencies [59]. The NID was authorized by Congress in 1972 and first published in 1975. Federal and state dam agencies are now able to update these data in real-time, rather than annually. Grubert [60] provides a dataset linking NID dams with EIA power plants.

Beginning in July 2015, the U.S. Energy Information Administration began collecting hourly transfer data via Form EIA-930. Form EIA-930, 'Hourly and Daily Balancing Authority Operations Report', collects hourly electric system data from balancing authorities, including actual demand, net generation, and interchange between balancing authorities [54]. BA-to-BA transfer data were reported as-is by the EIA, and the cleaning process we used to handle discrepancies in reporting is outlined in section 4 of the supporting information.

3.2. Blue water footprint

The total blue water footprint (m^3 of water) is the sum of the reported thermoelectric footprint (with gaps filled by estimated values) and the estimated hydropower footprint (equation (1)),

$$\mathrm{BWF} = \mathrm{BWF}_{\mathrm{thermo}} + \mathrm{BWF}_{E,\mathrm{hydro}}. \tag{1}$$

The blue water footprint has two main components: the water consumed by thermoelectric power generation ($\mathrm{BWF}_{\mathrm{thermo}}$) and the water evaporated from hydroelectric reservoirs ($\mathrm{BWF}_{\mathrm{hydro}}$). The water consumed by thermoelectric power plants (reported blue water footprint, $\mathrm{BWF}_{\mathrm{R,thermo}}$) is reported in EIA-923 for plants with a total steam capacity of greater than or equal to 100 MW. Thermoelectric water consumption was also estimated based on water use factors from literature (estimated blue water footprint, $\mathrm{BWF}_{\mathrm{E,thermo}}$). These estimated values were used to fill gaps in the reported data and to quantify uncertainty in the thermoelectric water footprint data ($\mathrm{BWF}_{\mathrm{thermo}}$).

The blue water footprints of hydroelectric power generation ($\mathrm{BWF}_{\mathrm{E,hydro}}$) were estimated based on regional net evaporation rate estimates from Grubert [42, 60]. The Penman–Monteith model [42] uses climate and land cover data to estimate evapotranspiration for 20 regions. This model was similarly applied to estimate hydropower water consumption by eGrid region [61]. We linked EIA hydropower plants with NID data using the dataset provided in Grubert [60]. Reservoir storage and surface area from the NID were used with the Penman–Monteith evapotranspiration rates to calculate monthly water consumption for each BA. Net consumption was calculated for two allocation scenarios: primary purpose hydroelectric dams and all hydroelectric dams. These scenarios were used as minimum and maximum blue water consumption estimates.

The primary purpose hydroelectric scenario only estimates evaporative consumption for dams listed in the NID as having a primary purpose of 'Hydroelectric'. Therefore, only evaporation from reservoirs listed as having a primary purpose of 'Hydroelectric' is attributed to hydropower generation. These values were used as minimum estimates. However, this method may exclude impacts of major reservoirs based on somewhat arbitrary labeling. For example, Grand Coulee Dam, the largest hydropower facility in the United States, is currently listed as having a primary purpose of 'Flood Risk Reduction' and other purposes as 'Irrigation'. If reported purposes were exclusively considered, evaporation related to Grand Coulee Dam would be completely ignored. To acknowledge this data shortcoming, we also estimated consumption for all hydropower dams that are reported in Form EIA-923, have an associated NID ID listed in Grubert [60], and report reservoir surface area and normal storage in the NID database.

Although the region-based consumption estimates based on Grubert [42] were used to quantify the minimum, maximum, and average water footprints in this analysis, three other methods were used to calculate hydropower consumption for comparison purposes. A spreadsheet comparing these values (monthly BA hydropower water footprint) is included in the supplementary data.

(a) Hydroelectric water withdrawal and consumption was estimated based on average, minimum, and maximum gross evaporation factors from Macknick *et al* [49].
(b) Hydroelectric water consumption was estimated based on the water consumption factors (in net m^3 GJ^{-1}) for 'primary purpose allocation', 'economic valuation 1', and 'all to hydro' allocation schemes from Grubert [42].
(c) Life-cycle water consumption factors for hydroelectric power from Grubert and Sanders [62] were also applied for comparison purposes.

These three methods have their own drawbacks. Gross evaporation factors overestimate consumption by failing to account for evapotranspiration pre-inundation, and the Macknick *et al* [49] hydropower factors are based on a small sample size and dated references. Applying a single factor spatially and temporally will overestimate consumption in most regions and underestimate in some warmer regions. A comparison of the impact of using regional monthly factors, static factors, and excluding hydropower on total blue virtual water transfers is provided in section 5 of the supporting information.

3.3. Grey water footprint

The grey water footprint is included in addition to the blue water footprint to account for the burden of thermal pollution. While the blue water footprint accounts for water consumption that is 'virtually' removed from the region by the transfer of electricity, the grey water footprint accounts for the negative impacts of water withdrawal that are not represented by a consumptive blue water footprint. The reported grey water footprint (GWF_R; (m^3 of water)) was calculated based on state thermal pollution regulations and water discharge volumes reported in EIA-923 (WD_R) for thermoelectric power plants with a total steam capacity of 100 MW or greater. Smaller power plants are excluded from the analysis because intake and effluent temperatures are not reported in EIA Form-923. Grey water calculations were based on equations and state and plant-level thermal regulations from Chini *et al* [25] shown in equations (2) and (3) [46].

$$\mathrm{GW}_{\mathrm{absolute}} = \mathrm{WD}_R \times \left(\frac{T_{\mathrm{effl}} - T_{\mathrm{amb}}}{T_{\mathrm{allow}} - T_{\mathrm{amb}}} \right) \tag{2}$$

$$\mathrm{GW}_{\mathrm{change}} = \mathrm{WD}_R \times \left(\frac{T_{\mathrm{effl}} - T_{\mathrm{amb}}}{T_{\mathrm{allow}}} \right). \tag{3}$$

The ambient water temperature, T_{amb}, and the effluent water temperature, T_{effl}, are the average intake and discharge temperatures (° F), respectively, reported in EIA-860. The allowable temperature, T_{allow}, is the allowable temperature change or absolute temperature maximum regulated on the state level by the Clean Water Act. The denominator is the maximum acceptable temperature increase [46], which is defined by T_{allow} for change laws and by the difference between T_{allow} and T_{amb} for absolute temperature limit laws. For absolute temperature laws, in scenarios where T_{amb} was greater than T_{allow}, a denominator of 5° F was used [25, 46].

3.4. Virtual water transfers

The blue water content (m^3 of water MWh^{-1}), BWC, of a BA is equal to the sum of the blue water footprint of each power plant within the BA divided by the total electricity generation in the BA (equation (4)). Blue water content factors were calculated for each BA on a monthly scale. Grey water content (m^3 of water MWh^{-1}), GWC, was calculated using the same process (equation (5)),

$$\mathrm{BWC}_{i,m} = \frac{\sum^n \mathrm{BWF}_m}{\sum^n P_m} \tag{4}$$

$$\mathrm{GWC}_{i,m} = \frac{\sum^n \mathrm{GWF}_m}{\sum^n P_m}. \tag{5}$$

Generation (MWh) is denoted by P, m is the month, and n is the number of power plants in BA i. Hourly electricity data are reported in EIA-930 between 169 BA pairs, making 333 directed network links. The data cleaning process created an upper and lower transfer value (in MWh) for each pair and hour (detailed in section 4 of the supporting information) to impose an energy balance where values were unequal. The hourly electricity data between BAs were then aggregated to the monthly scale. The upper, lower, and average values were used to calculate monthly transfers between balancing authorities along with quantifying the uncertainty of the electricity transfer data. Virtual water transfers (m^3 of water) from an exporting BA (BA_e) to an importing BA (BA_i) ($VW_{e,i}$) are calculated by multiplying the monthly electricity transfers from BA_e to BA_i by the water content of BA_e (WC_e) (equation (6)).

$$\mathrm{VW}_{\mathrm{e,i}} = E_{\mathrm{e,i}} \times \mathrm{WC}_{\mathrm{e}}. \tag{6}$$

4. Results

4.1. Seasonality of virtual water transfers

Although the time frame of our analysis (2016–2021) is limited by the availability of hourly electricity transfer data from Form EIA-930, the seasonal variability of virtual water transfers can be seen in figures 2 and 3. Total virtual blue water transfers are dominated by hydropower generation and peak around November, when evapotranspiration is highest [60]. Virtual grey water transfers peak in the summer months between July and September. A previous study identified the winter peak in intra-annual grey water footprint to be a result of a more pronounced difference between ambient water temperature and effluent water temperature [34]. We deduce that the peaks in virtual water transfers are influenced by evaporation rates from hydropower reservoirs and electricity demand in response to ambient temperatures (i.e., heating and cooling).

We quantified uncertainty for virtual blue water transfers based on the BA-to-BA electricity interchange data and thermoelectric and hydroelectric power plant water consumption estimates. As described in section 3, for each hour and connected BA pair, an upper, lower, and average electricity interchange quantity was determined, and aggregated to a monthly timescale. The uncertainty from transfer data is represented by the shaded orange region in figure 2. The upper dashed orange line represents the virtual blue water transfer estimate based on the maximum electricity interchange quantities and the average blue water factors, while the lower dashed orange line represents the virtual blue water estimate based on the minimum electricity interchange quantities and the average blue water factors. Similarly, the shaded blue region represents the uncertainty quantified based on gaps in the reported thermoelectric water consumption data and uncertainty around hydroelectric consumption estimates. The upper and lower blue dashed lines represent virtual blue water transfers estimated based on maximum and minimum blue water footprint factors and average electricity interchange values. The black dotted lines show the upper/lower limits calculated with the maximum/minimum electricity interchange quantities and maximum/minimum blue water factors.

The total virtual blue water transfers are dominated by hydropower generation, particularly in the Southwestern United States. The water footprint of hydroelectric generation is less dominant in the Eastern United States. Figures S12 and S13 in the supporting information illustrate the differences in seasonality in virtual water exports from BAs in the Eastern and Western Interconnections. Including hydropower blue water footprints increased the total volume of virtual blue water transfers by an average of 72% and shifted the peak from late summer to late autumn. To illustrate the impact of including hydropower blue water footprints in calculations, we show blue water footprint factors for thermoelectric generation only in purple; see figure 2. The upper/lower purple dashed lines represent virtual blue water transfers estimated based on maximum/minimum electricity transfer values and maximum/minimum blue water footprint factors based on thermoelectric power plants only; the solid line represents the product of the averages.

For virtual grey water transfers, uncertainty was quantified based on the BA-to-BA electricity interchange data. Similar to the virtual blue water transfers, the upper and lower dashed grey lines in figure 3 denote total virtual grey water transfers based on maximum and minimum electricity interchange values and grey water footprint factors. While there is additional uncertainty surrounding the grey water footprint calculation, it is difficult to quantify. It should also be noted that due to data limitations, the grey water footprint is likely underestimated, as Form EIA-923 only provides average monthly inlet and outlet temperatures and these temperatures are not reported for all power plants. Further discussion on uncertainty is provided in section 5.

Total annual average virtual blue water transfer volume varies from a minimum of 1.72 km^3 in 2016 to a maximum of 2.13 km^3 in 2021. The total annual virtual blue water transfers increased by an average of 3% as a result of filling gaps in the reported thermoelectric water consumption data with estimated values. Total annual average virtual grey water transfer volumes are notably larger, varying from a minimum of 20.9 km^3 in 2021 to a maximum of 25.71 km^3 in 2016. Average total monthly transfers are provided in table 1.

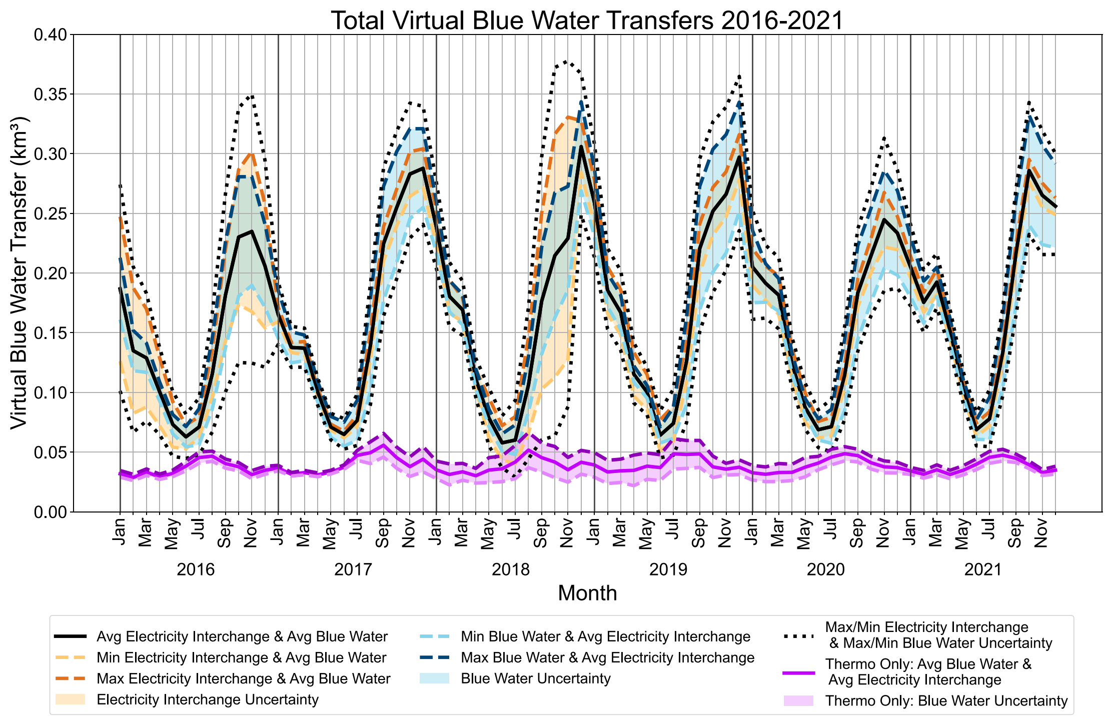

Figure 2. Total virtual blue water transfers on the contiguous United States electric grid between 2016 and 2021. The center solid black line represents the average virtual blue water transfers in cubic meters. The orange lines represent uncertainty based on electricity interchange data. The blue lines represent uncertainty based on blue water footprints for thermoelectric generation cooling and hydropower reservoir evaporation. The purple lines represent average total virtual water transfers and uncertainty based on blue water footprints for thermoelectric generation cooling only.

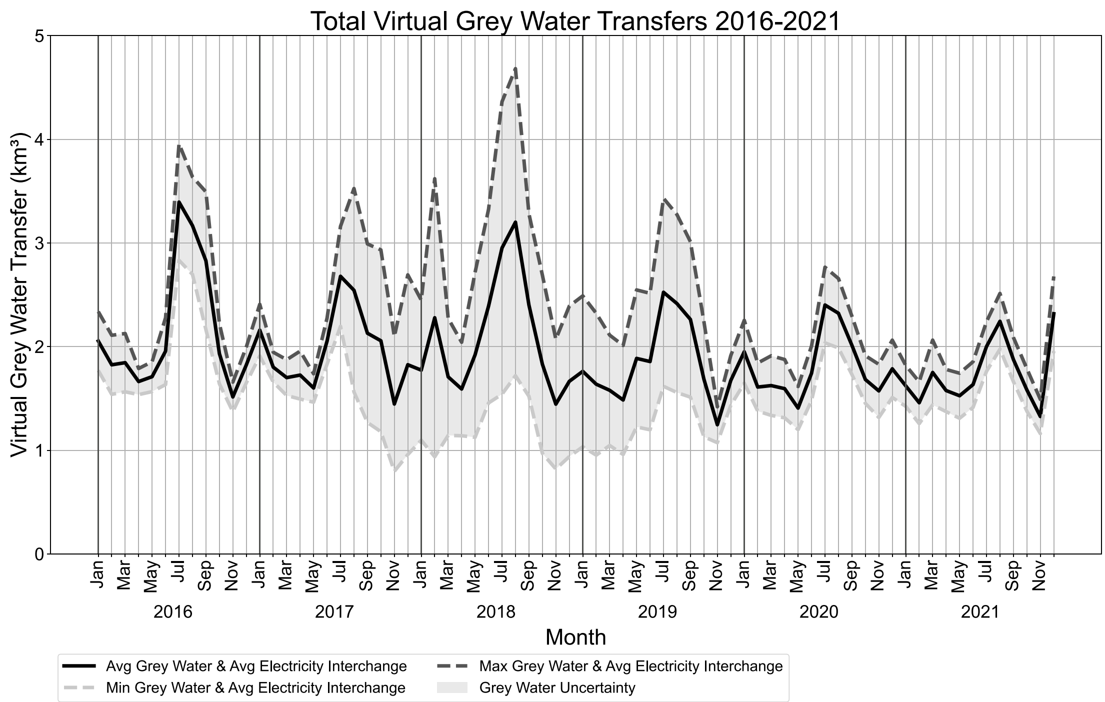

Figure 3. Total virtual grey water transfers on the contiguous United States electric grid between 2016 and 2021. The center solid line represents the average virtual grey water transfers in cubic meters. The upper and lower dashed lines represent maximum and minimum grey water transfers based on uncertainty from hourly BA-to-BA electricity interchange.

4.2. Spatial variability of virtual water transfers

In addition to monthly and annual variability, blue and grey virtual water transfers vary spatially. Figure 4 illustrates the network of net virtual blue and grey water transfers for the months with maximum and

Table 1. Monthly average (minimum and maximum) total blue and grey water transfers from 2016 to 2021 for the overall electric grid.

Month	Total blue water transfers (km^3) Average (Min–Max)	Total grey water transfers (km^3) Average (Min–Max)
January	0.21 (0.17–0.26)	1.89 (1.62–2.16)
February	0.17 (0.13–0.19)	1.77 (1.46–2.28)
March	0.16 (0.13–0.19)	1.70 (1.58–1.85)
April	0.12 (0.10–0.15)	1.61 (1.49–1.73)
May	0.09 (0.07–0.10)	1.68 (1.41–1.92)
June	0.06 (0.06–0.07)	1.94 (1.63–2.39)
July	0.07 (0.06–0.08)	2.66 (2.00–3.39)
August	0.12 (0.11–0.14)	2.65 (2.24–3.20)
September	0.20 (0.18–0.22)	2.25 (1.88–2.83)
October	0.24 (0.21–0.29)	1.80 (1.58–2.06)
November	0.25 (0.23–0.28)	1.43 (1.25–1.57)
December	0.26 (0.21–0.31)	1.85 (1.67–2.32)

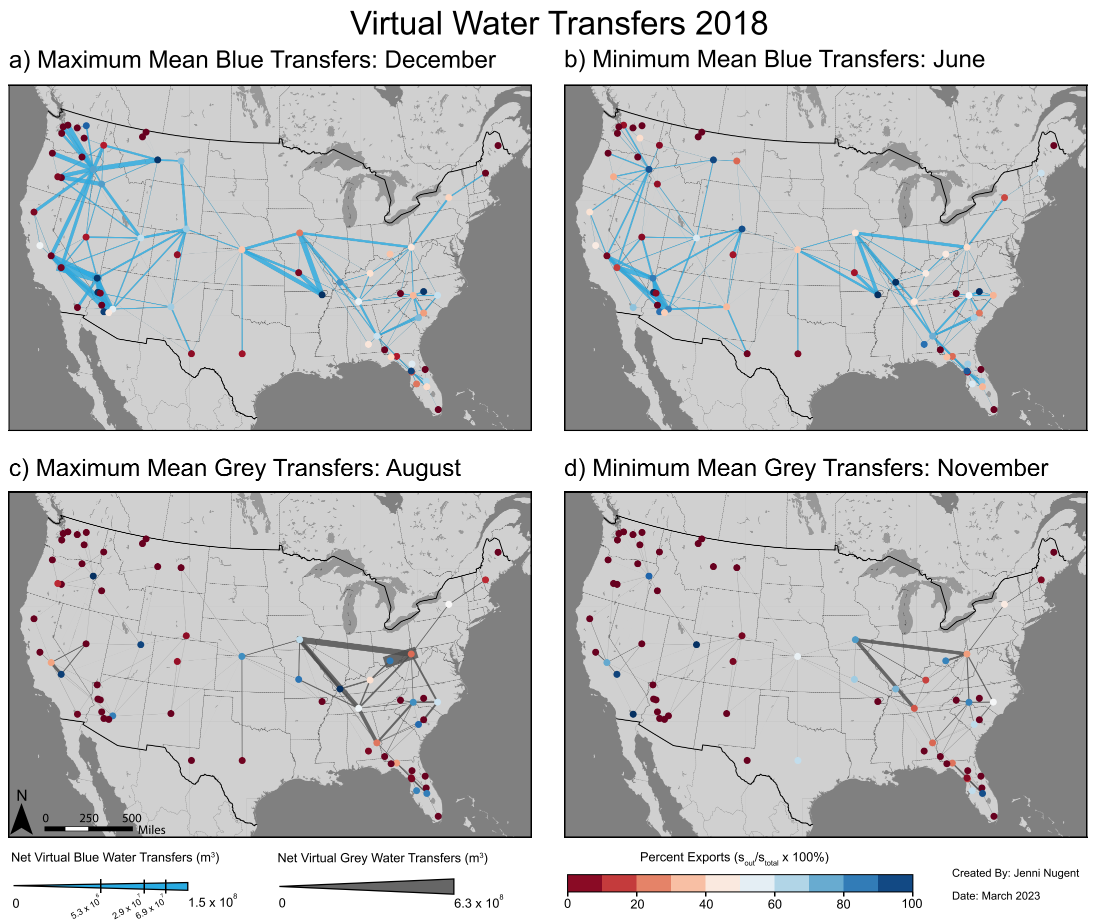

Figure 4. Map of net blue and grey virtual water transfers in the contiguous United States. The nodes of these maps represent the geographical centroid of the balancing authorities, and the thickness of the connecting lines represent the volume of net virtual water transfers between BAs. The color of the node is the percent exported. A blue node indicates that the BA is primarily exporting virtual water, while a red node indicates the BA is primarily importing virtual water. Panels *a* and *b* illustrate the months with the highest and lowest total blue virtual water transfers in 2018. Panels *c* and *d* illustrate the months with the highest and lowest total grey virtual water transfers in 2018.

minimum total virtual water transfers in 2018. The maps of blue and grey virtual water transfers (in both PDF and GIF formats to showcase changes over time) for all months from 2016 to 2021 are provided in the Supporting Data. The nodes of these maps represent the geographical centroid of the balancing authorities. The thickness of the lines represents the magnitude of net virtual water transfers (the difference between imports and exports) between balancing authorities. In network terms, imports are the strength in (s_{in}), and exports are the strength out (s_{out}) of the BA. The color of the nodes represents the ratio of exports to the total

Table 2. Top virtual blue water exported by region.

Export region	Origin BA	Recipients of net blue water exports	Average annual net transfers (m^3)
Southwest	WALC	California (LDWP, CISO, IID)	$7.24 \times 10^{+08}$
		Arizona (SRP, TEPC, AZPS, GRIF)	$2.26 \times 10^{+08}$
		Nevada (NEVP)	$4.32 \times 10^{+07}$
	AZPS	California (CISO, LDWP, IID)	$2.63 \times 10^{+07}$
		Southwest/California (WALC)	$1.49 \times 10^{+07}$
		Arizona (TEPC, SRP, GRMA)	$1.01 \times 10^{+07}$
		New Mexico (PNM)	$3.15 \times 10^{+06}$
		Central Rockies (WACM)	$1.54 \times 10^{+04}$
	SRP	Arizona (AZPS, TEPC, HGMA, DEAA)	$4.85 \times 10^{+07}$
		California (CISO)	$4.17 \times 10^{+07}$
Pacific Northwest	BPAT	PNW (PSEI, PGE, PACW, AVA, SCL, TPWR, GCPD, IPCO, GRID, NWMT, AVRN, CHPD, DOPD)	$1.11 \times 10^{+08}$
		California (CISO, LDWP, BANC)	$6.41 \times 10^{+07}$
		Nevada (NEVP)	$1.23 \times 10^{+06}$
	NWMT	PNW (BPAT, AVA, IPCO, GWA, WWA)	$4.57 \times 10^{+07}$
		Upper Great Plains (WAUW)	$3.06 \times 10^{+06}$
		Central Rockies (PACE)	$4.07 \times 10^{+06}$
	WACM	Central Rockies (PSCO, PACE)	$2.23 \times 10^{+07}$
		Southwest/California (WALC)	$7.55 \times 10^{+06}$
		Southwest (AZPS, PNM)	$4.65 \times 10^{+06}$
		Central Plains (SWPP, WAUW)	$3.34 \times 10^{+05}$
Eastern	SPA	Midwest (MISO, AECI)	$1.30 \times 10^{+08}$
		Central Plains (SWPP)	$5.02 \times 10^{+07}$
	PJM	Midwest (MISO)	$2.97 \times 10^{+07}$
		New York (NYIS)	$1.09 \times 10^{+07}$
		The Carolinas (CPLW, CPLE, DUK)	$1.86 \times 10^{+06}$
		Central Appalachia (LGEE, TVA, OVEC)	$1.66 \times 10^{+05}$
	SOCO	The Carolinas (SCEG, SC, DUK)	$1.19 \times 10^{+07}$
		Florida (FPC, TAL, FPL)	$9.70 \times 10^{+06}$
		Midwest (MISO)	$6.14 \times 10^{+06}$
		South (AEC, SEPA)	$3.00 \times 10^{+05}$
		Tennessee (TVA)	$1.60 \times 10^{+04}$
	TVA	Appalachia/Mid-Atlantic (PJM, LGEE)	$8.07 \times 10^{+06}$
		South (SOCO)	$6.10 \times 10^{+06}$
		Carolinas (DUK, CPLW)	$1.47 \times 10^{+06}$
		Midwest (EEI)	$2.02 \times 10^{+05}$
	MISO	Central Appalachia (TVA, LGEE)	$2.04 \times 10^{+07}$
		Mid-Atlantic (PJM)	$8.09 \times 10^{+06}$
		South (AEC, SOCO)	$8.92 \times 10^{+04}$
		Midwest (EEI, GLHB, AECI)	$2.44 \times 10^{+05}$

volume of exports and imports for a given BA ($s_{out}/s_{total} \times 100\%$). A blue node indicates that the BA is primarily exporting virtual water, while a red node indicates the BA is primarily importing virtual water.

Virtual blue water transfers are largest in the Western United States in late autumn due to hydroelectric power generation. Transfers out of the Southwest, due to both evaporation from hydropower reservoirs and large net electricity interchange, are notably larger than all other transfers. For visualization purposes, the width of the lines representing virtual blue water transfers are scaled logarithmically. Maps of virtual blue water transfers for all months from 2016 to 2021 are provided in the supporting data with the width of the links scaled both linearly and logarithmically. Virtual grey water transfers dominate in the Eastern Interconnection where once-through cooling systems are more common at thermoelectric power plants. Figure S11 in the Supporting Information shows a comparison between net electricity transfers and net virtual blue and grey water transfers between balancing authorities.

Table 3. Top virtual grey water exported by region.

Export Region	Origin BA	Recipients of net grey water exports	Average annual net transfers (m^3)
Eastern	PJM	Midwest (MISO)	$2.26 \times 10^{+09}$
		New York (NYIS)	$8.69 \times 10^{+08}$
		Carolinas (DUK, CPLW, CPLE)	$1.13 \times 10^{+08}$
		Central Appalachia (LGEE, TVA)	$3.50 \times 10^{+07}$
	MISO	Central Appalachia (TVA, LGEE)	$1.64 \times 10^{+09}$
		Mid-Atlantic (PJM)	$7.45 \times 10^{+08}$
		Midwest (EEI, GLHB, AECI)	$2.43 \times 10^{+07}$
		Central Plains (SWPP, SPA)	$2.38 \times 10^{+07}$
		South (AEC, SOCO)	$1.82 \times 10^{+07}$
Carolinas	DUK	South (SOCO, SEPA)	$1.15 \times 10^{+09}$
		Carolinas (CPLE, CPLW, SCEG, SC, YAD)	$9.50 \times 10^{+08}$
		Appalachia/Mid-Atlanticv (PJM, TVA)	$5.77 \times 10^{+08}$
	CPLE	Carolinas (DUK, SCEG, SC, YAD)	$8.72 \times 10^{+08}$
		Mid-Atlantic (PJM)	$6.02 \times 10^{+08}$
	SCEG	Carolinas (DUK, CPLE, SC)	$1.37 \times 10^{+09}$
		South (SEPA)	$3.97 \times 10^{+07}$
West	LDWP	California (CISO)	$7.80 \times 10^{+08}$
		Nevada (NEVP)	$4.26 \times 10^{+08}$
		Rocky Mountains (PACE)	$4.73 \times 10^{+07}$
		Southwest (WALC, AZPS)	$2.67 \times 10^{+06}$
		PNW (BPAT)	$8.61 \times 10^{+05}$

4.3. Virtual water transfers in the Western Interconnection

Top exporters of virtual blue and grey water are reported in tables 2 and 3, respectively. Exporting BAs are grouped by region and include recipient BAs and average net annual transfers from 2016–2021. The monthly net virtual water transfers between BA-to-BA pairs and aggregated by BA are provided in the supplementary data, along with monthly BA data and a list of BA names. The volume of net virtual water trade and the trade partners varies both monthly and annually. There is not a direct connection between the geographic size of the BA and the virtual water transfer in and out, as it depends on the generation and demand, which are constantly affected by a number of factors, including weather and price of electricity by fuel.

4.3.1. Southwestern United States

In the Western Interconnection, the centers of major net virtual blue water transfers are in Arizona and the Pacific Northwest where hydropower generation is prevalent. The Western Area Power Administration (Desert Southwest Region; WALC), Arizona Public Service Company (AZPS), and Salt River Project (SRP) are central to much of the virtual blue water exports in the Southwest. These large net exports of virtual blue water out of Arizona have large implications for water management in the lower Colorado River Basin. The BA with the highest blue water footprint factors (m^3 of blue water/MWh) is WALC, which geographically covers most of Arizona, a section of Northern California, and some of the bordering regions of Arizona in California, Nevada, Utah, and New Mexico. WALC transfers large volumes of virtual blue water to BAs in California, as well as transfers to Arizona and Nevada. WALC includes both Glen Canyon Dam and Hoover Dam on the Colorado River, as well as Davis Dam and Parker Dam. Other notable dams in WALC are Shasta Dam and Folsom Dam in northern California. WALC also includes the coal-powered Apache Generating Station east of Tucson, Arizona.

Other large exporters of virtual blue water in the Southwestern United States are AZPS and SRP in Arizona. AZPS transfers virtual blue water to BAs in California, within Arizona, New Mexico, WALC (the Southwest and California), and the central Rocky Mountains. The large net virtual water transfers out of AZPS are partially due to it being one of the largest net exporters of electricity. The largest power plant in AZPS is the coal-fired Four Corners Generating Station located in the Navajo Nation, which withdraws fresh surface water for its cooling towers. AZPS large power plants include the West Phoenix natural gas plant and the coal-fired Cholla power plant that pump fresh groundwater for their cooling towers. Cholla has the largest average annual blue water footprint factor of the three plants (160% greater than West Phoenix and 50% greater than Four Corners).

The largest electricity generator and water consumer in the SRP BA is the Palo Verde Nuclear Generating Station west of Phoenix, Arizona. The second largest power plant in the SRP was the coal-fired Navajo

Generating Station in the Navajo Nation near Page, Arizona, which closed in 2019 [63]. SRP exports large quantities of virtual blue water to California, as well as within Arizona. Regions surrounding Phoenix, Arizona have large thermoelectric cooling water consumption [64]. In addition to physical water transfers to California via the Colorado River Aqueduct, the All-American Canal, and the Coachella Valley Canal, the Southwest (particularly Arizona) transfers large volumes of virtual water to California through electricity transfers. The Colorado River Basin also exports large volumes of embedded water through the export of irrigated agricultural products [65, 66].

In the Western United States, the most notable grey water exports can be seen from the Los Angeles Department of Water and Power (LDWP). The LDWP exports large quantities of grey virtual water within California, and to Nevada, the Pacific Northwest, the Rocky Mountains, and the Southwest. As noted by Peer and Sanders [64], the California coast is the only region in the West that has once-through cooling for thermoelectric power generation.

4.3.2. Pacific Northwest

The Pacific Northwest (PNW) is reliant on large quantities of hydropower. Bonneville Power Administration (BPAT) is responsible for some of the highest net virtual blue water transfers annually, with transfers within the PNW, as well as to BAs in California and Nevada. This high blue water transfer is a result of BPAT having the highest net electricity transfers of any BA and having a large blue water footprint factor due to hydropower generation, though the PNW has lower evaporation rates than the Southwest [60]. BPAT's largest generators are Grand Coulee Dam and Chief Joseph Dam in Washington. The blue water footprint for hydropower is calculated based on evaporation rates and reservoir surface area; the power stations with the largest calculated blue water footprints in BPAT are the Albeni Falls Dam, Grand Coulee Dam, Libby Dam, McNary Dam, and Hungry Horse Dam. Columbia Nuclear Generating Station also produces large quantities of electricity at the expense of large volumes of water for BPAT.

Other PNW balancing authorities with large virtual blue water transfers include NorthWestern Corporation (NWMT) and Idaho Power Company (IPCO). NWMT also has several hydropower dams, but its largest generators are coal- and natural gas-fired power plants. NWMT's largest net virtual blue water transfers are to the PNW, as well as the upper Great Plains and the Central Rocky Mountains. IPCO transfers virtual blue water to the PNW and Nevada. Large hydropower dams in IPCO include American Falls Dam, Cascade Dam, Brownlee Dam, and C J Strike Dam.

Other top virtual blue water net exporters in the West include Western Area Power Administration (Rocky Mountain Region; WACM), PacifiCorp East in the central Rocky Mountain region (PACE), and Western Area Power Administration (Upper Great Plains West; WAUW). WACM transfers virtual blue water to the central Rocky Mountains, the Southwest, the Central Plains, and California. PACE transfers virtual blue water to the Northwest, Arizona, Nevada, and California. WAUW transfers net virtual blue water to the Central Rocky Mountains, Central Plains, and Northwest.

4.4. Virtual water transfers in the Eastern Interconnection

In the Eastern Interconnection, net virtual blue water exports are most notable from Southwestern Power Administration (SPA), PJM Interconnection (named for Pennsylvania-New Jersey-Maryland, though it now includes regions of 13 states), Southern Company Services (SOCO), Tennessee Valley Authority (TVA), and Midcontinent Independent System Operator (MISO). SOCO, PJM, TVA, and MISO are all top net exporters of electricity. The SPA is a small BA in the south-central region of the United States in parts of Arkansas, Oklahoma, and Missouri. SPA is consistently in the top three exporters of virtual blue water. This blue water footprint is a result of several hydropower dams, including the Bull Shoals Dam in Arkansas and the Eufaula Dam in Oklahoma.

PJM and MISO are both geographically large balancing authorities with a large number of generators. Water consumption for electricity generation is distributed across PJM and MISO, with the regions of greatest thermoelectric water consumption in Chicago and along the Ohio River [64]. Destinations of net virtual blue water transfers from PJM vary more month-to-month than other BAs, and include the Midwest, New York, the Carolinas, and Central Appalachia. PJM includes several nuclear power plants in Illinois, Ohio, and Pennsylvania that have large blue water footprints. PJM also includes several fossil fuel-fired power plants and hydropower plants. Net exports from MISO vary monthly and annually, and include Central Appalachia and the Mid-Atlantic, the South, the Midwest, and Central Plains (SWPP).

SOCO is a BA that covers most of Georgia, Alabama, and part of Mississippi. SOCO exports virtual water to the Carolinas, the surrounding South, the Midwest, Florida, and Tennessee. TVA exports to Appalachia and Mid-Atlantic, the South, Carolinas, and the Midwest. TVA includes large nuclear power plants such as Watts Bar Nuclear Plant, Sequoyah, and Browns Ferry. There are also several hydropower dams, but these have lower consumption than reservoirs in other regions due to lower regional evaporation rates.

Virtual grey water transfers are most prominent in the Eastern United States, most notably in the Midwest, Mid-Atlantic, and the Carolinas. Not only is thermoelectric power generation more prevalent in the Eastern Interconnection, once-through cooling systems are much more common at the older power plants in the East that have historically had more access to surface water than their Western counterparts [64]. These virtual grey water transfers peak across the country in the summer months when temperatures and electricity demand are highest. Water withdrawals in MISO are greatest along the Mississippi River and around Illinois along the Illinois and Ohio Rivers; in PJM, water withdrawals are notable at the southern part of Lake Michigan, along the Ohio River, and along the Atlantic Coast [64]. PJM and MISO both have large net electricity transfers and much of their electricity is generated by large nuclear, coal, or natural gas power plants with once-through cooling systems. Importers of net virtual grey water from PJM vary monthly and annually. PJM exports net virtual grey water to MISO, New York, the Carolinas and Central Appalachia, while MISO exports net virtual grey water to Central Appalachia and Mid-Atlantic, the South, the Midwest, and Central Plains.

The Carolinas also have large net virtual grey water transfers from Duke Energy Carolinas (DUK), Duke Energy Progress East (CPLE), and South Carolina Electric & Gas Company (SCEG). DUK and CPLE have particularly large GWF_R factors. The Carolinas have six geographically overlapping BAs (CPLE, CPLW, DUK, SC, SCEG, YAD), and the virtual grey water transfers are mainly between themselves. DUK's net virtual grey water transfers mainly stay within the Carolinas, but it also exports to surrounding regions to Appalachia and the South. CPLE exports net virtual grey water within the Carolinas region, as well as to PJM. SCEG exports net virtual grey water to the Carolinas, and the Southeast. The grey water footprint in these BAs is mainly produced by nuclear and coal-fired power plants.

5. Discussion

5.1. Major implications of blue and grey virtual water transfers

Studies on the impact of energy systems and water stress in the United States found water stress to be most prevalent in the Western area of the country, and most extreme in the High Plains and Southeast Arizona [9, 21, 24, 27, 29, 67]. This already-arid region is further stressed by public water demand in population centers, irrigation of farmland, and evaporation from reservoirs [7, 67]. Furthermore, the water stress impact of power plants varies seasonally, with most regions having the largest impact in the summer [9]. Previous studies have investigated the virtual water transfers associated with electricity transfers in the Colorado River Basin and Western U.S. states, but they have ignored the impact of hydropower [21, 27, 29]. Balancing authorities in the Southwest exported an annual average of 0.84 km^3 of water to neighboring states, the equivalent water for 6.4 million people (assuming 360 L/person/day). With limited electricity transfer between interconnections, the impacts of virtual water transfers mainly impact the sub-regions within the larger interconnections. Virtual water flows across transmission lines with greater ease than physical water in pipes, which increases the distance of these impacts.

Blue and grey water footprints change in response to water availability and water temperatures [17, 68]. Power plant curtailments and shutdowns have increased in recent years due to water availability [69, 70]. Decreases in hydroelectric capacity can shift the generation burden to thermoelectric power plants, if renewable energy supplies or storage are not available. The EIA reported that generation from hydropower plants in California was 48% below the 10-year average in 2021 [71]. The decrease in hydropower generation in California was replaced with increased natural gas generation and electricity imports from other regions [72, 73]. Thermoelectric power plant capacity and reliability can be threatened by several factors, including insufficient cooling water volumes, water temperatures too high to efficiently cool, and water temperatures too high to legally release effluent into surrounding water bodies. For thermoelectric plants in the United States, one study estimated a decrease in generation of 4.4%–16% for summers in 2031–2060 [17]. Another study estimated a worldwide capacity reduction of 61%–74% for hydropower plants and 81%–86% for thermoelectric power for 2040–2069 [12].

There are reliability concerns for regions with high blue water footprints as water availability concerns are exacerbated by climate change. Thermoelectric power plants may be able to supplement or switch cooling technologies to adapt to growing water scarcity. However, regions dependent on hydropower may be threatened by decreased snowpack in mountains and falling streamflow and reservoir levels. In 2021, the Hyatt Power Plant at Lake Oroville in California went offline for the first time due to low reservoir levels [70]. This decline in hydropower is particularly a concern in the Southwest, where hydropower reservoirs reached historic lows in the summer of 2022 [74, 75]. In this analysis, we found that the Southwest and Pacific Northwest export large volumes of virtual blue water to surrounding regions as a result of the large water footprint of hydropower generation and high electricity transfers. This condition can present reliability concerns if hydropower generation is threatened by water scarcity.

Water availability and temperature concerns are also significant in regions dependent on nuclear power. PJM included 19 nuclear power plants in 2016, and 17 by 2021 following the decommissioning of two of the lowest generating plants (Three Mile Island Nuclear Generating Station and Oyster Creek Nuclear Power Station). Nuclear power plants have the largest thermoelectric blue water footprints and often use natural draft cooling towers or once-through systems. The Byron Nuclear Generating Station (in the top four largest generators in PJM from 2016–2021) and the Dresden Nuclear Power Station (consistently in the top 10–20 generators in PJM) were both scheduled to shutdown at the end of 2021; however, the Illinois Senate passed the Climate and Equitable Jobs Act (CEJA; Public Act 102-0662) approving $694 million in subsidies over 5 years to keep the plants open [76]. The power plants with the highest net generation in MISO are primarily coal and nuclear power plants. The changing fuel mix of the grid, through decommissioning nuclear and coal-fired power plants, affects large electricity generators and large water users. Both PJM and MISO are large balancing authorities that serve a combined 110 million people, and rely on large quantities of coal and nuclear power in addition to natural gas [77–80]. As our results show, PJM and MISO are connected to many of the balancing authorities in the East, and any changes in reliability in those BAs could have far-reaching implications.

In addition to the reliability concerns associated with cooling water source availability and temperature, the Eastern United States also has to contend with the negative environmental impacts of releasing elevated-temperature water into water bodies. While studies have shown most once-through plants in the United States are located in regions where freshwater is typically abundant for cooling [9], this water abundance does not capture the harmful impacts of thermal pollution on the ecosystem. Not only can temperature directly harm or kill aquatic organisms, higher temperatures also decrease dissolved oxygen and exacerbate the effects of chemical pollution [81, 82]. Thermal pollution from thermoelectric power plants is one way humans impact water temperatures, in addition to physical alterations (e.g., dams, diversions, channelization) and land-use changes (e.g., urbanization, deforestation). Human impacts more often increase river temperatures, and aquatic organisms, particularly fish, are more sensitive to temperatures above their thermal optima [83]. Watersheds with the greatest potential biodiversity risk resulting from once-through cooling systems are in the Southeastern and Midwestern United States [84]. Water temperature issues threaten thermoelectric generation and grid operations, particularly in regions with high grey water footprints, which could affect regions importing large quantities of virtual grey water.

The large summer peak and smaller winter peak in total virtual grey water transfers shown in figure 3 are in part fueled by heating and cooling demands, which will be impacted by changing weather patterns and extremes due to climate change and end-use electricity demands. Heat waves increase air conditioning demand and subsequently electricity demand, causing states to set record breaking power demands and balancing authorities to alert customers to conserve energy to prevent outages [85, 86]. The winter peak in electricity demand will likely also grow with widespread electrification of heating [87, 88]. If electricity demand is met with thermoelectric power generation that releases cooling water effluent to the environment, then the winter peak in grey water transfers might also grow. As society moves towards electrification of more sectors, including residential and transportation, electricity consumption will increase [89], and generation capacity and energy storage will need to keep pace. Depending on what fuels and cooling technologies are implemented, this transition could impact regional water availability and quality.

The retirement of fossil fuel power plants will change the blue and grey water footprints of electricity in the future [19, 90]. One study estimated that between 2018 and 2035, 50% of the fossil fuel-fired power plants would retire, reducing water withdrawals by 85% and water consumption by 68% [19]. The energy transition will likely reduce water use, but by how much and where will depend on the fuels and technologies implemented to replace the loss in generation from fossil-fuel power plants. Therefore, virtual water impacts on the grid due to the location of shutdowns and new plants, new fuels, and new transmissions lines are difficult to predict.

The virtual water transfers, both blue and grey, shown in this analysis illustrate the burden shift of electricity between regions that consume electricity and those that produce it [91, 92]. This burden shift has equity implications because power plants are often located in rural and/or low-income areas. Historic red-lining (racial discriminatory housing policies) led to higher likelihoods of fossil fuel power plant siting in minority neighborhoods [93]. Not only do fossil fuel power plants consume and pollute water, they also emit particulate matter (PM), nitrogen oxides (NO_x), and sulfur oxides (SO_x), which are hazardous to human health. Health impacts of PM from electricity generation are highest among Black and low-income communities; in general, exposure to hazardous pollution is higher in communities of color [94]. Similarly, these regions are impacted by the water withdrawal, consumption, and pollution caused by power generation. Understanding how water is withdrawn, consumed, and exported allows for better management of vital and threatened water resources. This research specifically analyzes regional virtual water exports and imports, which aids decision-making and informs what stakeholders need to be included in these processes to ensure sustainability and equity.

5.2. Uncertainty and limitations

Challenges arise from aggregating data from disparate sources with varying levels of quality. Monthly power plant water consumption, withdrawal, and temperatures are reported by the power plant operators to the EIA for only a portion of the thermoelectric power plants (those with a steam capacity greater than 100 MW). Furthermore, cooling water usage rates and volumes (i.e., diversion, withdrawal, consumption, and discharge) are either measured or estimated via a number of methods with varying accuracy. Flow rates may be measured using a 'streamflow gage or weir', 'cumulative or continuous flowmeter', or an 'instantaneous flowmeter and pump running time', or they may be estimated based on pump capacity and running time [95]. Consumption can be estimated based on the difference between withdrawal and discharge or withdrawal and a loss coefficient [95]. Power plant operators can report vague methods of estimation such as 'based on power generation' or 'plant design characteristics' [95]. Even less reliable, some reported flow rates are not measured and are simply based on permitted values [95]. To better understand the water requirements and impacts of thermoelectric power generation, we need more reliable and accurate water usage data from power plants. Grey water footprint estimates are dependent on the availability, accuracy, and resolution of temperature measurements from cooling water intakes and outlets. Grey water calculations are based on monthly average discharges and temperatures and therefore lack peaks in temperature [34].

Uncertainty also arises from the BA-to-BA transfer data reported in EIA-930. For aggregated data, basic imputations remove anomalous data, but this approach is not done for the hourly BA-to-BA interchange published data [96]. The EIA-930 instructions state that generation, demand, and total interchange should balance hourly, but this energy balance is not met in the actual data. The hourly BA-to-BA electricity transfer data are reported as-is from the BA, with multiple discrepancies, particularly for the larger BAs. These discrepancies are discussed in section 4 of the supporting information, and include missing data, mismatched data between connected balancing authorities, and large outlier errors. The hourly electricity transfer data reported by EIA-930 since July 2015 are still valuable, as prior to its release only annual electricity transfer data from FERC Form 714 were available [97].

The largest uncertainty comes from estimating the water footprint of hydropower generation, in part because reservoirs can consume much larger volumes of water than thermoelectric generation, and because a standardized methodology for estimating hydropower water footprints or a database of reported consumption is lacking. Although cooling water consumption and withdrawal factors vary across literature, a significant amount of work has been done in the field of estimating the water footprint of fuel production and electricity generation [49, 62, 64, 98], while less consensus has been reached on hydropower water consumption [42, 43, 47–50]. Since the hydropower water footprint has the largest impact on virtual water transfers and the largest uncertainty, improvements to the measurement of evaporation from reservoirs, accuracy and robustness of dam and reservoir databases, and standardization of hydropower water footprint estimation methodology are needed.

6. Conclusion

Virtual water transfers, both blue and grey, vary spatially and temporally on the electric grid of the United States. Virtual blue water transfers reach a maximum peak around November due to the dominance of evaporation from hydropower reservoirs. Water stresses, such as droughts and declining snowpack in mountains, in regions with large virtual blue water exports could have far-ranging impacts on the grid. Falling reservoirs decrease hydroelectric generation capacity, and decreased water availability and higher water temperatures can increase risk of thermoelectric power plant curtailment and shutdown. There are notable blue virtual water transfers out of the already over-allocated and water-stressed Colorado River Basin. In the Eastern Interconnection, where virtual grey watertransfers are large, grid reliability could be impacted by the changing climate. Virtual grey water transfers peak between July and August when temperatures are at their highest, electricity demands are high, and surface water temperatures are higher and water levels are lower. Regions with large virtual grey water transfers bear the brunt of environmental impacts of thermoelectric power generation on their ecosystems, in addition to the associated air quality impacts of fossil fuel plants.

Understanding the spatial and temporal transfers of virtual water transfers has important implications for policy, water management, and equity. Improvements to power plant, dam, hydropower reservoir, and electricity interchange databases will enable better understanding of the impacts of electricity generation in both the regions where power is generated and consumed. Centers of high electricity demand, typically cities, shift the burdens of electricity generation (e.g., water consumption, water pollution, air pollution, negative health impacts) to regions that produce electricity, typically rural and/or low-income areas, presenting spatial and temporal sustainability challenges.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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ORCID iDs

Christopher M Chini https://orcid.org/0000-0002-1208-3646
Rebecca A M Peer https://orcid.org/0000-0002-9951-2625
Ashlynn S Stillwell https://orcid.org/0000-0002-6781-6480

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