Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-650
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 21 November 2017

Hydrology and Earth System Sciences
Open Access
Discussions

A Spatially Detailed and Economically Complete Blue Water Footprint of the United States

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Abstract

This paper quantifies and maps a spatially detailed and economically complete blue water footprint for the United States, utilizing the National Water Economy Database version 1.1 (NWED). NWED utilizes multiple mesoscale federal data resources from the United States Geological Survey (USGS), the United States Department of Agriculture (USDA), the U.S. Energy Information Administration (EIA), the U.S. Department of Transportation (USDOT), the U.S. Department of Energy (USDOE), and the U.S. Bureau of Labor Statistics (BLS) to quantify water use, economic trade, and commodity flows to construct this water footprint. Results corroborate previous studies in both the magnitude of the U.S. water footprint (F) and in the observed pattern of virtual water flows. The median water footprint (F_{CUMed}) of the U.S. is 181,966 Mm³ ($F_{Withdrawal}$: 400,844 Mm³; F_{CUMax}: 222,144 Mm³; F_{CUMin}: 61,117 Mm³) and the median per capita water footprint (F'_{CUMed}) of the U.S. is 589 m³ capita^{-1} ($F'_{Withdrawal}$: 1298 m³ capita^{-1}; F'_{CUMax}: 720 m³ capita^{-1}; F'_{CUMin}: 198 m³ capita^{-1}). The U.S. hydro-economic network is centered on cities and is dominated by the local and regional scales. Approximately (58 %) of U.S. water consumption is for the direct and indirect use by cities. Further, the water footprint of agriculture and livestock is 93 % of the total U.S. water footprint, and is dominated by irrigated agriculture in the Western U.S. The water footprint of the industrial, domestic, and power economic sectors is centered on population centers, while the water footprint of the mining sector is highly dependent on the location of mineral resources. Owing to uncertainty in consumptive use coefficients alone, the mesoscale blue water footprint uncertainty ranges from 63 % to over 99 % depending on location. Harmonized region-specific, economic sector-specific consumption coefficients are necessary to reduce water footprint uncertainties and to better understand the human economy's water use impact on the hydrosphere.

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1. Introduction

Increasing connectivity through national and global trade has decreased barriers to economic cooperation while concomitantly increasing the susceptibility of the global economy to geophysical and meteorological natural hazards (Castle et al., 2014; Diffenbaugh et al., 2015; Mann and Gleick, 2015; Vörösmarty et al., 2015). Drought – a condition of perceived water scarcity created by the collision of a dry climate anomaly and excessive human demand for water that outstrips water availability (Famiglietti and Rodell, 2013; Zetland, 2011) – is one such natural hazard to which the world is increasingly prone that can impair the production of water-intensive goods sold in the global marketplace (Vörösmarty et al., 2000; Joseph et al., 2008; Seager et al., 2007). Without adequate substitutes for water as an input to production, the economic impact of a drought will propagate beyond local hydrological systems, and dependent water-intensive industries, into the global economy. Compounding the exposure to drought is the vulnerability of port cities, and the infrastructure systems on which trade is dependent, to natural hazards such as tropical depressions and earthquakes. Disruptions to the production and distribution of water-intensive goods have the potential spread across seemingly disparate localities over short time periods and are inherently a coupled natural-human (CNH) system phenomenon (Liu et al., 2007). Understanding our vulnerability to these types of events requires a synthesis of network theory, hydrology, geoscience, and economic theory into a unified food-energy-water (FEW) system science that is only possible through the novel fusion of comprehensive economic, commodity flow, hydrologic and geospatial datasets.

A robust understanding of interconnected FEW systems is especially important in regions where policymakers and engineers have insulated the economy and society from water scarcity through infrastructure and subsidy. For instance, take the Cadillac Desert of the Western United

States, where infrastructure, policy, and market forces have transformed arid and semi-arid land into some the most productive and highly-valued agricultural land in the world (Reisner, 1993; Sabo et al., 2010). Due to global economic connectivity, a drought that diminishes the production and trade in water-intensive goods the from Cadillac Desert has consequences for water resources management worldwide. Substitutes for drought-affected agricultural products will have to be cultivated elsewhere by bringing new land under cultivation, intensifying production, or replacing existing crops with crops no longer viable in the Western U.S. (Mann and Gleick, 2015; Castle et al., 2014; McNutt, 2014). Given the climatic, political, legal, geographical, and infrastructural constraints to developing new water supplies, which exist to varying extents worldwide, the potential solutions to systemic global water resources problems now lie in optimally managing the scarcity, equity, and distribution of existing water resources through the global hydro-economic network rather than the large-scale development of new, physical sources of water (Gleick, 2003). However, physical hydrology and water supply are mostly localized issues of "blue" physical water stocks and flows of both human and natural origin. But the global emerges from the local, and actionable information regarding the scarcity, equity, and distribution of global water resources is attainable only by mapping the network of hydro-economic connections at a local level, associated with specific cities, irrigation districts, rivers, and industries. Hydro-economic connections are created through the trade of water-intensive products and can be measured through virtual water accounting and water footprinting.

This study utilizes the National Water Economy Database version 1.1 (NWED), a database mapping the complete U.S. hydro-economic network, including international imports and exports, and that provides sufficient spatial and economic detail to identify the economic sectors, cities, river basins, water supplies, and ports that expose the U.S. and its global trading partners to water supply teleconnections and dependencies (Rushforth and Ruddell, 2017). This article is the publication of record for NWED.

With data from NWED, we answer the following research questions:

(1) What is the annual blue water footprint of the United States aggregated by economic macro-sector and at the spatial mesoscale (county) level?
(2) How does urban or rural composition affect water footprints, virtual water flows, and net hydro-economic dependencies?
(3) Through which ports does the world access U.S. water resources, and vice versa?
(4) What are the structural and spatial differences between economic sectors' roles in the U.S. hydro-economy?
(5) What is the current mesoscale uncertainty associated with blue water footprints in the United States given current data resources, and with the understanding that the U.S. has some of the best data in the world?

2. Methods

2.1. Data

If we are to effectively manage the impacts of drought, and other natural hazards, in the 21st century, we need a detailed quantitative understanding of the world's hydro-economic network of direct (commodity flow) and indirect connections (virtual water) linking consumers to producers around the globe. We begin with a blue water footprint that includes saline and reclaimed water. Green water footprints, and the aquatic ecosystem impacts of water use, to future work.

The hydro-economic network constructed in NWED is built from existing commodity flow networks and data, specifically the Freight Analysis Framework version 3.5 (FAF) developed by Oak Ridge National Laboratories for the U.S. Department of Transportation (Southworth et al., 2010; Hwang et al., 2016). FAF is a detailed U.S. commodity flow database of 43 commodities traded between 123 freight analysis zones (FAZs), roughly equivalent to a metropolitan statistical area, over 8 transport modes. The international component of FAF includes the trade of the 43 commodities by 8 transport modes to 8 international regions. Details of the FAZs, commodity classes, and transport modes have been documented elsewhere and, as such, will not be reproduced in this paper (Southworth et al., 2010; Hwang et al., 2016; U.S. Bureau of Transportation Statistics, 2017). Note that prior studies have been published using NWED version 1.0 (Rushforth and Ruddell, 2016). The differences between NWED v 1.0 and 1.1 can be found in the Appendix (A1)

FAZ trade linkages were disaggregated to component counties/county equivalent areas using production factors on the production side and attraction factors on the demand side. Production factors were chosen based on the economic function and product of a sector. For example, the production factor for agriculture commodities is the area of cultivated irrigated lands for specific crops (USDA National Agricultural Statistics Service, 2012); the production factor for livestock is the number of livestock operations (USDA National Agricultural Statistics Service, 2012); the production factor for mining is the number of commodity-specific (e.g., coal, metallic, non-metallic, gravel) mines in a county (U.S. Geological Service, 2005); and the production factor for the industrial sector is 4-digit NAICS level employment (Bureau of Labor Statistics, 2012). Currently, the only attraction factor used in NWED is population, which is used as a surrogate for county-level economic demand for commodities (U.S. Census Bureau, 2013).

A harmonization procedure has been developed so that commodities in FAF can be grouped into larger economic sectors, such as agriculture, livestock, mining, and industrial sectors to match United States Geological Service (USGS) water withdrawal categories (Maupin et al., 2014), which NWED utilizes as input water withdrawal data. Water use categories included in NWED input data are public supply, domestic, irrigation, thermoelectric power, industrial, mining, and livestock, which is both livestock operations and aquaculture. Each water withdrawal category is also further subdivided into groundwater and surface water components as well as freshwater and saline components. The USGS water withdrawal data contains water withdrawal data for both the service and goods/commodity based economy, but NWED currently only contains data on the water footprint of the commodity-based economy. Future versions will provide detail on the water-energy nexus, embedded emissions through trade, and the service economy.

2.2. Temporal Representativeness

Both FAF data and USGS water withdrawal data are collected every five years. However, FAF data is published for years ending with 2 and 7 (i.e., 2002, 2007, and 2012) and USGS data is published every half decade (i.e., 2005, 2010). NREL ReEDS modeled power flow data is available biennially from 2010 to 2050 (Eurek et al., 2016). The current version of NWED utilizes FAF data published for 2012 and USGS water withdrawal data published for 2010. These data were used as the basis of the county-level U.S. National Water Economy Database version 1.1 (NWED). The results of this NWED data product are limited in representativeness to roughly the 2010 – 2012 post-recession timeframe but are not precisely linked to a single year.

2.3. Geography of NWED

The county-scale of geography and annual-scale of time are the appropriate scales of aggregation for a nationally-scoped water footprint analysis in the U.S. given the available water withdrawal and commodity flow data. For the purposes of planning, policy, and law, especially in the absence of larger cities, counties and county equivalents are socio-political units that effectively define the "local" scale of U.S. society and the economy. Additionally, most services are consumed locally within the county where they are produced. In rural areas, a county is an aggregation of socio-economically similar small towns and agricultural areas. In urban areas, a county is more socio-economically diverse, but its statistical data are dominated by a single major metropolitan area and the county is, therefore, representative of that metropolitan area. While the largest metropolitan areas in the U.S. cover several counties and range from a half million people to over 10 million, counties can still capture the economic diversity within the metropolitan area.

The FAF FAZ is a group of counties that roughly comprise a metropolitan area, reflecting the fact that the commodity distribution infrastructure of the United States is organized as a spoke-and-hub network with major metropolitan areas and their distribution centers as hubs, thus necessitating the need to develop a disaggregation method. FAZ were disaggregated to the county level using best practices from the literature: population as an attraction factor on the demand side and employment levels, the number of agricultural and livestock operations, and the number commodity-specific mining facilities on the production side (Viswanathan et al., 2008; Bujanda et al., 2014; Harris et al., 2012; De Jong et al., 2004). These data allow for the development of a robust set of disaggregation factors that ensure the production of a commodity occurs only where it is physically and economically possible.

Standardized water use data and water stress data are available nationwide at the county-scale but do not typically exist at finer scales. A spatial unit coarser than the county will fail to capture the dominant hydrological and socio-economic patterns in the water footprint, and a finer spatial unit of analysis is not yet possible due to a fundamental lack of consistent, national data at those scales. If finer scale or more up-to-date data do exist, those data may not be consistent with national data, so consistency becomes a primary quality control issue (Mubako et al., 2013). Nonetheless, sub-annual and sub-county scale water use, economic production, water stress, and trade data are all needed to achieve a higher level of detail in the water footprint.

2.4. NWED Naming Convention and Water Footprints

The general form of a trade linkage (T) in the FAF database is a commodity (c) that flows from an origin FAZ (O_o) to a destination FAZ (D_d) over a domestic transport mode (k_{dom}) represented as tons (t), currency ($\$$), and ton-miles (tm), where o and d are indices for the 123 FAZ. Additionally, each c is associated with a broader economic sector (s) that corresponds to the USGS water withdrawal categories. International imports and exports originate from and terminate at one of 8 international origin (O_I) and destination (D_E) zones via an international transport mode (k_{int}). For an import, a c is produced in an international region (O_I) and flows through a port of entry (O_o) and then to a D_d of final consumption. For an export, a c is produced in a O_o and then exits the U.S. through a port of exit (D_d) for consumption in an international region (D_E). Domestic, import and export trades can be also classified by a trade type index (f) Therefore, a trade linkage of a commodity in terms of t, $\$$, and tm between an origin zone and destination, which may not include a foreign region, can be represented as $T_{O_I,O_o,D_d,D_E,k_{int},k_{dom},c,f}(t,\$,tm)$. NWED builds upon FAF by further disaggregating O_o and D_d to origin (I_n) and destination counties (J_m), respectively, and by adding virtual water, represented generally as (VW). Each row in NWED is trade linkage, $T_{O_I,O_o,I_n,J_m,D_d,D_E,k_{int},k_{dom},c,f}$, with a corresponding flow of *t*, *$*, *tm*, and *VW* that can be aggregated by any combinations of index $O_I \rightarrow f$. However, we drop all of these subscripts for a simpler derivation of the NWED disaggregation algorithm.

2.5. Water Footprint of a Geographic Area

The water footprint of a geographic area (F_{Total}) is the sum of the direct water use (WU)and net virtual water inflows (VW_{In}) and outflows (VW_{Out}) (Hoekstra et al., 2012). For example, in NWED, the water footprint of withdrawals of geographic area for all economic sectors is $F_w = WU_w + VW_{In,W} - VW_{Out,W}$ or alternatively $F_{Total} = WU_W + VW_{Net,W}$, where $VW_{Net,W} = VW_{In,W} - VW_{Out,W}$. The per-capita footprint is *F*` and is calculated by dividing *F* by the population of the county. Within in NWED, Taking the sum of *F* across all domestic trade in the U.S. yields $VW_{In,W} = VW_{Out,W}$ to ensure the water balance is conserved. *F* and each of its components are reported for each economic sector within each county in the U.S. in NWED. The derivation of $VW_{In,W}$ and $VW_{Out,W}$ are shown in section 2.6 – 2.8.

2.6. Disaggregating Domestic Trade Flows to the County-Level

The disaggregation method proceeds from the origin side (*O*), disaggregating to origin counties (*I*), and then to the destination side (*D*), disaggregating to destination counties (*J*). Each *O* contains a distinct set of one or multiple origin counties (I_n), where $I_n \in O$, and each *D* contains a distinct set of multiple destination counties (J_m), where $J_m \in D$. Further, each county (*n or m*) within each *O* and *D* has a unique production factor (*PF*) and attraction factor (*AF*) for each economic sector and, where supported by data, each commodity produced in that county. Each *I* and *J* can be defined as a set of distinct of unitless *PF* or *AF* factors for each commodity, $\{I_n\colon PF_{c1}, PF_{c2}, \ldots, PF_{c43}\}$ and $\{J_m\colon AF_{c1}, AF_{c2}, \ldots, AF_{c43}\}$, repectively. Therefore, any O_o or D_d can be represented by a column vector of PF_c or AF_c corresponding to the I_n or J_m that belong to O_o or D_d. Given that the PF_c or AF_c define the proportion of production capacity and demand attraction a county has within a O_o or D_d, the sum of the PF_c or AF_c for a given O_o or D_d must be equal to 1 to conserve mass. Therefore, for a given commodity (*c*) with an associated sector (s) and *t*, *$*, and *tm* over 8 transport modes, *k*,

$$(1)\ \ O_{o,c} = \begin{bmatrix} I_{1PF_c,O_{o,c}} \\ I_{2PF_c,O_{o,c}} \\ \vdots \\ I_{nPF_c,O_{o,c}} \end{bmatrix} \ \text{or}\ \ D_{d,c} = \begin{bmatrix} J_{1AF_c,D_{d,c}} \\ J_{2AF_c,D_{d,c}} \\ \vdots \\ J_{nAF_c,D_{d,c}} \end{bmatrix}, \text{where } \textstyle\sum_n O_o = 1 \text{ and } \sum_m D_d = 1.$$

Disaggregating production from a O_o that contains counties $I_{1\to n}$, O = $\{I_1, I_2, \ldots, I_n\}$ for a *c* proceeds as follows:

$$(2)\ \ T_{O_o,D_d,c} \times \begin{bmatrix} I_{1PF_c,O_{o,c}} \\ I_{2PF_c,O_{o,c}} \\ \vdots \\ I_{nPF_c,O_{o,c}} \end{bmatrix} = \begin{bmatrix} T_{I_1,D_d,c} \\ T_{I_2,D_d,c} \\ \vdots \\ T_{I_n,D_d,c} \end{bmatrix}$$

Solving Equation 2 over all O_o for each commodity disaggregates FAZ-level commodity production to the county-level – from 123 origin FAZs (O_o) to 3,142 origin counties (I_n). A quality control is performed to ensure that no additional mass, currency, or ton-miles are produced for all commodities across all O_o. After the production-side disaggregation, 3,142 origin counties are linked with 123 FAZ destinations via trade of commodities (*c*).

Similarly, the goal of the demands-side disaggregation is to disaggregate flows to 123 FAZ to 3,142 counties; however, instead of the relative abundance of industries that produce a specific commodity to disaggregate production, population is used as a simple measure of a county's attraction (demand) of a commodity within a FAZ. It follows that disaggregation on demand side of the O-D trade linkage follows a similar process.

For a D_d that contains counties J_1 to J_n, $D_d = \{J_1, J_2, \ldots, j_n\}$ for g produced in an origin county, I_n, disaggregation proceeds as follows:

$$(3)\ T_{I_n,D_d,c} \times \begin{bmatrix} J_{1AF_{c,D_d}} \\ J_{2AF_{c,D_d}} \\ \vdots \\ J_{nAF_{c,D_d}} \end{bmatrix} = \begin{bmatrix} T_{I_n,J_1,c} \\ T_{I_n,J_2,c} \\ \vdots \\ T_{I_n,J_m,c} \end{bmatrix}$$

At this point, quality control is performed to ensure that no new mass, currency, or ton-miles are erroneously introduced for all commodities across all O_o and D_d. Performing this disaggregation step across all I_n disaggregates the flows of c in terms of t, $\$$, and tm to be between 3,142 origin counties and 3,142 destinations counties over 8 potential transport modes, k.

International flow disaggregation follows the same process; however, the 8 world regions are not disaggregated further and import flows are not further disaggregated into surface water and groundwater. After, import and export flows are disaggregated each world region is connected via a production of consumption trade flow with one of 3,142 U.S. counties flowing through a port of entry or exit.

2.7. Assigning Virtual Water Flows to Trade Flows

Economic sectors (s) in the FAF database were aligned with water withdrawal sectors (WU_s) using the detailed Standardized Classification of Transported Goods (SCTG) definitions of commodity groups (US Census Buearu, 2006; Dang et al., 2015). County-specific, sector-level water intensities ($WI_{I_n,s,W_{Total}}$) were calculated as the quotient of county-specific, sector-level water withdrawals ($WU_{I_n,s,W_{Total}}$) and county-level, sector-specific commodity production ($\sum_{D_d,c} T_{I_n,D_d,c}$) and have the units Mm^3 t^{-1}. In the initial step of calculating $WI_{I_n,s,W_{Total}}$, groundwater and surface water withdrawals are summed to a total sector-level water withdrawal figure for each county ($WI_{I_n,s,W_{Total}}$). Virtual water flows are disaggregated back to groundwater and surface water fractions in a later step.

(3) $$WI_{I_n,s,W_{Total}} = WU_{I_n,s,W_{Total}} / \sum_{D_d,c} T_{I_n,D_d,c}$$

The resulting $WI_{I_n,s,W_{Total}}$ can be interpreted as the average withdrawal-based water intensity of sector-level production.

Next, $WI_{I_n,s,W_{Total}}$ were multiplied by the corresponding $T_{I_n,J_m,c}$ to arrive at the virtual water flows by county and commodity by transport mode.

(4) $$VW_{I_n,J_m,c,W_{Total}} = WI_{I_n,s,W_{Total}} \times T_{I_n,J_m,c}$$

The $VW_{I_n,J_m,c}$ that results from this process assigns water withdrawals to a commodity based on the tons of a *c* produced within a county according to disaggregated FAF data. Future versions of NWED will refine this process with additional commodity specific water intensities, as explained further in section 2.4.

For notational clarity, when $VW_{I_n,J_m,c,W_{Total}}$ is summed for all unique origin counties (I_n) the term is simplified to $VW_{Out,Total}$. Conversely, when summed for all unique destination counties (J_m) the term is simplified to $VW_{In,Total}$. Additionally, $WU_{I_n,s,Total}$ summed over all sectors for all unique counties becomes $WU_{W_{Total}}$. This notation also holds true for consumption-based virtual water flows.

Minimum (*Min*), median (*Med*), and high (*Max*) water consumption scenarios for each sector in each county were determined by multiplying $WU_{I_n,s,W}$ by the corresponding sector-level minimum, median, and high consumption coefficients developed by the USGS (Shaffer and Runkle, 2007). Only the methodology for *Med* consumption scenario is shown below since both the *Min* and *Max* consumption scenarios follow an identical calculation process.

(5) $$WI_{I_n,s,CU_{Med,Total}} = (WU_{I_n,s,W_{Total}} \times CU_{Med,S}) / \sum_{D_d,c} T_{I_n,D_d,c}$$

(6) $$VW_{I_n,J_m,c,CU_{Med,Total}} = WI_{I_n,s,CU_{Med,Total}} \times T_{I_n,J_m,c}$$

Owing to these consumption coefficients being developed for the Great Lakes Region, and climatically similar states, the consumption-based virtual water flows in NWED are preliminary and serve as placeholders until region- or county-specific and sector-level consumption coefficients have been developed for the U.S.

Since the USGS water withdrawal data contains data on groundwater and surface water withdrawals for each sector within each county, $VW_{I_n,J_m,c,CU_{Max,Total}}$, $VW_{I_n,J_m,c,CU_{Med,Total}}$, and $VW_{I_n,J_m,c,CU_{Min,Total}}$ are split into groundwater and surface water components be multiplying each by the county-specific, sector-specific groundwater withdrawal percentage ($GW_{I_n,s,pct}$) and surface water percentage ($SW_{I_n,s,pct}$). The process is shown below for $VW_{I_n,J_m,c,s,t,k,CU_{Max}}$.

(7) $$VW_{I_n,J_m,c,CU_{Max,SW}} = VW_{I_n,J_m,c,CU_{Max,Total}} \times SW_{I_n,s,pct}$$

(8) $$VW_{I_n,J_m,c,CU_{Max,GW}} = VW_{I_n,J_m,c,CU_{Max,Total}} \times GW_{I_n,s,pct}$$

After this final step, NWED contains data detailing 3,142 counties trading 43 commodities with 3,142 counties, as well as 8 world regions, over 8 transport modes and each commodity trade linkage is measured by 15 metrics (The full list of metrics is in the Appendix, A2).

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2.8. Power Flow Estimation and Disaggregation

The flow of the electricity commodity is not like other commodity flows. There is no mass moved from point A to point B, and there is not a contract associated with such a flow. The concept of power flow is as philosophical as it is physical. However, we know some of the geometrical properties of the power grid. The grid is comprised of the U.S., at the first level of aggregation, of three interconnections: the Western Electricity Coordinating Council (WECC), the Eastern Interconnection (Eastern), and the Electric Reliability Council of Texas (ERCOT), with little transmission of electricity between them. Interconnections do not obey county or state boundaries, or even national borders; Mexico and Canada are participants in WECC and Canada in the Eastern. At the second level of aggregation, the grid is comprised of 134 balancing authorities within which a single authority has responsibility for maintaining a balance between supply and demand and managing power quality. Balancing authorities trade power between themselves, but strongly manage these transmission corridors. Within a balancing authority, there is a mixture of power generators, transmitters, and distributors that participate in a complicated web of heretofore uncatalogued contracts using a complex interconnected machine that maintains a constant voltage potential and frequency under variable loads. Adding to this complication is the absence of federally standardized power demand and transmission data; the only production is subject to federal data collection by the Energy Information Administration (EIA).

Given this unusual situation, we know of at least three methods for estimating the destination and routing of electricity. First, because we can assume there is little trade across an interconnection's boundary, a "mass balance" could be applied within an interconnection's subregions, allocating consumption first to the local generator's region and then in proportion to

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estimated demand in other regions (e.g. Ruddell et al., 2014). This method is not physically realistic because it ignores transmission constraints and balancing regions, but may be a useful approximation especially at coarser spatio-temporal scales. A second method is to follow contracts and payments for electricity and power services. This method provides the closest analogy to the commodity flow model, but the contract and payment data is not currently available. A third method is to perform power flow modeling on a spatio-temporally precise node-network model of the grid that incorporates detailed information about generators, demand patterns, and their economics to simulate power flows as an analogy to commodity trade. We use balancing region power flow modeling for NWED 1.1, disaggregated to the county scale using population.

The power flow data used in NWED is an existing published dataset produced using the Regional Energy Deployment System (ReEDS), which is a long-term power flow model to evaluate capacity-expansion, technology deployment, and infrastructure deployment in the contiguous U.S (Macknick et al., 2015; Eurek et al., 2016; Cohen et al., 2014). Only for the electrical power production sector, NREL data on water withdrawal and consumption data were used instead of USGS water withdrawal data to estimate the water withdrawal and consumption associated with power generation and flow (Macknick et al., 2012; Macknick et al., 2015).

ReEDS data contains both power generation by balancing authority and power inflows and outflow between balancing areas over sub-annual time periods. Balancing authorities are areas larger than counties. To harmonize with NWED and disaggregate ReEDS data from the balancing authority to the county-level, the model's production numbers are disaggregated proportionally using the heat content of fuel consumption for electricity for each county's power plants (Energy Information Administration, 2017) and electricity demand is disaggregated proportionally by population.

In addition to error introduced in disaggregation, power wheeling within balancing regions is a significant portion of power flow, and this is another source of error (Bialek, 1996a; Bialek, 1996b; Bialek and Kattuman, 2004). To help compensate for the effect of wheeling on the water footprint of electricity, the water intensity of a power outflows from each balancing area was taken as the source-weighted average of the water intensity of power generation and power inflows. Therefore, virtual water outflows from a county in NWED 1.1 is the virtual water outflow associated with wheeled power through a balancing area (including power originating from this area's generation) in addition to virtual water outflows associated with power generation within that county. Taking into account these modifications to the standard virtual water methods employed elsewhere, virtual water flows were estimated according to the methods in sections 2.5 – 2.6.

2.9. Urban-Rural Classification

Each county in the U.S. can be categorized using numerous classification schemes. For this paper, and for the purpose of understanding rural-to-urban transfers of virtual water in the U.S., we have classified each county in NWED by the National Center for Health Center for Health Statistics (NCHS) Urban-Rural Classification Scheme for Counties (Ingram and Franco, 2012). Within this classification scheme, counties are first separated into metropolitan and non-metropolitan counties. Metropolitan, or urban, counties are then further classified as Large Central Metro counties (*Central*), Large Fringe Metro counties (*Fringe*), Medium Metro counties (*Medium*); and Small Metro counties (*Small*). Generally, large counties have greater than 1 million people; medium counties have between 250,000–999,999 people; and small counties contain less than 250,000 people. Non-metropolitan, or rural, counties are divided into Micropolitan (*Micro*) counties (population between 10,000–49,999 people) and non-core counties are counties with a population too small to be considered micropolitan counties. Each county-to-county trade linkage has been classified and aggregated by the NCHS Urban-Rural Classification Scheme for Counties to understand urban to rural virtual water transfers (Section 3.1).

2.10. Simplifying Assumptions and Limitations

NWED water footprints, by necessity, are multiple water sources and types beyond simply groundwater and surface water. Saline, brackish, and reclaimed water are non-trivial components of water use in the U.S. and thus the U.S. hydro-economy. For example, only 71 % of power generation in the U.S. is from freshwater sources and the remaining fraction of water use for power generation is comprised of saline, brackish, and reclaimed water. Neglecting non-freshwater sources would underestimate the water intensity of the power grid. Reclaimed water is a direct substitute for fresh water, and brackish water is a substitute in some cases, so it is difficult to draw a clear line between included and excluded water withdrawals. Considering the entire U.S. hydro-economy, 15 % of water withdrawals are saline. However, the inclusion of non-freshwater sources does not impact the agricultural virtual water flows as no saline water withdrawals are reported in this sector. For simplicity in this paper, commodity-based virtual water flows are reported as 'blue water' even though we incorporate additional types of water beyond freshwater. Power flow-based virtual water flows are presented summed over all water types - not just freshwater. The freshwater footprint of electricity is somewhat smaller than the total water footprint, and this difference is larger on the coasts and in the West.

The current version of NWED uses national average U.S. water use efficiencies to estimate international virtual water flows. The first reason for this choice is data consistency. While the USGS water use data does contain some interstate variability due to data reporting methods, the variability is no doubt far smaller than international variability in data reporting methods among countries that mostly lack formal water census programs. Secondly, the U.S. is a large, and geographically, agronomically, climatically, and economically diverse country; water use efficiencies vary dramatically from region-to-region and sector-to-sector. This internal variability captures a large range of the world's variability. Third, the U.S.'s water use efficiency is near the middle of the international range. According to World Bank data, the U.S.'s average per GDP water use productivity between 2005–2015 was in the 65th percentile of reporting countries (World Bank, 2017). Fourth, the USGS presents comprehensive water withdrawal data for all types of mining products, which are an important import to the U.S. Finally, since NWED is U.S.-centric, this method normalizes virtual water flows to U.S. water efficiencies, allowing for a 1:1 equivalency between the volume of virtual water traded by the U.S. to the volume of virtual water flowing internally (Rushforth et al., 2013). In other words, 1 unit of water use outsourced from the U.S. via virtual water imports directly offsets and substitutes for 1 unit of water used in the consuming U.S. location; this is a useful comparison and was employed also by Mayer et al. (2016).

From the USGS water withdrawal data, we use total, surface water, and groundwater withdrawals from each county. The sum of all withdrawals in a county is the direct use component of that county's Water Footprint ($\sum_s WU_{I_n,s,W_{Total}}$, $or\ WU_{Total}$). WU_{Total} is the sum of agriculture ($WU_{I_n,Ag,W_{Total}}$), not including the irrigation of golf courses; industrial ($WU_{I_n,Ind,W_{Total}}$), which is estimated by taking the sum of industrial withdrawals and the difference between water withdrawal for public supplies and domestic uses by water systems; mining ($WU_{I_n,Min,W_{Total}}$); and livestock, which includes livestock and aquaculture withdrawals ($WU_{I_n,Liv,W_{Total}}$). $WU_{I_n,W_{Total}}$ is also known as the Water Metabolism of a county (Kennedy et al., 2015). Total, surface water, and groundwater water footprints within a county match the standard Water Footprint Accounting definition of the water footprint of a geographic area (Hoekstra et al., 2012). For withdrawal-based water footprints, we assume 100 % consumptive use (consumption coefficient $CU = 1$), forcing USGS-estimated water withdrawals equal to the direct use component of the Water Footprint, *WU*. Sector-level consumption coefficient data do exist, but these data are specific to the Great Lakes region of the U.S., and climatically similar states, and have large uncertainty ranges (Shaffer and Runkle, 2007). Due to the large uncertainties involved with the consumption coefficients, we have attempted to estimate the uncertainty associated with consumption by using three consumption coefficients for each sector – a minimum (*Min*), median (*Med*), and maximum (*Max*) (Table 1). The uncertainty introduced by the consumption coefficients, and how it propagates when applied over a trade network, is presented in Section 3.5. Future work can augment NWED by developing more accurate consumption coefficients estimate for all counties, or regions, in the U.S. for all economic sectors. NWED contains the following assumptions regarding water use categories: (1) USGS aquaculture and livestock are combined into one category since specific commodity codes includes both live meat and fish and because aquaculture is a *de minimus* water use compared to livestock; (2) USGS industrial water supply is calculated to include the component of public water supply that is not for domestic household consumption in addition to industrial water

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-650
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 21 November 2017

withdrawals; (3) each water use category includes both publically-supplied and self-supplied withdrawal figures; and (4) while virtual water flows associated with water use categories outside the scope of the FAF commodity flow database are neglected, direct water use is accounted.

With respect to (4), this specifically includes flows of services and labor across county or regional lines (Rushforth and Ruddell, 2015). There is a substantial absolute error introduced by zeroing virtual water flows out from counties that export services and FAF-ignored goods, and this error causes urban areas' net water footprints to be overestimated (and rural areas' to be underestimated by exactly the same amount). Water balances WU are unchanged. However, this error is small in relative terms because these sectors are a small part of total virtual water flows when compared with agriculture, power, and major industry. Labor and services are consumed largely within their county of production. Important exceptions may possibly include the financial services sector, which tends to be national and global in its trading patterns.

A limitation in the underlying FAF data is that an assumption must be made that commodity production occurs at the origin and commodity consumption occurs at the destination. Therefore, we must assume that there are no pass-through commodity flows. To the extent possible in the underlying data, this is controlled for at international ports because pass-through commodity flows are identifiable from commodity flow to or from the city in which the port is located. However, domestic pass-through commodity flows are not identified in the current version of NWED. A method to estimate pass-through commodity flows using input-output methods is under development and will be included in the next version of NWED.

Future iterations of the NWED power flow dataset will utilize purpose-built node-network power flow models developed at the county-level to differentiate between power outflows into generated power and wheeled power for each county.

3. Results

3.1. U.S. Water Footprint Statistics

The median annual water footprint, F_{CUMed}, of the U.S. is 181,966 Mm³ ($F_{Withdrawal}$: 400,844 Mm³; F_{CUMax}: 222,144 Mm³; F_{CUMin}: 61,117 Mm³). On per-capita basis, the median U.S. water footprint (F'_{CUMed}) is 589 m³ capita^{-1} ($F'_{Withdrawal}$: 1298 m³ capita^{-1}; F'_{CUMax}: 720 m³ capita^{-1}; F'_{CUMin}: 198 m³ capita^{-1}). Counties with the largest F_{CUMed} are often metropolitan areas with large populations or regionally-significant cities with neighboring counties that are heavily agricultural – Los Angeles County, California (L.A.); Harris County, Texas (Houston); Ada County, Idaho (Boise); Maricopa County, Arizona (Phoenix); and Fresno County, California (Fresno) (Fig. 1; withdrawal-based results are presented in the Supplemental Information.). On a per capita basis, the U.S. water footprint is smallest for urban areas, where $F'_{CUMed,\ Urban}$ is 282 m³ capita^{-1} ($F'_{Withdrawal,Urban}$: 828 m³ capita^{-1}; $F'_{CUMax,Urban}$: 399 m³ capita^{-1}; $F'_{CUMin,Urban}$: 97 m³ capita^{-1}) and largest for rural, agricultural counties $F'_{CUMed,\ Agriculture}$ is 1,053 m³ capita^{-1} ($F'_{Withdrawal\text{-}Basis,\ Agriculture}$: 1,927 m³ capita^{-1}; $F'_{CUMax,\ Agriculture}$: 1,217 m³ capita^{-1}; $F'_{CUMin,\ Agriculture}$: 344 m³ capita^{-1}).

NWED results are comparable to previous water footprint studies for the U.S. For example, Mekonnen and Hoekstra estimated the U.S. blue and grey water footprint to be 320,496 Mm^3 and 874 m^3 capita^{-1} (Mekonnen and Hoekstra, 2011), which is the closest equivalent to the water sources used NWED. The Mekonnen and Hoekstra U.S. water footprint figures sit roughly between the CU_{Max} and withdrawal-based (CU = 1) NWED scenarios. Further, results from NWED corroborate previous studies in both the magnitude of the U.S. water footprint and in the observed pattern of virtual water flows to cities concentrated in water-intensive irrigated agricultural and industrial goods (Rushforth and Ruddell, 2015; Zhao et al., 2015; Hoekstra and Wiedmann, 2014). Vital water footprint statistics are presented in Table 2 for the U.S. in addition to urban (*Central, Fringe, Medium*) and rural (*Small, Micro, Non-Core)* counties.

Counties in California's Central Valley – Fresno County and Tulare County located in the southern part of the Central Valley – have the largest virtual water outflows of any county in the U.S. Overall, the western U.S., the High Plains, the Mississippi Embayment, Texas Gulf Coast, and Florida provide the U.S. with virtual water exports. Coincidentally, all these source regions are highly prone to either drought or flooding (production-level uncertainty). Large virtual water outflows are often counterbalanced by nearby virtual water inflows within the same county (Fresno County, California) or region, as is the case with Fresno County, California, Pinal County, Arizona (net outflows from irrigated agriculture) and neighboring Maricopa County (net inflows to the Phoenix Metropolitan Area) and Brazoria County, Texas (net outflows from irrigated agriculture) and Harris County (net inflows to the Houston Metropolitan Area) in Texas. In general, we find that the water supply chain, especially the step of the chain bringing agricultural products from the farm to handling and processing facilities where these products become 'food' is mostly local and regional with a smaller but still significant transnational and international water supply chain.

3.2 Urban Dependencies on Rural Virtual Water

Circular virtual water flows – virtual water flows that originate and terminate within the same county – are highest for urban counties (Fig. 2). Conversely, rural counties often have small water footprints regardless of the presence of a large water-intensive industry, because rural populations do not consume the majority of the goods produced in those regions. If such an industry were present in a rural county, much of the water withdrawn flows out of the county as virtual water, thus counterbalancing the large withdrawals in the water footprint calculation. Counties that are in the middle of the urban-rural spectrum, often a medium-to-small metropolitan area, rely heavily on agricultural products as an economic input and tend to have the largest virtual water inflows of all U.S. counties. Medium to small cities tend to be food processing hubs where farm goods are transformed into "food", and irrigated agricultural blue water footprints are registered in those small cities rather than in the large cities where the food is largely consumed.

The central counties of large metropolitan areas (*Central)* tend to source virtual water equally across the urban-rural spectrum with a slight increase in virtual water sourcing from more medium metropolitan areas and rural counties. However, there is a comparatively small return flow of virtual water from large metropolitan areas back to counties with smaller populations (Table 3). Instead, virtual water originating from counties associated with large metropolitan areas tend to remain within that county as a circular flow or flow to other large metropolitan areas, enlarging the net VW inflow of large metropolitan areas.

One such county is Maricopa County, the central county of the Phoenix metropolitan area, which a "local water" hotspot where most of the water used in the community "stays local" in the form of locally consumed virtual water flowing to other users in the same community. This means the community is employing its blue water resources primarily for the hydro-economic benefit of its local consumers and businesses. It also means that this community's dependency on its own local water resources is amplified through circular self-dependence, so any disruption to local water supplies in Phoenix will have a circularly multiplied effect on that city's economy (Rushforth and Ruddell, 2015). The Phoenix metropolitan area is notable as a major city and population center that is simultaneously a large user of irrigation water for the production of agricultural commodities, including locally consumed food products. Phoenix is also relatively isolated geographically from other metropolitan areas and therefore keeps more of its metropolitan area's virtual water within the local boundary, unlike east coast cities where intra-metro trade and virtual water flows are more prevalent.

Counties that are associated with medium-sized metropolitan areas (*Medium)* break from large cities' and their fringes and take on a different role in the system. While medium metropolitan areas are by no means small, with a population between 250,000–999,999, they are often co-located with large agricultural areas. For example, Ada County, Idaho (Boise metro area), Fresno County, California (Fresno metro area), or Kern County, California (Bakersfield metro) are all counties that contain medium-size metropolitan areas that are co-located with intense agricultural production. In these counties, virtual water tends to be sourced from counties that are as rural as the place of consumption or more rural. Medium-sized metropolitan areas, in particular, are the largest destination of virtual water from rural America while also being one of the largest sources of virtual water for the U.S., especially large metropolitan area – effectively linking rural and urban counties. The medium-medium urban connection is the largest link in the U.S. virtual water flow network, and this link is dominated by the heavy industrial and bulk agricultural and processed food goods that do not tend to be produced by highly rural or densely urban areas. On a per capita basis, the Medium class of city is the core of the U.S. hydro-economic network. County-level virtual water flow data show that there is an urban-rural divide, suggesting that there is a fundamental difference in the roles of large urban areas, medium urban areas, and more rural communities in the U.S. hydro-economic network.

In the U.S. hydro-economy, economic sectors have different structural roles as either a virtual water sink or source depending on the degree to which a county is rural or urban. Structurally, the agricultural sector is the bulk of the rural-to-urban transfer of virtual water (59,119 Mm^3), but rural-to-rural and urban-to-urban virtual water flows are also signification (53,731 Mm^3 and 27,743 Mm^3, respectively). While similar, the livestock sector constitutes a minority of the rural-to-urban transfer of virtual water (6,100 Mm^3) but has little to no impact on virtual water exports. The mining sector is more geographically-dependent and regional on the location of resources and infrastructure. Therefore, while rural-to-urban virtual water flows are the largest within this sector (337 Mm^3), rural-to-rural and urban-to-urban virtual water flows are also prominent (175 Mm^3 and 165 Mm^3, respectively). In the power sector, the largest virtual water flow is from rural-to-rural (159 Mm^3) followed by urban-to-urban (22 Mm^3) and rural-to-urban (13 Mm^3). Finally, the industrial sector is primarily urban-to-urban virtual water transfers. Rural-to-urban virtual water transfers would only become more pronounced if *Medium* metropolitan areas were considered to be rural counties. While there is subjectivity to whether a county is rural or urban, especially in the middle of the urban-rural spectrum, the predominant flow of virtual water is from rural counties to urban counties.

3.3 U.S. International Virtual Water Imports and Exports

Overall, the U.S. is a net virtual water exporter, which qualitatively agrees with the findings from previous international virtual water flow studies (Water Footprint Network, 2013); the virtual water balance of the United States is -4,693 Mm^3. The volume of international virtual water imports and exports is 6.3 % the volume of domestic virtual water flow. Of the 8 world regions in NWED, the U.S. is a net virtual water exporter to each region, indicated by the negative virtual water balance (Table 4). The U.S. has the largest negative virtual water balance with Eastern Asian (-2,081 Mm^3) and Mexico (-1,215 Mm^3). The U.S. is a net importer of virtual water from Central and South America (Rest of Americas) and Europe.

Virtual water export from the U.S. is mostly agricultural commodities, such as corn, wheat, alfalfa, for which the U.S. is a large net exporter (Marston et al., 2015; Hoekstra and Wiedmann, 2014) and mining products, such as metallic and non-metallic ores. Major virtual water exporting regions are the Central Valley of California; the deserts of California and Arizona; the High Plains, including the Ogallala Aquifer Region, the Arkansas River Basin, and the Platte River Basin; the Columbia River Basin in the Pacific Northwest; Central Nevada; the Texas Gulf Coast; the Upper Missouri River Basin in Montana; Central and Southern Florida; and the Mississippi Embayment (Fig. 3). Many of these areas are major sources of virtual water domestically within the U.S.; however, these results show that some areas such as southwestern Idaho, Wyoming, and central Utah and New Mexico operate primarily in the domestic market, and other regions such as central Nevada (metallic ores) and western Washington (non-metallic ores) are more prominent in the international market.

The majority of virtual water exports from the United States flow through ports along the Gulf Coast (Houston, New Orleans, Corpus Christi, Beaumont) and the West Coast (Los Angeles/Long Beach, Washington State, San Francisco, Seattle, Portland). The ports of Los Angeles and New York City receive the highest volume of virtual water imports followed by Houston and Detroit. Due to where goods for export are sourced within the U.S., a region (or country) may receive a higher proportion of virtual water that originated as surface water or groundwater. Mexico, Africa, and Southwest and Central Asia are the only world regions that received more virtual water in that originated as groundwater (Table 5); suggesting that exports to these regions are more vulnerable to unsustainable, long-term groundwater management than annual fluctuations in surface water availability and drought (Marston et al., 2015). Conversely, Canada, Latin America, Europe, and Asia and Oceania are more susceptible to surface water availability and drought but less susceptible to unsustainable groundwater management. Given that the U.S. is a large hydrologically, agronomically, and climatically diverse country, it is not surprising that the type of water, surface water or groundwater, that an international trading partner may depend on varies based on which part of the U.S. is accessed and thus causing two trading partners to virtual water risk profiles that are vastly different.

Given the location of agricultural production and port cities in the United States, food exports are vulnerable to shocks that affect both food production and distribution. Droughts, such as the one that affected California in 2015, can create production-level risks due to the uncertainty of surface water supply or depletion. Specifically, this type of natural hazard has the potential to impair agricultural production in California's Central Valley; the southwest United States, particularly southern California and Arizona; the Pacific Northwest, particularly western Washington and Oregon; the High Plains; and the Mississippi Embayment.

For global commodity distribution, the Gulf Coast ports of Houston, Corpus Christi, New Orleans are especially vulnerable to hurricanes as are ports along the Eastern Seaboard such as Miami, Savannah, Norfolk, and New York. While damage from hurricanes could interrupt the flow of goods for days to months, natural hazards along the Pacific Coast could create longer-term interruption. The potential for catastrophic earthquakes along the Cascadia Subduction Zone in the Pacific Northwest and the San Andreas Fault Line in California has increased over time and could impact any port city along the Pacific Coast. Finally, all port cities in the United

States are vulnerable to sea-level rise, which would impact both the economic activity within the port city and operational activities at the ports.

3.4 Structural and Spatial Differences in Economic Sector Water Footprints

The U.S. water footprint is predominantly the production, manufacture, and distribution food. The agriculture (154,349 Mm^3) and livestock (15,917 Mm^3) economic sectors comprise 93 % of the U.S. water footprint (181,966 Mm^3), with the agriculture economic sector alone comprising 87 % of the U.S. water footprint. Overall, the agriculture and livestock water footprint is concentrated in the Western U.S., where there is a heavy dependence on irrigated agriculture to raise crops for human and animal consumption.

For agriculture, the Central Valley of California, the Front Range of Colorado, Central and Southern Arizona, and the Snake/Columbia River Valley are significant geographic regions where food is grown and where irrigation is a requisite for growing crops (Fig. 4a). Where irrigated agriculture is not as prevalent, urban centers are moderate water footprints as they serve as regional distribution for food (Omaha, Nebraska; Wichita, Kansas; Dallas, Houston, and Brownsville, Texas; New Orleans, Louisiana; Northwest Arkansas; and Central Florida). The U.S. livestock footprint is more concentrated on the west coast U.S. and Snake River Valley of Idaho; however, on the east coast, the Carolinas have the largest livestock water footprint (Fig. 4c). Outside these areas, the U.S. livestock water footprint is concentrated around cities where there is a relatively large inflow of virtual water with little to no virtual water outflows.

Unlike the U.S. water footprint of agriculture and livestock, in which both rural and urban counties play significant roles, the U.S. industrial water footprint (Fig. 4b), and to the same extent the U.S. water footprint of and power production and flow and domestic water consumption (Fig. 4e and 4f), is dominated by urban areas. Not surprisingly, domestic and industrial water use is highly co-located with urban areas as are virtual water inflows and outflows. Major nodes in the U.S. industrial water footprint network are Chicago, Illinois; Houston and Dallas, Texas; Los Angeles California; Seattle, Washington; Phoenix, Arizona; Las Vegas, Nevada; the Boston-Washington Corridor; Central and Southern Florida; and each major metropolitan area east of the Mississippi River. While the same areas are important in the domestic water footprint, the U.S. southwest – Southern California, Central and Southern Arizona, and Las Vegas, Nevada – have the largest domestic water footprints.

The U.S. mining water footprint is highly dependent on the location of mineral resources in addition to processing facilities and distribution hubs. Some geographic regions with substantial mining water footprint do not have a significant water footprint in other sectors; for example, northern Alaska; west Texas; the Gulf Coast; Oklahoma; North Dakota; northern Michigan and Minnesota; and parts of Nevada, Montana, Utah, New Mexico, and Wyoming (Fig. 4d). Southern California, and to a lesser extent Southern Arizona, is an exception to this because these are regions with substantial mining activity – oil and gas in Southern California and hard rock mining in Arizona – that are co-located with agricultural and industrial production in addition to high domestic water consumption.

The net export status of a county matters because a net virtual water exporter may have a very different approach to national water policy discussions than a net importer (Fig. 5). The (usually medium-sized) communities that sit in between the net-importing and net-exporting categories may take a distinct and more balanced position on national policy. Agricultural western communities tend to be net exporters, urban communities tend to be net importers, and rural eastern communities tend to be relatively neutral; midsize urban communities, such as those commonly found in the Midwest and East, may be relatively neutral as well.

3.5 Uncertainty Introduced by Consumption Coefficient Estimates

At the county-level, blue water footprint uncertainties introduced by consumption coefficients range several orders of magnitude in Mm^3 and relative percent (Fig. 6). The small rural counties of Bristol Bay Borough, Alaska and Kenedy County, Texas have the smallest water footprint uncertainties (<0.50 Mm^3). Los Angeles County, California has the largest water footprint uncertainty (4,050 Mm^3). After Los Angeles, 3 counties have a water footprint uncertainty between 3,000 – 4,000 Mm^3; 7 counties have a water footprint uncertainty between 2,000 – 3,000 Mm^3; 42 counties have a water footprint uncertainty between 1,000 – 2,000 Mm^3; and 79 counties have a water footprint uncertainty between 500 – 1,000 Mm^3. In relative terms, county-level water footprint uncertainty is 58.2 % – 99.9 % of a county's total water withdrawals. Relative water footprint variation tends to increase in the Eastern United States. However, in absolute terms, consumption coefficient variation is more important in the western U.S. due to the potentially large variation in virtual water outflows from the U.S.'s largest virtual water sources.

A community's role in the hydro-economic network, and its perspective on hydro-economic policy issues, can qualitatively change depending on our uncertainty. Uncertainties introduced by the consumption coefficients, which are quite large in absolute terms, roughly 17 % of U.S. counties can switch between roles as a net virtual water importer and exporter (+ or - $VW_{Balance}$) depending on the consumptive use assumptions (Fig. 7).

Results using the withdrawal-based ($CU = 1$) scenario are located in the Supplemental Information.

4. Conclusions

Mekonnen and Hoekstra reported that the U.S. combined blue and grey water footprint to be 320,496 Mm^3 and 874 m^3 capita^{-1} (Mekonnen and Hoekstra, 2011), which is the closest equivalent to the water sources used NWED. Results from NWED, which uses 4 consumptive use scenarios, for the median annual water footprint, F_{CUMed}, of the U.S. is 181,966 Mm^3 ($\mathrm{F}_{Withdrawal}$: 400,844 Mm^3; F_{CUMax}: 222,144 Mm^3; F_{CUMin}: 61,117 Mm^3). On a per-capita basis, results from NWED found the median U.S. water footprint (F'_{CUMed}) is 589 m^3 capita^{-1} ($F'_{Withdrawal\text{-}Basis}$: 1298 m^3 capita^{-1}; F'_{CUMax}: 720 m^3 capita^{-1}; F'_{CUMin}: 198 m^3 capita^{-1}). Given these statistics, the reported Mekonnon and Hoekstra water footprint and per capita water footprint falls between the *withdrawal-based (CU=1)* and maximum consumptive use coefficient (CU_{Max}) scenarios. Depending on the assumptions about consumptive use at the economic-sector level, these two datasets are in rough agreement regarding the scope of the U.S. water footprint.

The U.S. hydro-economic network is centered on cities and is dominated by the local and regional scales of trade, with medium-sized cities playing a disproportionate role. The proper framing of water governance and policy may be proportional to the structure of that network. Large cities source from all sizes of communities, but small and rural communities mostly source from other small communities, leading to a structural difference between the diversity and connectivity of urban and rural water supply chains. Further, medium-size metropolitan areas have a unique role in the U.S. hydro-economic as the link between rural virtual water production and urban virtual water consumption and are the most important single scale of community in the network. The U.S. hydro-economic network's connections and power structures are primarily local and regional except for the large metropolitan areas that operate at the national level and large-city ports that operate at the international level. This scale-specific finding is novel because most prior work on water footprints focuses on international trade.

Within the U.S., urban counties have a strong hydro-economic dependence on rural counties: there is a virtual water transfer of 114,953 Mm^3 from rural counties to urban counties, roughly a third of all virtual water flow in the U.S., with only a 33,876 Mm^3 return flow of virtual water. However, there is also strong urban-to-urban hydro-economic dependence. The virtual water transfer between urban counties is of the same magnitude as the rural-to-urban virtual water transfers (111,458 Mm^3). Taken together, rural-to-urban and urban-to-urban virtual water flow accounts for 58 % of U.S. domestic virtual water flow, illustrating the urban demand for not just water-intensive food sourced from rural counties, but also water-intensive power and industrial products sourced from urban counties.

The networked structure of water footprint sources creates systemic exposure to surface water scarcity and groundwater unsustainability at virtual water source locations. The U.S. and the global economy are particularly exposed to drought, and other system shocks, in the Western U.S. generally, especially in California, Central and Southern Arizona, Idaho, and the Great Plains. In the Eastern U.S., exposure to drought, or other system shocks, presents in South Texas, South Florida, the Chicago area, and the Lower Mississippi Valley. Because the whole U.S., and world, depend on these water supplies, these locations should be a priority for national water policy (Cooley and Gleick, 2012; Gleick et al., 2012); for public investment in water infrastructure to manage drought (Brown and Lall, 2006; Galloway Jr, 2011); and for innovative green infrastructure and market-based solutions that address water supply and demand problems. Additionally, the ports through which virtual water flows create transportation risks posed by war, strikes, tropical storms, earthquakes, and sea level rise. These locations should be a priority for national resilience policies and efforts, and alternative freight corridors should be developed so that port closures do not impact the ability of U.S. businesses to get their water-intensive goods to domestic and international markets (or vice versa).

The uncertainty introduced by water use data and consumption coefficients demonstrate the great need for the development of region-specific, sector-level water use data and consumption coefficients for the entire U.S. For example, water footprint uncertainty is roughly 58 % to over 99 % of a county's total water footprint, which increases in the eastern United States. However, in absolute terms, consumption coefficient variation is more important in the western U.S. due to the potentially large variation in virtual water outflows from the agricultural sector with largest blue water withdrawals.

Given the networked structure of the FEW system, the strong urban-rural dependence of FEW system flows, and the uncertainties presented by information gaps, future FEW system studies must address questions of worldview. For example, questions regarding which scale is the right scale (Vörösmarty et al., 2010; Vörösmarty et al., 2015) and which decision boundary is the best decision boundary (Rushforth et al., 2013) for understanding the FEW system interactions. In the U.S., the direct and indirect transfer of FEW system resources is concentrated at the mesoscale – regions and/or county equivalents – and not the national or global scales. This has implications for developing robust FEW system policy: the mesoscale is a manageable scale and there is the ability to manage aspects of FEW systems and craft FEW system interventions at this scale through extant and novel local and regional governance systems (McManamay et al., 2017).

NWED provides insight into which sectors and geographic areas need to be prioritized in the development of these consumption coefficients. The lack of certainty on consumption coefficients limits the ability to estimate or gauge one area's exposure to hydrological hazards in another area in its supply chain and must be addressed through the development of county- or region-specific and economic sector-specific consumption coefficients. We suggest starting with cities and irrigated agriculture in the Western U.S. due to the major influence that consumption coefficients have on water footprints, and because we lack locally accurate consumption coefficients to distinguish between regions this prevents us from accurately assessing local water balances or scarcity.

This paper presents the first spatially detailed and economically complete blue and grey water footprint of a major economy – using the novel data product, the National Water Economy Database 1.1. NWED contains spatially detailed, commodity and infrastructure specific commodity, value and virtual water flows, including groundwater and surface water, for the U.S. domestic and international hydro-economy. Findings from NWED qualitatively agree with previously published figures on the U.S. blue and grey water footprint and in order to consider uncertainty in water use data, NWED contains four consumptive use scenarios – a withdrawal-based scenario, and minimum, median, and maximum consumptive use scenario. Despite basic limitations imposed by the primary data sources, this is a robustly quantified blue water footprint; future refinements to NWED will seek to address these limitations and add additional functionality, such increased resolution on pass-through commodity flows. The empirical basis of this analysis, along with its economic completeness and spatial detail, make this result a landmark resource in the scientific discussion of water footprints, virtual water flow, and the sustainability and resilience of a nation's water resources in the connected global economy.

Code Availability:

The NWED 1.1 code will be made available on GitHub: https://github.com/NWED/v1.1.

Data Availability:

NWED version 1.1 is available at the Hydroshare data repository and can be accessed at: https://www.hydroshare.org/resource/84d1b8b60f274ba4be155881129561a9/

Appendices:

Appendix 1: Difference Between NWED Version 1.0 and 1.1

Data from NWED 1.0 have previously been published in by Rushforth and Ruddell (Rushforth and Ruddell, 2016). While the methodology is largely the same, there are key differences between the two versions of NWED.

- If updated disaggregation and attraction factors were available, these factors were updated.
- Specifically, agricultural disaggregation factors were updated at the crop level using the latest USDA NASS.
- Additionally, the mining sector been updated to have commodity code specific disaggregation factors using the location of mines and mineral production as disaggregation factors rather than employment.
- The power sector and domestic sector has been added to NWED version 1.1.
- Export virtual water flows have been disaggregated from virtual water flows to port cities.
- Import virtual water flows have been added to NWED version 1.1.
- The CU_{Max}, CU_{Med}, and CU_{Min} consumption scenarios were added to NWED version 1.1.
- Groundwater and surface water disaggregation of virtual water flows for withdrawal, CU_{Max}, CU_{Med}, and CU_{Min} scenarios were added.

Appendix 2: Commodity Trade Linkage Metrics

Each commodity trade linkage is measured by 15 metrics: – *t*, *$*, *tm*, $VW_{I_n,J_m,c,s,t,k,W_{Total}}$, $VW_{I_n,J_m,c,s,t,k,W_{SW}}$, $VW_{I_n,J_m,c,s,t,k,W_{GW}}$, $VW_{I_n,J_m,c,s,t,k,CU_{Max,Total}}$, $VW_{I_n,J_m,c,s,t,k,CU_{Max,SW}}$,

$VW_{I_n,J_m,c,s,t,k,CU_{Max,GW}}$, $VW_{I_n,J_m,c,s,t,k,CU_{Med,Total}}$, $VW_{I_n,J_m,c,s,t,k,CU_{Med,SW}}$, $VW_{I_n,J_m,c,s,t,k,CU_{Med,GW}}$,

$VW_{I_n,J_m,c,s,t,k,CU_{Min,Total}}$, $VW_{I_n,J_m,c,s,t,k,CU_{Min,SW}}$, $VW_{I_n,J_m,c,s,t,k,CU_{Min,GW}}$.

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Author Contribution:

R. Rushforth developed the NWED methodology and the executed code to carry out the methodology. R. Rushforth wrote the manuscript with help from B. Ruddell.

Competing Interests:

The authors declare that they have no conflicts of interest.

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Acknowledgements:

Funding for this research was provided by the National Science Foundation under award number ACI-1639529 (FEWSION). The opinions expressed are those of the authors, and not necessarily the National Science Foundation. The authors would like to acknowledge input from colleagues on the development of this manuscript and the anonymous peer referees of this paper.

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Table 1. Minimum, Median, and Maximum Consumption Use Coefficients (CU) Used to Estimate Consumptive Water Use in NWED[1]

Sector (*s*)	CU_{Min}	CU_{Med}	CU_{Max}	N[2]
Irrigated Agriculture	37 %	100 %	100 %	170
Domestic	0 %	13 %	73 %	229
Industrial	0 %	10 %	35 %	219
Livestock	10 %	100 %	100 %	158
Mining	0 %	14 %	86 %	141
Power	0 %	2 %	75 %	216

[1] Consumption coefficients adapted from (Shaffer and Runkle, 2007).

[2] The number of studies evaluated to approximate the consumption coefficients.

Table 2. U.S. Water Footprint and Virtual Water Statistics

Virtual Water Statistic	Withdrawal-Based ($CU = 1$)	CU_{Max}	CU_{Med}	CU_{Min}
Water Use – Domestic (Mm^3)	37,566	27,423	4,884	0
Water Use – Non-Domestic (Mm^3)	366,687	200,712	181,773	60,722
Water Use – Total (Mm^3)	404,253	228,135	186,657	60,722
Virtual Water Outflows, VW_{Out} (Mm^3)	362,690	196,857	178,622	59,870
Virtual Water Inflows, VW_{In} (Mm^3)	359,282	190,866	173,931	60,265
Virtual Water Balance, VW_{Bal} (Mm^3)	-3,409	-5,991	-4,691	395
Virtual Water Export, VW_{Export} (Mm^3)	10,671	9,039	7,739	2,653
Virtual Water Import, VW_{Import} (Mm^3)	7,263	3,048	3,048	3,048
Non-Domestic Water Footprint (Mm^3)	363,279	194,722	177,082	61,117
Total Water Footprint (Mm^3)	400,844	222,144	181,966	61,117
Total Water Footprint Per Capita (m^3 $capita^{-1}$)	1,298	720	589	198
Central Water Footprint Per Capita (m^3 $capita^{-1}$)	828	399	282	97
Fringe Water Footprint Per Capita (m^3 $capita^{-1}$)	981	368	250	83
Medium Water Footprint Per Capita (m^3 $capita^{-1}$)	1,705	1,076	936	315
Small Water Footprint Per Capita (m^3 $capita^{-1}$)	1,794	1,139	992	333
Micro Water Footprint Per Capita (m^3 $capita^{-1}$)	1,876	1,169	1,024	345
Non-Core Water Footprint Per Capita (m^3 $capita^{-1}$)	1,927	1,217	1,053	344
Rural to Urban VW Transfers (Mm^3)	114,953	70,648	66,524	22,496
Rural to Rural VW Transfers (Mm^3)	91,682	63,698	60,676	20,614
Urban to Urban VW Transfers (Mm^3)	111,458	39,921	32,338	10,459
Urban to Rural VW Transfers (Mm^3)	33,876	13,551	11,345	3,647

Table 3. Blue Virtual Water Transfers Between Urban and Rural Areas (Mm^3)

	Urban/Rural Classification	← Urban	Rural →						
		Central	Fringe	Medium	Small	Micro	Non-Core	$VW_{Out, CUMed}$	$VW_{Balance, CUMed}$
↑ Urban Rural ↓	Central	2,529	628	593	201	139	72	4,162	19,299
	Fringe	2,644	1,632	1,477	505	447	306	7,011	9,779
	Medium	**5,345**	3,174	14,316	4,311	3,371	1,992	32,510	26,102
	Small	4,022	2,318	8,626	4,111	3,607	2,138	24,822	2,757
	Micro	3,821	3,812	14,153	7,710	8,302	4,837	42,634	-15,755
	Non-Core	5,100	**5,227**	**19,446**	**10,740**	**11,013**	**8,218**	59,744	-42,182
	$VW_{In, CUMed}$	23,460	16,790	58,612	27,579	26,879	17,562	170,883	–

13 **Table 4. Urban-Rural Blue Virtual Water Transfer by Economic Sector (Mm^3)**

Origin County	Destination County	Sector	Virtual Water Flow (Mm^3)
Urban	Urban	Power	22
Urban	Urban	Agriculture	27,743
Urban	Urban	Industrial	2,694
Urban	Urban	Livestock	1,714
Urban	Urban	Mining	165
Urban	Rural	Power	6
Urban	Rural	Agriculture	9,583
Urban	Rural	Industrial	733
Urban	Rural	Livestock	950
Urban	Rural	Mining	73
Rural	Urban	Power	13
Rural	Urban	Agriculture	59,119
Rural	Urban	Industrial	955
Rural	Urban	Livestock	6,100
Rural	Urban	Mining	337
Rural	Rural	Power	159
Rural	Rural	Agriculture	53,731
Rural	Rural	Industrial	848
Rural	Rural	Livestock	5,764
Rural	Rural	Mining	175
Urban	Urban	Domestic	3,715
Rural	Rural	Domestic	1,168

14

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Table 5. U.S. Blue Virtual Water Exports and Imports to and Balances with World Regions

Region	Virtual Water Export (Mm^3)	% SW	% GW	Virtual Water Import (Mm^3)	% SW	% GW	Virtual Water Balance (Mm^3)
Canada	1,078	51%	49%	973	—	—	-105
Mexico	1,787	40%	60%	572	—	—	-1,215
Rest of Americas	672	67%	33%	597	—	—	-75
Europe	662	53%	47%	266	—	—	-396
Africa	448	33%	67%	43	—	—	-405
Southwest & Central Asia	355	45%	55%	102	—	—	-253
Eastern Asia	2,307	62%	38%	226	—	—	-2,081
Southeast Asia & Oceania	432	61%	39%	269	—	—	-163
Total	**7,741**	**52%**	**48%**	**3,048**	**—**	**—**	**-4,693**

SW – Surface Water; GW– Groundwater

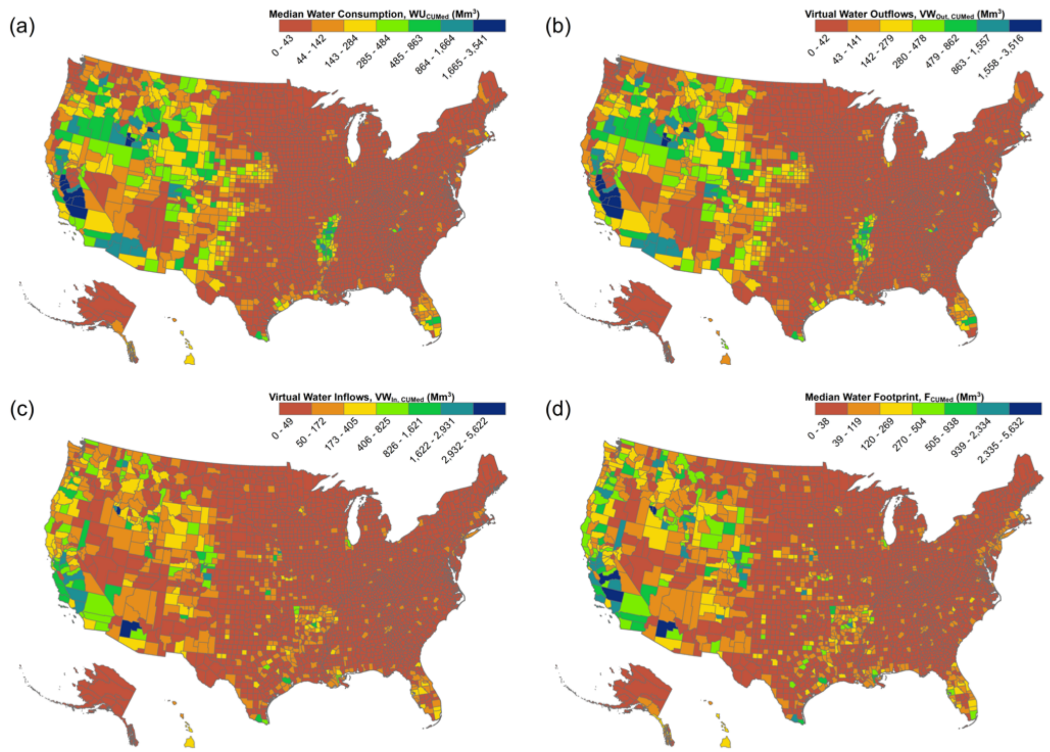


Figure 1. (a) Median county-level blue water consumption in the U.S. (b) Blue virtual water outflows from U.S. are concentrated in the western United States, particularly where irrigated agriculture is located, in addition to the High Plans, Mississippi Embayment, and south Florida. (c) Blue virtual water inflows are concentrated in Western U.S. cities, Western U.S. agricultural counties, metropolitan regions in the Eastern U.S., and in particular where a city also serves as a regional distribution center or has prominent food processing industry (Little Rock and Northwestern Arkansas, Chicago and Houston). (d) Annual Withdrawal-Based (CU_{Med}) Blue Water Footprint, F_{CUMed} [Mm^3], for U.S. Counties.

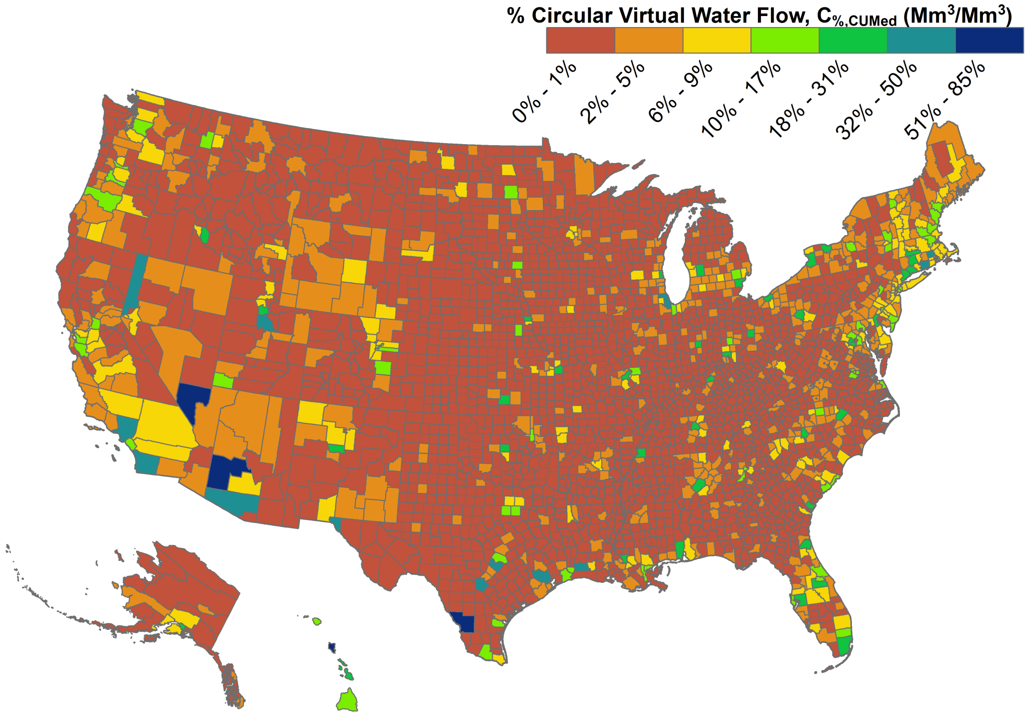


Figure 2. Circular blue virtual water flows (*CU_{Med}*), or blue virtual water flows that originate and terminate within the same county. This is a map of the use of "local water" in the hydro-economy. Phoenix, Arizona is a local water hotspot.

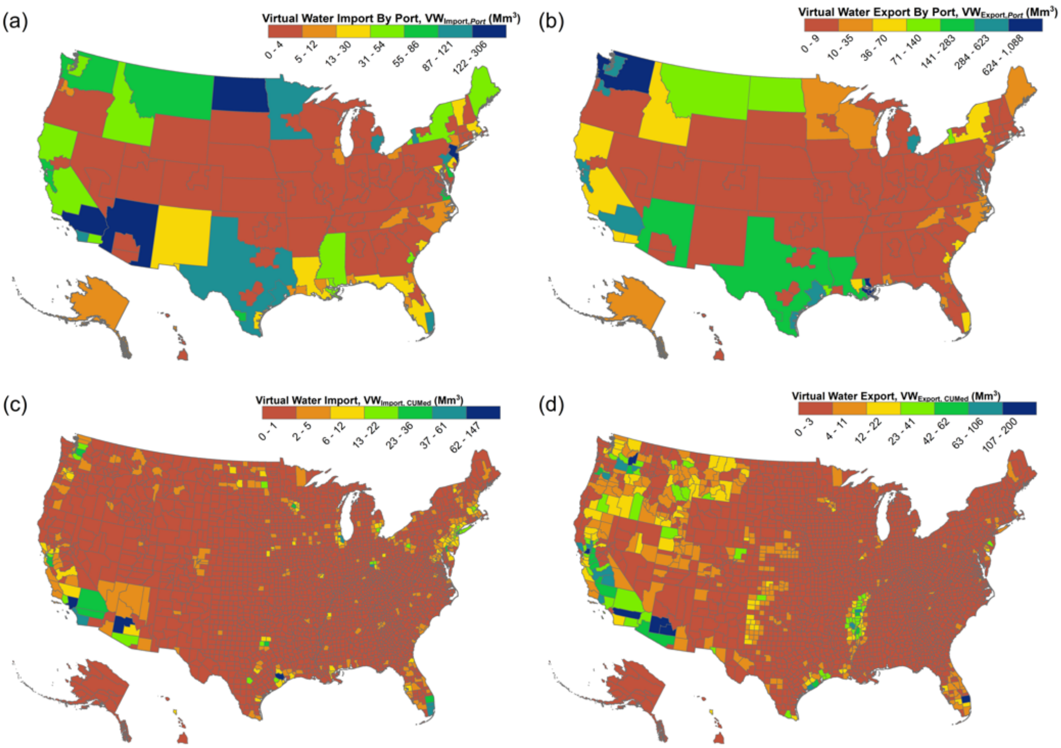
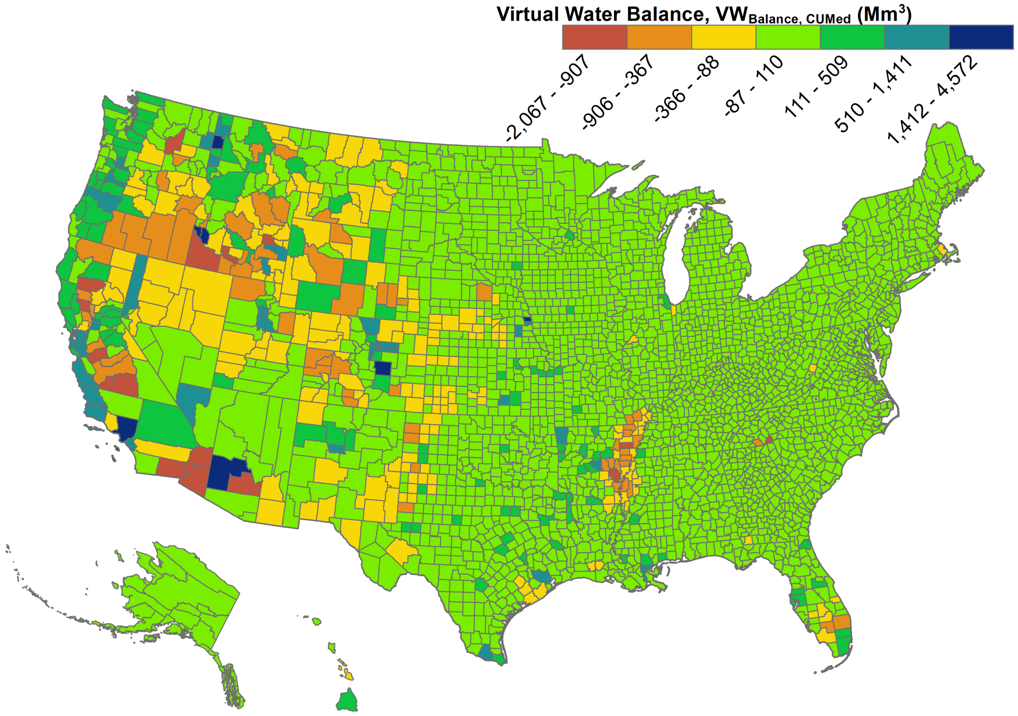


Figure 3. (a) The port and border regions through which the majority of U.S. blue virtual water imports (*CU_{Med}*) enter the U.S. market are primarily Los Angeles, New York, Arizona, North Dakota, Houston, Detroit, Buffalo and Detroit (FAZ's are used for port region boundaries). However, the whole land border with Canada and Mexico is import to U.S. virtual water import. (b) The ports through which the majority of U.S. virtual water exports (*CU_{Med}*) enter the global market are located in natural hazard prone areas along the West Coast, Gulf Coast, and Eastern Seaboard. (c) Cities such as Los Angles, Phoenix, Houston, New York City, Miami, Dallas, Seattle, and the San Francisco Bay area are the major destinations of U.S. virtual water imports (*CU_{Med}*). (d) U.S. virtual water exports (*CU_{Med}*) originate from California's Central Valley; Southern California and Southwest Arizona; the Columbia River Basin and the Pacific Northwest; Central Nevada and Northwest Utah; the Ogallala Aquifer region of the Midwest; the Texas Gulf Coast; the Mississippi Embayment; and South Florida.

Figure 4. (a) The county-level agricultural blue water footprint of the U.S. (b) The county-level industrial blue water footprint of the U.S. (c) The county-level livestock blue water footprint of the U.S. (d) The county-level mining blue water footprint of the U.S. (e) The county-level electrical power blue water footprint of the U.S. (f) The county-level domestic blue water footprint of the U.S.



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60 **Figure 5. The blue virtual water balance ($VW_{Balance, CUMed}$) for each U.S. county. Areas in**
61 **the Southwest U.S., Central Valley of California, Snake River Valley, Mississippi**
62 **Embayment, South Florida, South Texas, and the High Plains have virtual water outflows**
63 **that outstrip virtual water inflows.**

64

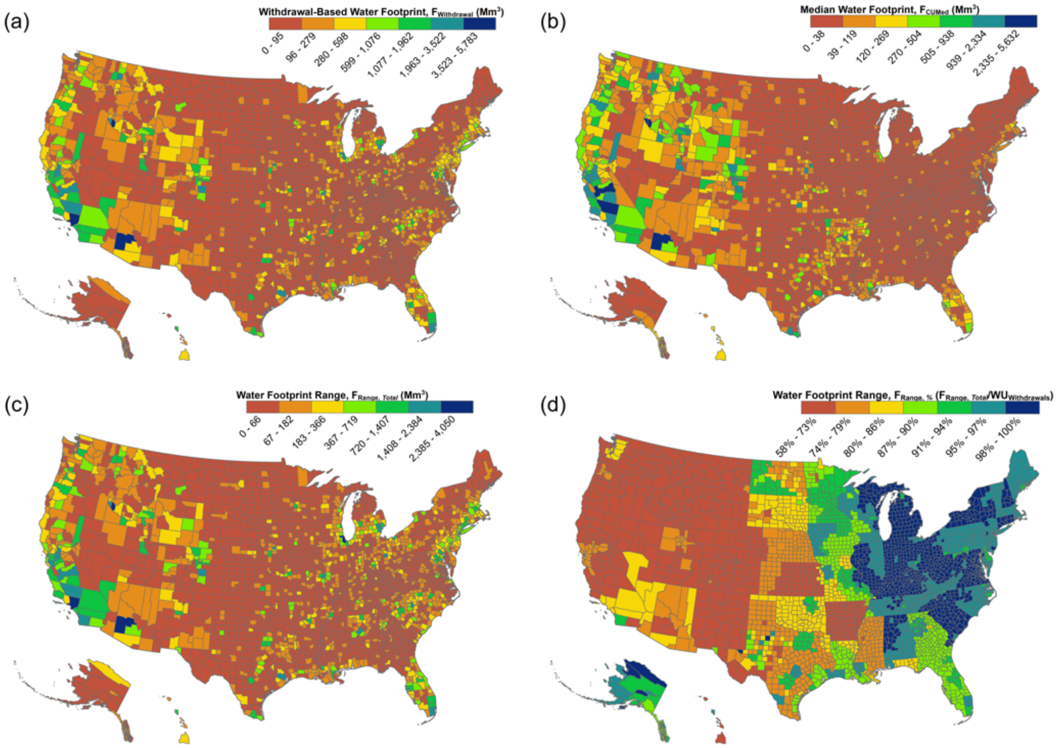

Figure 6. (a) The annual withdrawal-based blue water footprint, $F_{Withdrawal}$ [Mm^3], for U.S. Counties. (b) The annual med (CU_{Med}) blue water footprint, F_{CUMed} [Mm^3], for U.S. Counties. The minimum scenario was constructed applying minimum sector-level consumption coefficients. The range of uncertainty in the blue water footprint, F_{Range} [Mm^3], for U.S. Counties. F_{Range} is computed as the range between the highest and lowest water footprints of the withdrawal-based and three consumption-based scenarios. Absolute water footprint uncertainties are highest in the west, but relative uncertainties are highest in the east. (d) Relative water footprint variation tends to increase in the Eastern United States and county-level water footprint uncertainty can range between 58.2 % in much of the Western United States to 99.9 % in parts of the Eastern United States.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-650
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 21 November 2017

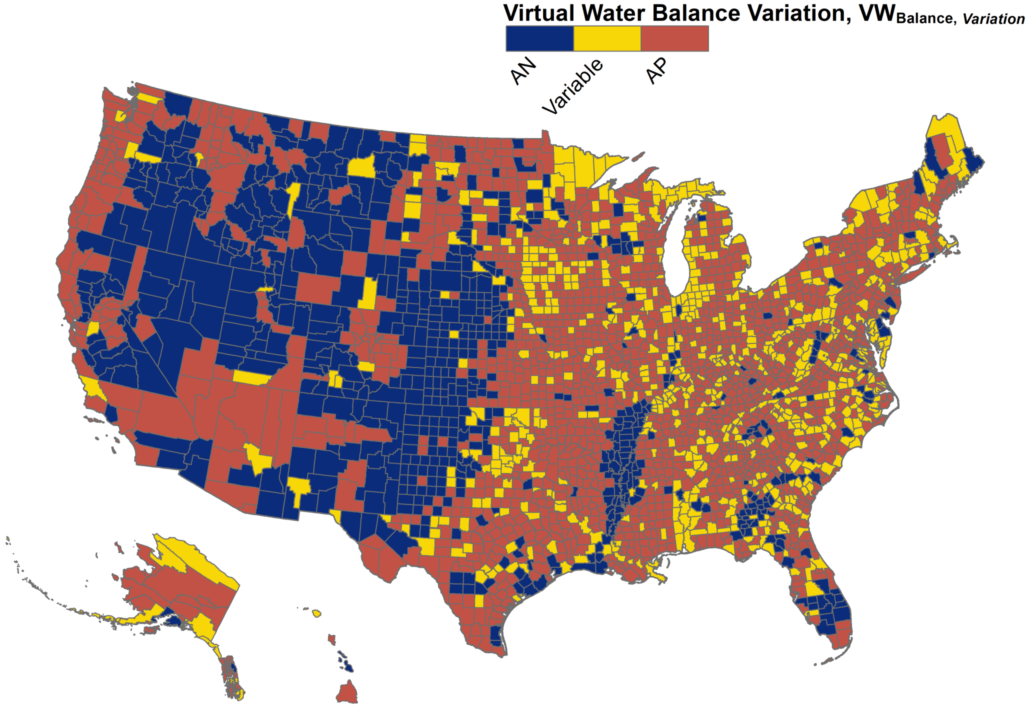

Figure 7. For many counties, whether a county has a negative or positive virtual water balance varies under the consumptive use scenarios. Counties in blue always have a negative virtual water balance (AN) and virtual water outflows are always greater than virtual water inflows. Counties in red always have positive virtual water balances (AP) and virtual water inflows are always greater than virtual water outflows. Counties in yellow have borderline-neutral net virtual water balances that depend on the consumptive use uncertainty (Variable).