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Integrating physical and economic data into experimental water accounts for the United States: Lessons and opportunities

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ABSTRACT

Water management increasingly involves tradeoffs, making its accounting highly relevant in our interconnected world. Physical and economic data about water in many nations are becoming more widely integrated through application of the System of Environmental-Economic Accounts for Water (SEEA-Water), which enables the tracking of linkages between water and the economy. We present the first national and subnational SEEA-Water accounts for the United States. We compile accounts for water: (1) physical supply and use, (2) productivity, (3) quality, and (4) emissions for roughly the years 2000 to 2015. Total U.S. water use declined by 22% from 2000 to 2015, falling in 44 states though groundwater use increased in 21 states. Water-use reductions, combined with economic growth, led to increases in water productivity for the overall national economy (65%), mining (99%), and agriculture (68%). Surface-water quality trends were most evident at regional levels, and differed by water-quality constituent and region. This work provides (1) a baseline of recent historical water resource trends and their value in the U.S., and (2) a roadmap for the completion of future accounts for water, a critical ecosystem service. Our work also aids in the interpretation of ecosystem accounts in the context of long-term water resources trends.

1. Introduction

Information about water assets and their use, quality, and economic value in a country is typically disaggregated across a variety of agencies (e.g., agriculture, environmental, and mining authorities and public utilities) and at different levels of government (e.g., national, state, and local; United Nations, 2012, Vardon et al., 2018). Moreover, data are collected for an agency's intended purpose(s) but are typically not compiled into a comprehensive water information system. With such fragmented data, it is difficult to confidently make connections between environmental information and related social and economic data. Systematizing scattered data and organizing it to connect to other types of data are some of the motivations for the establishment of the System of Environmental–Economic Accounts (SEEA) statistical standard (U.N. et al., 2014a; U.N. et al., 2014b, Vardon et al., 2018). We employ the SEEA-Water accounting framework[1] (United Nations, 2012) to address these challenges in the U.S., reorganizing and enhancing the usefulness of water-related data collected by the U.S. Geological Survey (USGS), U.S. Environmental Protection Agency (USEPA), Bureau of Economic Analysis (2017), and others. In this paper, we develop a set of accounts based on SEEA-Water to provide a clearer picture of (1) linkages between water and state and national economies (i.e., how water flows from the environment, between different water uses or industries, and back to the environment), (2) important changes in the quality of the Nation's water resources and their use and value over time, and (3) connections to related SEEA accounts on land and ecosystems (Heris et al., this issue, Warnell et al., 2020 this issue, Wentland et al., 2020 this issue). Water accounts can provide trusted data to address water

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[1] SEEA Water was established as an interim international statistical standard at the 2007 meeting of the U.N. Statistics Commission, pending the elevation of the SEEA to an international statistical standard (which occurred in 2012). The concepts underlying SEEA Water and the SEEA Central Framework are identical and their accounting tables are substantially the same.

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resource management challenges at national and subnational scales, as described below and in the discussion.

Scientific and popular understanding of the importance of water to economic activity, and of the supply and regulation of water as an ecosystem service,[2] has been increasing locally, regionally, nationally, and internationally (United Nations, 2012, USEPA, 2013, Garrick et al., 2017). Water-scarce countries and regions, such as Australia, have used water accounts to manage their resources and encourage industries to become more efficient in their water use (Vardon et al., 2007). In places like Sweden, where water scarcity is a relatively low concern, water accounts have been useful in developing regional plans for investments like water treatment facilities (Vattenmyndigeterna, 2017). For some types of economic activity, like irrigation or cooling of thermoelectric power plants, water use can be substantial (Dieter et al., 2018). As the demand for water increases, allocations between households, agriculture, and other economic activities with high water use will need to be made. Similar water allocation challenges surround issues related to virtual water, interbasin transfers, and ecosystem water needs. In some parts of the U.S., these tradeoffs are already happening. For example, in Colorado, population growth in the Front Range cities of the Rocky Mountains is driving demand for water that was previously used for agriculture in eastern Colorado, as well as interbasin transfers from the Colorado River basin. Legal agreements governing water use in the Lower Colorado River basin have resulted in the construction of water accounts for that watershed (Bureau of Reclamation, 2018). This is the only place in the U.S. where this has occurred, though calls for water accounts in California have emerged in the midst of recent extreme drought conditions there (Escriva-Bou et al., 2016). Combining economic and physical water data allows connections between water and the economy to be more easily identified, which can better inform policy and management of both natural resources and economic activities (Tidwell et al., 2018). For instance, through a related wealth accounts framework, Fenichel et al., 2016 combined physical and economic data on groundwater depletion in Kansas to value this asset and consider how offsetting investments can help maintain the state's overall wealth. Additionally, water accounts have become pivotal in key macroeconomic models that assess how changes in water availability will affect economic output (Liu et al., 2016), economic growth (Barbier, 2004, Cole, 2004), and development (Brown and Lall, 2006).

Accordingly, the SEEA Central Framework (SEEA-CF) provides guidelines for the compilation of three main types of accounts: physical flow accounts, economic activity related to the environment accounts, and natural-resource asset accounts (U.N. et al., 2014a). SEEA-CF and its subsystem for water (SEEA-Water) (United Nations, 2012) provide a framework to organize information about the contribution of water and other resources such as land, energy, materials, agriculture, forestry, and fisheries to national and subnational economies. Additionally, water accounts serve as one of four thematic accounts in the related SEEA Experimental Ecosystem Accounting (SEEA-EEA) framework, along with land, biodiversity, and carbon (U.N. et al., 2014b). SEEA-EEA addresses ecosystem services that fall fully outside the production boundary of the SNA – i.e., regulating and cultural ecosystem services – and adds spatial data on the supply and use of these services (e.g., Heris et al., this issue, Warnell et al., 2020 this issue). Established, comprehensive frameworks like the System of National Accounts for economic data (SNA, European Commission et al., 2009) or the SEEA for environmental-economic data allow data to be assembled into a consistent system, enabling the identification of missing or inconsistent information (Vardon et al., 2018).

In this paper, we used SEEA-Water as the starting point, populated different pieces of the framework with existing data, and identified key data gaps that, if filled, would give a more comprehensive view of the state of U.S. water resources. In this way, we identified inconsistencies and missing information. Where possible, we filled data gaps using other sources and appropriate statistical techniques. By organizing water data into the SEEA-Water framework, we obtained a more complete, consistent time series of water information for the U.S. covering roughly the years 2000 to 2015. Like other SEEA and SNA accounts, water accounts when properly implemented can provide a baseline set of trusted statistics that is strongly needed in an increasingly fragmented information landscape. Our work is part of a larger effort to develop natural capital accounts in the U.S. based on the SEEA (Boyd et al., 2018), including land (Wentland et al., 2020 this issue) and ecosystem (Heris et al., this issue, Warnell et al., 2020 this issue) accounts. Specifically, water accounts can help to tell a larger story of environmental and socioeconomic change when combined with other SEEA accounts, which we cover in further detail in the discussion. For instance, land, water, and ecosystem accounts can be used to jointly evaluate the effects of land-use change on water quality (Bariamis et al., 2017, Warnell et al., 2020 this issue, Wentland et al., 2020 this issue), while water and ecosystem accounts can similarly be used to quantify the role of trees and urban green space in promoting water quality in cities (Heris et al., this issue).

Our work focused primarily on the development of physical flow accounts for water, documenting its extraction and use, quality, and emissions.[3] We also estimated water productivity, i.e., gross domestic product (GDP) generated by a given industry divided by its water use, and developed initial water quality and emissions accounts. Due to data limitations, we did not compile accounts for water assets, hybrid physical supply and use, collective consumption expenditures of the government, or national expenditures and financing for water (United Nations, 2012). We achieved five specific outcomes: (1) the development of comprehensive physical supply and use tables (PSUTs) for water, organized by economic activity as defined by the North American Industry Classification System (NAICS, Office of Management and Budget 2017); (2) estimates of water productivity, based on these PSUTs and corresponding economic data from the national accounts; (3) water-quality accounts for surface and groundwater; (4) water emissions accounts for point sources; and (5) conceptual modeling of the connections between water use, water quality and economic activity, using expert elicitation. Repeated analysis using the methods presented will enable more robust time-series analysis and use of water accounts in resource management. Such accounts would be completed every five years at a minimum but ideally more frequently as new data allow.

2. Methods

We developed PSUTs and water productivity, quality, and emissions accounts (United Nations, 2012). We summarized these accounts at the national level, and for PSUTs and water productivity accounts provide results for all 50 states plus Washington, DC. Water-quality accounts data were available for only the 48 coterminous states. Additionally, we

[2] In light of the revision process for the SEEA Experimental Ecosystem Accounting (SEEA-EEA) framework, Portela et al. (2019) provide an in-depth discussion of the role of water supply in ecosystem accounting—specifically related to the quantity, timing, location, and quality of flows of water. The SEEA-EEA also addresses other water-related ecosystem services, including water purification (La Notte et al., 2019) and flood mitigation (Crossman et al., 2019).

[3] Definitions are found in the glossary of the SEEA Water guidelines (U.N. 2012, pg. 193). Several key definitions provided by that glossary include: Abstraction: "The amount of water that is removed from any source, either permanently or temporarily, in a given period of time for final consumption and production activities." Returns: "Water that is returned into the environment by an economic unit during a given period of time after use." Use: "Water intake of an economic unit" both abstracted from the environment or distributed to the economic unit by a different economic unit.

summarized results for PSUTs, water productivity, and water-quality accounts for six regions roughly following the USEPA, 2012 definitions: Northeast (Maine south to Maryland and West Virginia), Midwest (Ohio west to Missouri, Iowa, and Minnesota), Southeast (Virginia, Kentucky, Arkansas, and Louisiana, plus all states to their southeast), Plains (Montana, Wyoming, and the Dakotas south to Texas), Northwest (Washington, Oregon, and Idaho), and Southwest (New Mexico and Colorado west to California; see Supplemental Information 1). We included state-level accounting tables as Supplemental Information 4. Additionally, we conducted an expert elicitation to conceptually model the linkages between water quality and water use. In the discussion, we describe data gaps for water asset accounts, which prevented us from compiling these accounts but suggest a path forward for their completion in the future.

2.1. Physical supply and use accounts

States agencies collect most water-use data in the U.S., which is compiled by the USGS. The USGS also collects data from local, Federal, and non-governmental entities, and checks data for accuracy and to fill data gaps for areas or water-use categories that are not fully reported. Standardized methods and procedures for data collection and estimation are used (Bradley, 2017). These more complete data are distributed in a report every 5 years, most recently for 2015 (Dieter et al., 2018). These reports are the most comprehensive U.S. government-assembled information source about water use. The composition of water-use categories has changed somewhat over time (https://water.usgs.gov/watuse/WU-Category-Changes.html). However, the goal of the USGS National Water-Use Science Program remains to collect consistent and complete water-use data from all available sources that measure water use, improving the data using modeling and interpolation methods where needed. Since the 1950s, water use (withdrawals, deliveries, use, and returns) has been reported across various categories for states, counties, watersheds, and aquifers (see https://water.usgs.gov/watuse/WU-Category-Changes.html). Categories of use include: public supply, domestic (i.e., households), irrigation (crops and golf courses), aquaculture, mining, thermoelectric power, industrial, and livestock, among others. Some important information is lacking though (see the final paragraph of this section and Section 4.2.1). The USGS is aware of many of these issues (National Academy of Sciences, 2002, USEPA, 2013, Escriva-Bou et al., 2016) and aspires to improve their water information system (Alley et al., 2013).

We compiled water-use data (freshwater and saline water from groundwater and surface-water sources) from USGS reports for the years 2000 (Hutson et al., 2004), 2005 (Kenny et al., 2009), 2010 (Maupin et al., 2014), and 2015 (Dieter et al., 2018). We then aligned these water-use categories into PSUTs as best as possible using the NAICS 2017 industrial classification codes (Office of Management and Budget 2017), acknowledging that the eight water-use categories cover very broad swaths of the economy. When updated data were available for earlier years (i.e., where new data or methods have since been applied to earlier years and referred to as ‘best available data’), we substituted updated values for those drawn directly from the earlier published reports. In addition to the eight USGS water-use categories, we developed data for two other categories: hydroelectric power generation and golf course irrigation (Table 1). USGS reported data for these uses in its 5-year reports prior to the year 2000, defensible estimation methods exist for them, and new estimates enable cleaner matching of water-use and economic data (e.g., by splitting “irrigation” into economically distinct crop and golf course irrigation).

Water use for hydroelectric power generation can be measured in two ways: evaporative loss from reservoirs with hydroelectric facilities at the dam, and non-consumptive instream water that is used to power turbines. For evaporative losses, we used a combination of state-level (1) Energy Information Administration data on annual hydroelectric power generation (EIA, 2015) and (2) coefficients developed by the National Renewable Energy Laboratory on evaporative water losses per kilowatt hour of electricity generation, using the national average for states where data were lacking (Torcellini et al., 2003). While we exclude instream hydroelectric water use from our PSUTs, as it was last compiled nationally in 1995 (Solley et al., 1998) and its water-use values dwarf other categories, we discuss it further in the context of national PSUTs in the Results.

Golf course irrigation water use is reported by the USGS for some states; in other cases, it is combined with crop irrigation in a total irrigation estimate. For states and years where specific golf course irrigation data were lacking, we first estimated the number of courses by state and year using (1) spatial data on the current location of U.S. golf courses (UCLA Geoportal, 2018) and (2) industry information on changes in the number of golf courses over time, to estimate the number of courses by state and year (National Golf Foundation, 2017). We combined our estimates of the number of courses with industry data about per-course water use for the years 2008 and 2014 in seven agronomic regions with different average water-use levels (Golf Course Superintendents Association of America, 2009, Association of America, 2015). We reported these values as distinct from total irrigation and deduct the same value from total irrigation to avoid double counting and generate estimates of both crop irrigation and golf course irrigation for all geographies and years.

Some water-use data were lacking for several key components needed to build full depictions of PSUTs (enabling “closing of the water budget”). These include data on the movement of water flowing between public supply and use, and water volumes returned to the environment either through distribution losses (calculated as the difference between water produced and billed by water suppliers, e.g., Australian Bureau of Statistics, 2016) or intentional returns. For the latter, the USEPA’s Permit Compliance System and Integrated Compliance Information System (PCS-ICIS) database compiles individual Discharge Monitoring Report data (DMR, USEPA, 2018a), providing monthly return flows for most publicly owned wastewater facilities and some industrial facilities, though this data source has limitations (discussed below). We thus included DMR return flows data in our PSUTs only at the national scale. To track water flows between abstraction and use, all states reported public-supply deliveries to households in USGS reports, and some states reported deliveries to industrial and thermoelectric uses (for some years). These data, coupled with complete reports of self-supplied withdrawals and consumptive water-use data for thermoelectric power in 2010 and 2015 and crop irrigation in 2015, allowed estimation of return flows in these industries and years. Additionally, we lack nationwide, time series data on the use of “green water” by crops (i.e., rainfall that enters the soil and can be used by crops or “soil irrigation water”), which is important to agriculture and would ideally be included in PSUTs (e.g., Australian Bureau of Statistics, 2016). Finally, due to data limitations, we do not include imports and exports of water between the U.S. and Canada and Mexico, nor between U.S. states, though this would be proper to include in SEEA-Water. These data gaps, along with coarse temporal resolution and limited specificity in use categories, constrain the level of detail that we could include in the PSUTs.

2.2. Water productivity accounts

Water productivity is estimated by dividing GDP for a particular industry or the entire economy by its water use, providing a measure of how efficiently water is used as an input to economic activity. We estimated state, regional, and national level water productivity for the years 2000, 2005, 2010, and 2015, by dividing GDP (in constant 2009 dollars, BEA 2017) by water use in each year. We estimated water productivity across the entire economy using two measures: first, using water-use data directly reported by USGS, and second, by adding water-use estimates for golf course irrigation and evaporative losses from reservoirs with hydroelectric power generation facilities for all states,

Table 1
USGS water-use categories, descriptions and correspondence to North American Industry Classification System (NAICS) industry classification.

Water-use categories	Category description (Dieter et al., 2018 pgs. 59–61)	Closest corresponding NAICS 2017 industry classification
USGS water-use categories		
1. Public Supply	"Water withdrawn by public and private water suppliers that furnish water to at least 25 people or have a minimum of 15 connections. Public suppliers provide water for a variety of uses, such as domestic, commercial, industrial, thermoelectric-power, and public water use."	NAICS 221310. Water supply and irrigation systems*
2. Domestic	"Water used for indoor household purposes such as drinking, food preparation, washing clothes and dishes, flushing toilets, and outdoor purposes such as watering lawns and gardens" (12% self-supply, 88% from public supply deliveries in 2015; Dieter et al., 2018).	No NAICS code for households
3. Irrigation	Self-supplied "water that is applied by an irrigation system to assist crop and pasture growth, or to maintain vegetation on recreational lands such as parks and golf courses."**	NAICS 111. Crop production**
4. Aquaculture	Self-supplied "water use associated with the farming of organisms that live in water (such as finfish and shellfish) and offstream water use associated with fish hatcheries."	NAICS 1125. Animal aquaculture
5. Mining	"Water used for the extraction of naturally occurring minerals including solids (such as coal, sand, gravel, and other ores), liquids (such as crude petroleum), and gases (such as natural gas)."	NAICS 21. Mining
6. Thermoelectric Power	Self-supplied water "used in the process of generating electricity with steam-driven turbine generators."	NAICS 2211. Electric power generation
7. Industrial	Self-supplied water withdrawals for "fabrication, processing, washing, and cooling" of manufactured products.	NAICS 31–33. Manufacturing
8. Livestock	Self-supplied "water associated with livestock watering, feedlots, dairy operations, and other on-farm needs."	NAICS 112. Animal production (excluding 1125)
Additional water-use estimates presented		
9. Hydroelectric power generation	Water used for generating electricity at plants where turbine generators are driven by moving water, plus evaporative losses from hydroelectric power reservoirs.	NAICS 2211. Electric power generation
10. Golf course irrigation	Self-supplied water used to maintain vegetative growth on golf courses, including water lost in conveyance or due to inefficiencies of irrigation systems.	NAICS 713910. Golf courses and country clubs

*NAICS category 221310 is defined as "establishments primarily engaged in operating water treatment plants and/or operating water supply systems. The water supply system may include pumping stations, aqueducts, and/or distribution mains. The water may be used for drinking, irrigation, or other uses" (OMB 2017, pg. 122). This is distinct from the application of water to crops (NAICS 111).
**By subtracting golf course irrigation estimates from total irrigation, we obtain a more exclusive estimate of water use for crop irrigation, i.e., NAICS code 111.

and then deducting household self-supply and public supply deliveries to households. This adjustment brings the water-use data closer to the system boundaries of the SNA for calculating GDP. In theory, GDP should include household production of all goods, including water, which in this case should be added to the production of the water supply industry. However, in practice, water accounts typically separate self-supplied domestic production of water, which we maintain for consistency.

Additionally, we estimated water productivity for agriculture (summing irrigation, livestock, and aquaculture water uses) and mining, by dividing industry-specific GDP by industry-specific water use. Given our lack of data on soil irrigation water use by agriculture, our agricultural water productivity estimates reflect the economic value produced by water *actively supplied* by irrigation. In other words, they overestimate *total* agricultural water productivity (e.g., Australian Bureau of Statistics, 2016), which would be more homogeneous across the U.S. (i.e., if rainfall for wetter parts of the country were included in water productivity accounts, productivity in those regions would be lower and more comparable with that of drier regions). Because water-use data currently exist only for industrial self-supply of water, and not for public supply deliveries to manufacturing, accurate water productivity estimates regrettably cannot be generated for overall manufacturing or specific industries. Water productivity estimates are also not possible when GDP data are unavailable for individual industries (e.g., golf courses, where corresponding GDP data are only available for their higher-level 3-digit NAICS code, "Amusement, gambling, and recreation industries").

2.3. Water-quality accounts

The USGS National Water-Quality Assessment (NAWQA) project has tracked and reported nationwide water quality time-trend data in both surface-water bodies (Oelsner et al., 2017) and groundwater (Lindsey and Rupert, 2012), building on previous water-quality monitoring by the USGS and 73 other Federal, State, Tribal, and local monitoring organizations in the United States. Drawing on state and national databases, Oelsner et al. (2017) synthesize surface water quality trends for almost 1400 sites. As part of this process, the data underwent an extensive synthesis, screening, and cleaning process as well as sensitivity analyses; among other requirements, records were required to be located near a stream gage and to have at least 70% of years during a trend period with at least one sample per quarter, to maintain an adequate sampling effort for trend analysis. This surface water-quality monitoring network is opportunistic, including sites that are accessible and used for local, state, and federal agency monitoring efforts, rather than being systematically designed to provide a statistically representative national picture. We discuss further applications of these data related to drinking water standards and other effects on people and ecosystems in Section 4.2.3.

Surface water-quality data quantify changes in chemical, pesticide, and ecological parameters between start years of 1972, 1982, 1992, 2002, and an end year of 2012 (Oelsner et al., 2017). Water quality concentrations and loads are reported for 19 chemical parameters, 29 pesticide types, and over 30 biological metrics. We chose six water-quality constituents for inclusion in water-quality accounts, those having broad geographic coverage and likely connections with waters users (see expert elicitation below), as well as aquatic ecosystem health: chloride, nitrate, total nitrogen, total phosphorus, total suspended solids, and specific conductance. We summarized trends in concentration for these six constituents for USEPA, 2012 regions and states. However, since site data are spatially explicit, they could easily be summarized by Hydrologic Unit Code (HUC) watersheds in the future. We reported how many sites observed significant increases, significant decreases, or no significant change in pollutant concentration between 2002 and 2012 (measured as likely and somewhat likely change, with likelihood values of 0.7 or greater, Oelsner et al., 2017).

Groundwater data cover one "decadal" period, with the first NAWQA sampling period from between 1988 and 2000 and the second between 2001 and 2010 (Lindsey and Rupert, 2012). A third sampling is currently underway, allowing a continuation of time trend data going forward. This sampling effort covers 1235 individual wells in 56 well networks, which accounts for almost 80% of estimated groundwater withdrawals for drinking water in the U.S. Each well network typically includes 20–30 shallow wells sharing common hydrogeology and land-use (i.e., agricultural or urban) characteristics. Monitored groundwater-quality constituents include 13 inorganic compounds, six pesticides, and five volatile organic compounds (Lindsey and Rupert, 2012). Of these, we included concentrations of three water-quality constituents with wide geographic coverage and likely connections to water uses: chloride, nitrate, and dissolved solids. While a partial reflection of overall groundwater quality, these constituents reflect important anthropogenic influences like agriculture (nitrate, chloride) and road salting (chloride, total dissolved solids). We reported, at the national scale, the number of networks observing significant increases, significant decreases, or no significant change in water quality from the opening to the closing period, measured using the Wilcoxon-Pratt signed-rank test with 90% confidence level (Lindsey and Rupert, 2012).

2.4. Water emissions accounts (point-source loads)

Point source water-emissions data are compiled by the USEPA in two related databases – the PCS-ICIS and Toxics Release Inventory (TRI) (USEPA, 2018a). Both databases are used for regulatory enforcement of water quality, with neither designed as a statistical representation or complete sampling of water emissions. USEPA's Water Pollutant Loading Tool (https://www.epa.gov/nutrient-policy-data/nitrogen-and-phosphorus-pollution-data-access-tool), which allows flexible queries of these databases, is useful for constituent load accounting. These databases also have several limitations for seamless use in water accounting. The DMR data that are used to produce industrial emissions reports use the Standard Industrial Classification (SIC) – an old system that was replaced in the U.S. by NAICS in 1997. Converting SIC to NAICS codes requires added work and introduces uncertainty. DMR data are also self-reported into the PCS-ICIS system by industries, meaning that reporting errors occur with some frequency. Finally, PCS-ICIS data do not account for emission flows from industrial facilities directly to wastewater treatment plants (WWTPs), which would be useful in accounts. However, the vast majority of major- and many minor-sized WWTP facility water emissions are obtainable from PCS-ICIS (Maupin and Ivahnenko, 2011; Skinner and Maupin, 2019). The related TRI database reports on emissions to WWTPs, but the two databases are too dissimilar in reported facilities and water pollution constituents to be easily merged. We thus did not use TRI data in our initial water emissions account.

For this account, we report national-scale water emissions from the PCS-ICIS database by NAICS codes for the year 2015. While we could report results at finer scales, i.e., the state level, a national analysis minimizes the likelihood that erroneous data will give an inaccurate view of state-level water emissions trends. We selected the year 2015 as a more recent year (assumed to be less error-prone) that matches with water use and productivity data. We report on five groups of constituents: nitrogen, phosphorus, organic enrichment, solids, and metals (for parameter definitions, see Section 3.4). We report emissions for the top 15 NAICS codes emitting these parameters; these are responsible for > 95% of all nitrogen, phosphorus, and metals, 88% of organic, and 71% of solids emissions.

2.5. Expert elicitation to conceptually model freshwater quality and water use

To better describe the connections between water quality and water use, we conducted an expert elicitation to conceptually model these linkages in semi-quantitative terms. We received responses from 16 USGS and USEPA experts who generally specialize in the relationship between water uses and water-quality characteristics (individuals and their affiliations are provided as Supplemental Information 2). We first asked respondents to identify whether each of 14 water-quality constituents[4] had a strong, moderate, or minor effect on water use by the eight USGS water-use industry categories (Table 1), and whether that effect was positive or negative (for instance, salinity that could negatively impact irrigation water and corrode pipes for various water uses). We next asked these experts to similarly identify the impacts of each of these water uses on water quality (for instance, the release of particular pollutants or changes in temperature from using water for cooling). We allowed respondents to qualify their responses about each linkage – for example, differences or uncertainties in different parts of the country, times of year, or for specific industries within the eight broad USGS water-use categories. Our list of water-quality constituents differs from those evaluated in the water quality and emissions accounts. Those accounts had a more limited number of constituents with spatio-temporal coverage needed to produce national accounts, while the 14 evaluated here would be potentially informative in future water accounts.

After collecting individual responses, we held a series of conference calls to develop consensus about the relative magnitude and qualitative uncertainty of water quality-water use linkages. We produced diagrams illustrating the effects of (1) water quality on water use and (2) water uses on water quality, and recorded all appropriate uncertainties and contextual information.

3. Results

3.1. Physical supply and use accounts

Nationally, total water use declined by 22% from 2000 to 2015 (Table 2). This continues a longer-term trend, with total and per capita U.S. water use declining since 1980 (Donnelley and Cooley 2015, Dieter et al., 2018). Industries whose water use declined included mining (3%), self-supply domestic (household) and public supply (9–10%), livestock (11%), crop irrigation (15%), manufacturing (24%), and thermoelectric power generation (32%); in contrast, aquaculture water use increased (29%). The largest water uses in 2000 and 2015, respectively, were thermoelectric power (45% and 39%), irrigation (32% and 35%), public supply (10% and 12%, of which 51%[5] and 59% went to households), manufacturing (5% and 4%), and aquaculture (1% and 2%). Mining, livestock, and self-supply domestic use each accounted for about 1% or less of national water use in both years (Hutson et al., 2004, Dieter et al., 2018).

Total water use from 2000 to 2015 declined in 44 states (15 having declines of 25% or greater), largely due to reduced thermoelectric power water use. In some states, notable reductions were also seen in irrigation (California, Georgia, Texas) and manufacturing (Georgia, Ohio, Pennsylvania, Texas, West Virginia). Six states used more water in 2015 than 2000, with the largest increases by percentage being Wyoming (+52%, largely driven by crop irrigation), Arkansas (+27%, increases in crop irrigation), Alaska (+18%, increases in thermoelectric power and aquaculture), and North Dakota (+14%, increases in crop irrigation and mining). Our PSUTs report water abstraction, use by other industries, and returns (Table 3; state-level PSUTs are included as Supplemental Information 4).

[4] These included 12 water-quality constituents with nationwide data (calcium, chloride, magnesium, potassium, sodium, sulfate, nitrogen, phosphorus, salinity, sediment, temperature, and dissolved oxygen), plus pesticides and pharmaceuticals/personal care products—both issues of emerging concern.

[5] Public supply deliveries to households were only reported for 18 states in the year 2000, as opposed to all 50 in later years; this value for the year 2000 reflects the percentage of public supply deliveries to households in those 18 states only.

Table 2
National water use for 2000 to 2015 by North American Industry Classification System (NAICS) code. All values reported in millions of gallons per day. N/R: not reported.

Year	11. Agriculture, Forestry, Fishing, and Hunting			21. Mining	2211. Electric Power Generation, Transmission and Distribution			2213. Water, Sewage & Other (Irrigation)		31–33. Manufacturing	713910. Golf Courses and Country Clubs	Households (Domestic self-supply)	Total
	111. Crop Production (Irrigation)	112. Animal Production (Livestock)	1125. Aquaculture		Thermoelectric Power (Once-through cooling)	Thermoelectric Power (Closed-loop cooling)	Hydroelectric (Evaporative Use)	221310. Water supply (Public supply)	221320. Sewage treatment facilities (Wastewater)				
2000	137,064.3	2,362.1	5,792.9	4,129.6	174,307.8	18,395.4	14,630.1	42,740.8	N/R	19,496.6	1,928.0	3,576.3	424,423.9
2005	125,219.2	2,140.8	8,828.5	3,828.3	182,557.2	16,501.0	14,689.0	43,675.2	N/R	18,059.8	2,138.4	3,726.9	421,364.2
2010	113,929.3	1,993.4	8,946.3	3,965.3	150,525.5	8,855.5	14,803.9	41,357.3	N/R	16,179.3	1,569.2	3,524.2	365,649.2
2015	116,611.7	2,093.8	7,450.0	3,996.4	126,110.2	5,027.0	14,113.8	38,419.3	N/R	14,784.0	1,445.1	3,255.8	333,306.9

Total water use was dominated by irrigation in the West and thermoelectric power generation in the East (Fig. 2). Other industries that are locally important water uses (> 10% of state-level water use in 2015) in selected states include mining in Alaska, aquaculture in Alaska and Idaho, and manufacturing in Delaware, Georgia, Indiana, Iowa, Louisiana, Maine, Pennsylvania, and West Virginia. A full national compilation of instream hydroelectric-power water-use was last compiled in 1995, and reported 3.16 trillion gallons per day of instream hydroelectric use as compared to 402 billion gallons per day for all other water uses (Solley et al., 1998). Thus, a view of state-level water use that excludes all electric power generation (hydroelectric and thermoelectric) can provide a more nationally consistent view of water use, particularly for other important industries in the East (Fig. 2).

Despite overall declines in water use nationally and in all but a handful of states, groundwater use increased in key locations. In 2015, 12 states – primarily in the Southwest and Plains – relied on groundwater for more than a third of total water use, and 3 states (Arkansas, Kansas, and Mississippi) used groundwater for more than two thirds of their water use (Fig. 1). California used the most groundwater of any state in 2015 – just over 20% of the national total – followed by Arkansas, Texas, Nebraska, and Idaho. Between 2000 and 2015, 21 states increased their use of groundwater. USGS water-use reports in 1980 (Solley et al., 1983) and 2000 (Hutson et al., 2004) reported greater total groundwater use than 2015 (Dieter et al., 2018). However, national groundwater use as a percentage of total water use was greater in 2015 than in any year since the USGS began reporting water-use data in 1950 (McKichan, 1951).

3.2. Water productivity accounts

From 2000 to 2015, total national water productivity rose from $8.40 to $13.84 (in 2009 dollars per 100 gallons of water used) using USGS water-use data, and from $8.27 to $14.32 using adjusted water-use data (Table 4). This increase of 65% (unadjusted) or 73% (adjusted) over that 15-year period occurred as water use declined by 22% and GDP grew by 28%. Nationally, agricultural water productivity rose from $0.16/100 gallons per day in 2000 to $0.26 in 2015; mining water productivity rose from $14.17 to $28.16/100 gallons per day. These industries' water productivity gains were driven by both (1) smaller water-use reductions than the economy as a whole (13% and 8% for agriculture and mining, vs. 22–26% economy-wide) and (2) substantial increases in their GDP generated (44% and 83% for mining, vs. 28% for the entire U.S. economy).[6]

At the state level, total water productivity grew from 2000 to 2015 in all states except Wyoming, which had the greatest increase in water use, outpacing the state's GDP growth (Fig. 3). Water productivity patterns depend on each state's economy and water-use efficiency. Water productivity is generally lower in states with extensive irrigated agriculture. Investments in water efficiency for high-value crops can improve productivity, however. Inclusion of soil irrigation water provided by rainfall in these water-productivity estimates would lower productivity estimates for all states. This would be particularly true in

[6] During this period, price increases for food and mined energy and minerals paralleled the rise in GDP for these industries. The U.N. Food and Agriculture Organization's annual real food price index increased by 46% from 2000 to 2015 (FAO, 2020). Mining estimates for both GDP and water use include production of energy (oil, natural gas, coal), minerals, stone, clays, sand, and gravel. Oil, gas, and coal prices changed by 60%, −39%, and 88%, respectively during this period (Energy Information Administration, 2020a; Energy Information Administration, 2020b; Energy Information Administration, 2020c). Prices of seven metallic minerals noted by Lovelace (2009) as requiring substantial water for their extraction and processing and for which data were available (copper, gold, iron ore, lead, silver, vanadium, zinc) increased by 25–201%. Finally, sand, gravel, clay, and crushed stone prices rose by 30–148% while dimension stone prices fell by 33% (Kelly and Matos, 2014).

Table 3
National physical supply and use table for water, 2015, by North American Industry Classification System (NAICS) code. All values reported in millions of gallons per day.

	11. Agriculture, Forestry, Fishing, and Hunting			21. Mining	2211. Electric Power Generation, Transmission and Distribution			2213. Water, Sewage & Other (Irrigation)		31–33. Manufacturing	713910. Golf Courses and Country Clubs	Households (Domestic)	Total
	111. Crop Production (Irrigation)	112. Animal Production (Livestock)	1125. Aquaculture		Thermoelectric Power (Once-through cooling)	Thermoelectric Power (Closed-loop cooling)	Hydroelectric (Evaporative Use)[a]	221,310 Water supply (Public supply)	221,320 Sewage treatment facilities (Wastewater)				
A. Water use													
1. Total abstraction	116,611.7	2,093.8	7,450.0	3,996.4	126,110.2	5,027.0	14,113.8	38,419.3	N/R	14,784.0	1,445.1	3,255.8	333,306.9
1.i.1. Surface Water, of which is	60,135.2	868.6	5,839.4	1,132.2	125,986.1	4,555.4	14,113.8	23,268.4	N/R	12,076.9	754.4	46.6	248,777.0
Fresh	60,135.2	868.6	5,833.1	876.5	90,621.6	4,085.0	14,113.8	23,264.6	N/R	11,334.0	754.4	46.6	211,933.2
Saline	0.0	0.0	6.3	255.7	35,364.5	470.5	0.0	3.9	N/R	742.9	0.0	0.0	36,843.7
1.i.2. Ground Water, of which is	56,476.4	1,225.2	1,610.7	2,864.2	124.1	471.5	0.0	15,150.8	N/R	2,707.1	690.7	3,209.2	84,529.8
Fresh	56,476.4	1,225.2	1,610.7	1,004.1	80.8	342.5	0.0	14,887.7	N/R	2,664.2	690.7	3,209.2	82,191.4
Saline	0.0	0.0	0.0	1,860.1	43.4	129.0	0.0	263.1	N/R	42.9	0.0	0.0	2,338.5
2. Use of water from other economic units	0.0	0.0	0.0	0.0	51.8	112.3	0.0	0.0	N/R	376.2	0.0	22,952.4	23,492.7
Reclaimed wastewater	654.7	0.0	0.0	0.0	8.2	141.2	0.0	331.0	N/R	92.9	266.6	0.0	1,494.7
3. Total use of water	117,266.4	2,093.8	7,450.0	3,996.4	126,170.3	5,280.5	14,113.8	38,750.3	N/R	15,253.1	1,711.7	26,208.1	358,294.2
B. Water supply													
4. Supply of water to other economic units	N/R	N/R	N/R	N/R	N/R	0.5	N/R	23,492.7	N/R	N/R	N/R	N/R	23,493.2
5. Total returns[b]	45,539.4	19.2	2,870.3	13,475.1	124,810.0	2,456.4	N/R	2,892.9	37,976.6	40,954.8	321.9	271.0	271,587.6
6. Total supply of water	45,539.4	19.2	2,870.3	13,475.1	124,810.0	2,456.9	N/R	26,385.6	37,976.6	40,954.8	321.9	271.0	295,080.8
7. Consumption	71,727.0	2,074.6	4,579.7	−9,478.7	1,360.3	2,823.6	14,113.8	12,364.7	0.0	−25,701.7	1,389.8	25,937.1	101,190.2

N/R: Not reported.
[a] Coefficient-based estimate.
[b] Return data based on U.S. Environmental Protection Agency's Permit Compliance System and Integrated Compliance Information System (PCS-ICIS) database.

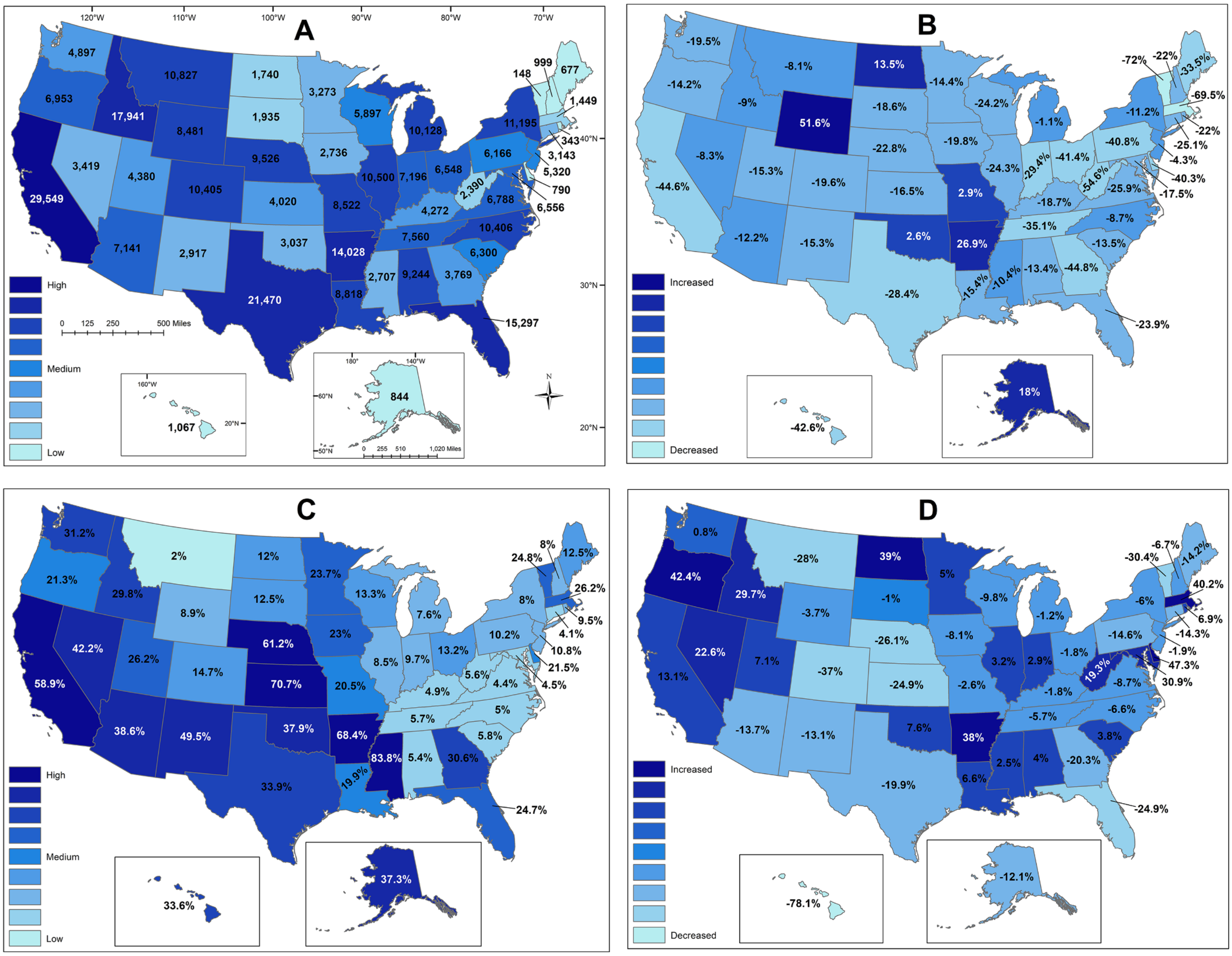


Fig. 1. (A) Total water use by state (million gallons/day), 2015; (B) percent change in total water use, 2000 to 2015; (C) percentage of water use coming from groundwater; (D) percent change in groundwater use, 2000 to 2015.

eastern states with greater rainfall and would thus reduce state-level variation.

From 2000 to 2015, agricultural water productivity increased in 32 states; 16 states had increases of > 50% (Fig. 3). Increases occurred in most regions of the coterminous U.S., except for the Northeast and parts of the Southeast. The highest overall agricultural water productivity occurred in the eastern U.S., particularly in the Midwest and parts of the Northeast. Mining water productivity increased in 28 states; 18 states had increases of > 50%. These increases occurred primarily in the Plains and parts of the Southwest, Midwest, and Northeast.

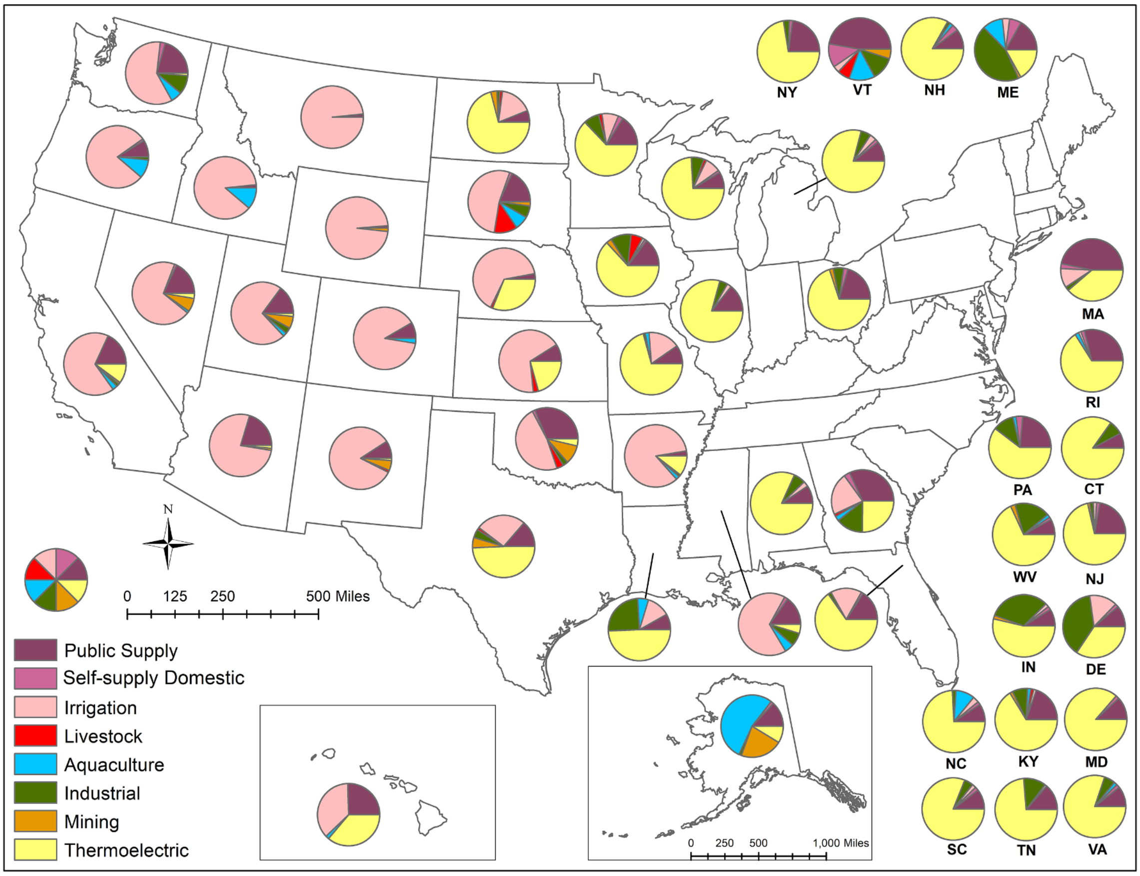
3.3. Water quality accounts

Nationally, about 20% of surface water-quality monitoring sites saw statistically significant changes in water quality for five constituents (concentration of total nitrogen and phosphorus, chloride, nitrate, specific conductance); just over 30% of sites saw significant changes for total suspended solids (Table 5, Fig. 4). Five of the constituents – all but total nitrogen – saw more concentration increases than decreases. At the regional scale, the Southeast, Plains, and Northwest regions had more sites with concentration increases than decreases for nitrate and total phosphorus (all three regions), total suspended solids (Southeast and Northwest), and specific conductance (Plains and Northwest). For the Northeast, Midwest, and Southwest, more decreases than increases in concentration were seen for total nitrogen (all three regions), chloride (Northeast and Midwest), nitrate (Northeast and Southwest), and total suspended solids (Midwest and Southwest).

For groundwater, of 56 monitoring well networks measuring chloride, 24 had statistically significant increases in concentration, while two had significant decreases (Lindsey and Rupert, 2012, Table 6). Of 56 networks measuring nitrate, 13 had increasing concentrations and 5 decreasing concentrations. Of 54 networks measuring total dissolved solids, 22 increased significantly and 1 decreased significantly. Large increases in groundwater chloride levels occurred in urban groundwater wells of the Northeast and Midwest, while increases in total dissolved solids occurred in the urban well networks in the Northeast and Midwest and in agricultural groundwater wells of the Southwest and Florida. No definitive pattern was observed for increases in nitrate (Lindsey and Rupert, 2012).

3.4. Water emissions accounts (point source loads)

In 2015, sewage treatment facilities (WWTPs) were the largest point-source emitter of nitrogen, phosphorus, organic enrichment, and solids; water supply (i.e., drinking water treatment and distribution facilities) and irrigation systems were the largest emitter of metals (Table 7). Other industries emitting 5% or more of the national total for a given water-quality constituent included food manufacturing and plastics manufacturing for phosphorus; pulp and paper, warehousing and storage, and waste treatment for organic enrichment; and water



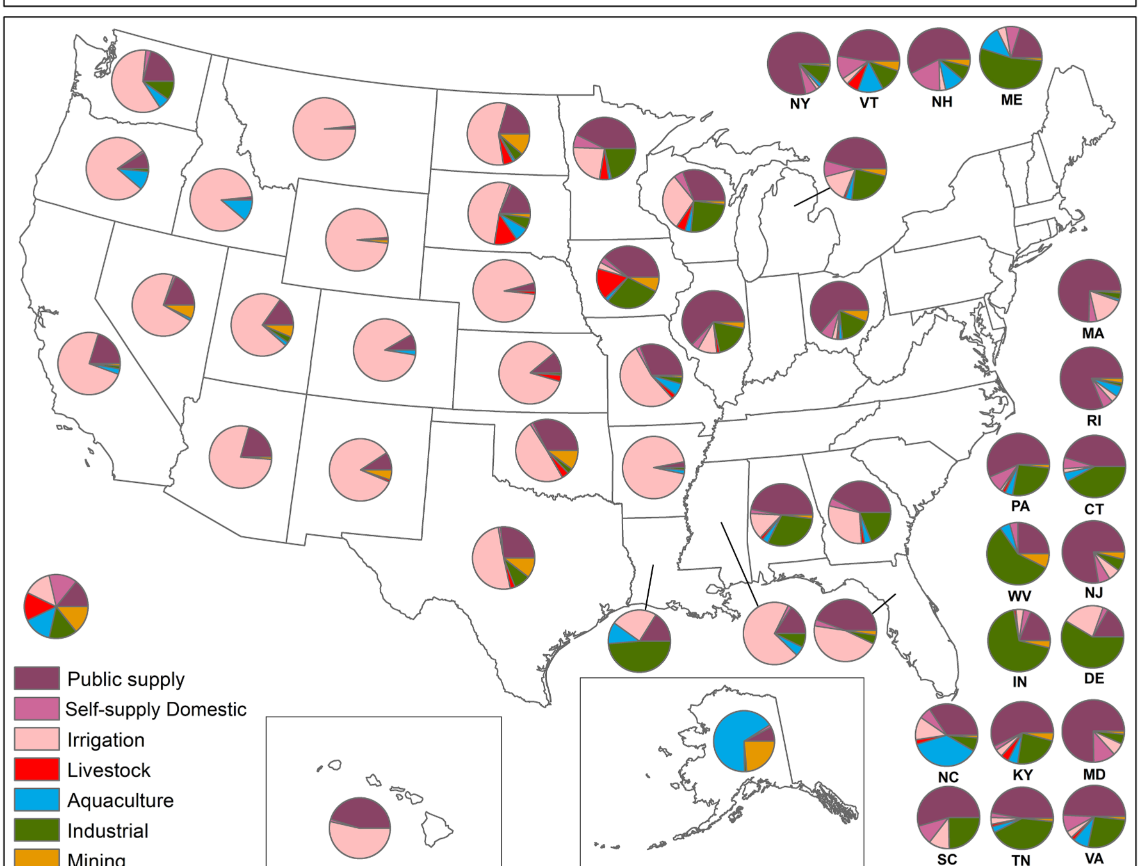


Fig. 2. Water use by industry and state, including (top) and excluding (bottom) thermoelectric, 2015.

Table 4
National water productivity ($ gross domestic product/100 gallons water use), by North American Industry Classification System (NAICS) code, 2000 to 2015.

	Water use (millions of gallons per day)				GDP (chained 2009 dollars)			Water productivity ($/100 gallons water use per day)			
	111 + 112. Agriculture	21. Mining	Total (adjusted)[a]	Total (USGS reported)[b]	111 + 112. Agriculture	21. Mining	Total	111 + 112. Agriculture	21. Mining	Total (adjusted)[a]	Total (USGS reported)[b]
2000	145,219	4,160	415,767	409,354	$83,896	$215,125	$12,544,372	$0.16	$14.17	$8.27	$8.40
2005	136,189	3,876	393,608	405,838	$101,645	$217,766	$14,120,577	$0.20	$15.39	$9.83	$9.53
2010	124,869	3,887	338,778	349,400	$111,457	$273,370	$14,526,531	$0.24	$19.27	$11.75	$11.39
2015	126,156	3,829	306,779	317,389	$120,821	$393,530	$16,036,634	$0.26	$28.16	$14.32	$13.84
% change, 2000 to 2015	−13.1%	−8.0%	−26.2%	−22.5%	44.0%	82.9%	27.8%	62.5%	98.7%	73.2%	64.8%

[a] Includes all industries, plus estimates for golf course irrigation and hydroelectric evaporative use. It excludes all domestic (household) self-supply use and all deliveries from public supply to domestic (households).
[b] As reported by the USGS. Includes all industries *except* golf course irrigation and hydroelectric evaporative use.

supply and electric power generation for solids. SIC code 3312, "Steel works, blast furnaces (including coke ovens), and rolling mills" emitted 19% of the nation's solids. However, we did not include this industry in our account because this SIC code does not cleanly crosswalk to a single 3-digit NAICS code (it corresponds to NAICS codes 324 and 331).

Emissions category definitions follow (https://echo.epa.gov/help/loading-tool/water-pollution-search/water-pollution-search-help#loads):

- Nitrogen: All parameters for total nitrogen, organic nitrogen, total Kjeldahl nitrogen, nitrite, nitrate, and ammonia.
- Phosphorus: All phosphorus and phosphate pollutant parameters.
- Organic enrichment: All biochemical oxygen demand (BOD) and chemical oxygen demand (COD) pollutant parameters.
- Solids: All parameters for suspended and settable solids. This category does not include chemical-specific solids, such as suspended copper.
- Metals: All metals parameters. Hexavalent or trivalent metals and metals in ionic form (e.g., hexavalent chromium and aluminum, ion) are included, but metal compounds (e.g., calcium chloride) are not included.

3.5. Expert elicitation to conceptually model freshwater quality and water use

Water-quality impairments can have numerous effects on the economy, society, and ecosystems. These include biological effects (reduced growth or toxicity for crops, fish, livestock, or people), corrosion, scaling, or clogging of pipes and water infrastructure, and increased treatment costs (Table 8). Additionally, there are other potential societal and ecosystem effects beyond the eight water uses shown in Table 8, such as those affecting fish and wildlife, recreation, commercial fisheries, and homeowners living near water bodies. High levels of salinity, sediment, pesticides, pharmaceuticals and personal care products, and low dissolved oxygen carry costs for water users related to treatment, infrastructure, or health impacts. For ions, nutrients, and temperature, some users benefit from levels of these water-quality constituents that are neither too low nor too high (represented as +/−, Table 8). Expert consensus was that higher levels of most water-quality constituents (but lower levels of dissolved oxygen) generally result in adverse economic impacts. By contrast, good water quality generally yields positive economic impacts.

Along with having different water quality *requirements*, users have varying *impacts on* water quality. These impacts can include both the direct discharge of pollutants and consumptive water use that reduces surface water levels in streams and lakes, which can increase pollutant concentrations. For both parts of the exercise, experts noted that the heterogeneity of the water-use categories means that within-class water-quality effects can vary. For instance, different types of manufacturing and mining differ widely in their water quality needs and effects, while livestock water-quality effects will differ in feedlots versus free-range grazing. Studies exist to describe some of these relationships in far greater detail, e.g., for agriculture, including crops and livestock (Capel et al., 2018).

4. Discussion

Our results synthesize data from multiple sources, including BEA, USEPA, and USGS, using concepts and methods based on the SEEA Central Framework. One of the key benefits of the SEEA Central Framework was summarized as:

*"The System of National Accounts (SNA) is a measurement framework that has been evolving since the 1950s to embody the pre-eminent approach to the measurement of economic activity, economic wealth and the general structure of the economy. The SEEA Central Framework applies the accounting concepts, structures, rules and principles of the SNA to environmental information. Consequently, the SEEA Central Framework allows for the integration of environmental information (often measured in physical terms) with economic information (often measured in monetary terms) in a single framework. The power of the SEEA Central Framework comes from its capacity to present information in both physical and monetary terms coherently" (*U.N. et al., 2014a*, §1.38).*

National-scale water data had not previously been integrated with economic data to comprehensively quantify water resource trends and their value to the U.S. economy. By using similar accounting concepts and principles as the SNA, SEEA-Water aligns accounting information on water stocks and flows consistently with both the timing and geographic reporting of U.S. SNA accounts. Because this accounting framework is followed by countries around the world, a consistent framework for water can facilitate comparisons across countries for analysis relevant to policymakers and the academic literature, just as national economic accounts have fueled empirical macroeconomic research.[7] By aggregating data at state levels, we have shown how to measure subnational water productivity over specific time intervals

[7] Specifically, the 2008 SNA describes the benefits of universality and consistency of economic accounting: "The basic concepts and definitions of the SNA depend upon economic reasoning and principles which should be universally valid and invariant to the particular economic circumstances in which they are applied. Similarly, the classifications and accounting rules are meant to be universally applicable" (European Commission et al., 2009, §1.4). Further, it underscores how this is relevant for comparative analysis: "The resulting data are widely used for international comparisons of the volumes of major aggregates…Such comparisons are used by economists, journalists or other analysts to evaluate the performance of one economy against that of other similar economies. They can influence popular and political judgements about the relative success of economic programmes in the same way as developments over time within a single country" (European Commission et al., 2009, §1.33).

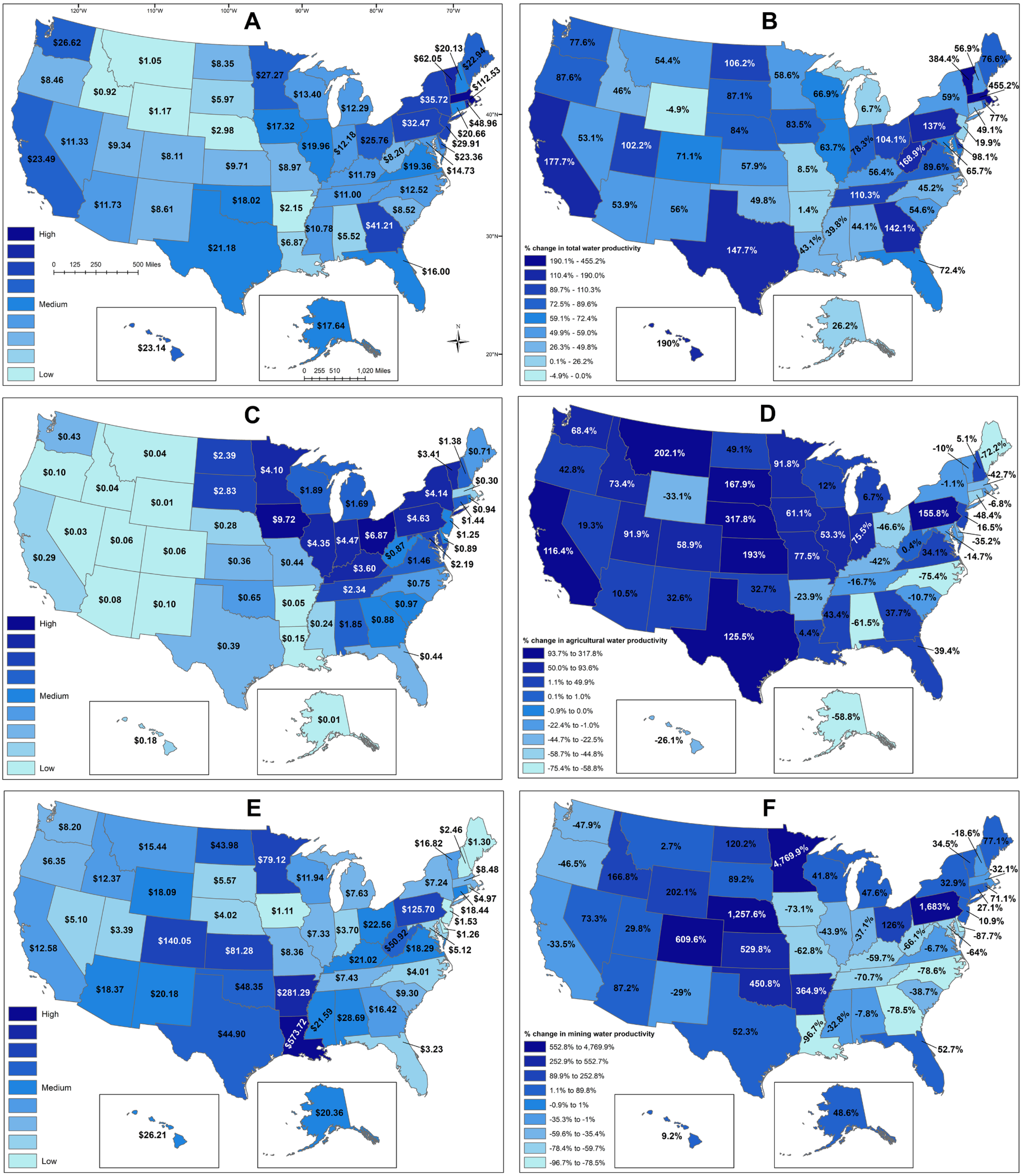


Fig. 3. State-level 2015 water productivity (2009 dollars per 100 gallons/day) and percent change in water productivity between 2000 to 2015 for (A and B) all water use, (C and D) agriculture, and (E and F) mining.

aligned with those used for economic data (see Warnell et al., 2020, this issue for a similar analysis by metropolitan statistical area). This coherence and consistency are key strengths of the SEEA accounts, providing diverse opportunities for potential users to develop linkages with other types of economic data for national or subnational analysis. This has been the case in other countries where water accounts data have been used to review water pricing and model economic impacts of changing industry water allocations, including Australia, Botswana, Colombia, Costa Rica, The Netherlands, and The Philippines (Vardon et al., 2007, Nagy et al., 2017, Pule and Galegane, 2017).

While water accounts may be useful for varied applications, our work has illuminated a number of ways that new or updated data could

Table 5
Regional surface-water quality changes: number of monitoring sites with statistically significant increases or decreases in concentration, 2002–2012 (derived from Oelsner et al., 2017).

Region		Coterminous U.S.	Southeast	Northeast	Midwest	Plains	Southwest	Northwest
Chloride	Decreased	25	7	1	8	6	2	1
	No change	245	59	16	50	81	31	8
	Increased	29	7	0	6	13	3	0
Nitrate	Decreased	31	12	7	5	4	2	1
	No change	307	86	44	94	38	20	25
	Increased	44	16	3	8	10	1	6
Specific conductance	Decreased	55	15	7	6	15	6	6
	No change	527	136	63	62	138	68	60
	Increased	62	15	9	5	17	9	7
Total nitrogen	Decreased	29	9	6	6	3	4	1
	No change	222	71	58	55	21	9	8
	Increased	19	14	0	2	2	1	0
Total phosphorus	Decreased	30	6	6	6	8	4	0
	No change	281	73	50	68	66	15	9
	Increased	48	19	4	7	12	5	1
Total suspended solids	Decreased	27	6	3	5	7	2	4
	No change	122	39	15	18	21	5	24
	Increased	28	12	3	0	5	0	8
Total monitoring sites*		974	255	117	160	245	108	89

*The total number of sites for each constituent is smaller than the overall number of monitoring sites, because not every site was monitored for every constituent.

substantially improve their potential (see Section 4.3). Key new data would include (1) PSUTs compiled for more specific water-use categories and more frequent temporal resolution (i.e., annually), the former enabling development of detailed water productivity accounts and the latter enabling analysis of long-term water-use trends in context of drought cycles (as is done in some countries including Australia, Botswana, and the Netherlands); (2) complete emissions and water-quality data, which would support analysis of the full causal chain of water-quality impacts – understanding when and where declining water quality may impact water uses, including instream flows that support pollutant dilution and biological resources; and (3) water asset accounts, which would enable tracking of water stocks and their year-to-year changes, including difficult-to-measure groundwater resources.

Natural capital accounts are iterative, and their continual compilation tends to promote improvement in coverage and quality as well as use over time (Vardon et al., 2018). Our pilot U.S. water accounts provide a baseline; by addressing data inconsistencies and gaps, they can move toward this more advanced status. With mature water accounts, water resource planners would be able to fully evaluate tradeoffs across multiple water uses, including environmental water needs, at multiple spatial and temporal scales. Although not a primary goal of SEEA-Water, sub-annual water accounts could help with managing water supply and demand, particularly where there are distinct seasonal differences in water availability.

4.1. Water accounts to support water policy and water resources management

The water accounts we show here and more comprehensive future accounts can inform a wide range of decisions related to water allocation, productivity, reuse and distribution, and adaptive management. Diverse policy and water-management instruments can be used to influence water use, availability, and quality (United Nations, 2012, Nagy et al., 2017). For example, these include management relating to: (1) water permits, their number and restrictions/allowances; (2) water pricing and water-use taxation and subsidies; (3) business evaluation of water-resource related economic viability and risk; (4) water distribution and storage or release through the management of built water infrastructure and groundwater and surface-water resources; (5) water-use efficiency improvements, including water reuse, distribution, or storage efficiencies, at the household, industry, local, regional, and national levels; (6) management of water quality through water emission controls (e.g., permits), improvements for targeted use (e.g., water treatment for drinking water), or water emissions (e.g., WWTPs), or targeted allocation of water-quality distributions for water availability and use (e.g., wastewater reuse for agriculture, blending of waters for desired use); (7) virtual water imports, exports, or tradeoffs; (8) negotiated water allocation and water quality agreements between users, states, or national governments; and (9) establishment or modification of laws, legal processes, or legal frameworks (local, tribal, state, interstate, national, international). We provide tables showing water policy action and actors, water accounts information to inform such actions, and U.S. policy drivers and water accounts information needs as Supplemental Information 3.

The above list is undoubtedly incomplete. These policies may be affected at different political or management scales, ranging from individuals and private enterprises to states, watershed authorities, or the national government. Their spatial, temporal, and financial dimensions, and associated investments, will generally increase depending on the size of the controlling entity. Knowledge and uncertainties factor into these decisions: the greater the perceived benefits in relation to real or perceived costs, the more likely they are to gain support for potential implementation. Increased information and decreased uncertainty are not always the ultimate drivers for policy and management decisions and actions. Ethical or governance-related considerations may also strongly influence decisions about desirable approaches and investments.

In addition, water accounts can be used for international reporting. The U.N.'s Global Sustainable Development Goals (SDG) have a number of indicators that could be populated using data from the water accounts, especially those related to Goal 6, "Ensure availability and sustainable management of water and sanitation for all." SDG Indicator 6.4.1 reports on both value added and water use for groups of industries to produce water use efficiencies over time. SDG indicators for water stress (6.4.2) from water asset accounts and wastewater (6.3.1) could also come from the water accounts. Water use is also part of the larger sustainable consumption and production focus in both the Aichi Biodiversity Targets and SDG agreements. Finally, water accounts can both inform and be informed by work on the Food-Energy-Water nexus (Smaigl et al., 2016, Endo et al., 2018).

Water accounts have numerous linkage points to SEEA land and ecosystem accounts and ecosystem services assessments more broadly. Land use-land cover change can have notable impacts to the quantity, quality, and timing of water flows (Capel et al., 2018, Carlisle et al.,

Fig. 4. Surface water-quality change by state for select constituents, 2002–2012 (number of monitoring sites with statistically significant concentration changes, derived from Oelsner et al., 2017): (A) chloride, (B) specific conductance, (C) total suspended solids, (D) nitrate, (E) total nitrogen, (F) total phosphorus. States with no monitoring data are shown in gray.

2019), which can be jointly recorded across land, water, and ecosystem accounts (Bariamis et al., 2017, Heris et al., this issue, Wentland et al., 2020 this issue). For example, Warnell et al., 2020 (this issue) provide an example of the joint analysis of economic, land, water, and ecosystem accounts for a rapidly urbanizing region around Atlanta, Georgia. Water accounts are one of four thematic accounts in the SEEA-EEA (U.N. et al., 2014b), recognizing the importance of evaluating water resources in the context of ecosystem services and their changes. Additionally, water-quality accounts could provide useful data for freshwater ecosystem condition accounts (Maes et al., 2018). The

Table 6
Groundwater-quality changes in the United States: number of monitoring well networks with statistically significant increases or decreases in concentration (derived from Lindsey and Rupert, 2012).

	Chloride	Nitrate	Total dissolved solids
Total well networks	56	56	54
Decreased	2	5	1
No change	30	38	31
Increased	24	13	22

supply of water and the regulation of its quality, quantity, and timing are well recognized as important ecosystem services (Crossman et al., 2019, La Notte et al., 2019, Portela et al., 2019). These services are frequently assessed using spatially explicit biophysical modeling; while such models are not a requirement of SEEA-Water accounts, they are regularly used in the SEEA-EEA. However, spatially explicit modeling can also be useful in the production of water asset and nonpoint-source emissions accounts (see Sections 4.3.3 and 4.3.4) and in providing added detail about changes in the water cycle and its implications for society (e.g., Republic of Rwanda, 2019, Box 2).

4.2. Interpretation of results

4.2.1. Physical supply and use accounts

SEEA-Water PSUTs follow guidelines for tracking how water flows from the environment, between industries, and back to the environment (United Nations, 2012). Declines in water use by thermoelectric power generators and crop irrigation have made the largest contribution toward national water use declines in the U.S. since 2000 (Table 2). However, this national-scale view obscures important subnational differences. Subnational water-stress analyses have also been compiled by others to explore these trends (Roy et al., 2012, Averyt et al., 2013, Moore et al., 2015). Additionally, five-year data mask our understanding of where agricultural water use, in particular, has taken place under drought or wet conditions.

Representing the PSUTs (Table 3) using a flow diagram (Fig. 5) shows flows of water between the environment and major industries and highlights data gaps. Data are lacking on flows to WWTPs, a component that is present in recent water accounts for Australia (ABS 2016) and Spain (Pedro-Monzonis et al., 2016, Gutiérrez-Martín et al., 2017) but missing for Botswana (Setlhogile et al., 2017). Data are also lacking on losses from water-delivery systems; given the number of water systems in the U.S., filling this gap would require a large synthesis and modeling effort. For example, when comparing abstraction by public water supply to all public supply deliveries and returns in 2015, a gap of over 12 billion gallons/day is unaccounted for in U.S. water deliveries (calculated as abstraction plus reclaimed wastewater minus supply to other economic units and returns). When comparing return flows from the PCS-ICIS database to abstractions from USGS water-use data, manufacturing and mining reported negative values for water consumption (i.e., they release more water than they use). In addition to potential reporting errors, incomplete reporting of public supply deliveries to manufacturers might explain this difference for manufacturing water use. For mining, differences could relate to produced water released as a byproduct of mining operations (Clark and Veil, 2009). Due to the potential for errors in the PCS-ICIS database, we only used DMR returns data at the national scale, and not for state-level water accounts (Supplemental Information 5).

Including water use for electricity (thermoelectric and especially hydroelectric power generation) overshadows other water uses. While these data are important in understanding the role of water in power generation, they can be separated out when examining other water uses to help identify meaningful analyses and actions relevant to these other industries (Fig. 2).

We chose to include the evaporation of water from artificial reservoirs as a water use in our estimates. Our water-use estimates for this category use an admittedly older and simpler method (Torcellini et al., 2003) that produced values about twice as large as those from a more recent and sophisticated analysis (Grubert, 2016), which would be better to replicate in future water PSUTs. Although it is not included in SEEA-Water (Nagy et al., 2009), water loss from reservoirs, which are artificial parts of the water distribution system, is analytically meaningful (Grubert, 2016). Reservoir water loss is also similar to treatment of evapotranspiration from other industries like agriculture (evapotranspiration of water incorporated into products, e.g., crops, is included in the SEEA-CF water PSUTs, but SEEA-CF places evaporation of water within the asset accounts, U.N. et al., 2014a). Differences arise in the interpretation of when water is "produced" in the SNA (i.e., enters pipes) and in how countries treat water losses in transmission from pipes. Future water accounts could thus choose to include or exclude this item.

4.2.2. Water productivity accounts

When developing productivity (or efficiency) measures for water use, combining physical and economic data within the same system boundaries is important for the reasons discussed above; our experience shows that alignment by industry and water-use categories has proved more challenging than by political boundaries. Due to the different purposes for which USGS has collected water data, water productivity could be calculated corresponding only to NAICS categories for which economic and water-use data were well aligned: farms (NAICS 111 Crop production plus NAICS 112 Animal production and aquaculture), mining (NAICS 21 Mining, quarrying and oil and gas extraction), and the whole economy (Table 4). The other USGS water-use categories combine too many economic activities to match with appropriate economic data. "Public Supply" includes so many different economic activities that its corresponding economic data cannot be identified. The opposite is true for industrial (manufacturing) water use – only industrial self-supply is included, but not the public-supply deliveries needed to quantify total industrial water use that could enable matching with economic data for manufacturing. Additionally, future water productivity estimates for golf courses and crop irrigation, which benefit from rainfall-derived soil irrigation water, should aim to include such data in their water productivity estimates. Doing so would shift these estimates from actively supplied to total water productivity estimates, putting them in better alignment with SEEA-Water guidelines.

Nationally, water productivity – economic production per unit of water – increased from 2000 to 2015 for all three categories – farming, mining, and for the whole economy (Table 4). This is clearly a positive trend (Donnelly and Cooley, 2015). State-level trends were mixed, with some states seeing water-productivity increases and others decreases. In states such as Pennsylvania and Oklahoma, where there has been a large increase in hydraulic fracturing, there is a marked increase in mining water productivity, despite that industry's water use. In states like Massachusetts, where there have been structural changes in the economy towards services and technology, the total water productivity increased markedly, from $20.27 per 100 gallons in 2000 to $112.53 in 2015.

Although limited in scope, our analysis illustrates that substantial improvements to the harmonization of USGS water-use categories with NAICS industrial classification used by BEA. Such harmonization could enable a richer understanding of productivity tradeoffs and trends across industries. This higher-level detail about water use and its economic value can help decision makers design more socially and economically optimal water policy.

4.2.3. Water-quality and emissions accounts

Despite their inclusion in SEEA-Water, water-quality accounts have been compiled in few countries to date, due to the inherent complexities in large-scale water quality measurement and reporting. Our initial

Table 7
National water emissions accounts: Net emissions from point sources (1000 lbs), 2015.

	Industries (by NAICS 2017 category)							
	211. Oil & Gas Extraction	212. Mining (Except Oil & Gas)	2211. Electric Power Generation	221310. Water supply & irrigation systems	221320. Sewage Treatment Facilities	311. Food Manufacturing	312. Beverage & Tobacco Product Manufacturing	321. Wood Product Manufacturing
Nitrogen	1,959	176	30,800	4,625	1,707,044	9,076	224	2,305
Phosphorus	1,813	1,080	3,518	278	229,370	46,984	483	67
Organic enrichment	17,864	1,528	7,921	1,878	794,385	126,283	58,362	63,112
Solids	31,839	47,734	815,669	1,413,230	2,402,702	256,620	4,365	189,360
Metals	84,022	94,431	53,179	15,175,582	486,175	9,731	82	361

	Industries (by NAICS 2017 category)							Other industries*	Total	% as other industries
	322. Paper Manufacturing	325. Chemical Manufacturing	326. Plastics & Rubber Products Manufacturing	488. Support Activities for Transportation	493. Warehousing & Storage	562. Waste Management & Remediation Services	721. Accommodation			
Nitrogen	4,477	11,390	690	2,745	276	41,457	1,713	61,160	1,880,116	3.3%
Phosphorus	3,062	4,483	22,353	57	1	53	7,846	2,468	323,917	0.8%
Organic enrichment	221,832	31,190	32,722	32,693	102,963	89,413	7,771	213,202	1,803,117	11.8%
Solids	319,346	291,293	937,321	268,139	5,059	305,549	15,089	3,023,845**	10,327,160	29.3%
Metals	1,338	4,025	8	97,101	73	60,816	21	184,521	16,251,467	1.1%

*Other industries include those with ambiguous matches between Standard Industrial Classification (SIC) and North American Industry Classification System (NAICS) codes and those with emissions less than the top 15 industries by NAICS 2017 code.
**1,966,506 of which were emitted by SIC 3312, “Steel works, blast furnaces (including coke ovens), and rolling mills,” which corresponds to both NAICS 324 “Petroleum and coal products manufacturing” and 331 “Primary metal manufacturing.”

estimates thus have value in demonstrating their compilation. Surface water-quality trends between 2002 and 2012 were most evident at regional levels, where we identified differing concentration improvements and declines by constituents and regions. Groundwater chloride, nitrate, and total dissolved solids levels had more consistent and widespread increases in concentration, indicating national-scale groundwater quality declines. In addition to their use in the water accounts, water-quality data can also inform SEEA-EEA accounts for freshwater ecosystem condition (Maes et al., 2018, Warnell et al., 2020, this issue).

Longitudinal water-quality datasets (Oelsner et al., 2017) are enabling new analyses that inform our accounts and other studies. Shoda et al. (2019) found that nutrient, chloride, sulfate, and total dissolved solid levels very rarely crossed thresholds for drinking water standards. This means that measured water-quality parameters are rarely improving or declining relative to human uses at a decadal time scale (though exceedance of water-quality parameters at finer time scales may still occur and be important for water uses). Total nitrogen and phosphorus concentrations frequently exceeded recommended USEPA benchmarks, and are improving in some locations while worsening in others, illustrating the localized nature of U.S. water-quality management. Other recent studies based on Oelsner et al.'s (2017) data have evaluated changes in nutrient loading to U.S. coastal ecosystems (Oelsner and Stets, 2019) and the interaction between watershed management and streamflow in changing water quality (Murphy and Sprague, 2019). National increases in salinity have been noted (Kaushal et al., 2018), particularly due to runoff of road salts and evaporation from irrigation water. This has potentially important impacts on water uses and the economy (Stets et al., 2018; see section 4.2.4).

Our pilot water emissions account enabled the estimation of national-level totals for five pollutants, and the top emitting industries for each. The PCS-ICIS database includes only facilities requiring a National Pollution Discharge Elimination System (NPDES) permit, making this database a subset of point-source emitters, but one that includes major emitting industries. By comparison, two studies have previously evaluated nationwide point-source emissions, but only for nitrogen and phosphorus. Maupin and Ivahnenko (2011) estimated national-scale emissions for 1992, 1997, and 2002, illustrating a downward trend in nutrient loads and an improvement over time of reporting for major municipal and industrial wastewater treatment facilities. More recently, Skinner and Maupin (2019) compiled a comprehensive national database of point-source nitrogen and phosphorus emissions for the year 2012 only. Using a more sophisticated modeling approach than in our study, they quantified national point-source nitrogen and phosphorus loading at 69% and 56% of our estimates, respectively. Major facilities (numbering 5430, versus 11,537 minor facilities) were responsible for 95% of nitrogen and 94% of phosphorus emissions.

4.2.4. Expert elicitation to conceptually model freshwater quality and water use

Our expert elicitation produced conceptual maps that could be used to better track the potential impacts of water-quality changes on different water uses and the economy (Table 8, Fig. 6). In ecosystem accounting terms, this addresses the full causal chain of both the beneficiaries of clean water and "enabling actors" responsible for water emissions (La Notte and Marques, 2017). Our work could also inform future research on the economic value of water quality – for instance to identify states or watersheds where water-quality problems are evident, highlighting industries causing or affected by water quality problems, and their implicit economic tradeoffs. For instance, aquaculture is expected to grow in importance as global protein demand continues to increase (Gjedrem et al., 2012). In a world of scarcer water resources, operators and permitting agencies will need to consider not just water availability but also its quality when siting aquaculture facilities (Fig. 6). Both the direct water quality needs of aquaculture facilities and facility impacts on downstream water uses, including environmental flows, will matter. Dilution flows, i.e., adequate in-stream flows to dilute discharges by WWTPs, are also a relevant consideration for water management.

Salinity has diverse impacts on water uses, including crop toxicity and the inability to use saline water for other biological uses (aquaculture, livestock, or human consumption) without desalination (Fig. 6). Increasing salinity levels nationwide are a concern for aquatic health. They also have the potential to corrode pipes and impact human health (Kaushal et al., 2018, Stets et al., 2018). By limiting our initial analysis to the eight USGS water-use categories, we excluded some sources of pollutants from the economy (e.g., transportation, logging) and impacts to both people (e.g., recreation, commercial fisheries, property values) and ecosystems. This shows the importance of further quantitative work to more fully understand connections across multiple water uses at both national and regional scales (e.g., Capel et al., 2018).

4.3. Data gaps and data quality improvements

To reach their full potential to inform decision making, more and better data are needed to populate U.S. water accounts. U.S. water data are relatively comprehensive but like in many nations are dispersed; proposed data collection, management, and analysis platforms (Blodgett et al., 2016, Patterson et al., 2017) offer potential to develop highly informative, next-generation water accounts. If compiled annually, water accounts could better align with events that impact water price and availability, making more timely data available for urgent decisions.

Compiling data at the watershed scale, rather than just at administrative levels, remains an issue. SEEA-Water notes the need for subnational data but does not provide guidance for assigning the information to specific geographic areas, such as from administrative to watershed boundaries. Other approaches would thus be needed to take county- or state-based data and reassign it to watersheds. For example, USEPA's EnviroAtlas has begun to compile agricultural, domestic, industrial, and thermoelectric water use by HUC watershed, using USGS data or similar methods to the USGS (USEPA, 2018b).

4.3.1. Physical supply and use accounts

Improving the frequency, timeliness, and industry specificity of water-use data would improve the usability of both PSUTs and water productivity accounts. The 2017 Economic Census asks about water use in selected industries, which may help improve future estimates for both sets of accounts (U.S. Census Bureau, 2018). In particular, quantifying public water-supply deliveries to manufacturing and other industries would give a more complete view of the U.S. water-use picture (Fig. 5). WWTP discharge data are included in the PCS-ICIS database, and partial data on deliveries to and removals at WWTPs are included in the TRI database. Neither of these databases were designed to support comprehensive national-scale water accounting, and their reporting errors and data gaps currently limit our ability to track full physical flows of water.

Matching USGS water-use data to finer-grained NAICS categories could enable more sophisticated analysis in PSUTs and water productivity accounts. If water-use data were available for 3-digit NAICS codes, analysts could explore how changes in the economy underpin water use (see Table 7 for examples of NAICS codes). For instance, from 2000 to 2015 major changes in the U.S. economy included (1) growth in shale gas production, i.e., hydraulic fracturing, (2) expansion of agriculture, partly in response to ethanol mandates for biofuels, and (3) increasing importance of computers and electronics, of which some types of manufacturing (e.g., semiconductors) require very high-quality water. Regrettably, linked water and economic trends related to these changes could not be evaluated, because (1) mining water use is reported too coarsely (i.e., grouping all energy and minerals into one category), (2) 5-year water-use reporting masks year-to-year changes in

Table 8
Expert consensus on the potential effects of water quality on water users (top), potential effects of industries on water quality (bottom). +++/−−−: Strong positive/negative impact; ++/−−: Moderate positive/negative impact; +/−: Minor positive/negative impact.

Water quality metrics		Water uses/industries							
		Aquaculture	Domestic	Industrial	Irrigation	Livestock	Mining	Public Supply	Thermoelectric Power
Ions	Calcium	+/--	+/--	-	+	+	+/-	+/--	-
	Chloride	-	+/--	-	-	-		+/--	-
	Magnesium	+/--	+/--	-	+	+	+/-	+/--	-
	Potassium		+/--					+/--	
	Sodium	-	+/--	-	-	-		+/--	-
	Sulfate	--	+/--	-	-	-	-	+/--	-
Nutrients	Nitrogen	++/---	--		+/-	+/--		--	
	Phosphorus	++/--	+/--		+/-	+/-		--	-
	Salinity	--	--	--	---	--	-	--	--
	Sediment	--	--	--	--	--	--	--	--
	Temperature	--	+/-	+/-				+/-	+/-
	Dissolved oxygen	---	-	-			-	--	-
Emerging concern	Pesticides	--	--	-	--	--		---	
	Pharmaceuticals & personal care products	--	--	-	--	--		---	

Water quality metrics		Water uses/industries							
		Aquaculture	Domestic	Industrial	Irrigation	Livestock	Mining	Public Supply	Thermoelectric Power
Ions	Calcium			-	-		-		
	Chloride	-	-	-	--	-	-	-	
	Magnesium			-	-		-		
	Potassium			-	-		-		
	Sodium	-	-	-	--	-	-	-	
	Sulfate			-	-		-		-
Nutrients	Nitrogen	--		-	--	--	-		-
	Phosphorus	--		-	--	--	-	-	
	Salinity	-	-	-	--	-	-	-	-
	Sediment			-	-	--	-		
	Temperature			-					--
	Dissolved oxygen	-		-	-	-	-		
Emerging concern	Pesticides			-	--				
	Pharmaceuticals & personal care products	-		-		--		-	

wet and dry years relevant for crop irrigation water use, and (3) we lack data on public supply deliveries to manufacturers and finer-scale industrial water-use data that could evaluate water-use changes in specific industries (Fig. 3). Others have modeled processes that could be used in future accounts to more fully understand water's role in the U.S. economy, including flows of water between industries (Marston et al., 2018), water imports and exports (Rushforth and Ruddell, 2018), and virtual water flows (Dang et al., 2015).

Finally, there is a need for better data (particularly at the national scale and in time series) on (1) imports/exports of water to Canada and Mexico, as well as other nations through trade in virtual water, (2) crop use of soil moisture, and (3) groundwater asset accounts to better support accounting for groundwater extractions, which have increased as a percentage of U.S. water use (Dieter et al., 2018). Pairing PSUTs with water asset accounts for groundwater (see Section 4.3.4) would inform our understanding of the sustainability of groundwater use and the associated ecological and socioeconomic effects of increasing groundwater use (Famiglietti, 2014, McNutt, 2014, Grafton et al., 2018).

4.3.2. Water productivity accounts

Beyond improving the alignment between industry water use and economic data, future work could also incorporate more monetary information into the accounts. Theoretically, since users pay for water either directly or for self-supplied systems, water expenditures data would exist in the national economic accounts as would the value of the water supply infrastructure (e.g., dams, pipes, pumps). Regrettably, water is not tracked as a separate product in the BEA's use tables. From the SNA perspective, monetary use is a means to aggregate heterogeneous products and assets. It is not the only way to do so, but does allow for more meaningful comparisons of very different things. As a simple example, an economy that only produces cars and computers could tally the number of physical units produced, organizing them using physical accounts as we have done. However, cars and computers differ across numerous dimensions, making physical counts very limited in their comparability across products and over time. While still useful to know the physical counts, it is more useful to know how the differences across these products are valued by their users (consumers), which is where monetization comes in. GDP and other SNA accounts are not expressed in monetary terms because money is all important, but because monetization allows us to more easily compare different quantities of the myriad products and assets that make up any economy. Similarly, not all water is created equal in terms of its value to users (Young and Loomis, 2014); differences in its quality and availability meaningfully change its usability across space and time. Additional work on monetization could strengthen the policy relevance of U.S. water accounts.

4.3.3. Water-quality and emissions accounts

Data on nonpoint-source emissions would be valuable for both water-quality and emissions accounts. For example, Stewart et al. (2019) estimate county-level nonpoint-source nitrogen and phosphorus inputs from fertilizer for the year 2012 for the coterminous U.S. Additionally, the SPAtially Referenced Regressions On Watershed attributes (SPARROW) model can be used to estimate the impact of nonpoint-source nutrient emissions on water quality in the U.S. (Schwarz et al., 2006). However, with the exception of SPARROW models developed for the Chesapeake Bay, its applications have not included temporal dynamics. Future iterations of SPARROW that are both national scale (e.g., Saad et al., 2019) and temporally explicit could be extremely useful in informing emissions and water-quality accounts.

For point-source emissions, an ideal data source (1) would be long-

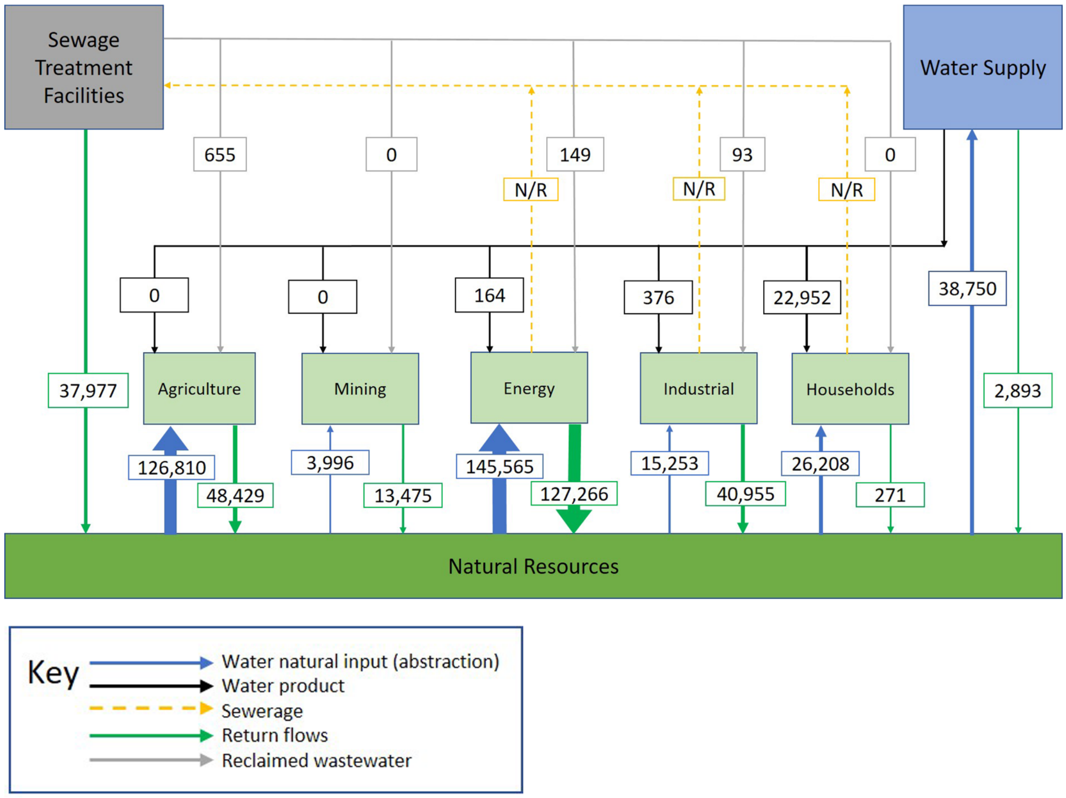


Fig. 5. Major physical flows of water from the natural environment to the economy and returns to the environment: visualization of the 2015 U.S. physical supply and use tables (compare to United Nations, 2012, Figure II.2 for all physical flows of water). Data sources include Dieter et al. (2018) for water use and deliveries and PCS-ICIS returns data (USEPA, 2018a). Line thickness corresponds to water flow volumes. Numeric values are in million gallons/day. Dashed lines and N/R: not reported.

term and complete (by industry, including emitters exempted from NPDES), (2) have minimal error, and (3) capable of tracking emissions from industries and households to WWTPs or water bodies, removals by WWTPs, and discharge back into the environment. Pieces of this information are contained in the PCS-ICIS and TRI databases, but the PCS-ICIS database is generally more comprehensive than TRI, making the two difficult to integrate. Though designed for regulatory rather than statistical purposes, more reliable DMR data could strongly support future water emissions accounts. Mandatory electronic reporting, introduced in late 2016, should reduce the number of errors in the database. Additionally, database users can report errors to EPA, which in some cases are corrected, though some state environmental agencies require the NPDES permit holder itself to make the correction. This shows that the database is being improved with greater scrutiny and use. Further, reporting by NAICS codes, rather than SIC, would increase the compatibility of DMR and national accounts data. Finally, for both water-quality and emissions accounts, future work could use statistical sampling to evaluate the reliability and accuracy of current estimates.

While temporal coverage of surface water-quality data was good (decadal from 1972 to 2012, Oelsner et al., 2017), spatial coverage of monitoring sites was limited for a number of water-quality constituents. For the six constituents we evaluated, data were limited for northern New England, parts of the Intermountain West, and Alabama, Mississippi, and Tennessee. Further data availability in these areas and for additional water-quality constituents (e.g., those included in Table 8) would enable the production of more comprehensive water-quality accounts.

4.3.4. Water asset accounts

Although we lacked the data to compile them, water asset accounts, which track stocks of water resources (i.e., surface water, groundwater, soil moisture, snow and ice) and their change over time, would be highly informative for water resource management. Asset accounts enable the tracking of surface and groundwater quantities, to better understand the sustainability of their use. Water asset accounts would also let us understand whether USGS 5-year water-use data come from drought or wet years. This is particularly important for interpreting water-use trends for crop irrigation or to highlight trends in water-scarce areas (Konikow, 2015; though much more frequent water-use reporting, i.e., daily to monthly, is targeted for the future, Alley et al., 2013). Drought indices (Keyantash and Dracup, 2002) could be used for the same purpose, but would need to be spatiotemporally aggregated in a meaningful way to address specific water uses like crop irrigation. Although satellites like Gravity Recovery and Climate Experiment (GRACE) track changes in water resources (Famiglietti, 2014), they do not quantify stocks of water. Doing so would require rigorous hydrologic modeling incorporating best practices such as calibration and uncertainty analysis, which is currently being undertaken at the national scale by USGS (Alley et al., 2013, Reitz et al., 2017). Important data gaps preventing the compilation of water asset accounts include rigorous, national, time-series data on soil moisture, unsaturated zone water, and snow and ice, as well as suitable judgments on how to account for groundwater and brackish water resources. The USGS aims to develop the needed data to compile water asset accounts, as called for by the SECURE Water Act of 2009 (Alley et al., 2013), through regional and national Integrated Water Availability Assessments (U.S. Geological Survey, 2020).

5. Conclusion

U.S. water accounts provide information in a way that can be connected to other data, such as land (Wentland et al., 2020 this issue) and ecosystem accounts (Heris et al., this issue, Warnell et al., 2020 this issue), economic production and employment, using various geographic

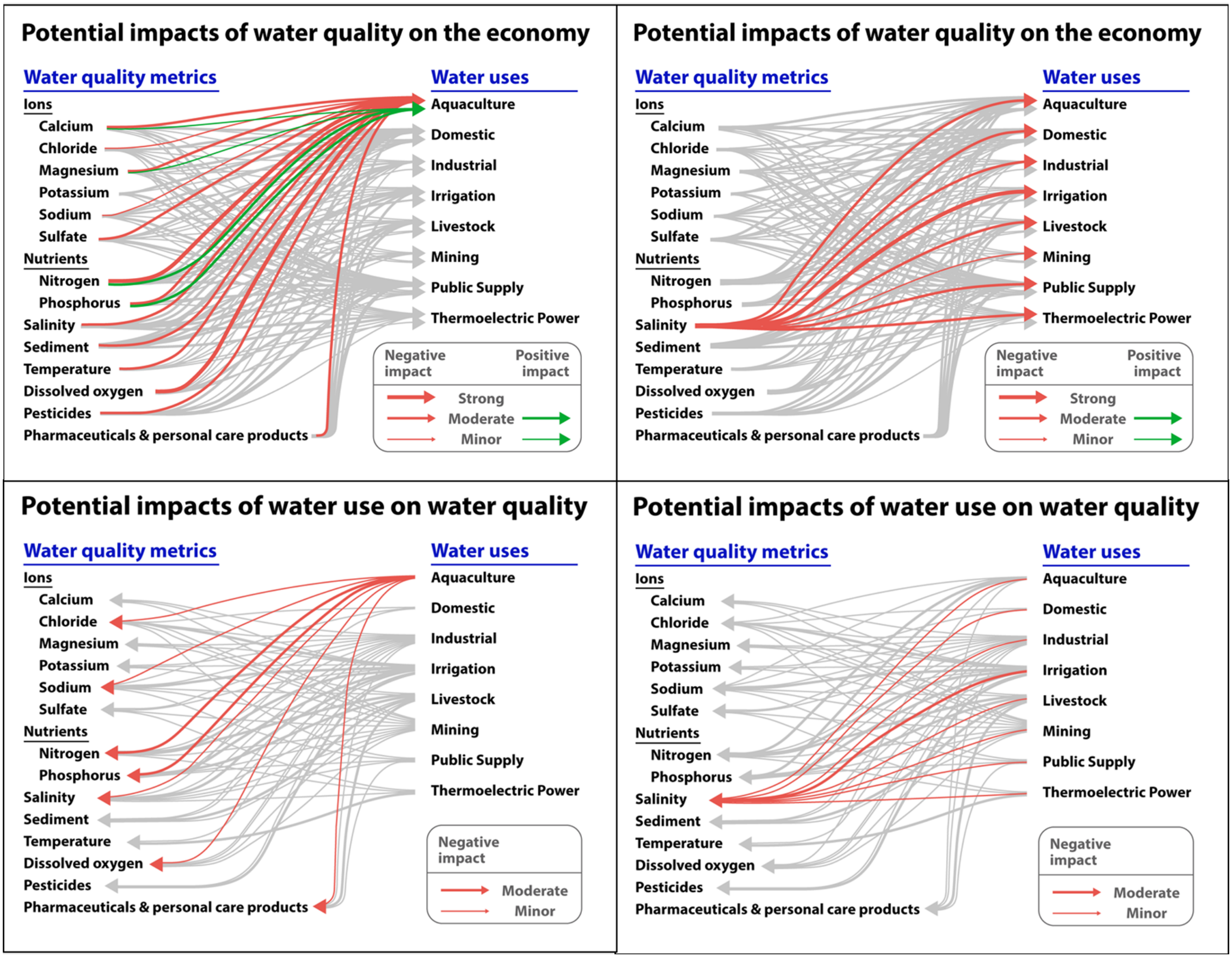


Fig. 6. Connections between water quality and aquaculture (left); connections between salinity and water use (right).

aggregations, including watersheds (National Academy of Sciences, 2018). Although SEEA-Water is one of the best established of the SEEA accounts, and a variety of use cases now exist (Nagy et al., 2017, Vardon et al., 2018), no nation collects all data needed to produce the full range of water accounts (Vardon et al., 2018). We illustrate the development of U.S. water accounts at the national, regional, and state levels; such accounts are also possible at other scales, e.g., metropolitan statistical areas (Warnell et al., 2020 this issue).

In a recent assessment of USGS strategic science directions for its Water Mission Area, the National Academy of Sciences (2018) developed five questions with high scientific and societal importance and relevance to USGS and its partners. Two of these questions—“How do human activities affect water quantity and quality?” and “How can water accounting be done more effectively and comprehensively to provide data on water availability and use?” – are directly relevant to this work. Robust water accounts may help to address additional questions identified by the National Academy of Sciences (2018) with relevance to water management and have been called for by numerous other authors (Escriva-Bou et al., 2016, Garrick et al., 2017, Patterson et al., 2017, Boyd et al., 2018, Grafton et al., 2018). Our pilot accounts identified numerous data gaps and fall short of water accounts’ full potential but will improve over time as new data sources are incorporated, time trends are extended, and inconsistencies are reconciled. By compiling these accounts, we thus lay the groundwork for future water accounts that fully integrate physical and economic information in diverse hydrologic and socioeconomic contexts across the United States.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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