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Landon T. Marston

Adel M. Abdallah

Kenneth J. Bagstad

Kerim Dickson

Pierre Glynn

See next page for additional authors

Authors
Landon T. Marston, Adel M. Abdallah, Kenneth J. Bagstad, Kerim Dickson, Pierre Glynn, Sara G. Larsen, Forrest S. Melton, Kyle Onda, Jaime A. Painter, James Prairie, Benjamin L. Ruddell, Richard R. Rushforth, Gabriel B. Senay, and Kimberly Shaffer

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Water-Use Data in the United States: Challenges and Future Directions

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Research Impact Statement: To inform future decision-making regarding water supplies and uses, we must coordinate efforts to substantially improve our capacity to collect, model, and disseminate water-use data.

ABSTRACT: In the United States, greater attention has been given to developing water supplies and quantifying available waters than determining who uses water, how much they withdraw and consume, and how and where water use occurs. As water supplies are stressed due to an increasingly variable climate, changing land-use, and growing water needs, greater consideration of the demand side of the water balance equation is essential. Data about the spatial and temporal aspects of water use for different purposes are now critical to long-term water supply planning and resource management. We detail the current state of water-use data, the major stakeholders involved in their collection and applications, and the challenges in obtaining high-quality nationally consistent data applicable to a range of scales and purposes. Opportunities to improve access, use, and sharing of water-use data are outlined. We cast a vision for a world-class national water-use data product that is accessible, timely, and spatially detailed. Our vision will leverage the strengths of existing local, state, and federal agencies to facilitate rapid and informed decision-making, modeling, and science for water resources. To inform future decision-making regarding water supplies and uses, we must coordinate efforts to substantially improve our capacity to collect, model, and disseminate water-use data.

(KEYWORDS: water use; data management; water conservation; watershed management; planning.)

INTRODUCTION

The food we eat, the electricity we need for our homes and businesses, and the manufactured goods that we produce are some of the many ways society relies on water (Marston et al. 2018). Water, however, is a finite resource not always available in the necessary quantity or quality at the desired time and place. To resolve this mismatch, we must understand

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Department of Civil and Environmental Engineering (Marston), Virginia Tech Blacksburg, Virginia, USA; Western States Water Council (Abdallah), Murray, Utah, USA; Geosciences & Environmental Change Science Center (Bagstad), U.S. Geological Survey Denver, Colorado, USA; Department of Civil Engineering (Dickson), Kansas State University Manhattan, Kansas, USA; Consortium for Science, Policy & Outcomes (Glynn), Arizona State University Washington, District of Columbia, USA; Upper Colorado River Commission (Larsen), Salt Lake City, Utah, USA; Cooperative for Research in Earth Science and Technology (Melton), NASA Ames Research Center Moffett Field, California, USA; Internet of Water, Center for Geospatial Solutions (Onda), Lincoln Institute of Land Policy Cambridge, Massachusetts, USA; South Atlantic Water Science Center (Painter), U.S. Geological Survey Norcross, Georgia, USA; U.S. Bureau of Reclamation (Prairie), Boulder, Colorado, USA; School of Informatics, Computing, and Cyber Systems (Ruddell, Rushforth), Northern Arizona University Flagstaff, Arizona, USA; Earth Resources Observation and Science Center Core Science Systems Mission Area (Senay), U.S. Geological Survey Denver, Colorado, USA; and Observing System Division, Hydrologic Networks Branch (Shaffer), U.S. Geological Survey Columbus, Ohio, USA (Correspondence to Marston: lmarston@vt.edu).

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how much is available and the volume and timing of water diversions for environmental and societal purposes. As water demands outpace supplies, with an increasingly variable climate and aridification (Overpeck and Udall 2020), greater consideration to the demand side of the water balance equation is needed.

In the United States (U.S.), water resources management is generally conducted at a local or regional level, with fragmented data collected for where and who uses water and the volumes used. Growing cities, expansion of irrigated agriculture, and continued development of the arid western U.S. led to new water rights and uses (Sabo et al. 2010). Gauging of streamflows and monitoring of precipitation have proved critical in the design of infrastructure for water storage and redistribution. While consistent high-quality water supply measurements exist across the nation, those for water use vary by state. Increasing water demands and dwindling water supplies require a transition from a narrow focus on water supply development to water conservation, which is centered on improved water-use measurements and accounting, enhancing previous water monitoring and infrastructure investments, and providing a path for greater adaptation through water transfers and markets (Doherty et al. 2012).

The future of water management requires working within existing legal frameworks as well as developing new and potentially more flexible systems to maximize previous investments to meet uncertain societal water demands and priorities. While the last two centuries have focused on developing and measuring water supplies, the next century will be defined by adaptation, efficiency, markets, innovation, mitigation, environmental concerns, and reform (Figure 1). Difficult choices and tradeoffs that have been delayed will become unavoidable. High-quality, nationally consistent water-use information with improved spatial and temporal resolution will be essential when faced with these decisions. Although data on water supplies will still be necessary, targeted investments in the collection, curation, and dissemination of water-use data will be critical in informing decision makers, as well as improving understanding of society's use of water and its impacts on water availability, the environment, and the economy.

WATER-USE DATA IN THE UNITED STATES

Allocation and administration of water rights in the U.S. are the responsibility of states and state agencies. Likewise, water-use data collection and management are primarily administered by state agencies. State laws dictate or affect what data are

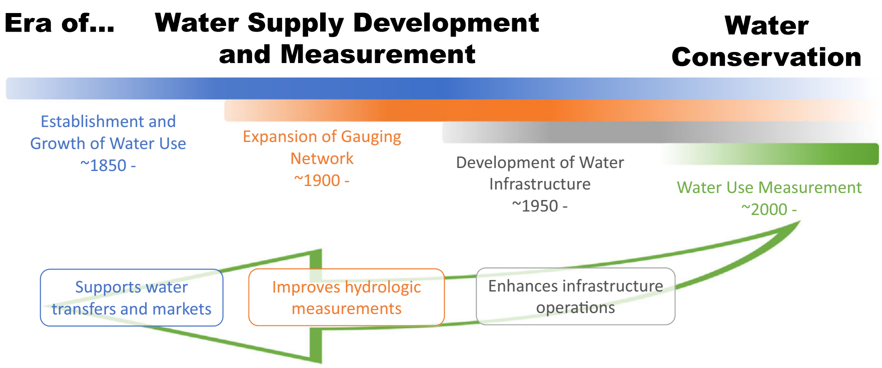

FIGURE 1. Water resource management decisions and investments of the 19th and 20th Centuries shaped the current state of water resources in the United States (U.S.). Streamflow and precipitation records proved critical in water infrastructure design. The early- to mid-20th Century saw the largest increase in active streamgages, while the vast majority of the nation's water supply infrastructure was constructed in the mid- to late-20th Century (Doyle et al. 2008). This is now the era of water conservation, which will enhance previous water monitoring and infrastructure investments and provide a path to greater adaptation through water transfers and markets. While water conservation efforts are primarily driven by water scarcity, several other factors aided in the transition to this new era. The 1972 Clean Water Act established federal regulations for water discharge and resulted in water conservation by many states and cities due to increased treatment costs related to excess water use (NRDC 2014). In the 1980s, the digital computer era enabled a new generation of federal surveys and data collection focused on understanding the nation's water use. Urban water conservation gained traction in the 1990s through new regulations and incentives on water-efficient appliances, fixtures, and landscapes (Vickers 2001; Baker 2021). At the same time, the WateReuse Association (watereuse.org) was established to promote water recycling as a means to gain additional utility from every drop of water. The Science and Engineering to Comprehensively Understand and Responsibly Enhance Water Act of 2009 demonstrated congressional recognition of water scarcity and proposed measures to understand, measure, and take actions to improve water availability. Today, remote sensing tools, web platforms, and smart devices can enable access to a wide array of new water-use measurements that once fully harnessed will dramatically improve our understanding of water use.

collected and how they are used, stored, and distributed (Josset et al. 2019). In addition to the state agencies, many federal and local governmental agencies, utilities and utility districts, and non-governmental organizations collect and compile available water-use data at local, regional, and national scales (Table 1). A lack of a shared vocabulary and definition of "water use" can also make data sharing and comparison challenging.

Nationally, the U.S. Geological Survey (USGS) has estimated water withdrawals every five years since 1950 by working with state and territory agencies and using data from other sources. The USGS national estimates are reported for eight water-use sectors (since 2000): public supply, domestic, irrigation, thermoelectric power, industrial, mining, livestock, aquaculture. A combination of reported and estimated values is provided using various methods and guidelines (Bradley 2017). Water-use estimates are further subdivided into groundwater or surface water and fresh or saline water uses, which are aggregated and reported at the county, state, and national scales. The USGS aggregates site-specific water withdrawals and use data, which are shared by the states, into use categories for each county, subwatershed, or primary aquifer. Thus, site-specific data are not shared publicly.

Although USGS water-use estimates rely on the best available reported data and recommended estimation guidelines, there is uncertainty in these estimates due to differences in how states report or estimate water use. This variability challenges the development of consistent and high-quality water-use data at regional to national scales (Tidwell et al. 2014) needed to inform policy decisions. While most states have laws requiring withdrawals to be reported, the reporting requirements vary by state and limit the development of a more cohesive national dataset. State agencies often address water resources management with varying levels of regulation and enforcement. Some have more extensive programs that oversee water-use monitoring and measurement per legal statute while others do not. The different methods across states, years, and sectors can contribute to uncertainty and inaccuracy.

In 2019, the USGS and Western States Water Council hosted a workshop with local, state, federal, private, and academic partners to address the challenges related to estimating, reporting, accessing, and sharing water-use data (Abdallah and Maupin 2019). The workshop participants identified six key factors that influence the ability to supply useful and accurate water-use estimates (Table 2).

To assist states in water-use data collection and sharing, the USGS Water-Use Data and Research (WUDR) Program was authorized under the Science and Engineering to Comprehensively Understand and Responsibly Enhance (SECURE) Water Act (Sec. 9508 (c)). The USGS began to provide financial assistance through cooperative agreements to state water resource agencies in 2015 (U.S. Geological Survey 2021). The WUDR cooperative agreements provide federal support for States or their representatives to (1) improve the availability, quality, compatibility, and delivery of water-use data that are collected and/or estimated by states to support national water-use assessments; and (2) integrate the water-use data into USGS databases in electronic or machine-readable formats.

A PATH TO IMPROVED WATER-USE DATA COLLECTION, ESTIMATION, AND ACCESS

The passage of the SECURE Water Act in 2009 established a National Water Availability and Use Assessment Program, also known as the National Water Census. Section 9508 of the SECURE Water Act authorizes a program within the USGS to: (1) provide a more accurate assessment of the status of water resources of the U.S.; and (2) develop the science for improved water-availability forecasts for future economic, energy production, and environmental uses. In response to two National Academy of Sciences reports (National Research Council 2002; National Academies of Sciences, Engineering, and Medicine 2018) and the SECURE Water Act, the USGS Water Mission Area is working to enhance its capabilities across programs related to data collection, modeling and prediction, and delivery. The National Academy's recommendations include: (1) enhancing spatiotemporal water-use data collection; (2) an increased focus on the relationships between human activities and water; (3) distinguishing between consumptive and non-consumptive water use; and (4) collaborating to develop new data sources and platforms.

The USGS Water Availability and Use Science Program (WAUSP), which supports research and the development of tools to aid in water resources planning and assessment, must overcome various challenges to achieve the aforementioned four goals laid out by the National Academy. Nonetheless, over the next several years, USGS will be building capacity for nationally consistent modeling approaches to estimate water withdrawals, consumptive use, and associated uncertainty at the daily scale for 12-digit hydrologic unit code subwatersheds. Through the USGS Next Generation Water Observing System Program (NGWOS) and cooperative agreements with

TABLE 1. Organizations with primary, secondary, and tertiary roles in collecting, estimating, managing, and/or sharing water-use data. Primary: collects, estimates, or aggregates water-use data. Secondary: collects, estimates, or aggregates secondary data that could be used for water-use estimation. Tertiary: acts in a supporting role to primary or secondary organizations.

Organization	Level	Role
National Aeronautics and Space Administration (NASA)	Federal	*Secondary*: Develops, launches, and operates Earth-observing satellites and supports applied research in partnership with federal, state, and local agencies and the private sector to develop capabilities for remote sensing of key measures of water use, such as evapotranspiration, water surface elevation, and ground subsidence
National Oceanic and Atmospheric Administration (NOAA)	Federal	*Tertiary*: Provides climate and drought reports, as well as weather, hydrologic, and climate forecasts for the U.S. and its territories
Natural Resources Conservation Service (U.S. Department of Agriculture)	Federal	*Secondary/Tertiary*: operates an irrigation management service that helps farmers monitor irrigation water and fertilizer applications and losses from their fields *Tertiary*: operates the Soil Climate Analysis Network (SCAN) monitoring soil moisture and temperature, as well as the Snow Telemetry (SNOTEL) snow depth monitoring network. Has modeling tools that allow interpolations and modeling
U.S. Army Corps of Engineers (USACE)	Federal	*Secondary*: Water control and release information for navigational needs, for ecological needs, for wetlands, water quality and invasive species management, flood control, and water supply, for "system-wide water resources." USACE is also involved in Inter-State Compacts and inter-basin transfers, which are related to water use
U.S. Bureau of Reclamation (USBR)	Federal	*Primary*: Estimates, collects, and reports information on water use in the Colorado River Basin to satisfy the Secretary of the Interior's obligations under the Colorado River Basin Project Act of 1968 (PL 90-537) and Article V of the Consolidated Decree of the U.S. Supreme Court in *Arizona v. California*, 547 U.S. 150 (2006) *Secondary*: Maintains records on diversion flows, water control, and distribution operations (including for irrigation) across the western U.S.
U.S. Census Bureau	Federal	*Primary*: Surveys water uses in manufacturing and mining through the *Census of Manufactures: Water Use in Manufacturing* and *Census of Mineral Industries: Water Use in Mineral Industries*, respectively. However, these surveys are either discontinued or infrequently conducted *Secondary*: Reports annual population, demographic estimates, and economic activity at the subcounty-, county-, and/or state-levels
U.S. Department of Agriculture National Agricultural Statistics Service (NASS)	Federal	*Primary*: In years ending in 3 and 8, NASS administers the Irrigation and Water Management Survey (formerly called the Farm and Ranch Irrigation Survey) to collect self-reported estimates of crop-specific irrigation depths and related irrigation information. Responses are aggregated to the state-level *Secondary*: In years ending in 2 and 7, NASS administers the Census of Agriculture that inventories farms and the number of farms, land in irrigated farms, crops, and livestock, aggregated to the county- and state-level. The Census of Aquaculture is administered periodically (last two were in 2005 and 2013) to collect information on aquaculture production including species and source of water used. Responses are aggregated to the state level
U.S. Energy Information Administration (USEIA)	Federal	*Primary*: Collects site-specific water use and power data in the annual electric generator report and the power plant operations report *Secondary*: Publishes an annual energy outlook each year with future projections
U.S. Environmental Protection Agency (USEPA)	Federal	*Primary*: Maintains records on drinking water controls (locations of public supply intakes, return flows, and wastewater releases) and water conservation monitoring and controls (e.g., WaterSense) *Secondary*: Data on pollution emissions affecting drinking water and ecological needs. Volunteer watershed monitoring community
U.S. Fish and Wildlife Service (FWS)	Federal	*Tertiary:* Has information on minimum flows (and maximum stream temperatures) needed for ecological needs. Maintains information on the Record of Decision concerning limits placed on societal water

(continued)

TABLE 1. (continued)

Organization	Level	Role
		withdrawals due to potential or actual impacts to threatened and endangered species
U.S. Geological Survey (USGS)	Federal	*Primary*: The Water Availability and Use Science Program (WAUSP) assists in the determination of water that is available for human and ecological uses, now and in the future. This includes evaluating the quantity and quality of water, identifying long-term trends in water availability, and developing an improved ability to forecast water availability for economic, energy production, and environmental uses *Secondary*: Maintains extensive streamgage network and hydrologic modeling capabilities that can help infer water use
Water districts, utilities, irrigation districts, and municipalities	Local	*Primary*: Serve as the most granular collector of water-use data, often maintaining user-level water-use data. Public water systems, including community water systems and irrigation districts, often collect and report their water withdrawals, water deliveries, and water loss audits to state regulatory agencies
Internet of Water	Non-governmental organization (NGO)	*Tertiary*: Aim to mobilize cultural and behavioral change across individuals, agencies, and institutions to bring about the necessary technological change that will transform water data and information and enable better water management outcomes
OpenET	NGO	*Primary*: Provide satellite-based consumptive water-use estimates for irrigated agriculture in the western U.S.
Regional Water Commissions	Regional	*Great Lakes Commission* *Secondary*: Aggregates water-use information, including withdrawals and consumptive use, including by source, jurisdiction, and watershed, for the surrounding states and Canadian provinces. They provide annual water-use reports and host a searchable data-sharing platform with records dating back to 1987 *Upper Colorado River Commission* *Secondary*: The Upper Colorado River Commission (UCRC) works with the four Upper Division States of the Colorado River Basin (Utah, Wyoming, New Mexico, and Colorado) to ensure that Colorado River flow obligations required by the 1922 Colorado River Compact to the Lower Division States are met. Regarding water-use data, UCRC works with the Upper Division States to provide estimates of current consumptive use and future water demand for planning and modeling purposes *Upper Mississippi River Basin Association, Delaware River Basin Commission, Ohio River Valley Water Sanitation Commission, others* *Tertiary*: Most organizations do not collect primary data or maintain original water-use records. Typically, they oversee a unified approach to managing the river system without regard to political boundaries of its member states, which may help facilitate consistent data across states
Western States Water Council — Water Data Exchange (WaDE) Program	Regional	*Primary*: Promote the conservation and management of water resources, provide a forum for the exchange of perspectives, ideas, and experiences among members, and help track water-use data for each region. Assist 18 western states and streamline their water rights and water-use data with one another, the public, and federal agencies, including the USGS Water Use Program
State Agencies	State	*Primary*: Responsible for water permitting and enforcing water rights depending on legislation and agency purpose. Many state agencies monitor and collect water-use data for various sectors. Often, state agencies report user-level or aggregated water uses online or make these data available upon request *Secondary*: Ensure compliance with Inter-State Water Compacts and often record inter-basin transfers
Native American Tribes	Tribal	*Primary*: Specific to the Colorado River Basin, in 2018 Reclamation and the Ten Tribes Partnership published the Tribal Water Study (USDOI 2018. Accessed April 20, 2021), which among many other topics aggregates current water use and also projected future demand and development for Partnership tribal communities. Confederated Salish and Kootenai Tribes in Montana have an online Hydrology data portal

TABLE 2. Factors that inhibit the collection and dissemination of accurate and timely water-use data. Successful data collection and sharing initiatives must overcome these barriers.

Factors	Description
Staffing and coordination	Some State agencies have dedicated staff for water-use reporting while others do not. Different aspects of the water-use data lifecycle may be the responsibilities of different agencies or working groups with no central database and minimal coordination. Budgetary and training constraints affect an agency's ability to perform quality assurance (QA) and quality control (QC) of data streams
Statutes or laws	State enforcement or voluntary processes for measuring and collecting water-use data, as well as the reporting threshold and ramifications of non-compliance, vary significantly between states. Privacy or sensitivity of information related to water supply security also affects reporting water use and its metadata
Information Technology	Interoperability between different water-use databases, software, and schemas within state agencies and between state and federal collections can challenge data exchange. In some states, historical water rights and use records have not been fully digitized. Lack of Internet access or insufficient and inadequate electronic communications with water users affect the speed of reporting
Procedures and methods	Methods used to estimate water-use data, as well as collect and report metered records, vary between agencies. The variability extends to terminology, definitions, metadata schemas, and the standard procedures to collect, verify, review, report, and manage the data. Some agencies have advanced QA and QC automated procedures to perform checks and verifications while others have basic manual processes. The lack of data standards affects data integrity, consistency, completeness, and metadata reporting
Cost	Limited budgets may prohibit necessary investments for software and equipment used to maintain databases for water withdrawals, staff to QA/QC data, and meters to measure withdrawals. Investing in science, in situ measurements, and applications can be cost-prohibitive. Agencies may use proxy methods such as power usage or remote sensing to estimate water use, though these may involve tradeoffs in accuracy and require technical expertise
Spatial and temporal inconsistencies	Various spatial and temporal scales are used to collect and report water-use data that comply with legal statutes. A consistent and comparable national water-use product is confronted by inconsistencies between spatial and temporal scales over time and between states, as well as gaps in coverage of water-use data for certain sectors

partners, new monitoring data are being collected to fill the needs of accurate and reliable water-use reporting. Efficient collection, storage, and sharing of high-quality data will be needed to make timely and relevant information available to decision makers. This requires collaboration among many federal, state, and regional entities (Table 1).

The next generation of water-use data and forecasting will require (1) a better understanding of water-use drivers, (2) advanced models, sensors, and meters, (3) data frameworks that make data Findable, Accessible, Interoperable, and Reusable (FAIR, Wilkinson et al. 2016), and (4) coordination and collaboration between the various water-use stakeholders. Below, we highlight new and proposed efforts to improve water-use data collection and sharing. Strategies to address the challenges inhibiting consistent collection and management of U.S. water-use data (Table 2) must recognize that these problems are not just technical but involve capacity and resources, legal and regulatory frameworks, and data privacy issues.

To support projections and forecasting, water-use models will require reliable, integrated regional data recording the quantity, location, and purpose of withdrawals and diversions, public supply deliveries, and potential returns to water sources, each at as fine a spatiotemporal resolution as possible. Understanding of the socioeconomic, physiohydrologic (including streamflow, groundwater levels, and surface and reservoir storage volumes), and climatological drivers relevant to water use will further improve estimates of water demand and availability. Water-use information needs to be meaningfully spatially indexed, both geographically and hydrographically. Then, a nuanced understanding can be built of which water fluxes occur up or downstream of each other, or otherwise depend on each other. Greater understanding of how infrastructure stores and connects water sources to water users can further help refine estimates of water withdrawals, consumption, and return flows, including those that cross watershed boundaries (Dickson et al. 2020). For this information to be effectively used, it also needs accompanying metadata documenting data provenance, quality, precision, and reasons for gaps in coverage.

More accurate and spatially/temporally refined estimates of public supply, agriculture irrigation, and thermoelectric power water uses should be prioritized because these three categories account for 90% of all U.S. water withdrawals (Dieter et al. 2018). While water utility records of aggregate water deliveries are often available, the number and diversity of water users and privacy rules prohibiting the sharing of individual water uses make it challenging to predict public supply water uses at the user or sector level. Worland et al. (2018) suggest various socioeconomic and environmental drivers of public supply variability across the U.S., but more work is needed to understand how a city's water pricing structure, water availability and sources, distribution losses and inefficiencies, climate, diverse water uses and economic composition (e.g., indoor vs. outdoor domestic use, retail vs. heavy industry), and other factors influence water use at a more granular level.

Thermoelectric power plants with energy production over 1 MW/year report their annual cooling water withdrawals and consumption to the Energy Information Administration (EIA Forms 923 and 860). Though there have been recent improvements in these self-reported water-use records (Peer and Sanders 2016), some of the EIA-reported water withdrawal and consumption estimates are not thermodynamically plausible (Diehl and Harris 2014). Nationally consistent methodologies that pair plant-specific information with advanced modeling of thermoelectric power plant water withdrawals and consumption can better define uncertainties and improve the accuracy of water-use values in this sector (Harris and Diehl 2017).

In assessments of information needs conducted with the U.S. water management community, evapotranspiration (ET) and consumptive water use in the irrigated agriculture sector have been frequently identified as a significant data gap and a barrier to comprehensive water management in the western U.S. (Jenkins et al. 2018; National Academies of Sciences, Engineering, and Medicine, Space Studies Board 2019; WWAO 2020). Building upon advances in remote-sensing science and technology for detecting and measuring ET of water use by crops and other vegetation, OpenET provides an automated operational system for providing field-scale ET data (30 × 30 m), mapped across the western U.S. (Melton et al. 2021) at daily, monthly and annual time steps. OpenET is a collaborative effort involving six ET modeling teams from the U.S. and Brazil, three federal agencies, non-profit conservation groups, private sector organizations, eight universities, and key partners from the agricultural sector, water resource management agencies, and conservation communities.

OpenET provides data from an ensemble of satellite-based ET models driven with the petabytes of satellite and meteorological data available on the Google Earth Engine (Gorelick et al. 2017) cloud-based computing platform. The OpenET framework includes reporting and data analysis tools, as well as open data services and an application programming interface (API) that follows the OpenAPI Specification to facilitate automated data retrieval and integration with other applications. The project has conducted an extensive intercomparison and accuracy assessment for the ensemble of ET models using ground measurements of ET from 139 flux tower sites instrumented with open path eddy covariance systems. After extensive calibration and validation, OpenET was made publicly available in the fall of 2021. It is currently being used by agricultural, water management, and conservation partners seeking improved agricultural consumptive water-use data at scales ranging from daily, field-scale to annual, regional-scale estimates. Water deliveries for irrigated agriculture in the western U.S. are infrequently measured, making OpenET data a key resource for developing consumptive use estimates and reporting total water withdrawals required for agricultural water use.

Data on ecological water needs are also necessary to frame tradeoffs for decision makers. The lack of consensus on how to estimate environmental flow requirements and the absence of a regulatory framework to provision for environmental water needs inhibits nationally consistent estimates of environmental water use. The Endangered Species Act of 1973 has been used in some basins to establish environmental flow requirements but this cannot be applied to all basins. The existing USGS streamgage network could be leveraged to determine if environmental flow requirements are met but the more challenging task will be to first resolve the regulatory, political, and scientific barriers to estimating environmental water use.

The next generation of water-use estimates should better inform decisions on water supplies and allocations, water budgets, infrastructure investments, and basin-level modeling and impacts. Operational planning, decision-making, and forecasting of water use will benefit from a significant decrease in data latency and uncertainty, as well as improved temporal resolution. We need to account for the amount and timing of withdrawals of water, its recycling, quality transformation, and conveyance, and the location and timing of its release back into the environment. Better data and metadata, models, techniques, and assessments are needed to explain and predict these flows, including the environmental, social, technological, legal, infrastructural, and economic factors driving water uses. Water-use estimates that link a specific source watershed or aquifer to the location of water use (the current National Water Census only reports the place of withdrawal, not location of use) will highlight locations where water is used outside the watershed or aquifer recharge area and return flows may not return to the source. Knowing the water source, place of use, and destination of return flows will greatly improve water budgets and hydrologic modeling. Furthermore, identifying key infrastructure, such as reservoirs, treatment facilities, pipelines, and canals used to link water users to a water source will provide a detailed national view of how water infrastructure underpins water use, helping to prioritize future infrastructure investments. The need for more granular water-use data, however, must be balanced against data privacy and national security interests because these may sometimes be at odds with each other.

In cases where water use is metered, various U.S. state and local laws regulating water-use data privacy must be considered, even within federal data projects. Many states have regulations prohibiting the public release of individual water-use records for specific types of water users, instead requiring aggregation of usage records into groups of 15 or more customers to preserve privacy (the "Rule of Fifteen") (Ruddell et al. 2020). The water usage of public water utilities is generally public information, however. In some states, irrigators, power plants, and large industrial operations' water usage is also public information. Because water-use data collection takes place at the state level, federal programs like the USGS Water Use Program help guide states and ensure a nationally consistent data product describing water use. Thus, federal support for standardization of water-use data would likely be necessary to streamline nationwide data access. Although water-use data have no federal regulation, they are closely associated with water supply infrastructure and thus, can frequently run afoul of Protected Critical Infrastructure Information (PCII) regulations (Ruddell et al. 2020).

Following FAIR principles in providing water-use information — to the extent allowed by data privacy requirements — would provide efficiency for data acquisition and analysis. Sensitive information may be secured and aggregated to meet privacy needs while enabling useful accessibility. An ever-growing number of water use-relevant data resources are published online through environmental monitoring and water-use estimation data systems. Despite substantial growth of public data repositories and other open science infrastructure over the last 15 years making data findable and accessible, interoperability and reusability have proven much more difficult to achieve (Borycz and Carroll 2020). Key needs to improve data interoperability and reusability of water-use data include the use of: (1) standard data models, data exchange formats, workflows, and APIs to publish data and enable the querying of data across data systems; (2) persistent identifiers and linked data principles to improve data interoperability related to common environmental features (e.g., the National Hydrography Dataset); and (3) clear, community-approved language, and vocabularies for metadata that remove ambiguity in data representation and enable its appropriate reuse. Initiatives like the Water Data Exchange (WaDE), WUDR, Internet of Water (2021. Accessed April 20, 2021), and others are working together on approaches to meet these challenges.

It is likely decentralized water data governance will continue into the future. Therefore, of primary importance to improve water-use data is to follow the FAIR principles in the pursuit of a decentralized linked data architecture that will enable the integration and analysis of data at virtually at any scale and time period. To help create a common, streamlined water-use data framework, the Western States Water Council, along with the Western Governors' Association, the U.S. Department of Energy, and the Western Federal Agency Support Team (Larsen and Young 2014), launched the WaDE program. WaDE has partnered with the 18-member states of the Western States Water Council to develop a common data dictionary and vocabulary to share administrative and water-use data. The data dictionary and architecture have been created with a focus on data interoperability needs related to sharing time series data. WaDE intends to share site-specific data with the public using generalized locations to follow state policies. While WaDE simplifies access to state water-use data, the issue of differing, and sometimes inconsistent, water-use estimation methods across states remains.

The USGS, WaDE, Internet of Water (IoW), Consortium of Universities for the Advancement of Hydrologic Science, Inc., U.S. Environmental Protection Agency, and others have begun experimenting with implementing a linked data architecture for the water data community, organized around the Geoconnex project (Internet of Water 2020. Accessed April 20, 2021). This architecture would allow water data providers to publish metadata about common environmental features using standardized approaches amenable to automated aggregation and inference of relationships between the underlying datasets without the need for centralized data governance and storage (Figure 2).

Collectively, OpenET, WaDE, and IoW provide a path forward for the establishment of an operational framework for production and access to accurate water-use data for the U.S. Each of these systems follows the FAIR data principles and results from close work with partners in the water resources management and agricultural communities to develop data services that increase access to needed water-use information that supports data-driven planning and decision making. By collaboratively working to develop consumptive water-use estimates while addressing diverse stakeholder needs, more unified water-use estimation methods and results can be produced that can be better aggregated across spatial and temporal scales. As OpenET, WaDE, and IoW are accepted, supported financially, and integrated

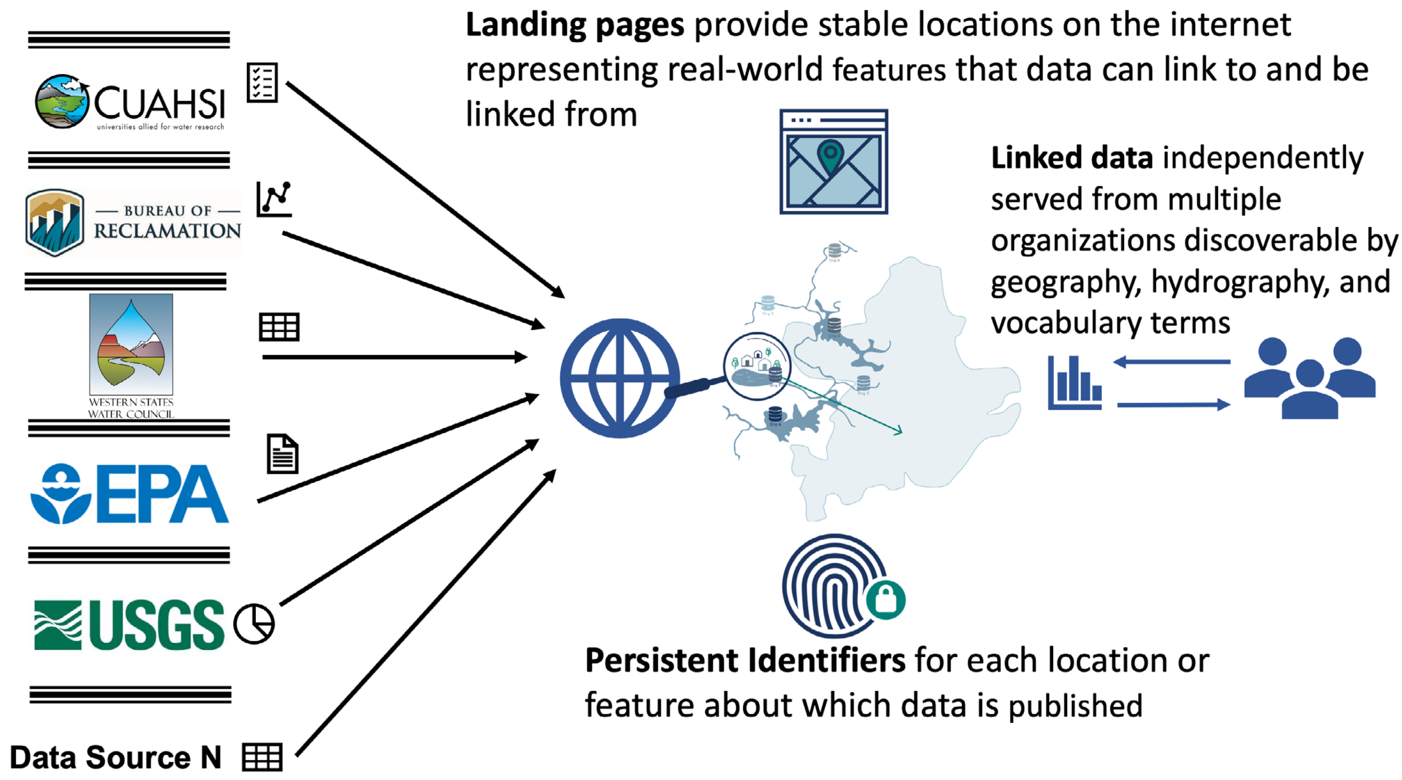

FIGURE 2. The Internet of Water Geoconnex Project is establishing a common metadata framework based on landing pages with persistent identifiers for real-world environmental features that will link disparate water datasets and enable users to search data across data systems. Credit: Lilli Watson, Internet of Water.

into other operational water data systems and management applications, they can also enhance our ability to identify trends and change in ET as a key indicator of consumptive water use by agriculture, which will support better assessment of water availability, two critical areas targeted in the Secure Water Act (2009).

Advanced data architectures are of very little use, however, without data to populate them and stewards to manage them. Coordination and collaboration among collectors of water-use data (namely, state and local partners) and regional and national data aggregators are required to create timely and useful data products. The aforementioned 2019 stakeholder workshop convened by the USGS and Western States Water Council represents an early effort to build a common understanding of water-use data challenges and opportunities. Sharing of perspectives, experiences, and knowledge between water-use stakeholders facilitates deeper coordination of efforts and promotes greater sharing of data.

We cannot control the weather and the natural water supply, but we can support our public and private decisions about how we use and share water, as well as the data that describe it. Better information about water use is a key to better decisions at all levels. Information can help to build public support for and confidence in major investments in water infrastructure or those that depend on a secure water supply. Robust water-use data can inform science-based water allocation policies and adaptive regulations that achieve desirable outcomes. Accurate, timely, and relevant data can also be used to protect water-related environmental services, properly price water transactions, and develop efficient and fair legal agreements. To inform future decision-making regarding water supplies and uses, we must work now to coordinate our efforts and improve our capacity to collect, model, and disseminate water-use data.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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AUTHOR CONTRIBUTIONS

Landon T. Marston: Conceptualization; Funding acquisition; Supervision; Writing – original draft; Writing – review & editing. **Adel M. Abdallah:** Conceptualization; Writing – original draft; Writing – review & editing. **Kenneth J. Bagstad:** Writing – original draft; Writing – review & editing. **Kerim Dickson:** Writing – original draft; Writing – review & editing. **Pierre Glynn:** Writing – original draft; Writing – review & editing. **Sara G. Larsen:** Writing – original draft; Writing – review & editing. **Forrest S. Melton:** Writing – original draft; Writing – review & editing. **Kyle Onda:** Writing – original draft; Writing – review & editing. **Jaime A. Painter:** Writing – review & editing. **James Prairie:** Writing – original draft; Writing – review & editing. **Benjamin L. Ruddell:** Funding acquisition; Writing – original draft; Writing – review & editing. **Richard R. Rushforth:** Writing – review & editing. **Gabriel B. Senay:** Writing – review & editing. **Kimberly Shaffer:** Writing – original draft; Writing – review & editing.

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