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U.S. Manufacturing Water Use Data and Estimates: Current State, Limitations, and Future Needs for Supporting Manufacturing R&D

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Abstract

Water is essential to manufacturing operations; without it, many facilities could not operate or meet production demands. Physical, reputational, and regulatory risks to water supplies compounded by climate change-induced impacts on hydrological conditions threaten the adequacy of water supplies for manufacturing. Manufacturing water use has not been a major focus of either water or manufacturing-related research. Research and development (R&D) aimed at helping manufacturers use water more sustainably and adapt to changing water conditions is needed to ensure a thriving sector and economy. However, the ability to identify R&D needs is severely limited due to a lack of current, statistically representative data on manufacturing water use and its environmental implications. In this perspective, we outline four key questions to inform R&D on manufacturing use and highlight how the current state of water data in the U.S. does not support adequately investigating these questions. We make recommendations for the water data characteristics needed to explore the research questions and knowledgeably inform R&D on manufacturing water use.

Introduction

Water resource exploitation beyond the recovery rate of ecological systems—from the perspectives of both water consumption and water quality—can lead to consequences across regions and economic sectors. Economic development and water availability are interconnected, and this is evident in the manufacturing sector. While economic forces drive manufacturing water use and consumption, lack of water availability can hinder development.[1] With increasing water demands, manufacturing industries can find increased competition for limited resources with other water users (e.g., agriculture and the municipal sector). Deteriorating water quality and diminishing water quantity as a result of both hydro-climatic changes[2] and manufacturing operations themselves can increase physical, reputational, or regulatory risk, and they can even impact manufacturing operations. In the most severe cases, these risks can shut down a facility's operations.

Due to the lack of publicly available data, the research community lacks insight and knowledge of how manufacturers use water and how that use impact watersheds, with the latter being a key driver of risks; understanding these risks is essential to the manufacturing sector's adaptation to future water-related changes. To understand the manufacturing sector's impact on watersheds and to identify opportunities for water technology R&D and policy, we identified the following key research questions:

- (Q1) How do water withdrawals, discharges, and constituents of concern from different manufacturing industries impact local watersheds and communities, and what are the quantitative metrics that capture these impacts?
- (Q2) How do manufacturers use water within their facilities, in relationship to both quantity and quality requirements, and how does their use compare to the theoretical minimum amount of water needed to provide an economic service?
- (Q3) What process improvements (e.g., water reuse technologies, water efficiency improvements, and detailed sensor monitoring and controls) are available to manufacturers, and what R&D is needed to develop technologies to lessen the impacts of manufacturing water use on watersheds?
- (Q4) How do current and future manufacturing water use and industrial colocation impact regional planning processes and how does changing water availability impact manufacturing operations and investment decisions?

(Q1) seeks to understand and limit the impact of manufacturing water use on watersheds and local environments. Without a detailed understanding of possible answers to this question, it is impossible to establish metrics for watershed impacts, risk severity, water efficiency, water-related emissions, resilience, and compliance costs for manufacturers. An understanding of (Q2) and (Q3) would allow for targeting water end uses with high potential for conservation and identifying needed improvements to encourage water recirculation, reuse, recycling, and efficiency measures within manufacturing plants. Water reuse and efficiency can reduce impacts on the local environment, but without understanding where to look for opportunities and the associated cost trade-offs and other impacts, reuse and efficiency are unlikely to be adopted broadly across the manufacturing sector. Answers to (Q2) and (Q3) can facilitate the development of R&D targets for new technologies and processes, as well as water conservation goals for existing processes and equipment. Finally, (Q4) looks to existing and future impacts and potential competition with other sectors in a changing climactic and regulatory environment. With the increasing potential for drought and other precipitation changes, the manufacturing sector will compete with other uses of water, and the increasing competition might have negative impacts on manufacturing production, local economies, and the environment. Irrespective of competition from other sectors, changes to current manufacturing operations and practices may be required to adjust to new water availability conditions. Ensuring that up to date water metrics are available to regional planners and manufacturers will allow for better informed decisions regarding local water use.

In this perspective, we review the current state of data on manufacturing water use and show that they do not support a detailed understanding to any of our four key questions. We compare the currently availability of data to aspirational data sets, highlighting the degree and depth to which the aspirational data sets could inform the four key questions. We then recommend the development of what we call an “enabling standard” that strikes a balance between burden (on both the policymakers tasked with collecting data and the manufacturing facilities whose data would be collected) and insight into the four key questions. This perspective seeks to raise awareness of the lack of data on manufacturing water use and motivate the water research and policy communities to improve on the current state. Doing so would allow the research community to support the manufacturing sector, maintain watershed health, and protect our threatened water sources.

Assessing Manufacturing Water Impacts

The United States is the largest user in the world of water for manufacturing, directly withdrawing more than 18.2 billion gallons per day.[3,4] In 2015, the manufacturing sector accounted for about 6% of total U.S. water withdrawal,[5] including 5% as self-supplied withdrawal from surface-water and ground-water sources[6] and 1% through public water supplies.[7,8] Although national-level manufacturing water use data are scarce, past national surveys,[4,7] representations of water use from other nations,[9] and corporate sustainability reporting[10] have shown there is heterogeneity in water use volumes, water sources, water quality requirements, reuse and recirculation, and disposal practices across sectors and regions. Currently, accurate, up-to-date, and comprehensive data are unavailable for U.S. manufacturing water withdrawals, consumption, quality requirements, and reuse within a plant, and discharge volumes and quality.

Because many factors drive manufacturing agglomeration and colocation, manufacturing sites tend to be concentrated in specific regions. Such concentration results in heterogeneous water demand across states and watersheds. Therefore, higher spatial disaggregation of manufacturing water demands—at the county level or eight-digit Hydrologic Unit Code (HUC-8) subbasins—reveal the inequality of water demands. Based on data disaggregation models, manufacturing water use can comprise a much more substantial share of overall water withdrawals at the county level than the national level. Rao et al. (2015) found manufacturing water uses makes up over 75% of water withdrawals for 60 counties in the United States.[5] Consequently, at the national level, water withdrawals for manufacturing-specific activities are a small percentage of the U.S total; whereas at the regional level, a much larger percentage of water use has been observed for these activities.[5] This motivates the need for collection of water data at the regional-level to fully support watersheds and regional planning.

Manufacturing facilities interact with the environment and watershed as shown in Figure 1. Both (Q1) and (Q3) relate to the interactions of withdrawals (Flows 1 and 2) from the watershed and discharges back to the environment (Flows 8 and 9), from both volumetric and quality perspectives. Required for (Q2) and (Q3) is an understanding of water use within facilities (Flows 4 and 5), reuse opportunities (Flows 6 and 7), and water efficiency metrics and opportunities (Flows 4, 5, 10 and 11).

With respect to Figure 1, publicly available data can be found for some of the water flows within a plant. Flow 1 can be ascertained and compiled from utility water bills but is not currently readily available. Flow 2 is available from the U.S. Geological Survey (USGS) water survey[6] at the county level but only separated into eight macro sectors (e.g., industrial, power, agriculture). At any given plant, Flows 2 and 3 (the volume of self-supplied water) is likely unknown, as it is often not metered and is "free" to the manufacturer except for pumping, treatment, and permitting costs; water from flows 2 and 3 can often make up a larger share of withdrawals than municipal flows.[8] For Flows 4–6,[a] few data are currently available, except for a few facilities that monitor. Flows 6, 7, and 8 are somewhat available at a facility level through the U.S. Environmental Protection Agency's (EPA's) National Pretreatment Program; however, that data set is unavailable in a readily usable form and it has inconsistencies.[11] Flow 9 is perhaps the most readily available data at a facility level; those data are available through the EPA's Discharge Monitoring Report, but there are concerns with some data quality for the volumetric flows, which are not often metered (however, constituent information is well understood if the constituent is regulated by the Clean Water Act).

Because we cannot account for all these flows, the research questions laid out in this paper cannot be answered. Because of these data gaps, we do not have the data to understand the impact of manufacturing operations on the local watershed and subsequently cannot support the manufacturing community as it adapts to water-related risks.

[a] Water use within a facility can encompass onsite water treatment, water use in industrial processes (e.g., pulp making in paper plants), cooling/condensing for power generation, cooling/condensing for air conditioning, boilers for power generation, boiler for facility needs, kitchen/restrooms and other sanitary uses, and use by landscaping and other systems

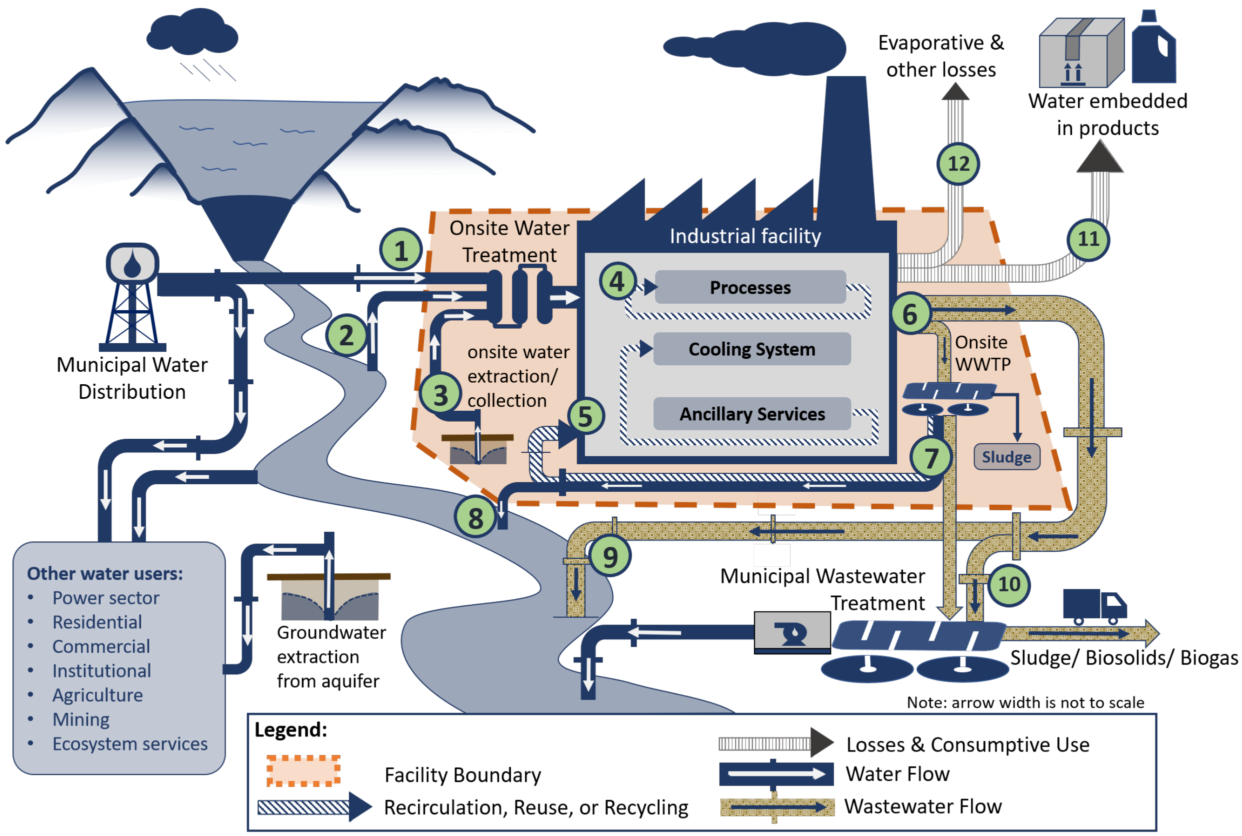

Figure 1: Manufacturing water and wastewater flows within the context of the watershed (Flows referenced in the text are identified by the numbers in green circles in the figure.)

Current Data Gaps

U.S. manufacturing water use data suffers from gaps, inconsistencies, and lags in reporting. One reason for the inconsistency is the nature of regulations and the fact that there is no single overarching water regulator; water withdrawals are regulated at the state and regional scales. On the other hand, multiple federal agencies have purview over water. For instance, EPA regulates and reports water effluents and constituents, USGS collects and reports estimates of national water withdrawals, Bureau of Reclamation of the U.S. Department of Interior operates federal water projects in multiple states, U.S. Energy Information Administration collects and reports water use for thermoelectric cooling, U.S. Army Corps of Engineers is responsible for flood control and regulation of navigable waterways and generates estimates of water use through its Institute for Water Resources, and Federal Emergency Management Agency provides data and information on flood risks. Along with these federal agencies, regional agencies and institutions are directly or indirectly relevant to manufacturing water use. Water withdrawals are regulated by state laws, and there is no standard data collection protocol to collect this information. Given these many players, data sets are often fragmented and difficult to cross-link.

Even when data are collected, manufacturing water use is often grouped with other non-manufacturing economic activities/sectors. The classification of data can differ greatly among agencies and lack adequate disaggregation, making the evaluation of water use difficult.[12] For example, the USGS water survey categorizes manufacturing with construction,[13] California's Groundwater Information System categorizes manufacturing with irrigation (in a broader category called Irrigation/Industrial),[14] the Colorado Water Plan lumps manufacturing into a Municipal and Industrial category,[15] and the Indiana's Water Shortage Plan groups industrial with commercial uses when listing water shortage mitigation actions.[16] Even though the aggregation of sectors with low water intensity may have little impact (e.g.; water use for construction is often much less than industrial sector water usage[17]) in water withdrawal volumes at the national or regional scale, localized water use estimates and metrics on a per-employee basis could be skewed.

Some characteristics of space cooling and domestic water uses (e.g., cafeterias and landscaping) in multiple economic sectors are also pervasive in manufacturing sites and may justify the aggregation of sectors. However, evidence suggests that water uses unique to the manufacturing sector (e.g., process cooling, steam generation for process heating, water incorporated in products), account for the largest water volumes in the sector. The most recent detailed water use information was collected for the U.S. manufacturing sector was through the Survey of Water Use in Manufacturing (SWUM) from 1954 to 1983. An analysis of the 1978 survey microdata found that cooling & condensing and process water in contact with products are the two single largest uses in manufacturing (44.8% and 28.7% of water intake, respectively) .[7] Moreover, manufacturing processes have distinctive requirements and effluents of varying quality that set them apart from other economic sectors. By grouping manufacturing with other sectors, the specific needs and opportunities of the sector may be overlooked. This limits R&D initiatives and may impact water conservation efforts in regions with high demand of water for manufacturing activities.

Due to the nature of manufacturing processes, a portion of water withdrawals is consumed through evaporation or is incorporated into products, while the remaining is either recirculated, reused, or discharged. Currently, no comprehensive data set links water withdrawal, discharge, and manufacturing identifier (i.e., NAICS) in any usable format for individual facilities to benchmark their consumptive water uses. The EPA Discharge Monitoring Report (DMR) contains yearly facility-level water discharges with NAICS identifier only for facilities required to have a NPDES (National Pollutant Discharge Elimination System) permit. This excludes facilities that do not discharge effluents into waterways or with effluent rates and constituents that are below reporting thresholds. [18]

Current Availability of National Data

Multiple attempts have been made to synthesize manufacturing water use. For instance, Becker (2015) analyzed the microdata of the discontinued SWUM and found patterns of water withdrawal and recirculation.[7] Unfortunately, water use intensities generated (water volume per dollar of sectoral production) may no longer be applicable because of technological improvements, new product lines and specifications, process changes, and sweeping changes to the manufacturing sector more broadly. Also, it is likely difficult to compare certain sectors in operation now with their 1970's counterpart (e.g., electronics and semiconductors). Concurrently, from the 1950s' until now, USGS, through their quinquennial (every five years) circulars, has published self-supplied water use estimates for the manufacturing sector based on a mixture of state-level data reporting efforts and modelled estimates. However, these estimates do not disaggregate by subsector or industry thereby limiting their utility towards answering any of the four questions posed.[6]

The lack of consistent sampling and reporting of manufacturing water use, has motivated attempts to estimate and disaggregate manufacturing water data by combining disparate data sets with estimates that cannot be validated (see Table 1). Estimation methods usually involve simple regression models and extrapolation of water use coefficients (i.e., m^3/ton of production, m^3/employee, m^3/USD) based on one main source of water use data at a national level or at a high sectoral aggregation (three-digit North American Classification System, or NAICS,[b] codes) and variables obtained through U.S. Bureau of Economic Analysis (e.g., sectoral gross production), U.S. Census Bureau (e.g., population), or U.S. Bureau of Labor Statistics (e.g., sectoral employment). A major limitation of extrapolating water use coefficients is that the effect of spatial-, sectoral-, or temporal-specific factors such as climate, resource availability, and technological changes over time are neglected. In general estimation methods are prone to high uncertainty because of errors intrinsic to surveys or census data, strong assumptions in estimation models, and error propagation. Recent, national-scale studies that attempted to derive water use for industrial sectors are presented in Table 1. Note that this list is inexhaustive and only represents recent and relevant studies for national-scale estimates of industrial water use.

Table 1: Past water estimation studies

Study	Scale	Method	Main Source Data	Limitation
Marston et al. 2018[19]	-117 areas (Commodity Flow Survey areas) -378 industries -For year 2010	Allocation based on employment	USGS estimates of Canadian water use parameters IWR-MAIN Water Demand Forecasting Software consumptive factors	Single variable allocation method; low correlation with water use at a specific facility
Yang et al. 2017 and Environmentally-Extended Input-Output (USEEIO) models[20]	-Six-digit NAICS -National level -For year 2010	Allocation based on gross domestic product (GDP) and employee compensation.	Canadian water use survey U.S. purchase of	Based on USGS and Canadian data at three-digit NAICS resolution, at the most;

[b] North American Industry Classification System: https://www.census.gov/naics/.

		Reported as m^3/USD	water, sewage, and other systems	national-level data availability
Blackhurst et al. 2010[21] and Economic Input-Output Life Cycle Assessment (EIO-LCA) method	-Six-digit NAICS -National level -For year 2005	Allocation based on sectoral employment; reported as gallon per million USD	Canadian water use survey USGS estimates	Allocation of public supply assumes geographically uniform water price; assumes domestic industrial practices are similar to Canadian to allocate self-supplied water.
Boero and Pasqualini, 2017 [22]	-Three-digit NAICS -County level; Level II EPA ecological regions -for year 2010	Linear regression using regionalized county-level GDP	USGS estimates	Industrial water from USGS data set is the industrial self-supplied water plus all non-domestic public supply. Regression only uses GDP as explanatory variable for water use.
Rao et al., 2017[5]	County, three-digit NAICS	Single metric, intensity- corrected using USGS data	USGS and Canadian Industrial Water Use Survey	Includes construction, cannot validate subsector or county-level estimates

To investigate the usability of the other data sources, we performed several data compilation and analysis efforts. First, a bottoms-up, state level analysis was performed to collect disparate data sets. Second, we used information in the Industrial Assessment Center database. Third, we compared water use coefficients from the past analytical studies to determine sectoral accuracy. Finally, we attempted to use multi-variable regression methods to see whether improvements could be achieved. These attempts are described below.

Current State level Data Availability

To fill in data gaps, we compiled facility-level water withdrawal data from individual states and at an industrial level to perform a bottom-up water accounting analysis. This approach consisted of adding up the water used by individual facilities by sector and validating it by comparing the summation against aggregated withdrawal data from the EPA DMR.

Primacy of water withdrawal regulations falls to state water agencies, which vary by state, complicating the consolidation of data. The compilation of water withdrawal data required several data collection and processing steps. First, a cursory search of online data available at state permitting agencies was performed. Second, if data were not readily available, the relevant employees at the state agencies were contacted, both by email and phone, to see whether data could be found. Finally, if data were available, they were formatted to allow for comparison of data across states. During data collection, only 19 states had water withdrawal values available at the facility level. Other states contained county-level data or aggregated into one macro sector, similar to the USGS water use circulars. Overall, the analysis found no standard reporting methods on a state-by-state basis.

Out of all available state data, only one State (North Carolina) published data at a facility level that contained water withdrawal, water discharge, and NAICS information. There were three other States (Texas, New Hampshire, and Maine) that contained water withdrawal values and NAICS identifiers, but no discharge data. Out of the remaining 15 states[c] with water data at a facility level, no state reported the NAICS code. Where available, facility identifiers or a geo-coded address were used to match discharge data from the DMR, but this was only widely available for 7 of the 15 state-level data sets and only represented 3% of facilities within the overall DMR data set.

As a validation step, we aggregated withdrawal and discharge data at the industry level where it was available in 2010 and compared sector level withdrawal and discharge values. Of the most water-intense NAICS codes in the compiled data set, the summation of withdrawals across an industry were an order of magnitude less than the discharge volumes from the EPA DMR, highlighting data gaps in the bottom-up analysis. This could mean that either the data set did not capture all water withdrawals (e.g., self-supplied, surface, ground, purchases) or the data sets were not comparing similar timeframes. Whatever the case, the data were unusable for any meaningful analysis and highlights the need for homogenized protocols for data collection and integration among agencies.

Industrial Assessment Center (IAC) Database

We also analyzed manufacturing water use data collected through the U.S. Department of Energy (DOE)-sponsored program, Industrial Assessment Center (IAC).[d] IACs are university-based organizations that provide free audits to small- and medium-sized manufacturing facilities across the U.S. The program focuses on the collection of utility data from manufacturing facilities that choose to participate in an effort to "identify opportunities to improve productivity and competitiveness, reduce waste, and save energy."[23]

The IAC database contains data from 19,085 assessments collected over 40 years for small- to medium-size facilities, out of which only 664 (<5%) assessments collected water use information starting in 2016. The water use information collected is only intended to report the total volume and cost of water supplied and billed by municipal water distribution systems. The assessments do not inquire about the specific uses of water (e.g., for process, cooling, irrigation), alternative sources of water (e.g. self-supplied groundwater, self-supplied surface water, stormwater collection), consumptive uses, or recirculation rates. In addition to water and energy use/cost

[c] Georgia, Indiana, Iowa, Kentucky, Maryland, Massachusetts, Michigan, Minnesota, Missouri, Mississippi, New Jersey, New York, Oklahoma, Tennessee, West Virginia

[d] U.S. DOE's Industrial Assessment Centers: https://iac.university

data, IACs collect data on sales, facility size, production, operation hours, number of employees, and location. The primary goal of analyzing water use data from IAC assessments was to find variables through the use of regression analysis that could help estimate water use and cost for facilities where this information was not collected.[24]

The study revealed large variability in publicly-supplied water use at the three-digit and six-digit NAICS sectoral aggregation. From reported values of water volume and annual cost of publicly supplied water, we calculated the average unit water cost (USD/gallon), which resulted in values that were unreasonably high based on national averages. The variability could be due to facilities using a variety of tiered utility rates or reporting self-supplied volumes mixed with publicly supplied water. In any case, the data could not be validated, and this limited the ability to generate reliable statistical models. Although an opportunity exists to use data collected through IAC assessments for a water use or cost-predictive facility-level analysis, increasing the amount of data collected and improving the data collection quality is needed for a useful sector or regional analysis. Because of multiple concerns of unreliable data points, we determined a more careful investigation is needed.

Estimation and Regression Techniques

Different methodologies have been used to estimate the average water withdrawals by industrial sectors from data sets such as the Canadian Industrial Water Use Survey (IWUS) or USGS publications. Environmentally extended input-output (I-O) methodologies have traditionally been used to estimate the direct and indirect water use of products along supply chains.[25] These models require the use of direct water use coefficients (referred to as satellite tables or externalities in economics parlance) for each sector. Therefore, developers of I-O models have attempted to derive water use coefficients in the units of water volume needed to produce a given amount of economic output (e.g.: $m^3/\$$). I-O models such as the EPA's Environmentally-Extended Input-Output models and Carnegie Mellon University's Economic Input-Output Life Cycle Assessment (EIO-LCA), which uses the water use estimates from Blackhurst et al. (2010), have been used as reference for their water use coefficients.

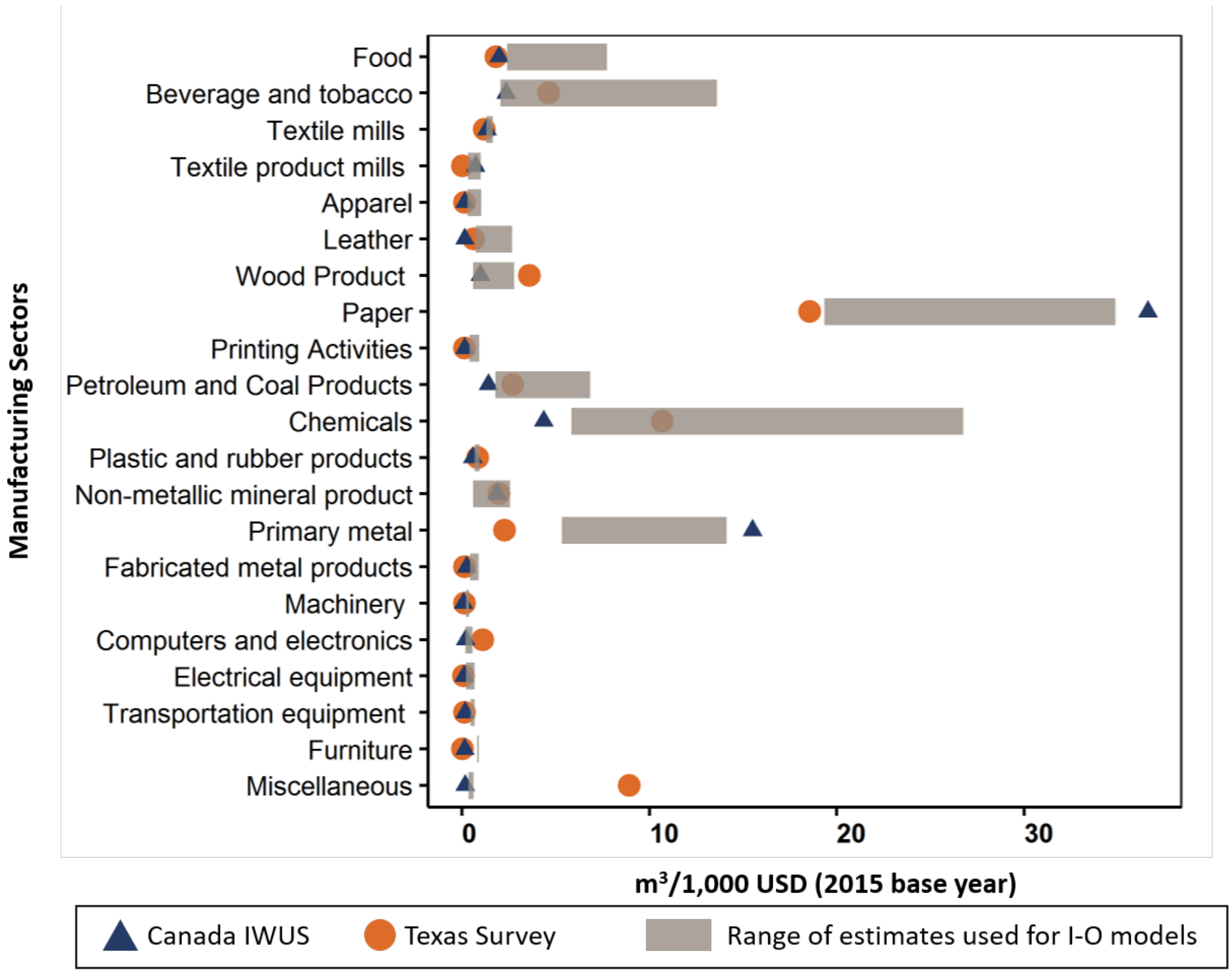

Figure 2: Comparative water withdrawal coefficient estimates

Figure 2 represents a range of water coefficients calculated from 1) past studies[19–22] and their ranges (orange), 2) 2015 Texas industrial water survey data[26], and 3) Canadian industrial water use statistics.[27–29] There is a wide range of water use coefficients from the different data sets, and the range is broader for most water-intensive industries. The wide variability in estimates of water use by facility may be based on several factors such as plant age and technology, product type, availability of water, and company standards, but currently available data is not sufficient to validate these numbers or provide an accurate range and standard deviation of water use by plant industry. It should also be noted that economic flows between sectors may not always mirror the physical water flows behind the material exchanges between those sectors, thereby creating room for data distortions. While this range may highlight inaccuracies in data, it could also provide evidence that water use across facilities within the same sector may utilize water differently and lead to the range, but a touchstone data set to validate this is unavailable. Even single point estimates from the latest Texas data and the widely used biennial Canadian statistics are mostly outside past study ranges, likely because of different data frames. Not only is the single economic output-based metric inadequate to estimate water use at the three-digit industry level, but also the temporal and spatial considerations may be important to capture, as each study only represents a snapshot in time.

As a proof of concept and to advance estimation techniques beyond single intensity metrics, we attempted to apply advanced statistical methods to estimate subsector-level water use to account for multiple variables that might impact water use; specifically, we sought to apply regression methods to national-level data to develop predictive models for manufacturing subsectors. We attempted to regress the longitudinal data from the Canadian IWUS for all years available (every two years from 2005 to 2015 for six data points in all) against independent variables that are publicly available in both Canada and the U.S. by subsector and county. Four independent variables were identified: cooling degree heating days, heating degree days, subsector employment, and number of establishments within the subsector. Requirements to determine the statistical validity of the models were set such that the adjusted R^2 had to be greater than or equal to 0.75, all P-values for the independent variables had to be less than or equal to 0.2, and the F statistic had to be greater than $F_{critical}$ (determined based on the number of independent variables). Using this method, we could develop valid models for 6 of the 21 manufacturing subsectors at the three-digit NAICS designation . If the R^2 threshold is dropped to 0.5, then an additional 4 subsectors would have valid models. Based on these results, we deemed the proof of concept inadequate towards studying the four questions posed in this paper and concluded a more rigorous approach is needed. This would entail the development of regression models at a statistical sampling of facilities within a subsector. The sampling would need to include enough facilities to account for intra-subsector variability (e.g., due to differences in water management/efficiency, production processes, local water conditions). Further, as with any statistical approach, the credibility of a more rigorous approach would greatly benefit from having a U.S. data set against which to validate the models.

Data Collection Needs

Based on past analyses and the present study findings, manufacturing water use data are unavailable in a form that can be used to answer the key questions laid out in this paper. So here, we propose two levels of data that could be collected and made public: an "aspirational standard" and an "enabling standard." We present how each proposed level compares to the current level of data availability in terms of informing the questions posed in the paper. We propose that the enabling standard would strike a balance between rigorously informing the four key questions and lessening the burdens on organizations of making the data available.

Our aspirational standard of water data is a time series data set for individual facility water flows as outlined in Figure 1. The number of data points collected at each facility are determined by the number of sources of intake water, discharge locations, uses and quality of water (e.g: process water that requires treatment or non-contact cooling water), and presence of reused, recirculated, and recycled water flows. The data would be collected at a geographically diverse number of facilities and would be aggregated at the six-digit NAICS designation with a high level of statistical confidence/certainty. The temporal frequency of data collection would be dictated by the seasonality of water demands and availability. This aspirational standard data set would enable facility-level analysis and could be aggregated in many ways (e.g., across processes, by region/watershed, or by subsector). Because the data would be collected at the facility-level, impacts across the most granular watershed or political boundary disaggregation (i.e., HUC 12 or towns) would be possible. However, collection and sharing of this type of data would require a large effort on the part of policymakers to enact policies that would coordinate data reporting and the facilities that must produce and share the data. This likely would present competition concerns amongst manufacturers and require the need to collect, scrub, and anonymize the data. Further, based on the lack of water monitoring at industrial facilities currently, it presents challenges from both a sensor and monitoring perspective and from a data sharing and regulatory perspective. Cybersecurity concerns for such a data-intensive critical infrastructure system must also be considered and addressed.[30] When water flow and quality submetering is more readily deployed, this aspirational standard data set may become more tenable. However, it will likely be infeasible for the foreseeable future based on metering and the current availability of data. Advances in metering, metering standard, digital twin analysis methods, and cybersecurity may enable these data sources, but this data set likely represents the future of data collection. Some facilities and companies may choose to adopt these metering standards, but likely not until midcentury or later (2050s) will it be common in industry without enabling technologies.

In the interim, our enabling standard represents a midpoint between the current state of data and the aspirational standard and provides a touchstone data set that researchers, policymakers, and technology developers could use to inform R&D. Under this standard, a statistical sample of facility-level water use data is collected from across manufacturing subsectors (that are at a minimum aligned with the NAICS three-digit disaggregation). The enabling standard includes water withdrawal and discharge information as well as water use characteristics of key processes and facility equipment (e.g., boilers, clean-in-place, and cooling towers). The enabling standard resembles the current national-level Canadian IWUS and (in its frame) the energy consumption surveys conducted by U.S. Energy Information Administration for the manufacturing sector (the Manufacturing Energy Consumption Survey, or MECS). MECS has served as a cornerstone for energy analysis, with many works depending on it. One such set of analyses is the DOE's Energy Bandwidth Studies, which detail the sector-wide energy savings potential from the adoption of emerging technologies. Such analysis, if done for water, would directly inform (Q3). Sampling and collection methods from IWUS and MECS would likely form the foundation for development and implementation of the enabling standard data set.

Table 2 compares the data qualities, benefits, and drawbacks of current data and both data standards we propose. Each data set affords a different level of insight into the four key questions posed in this paper. In general, the current level of data provides limited insight into the first three questions but does allow for some regional planning efforts. This conclusion is reflected in the current lack of conclusions or information for (Q1) – (Q3). Our aspirational standard allows for answering any of the four questions to a high level of statistical confidence and spatial and temporal resolution for any aggregation (e.g., subsector, regional, or watershed). Our enabling standard allows for insight into all four key questions, though aggregations and depth of insight will be limited. Table 3 summarizes the insight allowed by each of the data sets for each of the key questions.

Table 2: Data set considerations, benefits, and drawbacks

Data Set Type	Data Quality Considerations	Benefits of Data Set Type	Drawbacks of Data Set Type
Current Data: quinquennial (every five years) data survey, water use coefficients, disaggregated state-level data	• No consistent subsector identifier • Aggregated over a county or state level • Aggregated with other uses (i.e., construction) • Limited facility-level data • No process-level data • Data updated every 5 years • Relies on 1980's era water coefficients • Unlinked withdrawal and discharge data • Annual data	• "Status quo" • Currently available • Enables macro-level analysis • Reports which data are being monitored by manufacturers	• Insufficient granularity for modeling • Not updated with enough frequency • Does not allow for facility-level analysis • Leads to wide variance in water use coefficients • No industry-specific or process-level distinctions
Aspirational: real-time, facility-level water data broken out by process	• Facility-level water use and discharge, both quality and quantity • Process-level information within facility • Facility identification at six-digit NAICS level • Time series data; interannual data • HUC-12 watershed information	• Enables location-specific risk assessment • Allows for watershed and climatic change modeling • Ease of environmental, social, and governance reporting	• Competition and privacy concerns • High accuracy required high granularity • Significant effort and cost to manufacturers • Manufacturers likely do not have these data currently. •
Enabling Standard: touchstone data set with enough information to inform policy making and economic decisions	• Linked withdrawal and discharge coefficients • Minimum three-digit NAICS identifiers • Aggregated facilities at watershed level (HUC-8) • High level process information (cooling versus sanitary versus manufacturing) • Data updates every 1–2 years • Annual reported data	• Enable an industrial water use bandwidth study • Provides touchstone data set for regression analyses • Avoids large collection efforts required by the aspirational standard • Linked withdrawals, discharges, and consumption for watershed • Ability to perform impact, risk, and water efficiency analyses • Informs industrial water R&D	• Policy measures likely needed for survey or data collection • Cost to manufacturers for metering upgrades

Table 3: Ability of data sets to answer research questions

Data Identifier	**(Q1) How do water withdrawals, discharges, and constituents of concern from different manufacturing industries impact local watersheds and communities, and what are the quantitative metrics that capture these impacts?**	**(Q2) How do manufacturers use water within their facilities, in relationship to both quantity and quality requirements, and how does their use compare to the theoretical minimum amount of water needed to provide an economic service?**	**(Q3) What process improvements (e.g., water reuse technologies, water efficiency metrics, and detailed sensor monitoring and controls) are available to manufacturers, and what R&D is needed to develop technologies to lessen the impacts of manufacturing water use on watersheds?**	**(Q4) How do current and future manufacturing water use and industrial colocation impact regional planning processes and how does changing water availability impact manufacturing operations and investment decisions**
Current Data: quinquennial data survey, water use coefficients, disaggregated state- level data	Can provide insight across the combined industrial sector (manufacturing and construction) at the county level with some subsector information available at the state level though likely not statistically representative.	No statistically relevant insight provided	No statistically relevant insight provided	Good insight provided, though not enough to understand manufacturing contribution to municipal supplied water demand
Aspirational Standard: real-time, facility-level water data broken out by process	Comprehensive analysis afforded	Comprehensive analysis afforded	Comprehensive analysis afforded	Comprehensive analysis afforded to inform regional planners and update water use coefficients
Enabling Standard: touchstone data set with enough information to inform policy making and economic decisions	Can provide insight by key subsector disaggregation across a year, but cannot inform seasonal or interannual variations	Insight provided for major water end uses	Insight provided for major water end uses	Good insight provided, though not enough to understand manufacturing contribution to municipal supplied water demand

Practical Implications of Data Sets

There will always be a cost of acquiring and reporting more data. The cost of this data acquisition (or Value of Information) to inform decisions will need to be balanced with the benefit to society and the environment.[31] The ability to accurately assess water use and identify facility water efficiency measures could potentially save money across the economy, but, more importantly, it can help mitigate risks to the manufacturing sector. There already is strong evidence for reduced water and energy consumption and net economic benefits to the order of billions of dollars in water utilities sector when adopting data-driven strategies using targeted and timely water data.[32,33] For context, the cost of the California drought in 2015 was estimated to be $2.74 billion to all economic sectors in the state, in addition to the ripple effect across the country than can have implications for food security and economic growth.[34] Installing meters to identify technology improvements and efficiency measures within facilities could potentially limit the impact of future droughts and allow for flexibility in operations. Based on this cost of acquiring new data, a staged approached for monitoring water flows may be needed. This could either be through monitoring specific, high priority flows in Figure 1 or by starting with high volume water users in different industries. Ensuring that a framework to capture a statistically relevant (both a majority of large water users and proportion of small water users) number of reporting respondents should be considered, similar to the MECS sampling framework.

Requiring increased reporting of these flows would necessitate installation of numerous meters across every manufacturing facility in the U.S. to get an accurate assessment of water use across the manufacturing sector. Even with installation of meters, many of the flows would be difficult to constantly monitor due to current metering technology limitations such as accuracy, fouling, and maintenance. There are also concerns with industry competition and how these data sets would be used or how much data would be needed to be useful to industry stakeholders. Local water managers could benefit from accurate water planning estimates for facilities in their regions along with an identification of potential efficiency measures to conserve water resources. For watershed level impacts, a reliable assessment of Flows 1-3, 8, and 9 in Figure 1would be needed; however, manufacturers will care about the costs of obtaining and treating water but maybe more interested in intra-plant operations to inform operations.

Several frameworks currently exist that can be used as a guideline to collect water data needed for our enabling standard. North Carolina water reporting requirements already link facility-level information with NAICS codes, water withdrawals, and discharges on an annual basis. As stated above, U.S. Energy Information Administration captures similar information by energy use within manufacturing facilities in the MECS program.[35] Through the Better Plants Program, Oak Ridge National Laboratory developed the Plant Water Profiler tool to help facility managers quantify and identify water saving measures within a facility.[36] Census employees have revitalized the SWUM to update water use coefficients to current practices.[7] These examples are only provided to highlight frameworks that have either already increased, or could increase, data transparency and analysis capabilities for the manufacturing industry. Any framework will need to balance the cost of reporting versus the benefit to society.

Conclusion

From publicly available data, the research community lacks the insight—and the subsequent knowledge—of how manufacturer's use water and their subsequent impacts on the watershed. Impacts on the local environment and watershed are key drivers of risk; understanding those impacts will support the manufacturing community as it adapts to water-related risks by identifying needed R&D opportunities. There is a lack of comprehensive data that links water withdrawal, discharge, and a manufacturing identifier (i.e., NAICS) in any usable format for individual facilities to support these research questions. Analysts have tried different analysis and regression-based approaches to gain insight on manufacturing industry water withdrawal and discharge needs. We tried to add various methods to these approaches (bottoms-up data collection, analysis of other data sets, comparison of regression methods, and multi-variable regression analysis), but we were unable to create anything of use to the research community. Lacking validation data, statistical approaches will always suffer from an unknown level of uncertainty. Therefore, the use of regression models cannot be considered a substitute for direct water data collection. Rather, regression models would benefit from and the extend the utility of such a data survey. Therefore, we propose two levels of data that could be collected and made public: an aspirational standard and an enabling standard. We presented how each proposed level compares to the current level of data availability in terms of informing the questions we posed in this paper. Finally, we proposed that the enabling standard would strike a sufficient balance between rigorously informing the four key questions and lessening burden on policymakers and facilities.

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