

A review of water valuation metrics: Supporting sustainable water use in manufacturing^{☆, ☆☆}

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ABSTRACT

In the manufacturing sector, water has been often considered too cheap to conserve. Such thinking relies on water valuations that limit the value of water to the price paid. Using such simple methods, the share of water cost to total manufacturing cost is significantly small, <3%. As a result, conserving water and enabling technology uptake is difficult to justify economically and slow to advance, hindering progress toward sustainable water use.

However, the value of water to a manufacturer is far greater than the price paid. Valuations such as the true cost of water consider the additional in-plant treatment and energy costs and have been gaining greater traction in the manufacturing sector. However, true cost alone still undervalues water by not accounting for economic and social costs related to scarcity and environmental externalities.

This paper makes the case and presents a framework for valuing manufacturing water beyond the price paid and the true cost. The proposed fuller valuation of manufacturing water takes into account the internal and opportunity costs associated with the realization of water risks. The paper follows with a review of a wide range of water valuation metrics, both at the specific industry level and regional/economy-wide level. The use of various valuation metrics incorporating the relationship between the change in value with change in water use, such as marginal value of

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water, shadow price, and elasticity at the specific industry level, has been limited in the U.S. manufacturing sector. Further, a limited number of studies exist on data-intensive subjective evaluation techniques such as computable general equilibrium modeling and input-output modeling for regional water valuation.

After reviewing water value metrics, several recent case studies from manufacturers from the literature are presented to illustrate both the promise and challenges of a fuller valuation of water as proposed here. Some large multinational corporations have moved toward assessing the value of water via supply chain sustainability initiatives, environmental profit and loss accounting, estimating risk-adjusted values of water, hydro-economic modeling, natural capital asset valuation, and developing value chain indices. This paper provides policymakers and technology developers a framework for monetizing water value beyond its true cost and current metrics. If adopted, such fuller water valuations can help make the business case for the development and deployment of cost-effective water-conserving technologies, thereby improving the sustainability of the manufacturing sector with respect to water.

1. Introduction

Water is a critical component for many manufacturing processes. Aside from its use in manufacturing process operations, water in the manufacturing sector can also be used for other purposes like cooling, power generation, sanitation, and fire protection. Often, these uses are essential to operations. For example, without water for cooling and an alternate heat sink, process equipment can overheat, fail, and cause a plant to shut down. Consequently, water demand and its subsequent value become an important issue when faced with managing or mitigating water-related risk events or shocks (e.g., price, availability, quality). These water shocks could occur due to a lack of reliable water supply, which could result in higher temporary regional water prices. Unlike other commercial commodities, the price paid for water does not fully reflect the value it provides to the consumer. As a result, this underpriced resource—the uninterrupted supply of which is essential to many manufacturing operations—is not optimally utilized, and large operational inefficiencies occur. The mismatch between price and value inhibits the development and deployment of water-saving technologies, as the return on investment is calculated using the price and not the value. Further, the low price of water often means that capital improvements to increase the utilization efficiency of other resources with higher operational costs (e.g., electricity) are higher priority to manufacturers [1–3]. To advance the state of water-saving technologies and realize sustainability objectives, a reframing of water price to better incorporate value is needed.

Water cost and price (e.g., utility tariff) are the two commonly used metrics to understand the economic impacts of either industrial self-supply water withdrawals or utility water use. In economic terms, cost represents the expenditures incurred to produce a certain good, while price is defined as the rate at which one exchanges money for a good. Market prices demonstrate the relation between supply (what is produced, and at what cost) and demand (the value to buyers), and appropriate pricing mediates between the full costs of production and the demand for the resource. However, water prices often do not even cover direct costs of supply, let alone the full value of water (including opportunity and externality costs)—precluding the efficient and sustainable use of water [4,5]. The share of water cost relative to total manufacturing cost is significantly small ($< 3\%$) [6,7], driven mainly by low utility tariffs and self-supplied sourcing (i.e., no volumetric water or connection costs) without consideration of additional necessary in-plant costs. U.S. industrial water tariffs vary widely over space and time in the range of ~ 1 to 3 \$/kgal per month [8,9]. Moreover, three quarters of U.S. manufacturing water intake stems from self-supplied sources [10].

Water is a highly location-specific resource, meaning that localized water stress is a risk factor for manufacturing operations nearby [5]. To date, abundant domestic water supply has caused only limited supply risk impacts in specific regions such as California and the Southwest. Further, property taxes and local bonds often make up the difference of utility tariffs between the utility cost and the tariff paid by consumers. When utilities are still unable to cover their costs, delayed maintenance and investments have resulted in failing water infrastructure, with negative effects on water quality and reliability of supply. For example, disruptions to water service in 2019 represented economic losses of \$51 billion for the 11 industries most reliant on water, including manufacturing [11]. Because current tools to assess water risks do not fully account for the economic value of water to individual businesses or other stakeholders, manufacturers are likely to misunderstand or undervalue water risks, particularly in highly developed river basins [12]. However, water supply disruptions are projected to increase with industrialization, environmental water discharge regulations, and more drought and extreme weather due to climate change impacts. The full value of water to manufacturers should encompass the risks of water shortages or poor water quality that could lead to the disruption of production. Appropriate water valuation is important to quantify these external and indirect water supply disruption impacts, and critical for assessing the potential of cost-effective industrial water conservation technology opportunities. In addition, water valuation would enable individual manufacturers to better understand tradeoffs related to water use, when inputs and outputs are stated in financial (e.g., dollar) terms. Water valuation would also be beneficial to local utilities with respect to the efficient allocation of water resources. More comprehensive economic evaluation methods specific to the manufacturing region are necessary to facilitate the development and deployment of water savings technologies in industry.

This paper seeks to establish a framework for improving the valuation of water in order to support decision-making processes impacting the sustainable use of water in the manufacturing sector. Based on findings from the literature, this paper identifies and recommends the considerations necessary to appropriately value water as a resource, focusing on upstream and downstream impacts

to the facility and the ecosystem within which it operates. Next, metrics used in the literature for understanding the value of water are compiled and reviewed. Finally, the paper concludes with summarizing findings from case studies of industrial facilities using a more comprehensive valuation of water.

2. Water valuation concepts – Concept of cost, price and value

The price of a typical commodity is conditioned on its quantity. Water is a nonstandard commodity, meaning it possesses special attributes beyond quantity with no market pricing impacts [13]. Special water attributes include the following: water is mobile (flows instead of stocks), but challenging and expensive to transport across large distances/elevations, making it difficult to establish property rights and to dispatch it where needed; freshwater availability varies across space and time due to weather/climate; water quality matters for specific applications; it performs multiple social functions calling for regulated pricing; it has associated externalities due to high interdependencies among users; there is a natural monopoly where cost is mainly driven by amount and type of supply source; it can have high demand variability; and having numerous decision-makers at various levels causes difficulties in public regulation [9,14]. In some regions, innovations to price these attributes have taken place. For example, farmers, hedge funds, and municipalities alike are now able to hedge against—or bet on—future water availability in California, the biggest U.S. agriculture market and world's fifth-largest economy. CME Group Inc.'s January 2021 contract, linked to California's \$1.1 billion spot water market, last traded at 496 index points, equal to \$496 per acre-foot [15]. Ideally, for sustainable use of water, price and value should balance each other [16].

Price and allocation of water is mostly regulated by government authorities because of the many critical social functions that water performs. The price will depend on the set utility tariff in that given region. From the utility perspective, efficient price signals would help promote water conservation, justify expenditures on water-saving technologies, and help collect sufficient revenue for daily operation and maintenance of the water delivery system and future infrastructure investments [9,17].

While for utilities water prices often do not even recover the costs of supplying that water, manufacturers generally think of **water cost** and **price** as synonymous: the amount to be paid to utilities for its use, similar to obtaining or use of any product/resources. However, the cost and price will be dependent on whether or not the manufacturing facility purchases or self-supplies its water, leading to different costs and prices for each. Manufacturing facilities that purchase water from utilities are charged a certain **price** based generally on the quantity of water purchased. These facilities tend to directly equate this price with the cost of water at their facility. In contrast, self-supplied industrial facilities in most cases need not pay anything for their raw water input [18]. If any costs exist, their effective price could be the sum of the miscellaneous costs involved, such as abstraction licenses, infrastructure, and technology costs [19]. In either case, additional direct costs are incurred to use the water. Direct costs are expenditures directly associated with the establishment and maintenance of the manufacturing facility's water supply infrastructure (e.g., circulating pumps, chemicals for treatment). In simple terms, they relate to costs associated with capital investment and O&M, or even investing in water-conserving technologies.

As illustrated in Fig. 1, the price of water is a fundamental type of cost involved in industrial water use today, but is a small part of the overall value of water. Price does not capture all the cost elements involved in industrial water use. This is where the concept of **true cost** must be introduced, as shown as the second innermost concentric circle in Fig. 1. In addition to the price, true cost also takes into account direct user ancillary costs like those related to energy, chemicals, and permits. True cost is significantly higher than conventional direct cost/utility price, but it does not include either the costs associated with managing disruptions or the social costs related to scarcity and environmental externalities, commonly referred to as indirect or opportunity costs. Other alternate costs include

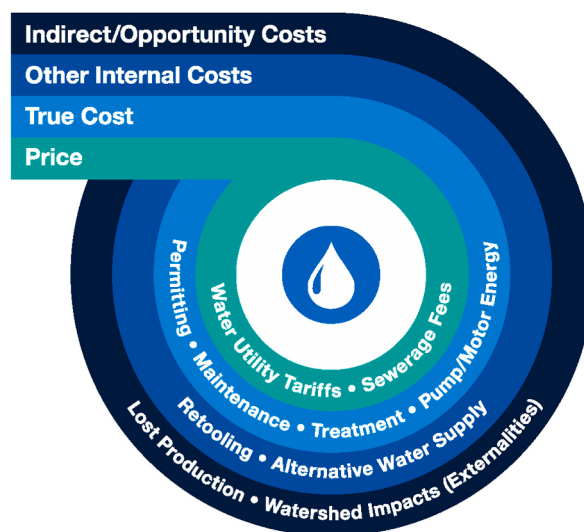


Fig. 1. The value of water encompasses price paid to utilities or municipalities, true cost, other internal costs, and indirect/opportunity costs.

the costs associated with ensuring an adequate supply of water to meet production demands. This could involve securing an alternate supply of water or re-tooling equipment to use water of different quality. Indirect/opportunity costs represent the loss of potential benefits due to misallocation of a resource. Externalities are the economic or environmental costs imposed on third parties due to an activity over which these parties do not exert any control, and which are not reflected in the cost of the goods or services involved. For example, water pollution due to an industrial establishment could result in increased cost of wastewater treatment for downstream users (economic externality) or negative impacts to the ecosystem (environmental externality) [17]. Social costs for industrial water use may be due to re-settlements resulting from water infrastructure expansion and scarcity of water or social conflicts like loss of income or employment opportunities from a lack of water resources.

Currently, the full value of the services water provides remains externalized and thus unaccounted for, in the manufacturing sector as well as others. However, Fig. 1 shows a framework in which the full value of manufacturing water includes all costs depicted, as expressed in Equation (1).

$$\text{full value of water} = \text{price} + \text{true cost} + \text{other internal costs} + \text{indirect/opportunity costs} \quad \text{Equation 1}$$

Fig. 1 aligns with the work done by Rogers et al. (2002) [4], where the full supply cost contains O&M cost and capital charges, the full economic cost includes the full supply cost in addition to opportunity cost and economic externalities, and the full cost encompasses the full economic cost in addition to environmental externalities. Ideally, the full cost as defined by Rogers et al. should be equal to the value, which includes the value to water users, net benefits from return flow, net benefits from indirect uses, adjustment for societal objectives, and the intrinsic value of water. Appropriate valuation of resources is important in accurately evaluating various tradeoffs that come into play when working to achieve sustainable resource use [20].

2.1. Monetizing water beyond true cost

The concept of the true cost of water is beginning to make inroads in corporate financial frameworks [21]. However, the ‘other internal costs’ and ‘indirect/opportunity’ costs shown in Fig. 1 are not often incorporated. Various types of risks caused by shocks, perturbations, and cross-sector competition to the industrial water supply can impact manufacturing operations. Even in the case of self-supply water withdrawals, water availability could be impacted, and the indirect/opportunity costs indicated in Fig. 1 will go up. With drastic changes in climatic conditions on a global scale, adverse events affecting manufacturing water supplies that are acute (short events), like droughts and floods, and chronic (events that unfold slowly), like changes in agricultural growing seasons and large shifts in populations needing access to clean water, could negatively impact manufacturing water supplies. The acute events could create shocks and perturbations throughout the year, leading to periods of water unavailability, and the chronic events could exacerbate cross-sector competition for water supplies. This highlights the urgency for industries to better monetize the potential impacts of future water risks on their manufacturing capabilities—and thereby the value of water beyond cost/price considered today and more aligned with the framing in Fig. 1.

Water-associated risks can be broadly classified into several types—physical, regulatory, and reputational—that lead to economic impacts for manufacturers [22,23]. **Physical risks** are associated with restricted access to adequate and reliable water supply, causing impacts on its price irrespective of any uncertainties due to future water supply impacts. Causes of restricted water supply include droughts or floods damaging the water supply infrastructure in addition to loss of water system capacity simply due to aging infrastructure and deferred maintenance, changes in water availability (e.g., changes in snowmelt and timing of runoff), and the aforementioned cross-sector competition. **Regulatory risks** are associated with sudden changes in laws or regulations that alter a facility’s access to water supplies/services and discharges. This risk type may affect the water cost associated with the discharge. Risks from harmful production activities perceived to have negative water-related impacts are **reputational**, and these may subsequently cause damage to the ecosystem and decrease brand value or consumer loyalty. The value of water to the ecosystem is mostly characterized by these risk types, which are not being considered by the industry today. The type and nature of these risks depend on several factors, such as geographic location or even water use patterns, that are unique to each industrial sector, and have been quantified both qualitatively and quantitatively with a variety of metrics as discussed in the following section.

3. Review of water valuation methods/metrics

Limited attempts have been made to quantify the value of manufacturing water use. With anticipated growth in the domestic manufacturing sector, the effects of manufacturing water use will be localized. Localization and agglomeration of facilities in specific regions could aggravate regional water scarcity. Within the manufacturing sector, the use of indicators in conjunction with water price can help to identify blind spots associated with the sustainability of its water use. In turn, this can lead to the identification of water uses that significantly affect production. If a particular water use is found to have an enormous impact on production, then the facility may decide to take actions towards improving the reliability of the water supply for that use. In particular, metrics that support the ability to measure the value of water and quantify trends/shifts are needed. Such a class of metrics—herein referred to as water valuation metrics—can help identify where technologies are needed and evaluate their impacts.

3.1. Methodology

To accomplish the objectives of this study, it was essential first to establish the type of metrics that would most appropriately

capture the valuation of water use in the manufacturing sector. An initial online search (through Google Scholar and Scopus) conducted in 2019 revealed a limited number of studies available on a global scale that attempted to quantify water use in the manufacturing sector. Studies focusing on cost and price of water use were excluded, while the emphasis was given to studies that focused specifically on the valuation of water use in the manufacturing sector, typically from the economic valuation discipline.

Table 1

Marginal water value estimates for three types of metrics across country-wide industrial sectors, at the 3-digit NAICS manufacturing subsector level.

NAICS code	Value Metric Industry	Water value (in 2021 \$/m ³)								
		VMP (Marginal Value of Water)				Water avg. productivity		Shadow price of water		
		Köseoglu (2018) [26]	Ku and Yoo (2012) [25]	Nahman and De Lange (2012) [29]	Wang and Lall (1999) [30]	Vásquez-Lavín et al. (2020) [31]	Rojas (2005) [6]	Fujii et al. (2012) [32]	Kumar (2006) [33]	Dachraoui and Harchaoui (1996) [18]
		Scotland (UK)	Korea	South Africa	China	Chile	Mexico	China	India	Canada
31–33	Manufacturing sector	6.35	2.17; 1.55	59.43	0.74	9.44	166.54	0.30	7.70	1.30
311	Food Manufacturing	1.38	1.32; 0.57	-18.63	0.77	29.94	518.60	0.20	-	0.27
312	Beverage and Tobacco Product Manufacturing	1.38	1.32; 0.57	1009.67	0.77	-	269.04	0.27	-	1.30
313	Textile Mills	7.94	0.74; 0.91	93.86	3.44	9.66	445.56	-	9.82	-0.61
314	Textile Product Mills	7.94	0.74; 0.91	93.86	-	-	445.56	-	-	0.07
315	Apparel Manufacturing	7.94	-	-	-	9.34	-	-	-	-0.37
316	Leather and Allied Product Manufacturing	-	-	-	5.23	2.62	-	0.05	-	1.64
321	Wood Product Manufacturing	-	2.48; 1.65	25.36	-	20.92	-	-	-	-0.03
322	Paper Manufacturing	2.93	2.48; 1.65	25.36	0.25	5.93	77.91	1.24	2.22	0.88
323	Printing and Related Support Activities	-	2.48; 1.65	-	-	-	-	-	-	0.57
324	Petroleum and Coal Products Manufacturing	20.71	2.02; 0.81	1237.58	1.81	-	-	0.06	12.36	2.48
325	Chemical Manufacturing	5.18	-	5115.76	0.30	10.12	159.48	0.12	7.36	0.55
326	Plastics and Rubber Products Manufacturing	-	-	-	-	8.50	-	-	-	3.50
327	Nonmetallic Mineral Product Manufacturing	-	3.86; 4.49	-	-	8.18	-	-	-	-0.39
331	Primary Metal Manufacturing	-	-	153.78	0.27	-	126.61	-	6.92	0.70
332	Fabricated Metal Product Manufacturing	-	-	-	-	-	-	-	-	-0.07
333	Machinery Manufacturing	-	4.19; 1.73	0.00	2.66	5.07	-	-	-	-0.58
334	Computer and Electronic Product Manufacturing	-	1.6; 1.67	1320.91	7.31	-	-	-	-	-
335	Electrical Equipment, Appliance, and Component Manufacturing	7.07	5.21; 2.63	1320.91	-	10.53	-	-	-	-
336	Transportation Equipment Manufacturing	-	14.98; 13.77	23.77	8.04	15.60	-	-	-	1.40
337	Furniture and Related Product Manufacturing	-	6.82; 4.85	-	-	10.76	-	-	-	0.67

A search strategy was formulated to systematically target books and journal articles that would discuss water use valuation based on the type of metrics identified below (e.g., willingness-to-pay, value of marginal product, and elasticity). Limited available studies specifically for the manufacturing sector were mostly addressed in the economics literature and for mostly developing countries in Africa and East Asia where water scarcity has been a major economic issue for decades. The search and subsequent filtering process resulted in finding a total of 20 relevant technical literary sources. The primary criteria for identifying these shortlisted studies were discussion of single or multiple water valuation metrics and their applications within specific industrial manufacturing sectors (such as food, paper, plastics and rubber products, leather, steel and metal, etc.). Available estimates of metrics were tabulated by the metrics type, manufacturing sector, and countries/regions, including the aggregate estimates. This approach facilitated an understanding of the application of these valuation metrics and their variation across different countries on both regional and global scales.

The next section will summarize various water valuation metrics. Specifically, it will examine willingness-to-pay, value of marginal product, and elasticity.

3.2. Summary of various water valuation metrics

With potential risks due to climate change and the resultant possibility of water scarcity, it is important for industries to assess their willingness-to-pay (WTP) beyond the cost/price paid today for their water needs. The WTP metric considers water risk types in terms of the maximum price at or below which a consumer will definitely buy one unit of a product. Water WTP valuation techniques can be classified into two major categories, namely inductive and deductive techniques [23], depending on the type and data level used for industrial value estimation. The former technique is applicable mostly at the specific facility/industry level and is based on real-world data to establish general relationships using a range of methodologies such as econometric, contingent valuation, and damage cost. On the other hand, deductive techniques such as value added, computable general equilibrium (CGE), and alternative cost models are less data-intensive, but more logical and analytically applicable for macro-level regional or country-wide estimation [24].

Some other commonly used metrics to quantify the value of water are value of marginal product (VMP, also known as marginal value of water), average water productivity, shadow price, and elasticity coefficients. VMP represents the increase in output value per unit increase in water intake, while average water productivity is the total output divided by water input. Both are expressed in terms of $\$/\text{m}^3$. The shadow price of water represents the intangible social opportunity cost of water (e.g., the value of a good that can be produced by the marginal unit water used, given the quantity of the other inputs, such a labor and raw materials), also expressed in terms of $\$/\text{m}^3$.

Elasticity is another frequently used water valuation metric employed to understand the degree of responsiveness of industrial water demand and output to variation in various parameters. Accordingly, two types of water demand elasticity metrics have been analyzed through studies: (1) Price elasticity of water demand: which depicts the change in demand of water with respect to change in price (or cost) of water, and (2) Water elasticity of output, which depicts the change in output per unit change in water input.

Subsequent sections will discuss the various studies that have applied these techniques and metrics to analyze and quantify the value of water by means of cross-industrial sector analysis, including a few at a regional scale.

3.3. Facility/industry water valuation metrics/methods

Many industrial water valuation estimates (as shown in Table 1) rely upon econometric methods. These methods use an industry representation as a production process where the manufacturing output is a function of capital, labor, energy, materials, and water. Further, econometric methods have been employed at the level of different manufacturing subsectors, represented by the North American Industry Classification System (NAICS) code range of 31–33, which are further characterized by a total of 21 subsectors of 3-digit NAICS codes. Some examples of commonly used production functions include the Cobb-Douglas function and the translog function model. Regression techniques are then used to determine the coefficients associated with each independent variable. Standard statistical validations (e.g., R^2 value and f -statistics), are applied to validate the model. The production function approach is generally used to estimate the VMP of water, water average productivity, and the price and output elasticity of water demand.

Table 1 shows several published water-value estimates at the 3-digit NAICS manufacturing subsector level across different countries. The VMP is the most commonly used: the total number of published estimates for the VMP is higher than the other two commonly used metrics, water average productivity and the shadow price of water. Two sets of value estimates based on two types of production functions (i.e., Cobb-Douglas and translog functions) have been used by the Ku and Yoo study (2012) [25] as shown in Table 1. Estimates by Köseoglu (2018) [26] are the average of estimates from eight primary published studies. The estimates in Table 1 were initially converted to US dollars for the same year using the currency exchange rate [27], and finally to 2021 U.S. dollars using the appropriate country GDP deflator [28].

The leading industrial sectors represented in Table 1 are: Food Manufacturing (NAICS 311), Petroleum and Coal Products Manufacturing (NAICS 324), Chemical Manufacturing (NAICS 325), Paper Manufacturing (NAICS 322), Electrical Equipment, Appliance, and Component Manufacturing (NAICS 335), Textile Mills (NAICS 313, 314), and Transportation Equipment Manufacturing (NAICS 336). Geographical location was observed as one of the key factors for the variation in these estimates across different studies (e.g., Köseoglu (2018) [26], Fujii et al. (2012) [32], and Wang and Lall (1999) [30]). The marginal values in water-scarce north China are about twice the values in south China based on the 1996–2006 period analyzed in the Fujii et al. (2012) [32] study. Industrial water use efficiency improved over the years during this period, while provinces in the northern region were more efficient in reducing freshwater use. For the same reasons of high water scarcity and risk, the VMP of water in South Africa [29] was estimated to be several orders of magnitude higher compared to other developed countries. All published estimates are for non-U.S. countries, but the two estimates for

developed Western countries (i.e., Canada and United Kingdom) may provide some insights for U.S. water use valuation.

Aside from marginal or average water valuation metrics, elasticity is another popular concept evaluated by most studies to date. Like water value estimates, industrial water demand elasticity is generally derived from a production function. Most of the studies mentioned in Table 1 have also estimated price elasticity or the output elasticity of water demand at the industry level as shown in Tables 2 and 3, respectively.

Industrial water demand price elasticity estimates for the overall manufacturing sector (as shown in Table 2) were mostly found to be negative and between 0 and -1 in U.S., Canada, Mexico, U.K., and India, indicating that the water demand is relatively inelastic—signaling that price increases would not necessarily be mitigated by or cause a reduction in water demand. The manufacturing

Table 2

Price elasticity of water demand estimated and compared across industrial sectors and countries, at the 3-digit NAICS manufacturing subsector level.

NAICS code	Industry	Price elasticity of water demand							
		Vásquez-Lavín et al. (2020) [31]	Köseoglu, (2018) [26]	Nahman and De Lange (2012) [29]	Kumar (2006) [33]	Rojas (2005) [6]	Dupont and Renzetti (2000) [34]	Wang and Lall (1999) [30]	Babin et al. (1982) [35]
		Chile	Scotland (UK)	South Africa	India	Mexico	Canada	China	United States
31–33	Manufacturing sector	-1.23	-0.8	-3	-0.9	-0.29	-0.8	-1.03	-0.56
311	Food Manufacturing	-1.18	-0.8	-0.78	-0.92	-	-	-1.04	0.14
312	Beverage and Tobacco Product Manufacturing	-1.16	-0.8	1.1	-0.91	-	-	-1.04	-
313	Textile Mills	-1.23	-1.4	-2.08	-	-	-	-1.1	-
314	Textile Product Mills	-	-1.4	-2.08	-	-	-	-	-
315	Apparel Manufacturing	-1.24	-1.4	-	-	-	-	-	-
316	Leather and Allied Product Manufacturing	-2.73	-	-	-0.94	-	-	-1.2	-
321	Wood Product Manufacturing	-1.12	-	-6.81	-	-	-	-	-
322	Paper Manufacturing	-1.36	-1.4	-6.81	-	-	-	-0.88	-0.66
323	Printing and Related Support Activities	-	-	-	-	-	-	-	-
324	Petroleum and Coal Products Manufacturing	-	-1.8	-5.19	-	-	-	-0.99	-
325	Chemical Manufacturing	-1.22	-0.9	-5.69	-0.92 (Chemicals)/-0.30 (Drugs)	-	-	-0.96	-
326	Plastics and Rubber Products Manufacturing	-1.26	-	-	-	-	-	-	-
327	Nonmetallic Mineral Product Manufacturing	-1.27	-	-	-	-	-	-	-
331	Primary Metal Manufacturing	-1.28	-	-5.08	-	-	-	-0.85	-
332	Fabricated Metal Product Manufacturing	-	-	-	-	-	-	-	-0.41
333	Machinery Manufacturing	-1.5	-	-	-	-	-	-1.03	0.14
334	Computer and Electronic Product Manufacturing	-	-	-3.05	-	-	-	-1.14	0.54
335	Electrical Equipment, Appliance, and Component Manufacturing	-1.21	-1.8	-3.05	-	-	-	-	0.54
336	Transportation Equipment Manufacturing	-1.15	-	-3.13	-	-	-	-1.16	-
337	Furniture and Related Product Manufacturing	-1.21	-	-	-	-	-	-	-
339	Miscellaneous Manufacturing	-	-	-	-0.87	-	-	-	-

water demand in water-scarce South Africa was found to be the most sensitive to its prices (or cost), with its price elasticities significantly greater than -1 in the study by Nahman and De Lange (2012) [29]. A review of price elasticity estimates across 26 studies by Köseoğlu (2018) [26] shows some pattern in elasticity based on industry type. Industries using water as a raw material, such as food and beverage manufacturing and chemical manufacturing, show relatively inelastic demand in comparison with relatively elastic demand for industries using water as a process input like textiles and apparel, paper, petroleum, and electrical equipment. For a few regional U.S. industrial sectors, elasticities are estimated to be positive, although Babin et al. [35] state that standard errors in the cases of NAICS codes of 333, 334, and 335 were large enough that these elasticities may not significantly differ from zero.

Some of the studies also estimated the cross-price elasticity of demand between water and other production inputs. The cross-price elasticity of water provides insights on its relationship to other production inputs. Cross-price elasticity of demand, ϵ_{ij} is the percentage change in quantity of i th input resulting from unit percent change in price of j th input. The value of cross elasticity helps in determining whether the inputs are substitutes (i.e., a unit increase in the price of one input will lead to an increase in demand for the other inputs) or complements (i.e., a unit increase in the price of one input will lead to a decrease in demand for the other inputs) in the production process. Positive cross-price elasticity means the inputs are substitutes, while negative cross-price elasticity means the inputs are complements. Cross-price elasticity of demand is zero if two inputs are not related. Estimates from Rojas (2005) [6] for cross-price elasticity of water with other inputs show that water is a substitute for both labor and material. Kumar (2006) [33] found water to be a substitute for capital but a complement to materials and labor for all industries, while Vásquez-Lavín et al. (2020) [31] found water to be a substitute for capital, labor, and material but a complement to energy. In their study on water use for Canadian industries, Dupont and Renzetti (2000) [34] included two variables in the production function for water use: water intake and water recirculation. As expected, water intake and recirculation are substitutes, and the former parameter is a substitute for capital, labor, and energy.

Output elasticity of water demand is an alternative elasticity metric denoted as positive values to estimate the output impacts of returns to scale from changing the water intake. Limited estimates of various industrial sectors from two studies are shown in Table 3. A range of estimates from the Ku and Yoo study (2012) [25] corresponds to the two types of production functions used (Cobb Douglas and *trans*-log). Output elasticity of water is significantly small and less than 1, implying an increase in water use does not lead to an increase in final product output (quantity). Water availability has not been found to be one of the major factors of the final manufacturing output for these two countries.

3.4. Regional/economy water valuation metrics

Shifting the focus from facility-level valuations to regional valuations enables better policy around industrial water use to advance technology uptake. Water valuation metrics used at the regional or economy-wide level are based on the analysis of macro-level regional data for the estimation of regional scale water-related economic impacts. The number of studies that have used metrics in this area is comparatively limited, with estimates from such studies shown in Table 4. Average and median water value estimates of Frederick et al. (1996) [36] were based on a wide variety of methods, such as average and marginal metrics using the production function approach and contingent valuation techniques for nonmarketed services from 41 different studies.

The most commonly recurring goal among the studies discussed in Table 4 was evaluating existing water usage policies within a

Table 3

Output elasticity of water demand comparison across different industrial sectors in two countries, at the 3-digit NAICS manufacturing subsector level.

NAICS code	Industry	Output elasticity of water demand	
		Ku and Yoo (2012) [25]	Wang and Lall (1999) [30]
		Korea	China
31 - 33	Manufacturing sector	0.02; 0.01	0.17
311	Food Manufacturing	0.018; 0.008	0.17
312	Beverage and Tobacco Product Manufacturing	0.018; 0.008	0.17
313	Textile Mills	0.016; 0.017	0.21
314	Textile Product Mills	0.016; 0.017	-
315	Apparel Manufacturing	-	-
316	Leather and Allied Product Manufacturing	-	0.26
321	Wood Product Manufacturing	0.022; 0.014	-
322	Paper Manufacturing	0.022; 0.014	0.1
323	Printing and Related Support Activities	0.022; 0.014	-
324	Petroleum and Coal Products Manufacturing	0.028; 0.012	0.15
325	Chemical Manufacturing	-	0.13
326	Plastics and Rubber Products Manufacturing	-	-
327	Nonmetallic Mineral Product Manufacturing	0.042; 0.048	-
331	Primary Metal Manufacturing	-	0.09
332	Fabricated Metal Product Manufacturing	-	-
333	Machinery Manufacturing	0.016; 0.0067	0.17
334	Computer and Electronic Product Manufacturing	0.01; 0.011	0.23
335	Electrical Equipment, Appliance, and Component Manufacturing	0.024; 0.012	-
336	Transportation Equipment Manufacturing	0.04; 0.036	0.24
337	Furniture and Related Product Manufacturing	0.035; 0.025	-
339	Miscellaneous Manufacturing	-	-

Table 4

Reviewed studies on manufacturing water valuation, including country, estimation metric, method, data sources, and estimated value.

Study	Country	Estimation metric for industrial sector	Method	Data sources	Estimated value
Hall (2019) [37]	Athens-Clarke County (U.S.)	• Jobs lost • Reduction in Gross Regional Product (GRP)	IMPLAN, a risk- based industry standard input/output economic model: used to understand the sensitivity of industries to reduced water use.	2014 county data for 536 economic sectors	Reduction in the GRP of \$244,000,000 and 4171 jobs lost
Cobti et al. (2017) [38]	Global scale	Quantitative scores for Vulnerability and Resilience between 1 (low risk) to 5 (high risk)	Water risk exposure estimated on regional and industrial scales	Data from 50 publicly listed global companies through: • WWF/DEG water filter tool • SASB materiality map • WRI Aqueduct tool • CERES Aqua Gauge tool • CDP water survey	-
Mueller et al. (2015) [39]	India, USA, Mexico, China, Brazil, Spain	Quantitative risk indicator scores (between 0 and 5)	Evaluation of 4 open-source water risk assessment tools.	GPS coordinates and water use data for each location and industrial sector	-
Li and Ma (2014) [40]	China (30 provinces in mainland China)	Shadow price	Meta-frontier model analysis	China environment Statistical Yearbook (2000–2014), focused on data from 30 provinces	6.3 (2021 \$/m ³)
Feng et al. (2005) [41]	China (based on China's South to North Water Transfer Project)	Shadow price	Computable general equilibrium model (CGE)	Water resource fee data from Water Social Accounting Matrix database	6.62 (2021 \$/m ³)
Frederick et al. (1996) [36]	United States	Average and median water value - overall	Review of water value estimates from multiple studies	7 estimates of water value for industrial processing	0.38 (2021 \$/m ³)

given geographical region to understand the obstacles hindering sustainable water supply/use and resultant economic growth. Some of the studies employed quantitative analysis to estimate the intangible avoided cost not considered by conventional metrics, such as shadow price (\$/m³), or other economic parameters like potential loss of jobs or economic output. Table 4 also includes studies that conducted qualitative analysis to identify the potential risks associated with these obstacles and the resultant economic impacts [38, 39]. The obstacles were quantified via scores ranging from 0 to 5 to display the degree of risk associated with water scarcity.

These metrics were estimated using deductive techniques, some common examples of which are methods like CGE models or input-output model techniques. CGE models use actual economic data to estimate how an economy might respond when stimulated by changes in policy or other external factors. The Feng et al. (2005) [41] study is a classic example of such a study, using the CGE model to determine if additional water supply from a large-scale water transfer project would help overcome potential obstacles due to regional water resource vulnerability. Another unique modelling approach observed was the meta frontier model analysis technique adopted by Li and Ma [40], which attempted to identify required policy changes to address the issue of low industrial water use efficiencies in industrial firms located across 30 different Chinese provinces. The analysis also quantitatively established that the estimated average shadow price was 12 times higher than the actual average price of industrial water across the eastern, central, and western regions of mainland China [40].

Input-output models have also been applied to quantitatively analyze regional-level data to understand any change in production output due to change in industrial water supply. A study conducted in Athens-Clarke County (GA, USA) used this approach to quantify the risk of drought occurrence in terms of potential industrial jobs lost and loss of economic output [37], in the absence of any water conservation measures. Using the county-level data for 536 economic sectors, adverse economic impacts were estimated in terms of reduction in the gross regional product (GRP) of \$244 million and the loss of 4171 jobs, even at a small level of risk of drought occurrence of 5% [37]. Most of these studies are focused on valuation efforts for specific geographic locations within a country. A complete country-level analysis is inappropriate due to a wide variation in both spatial and temporal water use, requiring a vast range of data and parameters for complete analysis.

4. Case studies of water valuation by manufacturers

The Millennium Ecosystem Assessment estimates that in the last half of the twentieth century, urbanization, industries, agriculture, forestry, and fisheries have driven the decline of 60% of all ecosystem services (e.g., carbon sequestration, freshwater provision, air and water quality regulation, storm protection, disease control, and habitat provision), in large part because the benefits of these public goods are generally not priced, so markets rarely mirror the full social and environmental cost of production [42]. Another estimate signifying enormous pressures on the ecosystems on which economies rely is that global production systems externalize \$4.7 trillion annually in environmental costs [43]. The effective development of payment for ecosystem services (PES) mechanisms and physical indicators of ecosystem health are examples of the types of better incentives, data, and decision-support tools that will be critical for companies to quantify and manage environmental impacts and business disruption risks across the production life cycle [42,43]. Further, incorporation of PES into internal corporate water management practices can lead to wider adoption of water-saving technologies.

The appropriate valuation of water in the manufacturing sector is nascent, but several multinational corporations have made strides in the last decade. Within the apparel industry, supply chain sustainability initiatives concerning the water use of production include the Better Cotton Initiative, the Sustainable Apparel Coalition Higg Index, PUMA Environmental Profit & Loss, Levi's E-valueate and Water < Less, Nike ColorDry and FlyKnit, Zero Discharge of Hazardous Chemicals, and Levi's Wellthread [43]. In 2011, the footwear and apparel company PUMA published an Environmental Profit and Loss (EP&L) Account encompassing the cradle-to-gate impact of its products on ecosystems, appraising the cost to society of water used in PUMA's supply chain as €47 million per year—on par with greenhouse gas emission costs [44]. This estimate was modeled by PWC and TruCost using a relationship between water scarcity and value derived from a wide literature search in order to evaluate in economic terms the drop in the direct use value of water to third parties as a consequence of PUMA's water consumption. As a result of the EP&L accounting, PUMA is now focusing on its supply chain (specifically, water to grow chemical and make leather) rather than on its own operations to reduce its water impacts.

Another large multinational that has investigated water valuation is Unilever, a consumer goods company with more than 250 manufacturing sites worldwide. The Unilever Sustainable Living Plan has identified water shortages and poor water quality as risks to continuous business operations, with recent droughts in Taiwan, Brazil, and Poland potentially threatening to disrupt production [5].

Table 5

True (risk-adjusted) value of water estimates in four cases of Unilever plants [adapted from Ref. [5]].

Case No.	Case 1	Case 2	Case 3	Case 4
Product Category	Laundry products	Laundry products	Beverages	Hair products
Baseline water stress	3.61	5	0	0
Days of inventory	7	0	2	1
Purchase price of water (2016\$/m ³)	2.36	0	0.14	0.62
Process & handling cost (2016\$/m ³)	0.62	0.62	0.62	0.62
Business disruption cost (2016\$/m ³)	0.77	8.94	2.09	1.63
True value of water (2016\$/m ³)	3.75	9.56	2.85	2.87
Percent increase from purchase price to true value of water	59%	N/A (cannot divide by zero)	1936%	363%

Working with Unilever, MIT researchers used the WRI Aqueduct tool to identify numerous business disruption scenarios related to water, estimated their likelihood and consequences, and determined available mitigation options to create a risk-adjusted value of water aggregated across all event scenarios. Table 5 demonstrates the substantial differences between the true value and the purchase price of water for four modeled Unilever plants.

The variation in each site's value-at-risk, or business disruption cost, would help Unilever incentivize water efficiency and basin-based stewardship initiatives where and when most crucial, improving the resiliency of its manufacturing operations via more optimal water use.

In Texas, the Dow Chemical Company partnered with The Nature Conservancy to better understand water risks for its Freeport Facility on the Brazos River. One effort involved hydro-economic modeling to characterize future water availability in the Brazos River basin and project the scale of economic losses from future water shortages [12]. A conservative approximation of loss due to water shortages affecting this single facility was estimated at \$900 million (30-year NPV). More broadly, this study underlines that the benefits of water markets—and potential implications of cross-sector competition—in which agricultural users sell their water to municipal and industrial users are lessened in the context of industrialized or water-stressed river basins, and presents a methodology for businesses to inform strategic planning processes via evaluating basin-scale water risks. This resulted in the facility pursuing tracking of indicators of water supply shortages, convey risks associated with industrial and municipal dominated basins, and explore options outside of water trading. The same researchers extended their analysis by using natural capital asset valuation to calculate the changing value of all industrial water rights in the Brazos River basin under varying water demand and climate change scenarios [45]. Employing multi-criteria analysis for water scarcity solutions using private, public, and biodiversity-related costs and benefits revealed that three scenarios are competitive on cost with the business-as-usual solution of increased reservoir storage. However, because these scenarios provide collective benefits to other water users and ecosystems in the basin while individual stakeholders bear the costs, more widespread payment for ecosystem services or water funds are necessary to correctly align incentives.

Finally, the apparel company Patagonia calls for the widespread adoption of value chain indices (VCI) to bring the previously externalized environmental and social costs of production inside individual firms' balance sheets [46]. A value chain index quantifies ecosystem services (e.g. for water, land use, and carbon) in dollar terms on the basis of cradle-to-grave production impacts, and should ideally be developed jointly by various competitors in a sector and draw on objective life-cycle analysis databases. Achieving "true cost accounting" would enable manufacturers to find improvements all throughout their value chains while "powerful market forces would be put in the service of sustainability's goals" [46].

5. Conclusions

The importance of water valuation in support of the use of water as a scarce natural resource has been limited to date. In addition to the true cost, the value of water must also include the indirect/social costs associated with industrial water use. A fuller monetization of water that incorporates ecosystem impacts from its use and costs associated with the realization of various water risks will create a more fertile environment for the development of water-saving technologies and implementation of conservation efforts. Until then, technology development and conservation efforts will be saddled with the common refrain that "water is too cheap".

This paper reviewed the economic valuation literature to summarize what is known about and understand general trends regarding the valuation of water used in manufacturing. It highlights the need to incorporate the true cost of water, indirect/opportunity costs, and other costs associated with the realization of water risks into the value of water. Indirect/opportunity costs include considerations for the loss of revenue from reduced production associated with lost or curtailed water supplies, as well as the environmental impacts associated with water use and wastewater disposal. Costs associated with water risk realization include costs of finding and utilizing alternate water sources and retooling a plant for using water alternatives. Risks that could trigger such costs can be categorized into three types: physical, regulatory, and reputational.

With the versatile role water plays in the daily functioning of manufacturing operations, the value of water for the industrial or manufacturing sector is close to surpassing that of other sectors like agriculture, domestic use, power generation, and mining. Most studies indicate the marginal value of manufacturing water use is mostly higher than the price (or cost) of water supply, thereby indicating the need for manufacturers to use value estimates rather than cost estimates for water risk evaluation. Available water valuation estimates based on a range of different metrics, both at the industrial and regional scale in terms of a change or value per unit of water use, indicate a wide variability not only across different manufacturing sectors and locations within a study, but also across various studies for a manufacturing sector.

Valuation metrics in terms of change in value with change in water use amount such as VMP, shadow price, and elasticity are appropriate for the evaluation of economic competitiveness of water conservation technologies. Elasticity is one of the metrics used for an understanding of the responsiveness of water demand to price and process output. Sectors using water as process inputs (like paper, textile, electrical industries) have relatively elastic price demand compared to sectors that use water as a direct input to production (like food and beverage industries), implying that the effect of pricing on water conservation is expected to be higher for the former sectors. Alternative econometric valuation estimation methods used are historically data-intensive, and the limited availability of such manufacturing data make their implementation difficult to predict future valuation accurately. The appropriate water valuation metric will be case-specific with a consideration of both regional and temporal risks. Industrial sectoral level valuation analysis is critical to the overall regional water valuation (using some of the macro evaluation techniques, e.g., computable general equilibrium modeling and input-output modeling) for the estimation of indirect local economic impacts from reductions in water availability for the manufacturing sector, such as job and Gross Regional Product losses.

Finally, several recent case studies of manufacturers provide examples for others while illustrating both the promise and challenges

of water valuation. While the environmental and social costs of manufacturing water use are still externalized, some large multinational corporations have moved toward assessing the value of water via supply chain sustainability initiatives, environmental profit and loss accounting, estimating risk-adjusted values of water, hydro-economic modeling, natural capital asset valuation, and developing value chain indices.

Future work in this area could involve employing the information summarized in this review article to develop guidance or a specific methodology for the valuation of water used in manufacturing that encompasses the full extent of associated economic and environmental impacts of such use. The emergent linkages between economic valuation and virtual water (or water footprint) [47,48] could be examined in the manufacturing context to understand more about how valuation metrics of virtual water inputs (e.g., raw material inputs) would assist manufacturers in evaluating the reliability of their suppliers. In addition, researchers collaborating with industry to develop and disseminate case studies on the implementation of water valuation metrics may help make the case for more widespread adoption of such approaches. Manufacturers that integrate the full value of water into decision-making are better able to achieve sustainability goals by justifying expenditures on water conservation technologies, planning for water-related risks, incentivizing water efficiency and stewardship, enhancing their reputation among customers and shareholders, and improving the resilience of their operations.

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Credit authors contribution statement

Sujit Das: Conceptualization, Methodology, Writing- Original draft preparation, Reviewing and Editing, Supervision **Heidi Fuchs:** Methodology, Writing- Original draft preparation, Reviewing and Editing **Ritu Philip:** Data curation, Formal analysis, Writing- Original draft preparation **Prakash Rao:** Writing – Original draft preparation, Conceptualization, Methodology, Reviewing and Editing, Supervision.

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.

Data availability

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