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Plant Water Profiler: A Water Balance and True Cost of Water Calculator for Manufacturing Plants

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OAK RIDGE NATIONAL LABORATORY
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ORNL/TM-2021/1918

Manufacturing Science Division

PLANT WATER PROFILER: A WATER BALANCE AND TRUE COST OF WATER CALCULATOR FOR MANUFACTURING PLANTS

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ACRONYMS

EIO-LCA	Economic Input-Output Life Cycle Assessment
INPLT	in-plant training
NAICS	North American Industry Classification System
PWP	Plant Water Profiler Tool
STATCAN	Statistics Canada

SYMBOLS

x	water using subsystem x; x = 1 to X
s	water intake source s; s = 1 to S
p	product p; p = 1 to P
o	wastewater discharge outlet o; o = 1 to O
t	water treatment process t, t = 1 to T
t'	wastewater treatment process t’, t’ = 1 to T’
d	depth of irrigated water
$I_{x,s}$	water intake by system x from source s
R_x	water recirculated within system x
$R'_{in,x'}$	water incoming from other subsystems to subsystem x
$R'_{out,x'}$	water outgoing to other subsystems from subsystem x
P_x	water used in products by subsystem x
E_x	evaporation or irrigation loss associated with subsystem x
$W_{x,o}$	wastewater discharge from subsystem x to outlet o
L_x	unknown loss associated with subsystem x
$T_{x,t}$	water treated by process t
$T'_{x,t'}$	wastewater treated by process t’
$Elec_x$	electricity consumption by subsystem x
$Fuel_x$	heating fuel consumption by subsystem x
$\dot{\$}_s$	unit cost of water intake from source s
$\dot{\$}_o$	unit cost of wastewater discharge to outlet o
$\dot{\$}_t$	unit cost of water or wastewater treatment t
$\dot{\$}_{elec}$	unit cost of electricity
$\dot{\$}_{fuel}$	unit cost of heating fuel
MGPY	million gallon per year

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ABSTRACT

As the uncertainty of a sustained water supply, regulatory constraints, competition among end users, and public scrutiny increases, a growing number of manufacturing sectors are adapting to current and emerging water-related risks by optimizing productivity and reducing waste. As a step toward increasing water use efficiency and making informed business decisions, corporations must make an effort to understand and track their water demands, losses, and costs associated with each subsystem within their facilities.

Manufacturers are often unaware of the "true cost of water" (i.e., the total costs associated with procurement, treatment, and consumption of water, and wastewater disposal), which reduces the visibility of the actual impact of water-saving measures. To help manufacturers account for water procurement and use in manufacturing operations, quantify the true cost of water, and identify potential areas for water and associated energy cost savings, an open access tool—Plant Water Profiler (PWP)—was developed. The tool is based on water mass balance analysis and has been adopted as the core analysis tool for plant water use assessments, Water In-Plant Training (Water INPLT), as part of the US Department of Energy's Better Plants program. During three pilot INPLTs conducted in 2019 at three manufacturing facilities, the PWP tool allowed users to understand water flows within the facilities and provided additional capabilities to analyze their water use. This paper describes the methodology behind the PWP tool and its implementation through pilot Water INPLT trainings delivered in three manufacturing facilities in the United States. The three case studies demonstrate opportunities to improve water efficiency and reduce associated costs and the challenges encountered in three different manufacturing sectors.

1. INTRODUCTION

As the uncertainty of sustained water supply (Borgomeo, Hall, & Guillod, 2018; Orr, Cartwright, & Tickner, 2009), regulatory constraints (Gouws, Majozi, Foo, Chen, & Lee, 2010), competition among end users (UN, 2007), and public scrutiny increases (Morrison, 2009), a growing number of manufacturing sectors are adapting to current and emerging water-related risks by optimizing productivity and reducing waste. As a step toward greater water use efficiency, corporations must understand and track the water demands of each of the main water-using components in their facilities (Larson, 2012). Besides the benefits to the surrounding environment, improvements in water efficiency can be coupled with energy-efficient practices and a reduction of costs (EPA, 2011). The true cost of water in a facility goes beyond the price paid for water acquisition and must be quantified in the context of a water-energy nexus (e.g., cost of energy for water extraction and pumping) and account for changes in water quality (e.g., cost of treatment and disposal). To support the manufacturing sector in identifying opportunities for water use efficiency and assessing the true cost of water, Oak Ridge National Laboratory (ORNL) developed a Plant Water Profiler (PWP) tool. This report describes the development and capabilities of the tool as well as summarizes the results from three pilot water assessments performed by ORNL using the PWP tool.

The PWP tool is an open-access tool designed to help facilities understand their water balance, cost, and opportunities for water saving. Unlike commonly used tools, PWP is applicable to any manufacturing sector, allows the assessment of water balance, estimates the true cost of water, and provides results at a subsystem level. Several tools have been developed in the past to manage water use [e.g., spreadsheets, audits, and scorecards (AWWA, 2006; EDF-GEMI, 2014; FEMP, 2016)] and assess facility water balance [e.g., GEMI's Collecting the Drops (GEMI, 2002), Blue Plan-It (Carollo, 2016)] and the true cost of water (BIER, 2018; Colgate-Palmolive, 2015; Veolia, 2013). Moreover, large water-intensive companies have also developed their own systems as part of their environmental stewardship programs [e.g., PepsiCo Resource Conservation (ReCon) (PepsiCo, 2017), Nestle Environmental Management System (NEMS) (Nestlé, 2013)]. The PWP tool encompasses the capabilities of true cost calculators, the simplicity of water balancing tables for data input, and the flexibility to estimate water use for subsystems in the absence of comprehensive submetering. The tool has been implemented by ORNL in partnership with three manufacturing facilities through the US Department of Energy's (DOE's) Better Buildings, Better Plants program (U.S. Department of Energy, 2014, 2016). The water assessment was accompanied by an In-Plant Training (INPLT) at such facilities and identification of water-saving opportunities through a treasure hunt inspection modality. The subsequent analysis encompassed a water balance calculation, determination of the true cost of water, and identification of opportunities for improvement. Section 2 of this report summarizes the calculation methodology and tool capabilities.

While the manufacturing sector is responsible for a relatively small portion of national water use, water conservation potential can vary greatly among technologies, industries, and regions, presenting a unique challenge for stakeholders (Gleick, 2003). In 2015, the manufacturing sector accounted for about 6% of total US water use (Rao, Sholes, Morrow, & Cresko, 2017), including 5% as self-supplied withdrawal from surface-water and groundwater sources (Dieter et al., 2018) and 1% through public water supplies (Becker, 2015; Solley, Pierce, & Perlman, 1998).[1] Although national-level manufacturing water use data are scarce, past national surveys (Becker, 2015; Kenny et al., 2009), homologous surveys for other nations (Renzetti, 1993), and corporate sustainability reporting (CDP, 2018) have shown that there is heterogeneity in water use volumes, water sources, quality requirements, reuse and recirculation, and disposal practices across industries technologies and regions. Some of the sectors found to be the largest water users are pulp and paper, primary metals, chemicals, petroleum and coal, and food, accounting for more than 90% of manufacturing water intake (Rao et al., 2017; Peter Rogers, 1993). Within manufacturing facilities, water demand also varies among processes, equipment, and subsystems, which are generally divided into three macro-purposes: process water, water for cooling, and water for heating (Ellis, Dillich, & Margolis, 2001). The major uses of water in the studied facilities were found to be for processes and cooling, accounting for, at least, 98% of freshwater intake. Over time, plants have transitioned from inefficient practices such as "once-through" cooling systems to more efficient "closed-loop" cooling (Dorjets, 2014), which recirculates water within cooling towers. Although it is more prevalent in water-intense sectors (Peter Rogers, Llamas, & Martinez-Cortina, 2006), the implementation and optimization of water recirculation can significantly reduce a facility's dependence on freshwater. For instance, a fiberglass manufacturing facility freshwater intake was found to be less than 4% of its gross use of water (i.e., intake water and recirculation; see Section 3.2), reflecting the importance of water recirculation.

Section 3 summarizes the findings, challenges, and opportunities observed during the implementation of the PWP tool for the three facilities studied in three different manufacturing sectors (steel, fiberglass, and construction materials), highlighting the possibility of using the tool despite the inherent differences in their operations. Some of the major challenges during the implementation of the tool were the lack of submetering and tracking of water uses at the subsystem level and the lack of metering of self-supplied water (i.e., surface water or groundwater not supplied or billed by municipal utility services). Without adequate submetering, the tool requires the estimation of water use based on equipment-specific operation parameters (e.g., cooling tower load, cooling tower makeup water conductivity, boiler horsepower) and may not reflect water flows accurately. The water mass balance of the facilities was assessed at the subsystem and facility level by comparing metered, estimated, and billed water flows when available; imbalances reflected water losses, unaccounted flows, or inaccurate estimations. Subsequent to the assessment of the water mass balance, the tool was used to estimate the true cost of water by accounting for all the direct costs associated with the procurement, use, disposal, and treatment of water. The true cost quantification reflected that facilities could be spending up to three times their billed cost of water.

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[1] Public-supply deliveries to commercial, industrial, and thermoelectric-power users have not been reported by USGS since 1995. According to Dieter et al. (2018), self-supplied industrial water withdrawal was 5% of total US water use in 2015. As reported in Becker (2015), about 82% of industrial water was self-supplied (Solley et al., 1998), the last year this estimate was made. Assuming this same proportion, total manufacturing water intake in 2015 was approximately 0.05/0.82 = 6.1%.

2. DEVELOPMENT OF PLANT WATER PROFILER TOOL

Several tools have been developed in the past to help facilities estimate their true cost of water. Some of the widely known tools are designed for a specific manufacturing sector (e.g., BIER, 2018), are proprietary tools for specific corporations (e.g., PepsiCo, (2017), or are not accessible free of charge (e.g., Veolia, (2013). While the range of complexity in the tools varies from spreadsheet-based tools to web-based platforms, the first step in determining the true cost of water is accurate water accounting. A number of studies use the water mass balance framework for water accounting, monitoring, and optimal operation in a variety of contexts [e.g., in industrial parks (Pham et al., 2016); urban environments (Kenway, Gregory, & McMahon, 2011)]. Kurle, Herrmann, & Thiede (2017) presented a structured approach to identify and visualize water-related hot spots in manufacturing sites, supported by generic modeling tools available to facilities. Sachidananda and Rahimifard (2012) presented a transparent methodology for minimizing water use within manufacturing processes and a decision support tool for testing scenarios. The PWP tool uses a water mass balance framework to account for flows within a facility, allowing for different sources of water, treatment, recirculation, and disposal. The tool is presented as an excel spreadsheet that is accessible to facilities, with a transparent methodology that aids manufacturing sites identifying unaccounted flows and hidden costs, at the subsystem or equipment aggregation desired by the facility.

A subsequent step in the water profiling is establishing the energy-water connection by accounting for energy use associated with water uses. Many studies performing water use modeling have also expanded to analyze the water-energy interdependence. Mousavi, Kara, & Kornfeld (2015) introduced a simulation-based approach based on a water footprint methodology to model energy and water flows in manufacturing systems. Thiede, Schonemann, Kurle, & Herrmann (2016) modeled the interdependence of water and energy flows among facilities' processes, machines, products, and resources in a dynamic way that other methodologies such as material flow analysis cannot incorporate. The PWP tool acknowledges the energy-water interdependence by accounting for energy used for water pumping and the fuel associated with unrecovered heat in wastewater.

Finally, the true cost of water is estimated using information from the water balance model, the energy-water connections, and additional direct operational costs. The essential cost components of the true cost of water include the costs of water procurement, treatment, processing, and its use in water-using subsystems and processes in the facility over a specific period (Henderson, Somers, & Stuchtey, 2013; Rao, McKane, & Fontaine, 2015). Walsh, Bruton, & O'Sullivan (2017) have used the term "true value" to account for the financial value-added costs involving labor, materials, energy, and equipment required for operations such as purification, chemical treatment, and disposal, as well as all installation and operation costs. Veolia's True Cost of Water tool (Veolia, 2013) accounts for direct costs (for procurement, operation, and investments in water infrastructure)and indirect costs (administrative, legal, and corporate social responsibility costs, and costs related to risks such as operational, financial and regulatory, and reputational risks). The PWP tool adopts the terminology of Rogers, de Silva, & Bhatia (2002) in which the price of water refers to the tariffs paid to municipalities for water acquisition and the cost is accounted for through the direct operational costs associated with water procurement, treatment, and disposal. Indirect administrative costs, legal costs, and capital expenditures are not currently accounted for.

2.1 OVERVIEW OF THE TOOL

PWP starts by defining the boundary of the analysis as a system with its corresponding subsystems in which water is used. The analyzed system can be an entire facility or a group of processes, while the subsystems can be a specific process (e.g., assembly, casting, coating), equipment (boiler, chiller, cooling tower), operation (heating, cooling, pumping, power generation), ancillary service (e.g., landscaping, kitchen, toilets), or a combination of them (e.g., cooling for processes, cooling for power generation, boiler for power generation). When information of inflows, outflows, and recirculation for each subsystem is provided or estimated, the PWP tool can assist in identifying unaccounted flows and losses and compare water use across subsystems.

The tool also allows the user to assign a cost associated with water uses. The cost can be explicitly associated with water procurement, treatment, and disposal or hidden in the connections between energy and water such as electricity used for water transport and fuel use associated with unrecovered heat energy in wastewater that leaves the plant boundary.

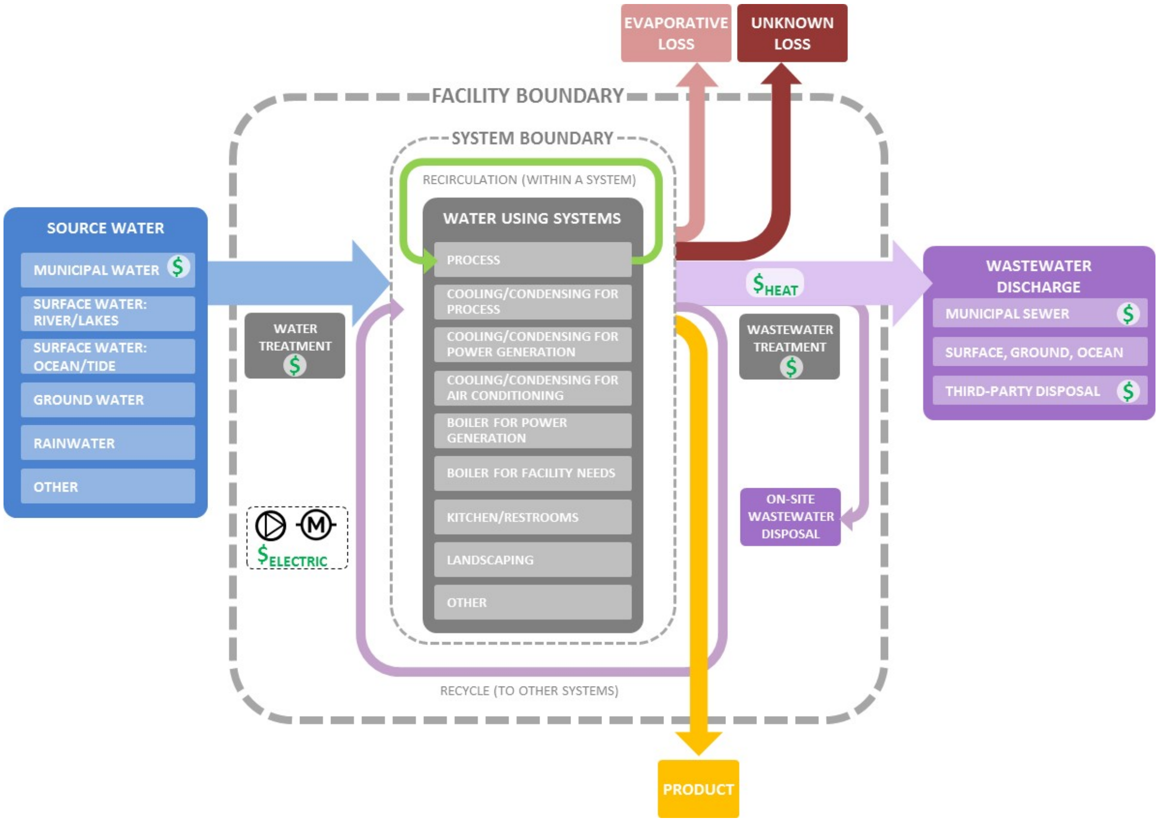

Figure 1. Water flow diagram with true cost components.

Figure 1 shows the definition of boundary around the analyzed system (plant) and its water-using subsystems. The illustration shows the possible water flows that are used to compute the water mass balance. Inflows from different sources are shown in blue, wastewater generated is shown in purple, water incorporated in products is shown in yellow, water recirculation is shown in green, and water losses are shown in red. The dollar sign symbolizes the costs that are used to compute the true cost of water.

The PWP tool, by analyzing water flows at the subsystem scale, allows facilities to identify, compare, and rank subsystems by their share of intake water use. Additionally, by coupling water volumes to water costs, the tool contrasts the volume of water to the cost for each subsystem. Through this step, the tool identifies instances such as subsystems that require small volumes of high-cost water and vice versa.

Further, PWP assesses the water efficiency status of a plant and its individual subsystems by providing a tailored list of water-efficiency measures and opportunities specific to the plant. Thus, PWP is a first step that industrial manufacturing plants can take to identify opportunities for minimizing water use and reducing cost.

2.2 CALCULATION METHODOLOGY

PWP uses a systematic water mass-balance framework to characterize inflows, outflows, and recirculation for each of its subsystems and identifies unaccounted flows by assessing the closure of the water mass-balance. While the tool is capable of using high granularity data, submetering of water flow is usually rare in industrial settings because of (1) high upfront installation cost and high, recurring maintenance expenses, (2) monthly service charges for specialized assistance with meter reading and allocation, (3) regulatory issues involving permits, inspections, and fees for submetering equipment (City of Richmond; City of San Diego, 2020), and (4) liability concerns related to system malfunction and leaks (Fehl, 2017). Therefore, the user inputs for unmetered subsystem-level water flow can be unreliable. PWP guides the estimation of water flows in different subsystems via a bottom-up approach that uses equipment-specific operation parameters (Section 2.2.1).

The aggregation of all subsystem estimates provides estimated facility-level water flows. The model calibration portion takes a top-down approach that uses plant-level utility bills or metered data for water intake and effluent and compares it with the aggregation of subsystem estimated volumes. Disparities between both approaches (top-down and bottom-up) at the facility level or a failure to match inflows and outflows at the subsystem level indicate the presence of unaccounted for flows that must be investigated and manually corrected within the tool.

The inputs and calculations programmed in PWP are outlined in the following sections.

2.2.1 Subsystem Water Use Calculations

Once all the water-using subsystems have been defined by the user, specific parameters of processes and equipment can be specified. The parameters are used to calculate specific water intake, recirculation, gross water use, consumptive water use, and effluent. Tables 1–5 show the parameters that users can specify for processes, cooling towers, boilers, and ancillary services such as sanitary use and landscaping, respectively. The left-side column in each table shows the inputs required by the user, and the right-side column shows the calculations performed by the tool.

For processes (Table 1), parameters include estimates of the number of production units, process water use, water incorporated in products per production unit, and recirculation ratios to calculate the volumes of total water use, consumptive water use, and recirculated water.

Table 1. Process water use calculations.

User Inputs	Calculations
For subsystem x=Process:	
N: Number of Units Processed per Year (units)	Gross Water Use, $G_x = N * g/10^6$ (MGPY)
g: Water Use (gal per production unit)	Recirculated Water, $R_x = G_x * r$ (MGPY)
r: Fraction Recycled or Reused	Makeup Water, $M_x = G_x - R_x$ (MGPY)
p: Water Consumed in Product (gal per production unit)	Water Consumed in Products, $P_x = N * p/10^6$ (MGPY)

For cooling towers (Table 2), annual hours of operation, tonnage, load fraction, evaporation rate, temperature drop across cooling tower, makeup water, and blowdown conductivity measurements are used to calculate makeup water (water intake), gross water use and recirculated water, evaporation loss (consumptive use), and blowdown (effluent). The estimation of the gross water use follows the rule-of-thumb of 3 gallons per minute per ton of cooling (i.e., tonnage * load fraction) (Boyd, 2011). The water loss due to drift is ignored. Evaporation rate is entered as a percentage of gross water use per 10°F temperature drop, which is typically 0.85%, with a typical range of 1.0–1.2% for dry climate to 0.65% for moist climate (CheCalc, 2017). For once-through cooling systems, water intake and discharge are calculated from the water flow rate (in gallons per minute) and hours of operation.

Table 2. Cooling tower water use calculations.

User Inputs	Calculations
For subsystem x=Cooling Tower:	
H: Hours of Operation per Year (hours)	Gross Water Use, $G_x = (3 * CT * L) * H * 60/10^6$ (MGPY)
CT: Chiller or Cooling Tower Tonnage	Evaporation Loss, $E_x = G_x * (e/100) * \Delta T/10$ (MGPY)
L: Load as a Fraction of Tonnage	Cycles of Concentration, $C = Bc/Mc$
e: Evaporation Rate per 10°F Temp. Drop (%)	Makeup Water, $M_x = E_x/(1 - 1/C)$ (MGPY)
ΔT: Temp. Drop Across Cooling Tower (°F)	Blowdown, $B_x = M_x - E_x$ (MGPY)
Mc: Makeup Water Conductivity (selected unit	Recirculated Water, $R_x = G_x - M_x$ (MGPY)
Bc: Blowdown Conductivity (selected unit)	
For subsystem x=Once-through Cooling:	
H: Hours of Operation per Year (hours)	Water Intake = Gross Water Use = Discharge Water = $F * H * 60/10^6$ (MGP
F: Water Flowrate (gal per minute)	

For boilers (Table 3), annual hours of operation, boiler capacity, load fraction, steam generation rate, and makeup water, feedwater and blowdown conductivity measurements to calculate makeup water (water intake), feedwater (gross water use), steam losses (water consumption), condensate return (recirculated water), and blowdown (wastewater discharge) (Boyd, 2011). Losses in deaerator are ignored.

Table 3. Boiler water use calculations.

User Inputs	Calculations
For subsystem x=Boiler:	
H: Hours of Operation per Year (hours)	Cycles of Concentration, $C = Bc/Fc$
BHP: Boiler Horsepower	Gross Water Use, $G_x = [e/(1 - 1/C)] * BHP * L * 0.002 * H * 60/10^6$ (MGPY)
L:Load as a Fraction of Boiler Horsepower	
e: Steam Generation Rate (lb/h) per BHP	Makeup Water, $M_x = (F_c/M_c) * G_x$ (MGPY)
Fc: Feedwater Conductivity (selected unit)	Blowdown, $B_x = (1/C) * G_x$ (MGPY)
Mc: Makeup Water Conductivity (selected unit)	Evaporation Loss, $E_x = M_x - B_x$ (MGPY)
Bc: Blowdown Conductivity (selected unit)	Recirculated Water, $R_x = G_x - M_x$ (MGPY)

For kitchens and restrooms (Table 4), the number of employees, work hours, and estimates of water use per employee are used to calculate the total water use. The user may estimate water use per employee based on a typical range of 10 gallons per shift when only toilets are used to 35 gallon per shift where there are toilets, showers, and full kitchen services (e.g., food preparation and dishwashing) (EPA, 2011).

Table 4. Sanitary water use calculations.

User Inputs	Calculations
For subsystem x=Kitchen and Restrooms:	
N: Number of Employees (employees)	Gross Water Use, $G_x = N_x * D_x * g/10^6$(MGPY)
D: Work Days per Year (days)	
g: Water Use per Employee (gal per day)	

For landscaping and irrigation (Table 5), the area of land irrigated and inch of irrigated water per unit area of land are used to calculate irrigation water consumption.

Table 5. Landscaping and irrigation water use calculations.

User Inputs	Calculations
For subsystem x=Landscaping and Irrigation:	
A:Square Feet of Land Irrigated (sq. ft)	Gross Water Use, $G_x = 0.623 * d * A * D/10^6$ (MGPY)
d: depth of of Irrigated Water per Year (in.)	Irrigation Water Consumption, $E_x = G_x$ (MGPY)

Subsystem water use calculations are optional but recommended, especially for unmetered subsystems. The accuracy of these estimates depends on the quality of the user-provided information. These estimates are used only to inform the subsystem gross water use and water outflow breakdown to generate the water flow model.

2.2.2 Water Flow Model, Water Balance Calculations, and Calibration

To develop the water flow model in a plant, the breakdown of subsystems' gross water use and water outflows is required as user input. Because water use is rarely metered at the subsystem level, the calculated subsystem water use (as outlined in Section 2.2.1) provides a starting point for facilities to characterize their flows.

Figure 2 shows the water flow model with respect to a generic subsystem "*x*" (solid arrows). The subsystem *x* has its corresponding source water inflow I_x from source I_s, wastewater discharge W_x at wastewater discharge outlet W_o, evaporative loss E_x, unknown losses L_x, recirculated water R_x, and water incorporated in products P_x leaving the system boundary. Dotted arrows are flows associated with the remainder of subsystems in the facility. The blue arrows indicate source water intake, and green arrows indicate recirculation within the subsystem or shared with other subsystems within the facility. Purple and red arrows indicate water that leaves the facility as wastewater or losses, incorporated in products, respectively. Table 6 shows the user inputs and the calculations performed by the tool to determine the flows associated with a generic subsystem *x* within a facility.

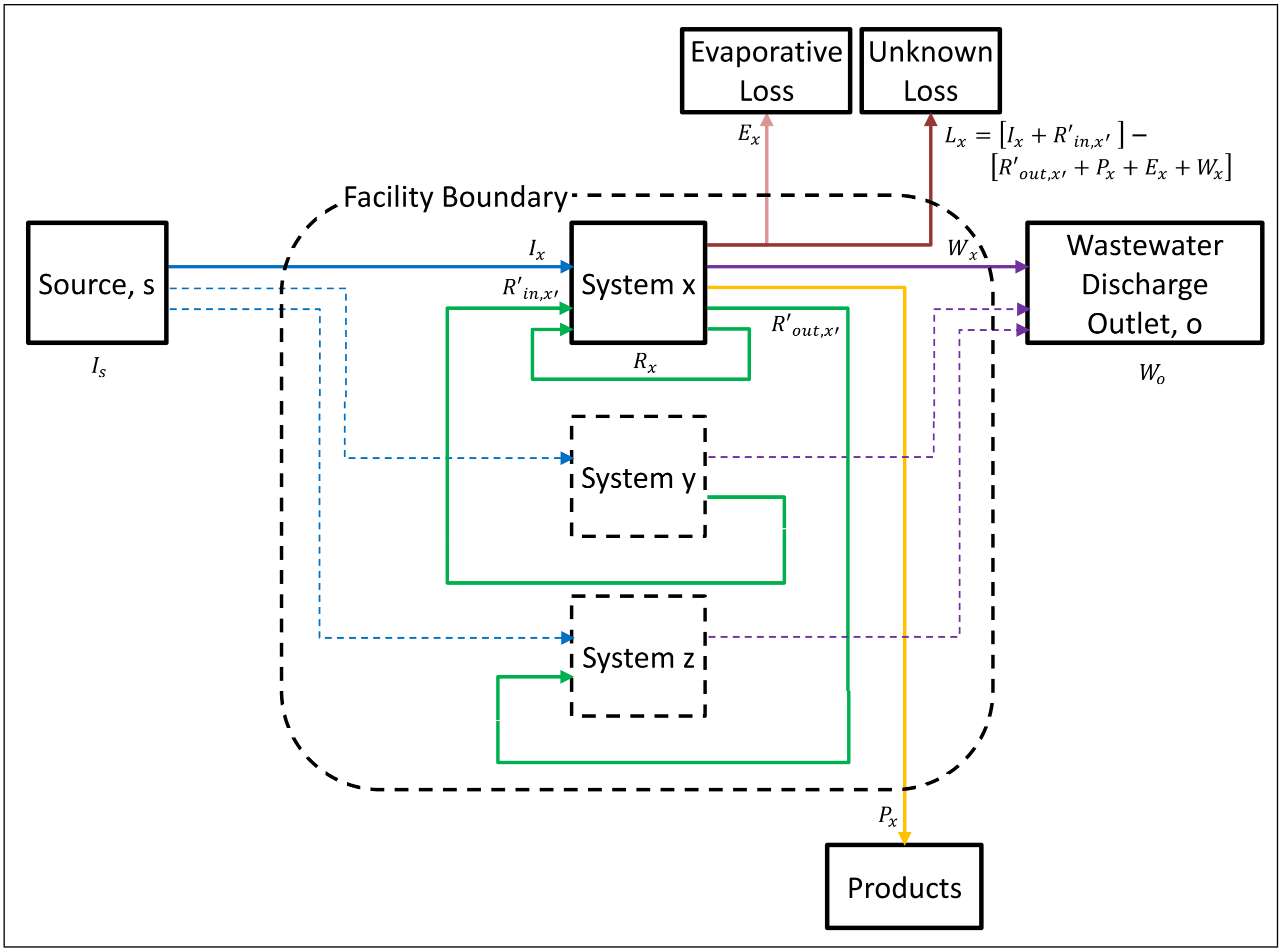

Figure 2. Water flow model with respect to a generic subsystem "*x*".

Table 6. Water balance calculations.

User Inputs	**Calculations**
Plant Water Intake and Wastewater Discharge	Water Flow Model Calibration:
I_s:Plant Water Intake by Source (MGPY)	$\sum_x I_x = I_s$
W_o:Plant Wastewater Discharge by Outlet (MGPY)	$\sum_x W_x = W_o$
Subsystem Gross Water Use	
I_x: Source Water Use (MGPY)	Unknown water loss in subsystem x,
$R'_{in,x'}$: Water from Other Subsystems (MGPY)	$L_x = \left[I_x + R'_{in,x'}\right] - \left[R'_{out,x'} + P_x + E_x + W_x\right]$ (MGPY)
R_x: Recirculated Water (MGPY)	
Subsystem Water Outflow	Unknown water loss in plant,
W_x: Wastewater Discharge (MGPY)	$L = \sum_x I_x - [\sum_x P_x + \sum_x E_x + \sum_x W_x]$ (MGPY)
$R'_{out,x'}$: Water to Other Subsystems (MGPY)	
E_x: Consumptive Loss (MGPY)	
P_x: Water Incorporated in Product (MGPY)	

The calibration consists of an assessment of the closure of the water mass balance at the subsystem and system (facility) level. Failure to match inflows to outflows signify the presence of unknown losses or unaccounted for flows. For each subsystem, the estimated inflows are compared against estimated outflows (Figure 3a) to assess the presence of unknown losses. Subsequently, the estimates for every subsystem are aggregated and compared with the plant-level utility bills or metered data for self-supplied water (Figure 3b) to calibrate the model. Discrepancies between the two sources of information indicate the need for reviewing calculations or investigating unaccounted for flows. The user is prompted to inspect potential unaccounted flows and manually add or correct flows as necessary. In cases where metered data is not available, the estimates from Section 2.2.1 are considered the most accurate information available. However, facilities are encouraged to collect information and not rely completely on estimations for their water accounting.

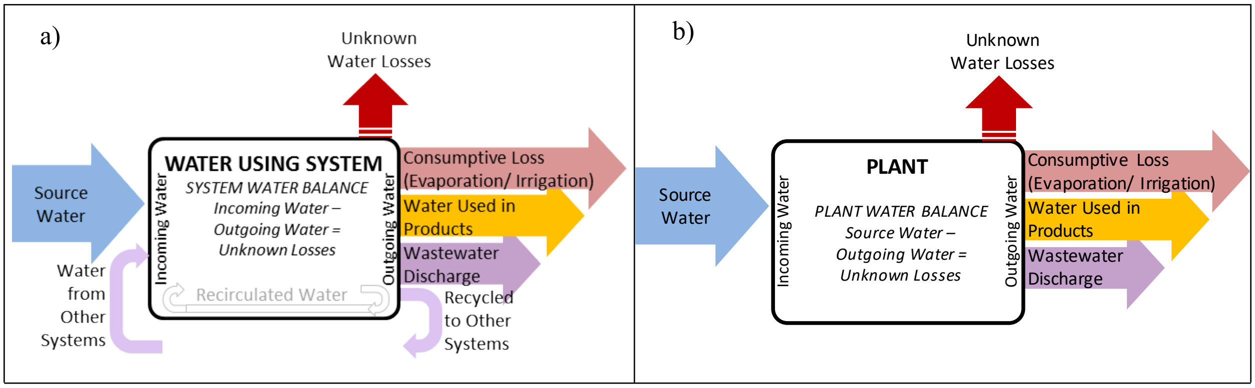

Figure 3. Panel a): Water balance for a subsystem. Panel b): water balance for the whole facility.

2.2.3 True Cost of Water Calculations

Once the water flow model is established and balanced, the cost components of the true cost of water are estimated. The specific variables and calculations to estimate the true cost are described in Table 7. The accounted components of the true cost are estimated in five steps as follows.

1. Volumes of water intake and wastewater discharge for every subsystem are calculated based on fractions of water use and discharge and system (facility) total water intake and discharge.
2. Volumes of water (intake or recirculated) and wastewater for every subsystem treated by each treatment process are calculated based on volumes of water used and wastewater discharged by each subsystem and the fractions of water that each treatment process *t* treats for the specific subsystem *x*.
3. Operational variables of pumps and motors, such as motor capacity, efficiency, and hours of operation, are used to estimate the energy used.
4. The fuel consumption associated with the heat energy in wastewater is computed using the average temperature of source water intake and wastewater discharge, the temperature rise, as well as water properties and heating fuel efficiency.
5. The true cost of water is computed by the sum of the products of water or energy embedded and the corresponding unit cost of each component of the true cost as follows.
    - The water intake and wastewater volumes ($I_{x,s}$ and $W_{x,o}$ from Step 1) are multiplied by the unit cost of water intake from and wastewater disposal to municipal services.

- The volumes of water and wastewater treated ($T_{x,t}$ and $T'_{x,t'}$ from Step 2) multiplied by a lump-sum unit cost of treatment is entered that combines the costs of chemicals, pumping energy, maintenance, and annualized cost of equipment installation.
- The energy used for pumps and motors ($Elec_x$ from Step 3) is multiplied by the unit cost of electricity.
- The fuel consumption associated with heat energy in wastewater ($Fuel_x$ from Step 4) is multiplied by unit cost of fuel.

Table 7. The five-step methodology to estimate the true cost of water.

	User Inputs	Calculations
1	**Subsystem Water Intake and Wastewater Discharge** $f_x(I_{x,s})$: Fraction of Water Intake by Source $f_x(W_{x,o})$: Fraction of Wastewater Discharge by Outlet	Water Intake by Subsystem x from Source s, $I_{x,s} = f_x(I_{x,s}) * I_x$, such that $\sum_x I_{x,s} \approx I_s$ Wastewater Discharge from Subsystem x to Outlet o, $W_{x,o} = f_x(W_{x,o}) * W_x$, such that $\sum_x W_{x,o} \approx W_o$
2	**Water and Wastewater Treatment** $f_x(I_{x,s,t})$, $f_x(R_{in,x,t})$, $f_x\left(R_{in,x',t}\right)$: Fraction of Intake and Recirculated Water associated with Subsystem x that undergoes Treatment Process t $f_x\left(W_{x,0,t'}\right)$: Fraction of Wastewater from Subsystem x that undergoes Wastewater Treatment Process t'	Subsystem Water Treated by Process t, $T_{x,t} = \sum_s \{f_x(I_{x,s,t}) * I_{x,s}\} + \{f_x(R_{in,x,t}) * R_{in,x}\} + \sum_{x'} \{f_x\left(R_{in,x',t}\right)$ Wastewater Treated by Process t, $T'_{x,t'} = \sum_o \{f_x(W_{x,o,t'}) * W_{x,o}\}$
3	**Pump and Motor Electricity Use** H: Hours of Operation per Year kW or hp: Motor Capacity η: Motor Efficiency V: Volts A: Amperage Pf: Power Factor	Pump or Motor Electricity Consumtion for Subsystem x, $Elec_x(\text{kWh/year}) = \sum_{\substack{all\ pumps/\\ motors}} \left\{ \begin{array}{c} kW * H\ or\ (hp * 0.7 \\ \left(\frac{V * A}{1000}\right) * Pf * H, \text{for singl} \\ \left(\frac{V * A}{1000} * 1.732\right) * Pf * H, \text{for} \end{array} \right.$
4	**Heat Energy in Wastewater** $T_{x,incoming}$: Average Temperature of Intake Water (°F) $T_{x,wastewater}$: Average Temperature of Wastewater (°F) η: Heating Fuel Efficiency ρ: Density of Water (lb/gal) C_p: Specific Heat of Water (Btu/lb · °F)	Fuel Consumption Associated with Heat Energy in Wastewater Discharged by Subsystem x (MMBtu/year), $Fuel_x = \rho * W_x * C_p * \left(T_{x,incoming} - T_{x,wastewater}\right)/\eta$

Table 7. The five-step methodology to estimate the true cost of water (continued).

5	**True cost of water** $\dot{\$}_s$: Unit Cost of Water Intake from Source s $\dot{\$}_o$: Unit Cost of Wastewater Discharge to Outlet o $\dot{\$}_t$: Unit Cost of Water Treatment t $\dot{\$}_{t'}$: Unit Cost of Wastewater Treatment t' $\dot{\$}_{elec}$: Unit Cost of Electricity $\dot{\$}_{fuel}$: Unit Cost of Heating Fuel	True Cost of Water for Subsystem x, $\$_x = \sum_s(\dot{\$}_s * I_{x,s}) + \sum_o(\dot{\$}_o * W_{x,o}) + \sum_t(\dot{\$}_t * T_{x,t}) + \sum_t(\dot{\$}_{t'} * T'_{x,t'}) + (\dot{\$}_{elec} * Elec_{x,pump/motor}) + (\dot{\$}_{fuel} \times Fuel_x)$

2.3 ADDITIONAL CAPABILITIES

2.3.1 Potential Water Savings Calculations

Based on the water balance and estimates of the cost components of the true cost of water, PWP estimates the potential water and associated cost savings from eliminating losses and increasing recirculation rates (e.g., by increasing cycles of concentration for cooling towers and increasing cycles of concentration and condensate return for boilers), as shown in Table 8.

Table 7. Potential water savings calculations.

User Inputs	Calculations
Cooling Tower: Increasing Cycle of Concentration	
E: Evaporation Loss (MGPY) C′: Cycles of Concentration $M_{baseline}$: Baseline Makeup Water (MGPY)	Reduced Makeup Water, $M' = E/(1 - 1/C')$ (MGPY) Makeup Water Savings, $\Delta M = M_{baseline} - M'$ (MGPY)
Boiler: Increasing Cycle of Concentration and Condensate Return	
$M_{baseline}$: Baseline Makeup Water (MGPY) H: Hours of Operation per Year BHP: Boiler Horsepower L:Load as a Fraction of Boiler Horsepower e: Steam Generation Rate (lb/h) per BHP C′: Increased Cycles of Concentration %R′:Increased Condensate Return (%)	Reduced Gross Water Use,$G' = [e/(1 - 1/C')] * BHP * L * 0.002 * H * 60/10^6$ (MGPY) Reduced Makeup Water, $M' = (1 - \%R'/100) * G'$ (MGPY) Makeup Water Savings, $\Delta M = M_{baseline} - M'$ (MGPY)

2.3.2 Comparison with Industry Average

Once a calibrated water flow model is established, normalized indicators to characterize the water use and true cost of water (i.e., per production unit or per production-unit cost) are determined. These indicators are compared with the industry average water data sets, which are obtained from two sources: the EIO-LCA (Economic Input–Output Life Cycle Assessment) (Carnegie Mellon University Green Design Institute, 2018) and the Statistics Canada (STATCAN) database (Statistics Canada, 2018). EIO-LCA estimates the materials and energy resources required and the environmental externalities resulting from several interlinked activities in the economy. PWP uses the water withdrawal data from the EIO-LCA database to create a benchmark for source water intake by a given manufacturing plant within its North American Industry Classification System (NAICS) code. The STATCAN database, based on the Industrial Water Survey conducted every 2 years, provides information on the intake, costs, sources, treatments, and discharge of water used by the industrial sector within Canada. PWP uses the averages and coefficients of variance of water use requested from STATCAN[2] to allow facilities to compare their water intake, gross water use (including water intake and recirculation), and discharge flow with those of peers within similar NAICS codes. This process helps facilities determine how much focus should be placed on water savings measures.

2.3.3 Evaluation of Plant Water Efficiency Status

PWP includes a set of questions about the presence of plant and subsystem-specific water efficiency measures. These questions were formulated based on industry best practices, guides, and publications (New Mexico Office of the State Engineer, 1999; Seneviratne, 2006; Trueblood, Chow, Ritchie, & Ganji, 2015; U.S. EPA, 2011) and can help plant management determine the next steps in implementing water efficiency measures, including management, considering alternative sources, minimizing losses, recirculation, and reuse. Sample questions regarding plant water management and cooling and condensing subsystem are included in Table 9.

Table 8. Example plant and subsystem water efficiency status evaluation questionnaire.

Plant Water Management	Cooling and Condensing Subsystem
1. Is there a formal water management plan at your plant?	1. Has once-through cooling water been eliminated with the use of chillers, cooling towers, or air-cooled equipment?
2. Is there a water management team at your plant?	2. Has blowdown/bleed-off control on cooling towers and boilers been optimized?
3. Is there a formal method of communication in place for employees?	3. Is treated wastewater (or other sources of water for cooling tower makeup) reused where possible?
4. Do you use life-cycle cost analysis for evaluating and selecting water-efficiency projects?	4. Are cycles of concentration for cooling towers maximized through efficient water treatment?
5. Are there economic criteria established for water-efficiency projects (for example, maximum payback period)?	5. Has a conductivity controller been installed on each cooling tower?
6. Does your plant recycle water onsite, for example, in the same process or treated and applied to other processes?	6. Have cooling towers been equipped with overflow alarms?
7. Is the quality of source water matched with the quality required by the use?	7. Have the ball float valves been set correctly?
8. Are measures implemented to minimize or eliminate potable water use for landscape irrigation, dust control, and cooling water?	8. Do condenser water pipes run above the height of the tower spray heads?
9. Are the thermal and chemical requirements of water in various processes and equipment in the plant well-understood?	9. Have maintenance programs been implemented to ensure leaks are routinely checked and fixed as needed?
	10. Are antisplash louvers installed?

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[2] Rao et al. (2017) outlines the similarities and differences between the economies of the United States and Canada and uses Canadian water use data normalized by employment data to make detailed estimates of US manufacturing water use. For PWP, no such adjustments are made.

Plant Water Management	Cooling and Condensing Subsystem
10. Are measures implemented to conserve water by reducing water use? 11. Are measures implemented to conserve both water and energy, for example, recycling warm water rather than heating intake water? 12. Are measures implemented to reduce wastewater as well as toxic waste disposal? 13. Do water and wastewater utilities provide rebates and other financial assistance for implementing water conservation measures? 14. Does your plant pay or have justification to request for reduced wastewater utility rates?	11. Are drift eliminators inspected and assessed by a specialist? 12. Have flow meters been installed on makeup and blowdown lines? 13. Are conductivity meters installed on blowdown lines? 14. Are blowdown lines operated in continuous mode? 15. Has side stream filtration been installed? 16. Has an automatic shutdown unit been installed for the unit? 17. Has sulfuric acid been added to adjust pH? 18. Are high-efficiency drift eliminators in use?

2.3.4 Evaluation of Water-Savings Priorities

PWP helps determine gross water use, quantify unknown losses, and determine the true cost of water for different water-using subsystems in a plant. This helps the user identify subsystems and water flows that are contributing the most to source water intake or the true cost of water and need the most attention, as shown in Figure 4. Accordingly, the user may prioritize measures to align with the company's priority for water savings versus cost savings.

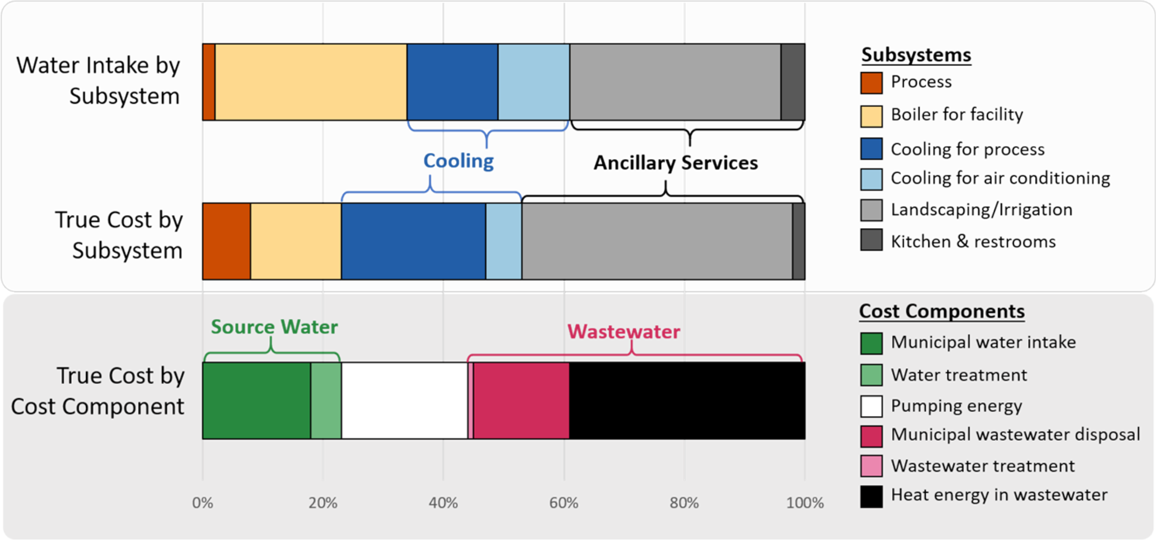


Figure 4. Example of breakdown and comparison of source water intake and true cost.

Measures for water savings would typically include considering alternative process-related methods requiring less water; installation of water efficiency measures; reuse; recycling; minimizing leaks; and water and wastewater treatment to reduce the need for makeup water. Measures for cost savings can additionally include those that may not reduce water use, such considering alternative sources of water, onsite wastewater disposal, and energy-saving measures associated with water using subsystems. The tool may help identifying cost-saving, water-saving, or energy-saving measures independently. Such measures may be conflicting, for instance in the case when water-saving measures imply more water treatment and recirculation, which may lead to higher cost and energy use. The selection of sustainability measures needs to be evaluated by the facility according to their goals.

3. IMPLEMENTATION OF PLANT WATER PROFILER TOOL

Through DOE’s Advanced Manufacturing Office (AMO), ORNL offers support to Better Plants program participants through Water In-Plant Training (Water INPLT) in the form of multi-day workshops performed by industry-recognized experts. The Water INPLT program was developed in line with the INPLT model by Alkadi, Nimbalkar, Fontaine, & Schoeneborn (2013) that includes both classroom and field-based sessions and trains attendees to identify water-saving opportunities, estimate savings, and implement projects (Guo, Wenning, Nimbalkar, Travis, & Levine, 2019). Three pilot trainings have been conducted during the second half of 2019. During these trainings, the PWP tool was used as the core analysis tool for plant water use assessment and true cost calculation. The facilities that benefited from the INPLT were one iron and steel manufacturing plant, one fiberglass manufacturing plant, and one vinyl siding manufacturing plant. The trainings were accompanied by facility inspections in the modality of “treasure hunts,” in which cross-functional teams of employees engaged in the process of identifying operational and maintenance water efficiency improvements. The following sections (3.1 to 3.3) describe for each facility the general water uses, the information that PWP tool can provide at the subsystem disaggregation level, best practices, opportunities identified, and common challenges encountered.

3.1 IRON AND STEEL MANUFACTURING FACILITY

The first pilot Water INPLT training was conducted at an iron and steel manufacturing plant. Due to the large size of the plant, only the cold mill was considered as a feasible plant boundary to analyze during the 2.5-day event. Figure 5 shows the water flows identified across the system boundaries in the cold mill. The main water-using subsystems in the cold mill included processes—a hot dip galvanizing line (HDGL), tandem mill and anneal, and pickle line—two cooling towers subsystems, and a kitchen and restrooms. The source water intake is municipal water, and wastewater disposal (after treatment) is into a river. The water intake to the HDGL is treated by a reverse osmosis (RO) system before use. The wastewater from the processes is treated by an oily wastewater treatment system and a metal removal system before being discharged to the river. The blowdown from cooling towers is directed to a lagoon in the facility boundary that serves as a water recycle system for other parts of the facility.

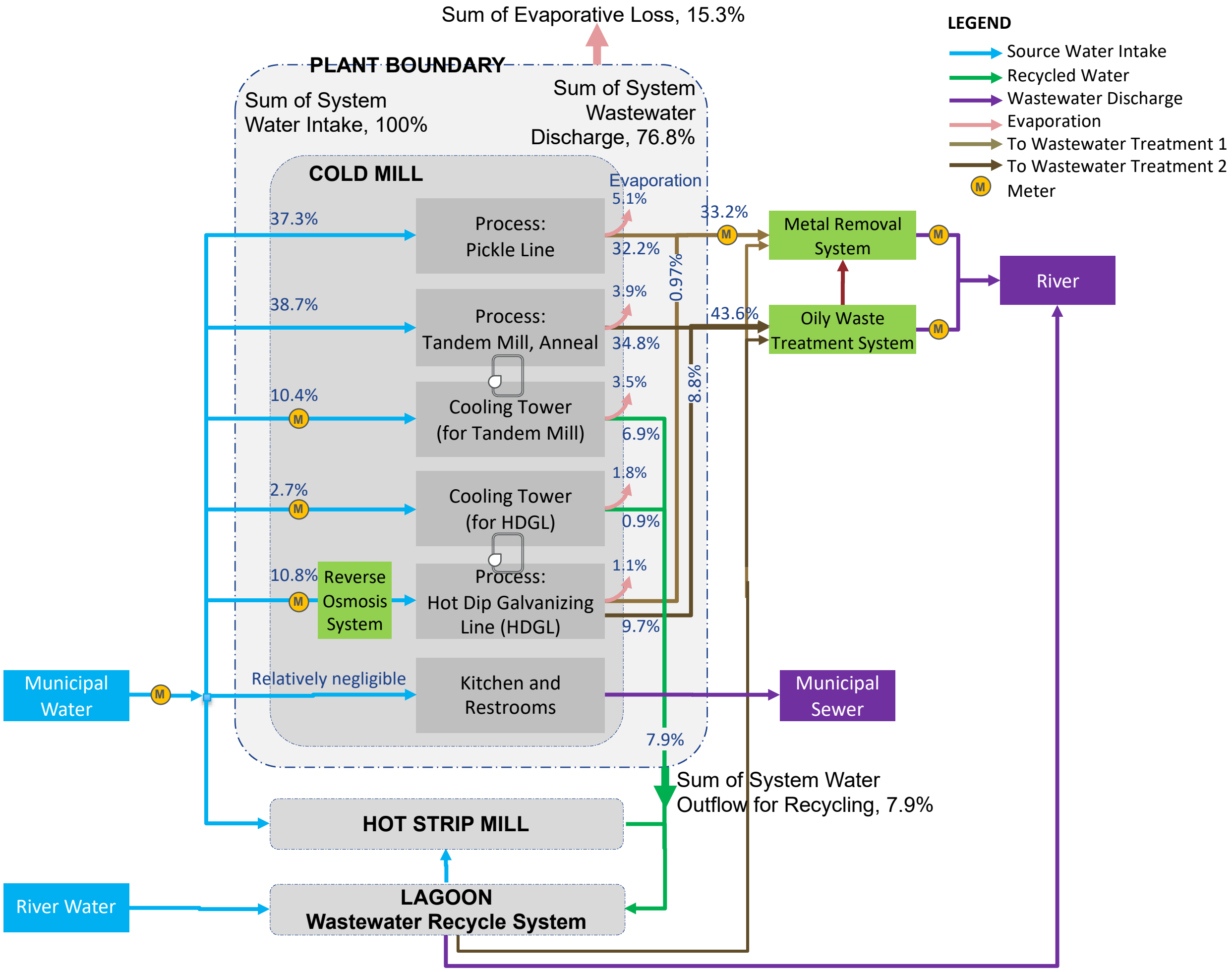


Figure 5. Water flow diagram for the cold mill of an iron and steel manufacturing plant.

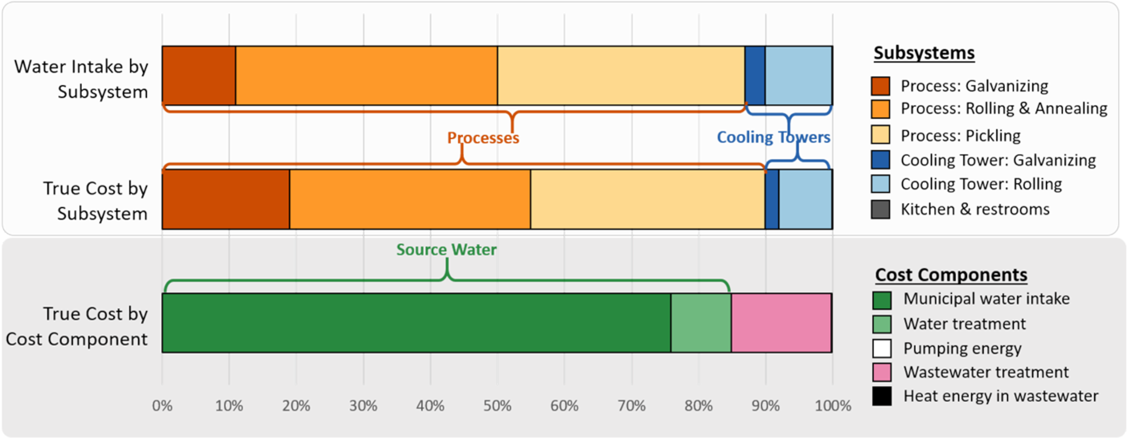
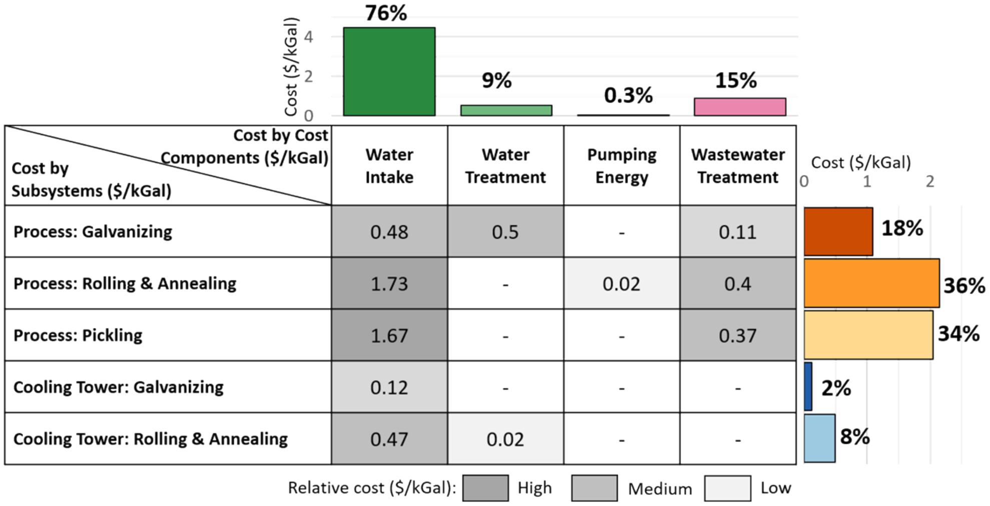


Figure 6 shows the breakdown of source water intake and the true cost of water by subsystems and cost component in the cold mill, as well as the true cost by cost component. Both pickle line and the tandem mill and anneal contribute about 35–40% toward source water intake as well as the true cost of water.

HDGL uses 11% of source water intake but accounts for 19% of the true cost of water.



Cost by Subsystems ($/kGal) \ Cost by Cost Components ($/kGal)	Water Intake	Water Treatment	Pumping Energy	Wastewater Treatment
Process: Galvanizing	0.48	0.5	-	0.11
Process: Rolling & Annealing	1.73	-	0.02	0.4
Process: Pickling	1.67	-	-	0.37
Cooling Tower: Galvanizing	0.12	-	-	-
Cooling Tower: Rolling & Annealing	0.47	0.02	-	-

Figure 7 shows the true cost of water by subsystem and cost components. The true cost components were 76% for municipal water intake, 15% for wastewater treatment, and 9% for water treatment.

Considering only the subsystem-level water flows, the cold mill used 0.12 thousand gallons per million metric ton of production and the true cost of water was $5.88 per thousand gallons, which was 1.32 times the direct cost of water that the facility is billed.

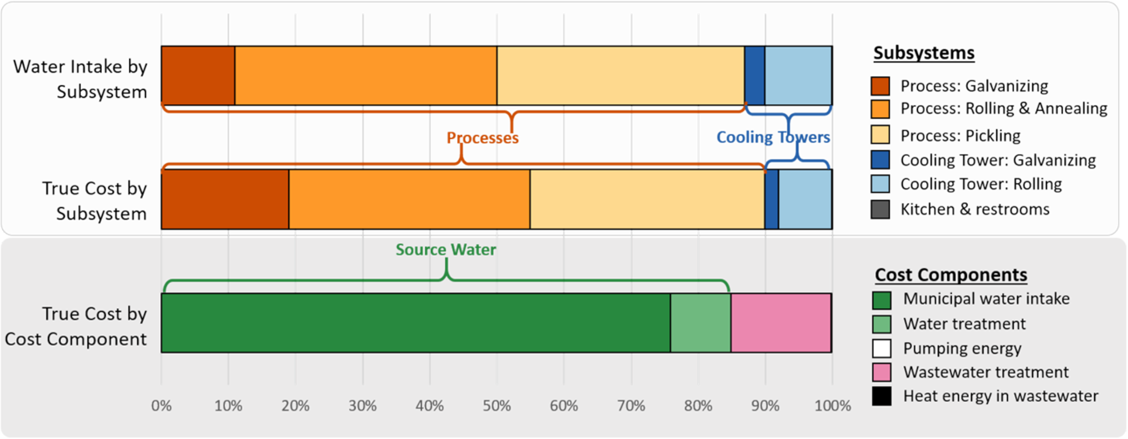
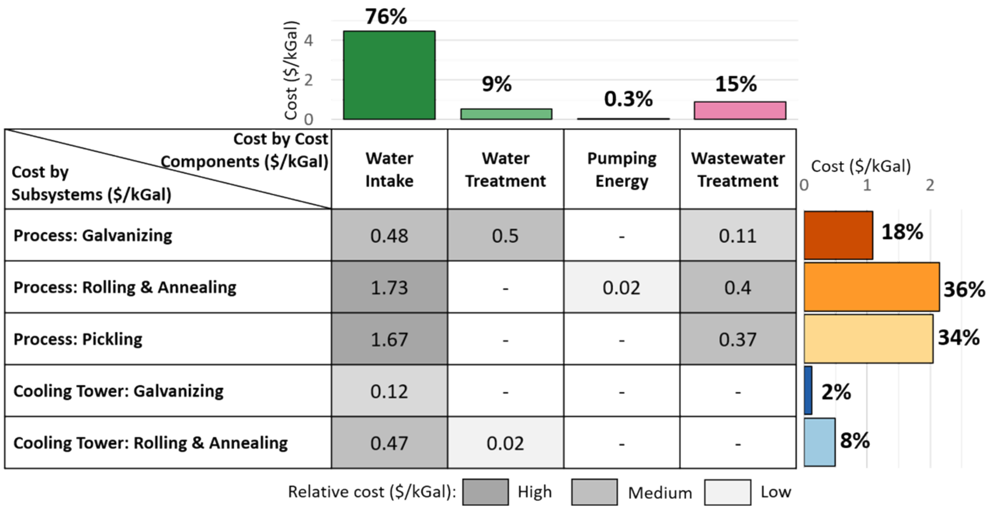


Figure 6. Water use and true cost by subsystem and cost component for the iron and steel manufacturing plant.



Cost by Subsystems ($/kGal) \ Cost by Cost Components ($/kGal)	Water Intake	Water Treatment	Pumping Energy	Wastewater Treatment
Process: Galvanizing	0.48	0.5	-	0.11
Process: Rolling & Annealing	1.73	-	0.02	0.4
Process: Pickling	1.67	-	-	0.37
Cooling Tower: Galvanizing	0.12	-	-	-
Cooling Tower: Rolling & Annealing	0.47	0.02	-	-

Figure 7. True cost of water by subsystem (rows) and by cost components (columns) for the cold mill of the iron and steel manufacturing plant.

The PWP exercise helped the facility identify water-intensive and cost-intensive subsystems at the facility. Based on this, appropriate areas were chosen for optimization and teams were put together to investigate the relevant water end users. The teams identified opportunities for water savings, and with the subsystem-level water flows determined using the PWP tool, the water and true cost savings from implementing these measures was determined. The best practices being followed in these areas were also identified as part of this activity.

The use of flow meters was observed throughout the plant. However, metering a few additional key flows would help. The steam trap management and blowdown recovery were also among the best practices at this plant. The cold mill cooling tower needs investigation and corrective actions in terms of correctly accounting the makeup water. The rolling and annealing and the pickling processes were found to be the most cost-intensive subsystems per unit source water intake, which makes them a potential subsystem for implementing water efficiency measures for a higher return of investment.

The water savings opportunities identified in the cold mill area of the plant included enabling a conductivity-controlled water supply for the cold mill cooling tower, installing a drift eliminator in HDGL cooling tower, and eliminating condensate leaks. With the subsystem-level water flows determined using the PWP tool, the water and true cost savings from implementing these measures was determined.

3.2 FIBERGLASS MANUFACTURING FACILITY

The second pilot Water INPLT training was conducted in a fiberglass manufacturing plant. The water intake source is groundwater. The wastewater from the processes is discharged to an industrial sewer and a domestic sewer. The main water-using subsystems in this plant included processes/subprocesses (e.g., forming spray and binder roller, drain bushing and wash down, chiller and dehumidifier system), a cooling tower, general cleaning and fire protection, and kitchen and restrooms. The forming and binding process requires groundwater treated by reverse osmosis (RO), whereas most of the remaining water-using subsystems require groundwater treated with bleach.

Figure 8 shows the water flows identified across the system boundaries. The water balance using the PWP tool identified subsystem-level and plant-level water imbalances. First, the sum of subsystem-level water intake and that of wastewater discharge were lower than plant-level metered water intake and wastewater discharge, respectively, indicative of unaccounted water use. Further, the plant total metered water intake exceeded the wastewater discharge plus the sum of known evaporative losses, pointing to unknown losses to be identified.

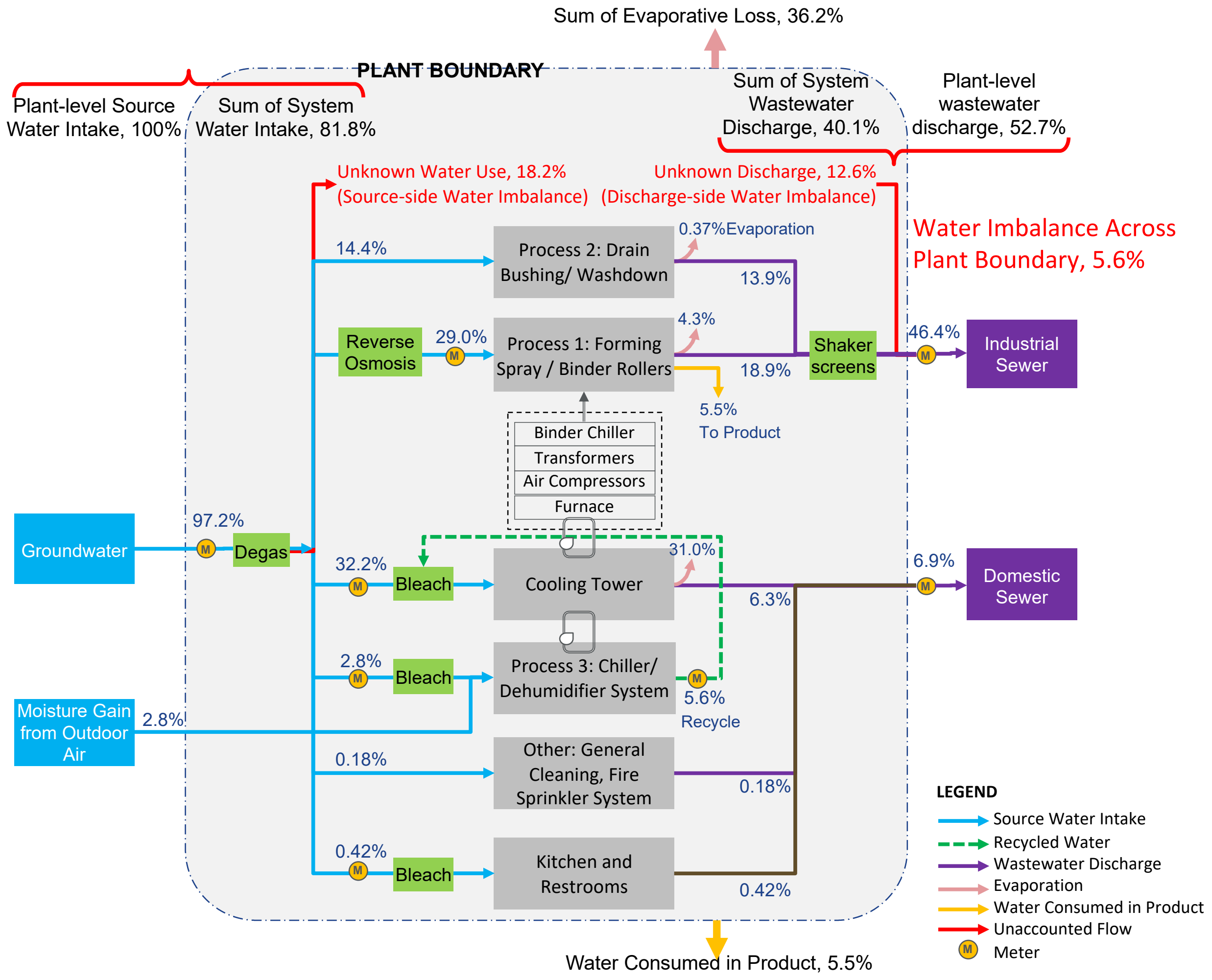


Figure 8. Water flow diagram for a fiberglass manufacturing plant (Pilot Training 2).

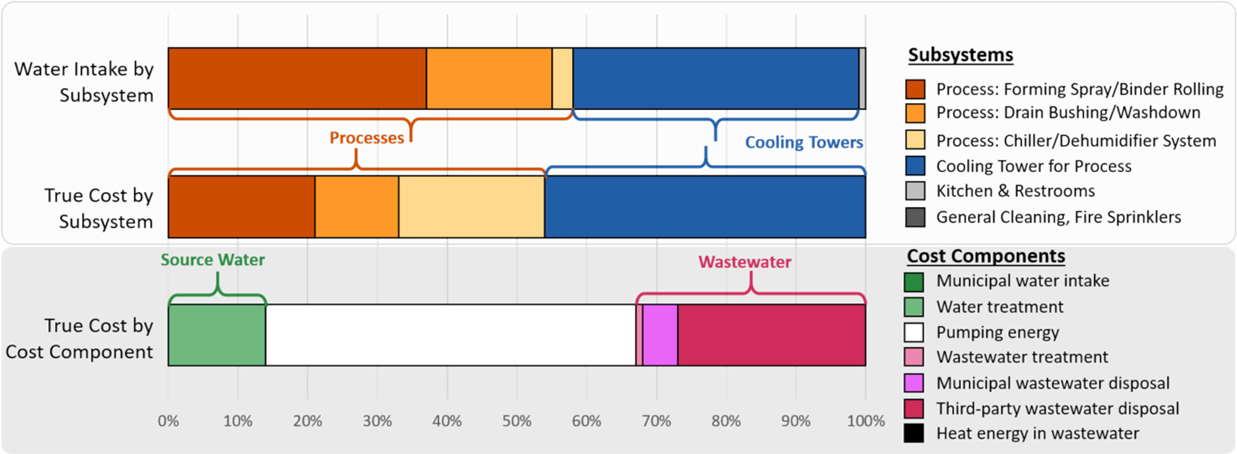
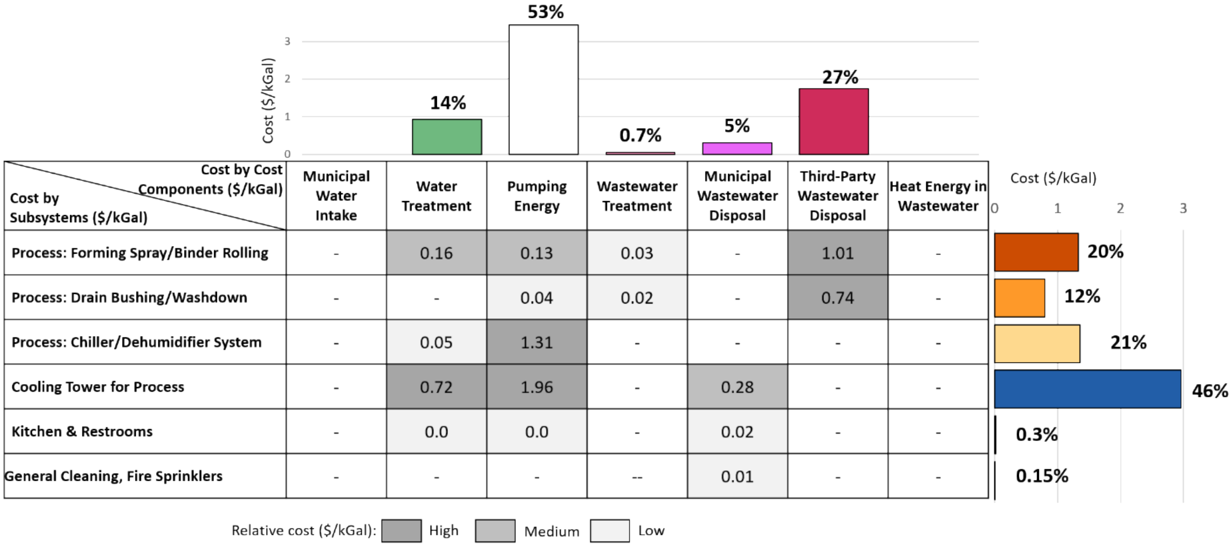


Figure 9 shows the breakdown of source water intake and the true cost of water by subsystems in the plant, as well as the true cost by cost component. The cooling tower contributed the most toward source water intake and the true cost of water (41% and 46%, respectively). The forming spray/binder roller accounted for 37% of source water intake and 21% of true cost of water, whereas the chiller/dehumidifier system with only 3% of source water intake contributed 21% toward the true cost of water.



Cost by Cost Components ($/kGal) / Cost by Subsystems ($/kGal)	Municipal Water Intake	Water Treatment	Pumping Energy	Wastewater Treatment	Municipal Wastewater Disposal	Third-Party Wastewater Disposal	Heat Energy in Wastewater
Process: Forming Spray/Binder Rolling	-	0.16	0.13	0.03	-	1.01	-
Process: Drain Bushing/Washdown	-	-	0.04	0.02	-	0.74	-
Process: Chiller/Dehumidifier System	-	0.05	1.31	-	-	-	-
Cooling Tower for Process	-	0.72	1.96	-	0.28	-	-
Kitchen & Restrooms	-	0.0	0.0	-	0.02	-	-
General Cleaning, Fire Sprinklers	-	-	-	--	0.01	-	-

Figure 10 shows the true cost of water by subsystem and cost components. The largest true cost components were 53% for pump and motor energy followed by 27% for industrial wastewater discharge (marked as third-party disposal) and 14% for water treatment.

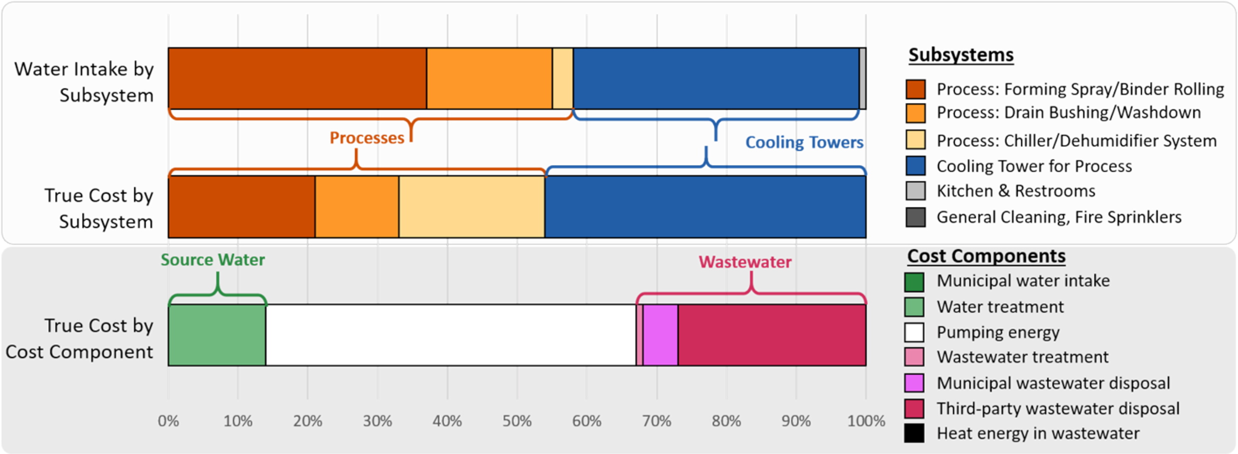
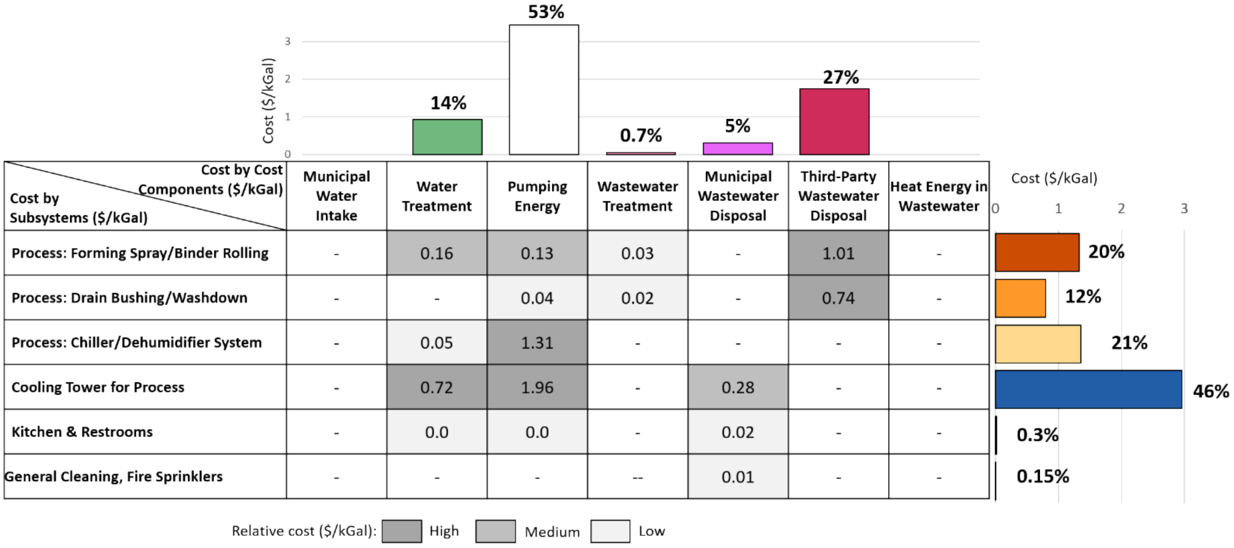


Figure 9. Water use and true cost by subsystem and cost component for the fiberglass manufacturing plant (Pilot Training 2).



Cost by Subsystems ($/kGal) / Cost by Cost Components ($/kGal)	Municipal Water Intake	Water Treatment	Pumping Energy	Wastewater Treatment	Municipal Wastewater Disposal	Third-Party Wastewater Disposal	Heat Energy in Wastewater
Process: Forming Spray/Binder Rolling	-	0.16	0.13	0.03	-	1.01	-
Process: Drain Bushing/Washdown	-	-	0.04	0.02	-	0.74	-
Process: Chiller/Dehumidifier System	-	0.05	1.31	-	-	-	-
Cooling Tower for Process	-	0.72	1.96	-	0.28	-	-
Kitchen & Restrooms	-	0.0	0.0	-	0.02	-	-
General Cleaning, Fire Sprinklers	-	-	-	--	0.01	-	-

Figure 10. True cost of water by subsystem (rows) and by cost components (columns) for the fiberglass manufacturing plant (Pilot Training 2).

Considering only the subsystem-level water flows, the facility used 0.57 thousand gallons per metric ton of production, and the true cost of water was $6.48 per thousand gallons, which was 3.15 times the direct cost of water that the facility sees on its bills.

The PWP exercise helped the facility identify water-intensive and cost-intensive subsystems at the facility. Based on this, appropriate areas were chosen for optimization and teams were put together to investigate the relevant water end users. The teams identified opportunities for water savings, and with the subsystem-level water flows determined using the PWP tool, the water and true cost savings from implementing these measures was determined. The best practices being followed in these areas were also identified as part of this activity.

The use of submetering was observed in the plant. However, submetering additional flows to the process line would help break down and understand the water flows better. The recycling of water from the chiller/dehumidifier system for the cooling tower makeup water was among the best practices followed at this plant. The cooling tower was found to be one of the biggest uses of water and an efficiently operated subsystem. However, pumping energy and recirculation can be reduced with better controls. Awareness regarding the true cost of water can help reduce open blowing.

The water savings opportunities identified at this plant included correcting the water leaks, dehumidifier management according to the season that would result is reduced chiller load; chilled water system optimization by adding variable frequency drives (VFDs) to pumps; adjusting condenser water temperature, and chiller sequencing; and removing spray nozzle used in the production line that were found redundant/ineffective. With the subsystem-level water flows determined using the PWP tool, the water and true cost savings from implementing these measures was determined.

3.3 PILOT TRAINING 3

The third pilot Water INPLT training was conducted in a small size vinyl siding manufacturing plant. The source water intake is municipal water and the wastewater from the facility is discharged to a municipal sewer. The main water uses in this plant were for processes. The water intake in a cooling tower, process cooling loop, and quench tanks requires different water treatments.

Figure 11 shows the water flows identified across the system boundaries. The water balance using the PWP tool identified subsystem-level and plant-level water imbalances. First, the sum of subsystem-level water intake and that of wastewater discharge were slightly higher than plant-level metered water intake and wastewater discharge, respectively. Further, the plant total metered water intake exceeded the wastewater discharge plus the sum of known losses by 7%, pointing to unknown losses to be identified.

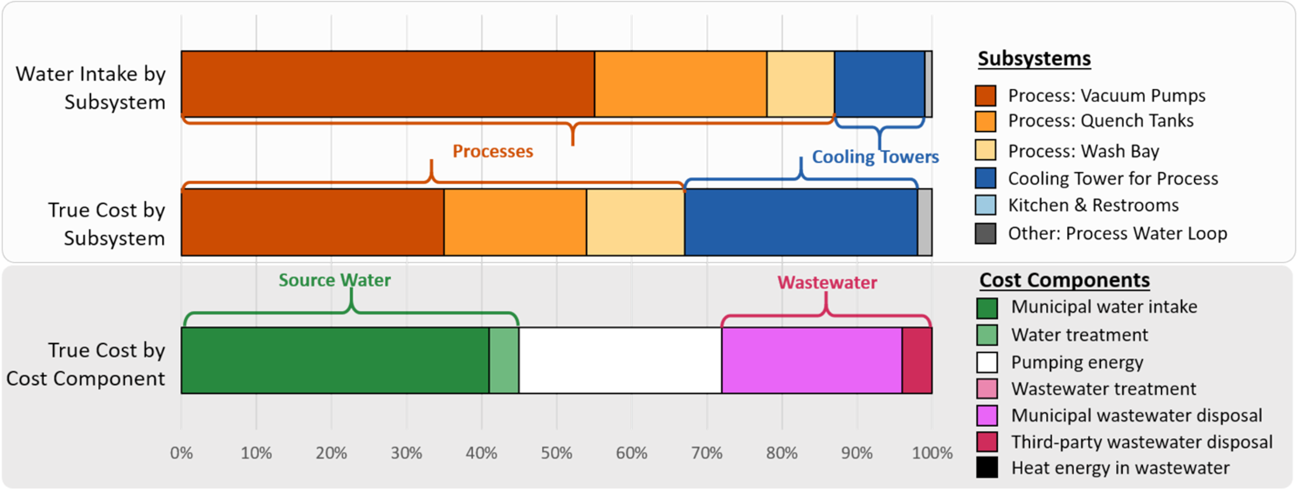
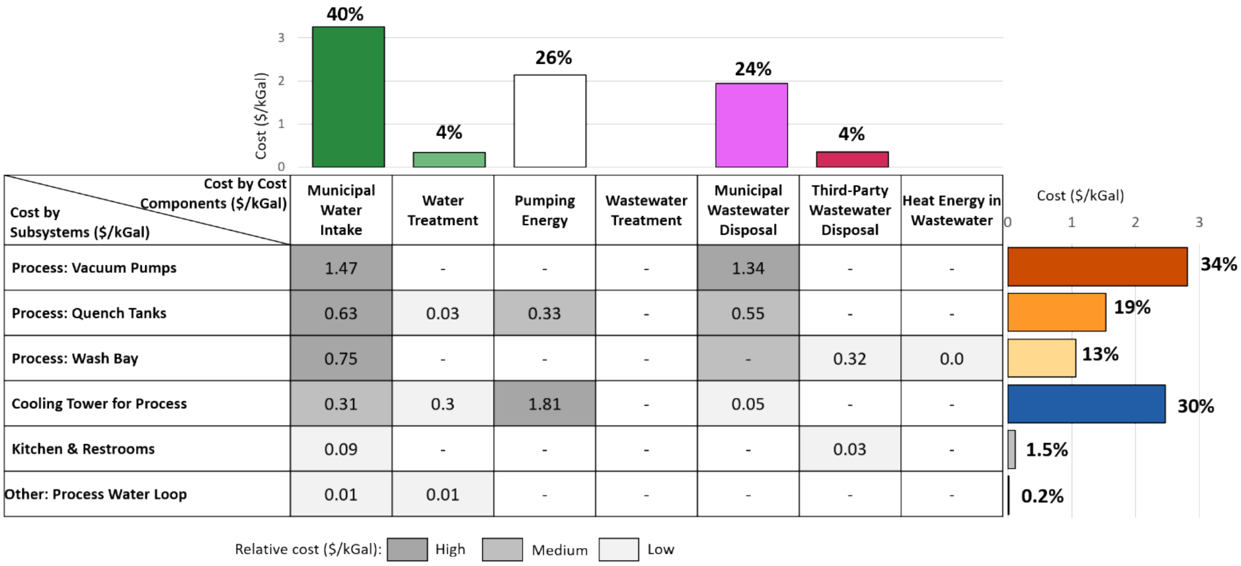


Figure 12 shows the breakdown of source water intake and the true cost of water by subsystems in the plant, as well as the true cost by cost component. The vacuum pumps contribute the most toward source water intake and the true cost of water (55% and 35%, respectively). The cooling tower subsystem with only 12% of source water intake contributed 31% toward the true cost of water. Quench tanks with 23% of source water intake contributed 19% toward the true cost of water.



Cost by Subsystems ($/kGal) / Cost by Cost Components ($/kGal)	Municipal Water Intake	Water Treatment	Pumping Energy	Wastewater Treatment	Municipal Wastewater Disposal	Third-Party Wastewater Disposal	Heat Energy in Wastewater
Process: Vacuum Pumps	1.47	-	-	-	1.34	-	-
Process: Quench Tanks	0.63	0.03	0.33	-	0.55	-	-
Process: Wash Bay	0.75	-	-	-	-	0.32	0.0
Cooling Tower for Process	0.31	0.3	1.81	-	0.05	-	-
Kitchen & Restrooms	0.09	-	-	-	-	0.03	-
Other: Process Water Loop	0.01	0.01	-	-	-	-	-

Figure 13 shows the true cost of water by subsystem and cost components. The largest true cost components were 40% for municipal water intake, 24% for municipal wastewater disposal, and 26% for pump and motor energy.

Considering only the subsystem-level water flows, the facility used 0.33 thousand gallons per 1000 lb production and the true cost of water was $8.01 per thousand gallons, which was 1.45 times the direct cost of water that the facility sees on its bills.

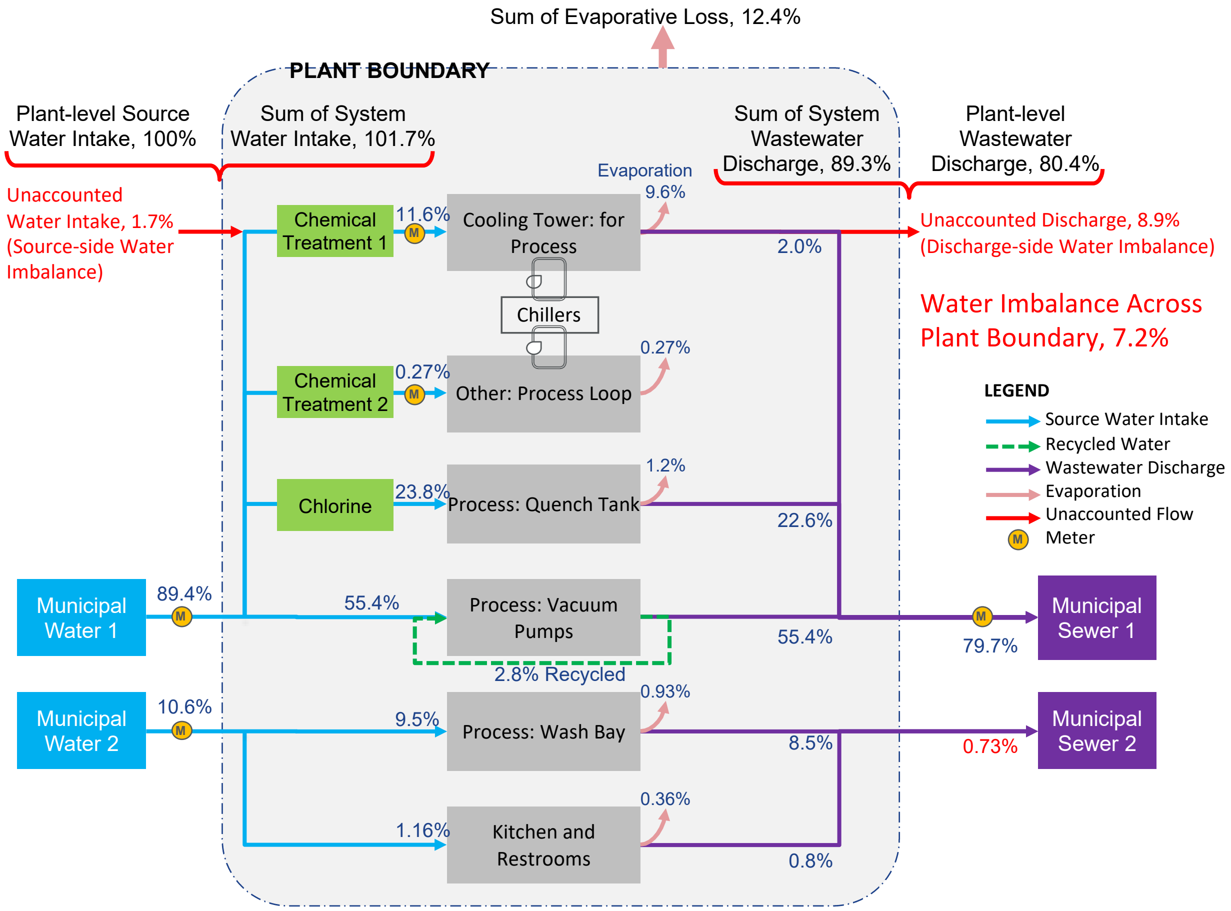


Figure 11. Water flow diagram for a vinyl siding manufacturing plant (Pilot Training 3).

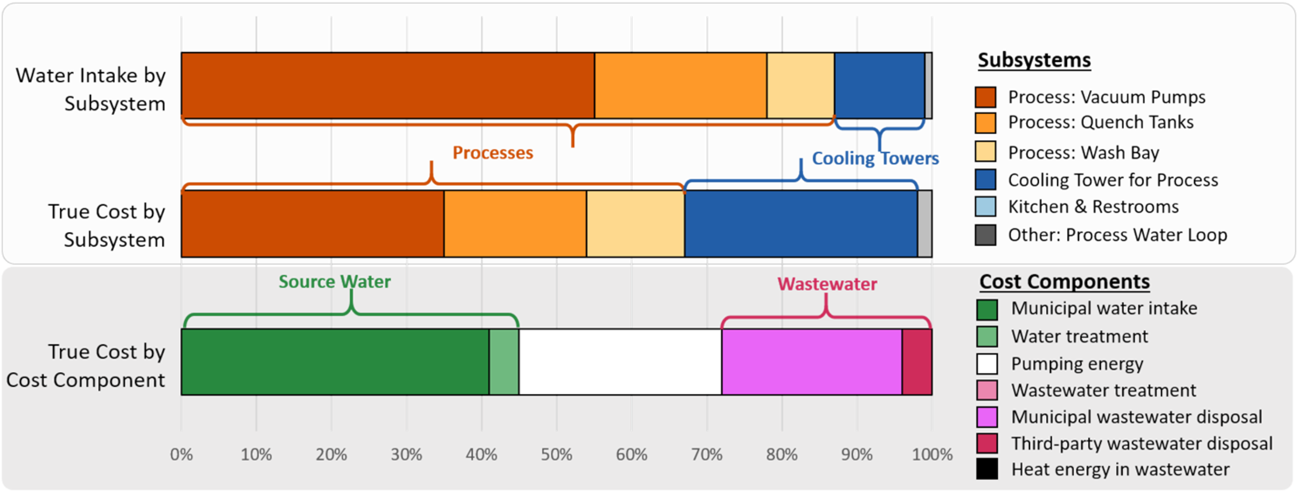
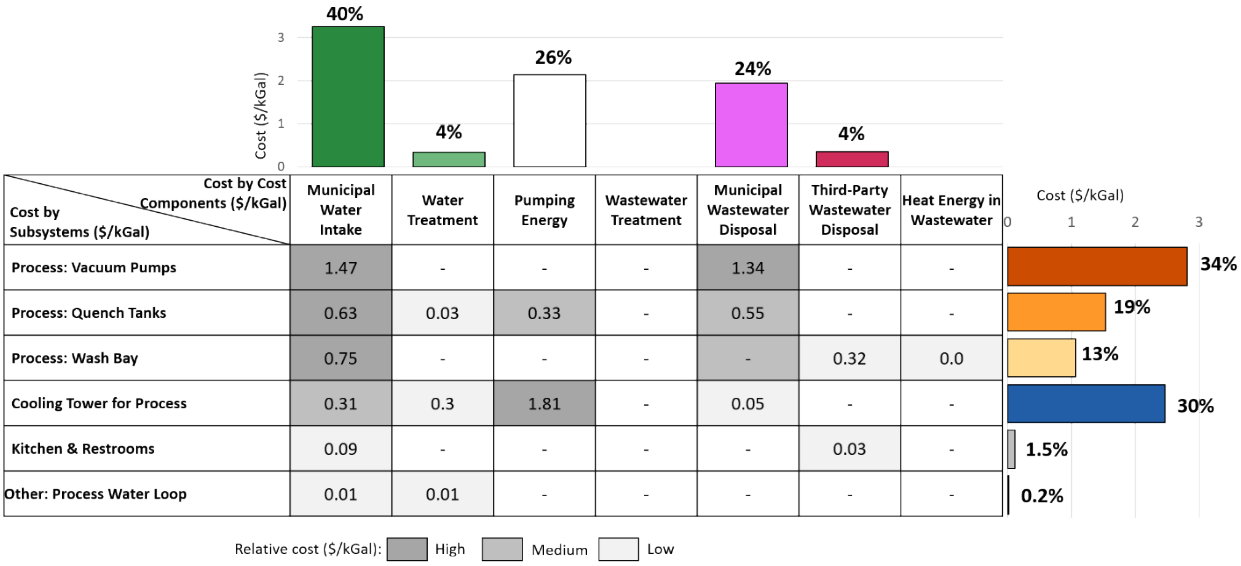


Figure 12. Water use and true cost by subsystem and cost component for the vinyl siding manufacturing plant (Pilot Training 3).



Cost by Subsystems ($/kGal) \ Cost by Cost Components ($/kGal)	Municipal Water Intake	Water Treatment	Pumping Energy	Wastewater Treatment	Municipal Wastewater Disposal	Third-Party Wastewater Disposal	Heat Energy in Wastewater
Process: Vacuum Pumps	1.47	-	-	-	1.34	-	-
Process: Quench Tanks	0.63	0.03	0.33	-	0.55	-	-
Process: Wash Bay	0.75	-	-	-	-	0.32	0.0
Cooling Tower for Process	0.31	0.3	1.81	-	0.05	-	-
Kitchen & Restrooms	0.09	-	-	-	-	0.03	-
Other: Process Water Loop	0.01	0.01	-	-	-	-	-

Figure 13. True cost of water by subsystem (rows) and by cost components (columns) for the vinyl siding manufacturing plant (Pilot Training 3).

The PWP exercise helped the facility identify water-intensive and cost-intensive subsystems at the facility. Based on this, appropriate areas where chosen for optimization and teams were put together to investigate the relevant water end users. The teams identified opportunities for water savings, and with the subsystem-level water flows determined using the PWP tool, the water and true cost savings from implementing these measures was determined. The best practices being followed in these areas were also identified as part of this activity.

Facility-level sustainability targets are being pursued. The use of submetering was observed in the plant. However, submetering production water would help understand water flows better. The cooling tower was found to be operated with high cycles of concentration. The recirculation of water in vacuum pumps system was among the best practices followed at this plant. However, pumping energy for recirculation could be reduced with better controls. Vacuum pumps were found to be the single biggest user of water and the most cost intensive. The second most cost-intensive component was the cooling of process water.

The water savings opportunities identified at this plant included installing automated quench tank water level controller, installing variable speed drives on process pumps, bypassing chiller during winter, installing low flow nozzles in wash bay, and managing leaks in sizer area drips. With the subsystem-level water flows determined using the PWP tool, the water and true cost savings from implementing these measures was determined.

4. DISCUSSION

The PWP tool is a comprehensive tool designed for use by manufacturing plants falling under NAICS (North American Industry Classification System) Codes 31, 32, and 33 to help their sustainability teams (1) understand the procurement, use, and disposal of water in their plants; (2) recognize the "true cost" of water, including the costs associated with water procurement, treatment, and consumption and wastewater disposal; and (3) identify opportunities for reducing water use and achieving associated cost savings.

Water-using subsystems in industrial manufacturing plants include processes, cooling and condensing subsystems for process, power generation, and air-conditioning; steam boilers for power generation; and ancillary services such as kitchen, restrooms, landscaping and irrigation, and fire sprinkler subsystems. The PWP tool, in its Microsoft Excel version (PWPEx), has helped facilities by breaking down the total plant water intake, wastewater disposal, and true cost of water by individual subsystems in the plant. By doing so, it has assisted facilities identifying components that contribute the most toward the facility's true cost of water and the most water-intensive subsystems. Results from the implementation of PWP in a facility can also be used to establish a baseline and track water use during subsequent years.

PWP Tool uses a water mass-balance approach to characterize inflows, outflows, and water flows within the facility. The systematic approach allows the estimation of water losses and potential savings. While the tool allows and encourages the use of high-granularity data, it is well known that there are challenges in submetering water flows in the manufacturing sector. PWP provides a way of estimating water use in case data cannot be collected at the moment of analysis. The use of calculated water uses as opposed to using accurately collected data has its drawbacks and may not allow facilities to properly identify losses and opportunities. Through continuous metering and submetering of water, by using appropriate tools to track water-use variability, and by assessing the water mass balance, facilities can acknowledge opportunities for improvement in the identification of losses from water leaks, increased costs of wastewater treatment due stormwater intrusion, as well as water recirculation opportunities.

The PWP tool assesses the water efficiency status of a plant and its individual subsystems and provides a tailored list of water efficiency measures and opportunities specific to the plant. Thus, the PWP tool is a "first step" that industrial manufacturing plants can follow to minimize their water use and achieve cost savings.

Three Water INPLTs have been conducted in manufacturing facilities in the United States. A summary of these efforts and outcomes is presented in Table 10.

Table 9. Summary of Pilot Water INPLT.

	Pilot Training 1	Pilot Training 2	Pilot Training 3
No. of participants	20	10	11
Industry type	**Iron and Steel**	**Fiberglass**	**Vinyl Siding**
Plant boundary	Cold Mill	Entire plant	Entire plant
Main water using subsystems	Cooling towers, Processes (cooling and washing)	Cooling towers, Process (RO Water), Cleaning	Process, Cooling towers, Cleaning
Intake water source	Municipal water (also, river water for other areas of the plant)	Groundwater	Municipal water
Discharge outlets	River, Onsite Lagoon	Municipal sewer, Industrial sewer	Municipal sewer
Source water use	0.12 kGal per metric ton production	0.57 kGal per metric ton production	0.33 kGal per 1000 lb production
True cost of water	$ 5.88 per kGal (1.32 times direct cost)	$ 6.48 per kGal (3.15 times direct cost)	$ 8.01 per kGal (1.45 times direct cost)

4.1 LESSONS LEARNED FROM VALIDATION EFFORTS

4.1.1 Analysis Approaches and Findings

During the implementation of the PWP tool, ORNL identified several findings and strategies to adapt the tool to different manufacturing sectors, facilities of different sizes, and different production processes such as the following.

1. Processes/production lines that have same water intake sources and discharge outlets can be grouped to simplify data collection and water balancing.

2. A water flow diagram and/or a master table with the identified groups and associated treatment processes help better understand water use and streamline the inputs for the PWP tool (Guidelines and Templates available).

3. For very large facilities, breaking down the plant into areas of manageable sizes and developing associated water flows and PWP models are effective.

4. True cost components are unique to each facility. Facilities with similar production processes can have very different cost components depending on water intake sources, discharge requirements, pumping infrastructure, etc.

5. Some facilities have two separate discharges to the municipality (industrial and domestic) and usually have a different sewer cost; they should be considered separately in the analysis. In some cases, the municipal water intake could also have a separate domestic and industrial use meter, and the cost difference between them could be significant.

6. There is a growing interest in water conservation, and developing a sector-specific PWP tool will be well received.

4.1.2 Data Collection Challenges

The INPLTs at the three facilities described in Section 3 revealed challenges that are pervasive in many manufacturing facilities such as the following.

1. Facilities do not always meter or track self-supplied water from on-site wells, surface water sources, etc.

2. Lack of metering and submetering on the subsystem level makes it difficult to acquire subsystem-level water use.

3. Individual subsystem-level discharges are difficult to meter as they usually drain to the facility outlet by gravity via underground channels which are hard to access.

4. Rainfall-derived infiltration and inflow (RDII) is difficult to estimate and causes errors to water balancing as it is typically drained to the same facility outlet.

5. Finding the right location to install strap-on ultrasonic flow meters for spot measurement is challenging. They require a clean pipe with a straight mounting section with a length at least 20–25 times its diameter and located away from any constriction points for accurate readings.

6. Behavior-driven water consumption (e.g., open spraying) varies significantly between shifts, making it hard to accurately estimate without continuous monitoring.

4.2 OPPORTUNITIES AND FUTURE WORK

There are numerous opportunities for facilities to improve their water efficiency and/or associated costs to reach their sustainability goals or reduce water-related risks. Corporations can benefit from defining clear goals and desired outcomes in any sustainability-related effort. The PWP tool helps facilities examine water use and true cost at the subsystem level and identify areas of greatest opportunities for improvement. Depending on the priorities of each facility, selecting from a list of process improvements with different potential outcomes may be required. For instance, there may be facilities exposed to regional water scarcity that are interested in reducing their intake water and discharges at the expense of increased energy use due to onsite wastewater treatment for recirculation.

The importance of metering and submetering is highlighted throughout this report. Facilities can benefit from creating a water management plan that includes water use at the facility level, including self-supplied water. The submetering of water use for specific processes is also crucial for planning improvements and optimizing resources. In cases where water use data are already being collected, it is important to emphasize the value of adequate data management practices that will allow facilities to extract useful information to make informed decisions.

There are diverse opportunities for facilities to apply advanced technologies for data management that can help optimize resources within a facility. Some of these technologies include advanced water meters, smart water quality sensors, Internet of Things (IoT) technologies that use networks of connected water quality or flow sensors, data aggregation and visualization in dashboards, and supervisory control and data acquisition (SCADA) systems that collect real-time data that allow smart decisions making and improve efficiency.

While there are multiple opportunities to improve water efficiency in a manufacturing facility, this report highlights the importance of the assessment of the true cost of water. The nominal cost paid by facilities to acquire water partially reflects the cost of the using water as a means of production. Measuring all the costs associated with water use can lead to the identification of cost-intensive operations in which optimization of water use can yield significant financial returns.

Future work will focus on the implementation of PWP to a wider variety of manufacturing sectors and tracking the benefits obtained by using the true cost of water as a metric for resource optimization. Additional effort may be made to include indirect costs associated with the true cost of water such as capital costs, permit fees, or even the cost of externalities related to the environmental cost of water use.

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