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Abstract: Over the past decade, many performance indicators have been developed for water utilities to track their system performance. This study proposes a set of normalized and time-integrated benchmarking performance indicators for sustainable long-term management of water distribution and wastewater collection networks. The benchmarking performance indicators are aggregated into three categories: (1) infrastructure, (2) sociopolitical, and (3) financial. To demonstrate the use and value of the benchmarking performance indicators, a system dynamics model is used to present a case study for three water utilities in southern Ontario, Canada. This study shows that the benchmarking performance indicators will allow water utilities with different attributes (such as number of customers, network pipe age profile, pipe material type, network size, and location) to benchmark the long-term variation in their performance with other utilities regionally and nationally. Furthermore, the benchmarking performance indicators can be used to forecast the future behavior of the system to ensure decision-making policies that will drive improvements and best practices. **DOI: 10.1061/(ASCE)WR.1943-5452.0000890.**

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Introduction

Over the past 15 years, many legislators, researchers, and industry practitioners have developed performance indicators for water utilities (Alegre 2006; AWWA 2008). The first step for a utility to benchmark its performance, internally from year to year and additionally to other utilities, is to establish relevant performance indicators (PIs) that are uniformly applicable, understandable, and meaningful to all utilities and decision makers (FCM and NRC 2002). Performance indicators, also referred to as performance measures, are system variables that measure the system effectiveness, reliability, and cost. Berg (2010) defines effectiveness as the extent to which the water utility achieves its targets and efficiency in terms of established standards (state of being efficient).

This study reviews existing performance indicators that water utilities commonly use to benchmark their water distribution (WD) and wastewater collection (WWC) systems within Canada and the United States. It then discusses the limitations of existing performance indicators that impede benchmarking between utilities with reference to a variety of disparate attributes, such as customer base and their associated consumption and conservation behavior, size and distribution of the network, inventory of pipe material types and age profiles, and financial strategies to balance revenue with expenses. The objective of this work is to introduce benchmarking performance indicators (BPIs) that normalize these attributes and enable effective benchmarking between utilities regardless of the utility scale. These BPIs can be used to help water utilities identify data required for a performance comparison, understand the strengths and weakness of their past and current performance, and forecast their future performance over the lifecycle of the infrastructure. These BPIs conform to the established and ubiquitous concepts of strategic targets, policy levers, sustainability, and lifecycle. Furthermore, they are organized into three categories: infrastructure, sociopolitical, and financial.

The merits of the BPIs are illustrated using data and parameters from the water distribution systems of three water utilities within southern Ontario, with 100-year infrastructure lifecycle forecasts obtained from (but not limited to the use of) the Rehan et al. (2013, 2015) system dynamics models. The results demonstrate the virtue of normalizing attributes from the infrastructure, sociopolitical, and financial sectors to enable effective benchmarking between utilities and to understand the complexity of these systems. Additionally, these results show how forecasting these BPIs enables a utility to demonstrate compliance with strategic targets and policy levers, and demonstrate long-term sustainability over the lifecycle of the infrastructure system.

Literature Review

Previous benchmarking frameworks, initiatives, and PIs have been developed worldwide to enable utilities to track their performance, identify data gaps, and prioritize areas for improvement (FCM and NRC 2002; Alegre 2006; MPMP 2007; AWWA 2008; USEPA 2008; OMBI 2012; OFWAT 2013; Danilenko et al. 2014; AECOM 2015). This section presents a review of benchmarking initiatives and PIs for water infrastructure in Canada and the United States,

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with a focus on those that pertain to water distribution and wastewater collection systems.

The National Water and Wastewater Benchmarking Initiative (NWWBI) was established in 1997 (AECOM 2015) to address the need of Canadian municipalities to measure, monitor, and benchmark their water utility performance. The focus of the NWWBI is on water treatment and distribution systems, wastewater collection and treatment systems, and stormwater management systems. The outcome of the NWWBI is to enable member utilities to identify opportunities for improvements and best practices (AECOM 2015). Table 1 itemizes a brief selection of NWWBI performance indicators that are relevant to water distribution and wastewater collection systems. While some of the PIs are normalized, others are not. Even those that are normalized, such as total operating and maintenance cost per kilometer length of pipe, are simply instantaneous measures of system performance. They do not directly denote time and hence without modification do not facilitate a utility to demonstrate long-term sustainability over the lifecycle of the infrastructure system. Additionally, a utility with greater urban densification resulting in more individuals accessing a given kilometer of pipe relative to another utility with a greater degree of urban sprawl may have identical values of total operating and maintenance cost per kilometer length of pipe. However, their performance could not be construed as being equivalent. Omission of population within the performance indicator does not give it clear meaning.

The Ontario Municipal Benchmarking Initiative (OMBI) measures, benchmarks, and shares the performance data and operational practices of 15 municipalities across 37 service areas (OMBI 2012). Two of their objectives for using performance indicators are to determine (1) efficient and effective water distribution and wastewater collection practices; and (2) maintenance of adequate capacity for existing communities and future developments. Table 1 itemizes three OMBI indicators. Note the overlap between the total cost of water distribution and wastewater collection per kilometer of pipe and the first NWWBI performance indicator listed on the same table. Clearly the same issues identified previously apply.

The Municipal Performance Measurement Program (MPMP) was developed by the Ontario Ministry of Municipal Affairs and Housing to enable Ontario utilities to report their annual

Table 1. Selected Performance Indicators

Initiative	Performance indicator	What it measures	Unit	Normalized
National Water and Wastewater Benchmarking Initiative (AECOM 2015)	Total operating and maintenance cost per kilometer length of pipe	Cost effectiveness	\$/km	Yes
	Number (#) of water- and wastewater-related customer complaints per 1,000 people served	Customer satisfaction	Number of complaints per capita	Yes
	Nonrevenue water in liters per service connection (sc) per day	System management, condition, and reliability	L/sc/day	Yes
	Percent of inoperable or leaking valves	System reliability	%	Yes
	5-year running average capital reinvestment replacement value	Level of infrastructure reinvestment	\$	No
	Percent of main length replaced	Level of infrastructure reinvestment	%	Yes
Ontario Municipal Benchmarking Initiative (2012)	Total cost of water distribution and wastewater collection per kilometer of pipe	Cost efficiency	\$/km	Yes
	Megaliters of treated water per 100,000 population	Service level	ML/capita	Yes
	Average age of water or wastewater pipe	Customer service	Years	Yes
Municipal Performance Measurement Program (2007)	Operation costs per kilometer of wastewater or water main	Operating costs efficiency	\$/km	Yes
American Water Works Association (Lafferty and Lauer 2005)	Operations and maintenance cost ratio	Ratio between the cost of operations and maintenance and number of accounts per millions of gallons of produced water	\$/account/m^3	Yes
	Distribution system water loss	Unaccounted water	m^3	No
	Return on assets	Financial effectiveness of the utility	\$	No
	Residential cost of water service	Average residential water bill amount for 1 month of service	\$/account	Yes
Water Research Foundation (2014)	Weighted average age of water or wastewater pipe	Infrastructure stability	Years	Yes
	Level of asset condition information	Infrastructure stability	—	No
	Extent to which the critical assets are identified	Infrastructure stability	—	No
	Appropriateness of balance of capital spending between debt and equity expenditures	Financial viability	%	Yes
	Per capita consumption	Water resource adequacy	gpcd, lpcd	Yes
	Water service affordability	Community sustainability	%	Yes

Note: gpcd = gallons per capita per day; lpcd = liters per capita per day.

performance data in the Financial Information Return (MPMP 2007). Table 1 provides MPMP indicator operation costs per kilometer of wastewater and water main operating to measure a network's operating costs efficiency. Effective January 1, 2015, the reporting requirement of Financial Information Return data ceased. The Ontario Ministry of Municipal Affairs and Housing still encourages municipalities to independently report their performance data to the public to demonstrate service improvement (MPMP 2015).

The American Water Works Association (AWWA) introduced the first version of the Utility Quality Service Program in 2003, which is now known as QualServ (Lafferty and Lauer 2005). QualServ contains PIs for the organizational development, customer relations, business operations, and water operations of water utilities (AWWA 2008). Table 1 provides four QualServ PIs that demonstrate attributes relevant to the infrastructure, financial, and sociopolitical sectors of all utilities. For instance, the operations and maintenance cost ratio further normalizes cost to the number of customer accounts and treated water. However, it does not normalize relative to the length of network. Other PIs such as the distribution system water loss remain nonnormalized.

The Water Research Foundation (WRF) developed a Microsoft *Excel*-based benchmarking tool to effectively manage water utilities (WRF 2014). The WRF benchmarking approach identifies primer practice areas to support the 10 attributes within the U.S. EPA's Effective Utility Management (WRF 2014): (1) product quality, (2) customer satisfaction, (3) employee and leadership development, (4) operational optimization, (5) financial viability, (6) infrastructure stability, (7) operational resiliency, (8) community sustainability, (9) water resource adequacy, and (10) stakeholder understanding and support. Furthermore, it improves the various QualServ business systems areas and their associated metrics. The WRF benchmarking tool enables water utilities to assess their own performance but does not provide cross-utility comparisons (WRF 2014). In keeping with this work, there is an intent to quantify concepts of strategic targets, policy levers, sustainability, and lifecycle. However, the methodology is not strongly articulated in the PIs itemized in Table 1.

Development of Benchmarking Performance Indicators for Water and Wastewater Pipelines

To address the shortcomings of the existing performance indicators reviewed previously, this section introduces BPIs to further enable water utilities to compare and contrast their performance against one another, and against their own strategic targets. Strategic targets are global assessments of abstract goals or ideals (FCM and NRC 2002), such as revenues equal expenses, or a more concrete rehabilitate 1% of the network's length every year. Fig. 1 illustrates the proposed framework for developing and organizing the benchmarking performance indicators. The framework conforms to the concepts of strategic targets, policy levers, sustainability, and lifecycle. Next, the performance indicators are grouped into three categories including (1) infrastructure, (2) sociopolitical, and (3) financial. These performance indicators are normalized to facilitate the comparison of water utilities' performance regardless of their scale (large, medium, or small).

Table 2 provides a detailed description of the key variables that are used to develop the benchmarking performance indicators shown in Fig. 1. Unlike existing PIs, all variables are time-varying to facilitate forecasting the BPIs over the asset lifecycle. Those denoted as $x(t)$ track system behavior instantaneously at time t, while those denoted as $X(T)$ are time-integrated, as noted in Eq. (1), to capture aggregate system behavior over the benchmarking period T

$$X(T) = \sum_{t=0}^{T} x(t) \tag{1}$$

where T = term of benchmarking period in years (and is representative of the lifecycle of the asset); and t = time with constraint of $0 \leq t \leq T$.

Aggregate system behavior is used to capture the sum of all actions taken by the utility to manage the infrastructure over T. The benchmarking period (T) can be the system's lifecycle, i.e., 50–100 years, or the typical budget period of 5–10 years. Key variables from Table 2 are then normalized within and across the infrastructure, sociopolitical, and financial sectors to generate the BPIs in Tables 3–5. These BPIs can then be used to explicate the complex interactions and feedback loops that exist among the sectors, and to facilitate the comparison of water utilities' performance regardless of their scale (small, medium, or large). Additionally, the BPIs can be used to forecast future behavior of the system by time integration over the benchmarking period. This enables a utility to determine long-term solutions that achieve sustainable performance targets and objectives.

Infrastructure Performance Indicators

Benchmarking performance indicators specific to the WD and WWC infrastructure are itemized in Table 3. Infrastructure efficiency and infrastructure density are the ratio of the network length to population and service area, respectively. Infrastructure backlog and infrastructure condition efficiency focus on the total length of WD and WWC pipes that have exceeded their design life $\mathbb{D}$ for WD or alternatively are in the worst internal condition grade for WWC. The rehabilitation efficiency is a ratio of the actual rehabilitation rate to target rehabilitation. The target rehabilitation rate (or preferred rehabilitation rate) is considered as a policy lever in the Rehan et al. (2014, 2015) models. Finally, the last two BPIs in Table 3 are the ratio of water loss for WD or inflow and infiltration for WWC, normalized by the network length, population served, and benchmarking period.

Sociopolitical Performance Indicators

Benchmarking performance indicators specific to the sociopolitical sector are itemized in Table 4. The fee hike ratio measures the ratio of the actual to the allowable fee hike rates on the variable unit cost of water or wastewater, with the allowable fee hike rate being a policy lever in the Rehan et al. (2014, 2015) models. The rest of the BPIs presented in Table 4 relate to the balance of water within the distribution and collection network between the water and wastewater treatment plants, with metered water indicating the consumption behavior of residents over the benchmarking period, as presented in Eq. (2) for WD and Eq. (3) for WWC

$$MW(T) = SW(T) - WL(T) \tag{2}$$

where MW = metered water; SW = supplied water; and WL = water loss.

$$MW(T) = WWT(T) - I\,\&\,I(T) + NCW(T) \tag{3}$$

where WWT = wastewater treated; $I\,\&\,I$ = inflow and infiltration; and NCW = nonconsumptive water. Nonconsumptive water is the volume of water received by consumers but not returned to the wastewater collect system—e.g., metered water used for lawn and garden irrigation, evaporated from pools, or vehicle washing.

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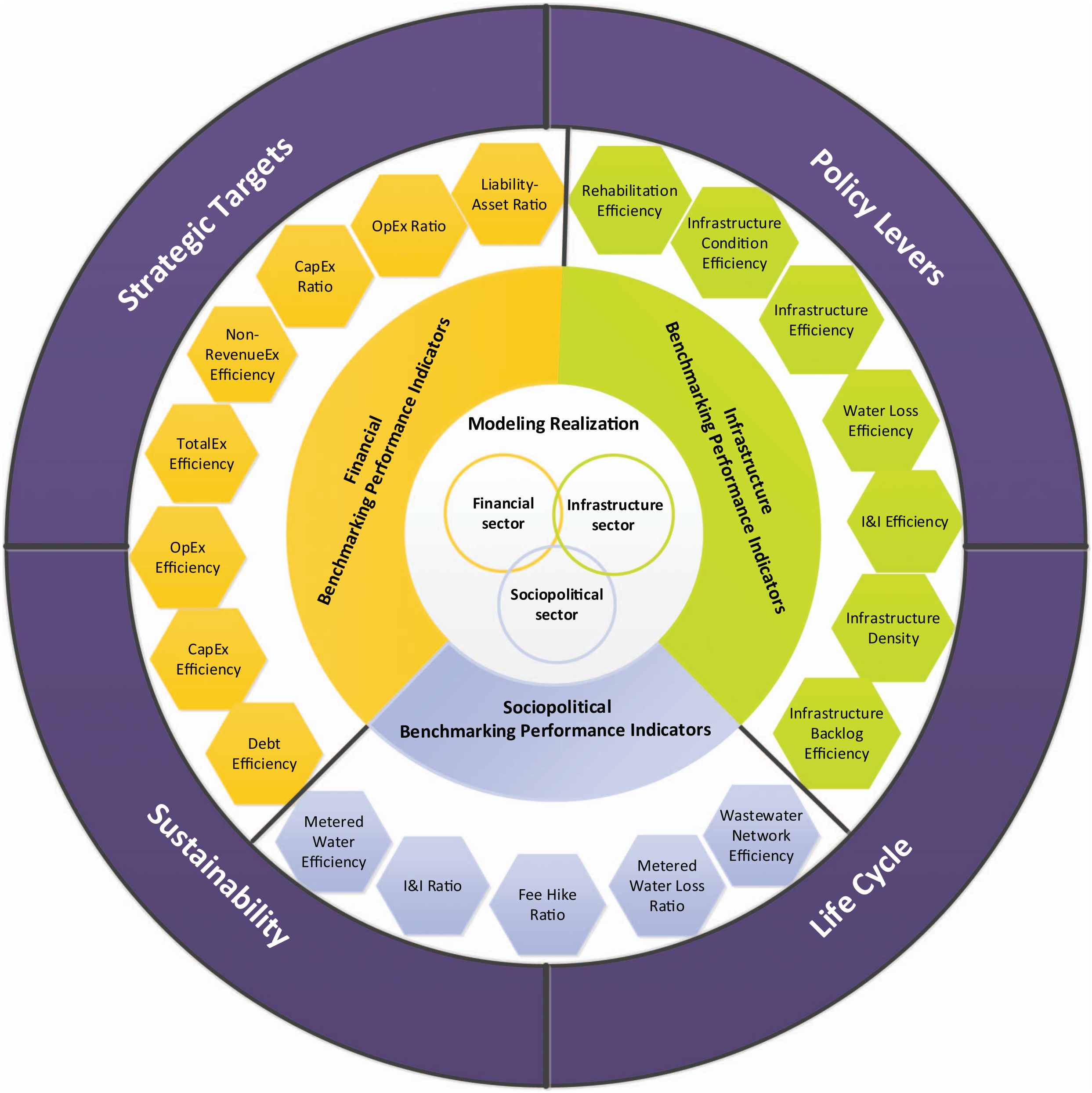

Fig. 1. (Color) Framework of the benchmarking performance indicators for water and wastewater pipelines infrastructure

An increase in the water user fee will lead to a decrease in the average daily water demand per capita per day due to price elasticity of demand. Conservation of metered water may not be transmitted to the water treatment plants (as SW) or wastewater treatment plants (as WWT) depending on the condition of the network. Sustainability would minimize WL, $I\,\&\,I$, and NCW over the lifecycle of the infrastructure.

Financial Performance Indicators

Benchmarking performance indicators specific to the financial sector are itemized in Table 5. The first 10 of the 13 BPIs are organized in terms of expenses generated by either the WD or WWC subcategories. Those that relate to WD are normalized by $SW(T)$, while those that relate to WWC are normalized by $WWT(T)$. Given that revenue is generated by metered water and given the need for the utility to balance revenues with expenses, either one could be normalized by $MW(T)$ with appropriate adjustment by metered water efficiency or wastewater network efficiency. All of these BPIs are further normalized by the length of the network and the population served.

The liability asset ratio BPI is quantified in terms of valuations pertinent to WD and WWC: debt, fund balance, cash reserve, cash required to rehabilitate or replace pipes that reached their design life, and network asset value. The last two BPIs in Table 5 are the ratio of capital, as well as operational expenditures to revenue generated by either WD or WWC.

Water Distribution Network Benchmarking Demonstration

A subset of the proposed BPIs is used to benchmark and forecast the future performance behavior of the water distribution networks

Table 2. Key Variables for Constructing Benchmarking Performance Indicators

Variable	Unit	Benchmarking calculation	Unit
Fee hike, $FH(t)$	%	—	—
Rehabilitation rate, $Rr(t)$	%	—	—
Network condition, $NC(t)$	ICG for WWC Year for WD	—	—
Population, $P(t)$	capita	$\bar{P}(T) = \sum_{t=1}^{T} P(t) \times \frac{\Delta t}{T}$	capita
Network length, $NL(t)$	m	$\overline{NL}(T) = \sum_{t=1}^{T} NL(t) \times \frac{\Delta t}{T}$	m
Fund balance, $FB(t)$	\$	$FB(T) = \sum_{t=0}^{T} FB(t)$	\$
Debt, $D(t)$	\$	$D(T) = \sum_{t=0}^{T} D(t)$	\$
Capital reserve, $CR(t)$	\$	$CR(T) = \sum_{t=0}^{T} CR(t)$	\$
Network asset value, $NAV(t)$	\$	$NAV(T) = \sum_{t=0}^{T} NAV(t)$	\$
Wastewater treated, $WWT(t)$	$\frac{m^3}{day}$	$WWT(T) = \sum_{t=0}^{T} W\dot{W}T(t) \times \Delta t$	m^3
Supplied water, $SW(t)$	$\frac{m^3}{day}$	$SW(T) = \sum_{t=0}^{T} S\dot{W}(t) \times \Delta t$	m^3
Metered water, $MW(t)$	$\frac{m^3}{day}$	$MW(T) = \sum_{t=0}^{T} M\dot{W}(t) \times \Delta t$	m^3
Water loss, $WL(t)$	$\frac{m^3}{day}$	$WL(T) = \sum_{t=0}^{T} \dot{W}L(t) \times \Delta t$	m^3
Inflow and infiltration, $I\,\&\,I(t)$	$\frac{m^3}{day}$	$I\,\&\,I(T) = \sum_{t=0}^{T} I\,\dot{\&}\,I(t) \times \Delta t$	m^3
Revenue, $RV(t)$	$\frac{\$}{year}$	$RV(T) = \sum_{t=0}^{T} R\dot{V}(t) \times \Delta t$	\$
Total expenditures, $TotalEx(t)$	$\frac{\$}{year}$	$TotalEx(T) = \sum_{t=0}^{T} Tot\dot{a}lEx(t) \times \Delta t$	\$
Inflow and infiltration expenditures, $I\,\&\,IEx(t)$	$\frac{\$}{year}$	$I\,\&\,IEx(T) = \sum_{t=0}^{T} I\,\&\,\dot{I}Ex(t) \times \Delta t$	\$
Water loss expenditures, $WLEx(t)$	$\frac{\$}{year}$	$WLEx(T) = \sum_{t=0}^{T} W\dot{L}Ex(t) \times \Delta t$	\$
Capital expenditures, $CapEx(t)$	$\frac{\$}{year}$	$CapEx(T) = \sum_{t=0}^{T} Ca\dot{p}Ex(t) \times \Delta t$	\$
Operational expenditures, $OpEx(t)$	$\frac{\$}{year}$	$OpEx(T) = \sum_{t=0}^{T} O\dot{p}Ex(t) \times \Delta t$	\$
Maintenance expenditures, $MaintEx(t)$	$\frac{\$}{year}$	$MaintEx(T) = \sum_{t=0}^{T} Ma\dot{i}ntEx(t) \times \Delta t$	\$
Interest expenditures, $IntEx(t)$	$\frac{\$}{year}$	$IntEx(T) = \sum_{t=0}^{T} In\dot{t}Ex(t) \times \Delta t$	\$
Wastewater treated expenditures, $WWTEx(t)$	$\frac{\$}{year}$	$WWTEx(T) = \sum_{t=0}^{T} W\dot{W}TEx(t) \times \Delta t$	\$
Supplied water expenditures, $SWEx(t)$	$\frac{\$}{year}$	$SWEx(T) = \sum_{t=0}^{T} S\dot{W}Ex(t) \times \Delta t$	\$
Metered water expenditures, $MWEx(t)$	$\frac{\$}{year}$	$MWEx(T) = \sum_{t=0}^{T} M\dot{W}Ex(t) \times \Delta t$	\$

Note: ICG = internal condition grade; T = benchmarking period in years; t = time; WD = water distribution; WWC = wastewater collection; Δt = time step.

for three water utilities in Ontario, Canada (arbitrarily called X, Y, and Z). The Rehan et al. (2013) system dynamics model for water distribution networks is used to forecast the future performance of each utility. The system dynamics model is a mathematical realization of the developed interactions among system variables over time and is comprised of three sectors, namely, water mains network, consumer, and finance. This is the first known development of a water distribution network system dynamics model. The water mains network sector accounts for the unique characteristics of water main pipes such as service life, deterioration progression, pipe breaks, and water leakage. The finance sector allows for cash reserving by the utility in addition to the pay-as-you-go and borrowing strategies. The consumer sector includes controls to model water fee growth as a function of service performance and a household's financial burden due to water fees. A series of policy levers is provided that allows the impact of various financing strategies to be evaluated in terms of financial sustainability and household affordability. The model also allows for examination of the impact of different management strategies on the water fee in terms of consistency and stability over time.

Table 3. Infrastructure Performance Indicators

Sector	Benchmarking performance indicator	Description	Calculation	Unit
WD and WWC	Infrastructure efficiency	Total network length (NL) divided by population (P) served by utility.	$\frac{\sum_i NL(t)}{P(t)}$	m/capita
WD and WWC	Infrastructure density	Total network length divided by utility serviced area (A).	$\frac{\sum_i NL(t)}{A(t)}$	m/m^2
WD	Infrastructure backlog efficiency	Length of pipes over design life ($\mathbb{D}$) divided by total network length.	$\frac{\sum_{NL>\mathbb{D}, i} NL(t)}{\sum_i NL(t)}$	m/m
WD	Infrastructure condition efficiency	Length of pipes over design life ($\mathbb{D}$) divided by population served by utility.	$\frac{\sum_{NL>\mathbb{D}, i} NL(t)}{P(t)}$	m/capita
WWC	Infrastructure backlog efficiency	Length of pipes in internal condition grade five (ICG5) divided by total network length.	$\frac{\sum_{\mathrm{ICG5}i} NL(t)}{\sum_i NL(t)}$	m/m
WWC	Infrastructure condition efficiency	Length of ICG 5 pipes divided by population served by utility.	$\frac{\sum_{\mathrm{ICG5}i} NL(t)}{P(t)}$	m/capita
WD and WWC	Rehabilitation efficiency	Percentage of actual rehabilitation rate (Rr) to target rehabilitation rate per year.	$\frac{\text{Actual } Rr(t)}{\text{Target } Rr(t)} \times 100$	%/year
WD	Water loss efficiency	Water loss (WL) divided by total network length per population served by utility over the benchmarking period.	$WL(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T) \div T$	m^3/m/capita/year or L/m/capita/year or ML/m/capita/year
WWC	Inflow and infiltration efficiency	Total volume of inflow and infiltration (I & I) divided by total network length per population served by utility over the benchmarking period.	$I\,\&\,I(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T) \div T$	m^3/m/capita/year or L/m/capita/year or ML/m/capita/year

Note: A = service area covered by a water utility; a = water main age; i = type of pipe material; ICG = internal condition grade.

Table 4. Sociopolitical Performance Indicators

Sector	Benchmarking performance indicator	Description	Calculation	Unit
WD and WWC	Fee hike ratio	Percentage of current fee hike (FH) to allowable fee hike per year.	$\frac{\text{Current } FH(t)}{\text{Allowable } FH(t)} \times 100$	%/year
WD	Metered water efficiency	Ratio of supplied water (SW) to metered water (MW).	$\frac{SW(T)}{MW(T)}$	m^3/m^3
WD	Metered water loss ratio	Ratio of water loss (WL) to metered water.	$\frac{WL(T)}{MW(T)}$	m^3/m^3
WWC	Wastewater network efficiency	Ratio of wastewater treated (WWT) to metered water.	$\frac{WWT(T)}{MW(T)}$	m^3/m^3
WWC	Inflow and infiltration ratio	Ratio of inflow and infiltration ($I\&I$) to metered water.	$\frac{I\,\&\,I(T)}{MW(T)}$	m^3/m^3

Policy levers controlling the forecasting exercise are made as identical as possible between each utility under the assumption they will have similar preferences (due in part to their geographic proximity) for strategic targets, policy levers, sustainability, and lifecycle. For this study, a pay-as-you-go financing strategy is considered over a 100-year lifecycle of the infrastructure system representing the benchmarking period (T). Pay-as-you-go means user fees are set to generate revenues that are sufficient to pay for all operational and capital expenditures. Model data can be output to a data file to track BPIs over the 100-year simulation period.

Input Data for the System Dynamics Model

Utilities X, Y, and Z have 361, 501, and 450 km of water distribution network pipes that serve 120,000, 130,000, and 83,000 customers, respectively. Their networks are comprised of pipes made of PVC, cast iron (CI), ductile iron (DI), and asbestos cement (AC). Initially, 5.5, 8.0, and 8.5% of their respective network lengths are more than 75 years old and beyond their design life $\mathbb{D}$. Note that $T > \mathbb{D}$ to accommodate an initial inventory of water main pipes of varying ages, with the various pipe segments reaching ($\mathbb{D}$) throughout T. Each water utility is assumed to be rehabilitating or replacing

Table 5. Financial Performance Indicators

Sector	Benchmarking performance indicator	Description	Calculation	Unit
WD	Water TotalEx efficiency	Total water distribution expenditures ($WDEx$) divided by supplied water (SW) over the benchmarking period (T) per network length (NL) per population (P).	$TotalWDEx(T) \div SW(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)$ $TotalWDEx(T) = \sum_{t=0}^{T}(O\dot{p}Ex(t) + Ca\dot{p}Ex(t) + In\dot{t}Ex(t)) \times \Delta t$ $OpEx(T) = MaintEx(T) + SWEx(T)$ $SWEx(T) = MWEx(T) + WLEx(T)$	$\$/m^3/m/capita$
WD	Water OpEx efficiency	Operational expenditures ($OpEx$) divided by supplied water over the benchmarking period per network length per population.	$OpEx(T) \div SW(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)$	$\$/m^3/m/capita$
WD	Water CapEx efficiency	Capital expenditures ($CapEx$) divided by supplied water over the benchmarking period per network length per population.	$CapEx(T) \div SW(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)$	$\$/m^3/m/capita$
WD	Non-RevenueEx efficiency	Water loss expenditures ($WLEx$) divided by supplied water over the benchmarking period per network length per population.	$WLEx(T) \div SW(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)$	$\$/m^3/m/capita$
WD	Water debt efficiency	Debt (D) divided by supplied water over the benchmarking period per network length per population.	$D(T) \div SW(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)$	$\$/m^3/m/capita$
WWC	Wastewater TotalEx efficiency	Total wastewater collection expenditures ($WWCEx$) divided by wastewater treated (WWT) over the benchmarking period per network length per population.	$TotalWWCEx(T) \div WWT(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)$ $TotalWWCEx(T) = \sum_{t=0}^{T}(O\dot{p}Ex(t) + Ca\dot{p}Ex(t) + In\dot{t}Ex(t)) \times \Delta t$ $OpEx(T) = MaintEx(T) + WWTEx(T)$ $WWTEx(T) = MWEx(T) + I\,\&\,IEx(T)$	$\$/m^3/m/capita$
WWC	Wastewater OpEx efficiency	Operational expenditures ($OpEx$) divided by wastewater treated over the benchmarking period per network length per population.	$OpEx(T) \div WWT(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)$	$\$/m^3/m/capita$
WWC	Wastewater CapEx Efficiency	Capital expenditures (CapEx) divided by wastewater treated over the benchmarking period per network length per population.	$CapEx(T) \div WWT(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)$	$\$/m^3/m/capita$
WWC	Non-RevenueEx efficiency	Inflow and infiltration expenditures ($I\,\&\,IEx$) divided by wastewater treated over the benchmarking period per network length per population.	$I\,\&\,IEx(T) \div WWT(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)$	$\$/m^3/m/capita$
WWC	Wastewater Debt efficiency	Debt divided by wastewater treated over the benchmarking period per network length per population.	$D(T) \div WWT(T) \div \sum_i \overline{NL}(T) \div \bar{P}(T)$	$\$/m^3/m/capita$
WD/WWC	Liability-asset ratio	Percentage of liabilities to assets.	$\frac{\text{Liabilities}(\$)}{\text{Assets}(\$)} \times 100 = \frac{D(T) + abs(neg.FB(T)) + CW(T)}{NAV(T) + (if FB > 0, (FB(T) - CR(T)), CR(T))} \times 100$	%
WD/WWC	OpEx ratio	Ratio of operational expenditures ($OpEx$) to revenue (RV).	$\frac{OpEx(T)}{RV(T)}$	\$/\$
WD/WWC	CapEx ratio	Ratio of capital expenditures ($CapEx$) to revenue (RV).	$\frac{CapEx(T)}{RV(T)}$	\$/\$

Note: abs = absolute value; $CapEx$ = capital expenditures; CR = capital reserve; CW = capital works; FB = fund balance; $IntEx$ = interest expenditures; $I\,\&\,IEx$ = inflow and infiltration expenditures; $MaintEx$ = maintenance expenditures; $MWEx$ = metered water expenditures; $neg.$ = negative; $OpEx$ = operational expenditures; $SWEx$ = supplied water expenditures; $WLEx$ = water loss expenditures; $WWTEx$ = wastewater treated expenditures; Δt = time step; (i.e., cash required to rehabilitate or replace pipe that reached their design life).

1.3% of their water distribution networks length every year (policy lever). The allowable fee hike rate (policy lever) on the unit cost of water needed to generate revenue to equal expenses thereby creating a zero fund balance (strategic target) under a pay-as-you-go financial strategy over the benchmarking period is 9.5% per year for Utilities X and Y, and 11% per year for Utility Z. Additionally, pipes beyond their design life are eliminated in 5 years (policy lever), and the percent of deteriorated pipes is targeted to be less than 5% of the total network length (policy lever).

The initial unit cost of water for Utilities X, Y, and Z is $\$1.55/m^3$, $\$1.68/m^3$, and $\$0.92/m^3$, respectively. The current cost of water treatment is $\$0.83/m^3$ for Utilities X and Y, and $\$0.54/m^3$ is used for Utility Z. Initial residential water demand is 280 L per capita per day (lpcd) for Utilities X and Z, and 322 lpcd for Utility Y with additional demand from industrial and commercial accounts. The minimum residential water demand for the three utilities is assumed to be 150 lpcd. Price elasticity of water demand for the residential sector is assumed to be equal to −0.35, which is the average of the range reported by Boland et al. (1984) and used by Rehan et al. (2011, 2014, 2015).

The unit cost for rehabilitating pipes 75–100 years old is $600/m, while for pipes more than 100 years old it is set at $700/m. Total unit operation and maintenance costs are provided in Table 6, and leakage rates for each age group of pipes are provided in Table 7 and are calculated in a manner identical to Rehan et al. (2015). Inflation rates are calculated in a manner identical to Rehan et al. (2015). For this analysis water treatment expenditures are excluded from the calculation of total expenditures.

Benchmarking Results

The infrastructure efficiency BPI is 3.0, 3.85, and 5.42 m/capita for utilities X, Y, and Z, respectively. These values are constant over the benchmarking period because the water network length and population are assumed to be constant. Based on these values, Utility Z has the highest amount of urban sprawl and Utility X has the lowest. A lower value suggests more efficient infrastructure usage and implies sustainability. Fig. 2 presents four BPIs for the three utilities demonstrating (1) infrastructure condition efficiency as noted in Table 3; (2) water TotalEx efficiency as noted in Table 5; (3) water loss efficiency as noted in Table 3; and (4) per capita water consumption (i.e., water demand) as noted in Table 1. The water demand PI, as shown in Fig. 2, is time integrated over the 100-year benchmarking period T to be consistent with Eq. (1) and the other three BPIs shown in Fig. 2.

Fig. 2(a) shows the infrastructure condition efficiency BPI, which is the fraction of pipes over 75 years old and beyond their design life, in units of meter per capita. Infrastructure condition efficiency BPI starts with a value of 0.2, 0.3, and 0.45 m/capita for Utilities X, Y, and Z, respectively. Generally, the three utilities show the same trend—a rapid linear decrease for the first 5–10 years, followed by linearly increasing trend to the end of benchmarking period. The initial decreasing trend is due to two policy levers: first, that each water utility is rehabilitating or replacing 1.3% of their water distribution networks length every year; and second, that no more than 5% of the network length can be aged beyond the design life. Thus, within 5–10 years all utilities generated enough revenue to support sufficient capital expenses to comply with the second policy lever. The post-10-year trend is due to aging of the pipes within the network as it reaches a sustainable condition that is constrained by both of the preceding policy levers. At 100 years, the time-integrated infrastructure condition efficiency BPI values are 0.08, 0.2, and 0.12 m/capita for Utilities X, Y, and Z, respectively. These values are all lower than their initial values, implying improvement in the system's condition due to the aggregate set of operation decisions made by each utility (due to enforcement of the policy levers) over the benchmarking period. The three utilities show a small rapid increase (bump) in the infrastructure condition efficiency BPI between years 20 and 40. This bump is the result of a cohort of PVC pipes that were installed in the 1960s suddenly reaching their design life of 75 years of age. Finally, Utility Y has the highest (worst) infrastructure condition efficiency value after 10 years. This is the result of Utility Y having insufficient capital works funds required to rehabilitate the fraction of highly deteriorated pipes. This funding shortfall is due to the maximum allowable fee hike rate being set too low.

Fig. 2(b) shows the water TotalEx efficiency BPI, which is a measure of a utility's ability to efficiently recover revenue by billing for metered water, and is quantified by revenue for metered water divided by the supplied water from the water treatment plant, and further normalized by the water distribution network length and population ($\$/m^3/m/capita$). Thus, a low value for the water TotalEx efficiency BPI suggests efficient performance and implies sustainability. In general, this figure shows a relatively constant BPI value for the first 20 years then a generally increasing linear trend with some curvature. During the first 20 years the water TotalEx efficiency starts with a value of $\$0.22/m^3/m/capita$ for Water Utilities X and Z, and $\$0.16/m^3/m/capita$ for Water Utility Y. At the end of the benchmarking period the BPI values are \$0.5, \$0.41, and $\$0.52/m^3/m/capita$ for Utilities X, Y, and Z, respectively. This increasing trend over time indicates that for all utilities the water TotalEx efficiency decreases over time. This trend is a function on two processes. First, Rehan et al. (2013, 2015) showed that inflation in operational and capital expenditures is greater than the risk-free rate used to discount all expenses to present value, thereby making late-time operational and capital expenses comparatively more expensive. Second, as the network gradually ages over the benchmarking period, the unit cost of OpEx shown in Table 6 increases, thereby requiring the utility to obtain more revenue from metered water. The three utilities ultimately achieve similar behavior over the entire benchmarking period with the spread in their water TotalEx efficiency never greater than approximately

Table 6. Total Unit Operation and Maintenance Cost for Water Distribution Pipes in Various Age Groups ($/m/year)

Water utility	Type of pipe	Age group of pipes (years)				
		0–24	25–49	50–74	75–99	100–124
X	CI	7.73	8.22	11.69	36.06	207.40
	PVC	7.72	8.07	10.11	21.81	89.18
Y	CI and DI	6.44	6.93	10.40	34.78	206.1
	PVC	6.43	6.78	8.2	20.52	87.90
Z	CI&DI	6.99	7.48	10.95	35.33	206.66
	PVC	6.98	7.34	9.37	21.08	88.45
	AC	6.99	7.40	10.06	26.97	134.53

Table 7. Leakage Rate of Water Distribution Pipes in Various Age Groups

Applicable to all water utilities	Type of pipe	Age group of pipes (years)				
		0–24	25–49	50–74	75–99	100–124
Leakage rate ($m^3/km/day$)	CI and DI	0.19	1.34	9.45	66.4	466.7
	PVC	0.17	1.0	5.75	33.1	190.5
	AC	0.18	1.16	7.37	46.89	298.19

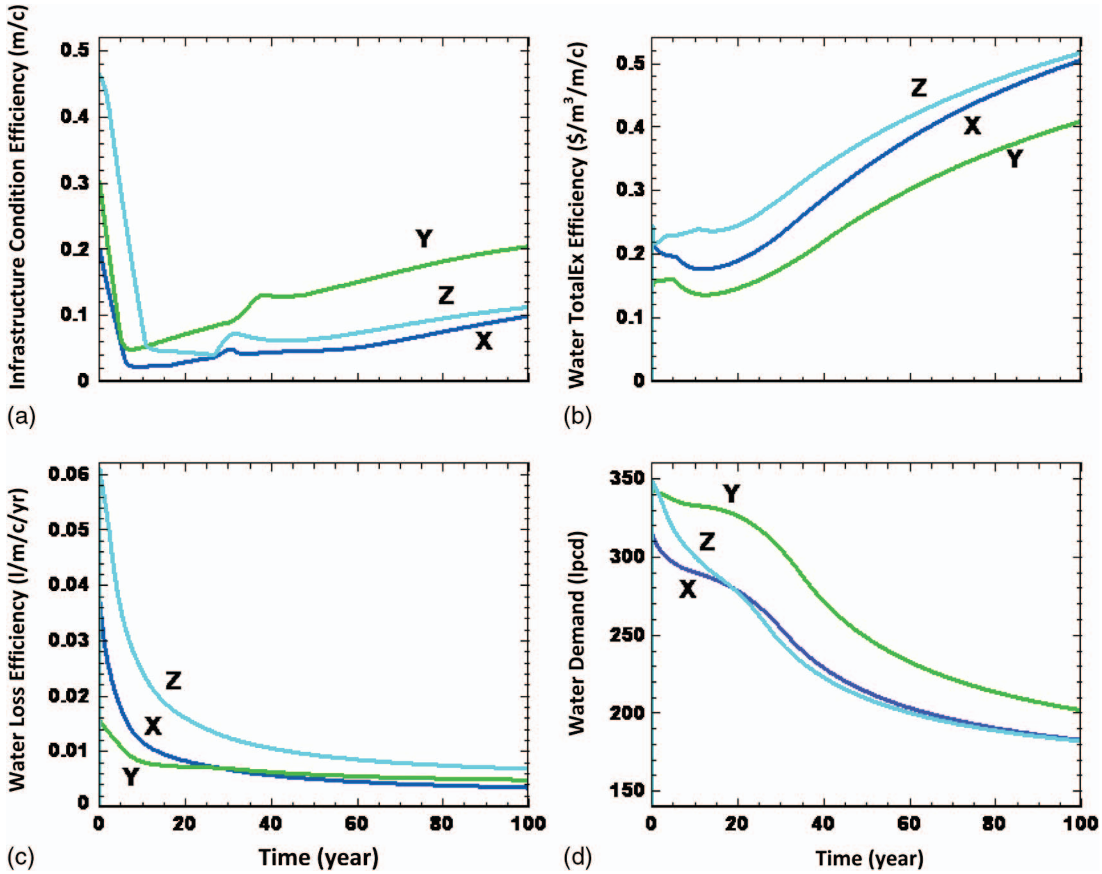

Fig. 2. (Color) Benchmarking results over a 100-year forecasting period for Utilities X, Y, and Z

$0.11 $m^3/m/$capita. This spread persists due to an allowable fee hike rate that permits each utility to have sufficient revenue to meet expenses over the benchmarking period. Fig. 2(b) shows that Utility Z consistently has the highest values of water TotalEx efficiency BPI over the benchmarking period compared with the other water utilities, and Utility Y consistently has the lowest values. Thus, Utility Y is deemed more efficient than Utilities X and Z. As shown in Fig. 2(a), Utility Z starts the benchmarking exercise with the highest fraction of deteriorated pipes. The need to eliminate these old pipes (policy lever) requires Utility Z to have the greatest capital work expenditures and hence water TotalEx efficiency BPI. Utility Y achieves its low water TotalEx efficiency due to its low infrastructure efficiency BPI of 3.85 m/capita compared with Utility Z with a value of 5.42 m/capita. Additionally, Utility Y has completed significant water infrastructure renewal prior to this analysis, resulting in the lower need for capital work expenditures compared with Utility Z.

Fig. 2(c) depicts water loss efficiency BPI quantified as the annual water loss through the water distribution network per meter of network length per capita [L/m/capita/year], with a low value implying efficient and sustainable network performance. Initial values for Water Utilities X, Y, and Z are 0.036, 0.015, and 0.06 L/m/capita/year, respectively, and then rapidly decline to minimal and sustainable values by the end of the benchmarking period. As noted previously, Utility Z initially has the oldest inventory of pipes and thus the highest initial leakage rate (Table 7). In contrast, Utility Y initially has the newest inventory of pipes and thus the lowest value water loss efficiency. The improvement in water loss efficiency for the three utilities over the benchmarking period is due to their efforts to remove a water distribution pipe that is beyond its design life, as shown in Fig. 2(a).

Fig. 2(d) shows the water demand BPI, which measures users' average daily water consumption (lpcd). This value is time-integrated to show cumulative change in behavior over the benchmarking period. The water demand BPI initially starts at 315, 345, and 350 lpcd for Water Utilities X, Y, and Z, respectively. Water demand then continuously declines for the three utilities over the benchmarking period to 183 lpcd for Utilities X and Z and 200 lpcd for Utility Y. The declining trend indicates water conversation due to water price increases and the price elasticity of demand function built into the Rehan et al. (2013, 2015) system dynamics model. The initial water demand is calculated as the sum of residential, industrial, and commercial water demand divided by the population under the assumption that all customer sectors experience the same price elasticity of water demand.

Discussion

The case study demonstrates that the three utilities can manage their assets across the same strategic target and policy levers controlling their targets. All three water utilities show different behavior over the benchmarking period and can implement different financial strategies (pay-as-you-go, borrowing, capital reserving, fixed and variable revenue) and decision-making policies for improvements and best practices and to meet strategic targets. The four presented BPIs demonstrate the complexity of water distribution systems and how the BPIs can be used to benchmark a utility's performance with different attributes—e.g., customer base, size of network, pipe material types and age profiles. The application of the entire set of BPIs should allow a better understanding of the total system responses and will further help drive improved long-term system performance with respect to strategic policies and targets.

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It is also envisioned that regulatory bodies can require water utilities to report key BPIs. Doing so will allow them to establish realistic and defensible target values to meet over time. For example, Fig. 2(c) shows that a water loss efficiency of 0.01 L/m/capita/year is achievable by all three water utilities. Thus, it is envisioned that BPIs can be used by regulators and/or governments to drive utilities to improve their practices regardless of utilities' different attributes. This will also help drive industry best practices.

The outcome of these BPIs is therefore to allow a water utility and its stakeholders to articulate acceptable objectives and paradigms, and then to negotiate and enact meaningful strategic targets and policy levers that will lead to sustainable management of the water distribution and wastewater collection systems.

The proposed BPIs allow the water utilities to demonstrate to their stakeholders, bond rating agencies, investors, regulators, and/or government agencies how well they managed their water distribution and wastewater collection systems in the short-term (5–10 years) as well as over the long-term (10–30 years).

Conclusions and Recommendations

This study demonstrates that many performance indicators have been developed and adopted by the water utilities that allow them to track their changes and improvements over time. It also indicates that most PIs lack normalization and scaling and do not denote time, thus making it difficult to compare or benchmark one utility's performance against other water utilities locally, regionally, and/or nationally.

A series of new normalized and time-integrated BPIs have been proposed that will allow water utilities to benchmark against each other. Benchmarking performance indicators will allow water utilities with different attributes, such as pipe inventories (materials, condition, and length), customer characteristics (population, consumption, and conservation patterns), and financial characteristics (allowable fee hike rate, water fee, funds), to benchmark their asset management and financial position relative to one another.

All proposed BPIs have been developed to conform to the following themes: (1) strategic targets, (2) policy levers, (3) sustainability, and (4) lifecycle. It is envisioned that these developed BPIs can be used by various stakeholders to negotiate and enact meaningful strategic targets and policy levers that can lead to the sustainable management of the water distribution system. For example, they can be implemented by regulators, state, and/or national government bodies to drive industry improvements and/or justify grant funding requests. They can also be used by the water utilities to justify rate increases or to demonstrate to its stakeholder, bonding agencies, investors, government agencies, and/or regulators how well a water utility is being managed now and in the future.

The presented case study example showed how BPIs can be implemented and tracked in an advanced forecasting system dynamics decision support tool to show how short-term (5- to 10-year) strategic policy decisions can have a significant impact on the long-term (10- to 30-year) network performance and can drive large long-term cost savings. It also shows that these systems are complex and that utility attributes will drive the need for unique policy decisions for each utility, i.e., there is no one solution that fits all and more work needs to be completed to better understand system optimization.

The list of BPIs developed and proposed in this study are not deemed to be a definitive list of BPIs, but rather a starting list of BPIs that the industry can adopt and/or modify based on industry needs. To standardize a list on BPIs, it is recommended that bodies or agencies such as the International Water Association (IWA) and/or AWWA should develop a list of key BPIs for the water industry.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request.

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