Review

Quantitative Measure of Sustainability for Water Distribution Systems: A Comprehensive Review

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Abstract: This work provides a comprehensive review of the quantitative measures of sustainability proposed for water distribution systems (WDSs) and their sustainable development. After a comprehensive literature review, eighteen studies overall, either clearly proposing quantitative measures of sustainability (three studies) or highlighting sustainable development (fifteen studies), were selected for a closer review. All three measures showed either a lack of applicability or were missing important aspects of sustainability. Additionally, they have not been thoroughly validated by demonstrating the measures under acceptable scenarios/conditions. The reviewed sustainable development practices showed that energy usage and greenhouse gas emissions, life cycle costing, and reliability were widely used to evaluate environmental, economic, and social impacts, respectively. The two primary recommendations made based upon reviews were to: (1) consider balancing usage (cost) and gain (benefit), rather than impacts; (2) consider indirect (cascading/consequential) interactions. Overall, existing measures of sustainability and sustainable development practices in WDSs must be advanced to accommodate a focus on restorative systems, as well as to maximize benefits and enable multidisciplinary and broader analyses.

Keywords: water sustainability; sustainable development; water distribution system; drinking water infrastructure

1. Introduction

Drinking water infrastructure, which ensures the necessary supplies for daily water usage, is one of the most critical infrastructures in sustaining communities. However, the performance of the infrastructure inevitably degrades as it ages which is a pressing concerns to the water utilities [1–3]. Moreover, other challenges such as climate change, population growth, and resource limitations are also jeopardizing its performance and sustainability [4]. The American Society of Civil Engineers (ASCE) continuously issued D- and D grade of the Infrastructure Report Card for the drinking water infrastructure even though pipe replacement has been actively carried out to improve the performance of the infrastructure [1,2]. Such a process has been done in cost effective ways as the budget is limited [5–7]. In fact, Walski [8] emphasized that it is difficult to identify either true or net benefit (benefits minus costs) when cost minimization is used, especially in water distribution system (WDS) design, and it often results in such designs become self-fulfilling prophecies. Additionally, several reports have emphasized that cost minimization may result in long-term and broader impacts being overlooked [5,9–12]. Therefore, cost minimization cannot guarantee the sustainability of a system.

Since the publication of the Brundtland Commission's report in 1987 [13], the concept of sustainability or sustainable development for drinking water infrastructure has been widely referenced and studied by many researchers [14–16]. Sustainable development, as defined in this report, is a

method to address the dilemma of advancing economic development while protecting environmental systems and enriching the quality of life for current and future generations [13]. This definition has been considered as a reference and revised according to specific contexts and applications [17,18].

One of the most well-known approaches to sustainability rating practices is the Leadership in Energy and Environmental Design (LEED) method [19]. In this method, the sustainability features of a project are rated but are limited to measuring the sustainability of buildings. Another oft-used method is the EnvisionTM Rating System (Envision), developed by the Institute for Sustainable Infrastructure (ISI) and is a sustainability rating system for infrastructure systems. Envision rates the sustainability of infrastructure projects using a life-cycle analysis (LCA) approach, balances against community needs, and rewards restorative aspects of the infrastructure [20]. A research group at the University of Virginia also provided a sustainability rating framework for water supply systems by providing seven indicator categories [16]. These sustainability rating systems are often regarded as qualitative frameworks because some of the considerations need personal judgment and results may differ from person to person [21]. Qualitative frameworks are excellent tools but may result in subjective decisions [14] and their applicability to WDSs is uncertain.

Undeniably, sustainability is and will continue to be a critical criterion for WDS planning and management, but there is little agreement on the definition and quantitative criteria of sustainability or its improvement (i.e., sustainable development) [14–16,22]. Hence, this paper provides a comprehensive literature review of the existing WDS sustainability literature, as well as recommendations to address the aforementioned questions. The main objective of this study is to review the existing sustainability measures for WDS to provide opportunities to advance related research topics. Specifically, we summarize here how studies were selected from the literature for review, as well as their findings, before considering definition(s) and examples of sustainability, sustainable development, and how they are measured quantitatively. Finally, we identify the gaps that exist in the literature and provide recommendations for future studies to improve WDS sustainability.

2. Review Methodology

To ensure that this review was comprehensive, the Web of Science and Google Scholar were used for searching the relevant literature in a very extensive and wide array. These identified studies were then filtered by examining their titles, abstracts, and methodology to constrain the scope of the review to modeling and quantitative measures of the sustainability and sustainable development of WDSs. In the selected literature, studies that clearly proposed quantitative measures of sustainability and/or highlighted sustainable development were shortlisted after a closer review. Through this process, we selected eighteen studies overall, including three sustainability measures and fifteen sustainable development studies (Table 1). Note that all studies were published after the 2000s, even though publication time has not been customized. Table 1 summarizes why selected studies considered sustainability (problem to be solved), what was proposed as solution to solve the problem, and how selected studies quantified sustainability.

Table 1. Summary of problems considered, their proposed solutions, and the sustainability evaluation method of the selected literature.

Reference	Problem	Proposed Solution	Evaluation
Aydin et al. [23]	Pressure deficit and water age issue	Add booster pump	Reliability, resilience, and vulnerability
Ramesh et al. [24]	Water scarcity	WDS design (rural)	Measure of sustainability of the system
Lee and Burian [25]	Aging	NA	Triple top line

Table 1. Cont.

Reference	Problem	Proposed Solution	Evaluation
Filion et al. [26]	N/A	Pipe replacement	Life-cycle energy analysis
Wu et al. [27]	Environmental impact	Pipe and pump design	Life-cycle cost (LCC) and greenhouse (GHG) emissions
Wu et al. [28]	Environmental Impact	Pipe and pump design and tank location determination	LCC and GHG emissions
Wu et al. [29]	Environmental Impact	Pipe and pump design	LCC, GHG emissions, and carbon pricing
Herstein et al. [30]	Environmental impact	Pipe and pump design	LCC and Environmental Impact Index
Kang and Lansey [31]	Water supply shortage	Dual water distribution network	LCC, GHG emissions, and reliability
Arif et al. [32]	Environmental impact	Pipe and pump design	LCC and life-cycle emissions with node pressures and reliability constraints
Nault and Papa [33]	Inefficient energy consumption (pumping)	Determine operational practices	LCA (net present value, LCC, energy consumption, GHG emissions)
Lee and Burian [7]	Aging	Pipe replacement	Triple top line
Lee et al. [34]	Aging and insufficient fund	User fee adjustment	Triple top line
Koo and Ariaratnam [35]	NA	Pipe replacement	Environmental impacts, economic benefits and outputs, social and cultural conservation and promotion, and structural soundness
Farmani and Butler [36]	Urban planning	WDS design with different Urban form (layout)	LCC, resilience, and water quality (water age)
Aydin et al. [37]	Water scarcity	Reclaimed water for non-potable water	Reliability, resilience, vulnerability, and energy intensity
Piratla [38]	Environmental Impact	Pipe and pump design	LCC, life-cycle CO ₂ emissions, resilience, and cost of reducing CO ₂ emission
Cunha et al. [39]	Uncertainties in future scenario	Phase design (pipe design)	Investment cost, CO ₂ emissions, and resilience/reliability

3. Sustainability of Water Distribution Systems

Among the various indicators of WDS performance, only those that quantify sustainability as a singular (or integrated) measure were selected for reviewing the quantification of sustainability. It is worthwhile to highlight that singular here implies the value is a representative value of sustainability that integrates multiple indicators or dimensions. Sustainable development was considered when it was clearly stated that a given work involved sustainable development and studies where surrogate measures (criteria) of sustainability were employed. Sustainable development often measures sustainability as a multidimensional measure rather than providing a singular measure. Here, we define the concept of “sustainability,” review the measures used to quantify sustainability and briefly review the existing literature on sustainable development in the context of WDSs.

3.1. Defining Sustainability

Sustainability or sustainable development has received much attention over the last few decades, yet there has been a lack of a general definition of “sustainability,” as it has been applied to different systems with different objectives [22]. Therefore, we reviewed the various definitions of sustainability and identified their common features with respect to WDSs. We do not provide a general definition of sustainability, but rather provide a review of how it is commonly defined to aid in the conceptual understanding of “sustainability.”

Loucks [40] defined sustainable water resource systems as the system satisfying social needs for now and in the future by maintaining ecological, environmental and hydrological integrity. Savic and Walters [41] emphasized that sustainability entails the minimum use of energy, loss of water, and number and consequences of pipe failures, as well as the most effective use of existing assets and meeting customers’ needs in both quantity and quality as the basic criteria of a sustainable water supply system. Both Loucks [40] and Savic and Walters [41] highlighted the importance of the environment and performance of the infrastructure itself. However, Sahely et al. [42] more recently defined the sustainability of urban infrastructure as the provision of more efficient services that maintain public health and welfare, are cost-effective, and reduce negative environmental impacts both today and in the future. Thus, not only the environmental impact and performance but also the economic and social impacts, are included in this latter definition. These are generally defined as the three components of sustainability (i.e., the triple bottom line, TBL). The Resilient Sustainable Interdependent Infrastructures (RESIN) definition of sustainability is similar to that of Sahely et al. [42], and involves the ability to provide adequate and reliable water, energy, and material resource supplies of the desired quality (now and for future generations) in a manner that integrates economic well-being, environmental protection, and social needs [18].

The definition of sustainability for WDSs has been very limited. Lansey [18] divided the sustainability of WDS into two facets: water resources and infrastructure. Resource sustainability is the ability to continually provide adequate water supplies of acceptable quality without diminishing the long-term supply. Meanwhile, infrastructure sustainability is the ability of infrastructure to meet the resource sustainability goal with a minimum TBL impact. Furthermore, Lee [22] defined WDS sustainability as the ability to maintain performance for now and future generations by balancing usage and benefits in terms of economic, environmental, and social impacts. In summary, it is generally agreed that the definition of sustainability should consider the degree of satisfaction of the three components of sustainability (i.e., the economy, society, and environment), for both current and future generations. Therefore, economic, social, environmental, and temporal dimensions should be considered to understand and evaluate the sustainability of WDSs.

3.2. Quantitative Measures of Water Distribution System Sustainability

Even though sustainability has been discussed in many studies, a quantitative measure of sustainability for WDSs has been proposed in only three studies. Aydin et al. [23] proposed a sustainability index (SI) for WDSs by revising the SI introduced by Loucks [40]. Loucks [40] emphasized that minimizing risk and uncertainty will maximize sustainability and evaluated sustainability in terms of reliability, resilience, and vulnerability [43]. The SI is applied to water resource systems and can be quantified as follows:

$$SI = REL \times RES \times (1 - VUL) \quad (1)$$

where *REL* is reliability, *RES* is resiliency, and *VUL* is vulnerability. The quantification of each of these criteria is based on the number of satisfactory and unsatisfactory performances during a given period, as shown in Table 2.

Table 2. Summary of the quantitative measure of each criterion used to calculate the sustainability index (SI) proposed by Loucks [40].

Criterion	Equation
Reliability	$REL = \frac{\# \text{ of times satisfactory occurs}}{\text{total \# of time steps}}$
Resiliency	$RES = \frac{\# \text{ of times satisfactory follows unsatisfactory}}{\text{total \# of times unsatisfactory occurs}}$
Vulnerability	$VUL = \frac{\sum \text{unsatisfactory values}}{\sum \text{all values}}$

In Table 2, *REL* quantifies the probability of satisfactory state quantified for the total time period in consideration. *RES* considers recovery to a satisfactory state from the unsatisfactory state. It is also related to speed of recovery as it divides the number of recoveries from the unsatisfactory state by the total time period of unsatisfactory. In addition, *VUL* investigates the degree of an unsatisfactory state and its duration for a certain time scale.

The main revision to Loucks' [40] original SI by Aydin et al. [23] created ways to define system performance (i.e., satisfactory and unsatisfactory performance) suitable for WDSs. Additionally, Aydin et al. [23] considered SI as the geometric means of *REL*, *RES*, and *VUL* following Sandoval-Solis et al. [44]. To calculate *REL*, *RES*, and *VUL*, the nodal pressure and water age are considered to be the system performance, which are the results of hydraulic and water quality analyses using the EPANET2.0 [45]. Specifically, Aydin et al. [23] defined the minimum and maximum pressure per node and the maximum water age at each node. If the pressure and water age of a node are within the set limits, only then it is regarded as satisfactory. This calculation was performed per node and per time step. Aydin et al. [23] also divided WDSs into different zones based on geographic location. The SI quantified for each node was then aggregated based on their demand as follows:

$$SI_{k,i} = \frac{\sum_{j=1}^{n_{nodes}} D_{i,j} SI_{k,i,j}}{\sum_{j=1}^{n_{nodes}} D_{i,j}} \quad (2)$$

where *k* is the performance in consideration, which is either pressure or water age, *i* is the zone index, *n_{nodes}* is the number of nodes, *D_{i,j}* is the demand of the *j*th node in *i*th zone, and *SI_{k,i,j}* is the pressure or water age SI of the *j*th node in the *i*th zone. The two SIs, pressure and water age, are considered and integrated using weights as follows:

$$SI_{overall,i} = \sum_{k=1}^n w_{k,i} SI_{k,i} \quad (3)$$

where *SI_{overall,i}* is the overall SI of the *i*th zone and *w_{k,i}* is a normalized weighting factor for each SI (i.e., $\sum w_{k,i} = 1$). Aydin et al. [23] applied equal weights for each SI by assuming that both pressure and water age are equally important. They also provided a standard to define the state of the system based on the range of SIs. The state was divided into four levels (i.e., unacceptable, moderate, acceptable, and ideal), the detailed ranges for which are shown in Table 3.

Table 3. Definitions of water distribution system (WDS) states based on the ranges of calculated SIs.

SI Range	State
0–0.25	Unacceptable
0.25–0.5	Moderate
0.5–0.75	Acceptable
0.75–1	Ideal

Ramesh et al. [24] constructed another quantitative measure of sustainability for WDS design. This was defined as a measure of system sustainability (SM), which is a function of the sustainability coefficient and adapted indices of effectiveness, as follows:

$$SM = f(\text{Sustainability Coefficient}, \text{Adapted Indices of Effectiveness}). \quad (4)$$

The sustainability coefficients include: (1) localization, (2) cost point, (3) overlap, (4) endurance, (5) loop, and (6) interaction coefficients. The localization coefficient explains the topographical area covered by a system and its interaction with the density of users. It considers the total network length function and the distance between various actors. Ramesh et al. [24] also divided the system into two main entities—actors and processes—with the actors including sources, pumps, storage, main networks, sub-networks, end taps, recharge, sensors, and communities; processes included the categorization of each actor by their functions—generation, transmission, distribution, and feedback. The cost point coefficient considers the cost associated with each process. The overlap coefficient evaluates the relationship among demand-and-supply-driven models by defining the number of users, normal water table level, water table level in summers, consumption rates, and the availability of energy sources. The endurance coefficient investigates the degree of a systems' reaction with various evaluation processes, while the loop coefficient quantifies the continuous flow of water and information in the system. The interaction coefficient is a function of community participation in the design, operation, and maintenance of the WDS, the number of activities performed, and the copying cost of water conservation. Each sustainability coefficient is normalized relative to the adaptive indices of effectiveness, which are summarized in Table 4. With the SM, Ramesh et al. [24] designed a WDS considering local community needs, the availability of labor, local resources, climate, cost, and time for implementation. The problem they focused on was water scarcity, especially in rural areas. However, they did not provide the details of their calculations.

Table 4. Adapted indices of effectiveness indicators (from Ramesh et al. [24]).

Sustainability Indices	#	Indices of Effectiveness	Adapted Indices of Effectiveness
Reliability and Adequacy	1	Percent of schemes supplying water as per design norms (design norm of 40 lpcd or more than 40 lpcd)	Percent of households receiving water as per design norm
	2	Percent of schemes supplying daily (at least four hours of regular daily supply)	Percent of households receiving water at least 12 h per day
	3	Percent of schemes with households spending less than 30 min per day in collecting water	Percent of households spending 1 < 30 min per day in collecting water
	4	Percent of schemes with no major breakdown in the past six months (a major breakdown is defined as more than two days of disruption in the water supply)	Percent of pack with no major breakdown in the past six months
	5	Percent of schemes with good water quality: (i) no bacteriological contamination; (ii) no chemical problems with arsenic, fluoride, or salinity	Percent of households with good water quality: (i) no bacteriological contamination; (ii) no chemical problems with arsenic, fluoride, or salinity

Table 4. Cont.

Sustainability Indices	#	Indices of Effectiveness	Adapted Indices of Effectiveness
Financial Sustainability	6	Percent of schemes with >80% operation & maintenance (O&M) cost recovery	Percent monthly collection with >60% O&M cost recovery
	7	Percent of schemes with >80% collection efficiency	Percent of households with >80% collection efficiency
Affordability	8	Water tariff for household connections as a ratio of rural per capita income	Percentage of households with >80% contribution efficiency
	9	Water tariff for stand post users (shared connections) as a ratio of rural per capita income	Household water tariff as a ratio of household income
	10	Percent of schemes with >50% household connections	Percentage of water taps utilized for more than 6 h a day
Environmental Sustainability	11	Percent of schemes with a source providing >80% yield (as per design norms)	Percentage of months the energy tariffs exceed design norms
	12	NA	Percentage of toilets using the water supplied under the scheme

Lee and Burian [25] also developed a measure of sustainability by focusing purely on quantification and proposed an SI for WDSs based on the triple top line (TTL) method, which was introduced by McDonough and Braungart [46] and has been a beneficial tool for assessing sustainability according to business agendas. It is a similar method to the TBL approach in that it considers coincident sustainability components (Figure 1); however, it considers beneficial aspects rather than impacts (or costs). TTL-based sustainable development typically aims to reduce, re-use, and recycle, creating “more goods and services while using ever-less resources and producing less waste and pollution.” In other words, the TTL approach tends to maximize benefits and minimize costs (or impacts), while TBL only focuses on minimizing impacts.

Figure 1. Schematic showing the factors considered in (a) triple bottom line (TBL) and (b) triple top line (TTL) measures of sustainability.

Another difference between the TBL and TTL methods is that the latter considers the relationships between different sustainability components. Figure 1 illustrates the configuration of both the TBL and TTL models. The TBL approach is composed of three triangles (or factors), while the TTL model has nine (three for each sustainability component). The attributes of the triangles between two sustainability components (e.g., Eco^{Soc} , Eco^{Env} , and so on) are determined based on the relationships between them. These triangles consider the adjacent components’ (what each triangle is adjacent to; shown as a superscript) problems from the perspective of the primary sustainability component. For example, Eco^{Soc} views social problems from an economic perspective; Lee and Burian [25] defined this as a customer’s affordability. All triangles are quantified as the ratio between benefits (including recycled)

and consumption. Table 5 summarizes the approach used to calculate each triangle shown in Figure 1 and detailed calculation examples can be found in [25].

Table 5. Calculations and descriptions for each WDS TTL factor.

Factor	Calculation *	Description
Eco^{Eco}	$Eco^{Eco}_t = \frac{\sum P_{i,t}}{\sum C_t}$	Economic benefit cost ratio
Eco^{Soc}	$Eco^{Soc}_t = \frac{\sum ECLIPS_{i,t} \times Q_{del,i,t} \times BI}{\sum P_{i,t}}$	Economic consequence benefit (customer's affordability)
Eco^{Env}	$Eco^{Env}_t = \frac{\sum Q_{del,i,t} - \sum E(Q_{leak,i,t})}{\sum Q_{sup,i,t}}$	Water efficiency
Soc^{Eco}	$Soc^{Eco}_t = 1 - 2G_{w,t}$	Social consequence benefit (equity)
Soc^{Soc}	$Soc^{Soc}_t = \frac{\sum Q_{req,i,t} \times U_{i,t}(c)}{\sum Q_{req,i,t}}$	Reliability (quantity/quality)
Soc^{Env}	$Soc^{Env}_t = \frac{\sum ((R_{t,j}/R_{new,j}) \times A_{w,j})}{\sum A_{w,j}}$	Structural efficiency (system age)
Env^{Soc}	$Env^{Soc}_t = \frac{\sum (GHG)_{red,t}}{\sum (GHG)_{gen,t}}$	Environmental consequence benefit (GHG emission)
Env^{Env}	$Env^{Env}_t = \frac{\sum E_{gen,t} + \sum E_{rem,t}}{\sum E_{sup,t}}$	Environmental impact
Env^{Eco}	$Env^{Env}_t = \frac{\sum (Q_{del,i,t} \times h_{i,t})}{\sum (Q_{sup,i,t} \times h_{i,t})}$	Energy efficiency

* Variables: $A_{w,j}$ = water flow area of j th pipe (m^2); BI = burdensome index; C_t = required cost, including construction, operation, and maintenance for all components of the WDS at time t (\$); $E_{gen,t}$ = generated energy at time t (J); $E_{rem,t}$ = amount of remaining energy in the system at time t (J); $E_{sup,t}$ = supplied (required) energy resource at time t (J); $E(Q_{leak,i,t})$ = expected water leakage at i th leakage location at time t (m^3); $ECLIPS_i$ = economic outcome i th node ($\$/m^3$); $G_{w,t}$ = water Gini coefficient at time t ; $h_{i,t}$ = head at i th node at time t (m); $i = 1, \dots, n_{nodes}$ = number of nodes; $j = 1, \dots, n_{link}$ = number of links; $P_{i,t}$ = revenue of i th node at time t (\$); $Q_{del,i,t}$ = delivered water demand (demand of EPANET) at i th node at time t (m^3); $Q_{req,i,t}$ = required water demand (base demand of EPANET) at i th node at time t (m^3); $Q_{sup,i,t}$ = supplied water demand from i th node at time t (m^3); $R_{t,j}$ and $R_{new,j}$ = roughness of the j th pipe at time t and when new ($t = 0$); $U_{i,t}(c)$ = combined utility of i th node at time t .

Economic factors (triangles in Figure 1) investigate the value to the utility, customer, and environment by the WDS service, where Eco^{Eco} is the value of the water utility, which is the ratio of revenue (mainly from a bill) and associated costs (e.g., from construction, operation, maintenance, etc.). Thus, a higher Eco^{Eco} will be achieved by lower O&M costs or increasing revenues by adjusting the price of water. Furthermore, Eco^{Soc} is related to Eco^{Eco} , but considers the affordability of the water price to customers, which is calculated using the ECLIPS factor introduced by Lee et al. [47] and Lee et al. [48], with consideration of the burdensome index (BI). Unlike Eco^{Eco} , Eco^{Soc} increases when the water price is low and the economic status of customers rises; Eco^{Env} considers the efficiency of the WDS and evaluates the ratio between the total water delivered and supplies (or billing if data is sufficient). In other words, Eco^{Env} estimates water leakage and can be improved once the leaks in a system are reduced.

Social factors are used to evaluate the distribution of benefits around the service area of the WDS. For example, Soc^{Eco} considers the social consequences benefit, which is the equity calculated by the Lorenz curve and Gini coefficient of water. For Soc^{Eco} , equity in the distribution of pressure is a goal and can be improved by regulating pressure, while Soc^{Soc} reflects the reliability of the WDS, which is calculated using demand, pressure, and water quality, as proposed by Shafiqul Islam et al. [49]. Therefore, improving Soc^{Soc} is possible once demand, pressure, and water quality are at acceptable levels. Finally, Soc^{Env} considers the structural efficiency of the system according to its age, as represented by the pipe size and length of weighted pipe roughness, which reflect the average age of the system and can be improved by performing maintenance.

Environmental factors consider the resource usage or environmental impacts of WDS service. For example, Env^{Eco} quantifies energy efficiency and aims to estimate the amount of avoided

energy losses from system failure. Lee and Burian [25] adapted the concept of resilience to reflect efficiency [50,51], which can be increased when energy loss is minimized. The environmental benefits are considered to be represented by the ratio between the amount of greenhouse (GHG) emissions reduced and those generated for the Env^{Soc} factor. Thus, Env^{Soc} can be improved by reducing GHG emissions (e.g., less fabrication of assets, more usage of renewable energy, and more water usage in green areas). Moreover, Env^{Env} considers energy usage and benefits using a life-cycle energy analysis (LCEA) approach [52]. Energy benefit is quantified as the energy generated (e.g., by in-line turbine or pump-as turbine) or available stored energy (e.g., in nodes or tanks).

The nine triangles of the TTL schematic (Figure 1) are combined into an SI measure of WDSs. This SI is determined by calculating the geometric mean of the TTL factors:

$$SI_t = \left(\prod TTL_f \right)^{1/9} \quad (5)$$

where TTL_f is each TTL factor (e.g., Eco^{Eco} , Eco^{Soc} , Eco^{Env} , etc.) and SI_t is the measure of sustainability of the WDS in the t th year, where the average SI_t over time provides the SI for the analytical period:

$$SI = \int_{t=1}^{LC} SI_t dt / LC \quad (6)$$

and LC is the duration (in years) of the life cycle or planning period. In contrast to the other studies reviewed, Lee and Burian [25] tested the TTL model with solutions to those issues having generally understandable trends in sustainability; for example, pipe aging is negatively correlated with sustainability. As a result, the aging of pipes, increase in water demand, reduction in water prices, and increase in the frequency of pipe breakage reduced sustainability.

3.3. Sustainable Development of Water Distribution Systems

Here, we summarize sustainable development examples from selected studies, including the quantitative measures and approaches employed therein. Examples are divided into three categories based on their consideration: (1) environmental impacts, (2) TBL objective, and (3) multi-objective. The first category includes studies that only considered environmental impacts. Research considering economic, social, and environmental objectives are included in the second category, and any other studies with multiple objectives in one sustainability component are classified into the third category. Each study is reviewed to answer three questions: (1) why selected studies considered sustainability (problem to be solved), (2) what was proposed as solution to solve the problem, and (3) how selected studies quantified sustainability.

3.3.1. Environmental Impact Objective

As most of the existing literature highlights the need for sustainable development with respect to climate change and resource depletion, there have been some attempts to account for environmental impacts induced by WDS operations and maintenance. WDSs require energy to operate (e.g., electricity for pumps), which is associated with GHG emissions [53–55]. Furthermore, even the fabrication of components requires energy (i.e., embodied energy) and resources [26]. A few studies have highlighted this aspect and considered it as the single-objective that must be minimized for sustainable WDS design. All types of energy consumption contribute to GHG emissions. Therefore, researchers have emphasized the importance of the energy-efficient operation and management of WDSs to reduce GHG emissions and minimize environmental impacts.

Filion et al. [26] proposed the LCEA approach, which estimates the embodied energy of a pipe and any associated energy for WDS operation in order to consider its environmental impacts for the purpose of sustainable design. The LCEA is based on the EIO–LCA model developed by the Green Design Institute [56]. A summary of the LCEA approach is shown in Table 6.

Table 6. Quantitative measure of each embodied energy.

Factor	Calculation
Fabrication Energy	$E_f = \sum_i^p L_i e_f$
Replacement Energy	$E_{rep} = n_{i,rep} \cdot \sum_i^p L_i (e_f + e_d)$
Rehabilitation Energy	$E_{rh} = n_{i,rh} \cdot \sum_i^p L_i (R \cdot e_f)$
Repair Energy	$E_{rp} = C_{rp} \cdot \sum_i^p L_i \cdot N_i(t) \cdot e_{b,i}$
Recycle Energy	$E_{rc} = \sum_{i=1}^p (E_{p,i}^r - E_{p,i}^s)$
Disposal Energy	$E_d = \sum_i^p L_i e_d$

Note, p = total number of pipes; L_i = length of the i th pipe (m); e_f = unit energy required to fabricate a pipe (GJ/m); e_d = unit energy required to dispose of a pipe (GJ/m); $n_{i,rep}$ = replacement frequency of the i th pipe during the simulation period; $n_{i,rh}$ = rehabilitation frequency of the i th pipe during the simulation period; R = rehabilitation ratio; C_{rp} = unit conversion factor (km/m/year); $e_{b,i}$ = unit energy required to repair the i th pipe (GJ/break); $E_{p,i}^r$ = energy required for the i th pipe under rough conditions; $E_{p,i}^s$ = energy required for the i th pipe under smooth conditions.

Information regarding the unit energies and calculation examples can be found in previous studies, including [26,52]. In contrast, Pérez-Sánchez et al. [57] reviewed energy recovery practices in a WDS, rather than minimizing energy usage or GHG emissions; this was a data-driven analysis, but energy recovery was concluded to be a sustainable solution by showing an improved, system-wide energy efficiency. Moreover, Pérez-Sánchez et al. [57] showed that energy recovery can be an economic solution even if it depends on the orography, topology, and volume of water consumed in the WDS. In summary, environmental impacts have generally been quantified based on energy usage and GHG emissions following such usage.

3.3.2. Triple Bottom Line Objective

As TBL objectives are considered important under the definition of “sustainability,” they have garnered extensive interest in sustainability assessments. The TBL approaches tend to minimize the impacts on economic, social, and environmental sustainability components. For example, Wu et al. [27] created an optimal WDS design to minimize both GHG emissions and costs as a multi-objective problem. For GHG emissions, they considered not only GHG emissions due to the usage of electricity but also the embodied energy [26]. In their follow-up study [28], they explored the trade-offs between cost and GHG emission objectives and showed that less cost will increase the amount of GHG emission. They also showed the sensitivity of discount rates to final decisions, similar to that which Simpson [58] noted. However, Simpson [58] highlighted the importance of having an accurate discount rate, as sustainability measures tend to analyze performance over a long time and require present values to be estimated based on the discount rate. More recently, Wu et al. [29] added a carbon pricing component into their earlier model [28].

Herstein et al. [30] considered both life-cycle cost (LCC) and an environmental impact index for WDS design. In contrast to other studies, they aggregated three different categories of indices into a single measure and defined it as the environmental impact index. The three index categories were resource consumption (nonrenewable energy use), environmental discharges (air pollutants, toxic releases into the air, water, and land), and environmental impacts (ecological fossil fuel footprint), and each category included several measured indices. Evaluating the environmental impact index starts by evaluating the measure indices. Once these are quantified, the categorical indices are computed as averages of the measured indices. Finally, the environmental impact index is determined by assigning

stakeholder weights for each category. Herstein et al. [30] applied the environmental impact index with LCC to design WDSs; as a result, the pumping cost was found to be a major contributor to increasing both the total cost and environmental impact, while pipe cost did not significantly affect the total cost or environmental impacts, but did significantly influence pumping costs.

Kang and Lansey [31] utilized a TBL approach to support decision-making for dual distribution system planning. Economic impacts were considered to include pure capital and the O&M costs of pipes and pumps. For environmental impacts, GHG production was considered, and the GHG emissions from manufacturing (i.e., embodied energy) to production, due to pump operation, were covered. Finally, system reliability was considered to quantify the social impact and the evaluation of sustainability was solved as a multi-objective problem. Note that system reliability is the percentage of total demand delivered to customers which calculated as the ratio between serviced demand and total demand. For each impact, the maximum values were used to normalize each objective function within 0–1. Kang and Lansey [31] concluded that a dual water distribution network could improve sustainability.

Arif et al. [32] considered LCC and life cycle emissions as an objective function while constraining reliability (>0.8) [59]. LCC includes capital, operational, maintenance, and repair costs, and the present net value (PNV) is applied to all costs except for capital costs. Life-cycle emissions include three stages: fabrication, installation, and operation. Data for estimating emissions were collected from multiple studies [60–62]. Reliability has been quantified based on breakage probability following [59]. Arif et al. [32] designed a WDS by determining the pump characteristic curves and pipe diameter and concluded that LCC alone is not sufficient to achieve a sustainable design.

Nault and Papa [33] presented a methodology that combined a process-based LCA with an EIO-LCA model to quantify the PNV LCC, energy consumption, and GHG emissions associated with a WDS pump. Operating factors, such as control via discharge valve throttling, pump deterioration, and refurbishment, were also considered. The sustainability measures of interest were PNV LCC (measured in \$USD), gross energy consumption (measured in GWh), and GHG emissions produced (t-CO₂-eq). The results showed that a combination of refurbishment and variable-speed pumping was the most effective means of improving sustainability.

Lee and Burian [7] and Lee et al. [34] present examples of TTL applications for the sustainable development of WDSs. In both studies, the aging problem of WDSs was noted. Lee and Burian [7] determined optimal pipe replacement and demand management strategies to improve the TTL of a WDS. Their results showed that sustainable solutions tend to replace pipes earlier than economic ones, and both higher and lower demand changes were ultimately unsustainable. However, the total cost of the sustainable solution was greater than that of the economic solution; therefore, increases in user fees were recommended to compensate for the increased total cost. Lee et al. [34] provided a solution to recover the increased total cost by increasing user fees. For this, they constructed a hybrid system dynamics (H-SD) model and analyzed the interconnections among different factors affecting sustainability. Water price elasticity was added to account for the social response to increased water fees. As a result, frequent increases with lower water price increases in rates were preferred for the higher water price elasticity system (i.e., sensitive to changes in water price).

In summary, there have been several studies that were purely focused on the components of sustainability in which researchers aimed to minimize impacts or maximize the benefits of each component to develop a sustainable WDS.

3.3.3. Multi-Objective

The many-objective problems of sustainability enhancement have been demonstrated in some studies by including the three pillars of sustainability, as well as other components (e.g., resilience, water quality, and structural soundness). For example, Koo and Ariaratnam [35] developed a multi-criterion sustainability evaluation tool, the sustainability assessment model (SAM), which considers four objectives for enhancing sustainability: (1) minimizing environmental impact, (2) maximizing economic

benefits and outputs, (3) social and cultural conservation and promotion, and (4) satisfying basic requirements, such as structural soundness and capacity. Such objectives were evaluated using six modules that took both qualitative and quantitative approaches. The first module was an analytic hierarchy process, which assessed twenty-nine sustainability indicators; these were qualitative and divided into economic, environmental, and social aspects. The second module was a real cost estimation module. The real cost considered individual economic impacts, including detailed direct construction and indirect costs (e.g., restoration, social costs, and environmental remediation costs). The third and fourth modules were focused on pollution and energy estimations and both were related to air emissions (GHG emissions) as a consequence of fossil energy consumption. Each module accounted for the generation of pollution and energy consumption. The fifth module was a time estimation module, which treated the length of construction time as a reflection of economic, environmental, and social impacts. The last module was a resource depletion analysis, which focused on nonrenewable natural resource consumption and the estimated depletion rates of such resources. Once these six modules had assessed sustainability, a weighted sum model was utilized to integrate the results.

Farmani and Butler [36] investigated the performance of a WDS with different urban forms (compact/uniform, monocentric, polycentric, and edge development), in which each urban form represented different socioeconomic scenarios. For each form, the total cost, resilience [63], and water quality were evaluated for different urban growth rates to identify the most sustainable form of development. A multi-objective optimization problem was constructed following Farmani et al. [64] except that water quality (water age) was considered. With the model, pipe sizing, pump design and operation, and tank characteristics were determined, and they concluded that an accurate growth forecast and associated demand are important for determining the capacity of a system to manage supply and demand. Meanwhile, Aydin et al. [37] applied the methodology proposed by Aydin et al. [23] to investigate both the technical and environmental sustainability of a WDS using reclaimed water to meet the non-potable water demand. Technical sustainability was evaluated using their earlier methodology [23] while environmental sustainability was calculated according to the energy intensity, which is the total energy consumption of a network divided by the total energy requirement. Trade-offs between technical and environmental sustainability were then identified by simple additive weighting.

Piratla [38] described the increased interest in growing carbon emissions and the scarcity of renewable energy in sustainability, along with resilience. In this regard, they considered three objectives (LCC, life-cycle CO₂ emissions [62,65], and resilience [66]) to optimally design a WDS to achieve sustainability and resilience. Additionally, design solutions were investigated with respect to social benefit, which was evaluated by the cost of reducing CO₂ emissions (\$20/ton CO₂ emission). To that end, Piratla [38] concluded that solutions with lower CO₂ emissions may have higher costs, but this will payout throughout the life cycle by counting the cost of reducing CO₂ emissions. Cunha et al. [39] also highlighted that sustainable solutions should take into consideration a wide range of possible future scenarios as noted by Loucks [40]. Furthermore, Cunha et al. [39] considered four dimensions in their study: economic, environmental, reliability, and societal. These dimensions were quantified by investment cost, carbon emissions, and resilience/reliability. Investment costs were estimated by considering the PNV, and only the carbon emissions of the pipe were considered based on the methodology proposed by Marques et al. [67]. For resilience, a minimum generalized resilience/failure index [68] was considered, and loop diameter uniformity [69] was considered as an indirect measure of reliability. Most importantly, Cunha et al. [39] adopted a phase design to account for uncertainties in future scenarios. The future scenarios considered included pipe aging (initial Hazen–Williams coefficient of 130 and reduced by 2.5 per decade), and demand scenarios were based on variations per phase. They considered four phases, including current time (i.e., year = 0) and each phase was 25 years in length; thus, Phase 2 began in year 25, and so on. For each phase, different demand variations were given to proportion to the base demand (e.g., demand in Phase 1), and constant changes of a 25%

increase in the maximum variation per phase or a 5% decrease in the minimum variation per phase were employed.

4. Discussion and Recommendations

In general, the need for sustainability has been widely agreed upon. However, no consensus on the definition or evaluation of sustainability has been reached. Therefore, we considered the issues identified from sustainability indices and measures and sustainable development applications in the literature to develop recommendations for improving WDS sustainability.

4.1. Quantitative Measures of Water Distribution System Sustainability

Overall, two SIs and one SM were identified to measure the sustainability of WDSs. Here, we compare these measures from three different aspects: (1) ease of application, (2) interpretation of the final value(s), and (3) validation of the measure. For the sake of simplicity, the SI proposed by Aydin et al. [23] is denoted as “SI_Aydin,” and that proposed by Lee and Burian [25] is denoted as “SI_Lee.”

In terms of the ease of application, SI_Aydin has an advantage over other methods as it only requires EPANET input files, while both SM and SI_Lee require specific data. Thus, other measures are site-specific and difficulties may arise when applying them to different networks, though this also indicates that SI_Aydin might provide limited information about the sustainability of a given WDS. Nevertheless, SI_Aydin can be improved by adding additional performance and its satisfactory and unsatisfactory states, which would also require a new direction to compute the SI in Equation (2). For example, if considering economic performance, budgetary constraints may be set and the SI defined as 1 when the total cost is less than the budgetary constraint; otherwise, it is computed as a ratio of the budgetary constraint to the actual cost. In this case, the weights to calculate the overall SI in Equation (3) should be defined. Regarding SM, some of the indicators (1, 4, 11, and 12) may involve personal judgments, as their exact boundaries are unclear. Moreover, some of the indicators (2, 3, 5, 7, 8, 9, and 10) require too much detailed information, which brings the acquisition of sufficient data into question. Furthermore, SI_Lee also requires detailed data, such as that from ECLIPS, which needs to classify each demand node with an appropriate NAICS code that might not be available for different networks. However, this issue can be overcome if customers’ income information is available (i.e., ECLIPS is unnecessary if affordability can be estimated using a different approach).

The common feature missing from all sustainability measures was a clear interpretation of the final result. Evaluating sustainability levels involves new and emerging criteria; it is often difficult to identify the maximum and minimum values or thresholds with which to define a system as sustainable or unsustainable [70]. As SM did not provide a specific example, it is unclear how the sustainability state might be determined under this approach. Each criterion of SI_Lee is a ratio of a benefit to a cost, so a value of 1 indicates a break-even point, but further details (e.g., threshold to define sustainability) besides this information were not given. However, SI_Lee used the variation of SI in different timesteps to assess the trends of changes in the SI and identify whether a system was sustainable or unsustainable. Only SI_Aydin provided a sustainability state based on the SI_Aydin range (Table 3). Even though it is given roughly, this type of systemized interpretation helps in understanding the sustainability state of a system. However, this is still an issue. SI_Aydin is based on the methodology of Loucks [40] whose method was based on the assumption that less risk is better for sustainability. While this may provide a good representative of sustainability for the current state, it is uncertain whether the performance will be retained in the future. In other words, it is missing the important sustainability characteristics of “now and (in) future generations.” Therefore, there is no evidence that a higher SI_Aydin magnitude will lead to higher values of sustainability in the future.

The last and most important step in demonstrating that a proposed measure can provide reliable conclusions is validation. In fact, most of the sustainability measures proposed lacked this step, rendering their conclusions doubtful. Rodríguez López and Fernández Sánchez [70] mentioned that this is mainly the result of a short history of sustainability evaluations. Therefore, there is insufficient data to judge whether a certain scenario or condition may be sustainable or not. Neither the SI_Aydin nor SM approaches included this step, while an attempt was made to validate SI_Lee with known-as unsustainable scenarios (e.g., aging, demand increase, etc.). Even though Lee and Burian [25] tried to validate their method and provide a graphical representation with which to identify sustainable and unsustainable states, this has not been tested in different systems or under different conditions/scenarios. To provide a generalized measure, more tests should be conducted. Additionally, the uncertainties of parameters should be discussed, as Simpson [58] and Wu et al. [28] noted that some time-dependent parameters (e.g., discount rate) are highly sensitive to the final results.

In summary, all three sustainability measures showed room for improvement. First, as the general definition agreed on consideration of all three sustainability components, it is important to consider all components to provide a holistic view. Second, validation of the sustainability measure with acceptable scenarios/conditions is in need to improve the reliability of the final results. In addition, this will help to provide a reference for determining states of sustainability depending on its value. Lastly, the downscaling of final results to the criteria level is required to identify weakness (i.e., low criteria). The SI may provide a different graphical tool, such as a spider or radar diagram that expresses the valuation of a project or alternative in relation to each indicator or dimension, to solve the problem.

4.2. Sustainable Development of Water Distribution Systems

In general, most of the sustainability measures and sustainable development studies considered resource depletion and climate change. From this perspective, many tended to consider the environmental impacts of the sustainable development of WDSs. The most common ways to consider environmental impacts are based on energy usage and GHG emissions. The economic component is also an uncontroversial part, as LCC is a traditional approach for planning and managing WDSs. The social component was the least-considered component of sustainability. However, reliability has been actively selected when considered. There have been some considerations in addition to sustainability components, such as resilience and water quality. As sustainability is usually considered for a longer duration, most of the studies considered the life cycle of the WDS of interest.

One interesting trend captured was that most studies were focused on minimizing impacts. This is important but it has a limitation in that minimizing impacts does not always translate into maximum benefits [8]. Returning to the definition of sustainability, the key issue is the satisfaction of sustainability components now and for future generations. Reflecting on this, the main focus should be on achieving a balance between usage (costs) and gain (benefits), not just minimizing usage, so the future generation can at least start at a similar starting point. However, minimizing impacts is often the focus of end-of-pipe initiatives in which negative effects are managed to produce fewer adverse outcomes. For example, new technologies might have higher implementation costs, which will lead to higher economic impacts at a glance, but the other benefits might outweigh the economic impacts [15]. In this simple example, a strategy focused purely on minimizing impacts will likely not implement the new technology because it cannot identify the other benefit. Likewise, while there is nothing wrong with such an approach, minimizing the negative effects (minimizing impact/usage part) will simply slow ecological destruction without mitigating it (maximizing benefit/gain part). Moreover, this approach can obscure opportunities to pursue innovation and create value in the design process by limiting economic constraints. Thus, quantitative measures of sustainability must evolve to focus on restorative and regenerative systems, and not simply seek to minimize impacts; for example, they should consider the balance between usage and gain rather than the usage alone.

Another limitation to the existing literature is that the majority of sustainability measures only take direct interactions into account from the water utility perspective, although the communities that receive water also have indirect (cascading/consequential) interactions [71–73]. Neglecting these consequential interactions and minimizing impacts may result in WDS designs that simply repeat the history of environmental degradation that emerged from the industrial revolution [74], and may lead to solutions being less innovative [15,46]. As Lansey [18] indicated, sustainability can have two different definitions: (1) infrastructure and (2) resource. Evaluating the continuous service of a WDS to support social activities by transporting environmental resources is “infrastructure sustainability,” which most sustainability measures consider; on the other hand providing continuous support from social and environmental resources for WDS service is “resource sustainability.” A lack of resource sustainability may lead to false sustainability by assuming that resources are always refilling (e.g., a WDS in a shrinking city). Thus, WDS sustainability should include both infrastructure (WDS) and resource sustainability by identifying interactions among all stakeholders, not just from a utility perspective.

5. Conclusions

Multiple challenges may jeopardize the performance of WDSs even though sustainability has become an important criterion for their planning and management. This paper comprehensively reviews the current status of quantitative measures of sustainability proposed for WDSs and sustainable development practices therein. Overall, three sustainability measures and fifteen sustainable development studies were selected for review.

By comparing three sustainability measures, three important requirements of sustainability measures have been identified. First, sustainability measures should consider all components to provide a holistic view. Second, sustainability measures should be validated with acceptable scenarios/conditions and provide a sustainability state depends on its value. Lastly, the downscaling of final results to the criteria level is required to identify weakness (i.e., low criteria).

Environmental impacts and economic components were the most popular considerations for defining sustainable development in the literature reviewed. In most cases, energy usage and GHG emissions were used to evaluate environmental impacts, while LCC was utilized to quantify the economic component. For social impacts, reliability was widely selected. Additionally, LCA was implicitly considered to investigate levels of sustainability, as it generally involves longer simulation periods. Though they were not considered as major criteria, resilience and water quality were also evaluated in a few studies. One interesting trend captured was that most studies were focused on minimizing impacts such that they may slow (but not stop) ecological destruction. Instead, we recommend that a balance between usage (costs) and gain (benefits) be considered in future studies. Finally, indirect (cascading/consequential) interactions were also needing to be considered. As the justification for the existence of a WDS is the prosperity of the community, interactions among all stakeholders must be identified to move toward sustainable development. In summary, existing quantitative measures of WDS sustainability and sustainable development practices require advancement to accommodate a focus on restorative systems, maximize benefits, and enable multidisciplinary and broader analyses.

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