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Article

Guidelines for the Technical Sustainability Evaluation of the Urban Drinking Water Systems Based on Analytic Hierarchy Process

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Abstract: The challenge of achieving and measuring urban water sustainability is hard because of its complex nature. The sustainability of urban drinking water system (UDWS) is no exception, as integration of technical, environmental, social, economic, and institutional elements of sustainability is defying and perplexing in terms of its application and evaluation. This paper deals with the technical aspects related to the design, construction, operation, and maintenance factors of a UDWS. Measurement of the status of such factors is almost impossible in generic formats. Therefore, a list of measurable sub factors was developed through an extensive literature survey and refined by involving appropriate stakeholders. This led to the development of a hierarchy from criteria to factors and from factors to sub factors, making a case for the utilization of an analytic hierarchy process (AHP) for multicriteria analysis (MCA). Appropriate stakeholders were included in this research to address the issues for which there were major gaps in the literature. A set of guidelines were developed for the evaluation of the status of various sub factors in a quantitative format. It is concluded that a trans disciplinary framework, the involvement of stakeholders, and guidelines for adopting appropriate processes and techniques may improve the sustainability of stressed urban water systems.

Keywords: AHP; guidelines; technical sustainability; urban drinking water systems; urban water resources

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1. Introduction

The concept of sustainable urban water resources has been under focus for the last few decades and well-received across the globe. Over the past few decades, sustainability evaluation as a prediction tool to guide decision makers towards sustainability has arisen in a variety of forms around the world. This vast discipline of sustainability assessment encompasses a variety of processes that are always changing, making the area conceptually complex and potentially challenging. In light of this, several attempts have been made to create conceptual frameworks to make sense of the diversity of practice. Focusing on water supply, a sustainable water system is essential for the social and economic health of urban society. Rapid urbanization, climate change, and economic development threaten access to safe and sufficient drinking water [1]. Water security for large urban areas has been and continues to be a challenge. The extraction of natural water resources is under extreme pressure as a result of rapid urbanization. Water stress in the urban sector has increased as a result of unrestrained water extraction. A rapid increase in the number of water-stressed cities was observed at the beginning of this millennium [2] due to a surge in household and end use of water. Consequently, an increase in the number of household-use studies was also observed, especially after 2010. Figure 1 provides a review of scientific studies reporting water usage at various levels in urban areas.

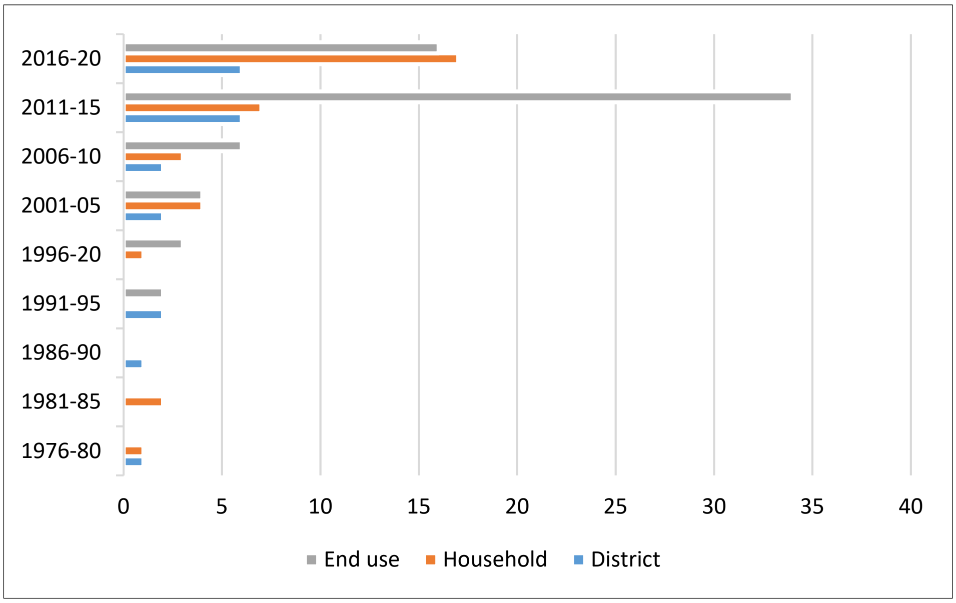

Figure 1. A review of scientific studies reporting water usage at various levels in urban areas (Source: [2]).

Water sustainability involves not only technical issues but also environmental aspects, such drainage issues, surface water body contamination, and groundwater table depletion. An integrated, adaptive, coordinated, and participatory approach is needed for sustainable urban water management. Urban water management is still a complicated and dispersed field that relies on conventional, technical, and linear management procedures.

As mentioned earlier, increasing urban water demand while maintaining both quality and quantity poses a great challenge to institutions responsible for water supply [3]. Researchers assert that the criteria indicated by the triple bottom line (TBL: environment, economy, and social equity) alone cannot provide a suitable structure to determine the sustainability of an engineering project such as an urban drinking water system (UDWS). It requires the involvement of technical and institutional aspects as well [4–7]. Optimum design, construction quality, and operation and maintenance are crucially important to maintain the physical health of a UDWS and achieve sustainability.

This research paper focuses on technical sustainability evaluation and is a part of a separate comprehensive study being carried out to assess the overall sustainability status of UDWS.

2. Methodology

The sustainability of UDWS was evaluated by identifying relevant criteria, as well as their factors and sub factors, through an intensive literature survey and expert stakeholder consultation. The framework developed by Rehman et al. [8], as shown in Tables 1 and 2, integrates not only the basic criteria of TBL but also technical and institutional aspects that are important to be considered in cases of an engineering project such as a UDWS.

Table 1. A brief description of criteria for the selection of stakeholders.

Stakeholders	Description
Technical stakeholders	Experts dealing with optimization of design, its safety against threats and construction quality, optimized water quantity, water quality at the consumer end, reliability, and the physical condition of the system.
Environmental stakeholders	Experts dealing with the capacity of water sources, their reliability in terms of quality and quantity, and their protection against natural and anthropogenic factors.
Economic stakeholders	Experts dealing with financial management for operation and maintenance of UDWS and their economic impacts.
Social stakeholders	Experts working in the field of social sciences related to public awareness of water-related issues, water usage practices, and population coverage in terms of numbers and sectors of society.
Institutional stakeholders	Officials and experts working with institutions related to overall management of UDWS including operation, maintenance, and rehabilitation.

Table 2. Framewok for sustainability assessment of UDWS.

Goal	Criteria	Weights (W_c)	Factors (F)	Weights (W_F)	Subfactors (f)	Weights (W_f)	SF Status (%)	Sustainability Score	Sustainability Results	Conclusions
1	2	3	4	5	6	7	8	9 = 7 × 8	10	11
To evaluate sustainability of an urban drinking water system (project)	Technical	18.19	Design and Construction	8.98	Design optimization	2.99	St_{111}	s_{111}	$\sum_{S124}^{S111}$ S1	Sustainable / Partially Sustainable / Not Sustainable
					Safety against threats and disasters	2.99	St_{112}	s_{112}		
					Construction quality	2.99	St_{113}	s_{113}		
			Operation and Maintenance	9.21	Optimized water supply	2.30	St_{121}	s_{121}		
					Physical condition of distribution infrastructure	2.30	St_{122}	s_{122}		
					Water quality at consumer end	2.30	St_{123}	s_{123}		
					Reliability–resiliency–vulnerability (RRV) index of distribution system	2.30	St_{124}	s_{124}		
	Environmental	27.86	Source capacity	12.97	Existing capacity	6.49	St_{211}	s_{211}	$\sum_{S222}^{S211}$ S2	
					Reliability of source for design period	6.49	St_{212}	s_{212}		
			Source quality	14.89	Water quality at source	7.44	St_{221}	s_{221}		
					Source protection	7.44	St_{222}	s_{222}		
	Economic	19.73	Finances	9.82	Reliability/continuity of finances	4.91	St_{311}	s_{311}	$\sum_{S323}^{S311}$ S3	
					Recovery for depreciation/cost recovery	4.91	St_{312}	s_{312}		
			Benefits	9.91	Direct benefits	4.96	St_{321}	s_{321}		
					Indirect benefits	4.96	St_{323}	s_{323}		
	Social	20.11	Awareness	10.74	Awareness of water-related issues	5.37	St_{411}	s_{411}	$\sum_{S422}^{S411}$ S4	
					Water usage practices	5.37	St_{412}	s_{412}		
			Involvement	9.36	Equity	4.68	St_{421}	s_{421}		
					Inclusion	4.67	St_{422}	s_{422}		
	Institutional	14.11	Capacity	5.94	Human resources	1.98	St_{511}	s_{511}	$\sum_{S523}^{S511}$ S5	
					Technical resources	1.98	St_{512}	s_{512}		
					Financial resources	1.98	St_{513}	s_{513}		
			Effectiveness	8.17	Integrated approach	2.72	St_{521}	s_{1521}		
					Preventive and remedial measure plans	2.72	St_{522}	s_{522}		
					Continuity of service to consumers	2.72	St_{523}	s_{523}		

Once the criteria are established, AHP, a multicriteria analysis technique developed by Saaty [9] was applied to determine relative weights of each criteria.

According to a number of criteria, the respondents in this study are referred to as "stakeholders". The term "stakeholders" refers to specific identifiable groups of people who have the power to influence or be impacted by a system or on whom the system is dependent. In keeping with this definition, the ICWE [10] and UNCED [11] define stakeholders as users, planners, and policymakers at all levels. Based on this definition and sustainability criteria, experts dealing with *technical, environmental, economic, social*, and *institutional* aspects related to UDWS were selected as the stakeholders for this research, as further elaborated in Table 1.

In order to measure the sustainability of a UDWS, a framework was proposed by Rehman et al. [8], as shown in Table 2. This framework integrates the basic sustainability criteria included in TBL with the technical and institutional aspects of UDWS.

A hierarchy of criteria, factors, and sub factors has been developed in this framework, which again depend upon certain parameters which are discussed later in this paper.

On the basis of the proposed guidelines, each parameter was observed for its existing/design value. The status of each parameter was thus determined by calculating the difference between the benchmark and observed value in terms of percentage. The summation of calculated values of parameters determined the status of each sub factor in percentage. Criteria, factors, and sub factors are given in columns 2, 4, and 6 respectively. Column 8 was developed on the basis of the guidelines proposed in the current study. The sustainability score of each sub factor (column 9) was calculated by multiplying values from columns 7 and 8. The overall score of technical sustainability of the system (column 10) was then evaluated by adding up all values of column 9. (W_C) in column 2 and the relative weights of corresponding factors (W_F) in column 4 were calculated using the AHP technique.

It was found that there is a negligibly slight difference between the calculated sub factors weights (on the basis of AHP) and equally distributed weights. Therefore, equal weights can be assumed for all sub factors within each parental factor. Once the weights of each sub factor are calculated, it is necessary to determine its sustainability score. The sustainability score can be determined only when the existing status of each sub factor is known. This requires guidelines based on which the existing status of these sub factors can be established.

Calculation of Relative Weights of Criteria using AHP

The expert stakeholders provided their opinion on a scale as a pairwise comparison of each criteria with another. An input judgment matrix, as collected in Table 3a, was developed on the basis of this opinion. This matrix was synthesized into a normalized output matrix, shown in Table 3b, that gives the relative weight of each criteria.

For sustainability criteria, respondents' judgment was synthesized by applying AHP, producing a (5 × 5) unit input matrix as shown in Table 3a. The values in the upper half of the matrix (in bold text) were calculated by taking the geometric mean of stakeholders' priorities. A normalized matrix was then developed that provided a relative weight for each criterion, as shown in Table 3b. The letters adopted to represent the criteria are as follows:

T, technical;
N, environmental;
E, economic;
S, social;
I, institutional

To determine the consistency of responses of the opinion holders, the consistency ratio was checked as proposed by Saaty [9], as shown in Table 4. The relative weights were considered finalized with a value of less than 10%. If the consistency ratio was more than 10%, the input opinions were revisited, extreme values of priorities in pairwise comparison were deleted, and the process was repeated. The weights of factors were calculated in the same way if there were more than two.

Table 3. (**a**). Input judgment matrix. (**b**). Normalized comparison matrix.

Based on Respondents' Data						
(**a**)						
	T	**N**	**E**	**S**	**I**	
T	1.00	0.72 *	1.16 *	0.79 *	1.05 *	
N	1.39	1.00	1.19 *	1.81 *	1.99 *	
E	0.86	0.84	1.00	1.04*	1.41 *	
S	1.27	0.55	0.96	1.00	1.70 *	
I	0.95	0.50	0.71	0.59	1.00	
(**b**)						
	T	**N**	**E**	**S**	**I**	**Weights**
T	0.182	0.199	0.231	0.150	0.147	18.19% †
N	0.254	0.277	0.237	0.347	0.279	27.86% †
E	0.158	0.233	0.199	0.199	0.197	19.73% †
S	0.232	0.153	0.192	0.191	0.237	20.11% †
I	0.173	0.139	0.141	0.113	0.140	14.11% †

'*' and '†' represent input values and resulting weights, respectively.

Table 4. Consistency of responses.

Weight Sum Matrix						**Weighted Sum Vector**	**Weighted Sum Vector/Avg.Weight**	λ_{max}	**CI**	**RI (Saaty, 1977)**	**CR = CI/RI**
	T	**N**	**E**	**S**	**I**						
T	0.182	0.200	0.228	0.158	0.149	0.917	5.041	5.052	0.013	1.12	0.01160 = 1.16%
N	0.253	0.279	0.234	0.364	0.281	1.412	5.068				
E	0.157	0.235	0.197	0.209	0.200	0.998	5.056				
S	0.232	0.154	0.190	0.201	0.240	1.016	5.052				
I	0.173	0.140	0.140	0.118	0.141	0.712	5.043				

The consistency of responses was checked and found to be within the allowable limit as described in Table 4.

An overview of the process adopted to evaluate the sustainability of UDWS is illustrated in the flow chart shown in Figure 2.

The methodology adopted for the current research is summarized in Figure 3.

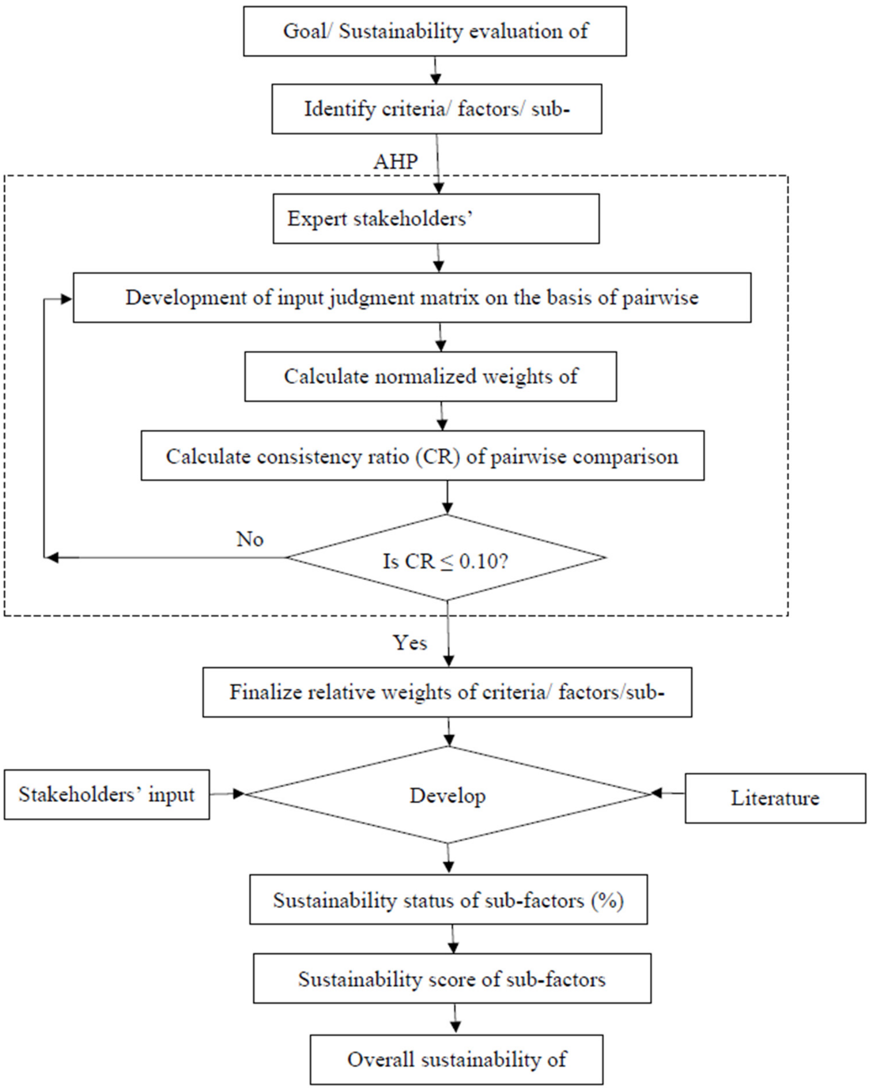

Figure 2. Flow chart for evaluation of the sustainability of UDWS based on AHP.

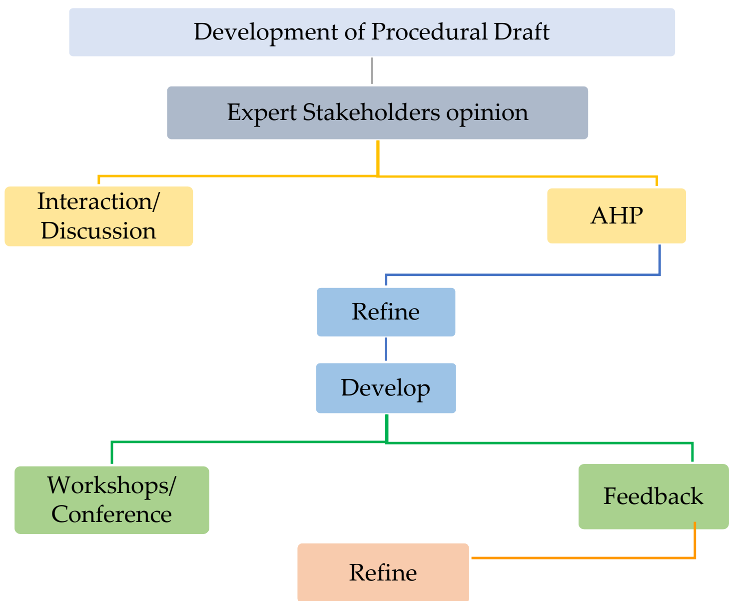

Figure 3. Methodology to develop guidelines for evaluation of the sustainability of UDWS.

3. Results and Discussion

The survey respondents consisted of 105 stakeholders (approximately 50% of the total number of experts approached). The distribution of the respondents is shown in Figure 4, with a relatively higher contribution from technical (29%) and institutional (28%) stakeholders, followed by social (21%), environmental (13%), and economic experts (9%).

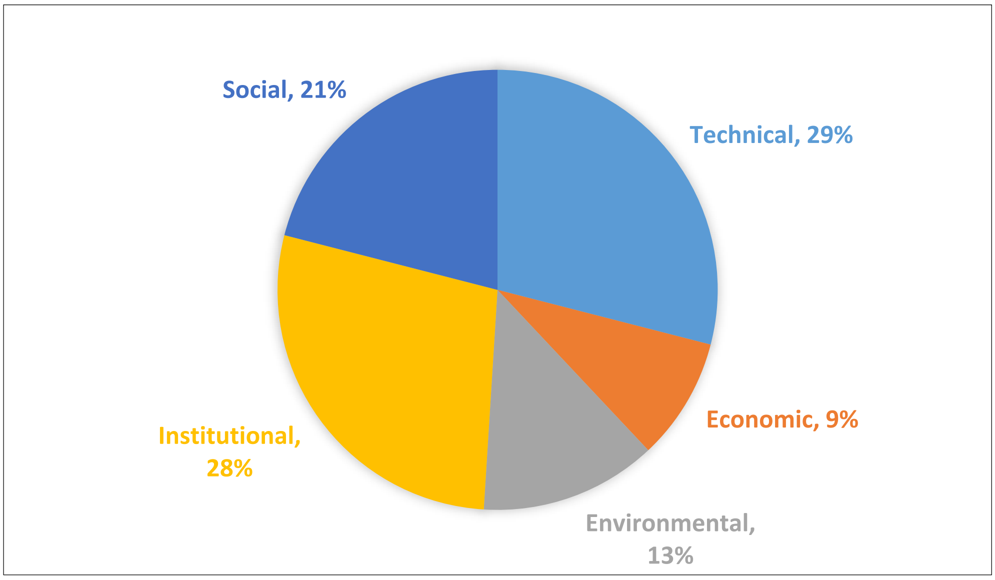

Figure 4. Percentage of respondents from the various groups of stakeholders.

We propose guidelines for the technical sustainability of UDWS in the subsequent sections. The proposed hierarchy of various sustainability criteria, factors, and sub factors is illustrated in Figure 5.

Relative Weights of Factors

On the basis of methodology discussed in the preceding section, relative weights of each sustainability criteria has been calculated. Since there are only two factors for each criteria, the weight for each factor was calculated by taking the geometric mean (GM) of all stakeholder input. Table 5 shows the relative weights of criteria. (W_C) in column 2 and the relative weights of corresponding factors (W_F) in column 4 were calculated using the AHP technique.

Table 5. Relative weights of sustainability criteria and factors.

Criteria	Weight (W_C) %	Factor (F)	Weight (W_F)
	Column 2		Column 4
Technical	18.19	Design and construction	8.98
		Operation and maintenance	9.21
Environmental	27.86	Source capacity	12.97
		Source quality	14.89
Economic	19.73	Finances	9.82
		Benefits	9.91
Social	20.11	Awareness	10.74
		Involvement	9.36
Institutional	14.11	Capacity	5.94
		Effectiveness	8.17

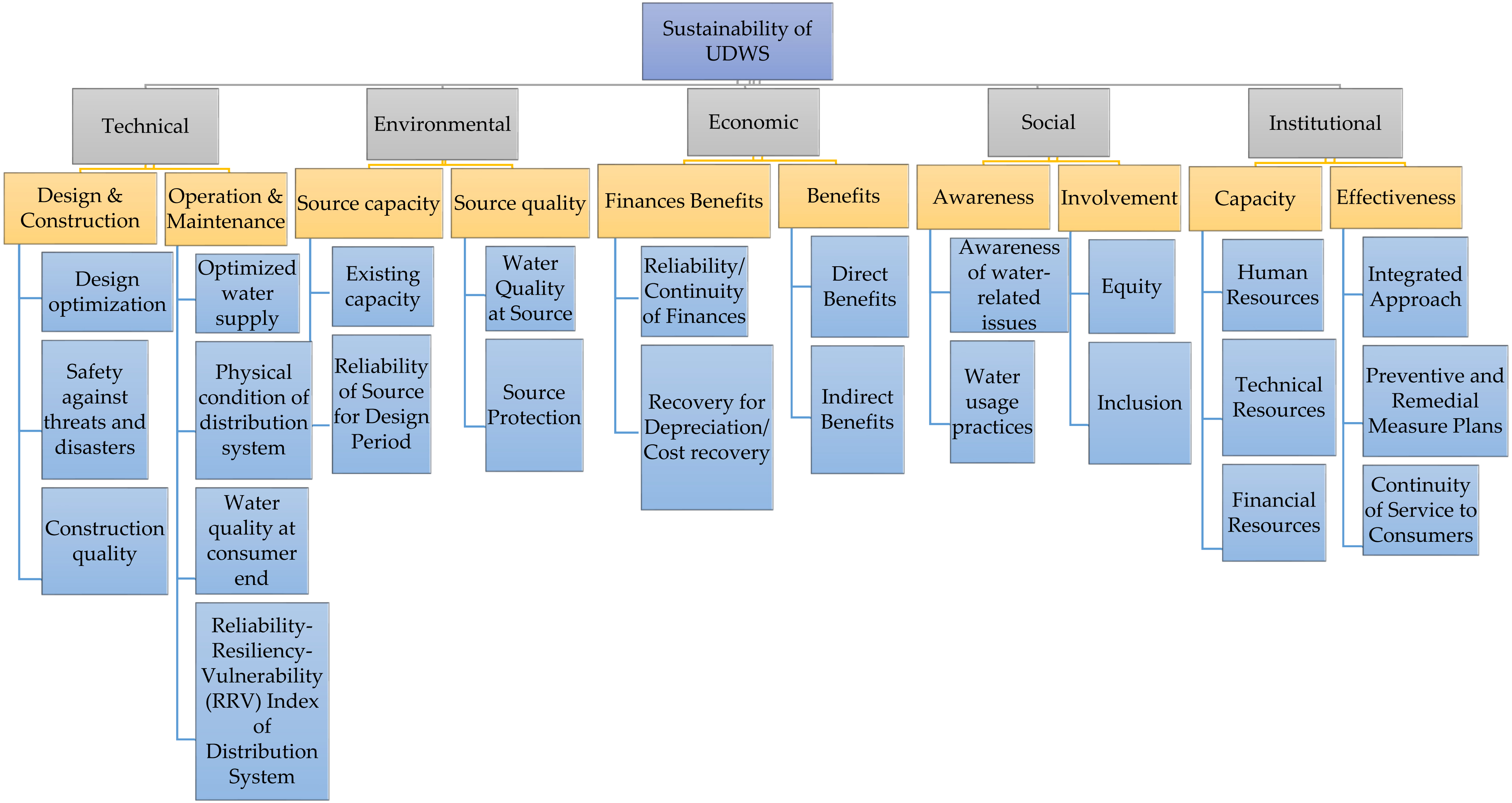

Figure 5. Sustainability criteria, factors, and sub factors for UDWS.

Once the weights of each sub factor are calculated, it is necessary to determine its sustainability score. The sustainability score can be determined only when the existing status of each sub factor is known. This requires guidelines based on which the existing status of these sub factors can be established.

The technical elements presented in Table 5 were aligned and organized in connection with main concepts of the integrating framework for evaluation of their status in the context of sustainability.

Figure 6 shows the relative weights of factors of various criteria. It should be noted that sum of all these weights is 100%. By calculating the existing status of each factor (that may fall between 0 and 100%), the overall sustainability of UDWS can be assessed as a percentage value.

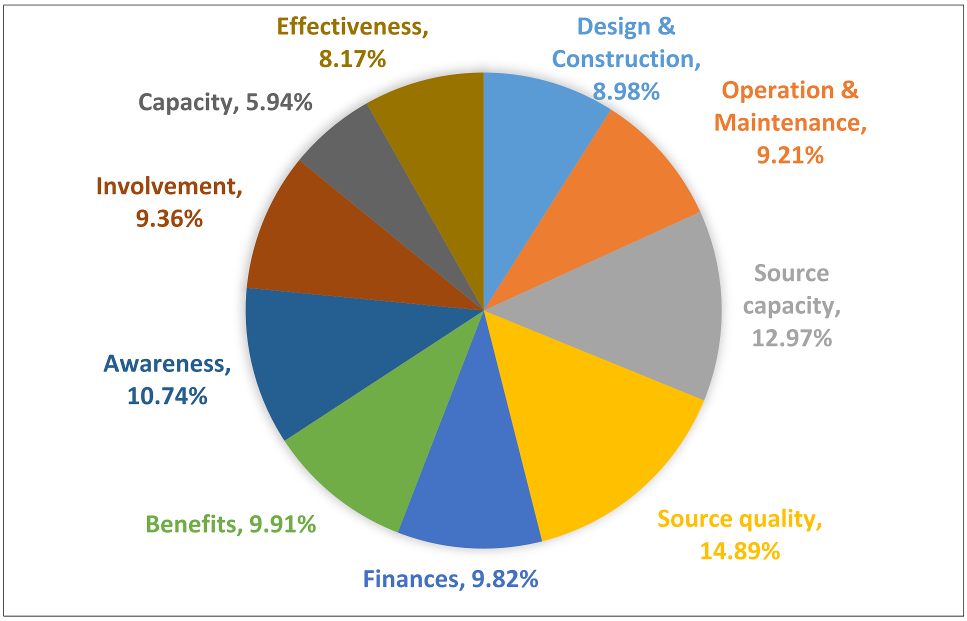

Figure 6. The relative weights of factors of various criteria.

It is important to note that no single blueprint of sustainability of any system can be developed for a universal application without considering the specific environmental, cultural, and socioeconomic conditions. Caution must be taken when adopting this framework and relative weights for considerably different specific conditions.

We emphasize that this paper deals only with technical sustainability, which is one of the five dimensions of overall sustainability of UDWS. The scope of the integrated framework for all five dimensions is much wider than the scope of one research paper. However, it is worth mentioning that this paper provides useful guideline to assess the technical dimension of sustainability of UDWS in its present form. A complete research program near its completion to conclude the holistic framework considering all five dimensions, including the technical dimension presented in this paper.

3.1. Technical Sustainability of UDWS

Researchers have observed that TBL cannot provide a suitable framework to determine the sustainability of an engineering project such as a UDWS, which also requires the involvement technical and institutional aspects [4,5,12]. A number of technical factors have been identified in the literature that have an integrated effect on the technical sustainability of the system. For example, in one case, users had to construct pumps in order to store water in tanks due to the impact of inconsistent pressure on the network's end-user pressure [13]. Additionally, many urban areas in poor nations frequently experience a loss of water pressure as a result of pump failure caused by the high electrical power costs in the water treatment budget [14]. The majority of non-revenue water comes from physical losses (such as leaks) within the system [15,16]. Important determining factors for leakage rates are the state of the infrastructure, the amount of water delivered, and the reliability of the supply [17]. In the developing world, the average rate of unaccounted-for water is between 37% and 41%. Corrosion in pipes and appurtenances at treatment plants and distribution networks result in contamination and leaks.

For technical sustainability, infrastructure should be designed and constructed for optimized demand and supply, safe against threats and disasters, and regularly maintained to ensure safe and sufficient water supply to consumers without interruptions unless required for scheduled and planned operation of the system. Table 6 presents a hierarchy of technical criteria, its factors, and sub factors and their relative weights.

Table 6. Technical criteria of sustainability, as well as factors, subfactors, and their relative weights in a UDWS (Source: [8]).

Criteria	**Weight (W_c)**	**Factors (F)**	**Weight (W_F)**	**Subfactors (f)**	**Weight (W_f)**	**SF Status (%)**	**Sustainability Score**	**Sustainability Results**
2	3	4	5	6	7	8	9 = 7 × 8	10
Technical	18.19	Design and Construction	8.98	Design optimization	2.99	St_{111}	s_{111}	$\sum_{S111}^{S124} S1$
				Safety against threats and disasters	2.99	St_{112}	s_{112}	
				Construction quality	2.99	St_{113}	s_{113}	
		Operation and Maintenance	9.21	Optimized water supply	2.30	St_{121}	s_{121}	
				Physical condition of distribution infrastructure	2.30	St_{122}	s_{122}	
				Water quality at consumer end	2.30	St_{123}	s_{123}	
				Reliability–resiliency–vulnerability (RRV) index of distribution system	2.30	St_{124}	s_{124}	

Technical criteria of sustainability are divided into two main factors:

1. Design and construction;
2. Operation and maintenance.

3.1.1. Design and Construction

Design and construction involve the composition, arrangement, and layout of various physical components of an infrastructure project while maintaining technical and physical planning, in accordance with material and workmanship standards for safety and economy. The use of all resources must be reduced, in addition to reuse and recycling, with careful attention during the design phase. The built facility should be meticulously maintained and managed during the operational phase, requiring renovation at some point during its service life. It should have little to no negative social or environmental effects, thereby meeting the criteria for sustainable development [18]. System failures that are visible in existing sociotechnical systems are linked to persistent issues [19]. When performance is maximized or kept at acceptable levels, technical targets are met. The success of the system is also determined by technical indicators [20].

One or more of the manifestations listed below can be used to demonstrate how water distribution systems are deteriorating [21].

- Reduced hydraulic capacity caused by internal corrosion (i.e., tuberculation) of unlined metallic components or calcium carbonate precipitation;
- Impaired water quality caused by internal corrosion of unlined metallic components, biofilm buildup, and/or inadequate maintenance methods;
- High leakage rates caused by corrosion entering pipe barrels through holes or joints that are degrading;
- Regular failures brought on by corrosion, material deterioration, improper installation techniques, production flaws, and operating circumstances.

Urban water management presents a fundamental challenge due to the abundance of potential supply sources, diffuse pollution sources, varied administrative boundaries, and numerous stakeholders, including various governmental levels. Technical targets are met when performance is maximized or kept at acceptable levels [20].

Sustainability of design and construction of a UDWS involves:

1. Design optimization;
2. Safety against threats and disasters;
3. Construction quality.

1. Design Optimization

For a water supply system, the objective of design optimization is to find the lowest-cost network that can supply the water demands under the given restrictions [22].

Theoretically, a design of a DWS is said to be optimized when the supply of water to the community is neither less nor more than its requirements for living a healthy and dignified life, without over exploitation of natural water sources and with a minimum possible initial and maintenance cost for the entire service life using appropriate materials and machinery. According to our literature review, an optimized design is a design of distribution infrastructure that ensures a safe and sufficient quantity of water for all consumers of a target population for its entire design life (or more) through appropriate pumping at all delivery points [4,23,24].

Design optimization helps to coordinate economic efficiency with operational requirements [25] and to maximize water use efficiency [26]. Therefore, a technically optimal design enables an efficient audit of the technical condition, e.g., deployment of a number of specialized staff, reliable databases, and equipment [27,28]. Thus, it is possible for managerial staff to receive early warnings of contamination [29] so they can plan the optimal time for replacement of existing pipes [30,31] and optimize maintenance and renewal of component parts [32]. Furthermore, the design problem is difficult mainly due to the presence of discrete elements, e.g., pumps, valves, and pipe segments [22]. The majority of the overall expenses of water supply schemes (between 80 and 90 percent) are related to the transmission and distribution networks. Therefore, it is crucial to optimize the design of these systems by careful pipe material selection and alignment of the pipeline pathways [33].

The following main parameters should be established when optimizing the design of a DWS:

i. Design period;
ii. Projected design population for the design period;
iii. Optimum water supply;
iv. Optimum water pressure;
v. Optimized pump efficiency.

   (i) Design Period The design period is the duration for which the system is capable of performing its intended function [34,35]. A system designed to sustain for a certain predetermined design period.
   (ii) Design Population Projected population can be calculated by applying various available methods, depending on trend of population increase [36].
   (iii) Optimum water supply The optimal value of water supply is a function of source capacity for the specified design period. The amount of supplied water

should not exceed the renewal capacity of the source but also be able to address basic needs while maintaining the dignity of human life.

(iv) Optimum water pressure The optimum value of pressure is selected on the basis of source capacity, as well as volume of water supplied. Pressure in pipes is kept between minimum and maximum standards for "safe, reliable, and economic operation" [37,38].

(v) Optimized Pump Efficiency The optimized pump efficiency is the ratio of input hydraulic power provided to water relative to the energy consumed. It can be calculated by the formula given in [23]. Pump efficiency involves the following parameters:

- *Pump Flow Rate*: The total volume of liquid or fluid that moves through a fixed place over time is the flow rate. A flow meter is frequently used to measure this parameter because it can determine the flow rate in any unit as required.
- *Total Head*: The distance between the liquid or fluid source and the pump's output, as well as the pressure the pump is generating at the pump outlet, is used to calculate the total head.
- *The Best Efficiency Point (BEP):* The flow for a certain impeller diameter at which the pump performs at its highest efficiency. When a pump is operated at flows that are either higher or lower than the BEP, this is termed as "operating pumps away from the Best Efficiency Point".

Smaller centrifugal pumps often have efficiencies between 50 and 70%, whereas many medium and larger pumps have efficiencies of 75–93%. Any motor with ten horsepower or more can be engineered to surpass the 90% efficiency mark, and large AC motors approach an efficiency of 97%.

The calculations for the status of design optimization are presented in Table 7.

Table 7. Status of design optimization.

S. No.	Required Parameter	Benchmark (BM) Description	BM Value	Observed Value or Design Value	Calculation of Status
1.	Design period	Time duration for which the system is capable of performing its intended function [34,35].	Benchmark value = x1; Select the nature of population growth: (a) For static growth, benchmark value for design period = x1 = life of distribution mains (yrs.); (b) For a growing population, design life = x1; (c) The absence of any model of population growth.	y1 [For both (a) and (b), if y1 ≥ (2 × x1), then z1 = 0]	*z1 = 1 − [(x1 − y1)/x1]* *If y1 ≥ (2 × x1), then z1 = 0*
2.	Projected design population for design period	Projected population is can calculated by applying one of various available methods, depending on the trend of population increase [36].	Benchmark value = x2; Arithmetic increase method: $P_n = P_o + nx$; Geometric increase method: $P_n = P_o (1 + r/100)^n$; Incremental increase method: $P_n = P_o + nx + n(n + 1)/2]y$.	y2	*z2 = 1 − [(x2 − y2)/x2]* *If y2 ≥ (2 × x2), then z2 = 0*

Table 7. *Cont.*

S. No.	Required Parameter	Benchmark (BM) Description	BM Value	Observed Value or Design Value	Calculation of Status
3.	Optimum water supply	The optimal value of water supply is a function of the source capacity for the specified design period. The amount of supplied water should not exceed the renewal capacity of the source and also be able to address basic needs while maintaining the dignity of human life.	Benchmark value = x3.	y3	$z3 = 1 - [(x3 - y3)/x3]$
4.	Optimum water pressure	The optimum value of pressure is selected on the basis of source capacity, as well as the volume of water supplied. Pressure in pipes is kept between minimum and maximum standards for "safe, reliable, and economic operation" [37,38].	Benchmark value = x3 = 20–40 psi.	y4	If $y4 = x4$, then $z4 = 1$ If $y4 < 20$, $z4 = 1 - [(x4 - y4)/x4]$ If $y4 > 40$, $z4 = 1 - [(y4 - x4)/x4]$ If $y4 \geq 80$, then $z4 = 0$
5.	Pump efficiency	[23]	Benchmark value = x5 $\eta_{pump} = \rho.g.Q.H/P_{mech}$.	Y5	$z5 = 1 - [(x5 - y5)/x5]$
		Status of Design Optimization			$\sum Z \times 100$ (%)

2. Safety against Threats and Disasters to DWS

Emergencies may happen due to threats of hazards and disasters. An emergency can range greatly in severity. Defining categories of severity can help decide the appropriate reaction activities because different levels of emergency call for different levels of response. The following terms are closely related to the safety of the system against threats and disasters:

- *Threats and Disasters:* The Cambridge Dictionary [39] defines 'threat' as a situation or event that can cause harm or violence, especially when a particular action is not followed. 'Hazard' is a situation that only poses a threat when it is in a dormant state; however, when active, a hazard is no longer just a threat but becomes a disaster.

Disaster, according to the Cambridge Dictionary, is an occurrence that results in significant harm, damage, death, or difficulties.

Hazard, threats, and disaster may be used as supporting terms. A hazard is an event when a threat to the system exists in a non-active form. The same threat becomes a disaster when it has occurred and caused destruction.

- *Hazard*: According to Cambridge Dictionary, a hazard is 'something that is dangerous and likely to cause damage'. It may be an action or inaction that has negative effects. The probability that a hazard will materialize and inflict damage (within a given time period) is measured by its likelihood. For instance, if everything else is equal, the risk from current dangers is higher than the risk from hazards that are unlikely to occur in the next ten years.

- *Risk:* Cambridge Dictionary defines risk as 'danger, or the possibility of danger, defeat, or loss'. Risk is the result of combining the severity of the harm that will be caused by a danger with the likelihood that it will occur.

  Risk = Probability of occurrence × Degree of harm

Each water supply system is at risk of the threats posed by natural, as well as anthropogenic effects. This may cause unbearable water quality at the source, during conveyance, or at the consumer end. Moreover, these threats can result in significant loss or reduction in source capacity.

Seismic activities, floods, landslides and erosions, and unpredictable climatic events such drought are among the natural causes that instigate serious water supply hazards. According to Perkins and Hutchings [40], earthquakes are the greatest of all natural hazards to a water supply system. Floods, landslides, fire, and drought are among the other hazards that can impede the functioning of a water supply system. The ASCE/UNESCO joint Task Committee on Sustainability Criteria [41] also stresses the need to include "risk measures and management" of probable system failures and consequences as an important criterion for the overall sustainability assessment of a DWS.

Threats can be against physical components of the system and can exist in the form of a chemical or biological agent or a cyber attack. Ownbey et al. [42] drew attention to the potential of terrorism as a threat to the safety of DWS. Physical damage to a reservoir or above-water tank could result in a long-term reduction in water storage capacity, downstream flooding, and destruction from the ensuing flood wave. Haimes et al. [43] and the WHO [44] recommend plans for coping with the intentional release of biological or chemical agents. The distribution system and storage reservoirs are possibly entry locations for the injection of contaminants into a community's water supply (water mains). Cameras, fencing, resident system operators, facility access policies, guards, and monitors that test the quality of water before and after it enters the distribution system are among the security features used in water supply systems.

Uncontrollable causes are outside the power of the water system operator to prevent. The following significant threats and disasters may be considered when determining the safety of a DWS. If such events cannot be controlled, measures can be taken to act quickly and proactively in case of a disaster [45].

i. Potential hazardous runoff in the watershed and infiltration in distribution lines;
ii. Vandalism, terrorism, and/or accidental contamination in the distribution system;
iii. Earthquakes;
iv. Erosion and landslides;
v. Floods and rains;
vi. Droughts;
vii. Power supply failures;
viii. Structural or operational failures of water supply treatment systems;
ix. Security of reservoirs and system-supporting structures.

Each of the above is discussed as follows:

i. Potential hazardous runoff in watershed and infiltration in distribution lines:

The presence of pollution sources, such as industry, livestock farms, agricultural activities, or wildlife, in the vicinity of a water source generates liquid and solid waste that may find its way into the source and distribution pipes along the runoff caused by rains in the watershed, leading to intrusion of microbial and chemical pollutants [41,46]. Pollution incidents in UDWS are quite frequent, gravely endangering human health [47]. Infiltration of sewage and backflow of contaminated water from consumer facilities is also a major cause of pollution [48].

ii. Vandalism, terrorism, and/or accidental contamination in the distribution system:

Terrorist activity or an unanticipated contamination event may result in massive disruption, contamination, and casualties on a massive scale [49–52].

iii. Earthquakes:

In terms of a drinking water systems, earthquakes generally result in hundreds or even thousands of water pipeline breaks, ruptures in storage and treatment tanks, and the collapse of structures [53]. This may result in a loss of water system pressure, pollution, and interruptions to drinking water supply. As reported in [23], earthquakes are the most dangerous threats because they have the greatest potential to destroy subsurface water supply components (such pipes and valves) and make it difficult to detect and repair the damage.

iv. Erosion and Landslides:

Heavy rains, floods, and earthquakes (and consequent liquefaction) often contribute to landslides, slope failures, and erosion in watersheds, as well as along the distribution network, resulting in rupture or blockage of surface reservoirs, foundation destabilization and acute bursting of pipelines, and heavy loss of water in the reservoir [40,54,55].

v. Floods and Rains:

Component structures of UDWS such as water treatment plants and complementary structures need to be protected against flooding. Flood-control berms boost facility security protect against stream or river flooding. Creek and watercourse flow monitoring helps to the potential of downstream flooding.

vi. Drought:

In terms of the number of people affected, drought ranks number one among all natural hazards as a particularly harmful climate extreme [56]. Droughts have resulted in severe ground and surface water shortage and deteriorated water quality, resulting in economic, social, and environmental impacts [57]. In contrast to other urban disasters (such as floods, earthquakes, and fires), urban drought occurs frequently and slowly with no outward signs.

Drought is a typical climate phenomenon, and it will inevitably happen again. It is the result of a long-term, natural decrease in the amount of precipitation. There are various ways in which drought is different from other natural disasters (such as floods, tropical cyclones, and earthquakes). First, it can be challenging to pinpoint when a drought begins and ends because its impacts frequently develop gradually over a long period and might last for years after the event has ended. In terms of the number of people affected, drought ranks first among all natural hazards as a particularly harmful climate extreme [56]. The *Encyclopedia of Climate and Weather* [58] defines drought as "an extended period—a season, a year, or several years—of deficient rainfall relative to the statistical multi-year mean for a region." Drought results in severe ground and surface water shortage and deteriorated water quality, resulting in economic, social, and environmental impacts [57]. In contrast to other urban disasters (such as floods, earthquakes, and fires), urban drought occurs frequently and slowly without any outward signs. When Cape Town was dealing with the "Day Zero" crisis in 2018, scientists stated, "Too often in Africa and the rest of the globe, actions to reduce drought risks kick off only after a drought hits". The chain effect of urban drought is another noteworthy aspect. Urban drought-related risks can operate like contagious diseases that can spread to other cities. It cannot be said that a water supply is drought-resistant if it solely draws from one water source. Reimagining the traditional urban fabric to enable natural water to be absorbed into the ground is another strategy to increase water supply [59].

vii. Power supply failures:

Power supply failures may be caused by power outages, transmission or distribution line breaks, pump failures, etc.

viii. Structural or operational failures of water supply treatment systems:

Failure of water treatment systems is a common threat that needs to be addressed promptly [41].

ix. Security of reservoirs and system-supporting structures:

This threat involves adequate safeguards against unwanted access to reservoir hatches (fencing, gates and locks, lighting, signs, etc.).

The status of safety against threats and disasters was calculated as shown in Table 8.

Table 8. Status of safety against threats and disasters.

S. No.	Required Parameter	Benchmark (BM) Description	BM Value	Observed Value or Design Value	Calculation of Status
1.	No. of threats to the system	Existence/non-existence of threat to the system	Number of potential threats = 0	Number of various threats to the system, x1	*If* $x1 \geq 2$ *then* $Z = 0\%$ *or* *If* $x1 = 1$ *then* $Z = 50\%$ *or* *If* $x1 = 0$ *then* $Z = 100\%$
Status of safety against threats and disasters					***Z (%)***

3. Construction Quality

Construction quality refers to the attainment of standards in terms of the function and performance of a structure. The inefficiency of water supply infrastructure is caused by not following the sustainability standards, starting with construction quality. For example, the selection of pipe material in the water distribution network governs the design parameters based on hydraulic, topographic, and environmental considerations and determines the socioeconomic acceptance and viability of the system as a whole [6]. Workmanship is linked to specific and measurable qualities. Achieving standards and codes requires certain qualifications for workers, which can only be attained through adequate training, proper instruction, and well-defined checklists. On-site supervision and monitoring is a continuing process to ensure capacity development and skill enhancement of workers. Lee et al. [60] underlined the significance of following standards when installing pipes at shallow depths, which makes them susceptible to vibrations. Quality workmanship is vital in situations in which water pipes are laid in the vicinity of sewers [61]. Faulty construction not only compromises the working standard of DWS but also adds to the losses of the construction company, as it has to deal with the scrap, defects, and rework [62]. Hence, the combination of material and workmanship dictates the construction quality and, consequently, the sustainable functioning of DWS.

Construction quality of water supply systems involves the maintenance of acceptable standards of material and workmanship in setting up a mechanism to transport a safe and sufficient amount of water from the source to consumers. Quality is achieved only when the structure meets the desired material and workmanship specifications.

The following aspects are considered when evaluating the construction quality of UDWS:

i. Physical condition of concrete structures;
ii. Faulty layout of distribution pipes;
iii. Inefficient fixtures.

i. Physical condition of concrete structures: This threat includes the existence of defects such as cracks, honey combing, leaching, crazing, etc., in mains and water reservoirs, as well as the corrosion of metal pipes, pumps, valves, and appurtenances.

ii. Faulty layout of distribution pipes: Pipes laid on the ground or with insufficient soil cover are exposed to impact loads such as vehicular traffic, pedestrians, etc., resulting in pipes running through contaminated water or soil.

iii. Inefficient fixtures: Inefficient fixtures include leaking joints and connection seals; malfunctioning, damaged, or defective valves; and other appurtenances.

Guidelines for sustainable construction quality:

Level 1: If the building's construction quality is excellent and no action is needed to change it, no structure evaluation is necessary.

Level 2: If construction quality is in very good condition, no major immediate measure is required.

Level 3: Although the system's construction quality is above average, it needs to be closely watched.

Level 4: Plans should be quickly implemented if construction quality is in severe condition.

Level 5: If construction quality is in undesirable condition, an immediate solution is required to improve the condition of the structure.

Insufficient input data (N): If construction quality is extremely low.

Status of construction quality can be calculated as shown in Table 9.

Table 9. Status of construction quality.

S. No.	Required Parameter	Benchmark (BM) Description	BM Value	Observed Value or Design Value	Calculation of Status
1.	Construction quality; level 1 to N	Level 1 Level 2 Level 3 Level 4 Level 5 Level N	Level 1 100%	If 1 then x = 100% If 2 then x = 80% If 3 then x = 60% If 4 then x = 40% If 5 then x = 20% If N then x = 0%	$Z = x$
		Status of Construction Quality			***Z* (%)**

3.1.2. Operation and Maintenance

Activities necessary to constantly supply consumers with a safe, appropriate, and dependable water supply are included in operation and maintenance. Operation includes tasks required to provide service, such as maintaining the system's functionality and enforcing rules and regulations. Maintenance includes tasks that keep the system in excellent working order, such as component evaluation, servicing, repair, and replacement [63]. Maintenance can be both proactive and reactive.

Operation is the execution of a practical task or method that enables a machine, system, or plant to operate as a whole or in part to create goods in line with the prescribed procedures.

Maintenance is the work done on equipment or facilities to reduce the risk of damage or a decline in performance caused by corrosion, pollution, or deterioration for ongoing use. Operations and maintenance (O&M) refers to the tasks, responsibilities, and labor required for regular repairs, part replacements, structural component upgrades, and other preservation-related tasks necessary to keep an asset functioning properly and extending its projected life.

System design and construction practices are prerequisites of the O&M of a water distribution system. Unsuitable pipe materials or pipes damaged during construction may be specified in a design, which could cause serious future system operating and maintenance issues.

In addition, effective operation and maintenance are necessary to guarantee that capital expenditures on new infrastructure lead to the supply of sustainable services. Otherwise, a brand-new water distribution system may quickly deteriorate to the point at which service delivery is jeopardized, increasing water losses, financial losses, and consumer health hazards. If operation and maintenance are neglected for an extended period of time, it may be essential to replace the system, necessitating an additional capital input that could otherwise be used for other requirements or to promote economic growth. Operation and maintenance of a DWS involve:

1. Optimized water supply;
2. Physical condition of distribution infrastructure;

3. Water quality at the consumer end;
4. Reliability–resiliency–vulnerability (RRV) index of the distribution system.

1. Optimized Water Supply Optimized water supply, as evident from the term, is the quantity of water provided to consumers according to their needs. In other words, optimized supply is the quantity of water that is neither more nor less than the actual requirement. Loucks 24 suggested a general guidelines for minimum water usage requirements, as presented in Table 10.

Table 10. Basic water consumption.

Type of Use	Suggested (Minimum) (Liters per Capita per Day)	Range (Liters per Capita per Day)
Drinking water	5 [a]	2–5 [b]
Sanitation requirement	20 [a]	20–75 [b]
Bathing and hygiene	15 [a]	5–70 [b]
Food preparation/kitchen use	10 [a]	10–50 [b]

'a' and 'b' represent suggested minimum and allowable range of water requirement respectively.

- For drinking purposes, 5 lpcd is the true minimum requirement to sustain life in a moderate climate;
- Lower values indicate minimum use in developing countries;
- The upper values represent the social preferences for moderately industrialized countries;
- For direct sanitation systems, an average of 40 lpcd is considered adequate;
- For water-rich areas, use may exceed the maximum amount;
- The UN [64] asserts that 50–100 lpcd of water is essential for basic human needs with minimum health concerns. Table 11 presents the calculation for the sustainability status of optimized water supply.

Table 11. Status of optimized water supply.

S. No.	Required Parameter	Benchmark (BM) Description	BM Value	Observed Value or Design Value	Calculation of Status
1.	Optimized Water Supply	Available volume of water within a range that caters to minimum human requirements, at the least, without overrunning the renewal capacity of the source [65].	*50 lpcd min.* or *x* lpcd	y	*If* $y < 50$, *then* $z = 0$ *or* *If* $y < x$ *then*, $z = (x - y)/x$ *or* *If* $y > x$ *then*, $z = (y - x)/x$ *or* *If* $y \geq (2x)$, *then* $z = 0$
		Status of Optimized Water Supply			$Z \times 100$ **(%)**

2. Physical Condition of Distribution Infrastructure

Deterioration of infrastructure affects the environment, institutions, and public health. According to Kleiner and Rajani [66], as cited in [67], there are two types of pipe deterioration: structural deterioration, which reduces the pipe's structural resilience and its capacity to withstand various types of stresses, and functional deterioration of the pipe's inner surface, which reduces hydraulic capacity and degrades water quality. A higher rate of water leakage causes greater water losses, as well as an increased likelihood of water infiltration and exfiltration, which can contaminate the water and cause an outbreak of waterborne disease [68]. Leaks and breaks also cause loss of pressure, causing a significant decrease in supply volume. According to studies, water-main leaks and breaks account for one-third of all water lost in urban water distribution systems [69]. According to extensive research carried out in [62,70–74] and many other studies, the following aspects are effective in determining physical condition of WDS:

i. Number of distribution-main breaks;
ii. Water loss due to leakages (m^3/yr.);
iii. Water loss due to breaks (m3/yr.);
iv. Pump failures (% time, yr.).

The above mentioned aspects are discussed as under:

i. Number of distribution-main breaks:

Rehan et al. [75] consider the number of main breaks an indicator of DWS performance, representing the physical condition of the system. Sahely et al. [74] also consider distribution losses as total volume due to breaks and leaks. Shamir et al. [76] proposed the following reasons for pipe breaks:

- The quality and age of the pipe, joints, and appurtenances;
- The pipe's surroundings, such as external stresses, soil corrosivity, and frost and heaving;
- How well the pipe was laid out in terms of workmanship;
- Pressure and water hammer in supply pipes.

According to Garfi et al. [77], the following are the important factors affecting pipe breaks:

- Method of pipe manufacture;
- Soil type;
- External forces on the main: Shrink/swell; Frost penetration; External corrosion.

Therefore, the number of water-main breaks cab be used as an indicator of the network's physical condition.

ii. Water loss due to leakage:

Leaks develop when joints or service connections are not tightly sealed. It has been asserted that the physical condition of a DWS can be determined by calculating the amount of leakage from the system. O'day et al. [78], as cited in [74], define leaks as "smaller volumes of water lost from loose joints and small main fractures (which are not replaced immediately)" and breaks as "larger volumes of water lost from main fractures (which are usually replaced once they are detected) and from pipes that have burst or collapsed".

iii. Water losses due to breaks:

Break occurs when a main fractures. Breaks usually occur at joints. The major causes of main breaks are excessive loads, temperature, and corrosion. Rehan et al. [75] are of the opinion that if the system experiences more breaks than the specified maximum number, then such pipes should be considered to be highly deteriorated. Shamir and Howard [76] suggested that number of pipe breaks is an important indicator of DWS performance, representing the physical condition of the system. They offered an empirical formula to measure main breaks: 0.1–0.3 breaks/ mile /yr. or 1 to 3 breaks/yr./1000 people served.

iv. Pump failures (% time, yr.):

Cullinan et al.,the DOH, and Kanakoudis et al. [79–81] are of the opinion that pump failure is of equal significance as pipe leaks and breaks with respect to the malfunction of a DWS. Likewise, Haider et al., Kanakoudis et al., the NRC-US, and the USEPA [70,82–84] have declared pump failure as a major performance indicator for system reliability. The WHO, Wagner et al., Shuang et al., Jeong suk Jun et al., and Yoo et al. [62,85–88] have also attributed pump failure, along with pipe leakages and breaks, as a cause of the breakdown of system serviceability.

Pump failures are among the main cause of pressure drops in pipes, allowing infiltration through leaks and joints. Contaminants can therefore enter the distribution system.

The calculation of the status of the physical condition of distribution infrastructure is shown in Table 12.

Table 12. Status of the physical condition of distribution infrastructure.

S. No.	Required Parameter	Benchmark (BM) Description	BM Value	Observed Value or Design Value	Calculation of Status
1.	Number of main breaks	An important indicator of DWS performance that represents the physical condition of the system [74–76].	x1 = 0.1–0.3 breaks/ mile /yr. OR 1 to 3 breaks/yr./1000 people served	y1	$z1 = (x1 - y1)/y1$
2.	Water loss due to breaks and leaks (m^3/yr.)	Smaller amounts of water lost due to cracks and loose joints [78], as cited in [74].	X2 = 20% of total water supplied	y2	$z2 = (x2 - y2)/y2$
3.	Pump failures (% time, yr.)	Pump failure is of equal significance as pipe leaks and breaks with respect to the malfunction of a DWS [79–81] and is a major performance indicator for the reliability of a system [70,82–84,86–88].	x3 = 10% of operational time/yr.	y3	$z3 = (x3 - y3)/y3$
		Status of Physical Condition of Distribution Infrastructure			$\sum Z \times 100$ (%)

3. Water Quality at the Consumer End

Water quality represents the physical condition of water in the context of its physical, chemical, and biological characteristics that render it suitable, or otherwise, for its intended use, such as drinking, domestic, or other public consumption. A safe and sufficient water supply is imperative for a sustainable DWS. The first line of defense against drinking water contamination is the prevention of microbiological and chemical contamination of source water. Public health has serious social and economic costs. Several international standards and guidelines for drinking water are available, yet millions of people in the world fall victim to bacterial waterborne outbreaks and chemical contaminants each year. In this research, the biological quality parameter was used as a proxy measure of the physical condition of distribution infrastructure, especially pipe deterioration and leaks. In many parts of the study area, it was commonly observed and supported by available literature that distribution pipes are laid near or under sewage pipelines. Under conditions of negative pumping pressure, infiltration of contaminated water/sewage occurs in deteriorated pipes.

Guidelines for Water Quality at the Consumer End:

Pakistan National Environmental Quality Standards (NEQS) recommend the following main drinking water quality parameters [89]:

Biological parameters:

Escherichia coli (E. coli) bacteria are frequently found in the intestines of warm-blooded animals and humans. E. coli bacterium is a waterborne pathogen. Its presence in water poses great danger to human health. E. coli strains are not harmful in general. However, some strains, such Shiga toxin-producing E. coli (STEC), can result in life-threatening foodborne illnesses such as diarrhea.

1. For water meant to be used for human consumption, E. coli or thermotolerant coliform bacteria:
    - Must not be detectable in any 100 mL sample
2. For all treated water entering the distribution system:
    - Total coliform bacteria, E. coli, or thermotolerant coliform bacteria must not be detectable in any 100 mL sample, or zero (undetectable) in 95% of the sam-

ples taken throughout any 12-month period. The status of water quality at the consumer end is calculated as shown in Table 13.

Table 13. Status of water quality at the consumer end.

S. No.	Required Parameter	Benchmark (BM) Description	BM Value	Observed Value OR Design Value	Calculation of Status
1.	Biological contamination	Presence of *E. coli*	Benchmark value = x Zero (undetectable) in 100 mL sample	y	*If y = x, then z= 100%* OR *If y ≠ x, then z = 0%*
		All water intended for drinking (treated or non-treated)	OR In case of large supplies in which sufficient samples are examined: zero (undetectable) in 95% of the samples taken throughout any 12-month period [73]		
Water Quality at Consumer End					***Z (%)***

4. Reliability–Resiliency–Vulnerability (RRV) Index of Distribution System

In view of the subjective nature of sustainability, RRV is a useful performance criterion for measuring and monitoring DWS sustainability. It is also a useful tool to determine the capacity of water distribution systems and helps in decision making and the development of operational policies [90–92]. RRV are quantifiable terms that can be used to determine the technical sustainability of a UDWS. The sustainability of a system is greater when reliability and resiliency are high and vulnerability is low.

Satisfactory conditions:
Pressure = 20–40 psi;
Water age = 1.3–3.0 days.

- **Reliability:**

Reliability is the measure of a system's ability to run in a satisfactory state.
R1 = Reliability = x1/x2,
Where:
x1 = No. of times a satisfactory state occurs;
x2 = Total no. of times.

- **Resiliency:**

A system's resiliency is its capacity to recover from a failure incident.
R2 = Resiliency = y1/y2,
Where:
y1 = No. of times a satisfactory state follows an unsatisfactory state;
y2 = Total no. of unsatisfactory states.

- **Vulnerability:**

Vulnerability is the duration and/or extent for which the system runs under unsatisfactory conditions.
V = Vulnerability = z1/z2,
Where:
z1 = $\sum$ Unsatisfactory value;
z2 = $\sum$ All values/

- **RRV Index**

RRV Index = I = RRV Index= $[R1 \times R2 \times (1 - V)]^{(1/3)}$
Table 14 shows the calculation of the status of the RRV index of a UDWS.

Table 14. Status of the RRV index.

S. No.	Required Parameter	Benchmark (BM) Description	BM Value	Observed Value or Design Value	Calculation of Status
1.	Reliability	The measure of the system's ability to run in a satisfactory state	1	$R1 = x1/x2$	Reliability
2.	Resiliency	Capacity of a system to recover from an episode of failure	1	$R2 = y1/y2$	Resiliency
3.	Vulnerability	The duration and/or extent for which the system runs under unsatisfactory conditions	0	$V = z1/z2$	
	RRV Index [3,93,94]		1		$I = [R1 \times R2 \times (1 - V)]^{(1/3)}$
		Status of RRV Index			$\boldsymbol{Z (\%)= I \times 100}$

4. Discussion

A wide range of appraisal procedures has been documented in the literature under the topic of "sustainability assessment/evaluation" of UDWS. However, present sustainability assessment practices need a comprehensive framework to address concerns that have been raised in the scientific community about how comprehensive and reliable the various types of assessment are.

Most of the reviewed studies failed to meet one or more of the evaluation criteria set forth in this research. The sustainability criteria proposed in this study are comprehensive and generic and were compiled from previous studies. There are many different situations, water supply sources, and management strategies for which this approach is appropriate. Our methodological framework aims to support the comprehensive sustainability evaluation of UDWS in which the philosophical, intellectual, and procedural foundations of sustainability science are acknowledged. When evaluating sustainability, thresholds that are based on research and expert stakeholder opinions were taken into account.

The research examined in this paper primarily concerns technical sustainability, and a broad range of evaluation standards were employed for this area. We found that long-term sustainable water planning cannot be thoroughly evaluated using case-specific frameworks. Here, a generic and broad-based framework was developed. The weights of the criteria, in seclusion, are not sufficient to draw conclusions. For this purpose, guidelines were established that can be adopted within the required spatial and temporal boundaries of any UDWS.

As mentioned earlier, the aim of this study was the evaluation of technical criteria of sustainability. Technical criteria are subdivided into two main factors: (1) design and construction and (2) operation and maintenance. These factors are further categorized into sub factors for which guidelines are presented in Table 6, Table 7, Table 8, Table 9, Table 10, Table 11, Table 12, Table 13. Each sub factor depends upon some parameters for which benchmark values were established by consulting the literature. Expert opinion was consulted when available and in areas for which guidelines were either unavailable or highly deficient in the literature. The observed/design value of a parameter suggests its existing condition. The current status of a parameter is indicated by the departure of its observed/design value from the benchmark value. The sum ($\sum Z$) of the status of all parameters indicates the current sustainability status of the parent sub factor in percentage. As described in Table 1, the status multiplied by its corresponding weight yields the sustainability score of each sub factor. Consequently, the sum of all sustainability scores of sub factors and that of factors indicate the sustainability status of each criterion.

5. Conclusions

The main contributions of this study are:

- Development of an approach, related methodology, and a model that can shift from multidisciplinary and interdisciplinary to transdisciplinary and holistic thinking to uncover the emergent characteristics associated with sustainability challenges;
- Awareness that there are still many issues in the research community regarding the integration of methods and models, especially when it comes to the paradox of attempting replication and comparability when dealing with the extreme complexity and non-linearities in the sustainability assessment of UDWS;
- The creation of an appropriate process and technique for emphasizing and focusing stakeholders' involvement and commitment throughout the process, shifting from consultation to coproduction of knowledge and shared obligations;
- Adaptation and definition of the objectives of the integrated assessment. This entails adding sustainability objectives and shifting from a comparative/analytical approach to a considerably more solution-oriented approach;
- The multicriteria nature of the sustainability of UDWS. Five key criteria and corresponding factors and sub factors of sustainability were identified. Based on stakeholder opinions, technical criteria were assigned a relative weight of 18.19%, with technical factors of design and construction and operation and maintenance assigned weights of 8.98 and 9.21, respectively. The sub factors were allocated the same weights as their corresponding factors. In order to determine the overall technical sustainability of a UDWS, the existing status of each sub factor was established in percentage according to the guidelines proposed in this study.

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