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Life Cycle Sustainability Assessment of Wastewater Systems under Applying Water Demand Management Policies

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Abstract: Sustainability assessment of urban water and wastewater infrastructures, especially when it comes to managing existing systems, is of paramount importance. Hence, this study presents a comprehensive approach to investigate the sustainability of a real wastewater system under different water demand management policies (WDMPs) in the operation and maintenance stage. In this regard, life cycle sustainability assessment (LCSA) is used through its three main pillars, which are (1) environment, (2) economy, and (3) society. Accordingly, (1) Environmental assessment is conducted using life cycle assessment (LCA) considering a thorough inventory dataset; (2) The economic assessment results are analyzed by the life cycle cost (LCC) method; and (3) Social life cycle assessment (SLCA) is conducted using the analytic hierarchy process (AHP) method, in which three main stakeholders "public and local community", "workers and employees", and "treated wastewater and sludge consumers" are considered. Finally, to prioritize scenarios, the results of LCA, LCC, and SLCA for every scenario are aggregated to account for the sustainability score using the AHP. The results of applying the proposed method to a real case study show that scenarios leading to less reduction in wastewater production are more sustainable options as they represent better performance regarding economic and social aspects. The proposed framework provides a better insight into the integrated sustainability analysis of urban water infrastructures. In addition, it can be used as a guideline for exploring the effects of WDMPs on wastewater systems in different study areas.

Keywords: demand-side management; life cycle assessment (LCA); life cycle cost (LCC); social life cycle assessment (SLCA); sustainability; wastewater system

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1. Introduction

Water is among the essential elements of sustainable urban development [1,2] with the final goal of fulfilling human safety and well-being in society [3]. However, water scarcity has become one of the most significant global crises, especially in arid areas [4], which is predicted to be aggravated by global societal and climate changes in the future and cause a reduction in water accessibility and quality [5]. Thus, sustainable water management, as one of the most significant parts of the water cycle [6], is among the most important challenges for humanity in the future, particularly in the urban sustainability context [7]. Indeed, urban areas are specifically at risk of water scarcity, and securing future water supplies has become a crucial policy challenge for decision-makers [5,6], as there is a threat to the sustainability of urban water infrastructures [8]. Hence, water demand reduction has been considered a fundamental part of water management programs [5,7]. In this regard, different policies of urban water planning, such as water demand management policies (WDMPs), have been employed so far [9], which, in turn, can directly/indirectly affect the sustainable development of cities [10] and could even influence urban water infrastructures [11]. On the other hand, different parameters could affect water usage like seasonality influencing the availability of urban water [12,13], which can also determine the strategies of policymakers to apply policies to reduce water usage. WDMPs, as a fundamental element of sustainable water management [5,6], has emerged as a substantial way to diminish water usage in cities [14]. WDMPs include measures, such as water-efficient fixtures, water tariffs, and greywater reuse [11], which not only could help to reach the goals of the sustainable development but could also reduce water usage to counter the water scarcity problems [15,16]. Nevertheless, implementing any policy for managing urban water may have both positive and negative consequences [11,17], such to the extent that it also affects urban sustainability. Hence, analysis of sustainability of urban infrastructures is of utmost importance. Sustainability has three pillars, including (1) environmental, (2) economic, and (3) social aspects, which help to cover needs without limiting the resources (such as water supply resources) [18]. Aggregating these three pillars represents every system's sustainability [3].

There are some studies in which the different aspects of applying WDMPs such as social [19], socioeconomic [20], and environmental aspects [11] have been considered, but integrating the whole of the sustainability pillars to make an aggregate score is lacking. Although the sustainability of urban infrastructures was neglected in the past, the concept of sustainability and its aspects have widely gained attention in water systems in the last decades [21]. Many publications deal with the water systems' sustainability using different approaches such as the life cycle perspective, and there is an ever-increasing number of papers in this regard [22]. Some of them only have considered one aspect of sustainability in urban water systems, like environment [23–25], economic [26–28], or social [29,30]. For instance, Rodríguez et al. [31] analyzed the environmental impacts of greywater reuse as one of the solutions for reducing urban water consumption. These studies could not provide a thorough perspective of all the sustainability aspects, as they solely focused on a particular part. On the other hand, some research has considered more sustainability aspects in their analysis. For example, García-Sánchez and Güereca [32] evaluated the social and environmental impacts of entire urban water systems to reach a tangible quantitative score of a system's sustainability. Still, their study lacks an economic analysis. In addition, the effects of changes in people's water consumption habits, like implementing WDMPs, were neglected in their social and environmental assessment.

On the other hand, a few previous studies have addressed all three aspects of sustainability of urban water systems by combining the environmental, economic, and social dimensions [10,33]. Opher et al. [10] assessed the sustainability of greywater reuse by defining different scenarios. They considered all three main pillars of sustainability through life cycle sustainability assessment (LCSA) and combined them using the analytic hierarchy process (AHP) to weigh the sustainability criteria. LCSA is a technique that provides the highest level of sustainability assessment by taking into account the three mentioned pillars [34]. This method evaluates the sustainability aspects either in the whole life cycle of the product/service (cradle-to-grave) or based on the defined system boundary [3]. In addition, AHP is a structured technique to categorize and analyze complex decisions [35]. Combining the LCSA and AHP method is an effective way to reach an overall sustainability score [10].

Reviewing previous research reveals a lack of studies on the sustainability assessment of applying WDMPs to wastewater systems (including wastewater collection network (WWCN) and wastewater treatment plant (WWTP)). Therefore, a question arose as to whether implementing WDMPs can affect the sustainability of wastewater systems or not, and how? Implementing WDMPs policies requires a thorough overview of the processes of the systems, the complex interactions between various elements, and the response of elements to possible changes, which can be achievable in an integrated assessment and modeling [17]. Hence, the current study considered all sustainability aspects (i.e., environmental, economic, and social domains) of a real wastewater system to evaluate the sustainability of the WWCN and the WWTP after applying different WDMPs using a comprehensive and integrated assessment approach. The present research framework and its results can inform decision-makers and scholars on the effects of implementing WDMPs on wastewater systems from various aspects, providing a comprehensive insight into the integrated assessment of these effects.

In the following sections, first, the section "Materials and Methods" is presented, including: (1) A detailed description of the goal and scope of the present study and considered scenarios; (2) Comprehensive provision about all the used methods, including LCA, LCC, SLCA, and LCSA in 10 separate steps in sub-section "The Procedure of the Study". Then, the results are presented and interpreted in the same order as the procedure of the study. In the end, the important conclusions are expressed and different recommendations for future studies are presented.

2. Materials and Methods

2.1. Goal and Scope Definition

The goal of the current study is to introduce a comprehensive method in assessing the overall sustainability of urban wastewater systems considering its environmental, economic, and social aspects. To this end, different scenarios of WDMPs are applied, and eventually, sustainability scores for all options are calculated and compared. The scope of the current research includes a real case study of Baharestan city, located in Isfahan province, Iran, with 86,011 inhabitants in 2018. Considering that Isfahan province, like many parts of Iran, has already suffered from severe and widespread water scarcity [36], water utility managers have had to implement strict WDMPs. These measures can affect the sustainability of urban water systems in such areas. The wastewater system of the case study is comprised of a fully gravity-driven WWCN with Polyethylene pipes, and a WWTP. The whole system was designed for the year 2036 as the last year of their lifetime. Hence, the spatial and temporal boundary of the system is limited to the wastewater system of Baharestan city and the lifespan of the system until 2036, respectively, in which both the changes of water consumption and population have been considered. As WDMPs are implemented only in the operation and maintenance stage, the sustainability assessment of other stages such as construction and end-of-life have been overlooked because they do not significantly affect the study's overall conclusions (note that this approach is known as gate-to-gate analysis and is approved by ISO [37]). Therefore, the sustainability of the wastewater system of Baharestan city (i.e., both WWCN and WWTP) is assessed only in the operation and maintenance life cycle stage. In addition, in life cycle analysis, inputs and outputs of systems are defined based on a reference denoted as Functional Unit (FU). In this work, FU is defined as 1 m^3 of wastewater going through the WWCN, entering into WWTP, and is finally treated there.

2.2. Considered Scenarios

- Scenario 0 (base scenario): This scenario represents the condition in which no WDMPs are applied to the system. Therefore, only the population growth rate of the case study and its effects until 2036 are considered in the modeling of this scenario. The average wastewater production is 165.4 L per capita per day.
- Scenario 1: This scenario represents the real condition of the case study in which decision-makers have applied severe water pressure management and awareness campaign policies to reduce water consumption. This policy reduced 8.84% of wastewater produced in the first year, and 20% ultimately [38]
- Scenario 2: This scenario combines the effects of reducing water consumption by applying water-efficient fixtures and social campaigns. The current scenario is established based on the literature review [39–41]. It has been assumed that water consumption and wastewater production are reduced by 30% in the considered lifetime of the system;

- Scenario 3: Reviewing previous research [42–44] showed that a water tariff policy could reduce water consumption by 15% to 36% depending on the social and economic situation of the study area. According to the current scenario, it is assumed that a water tariff policy can reduce wastewater production by 18%.
- Scenario 4: This scenario is the hypothetical combination of the prior scenarios reducing 68% of wastewater production for 19 years (the considered lifetime of the system). This scenario is supposed to highlight the effects of implementing WDMPs on the wastewater system.

Table 1 shows the trend of wastewater production per capita in every scenario and different periods until the end of the system's lifetime. In this table, the highest reduction percentage in wastewater production is 68% (from 163.39 lpcd in 2016 to 52.28 lpcd, average of 94 lpcd) by 2036, which occurred in the hypothetical scenario 4.

Table 1. Population growth and wastewater production reduction in every scenario.

Changes during the Years		2017	2018	2021	2026	2031	2036
All scenarios	Population	82,541	86,011	96,420	113,769	131,118	148,467
Scenario 0	Reduction percentage	0	0	0	0	0	0
	Average WW * production (lpcd **)	165.4	165.4	165.4	165.4	165.4	165.4
Scenario 1	Reduction percentage	0	8.84	15	18	20	20
	Average WW production (lpcd)	163.39	148.95	138.88	133.98	130.71	130.71
Scenario 2	Reduction percentage	0	10	15	20	25	30
	Average WW production (lpcd)	163.39	147.05	138.88	130.71	122.54	114.37
Scenario 3	Reduction percentage	0	8	10	13	15	18
	Average WW production (lpcd)	163.39	150.32	148.05	142.15	138.88	133.98
Scenario 4	Reduction percentage	0	27.84	40	51	60	68
	Average WW production (lpcd)	163.39	117.90	98.03	80.06	65.36	52.28

* Wastewater. ** lpcd stands for liters per person per capita per day.

2.3. The Procedure of the Study

The current study includes 10 steps, and the procedure of the study is presented in Figure 1.

2.3.1. Data Collection and Scenarios

1. The prerequisite data such as demographic, water consumption per capita, and sewer pipeline information are collected [38].
2. According to the real data gathered from the case study and using previous literature, the water consumption per capita in different scenarios of WDMPs is estimated for the considered temporal boundary.

2.3.2. Analyzing Wastewater and WWCN

3. Accordingly, the average wastewater production is predicted until the final time step (i.e., 2036). This anticipation is affected by the population growth rate and implementation of WDMPs that diminish the quantity of the produced wastewater. The importance of this step is its application to most of the next steps. Indeed, the changes in the amount of wastewater production influence many steps, such as hydraulic parameters analysis through changing velocity in sewer pipelines [16] (see also step (5)).
4. In parallel with the third step, the variations in qualitative parameters of wastewater after applying different WDMPs are analyzed. The outcomes of this step are utilized to measure emissions to the air. It is worth mentioning that analyzing qualitative

parameters play a vital role in identifying the critical elements of social life cycle assessment (SLCA) and decision making. For instance, the concentration of pollutants may impact the safe and healthy living conditions of workers and/or people living around the WWCN.

5. The hydraulic parameters of the WWCN are calculated in every scenario using the hydraulic model. Hydraulic parameters in scenarios, such as velocity, are considered to estimate gas emissions by relevant equations presented in Table S1 and to find the blockage rate.
6. Emissions from the WWCN, i.e., CH_4 and H_2S, and those emitted from the WWTP, i.e., CH_4, CO_2, and N_2O, are calculated through equations adapted from relevant literature (mentioned in Supplementary Materials). The amounts of gas emissions are used in the related assessment of environmental and social effects, such as global warming impacts and effects on the health and safety of the workers.

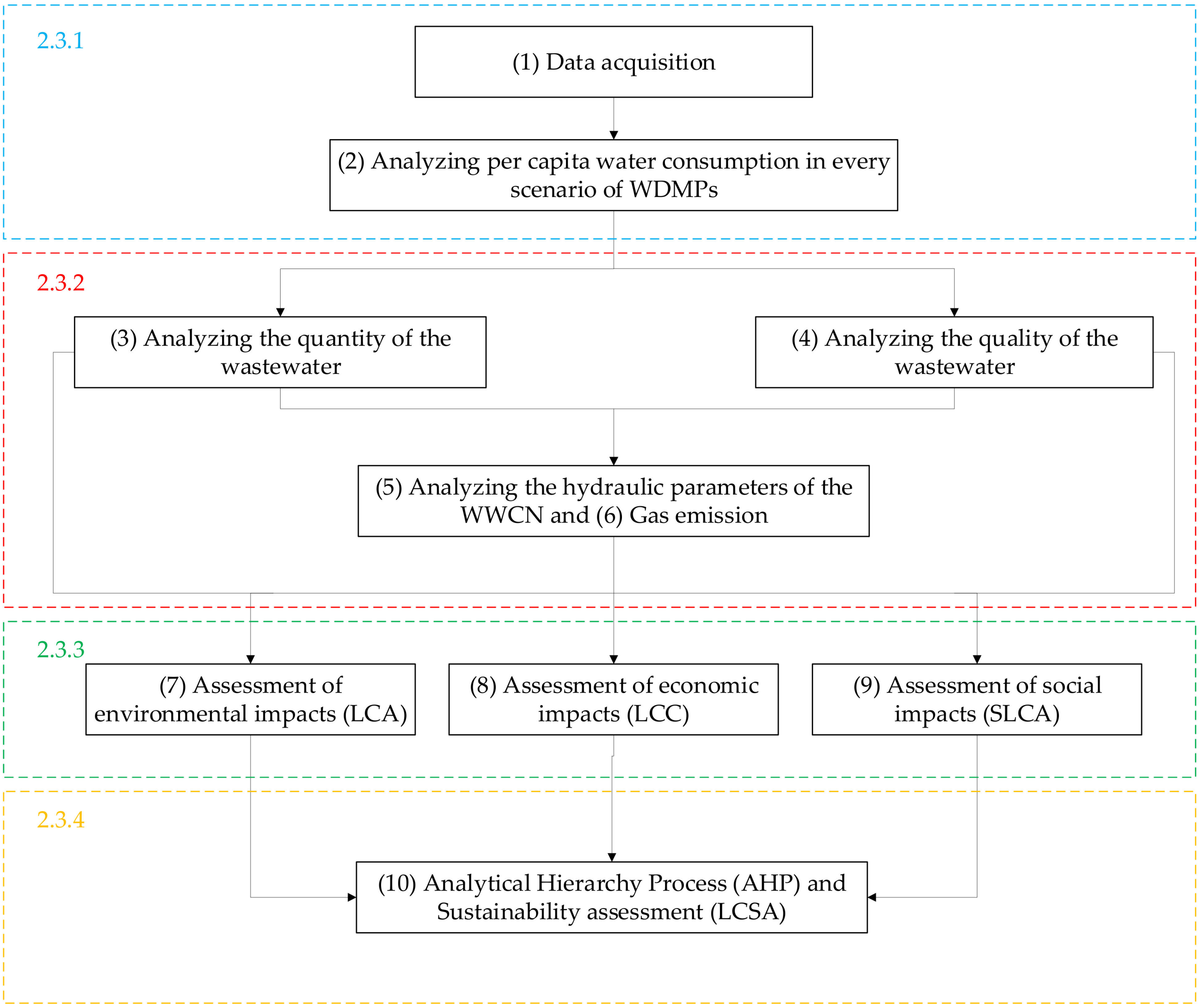

Figure 1. The research procedure of the present study. Section 2.3.1. (1) and (2); Section 2.3.2. (3)–(5); Section 2.3.3. (7)–(9); Section 2.3.4. (10).

2.3.3. Impact Assessment

7. In this step, the life cycle assessment (LCA) method is used to analyze the environmental impacts of applying WDMPs to the wastewater system. LCA, as a standardized method of assessing environmental burdens, consists of four main phases, including: (a) definition of goal and scope, (b) providing an inventory of the life cycle, (c) assessment of environmental impacts, and d) interpretation of the inferences [37]. The

overall goal of this step is to assess the environmental effects of the system under implementing WDMPs in the considered scope and system boundary. A comprehensive life cycle inventory that is considered based on the goal, scope, and system boundary of the present study is provided. The detailed inventory of WWCN in operation and maintenance stage consists of CH_4 and CO_2 emissions, repairing breaks in the pipes (including trench excavation and road construction), unclogging blockages, and manhole cover replacement. Additionally, a comprehensive inventory of the operation and maintenance stage of WWTP is considered, including CH_4, CO_2, and N_2O emissions, chemical material usage, energy consumption, and transportation. Through the ReCipe endpoint method, the environmental indicators are normalized, converted to a dimensionless number (point (pt)), and aggregated into the three endpoint damage categories, including human health, ecosystem, and resources [37,45]. Besides, the Ecoinvent 3.5 database is used for sub-process data.

8. For the economic analysis, the life cycle cost (LCC) method is applied using Equation (1) [27], where all costs and revenues relevant to the life cycle of the system are considered.

$$LCC = IN + \sum_{t=1}^{T} \frac{OC_t}{(1+r)^t}, \quad (1)$$

where *LCC* is the life cycle cost of the system, *IN* is the initial installed costs, *OC* is the operation and maintenance costs of the system for *t* years after installation, *T* is the lifespan of the system (years), and *r* is the annual discount rate (%). As previously mentioned, based on the system boundary of the current study, the initial installed costs are ignored. According to the considered system boundary, the costs contain energy demand, chemical material usage, the salary of workers and employees, repairing the pipelines, and advertisement for reducing water consumption costs. In addition, the income has only been limited to selling the treated wastewater. All costs and revenues are gathered in the base year (2018) and are predicted for 19 years of the lifetime of the system using Iran's inflation rate.

9. To assess the social impacts of applying WDMPs to the wastewater system in different scenarios, the SLCA method is employed in this step. This method considers both positive (e.g., human welfare) and negative (e.g., harmful to human health) effects of any product or service in its life cycle (cradle to grave) [3]. The main steps of analyzing the social impacts are (a) Specifying the stakeholders based on the guidelines of UNEP\SETAC [3], which comprise three main groups, including the workers and employees who work in the operation and maintenance stage of the WWCN or the WWTP, the consumers who use treated wastewater (i.e., industrial company) and sludge (i.e., farmers), and the public and local community stakeholders, which contains the people who live in the considered system boundary; (b) Determining and defining indicators that refer to each of the three groups of the stakeholders; (c) Designing a research-made questionnaire and completing it through face-to-face interviews with experts. To this end, a panel of 22 experts with different types of knowledge that its members cover various considered aspects of this research and that are familiar with the situation of the study area have been selected from water utilities and universities. They were then interviewed individually; (d) Calculating the weight of every indicator using the AHP method. The weights of each indicator for all experts are aggregated into one weight using a geometric mean [46]; € Estimating the intensity of indicators in different scenarios from the viewpoint of researchers/experts based on the gathered qualitative and quantitative data of the case study using the AHP method; (f) Interpreting results and comparing the scenarios. Finally, the aggregated weight of each indicator (step d) is multiplied to its importance in every scenario (step e), and the social score of every scenario is calculated.

2.3.4. Sustainability Assessment

10. One can see that the numerical values for the environmental and economic aspects of different scenarios are calculated in steps 7 and 8. Besides, the weights and intensity of social indicators are calculated in the previous step (step 9). Therefore, it is needed to aggregate the results of all aspects into a score to investigate the sustainability of each scenario. In this step, a sustainability score for every scenario is calculated. In this regard, (a) another questionnaire is designed and conducted to ask the importance of every aspect of sustainability (i.e., environmental, economic, and social) and environmental endpoint damage categories (i.e., human health, ecosystem, and resources) from the perspectives of experts to obtain their weights. (b) Then, after interviewing 22 experts who participated in the previous expert survey (SLCA's questionnaire), the weights are obtained from their viewpoints. Considering the results of two expert surveys (steps 9 and 10), the weight of all defined indicators in comparison to each other is computed using the AHP method. (c) The intensity of the indicators for all three sustainability pillars in different scenarios are obtained in previous steps (steps 7–9 for the environmental, economic, and social aspects, respectively). The obtained intensity of every indicator in every aspect is normalized into a number between 0 and 1, in line with Saaty's ideal mode [47], in which "0" is the worst scenario in every indicator, "1" is the ideal one, and other scenarios get a number between 0 and 1. (d) The aggregated weights multiply to the importance of every indicator in every scenario (i.e., the intensity of the indicators) in order to reach the scores of the pillars. (e) At last, the scores of the pillars are aggregated to a sustainability score for every scenario using the LCSA method. Equation (2) is used to calculate the final score of the *LCSA* [48].

$$LCSA = LCA + LCC + SLCA, \tag{2}$$

where *LCA* is the environmental life cycle assessment, *LCC* is the life cycle cost, and *SLCA* is the social life cycle assessment, detailed information about *LCA*, *LCC*, and *SLCA* is provided in the section "The Procedure of the Study" in steps 7–9, respectively. It is worthwhile to note that the system boundary for all three aspects of the assessment is consistent, i.e., the system boundary is ideally identical in all of them [22,48]. After calculating the *LCSA* of each scenario, the scenarios are compared and prioritized to select the most sustainable one. The sensitivity analysis is also considered to interpret the results better. In this regard, the weights of three aspects of sustainability are changed to assess the variation of the sustainability score in every scenario.

3. Results

3.1. Quantitative and Qualitative Analysis of Wastewater

Based on the collected data from Baharestan Water and Wastewater Utility and literature review, the amount of per capita water consumption and, accordingly, wastewater production under applying different WDMPs, is determined. The considered qualitative parameters are BOD (biological oxygen demand), COD (chemical oxygen demand), and TSS (total suspended solids). The load of these parameters is assumed to be constant for every person per day. From real data, the amount of BOD, COD, and TSS is 51, 106.5, and 40 g per capita per day, respectively. The annual wastewater production that is estimated regarding both population growth rate and applying WDMPs (wastewater reduction percentage) is used to calculate the concentration of the above-mentioned qualitative parameters (as mg per liter) and to update their amount (as per capita per day). The initial outcomes from qualitative analysis (concentration of qualitative parameters in different scenarios) and quantitative analysis (amount of wastewater produced in different scenarios) reveal that the concentration of the above-mentioned parameters increases as the wastewater production volume decrease. This is in agreement with the results of DeZellar and Maier [49], Parkinson et al. [39], and Marleni et al. [40]. Numerical results showed that the amount of BOD, COD, and TSS in the base scenario is 308.4, 643.9, and 241.3 mg/liter, respectively. In comparison, the numerical value of BOD, COD, and TSS in the last year of scenario 4 (with the maximum reduction of wastewater production) is 975.8, 2037.1, and 763.6 mg/liter, respectively.

3.2. Hydraulic Parameters and Gas Emissions

The gravity sewer network of Baharestan city consists of pipes with an average diameter of 240 mm built of polyethylene material. This network is designed for the year 2036 as the last year of the lifetime period. In this regard, the sewer network is analyzed based on the produced wastewater in different scenarios, and then, the results, such as sewage flow velocity, are compared. By decreasing wastewater production percentage from scenarios 0 to 4 derived by applying WDMPs, the hydraulic analysis results indicate that not only the wastewater depth in pipes but also the velocity of sewer in pipelines is decreased in line with the findings of Bailey et al. [16]. The difference in velocity between scenarios 0 and 4 is around 12%. Although in this research the velocity in pipelines is not less than the standard minimum velocity [50] even in scenario 4, the 12% reduction in velocity highlights the importance of considering WDMPs in designing sewer networks. As the case study data also confirms, this reduction in velocity and the ratio of wastewater depth to pipe height can lead to more blockages in the system [38].

The hydraulic model is used to calculate the hydraulic parameters such as HRT (hydraulic retention time) and velocity. Then these parameters are employed (see Equations (S1) and (S2) shown in Table S1) to estimate the gas emissions from the WWCN, including CH_4 and H_2S. Note that since the hydrilla parameters are changed in each scenario, the emitted gas from WWCN differs in scenarios.

CO_2, CH_4, and N_2O emissions from the WWTP are also considered (see Equations (S3) and (S6) in Table S1). Due to the lack of data for N_2O emission, we assume 3.2 g per capita per year as a constant number in all scenarios based on literature [51–53]. Note that as the BOD concentration per person per day is constant in this study, the overall gas emissions from the WWTP in scenarios is the same. This is while the amount of gas emissions from the wastewater treatment unit per FU in scenarios differs. For instance, CH_4 emissions from the WWTP are 14.1, 17.2, 18.1, 16.4, and 30.9 g per 1 m^3 (FU) of wastewater in scenario 0 to scenario 4, respectively. However, the amounts of gas emissions are used as inventory input data for the LCA model to provide the comprehensive inventory dataset for WWTP. There are no CH_4 emissions from the sludge treatment unit because the methane correction factor for aerobic sludge digester is zero [54]. The gas production of the WWCN and WWTP in different scenarios in the last year of the lifespan of the system are shown in Table 2. According to the findings, the less wastewater is produced in a scenario, the more gas is emitted per FU (grams per m^3) [55]. Further details of gas emissions and their environmental effects can be found in Safarpour et al. [55].

Table 2. The gas production in different scenarios from the WWCN and WWTP.

		WWCN		**WWTP**				
Scenario	**Reduction Percentage of WW * (%)**	**CH_4 (mg/L)**	**H_2S (mg/L)**	**WW Treatment Process**		**Sludge Treatment Process**		**N_2O (g/m^3 WW **)**
				CO_2 (g/m^3 WW **)	**CH_4 (g/m^3 WW **)**	**CO_2 (g/m^3 WW **)**	**CH_4 (g/m^3 WW **)**	
0	0	1.573	1.631	159.6	14.1	162.2	0	0.053
1	20	1.578	1.688	202.0	17.8	205.3	0	0.065
2	30	1.581	1.727	230.8	20.3	234.6	0	0.069
3	18	1.578	1.680	197.0	17.4	200.3	0	0.062
4	68	1.592	1.753	504.9	44.5	513.2	0	0.114

* WW = wastewater. ** 1 m^3 WW = FU.

3.3. Analytic Hierarchy Process (AHP)

AHP is a technique that is used widely to make decisions in sustainability assessments. In this method, level one is the primary goal of the assessment, and the other levels consist of the sub-categories and indicators. The hierarchical structure has been built by identifying levels of the technique, which is presented in Figure 2. As illustrated in this figure, the first level that is the study's goal is the assessment of the sustainability of the wastewater system under applying WDMPs. The second level is comprised of the three pillars of sustainability, i.e., environment, society, and economy. The environmental aspect includes three sub-categories of human health, ecosystem, and resources, which are the endpoint damage categories of the LCA method. The social aspect of the study has a big sub-tree in levels 3 and 4. These social elements consist of three separate stakeholders, including the workers and employees, the public and local community, and the consumers of the treated wastewater and sludge. Every stakeholder consists of its own specific sub-criteria (Table S3 in the Supplementary Materials shows the weights of social sub-categories). The last pillar, i.e., economy, has no sub-criteria and is considered as a single element.

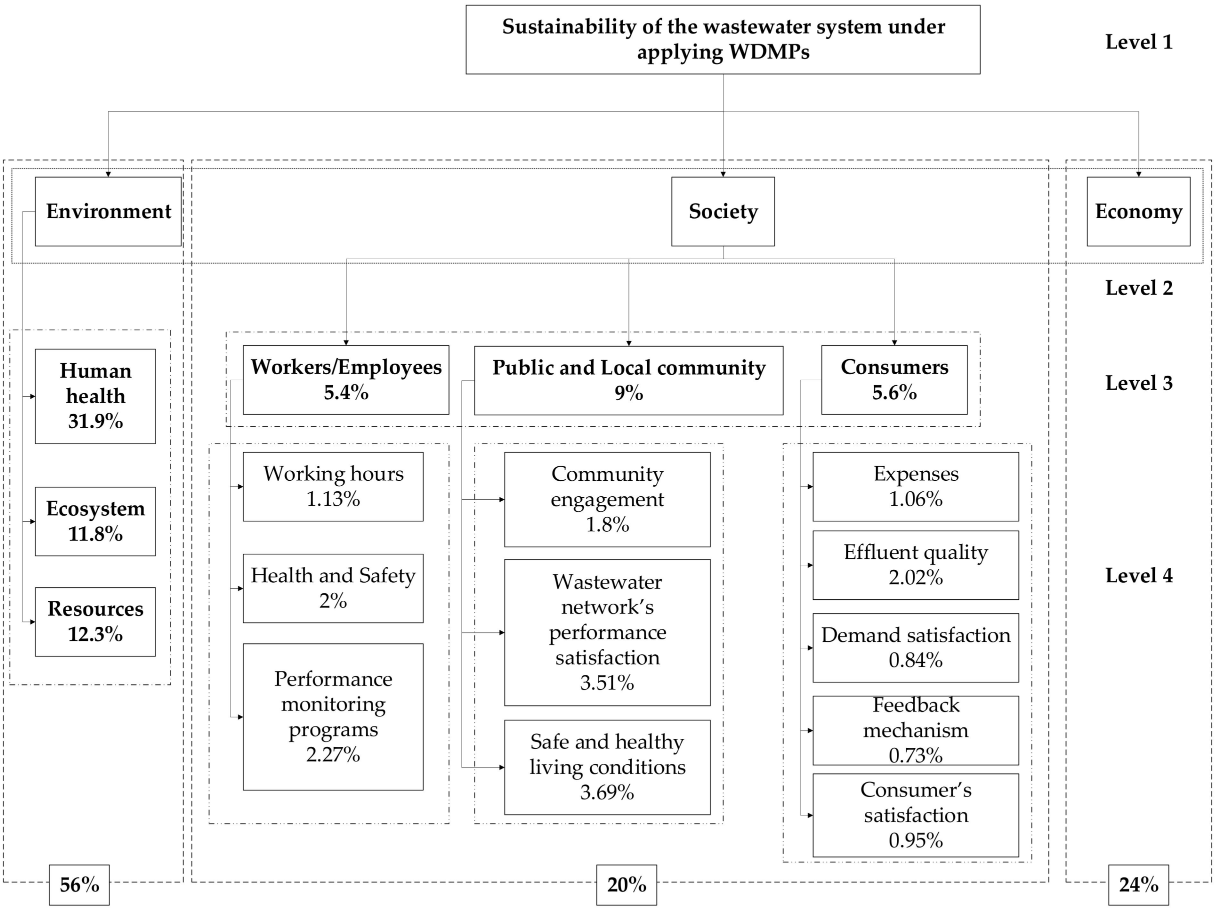

Figure 2. AHP hierarchy structure of the study and weights of every element.

The importance of decision-making elements (sub-categories and indicators) is drawn from the opinions of the experts and compared through the pairwise comparison system [56]. In this regard, Saaty's scale of 1 "the least important indicator" to 9 "the most important indicator" is used [57]. After completing the pairwise comparison matrices, the inconsistency index is automatically computed for each matrix, which is less than 0.1 [57,58]. The weight of every element of the hierarchical structure is mentioned in Figure 2, concluded from the viewpoints of the experts via expert surveys. Each of the mentioned weights is computed by multiplying the weight of every element to its predecessors' weight along the hierarchy branch. As the assessment of the opinions of the expert is revealed, the environment category (with a weight of 56%) is much more important than the society (with a weight of 20%) and economy (with a weight of 24%) categories. From the point of view of the experts, human health (with a weight of 31.9%) is also more vital than other sub-criteria of the environment category. Between the leaf nodes of the hierarchical social structure, the indicator for safe and healthy living conditions of the local community (with a weight of 3.69%) has the highest weight.

3.4. Life Cycle Assessment (LCA)

The environmental impacts of the wastewater system under applying different WDMPs through a thorough inventory is assessed. Inputs for scenario 0, as an example, can be found in Table S2. The overall results of the environmental impacts in different scenarios are shown in Table 3. The outcomes from comparing scenarios depicted an 18% decrease in environmental impacts by reducing 68% wastewater production, which coincided with population growth over the years of the lifespan of the system. Scenario 4, with the minimum amount of wastewater production (maximum demand reduction), has the best environmental performance in all three damage categories, which are 1.481, 0.135, and 0.010 Mpt (point (pt)) in human health, ecosystem, and resources, respectively. This is mainly because less wastewater production leads to the less adverse environmental burden, and in particular, it leads to energy consumption reduction as one of the most impactful elements of the system boundary on the environmental effects [11,59]. More details about using the LCA method for WDMPs, and effects of WDMPs on environmental midpoint categories, such as global warming and ozone depletion, can be found in Safarpour et al. [11,55]. To evaluate scores of every damage category in every scenario, Saaty's ideal mode is used [47], which is between 0 and 1. Accordingly, in terms of environmental aspect, "0" represents the worst scenario, and "1" shows the ideal one. Therefore, '1' is assigned to the scenario with the minimum numerical values of the environmental impacts (Scenario 4), and a number between 0 and 1 is assigned to other scenarios based on their LCA results. The intensity of the categories and their score are shown in Table 3, wherein the ideal score of categories in scenarios is highlighted.

Table 3. LCA of the examined scenarios and their normalized ideal mode score.

Damage Categories		**Scenarios**				
		0	**1**	**2**	**3**	**4**
Human health	**Mpt**	1.811	1.680	1.657	1.707	1.481
	Score	0.82	0.88	0.89	0.87	1.00
Ecosystem	**Mpt**	0.160	0.150	0.148	0.152	0.135
	Score	0.84	0.90	0.91	0.89	1.00
Resources	**Mpt**	0.019	0.016	0.015	0.016	0.010
	Score	0.50	0.61	0.64	0.58	1.00

The highlighted cells show the ideal score in scenarios.

3.5. Life Cycle Cost (LCC)

Equation (1) is used to analyze the study's economic aspect using the LCC approach. Based on the system boundary, the construction and end-of-life stages are eliminated from this equation. The expenses are represented in Iranian Rial (IRR). All costs and revenue are summed up in the first year of the study (i.e., 2018) by considering the discount rate of 37% [60]. The discount rate is also assumed to be constant for all the years of the study. Besides, USD 1 was equivalent to IRR 150,000 in 2018 [60]. Accordingly, the costs are as below:

- Salary of the workers and employees: The wages of all the workers and employees in the system boundary in the first year (2018) is in total about IRR 9.4 billion, which is constant in every scenario, and only the inflation is applied;

- Blockages in the WWCN: This cost depends on the discount rate and the number of blockages in pipes, which will be changed in every scenario yearly. The number of blockages is assumed to be altered regarding the wastewater discharge and the velocity of the sewer in scenarios. In other words, the percentages of wastewater production affect the number of blockages. While scenario 4 (68% wastewater reduction) imposes the most blockages on the system, the base scenario has the minimum of these costs;
- Energy: One of the most expensive parts of the WWTP is energy consumption. The amount of wastewater produced in every scenario affects energy consumption and its costs. Thus, this cost in the base scenario (without any reduction in wastewater production) is the highest;
- Chemical material usage: 1 kg of the chemical material used in the WWTP was about IRR 18,200 in 2018. By applying the rate of the discount and population growth, the expenses of this term during the 19 years of the study are estimated at approximately IRR 4.4 billion;
- Advertisement: Scenarios 1, 2, and 4 contain the educational campaigns and public awareness as a part of the WDMPs, which require expending money on administrating advertisements, including printing and distributing brochures among households, TV commercials, and billboards installation across the city. This term mainly affects the water sector, so half of the expenses are considered for the system boundary, which was about IRR 69 million in 2018.

The only revenue for the considered real case study is selling treated wastewater to the steel industry. The corresponding data were collected from the existing contract between the steel industry and Baharestan water and wastewater utility. Accordingly, the revenue in scenario 4 is the least because this scenario has minimum amounts of effluents. Since the sludge is not sold in this case study, no revenue is considered for that. The sum of all costs (with a negative sign) and revenue (with a positive sign) are displayed in Table 4. As presented in this table, the expenses in scenario 4 are much more than the revenue. On the other hand, the base scenario is the best scenario from an economic analysis point of view. To make the results comparable, the ideal mode scale [47], which is between 0 and 1, is obtained to prioritize scenarios in terms of the economic aspect. Accordingly, the "0" score is the worst scenario, and the "1" score is the ideal one. In this regard, as the expenses of scenario 4 are more than its revenue, the score of this scenario is considered to be 0, and conversely, the score of the base scenario is equal to 1.

Table 4. The sum of the costs (−) and the revenue (+) in every scenario and their normalized score.

Scenario	Sum in 2018 (Billion IRR)	Score
0	+110.7	1.00
1	+49.8	0.67
2	+36.3	0.60
3	+63.3	0.74
4	−73.4	0.00

The highlighted cell shows the ideal scenario.

3.6. Social Life Cycle Assessment (SLCA)

Based on the UNEP/SETAC [3] guidelines, social equity is assessed by the SLCA approach. More information regarding the procedure of SLCA was described in detail in Safarpour et al. [61]. In this work, the considered stakeholders and the definitions of their sub-categories are as follows:

- The workers and employees: Three sub-categories are chosen for all people who work in the system boundary.
    a. Working hours: This quantitative sub-category is directly related to the number of blockages in the WWCN. The fewer working hours in the scenarios, the better score it gets.

  b. Health and safety: Changes in both the concentration of the sewer's pollutant parameters and the amounts of gas emissions in every scenario will affect the intensity of the health and safety of workers. Scenario 4, with the highest concentration of pollutants, has the lowest intensity score.
  c. Performance monitoring programs: This is adapted from Padilla-Rivera et al. [29] to analyze the efficiency of the workers. The higher rate of difference in the sewer parameters from the designed situation, as in scenario 4, can lead to blockages or overflow and needs more accurate performance monitoring plans.

- The public and local community: The public and local community are different in the SLCA guidelines. However, due to the small size of the study area, these two stakeholders are considered the same. This stakeholder group contains people concerned with the problems of the WWCN, such as odor and blockages. The sub-categories are as below:
  a. Community engagement: This qualitative sub-category contains contacts and communications between society members and water and wastewater utility in order to report the problems of the sewer system in their living environment, such as odor and sewer overflow. By appropriate reporting, the issues would be solved faster and more effectively. In addition, it is considered that high amounts of reduction in wastewater production lead to more technical problems that can effect negatively the citizens–company relation, i.e., the communication is more like a conflict and discontent among citizens. The scenario with the average amount of wastewater reduction percentage is the best in this sub-category.
  b. The satisfaction with the performance of the WWCN: Lower velocity in scenarios with a higher reduction percentage not only affects the blockages of sewer pipes but also leads to more gas emissions and a bad smell of the sewer system. This fact influences the public and local community's satisfaction.
  c. Safe and Healthy living conditions: The quality of wastewater affects this sub-category directly. Therefore, the scenario with a minimum reduction of wastewater is preferable because it has less pollutant concentration. Due to the slight difference in the concentration of the qualitative parameters in scenarios 1 to 3, they are assumed to have a similar effect on this sub-category.

- The consumers: According to the boundary and scope of the system, the consumers are the industrial company and farmers who use the treated wastewater and sludge. This category has five sub-categories.
  a. Effluent quality: This sub-category is adapted from Padilla-Rivera et al. [29]. The WWTP is obliged to deliver the treated wastewater and sludge with standard qualities. Since there is no data available on the quality of the sludge used by farmers to check the required standards, the scores of this sub-category in all scenarios are close together to be on the safe side.
  b. Expenses: This sub-category is adapted from Opher et al. [30]. Consumers mostly pay money to get the treated wastewater and sludge. In this study, the steel industry factory has pre-purchased the treated wastewater for several years. As the expenses that the consumer pays have not differed and the sludge of this plant is also not sold to the local farmers, all the scenarios get the same score.
  c. Demand satisfaction: This sub-category is considered based on the recommendation by Padilla-Rivera et al. [29]. According to the mutual contract between the water utility and steel factory, the utility should provide undertaken effluent of the factory, even though using produced wastewater in other cities. Consequently, by diminishing wastewater production in the study area, the utility may be incapable of providing the needed amount of wastewater, and therefore, consumer satisfaction would be affected. This sub-category completely depends on the case study's situation. Therefore, the quantitative amount of the treated wastewater is used to score scenarios.

d. Feedback mechanism: This sub-category examines the number of organizational complaints against resolved ones so that the consumers can communicate and express their problems about the received sludge and treated wastewater. Based on the mutual contract, the wastewater utility is obliged to provide a prescribed amount of treated wastewater to the consumer, and the consumer has planned on that amount of wastewater. Conflicts would happen by reducing the amount of effluent from the specified amount in the contract between the water utility and steel factory (main consumer) in order to notify the water and wastewater utility to solve the problems of wastewater decrease. By reducing the amount of wastewater due to applying water demand management policies, the dissatisfaction of consumers, and, as a result, their complaints, will increase.

e. Consumers' total satisfaction: By reducing the amount of treated wastewater in the case study, the source of effluent supply would be changed to other cities' treated wastewater, or the consumer may need to make a new contract. Treated wastewater collection from various sources with different qualities would be challenging for the consumer. Therefore, the total satisfaction of the consumer would be affected. In addition, farmers who use sludge without any expenses face significant changes that may lead to their dissatisfaction.

As previously mentioned, all the sub-categories are compared in every scenario using the AHP method by researchers/experts' judgments based on the qualitative and quantitative results. In addition, interviews and consultations with water utility managers and specialists are involved in this judgment. The AHP results determine the weights for every sub-category in five different scenarios. These weights are normalized using Saaty's ideal mode in which the best scenario (the highest weight) gets "1" as a score, and other scenarios get a score between 0 and 1 depending on their weight. The score of every sub-category in every scenario is presented in Table 5 (Tables S4–S13, showing a comparison of the qualitative and quantitative sub-categories in different scenarios). This table shows that the base scenario mostly gets the best score from a social standpoint. This is because the base scenario represents the status without any changes from the designed situation of the system. Therefore, it can fit all the needs of stakeholders and existing contracts. As shown in the table, the scenario with a maximum reduction percentage is not ideal from a social perspective.

Table 5. Aggregated ratings of every sub-category of different scenarios.

Scenario	Workers/Employees			Public and Local Community			Consumers				
	Working Hours	Health and Safety	Performance Monitoring Programs	Community Engagement	Satisfaction of Performance of Wastewater Network	Safe and Healthy Living Conditions	Effluent Quality	Expenses	Demand Satisfaction	Feedback Mechanism	Consumers' Satisfaction
0	1.00	1.00	0.18	0.31	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	0.86	0.38	0.33	0.55	0.38	0.53	0.53	1.00	0.81	0.38	0.38
2	0.80	0.19	0.58	1.00	0.19	0.53	0.53	1.00	0.77	0.19	0.19
3	0.91	0.59	0.33	0.55	0.59	0.53	0.53	1.00	0.85	0.59	0.59
4	0.48	0.12	1.00	0.18	0.12	0.28	0.28	1.00	0.46	0.12	0.12

The highlighted cells show the ideal score in scenarios.

3.7. *Life Cycle Sustainability Assessment (LCSA)*

The three pillars of sustainability, including environment, economic, and society, are separately assessed in previous sections, and the final scores are computed. Based on results presented in Tables 3–5 (scores of every scenario) and Figure 2 (weights from experts' judgment), the intensity score of every sub-category is multiplied by its weight, and the total rating of the sustainability is computed. This procedure is conducted for every scenario. The sustainability scores of all scenarios are shown in Table 6. As displayed in this table, the more sustainable scenario is the base scenario, because this scenario is the best one from a social and economic perspective. In the sequence of the sustainable scenarios, scenario 3 ranks second because the average reduction percentage of this scenario is less than the other three scenarios. Although scenario 4 is the best option in terms of the environmental aspect (with a weight of 56% from the experts' questionnaire), its economic and social consequences lead it to place last in regards to total sustainability. This matter discloses the paramount importance of a comprehensive assessment for an urban water system when applying urban water management policies like WDMPs. In addition, the outcomes reveal that prediction of impacts derived from implementing WDMP could be of utmost significance in various aspects, including the design and management of urban wastewater systems.

Table 6. The score of LCSA for every scenario.

Scenario	0	1	2	3	4
Aggregated sustainability score	0.831	0.725	0.715	0.749	0.630
Normalized sustainability score	1.000	0.873	0.861	0.902	0.759

The highlighted cell shows the ideal scenario.

3.8. Sensitivity Analysis

The weights of the pillars depend entirely on the opinions of the experts. Nevertheless, in order to get more insights into decision-making and investigate the sensitivity of results to the weights, the final sustainability score is explored by changing the weights of the three aspects. To this end, the weight of every pillar is increased by 20% once and decreased by 20% once more. The weights of the other two pillars change equally to keep 100% as the sum of the weights. This process is repeated for every pillar to understand the importance of the weight of the aspects on the total score of sustainability. As shown in Table 7, the base scenario is the most sustainable one in all cases, because this scenario is the best one from a social and economic points of view.

Table 7. Sustainability of every scenario in the sensitivity analysis.

Scenarios		0	1	2	3	4
Situation with the Computed Weights of the Study		0.83	0.72	0.71	0.75	0.63
Changes in the weight of the environment	20%	0.80	0.77	0.77	0.78	0.80
	−20%	0.86	0.68	0.66	0.72	0.47
Changes in the weight of the economy	20%	0.87	0.73	0.70	0.76	0.50
	−20%	0.79	0.72	0.73	0.74	0.77
Changes in the weight of the society	20%	0.82	0.68	0.67	0.71	0.6
	−20%	0.84	0.77	0.76	0.79	0.66

The highlighted cells show sustainable scenarios.

To explain further, as it can be seen in Table 7, when the environmental aspect's weight is increased by 20%, it makes scenario 4 (the scenario with the best performance in the environmental assessment) the most sustainable one (with a sustainability score of 0.8). On the other hand, when the weight of the economic aspect is decreased by 20%, scenario 4 (the scenario with the worst performance in the economic assessment) is better from a sustainability standpoint (with a score of 0.77). Thus, scenario 4 with the minimum wastewater production is highly sensitive to the environmental and economic weights, so this sensitivity makes it less sustainable. The closeness of the final scores of scenarios 1–3 in the sensitivity analysis indicates that the appropriate wastewater reduction percentage in the case study would be between 18 and 30%. Since the case study suffers from water scarcity, WDMPs need to be applied. Therefore, a 30% reduction in wastewater production would be accepted based on the circumstances of the case study and reaching the proper sustainability score.

4. Conclusions and Recommendations

In the present research, a comprehensive approach has been proposed to explore the impacts of applying different WDMPs to the operation of a wastewater system and maintenance stage by considering the three pillars of sustainability. Based on the results, although the population rate has been growing over the years, wastewater production is decreasing due to applying different WDMPs. In addition, the concentration of qualitative parameters is increased by reducing the produced wastewater. Considering the reduction in the velocity of sewer pipes and the depth-to-height ratio of pipelines, gas emissions that depend on the hydraulic parameters in sewer pipes and qualitative parameters of the wastewater are increased in the scenarios. In addition, the results show that scenarios with a higher wastewater reduction percentage have lower environmental impacts. Based on the judgement of the experts, among three environmental endpoint damage categories (i.e., human health, ecosystem, and resources), human health is the most important category and gets the highest weight.

The results demonstrate that decreasing the wastewater production leads to an increase in the repairing costs (blockages in the sewer), a reduction of the energy costs, and a decrease in the revenue of selling treated wastewater. It can be concluded that scenarios with higher reduction percentages have lesser financial profits. The costs of scenario 4 (with the most wastewater reduction) are more than the revenue from selling the treated wastewater. In social assessment, based on the experts' point of view, the public and the local community is the most crucial stakeholder and achieves a higher weight. The base scenario (scenario 0) is the best from a social perspective because of the lack of changes and similarity of the system's situation with the designed conditions. In the end, the sequence of the sustainability score of the scenarios by considering the weight and intensity of every pillar of the sustainability are as follows: Scenario 0 (the status quo) > Scenario 3 (18% reduction in wastewater production) > Scenario 1 (20% reduction) > Scenario 2 (30% reduction) > Scenario 4 (68% reduction in wastewater production). In overall, in the considered case study (Baharestan city), applying WDMPs to reduce wastewater production is inevitable because of severe water scarcity. Sensitivity analysis results show that a 30% reduction in wastewater production of the study area would be an acceptable amount to solve water scarcity problems along with reaching sustainability.

In conclusion, it is essential to consider the effects of long-term planning on designing (or redesigning) WWCN and WWTP, especially when it comes to the implementation of WDMPs. It is recommended to consider other elements of an urban water system for future studies, including water resources, water treatment plants, and water distribution networks. In other words, it is suggested to expand the system boundary. In addition, due to the aim of the study, only the operation and maintenance stage is considered in this paper. However, it is recommended to consider the whole life cycle for potential future studies, including construction, operation, renovation, and end-of-life stages. The proposed approach in this paper can be used as a guideline for decision-makers to evaluate the sustainability of their systems under applying WDMPs and be aware of the long-term effects of their decisions. This will help them choose the most sustainable scenario according to the requirements of their system. Therefore, applying this approach to other case studies with wider system boundaries and real scenarios will be influential in the decision-making progress.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14137736/s1, Table S1: Equations for computing gas emissions [62–64]; Table S2: The LCA inputs for scenario 0 (the base scenario) [11]; Table S3: Stakeholders, Categories, and indicators of social impacts; Tables S4–S13: Comparison of qualitative and quantitative sub-categories in different scenarios of social assessment.

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