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Assessing the Sustainability of Decentralized Wastewater Treatment Systems in Rwanda

Amos Shyaka Kazora [1] and Khaldoon A. Mourad [2,3,*]

1 Water and Sanitation Corporation (WASAC), Kigali City 2331, Rwanda; shyakaamos@gmail.com
2 Pan African University, Institute of Water and Energy Sciences (Including Climate Change), Tlemcen 13000, Algeria
3 Faculty of Social Sciences, Centre for Middle Eastern Studies, Lund University, 22100 Lund, Sweden
* Correspondence: khaldoon.mourad@cme.lu.se; Tel.: +46-726-540-408

Received: 14 November 2018; Accepted: 3 December 2018; Published: 5 December 2018

Abstract: Kigali city, the capital of Rwanda, relies on decentralized, on-site, wastewater systems due to the absence of central sewerage systems and the limited finances to construct sustainable sanitation infrastructures. However, the city has increasingly shown failures in managing these on-site systems either at individual or collective levels. This study aims at assessing the sustainability of the operated collective public semicentralized sewage systems in Kigali city. To fully cover the sustainability assessment of such collective systems, the methods used were field observation, questionnaires, interviews, and laboratory tests. The study also reviewed the influence of national ruling sanitation legal instruments in addressing development, operation and management of such decentralized wastewater systems. The results showed that the sustainability levels of these systems were low in the technical, socioeconomic status, institutional, and legal dimensions. While the sustainability level was fair for the environmental quality. In conclusion, the research highlighted that the improved sanitation coverage does not mean coverage in terms of sewerage connection proportions for wastewater collection as these connections do not imply safe and sustainable treatment before being discharged into the environment.

Keywords: socioeconomic status; improved sanitation; legal instruments; semicentralized sewerage system; sewerage connection; Kigali

1. Introduction

Sanitation is one of the critical and essential infrastructure sectors for well-being health and environmental sustainability [1]. However, wastewater management has been one of the main challenges that faces developing countries due to population growth and the lack of sanitation and wastewater management practices [2,3]. Therefore, 80–90% of the generated wastewaters in developing countries are discharged directly into water bodies [4]. For example, 62% of the urban population in sub-Saharan Africa disposes wastewater directly to water bodies due to the lack of sanitation infrastructures [5].

Despite the fact that Rwanda as a country achieved MDG targets on improved sanitation, there are still unsafe and unreliable decentralized wastewater treatment practices [6]. In the city of Kigali, for example, there is no centralized public sewerage system while the few semicentralized wastewater treatment plants (SCWWPs) or semicentralized sewerage system (SCSSs) do not function appropriately as initially designed. According to thematic report utilities and amenities approved in March 2016, EICV4, 81.6% of the improved sanitation in Rwanda used pit latrines with solid slab due to the absence of sewage system/network in the country [7]. Hotels, hospitals, and big commercial buildings are obligatory required to install private SCSSs for the treatment of their wastewater before being discharged into the environment. However, due to the poor governmental monitoring the standards for their discharged treated wastewater do not meet the national standards [8].

Decentralized Wastewater Treatment Systems (DWWTSs) are on-site wastewater treatment systems for small volumes of wastewater produced either from individual homes, cluster of dwellings or businesses [9]. The low of needed costs and expertise, makes DWWTSs a good sanitation choice in developing countries especially for small communities [10,11].

The assessment of DWWTSs may cover the life cycle perspective (benefits and disadvantages), policies that relate to each technology, and the technologies themselves [12]. Therefore, the assessment should be based on environmental, managerial, socioeconomic, legal, and institutional aspects [1,13].

This paper aimed at identifying the sustainable technological solutions for efficient management of the existing SCSSs by proposing a management framework of the collective decentralized wastewater treatment systems in Kigali. This goal was achieved though: assessing the operation and management practices of the existing SCSSs for their technical and socioeconomic sustainability; evaluating the environmental sustainability of the existing SCSSs; and proposing a wastewater management framework for the decentralized systems.

2. Methodology

The paper was based on both quantitative and qualitative research approaches using a set of primary and secondary data. The primary data sources included four site-based surveys covering 17 DWWT plants sites.

2.1. Study Area

Kigali, the capital and the largest city of Rwanda, is located at the latitude of 1°58′ S and a longitude of 30°07′ E [14]. The city has more than 1.2 million inhabitants in three districts—namely Nyarugenge, Kicukiro, and Gasabo—over an area of 730 km^2, Figure 1. The city is dominated by unplanned resettlements and subjected to slums that were built before the establishment of Kigali city master plan in 2006.

Septic tanks and pit latrines are the main sanitation facilities in Kigali [8]. However, only 2% of the households in Kigali city empty the sludge from their pit latrines [15]. The little percentage of the emptied sludge is not treated for proper disposal rather it is just dumped in an open environment together with other solid and liquid wastes into dumping site in Gasabo District called NDUBA [16,17].

No sewerage system installed in most densely populated urban areas of Rwanda including Kigali city. However, there are few developed sewerage systems installed by estate developers (Cluster of houses) for small communities of high-income household levels in Kigali city. In addition, there are also some other SCSSs developed by business owners in some public areas like hospitals, hotels, and government institutions [8,18].

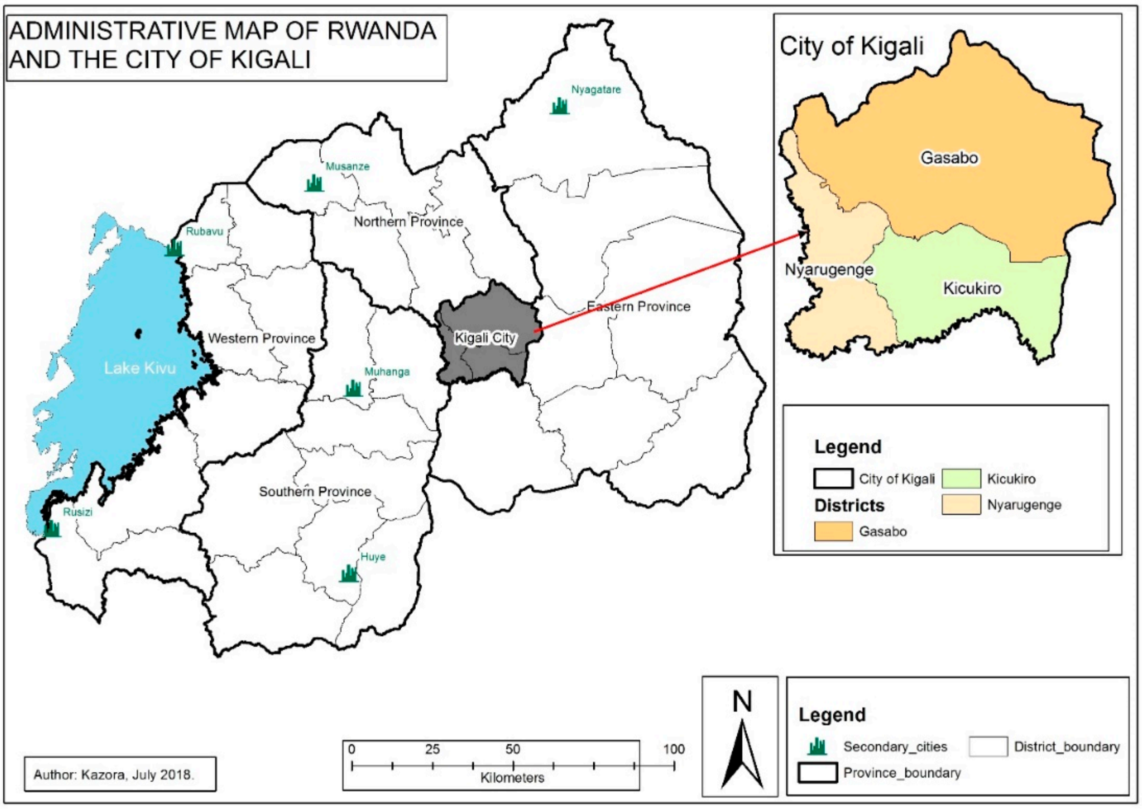

Figure 1. Administrative map of Rwanda, Kigali city [19].

2.2. Research Design

Four sampling sites were selected from the city, namely, Kacyiru, Gacuriro, Kabuga, and Gikondo to represent the different SCSSs and sanitation treatment plants STPs These sites have 19 recognized collective sewage treatment plants, Figure 2.

Three stages were employed in assessing the sustainability of existing SCSSs and their specific sewage treatment plants through (1) evaluating the infrastructures capacity, design competence, technology used, and possibility for extensions and (2) measuring the systems' applicability and performance in terms of effluent quality and variability. Laboratory tests for measuring the influent and effluents characteristics were used, and energy consumption were also determined. Monitoring systems and management of plant operations were also assessed; (3) analyzing the existing sanitation legal instruments (national sanitation policy, laws, and regulations) to determine the gaps that may limit the development, implementation, and management of the systems.

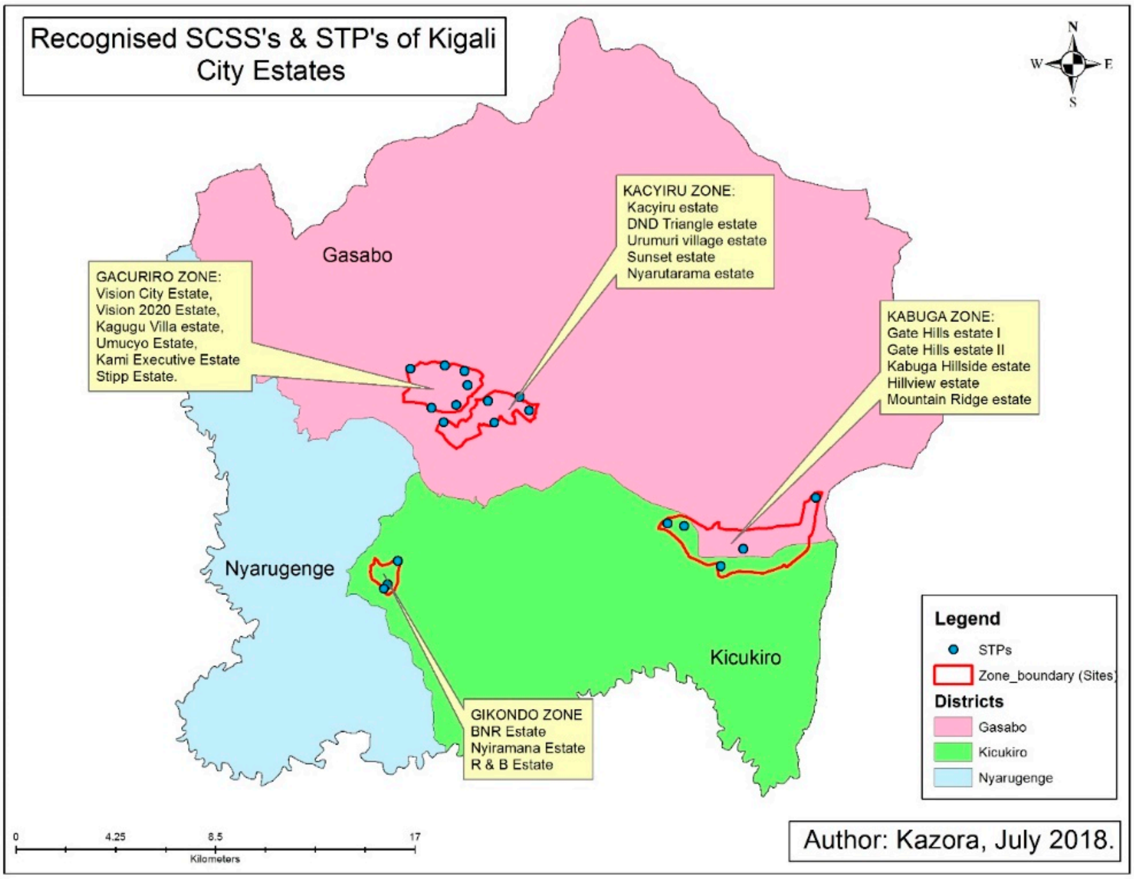

Figure 2. Sampling sites of the 19 collective STP's in Kigali city.

2.3. Data Collection

Primary data was collected by (1) interviews using open focus group discussions through personal observation, different local administrative levels, community management representatives of estates, and technical labors and (2) a structured questionnaire with a wide range of professional stakeholders from government officials, local authorities, and treatment plant developers.

Wastewater samples were collected at key treatment units of each decentralized wastewater treatment plant to measure influent and effluent quality in order to evaluate system's performance and the competence of each treatment unit in reducing the negative impacts of the wastewater.

The quantitative data of the collected wastewater samples from each of the four selected SCSSs were taken for assessing environmental sustainability using a designed WASAC sampling form [20]. The samples were taken from the influent and the effluent of each plant in a considerable time frame and then were taken to the laboratory for physical, chemical and microbiological testing. The measured parameters were Fecal Coliform, *E. coli*, color, Electrical Conductivity, Total Phosphorous (TP), Total Nitrogen (TN), Dissolved Oxygen (DO), Total Chemical and Biochemical Oxygen Demand (COD and BOD), Total Suspended Solids (TSS), Total Dissolved Solids (TDS), PH, Temperature variation, and Turbidity.

The qualitative data for the socioeconomic and technical sustainability of the sewerage systems were collected from the focus group discussions (FGDs) with a wide range of stakeholders through questionnaires, interviews, and meetings. In addition to the FGDs, secondary data were reviewed for the four selected STPs including sanitation policies and research papers. Rwandan national sanitation policy and strategies (NSPS), laws, and regulations were intervened in order to assess the gaps created by unapprised legal sanitation instruments for the sustainable management of SCSSs.

All the collected data were given codes and entered in an Excel sheet. The screening of the data pieces and marking the codes on the different variables were done to avoid confusions in data analysis.

2.4. Assessing the Sustainability of the SCSSs and STPs

The methods for evaluating the sustainability of different wastewater treatment systems have been altered depending on the locality in relation to the research scope [21]. Life Cycle Assessment (LCA), Rapid appraisal (Rap-fish), commonly known as R-Software, Environmental Impact Assessment, Target plot diagram, Exergy analysis, and Decision analysis were some of the used tools for assessing the system sustainability [1,21,22]. For all these tools, a set of indicators was divided into different dimensions including technical, environmental, socioeconomical, institutional, and legal systems.

According to many scholars, sustainability assessment is only achieved when using a multidisciplinary technique [20] and only when the end solution is generated from an integral point of view.

The assessing criteria are rated in the range score of 0 to 10, which was initiated during the assessment process and implemented for each attribute. The range is divided into three categories of sustainability as Unsustainable, Less/Fairly Sustainable, and Sustainable, which were later classified as Low, Medium, and High scoring, respectively.

The Low class (L) represents any parameter that performs poorly, in the range of 0 to 3, the Medium class (M) ranges from 4 to 6, while the High class (H) ranges from 7 to 10.

Each criterion is assumed to have a full maximum score of 10, the criteria for each dimension and its specific attribute were rated according to the laboratory results and the responses from the affected stakeholders through structured and non-structured questionnaires. Affected stakeholders included wastewater treatment professional, local residents, technical labors, Estate developers/operators.

Afterwards, all criteria and their weight scored for each dimension were entered into the Excel database for assessing their sustainability level. The total score for each dimension depended on the number of criteria analyzed. Dimensions with the lowest score were the ones that generated major negative influences on the system performance and hence the most unsustainable dimensions.

3. Results

3.1. Technical Evaluation

As seen in Table 1, the technical aspects were grouped in extensive and intensive criteria, and grouped according to their attributes (capacity, technical operations, efficiency, physical conditions, and layout conformity).

Table 1. Technical assessment of semicentralized sewerage systems (SCSSs) and STPs of Kigali City Estates.

Dimensions/Attributes	Scaling	Low	Medium	High	Criteria
Technical		**0–3**	**4–6**	**7–10**	
Physical Conditions and Layout Conformity					
			6		Designed Construction
			4		design plan horizon (Period)
			4		Construction of infrastructure works according to design
		3			Modified (Rehabilitated and Upgraded)
			5		Operation of plant
			6		Noise generation
			5		Odour generation

Table 1. *Cont.*

Dimensions/Attributes	**Scaling**	**Low**	**Medium**	**High**	**Criteria**
Technical		**0–3**	**4–6**	**7–10**	
Plant Capacity					
		3			Designed inflow (Influent)
			4		Number of Inhabitants
Efficiency					
		3			Wastewater complexity (Designed level of BOD5 for influent)
		3			Treatment efficiency for the removal of BOD5 and COD (effluent quality)
		3			Complexity of operation and maintenance
Technical Operations					
		3			Energy demand
		3			Availability of treatment reagents
		3			Skilled staff
Subtotal	**150**	24	33		
Average	**10**		**3.77**		

3.2. *Socioeconomical Evaluation*

As presented in Table 2, the capital and operational costs are the indicators that define the suitable alternative system. As it can be seen from Table 1, the irregular operations of the SCSSs of Kigali city were expensive, which made the public ignore their responsibilities/ownership in managing the facilities.

Table 2. Socioeconomic assessment of SCSSs and STPs.

Socioeconomic	**Scaling**	**Low**	**Medium**	**High**	**Criteria**
		0–3	**4–6**	**7–10**	
Costs					
		3			Capital Costs
		3			Operational Costs
		3			Depreciation of the fixed costs
		3			Extension costs for service coverage
Community					
			5		Social awareness and understanding of SCSSs
			4		Social acceptance and expectancy
		3			Community involvement in planning, development and management of SCSS
Service Satisfactory					
			5		Reliability of the services
			4		Affordability of the services
Subtotal	**90**	15	17		
Average	**10**		**3.53**		

3.3. Environmental Evaluation

The quality of the effluent reflects the performance of the treatment system in both technical and environmental aspects. Therefore, samples from four selected SCSSs were taken (influent and effluent) to assess their performance. The collected samples were analyzed at WASAC's Central Laboratory using the standard methods, Table 3. The analyzed results were classified according the Rwanda Standards Board, RS 110:2017.

Table 3. Environmental assessment of SCSSs and STPs of Kigali City Estates.

Environmental	Scaling	Low	Medium	High	Criteria Are Based on RS 110:2017 WW Discharge Limit Standards
		0–3	4–6	7–10	
PH				10	5.0–9.0
Colour (mg/L PtCo).		3			200
TSSo (mg/L).		3			50
Total Dissolved Solids (mg/L).				10	1500
Electrical Conductivity (µS/cm).		3			-
Temperature Variation (0 c).				10	3
Turbidity (NTU).		3			30
DO (mg/L)		3			-
COD (mg/L).				8	250
Biological Oxygen Demand (mg/L).				7	50
Total Nitrogen (TN)				7	30
Total phosphorous (TP)				8	5
Faecal coliform (MPN/100 mL).		3			<400
E. coli (MPN/100 mL).		3			-
Subtotal	**140**	21		60	
Average	**10**		**5.75**		

3.4. Legal and Institutional Evaluation

Three instruments were analyzed: Sanitation policy, law and regulations, and the institutional framework in managing the SCSSs.

There is no sanitation law in Rwanda though it is now under formulation. However, according to the survey, the sanitation sector in Rwanda is controlled by two legal instruments: National Sanitation Policy and Regulations on decentralized wastewater treatment systems.

Tables 4 and 5 below present the examined criteria with their weight. The institutions were divided into two classes according to their roles as "Policy-makers and Regulators" or "Implementers" to provide the relationship between the developed targets and its implementation.

Table 4. Legal and institutional framework assessment of SCSSs and STPs of Kigali City Estates by implementers.

Dimension/ Attributes	**Implementers (CoK and WASAC)**										**Conditions**
	Institute	**CoK I**			**CoK II**			**WASAC**			
	Scaling	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Criteria**
		0–3	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	
Institutional and Legal Instruments											
Sanitation Policy (50)											
				10	3					10	Available
		3			3				6		Available but not addressing proper development & management
		3			3			3			Available but not addressing complete development & management
		3			3			3			Available and fully addresses the development and management
		3			3			3			Enforcement
Sub-total	**400**	12		10	15			9	6	10	
Average/Class of Institute	**10**					**4.13**					
Sanitation Law (30)											
			6			6		0			Available
		0			0			0			Accountability for breaking laws for the working conditions
		0			0			0			Enforcement
Sub-total	**240**	0	6		0	6		0			
Average/Class of Institute	**10**					**1.33**					

Table 4. *Cont.*

Dimension/ Attributes		**Implementers (CoK and WASAC)**									**Conditions**
	Institute	**CoK I**			**CoK II**			**WASAC**			
	Scaling	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Criteria**
		0–3	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	
Regulations on Decentralized Wastewater Treatments Systems (30)											
				10	3					10	Available
			6		3				6		Political will to give SCSSs an appropriate attention
		3			3			3			Enforcement
Subtotal	**240**	3	6	10	9			3	6	10	
Average/Class of Institute	**10**					**5.22**					
Institutional Framework (60)											
			6		3				6		Defined the responsible institutions in sanitation policy
		3			3			3			Accountability for mismanagements or failures
				10			10	3			Institutional collaboration
		3				6		3			Consistency among responsible institutions
		3			3			3			Power delegation to the responsible institutions
			6			6			6		Institutional will
Sub-total	**480**	9	12	10	9	12	10	12	12		
Average/Class of Institute	**10**					**4.78**					
Average/Class of Institute	**10**					**3.87**					

Table 5. Legal and institutional framework assessment of SCSSs and STPs of Kigali City Estates by policy-makers and regulators.

Dimension/ Attributes	Policy Makers and Regulators (MININFRA, REMA, RURA, MoH)																Conditions
	Institute	**MININFRA**			**REMA I**			**REMA II**			**RURA**			**MoH**			
	Scale	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Criteria**
		0–3	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	
Institutional and Legal Instruments																	
Sanitation Policy (50)																	
				10			10			10			10			10	Available
		3			3			3			3			3			Available but not addressing proper development and management
		3			3			3			3			3			Available but not addressing complete development and management
		3			3			3			3			3			Available and fully addresses complete development and management
			6			6			6		3			3			Enforcement
Subtotal	**400**	9	6	10	9	6	10	9	6	10	12		10	12		10	
Average/Class of Institute	**10**								**4.76**								
Sanitation Law (30)																	
		3			3			3			3				6		Available
		0			0			0			0			0			Accountability for breaking laws for working conditions
		0			0			0			0			0			Enforcement
Subtotal	**240**	3			3			3			3			0	6		
Average/Class of Institute	**10**								**1.2**								

Table 5. *Cont.*

Dimension/ Attributes	**Policy Makers and Regulators (MININFRA, REMA, RURA, MoH)**																**Conditions**
	Institute	**MININFRA**			**REMA I**			**REMA II**			**RURA**			**MoH**			
	Scale	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Criteria**
		0–3	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	**0–3**	**4–6**	**7–10**	
Regulations on DWWT Systems (30)																	
				10	3					10			10	3			Available
			6		3				6				10	3			Political will to give SCSS an appropriate attention
			6		3				6				10	3			Enforcement
Subtotal	**240**		12	10	9				12	10			30	9			
Average/Class of Institute	**10**								**6.13**								
Institutional Framework (60)																	
			6		3			3			3			3			Defined roles and responsible institutions in sanitation policy
		3			3			3			3			3			Accountability for mismanagements or failures of SCSSs.
			6			6		3				6		3			Institutional collaboration
			6		3			3			3			3			Consistency among responsible institutions
			6		3				6			6		3			Power delegation to the responsible institutions
			6			6			6		3			3			Institutional will
Subtotal	**480**	3	30		12	12		12	12		12	12		18			
Average/Class of Institute	**10**								**4.1**								

3.5. Sustainability Assessment of the SCSSs

The overall assessment combined the scoring weight criteria for technical, socioeconomic, environmental, legal and institutional attributes. Figure 3 shows the sustainability level of the SCSSs of Kigali city. The assessment showed that the sustainability level was Less Sustainable in the technical, socioeconomic, legal, and institutional dimensions due to the poor management practices and the absence of legal instruments. The dimensions that were linked with community involvement and institutional framework were the ones that reduced the efficient performance of SCSSs and STPs.

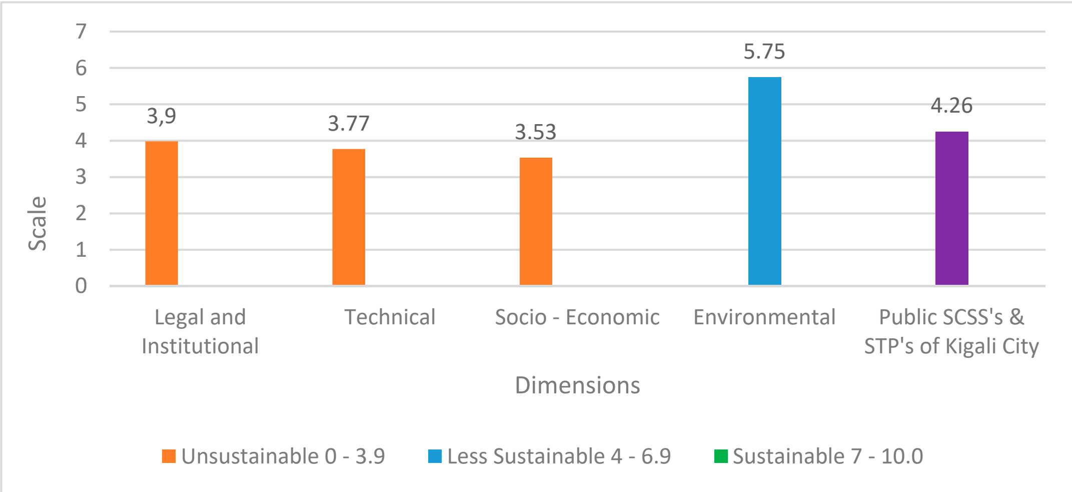

Figure 3. Sustainability of public SCSSs & STPs.

It was noticed that most of the sewerage network systems actually carried both sewage and storm water from houses, yet they were initially designed to carry the sewage only. This is against their initial designs. Moreover, most of the grease removal units on households' connections were clogged while others were sealed, which showed the lack of regular sewer inspection.

During the assessment, it was realized that most plants did not have designed sampling points at the inlet and the outlet of each treatment unit (settlers and bioreactor), which complicated separate sampling and monitoring.

From a technical point of view, the insufficient aeration and low residence time in the final settling tanks were the main technical problems, which was proven by laboratory results. Moreover, a high concentration of fecal coliforms was detected in the effluent of each plant compared to the limits. The TSS level was also high compared to the standards due to the irregular desludging of settlers. An average reduction of ~45% was observed between the raw wastewater and the final effluent. Figure 4 shows the sustainability level of each dimension in technical, environmental and socioeconomic sustainability of Kigali city estates.

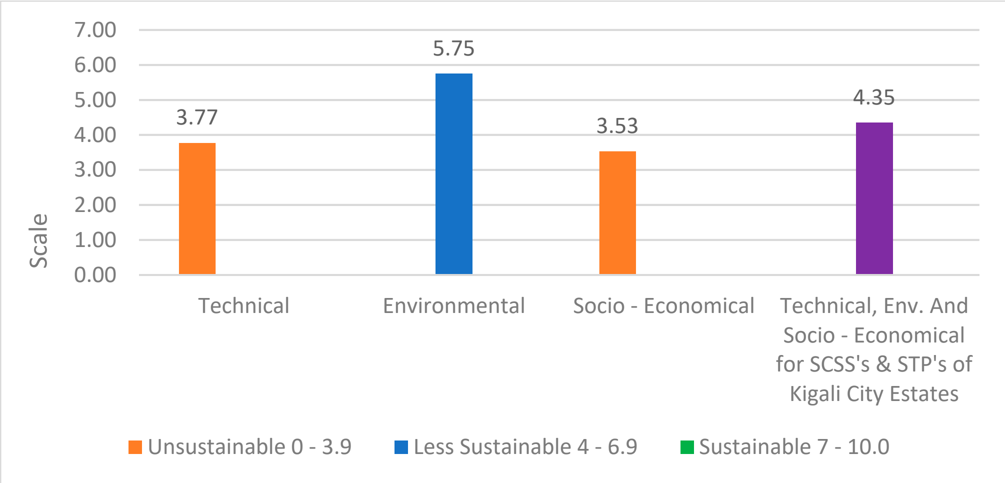

Figure 4. Technical, environmental, and socioeconomic sustainability levels.

The assessment revealed that the highest percentage of the poorly performing parameters were the ones associated with community involvement more especially technical and socioeconomic sustainability, which highlighted the need to raise awareness about SCSSs.

The legal and institutional assessment included sanitation policy, regulations and the institutional framework. According to the questionnaires, the institutional framework was almost unsustainable. Figure 5 gives an overview about the sustainability level of the legal and institutional assessments.

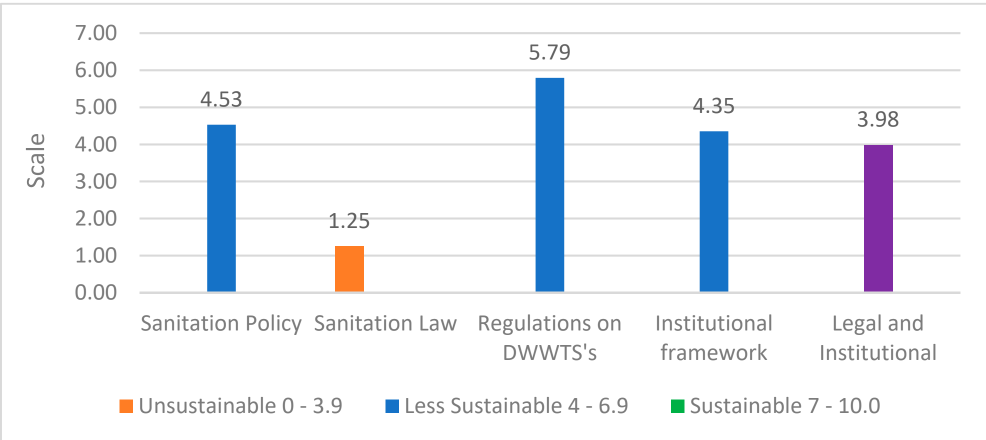

Figure 5. Legal and institutional assessment of Kigali city.

4. Conclusions

The paper evaluated the sustainability of DWWTSs precisely for the collective SCSSs of the public estates of Kigali city through technical, environmental, socioeconomic, legal, and institutional assessments. Based on the responses from most affected stakeholders, SCSSs were more favorable in densely populated areas of small communities. However, the results showed that the sustainability levels for the evaluated systems were low in the technical dimension, socioeconomic status, institutional, and legal dimensions.

The decentralized wastewater treatment in the case study showed significant performance failures regarding the effluent quality. The selected SCSSs were not effective in complying the effluent quality requirements. This study provided sufficient evidences to determine the potential of SCSSs in providing collective wastewater treatment services in densely populated areas of developing cities such as Kigali.

Attaining sustainable wastewater treatment systems is only possible if the treatment plant is well designed and properly managed. However, the paper showed that the construction of biological treatment tanks and reclamation parts were not at satisfactory conditions for sustainability due to the poor quality and incomplete civil construction works.

On the other hand, the absence of sustainable legal instruments for planning, developing and managing the SCSSs and STPs for collective urban communities will cause a failure in operation. Hence, the legal and institutional framework will be less supportive towards SCSSs in small communities. Therefore, there is a need to redefine, restructure and enforce the principles that govern the SCSSs in Rwanda.

Author Contributions: Methodology, A.S.K.; Analysis, A.S.K.; Resources, K.A.M., A.S.K.; Data, A.S.K.; Writing-Original Draft Preparation A.S.K.; Writing Review, Editing and Submission, K.A.M.; Supervision, K.A.M..; Open Access Publication, K.A.M.

Funding: This research received no external funding.

Acknowledgments: The authors thank the Center for Middle Eastern Studies at Lund University for funding the publication of this paper through the MECW program.

Conflicts of Interest: The authors declare no conflict of interest.

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