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Using Principles of Structured Decision-Making to Evaluate Wastewater Treatment System Alternatives

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Abstract: As a result of population growth, urban centers and metropolitan regions around major cities have seen a sharp increase in the sewage production. One of the many challenges this poses is how to respond to rapidly and haphazardly urbanization, in terms of selecting different Wastewater Treatment Systems (WWTS) alternatives. Therefore, this paper applies the concepts of Structured Decision-Making, which is one of the decision making analysis (DMA) process, in order to select specific WWTS Configurations into a given scenario to treat domestic sewage. It brings up a fresh and innovative perspective in the field of sanitation by proposing and evaluating centralized, decentralized and sustainable WWTS solutions using DMA. In addition, the goals are to provide a mechanism of DMA and hence to obtain the best solutions especially for underserved urban areas, which lack basic needs and planning. The method adopted also encompasses a case study of a Pilot Project which has conducted on campus at Federal University of Paraná. The data of the indicators previous selected were carefully observed, documented and subsequently compared with the data obtained in the literature. Furthermore, this research was able not only to analyze and compare different solutions, but still to present the design of the sustainable WWTS alternatives.

Key words: wastewater treatment systems, structured decision-making, sustainability

1. Introduction

Sewerage and drainage network systems have a long history and examples of sanitation infrastructure may be found in various ancient cultures such as Minoan societies in Crete, ancient Babylonia in present-day Iraq and the City of Mohenjo-daro in present-day Pakistan. In addition, the most widely known as the first wastewater system have dawned in Rome, which was built in the 6th century BC. It was an example of a combined system that received both domestic sewage and storm water, and used to control odour as well as diseases. Interestingly, the knowledge seems to have gone dormant and centralized sewer systems were not implemented on a broader scale until the late 19th century. In spite of the fast growth of cities and metropolitan areas in the past few decades, especially in the developing world, many communities continue without appropriate sewer systems, even though the health effects and social and economic impacts are well documented.

In this view, according to the United Nations [1] and World Health Organization [2], one third of the world's population, around 2.5 billion people, lack access to improve sanitation facility (ISF), and over a billion dumping excreta directly on the soil or rivers. Martinez et al. (2008) [3] discussed the meaning of the term ISF, which denotes the separation of human excreta from human contact. As a result of that problematic scenario, stormwater systems and rivers are often contaminated with raw sewage directly dumped, or often exacerbated during flooding or in cases of overflowing of the sewerage networks in heavy storm periods. As many developing countries, Brazil is confronted with the

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same issues which impact the health of large segments of its population, where a large portion of the population (approximately 45%) do not have access to ISF [4]. They are therefore forced to use water from rivers where the water is contaminated with infectious micro-organisms from domestic or industrial waste, which have caused diseases, such as cholera, leptospirosis, etc.

In fact, although the causes of this reality in the developing countries might be involved with economic and political factors [5], one of the most demographic trends of this current century is still the rapid and haphazard urbanization. Thereupon, one of the issues related to the unplanned urbanization is the irregular soil occupation by communities who will someday settle in underserved (so-called "peri") urban areas, where there are lacking of basic needs, planning, and hence sanitation [6]. In this scenario, the sewage is often discharged into an urban drainage system without treatment.

Even though the conventional end-of-pipe WWTS configuration has been lately highly likely used in many developed countries, it has also been considered as a massive energy demander, while a high amount of valuable resources has still been wasted, such as water, nutrients and energy [7]. It also has been discussed the capital and the operation costs associated with the conventional WWTS make it unsuitable for rapidly and haphazardly growing areas [5, 8]. It is commonly agreed that there is a necessity of encouraging a transition to more sustainable systems where sewage is seen as a resource rather than waste. In addition, future sanitation solutions also should concede social, economic and environmental criteria, where principles such as affordability and the potential of positively impact of health and living conditions for local population have to be aimed [9].

Moreover, besides several characteristics, it is argued that sustainable sanitation solutions should consider decentralization approaches [5, 10]. The difference between centralization and decentralization is basically based on the amount of the population served by the system [11]. Centralized systems have the characteristics of treating high amount of wastewater contributions, for instance higher than the contribution of 5,000 people, or flowrates over than 1,000,000 liters per day [11]. Although centralized systems seem to be a trend in the developed countries, there is an increasing propensity in the opposite direction concerning the developing world, where decentralized WWTS are becoming more suitable solutions for needed population [8]. In this view, in terms of decentralized systems with regards to the population served, there are currently several and different studies and classifications, even though they generally address to the same concept. Records of the US Environmental Protection Agency apud Libralato et al. (2012) [8], classify small decentralized plants as those that receive sewage from household contribution not greater than 5,000 people, which in the most cases encompass cesspools, sinkholes, anaerobic filters and septic tanks. Thus, three main advantages can be pointed to decentralized systems, e.g., the costs reduction in the transportation of sewage while pumping stations are eliminated; effluent reuse opportunities and, finally, issues found in specific unities do not cause collapse in the whole system [5, 12]. And it will be part of the evaluation process of this study.

In terms of the decision context, it is argued that there is no ideal WWTS applicable to all cases. That presumes the requirements of an individual evaluation for each scenario with regards to its specific characteristics. In order to perform the comparison analysis, it is required to confront parameters, or also so called indicators, with a set data, which can be obtained from literature, or data base [13]. These evaluation and validation process might be performed by using the principles of Structured Decision-Making (SDM), which can be defined as a process which supports collaborative and participatory decisions [14-18] (MARTTUNEM *et al*., 2015). In addition, one of the challenges of the SDM is the definition of the indicators to proceed the evaluation, and in the case of this study, for the most suitable WWTS solution. In light of this approach, one of the main aspects of choosing indicators is to considerate reliability, and also achievable information [19]. Gregory et al. (2012) [17] acknowledge this concept summarizing the SDM process as Fig. 1 ahead.

The six steps defined and shown in the Fig. 1 can be basically summed up as: (i) to define the problem and identify the stakeholders involved; (ii) to select a set of indicators and the evaluation criteria, whereas weighting and normalization also appear as important stages; (iii) to establish the alternatives with respect to different priorities across the elected criteria; (iv) to estimate the performance of the alternatives with regards to the evaluation criteria developed; (v) to perform a group discussion evaluating their preferences given different weighting for each objective previous defined; (vi) to identify mechanisms and monitoring the outcomes in order to improve future decision-making process in the same field. This study will only contemplate the SDM up to the 5th stage, as it will be seen on the next sections.

2. Objectives

This research addresses to the question of how to perform and implement a multiple alternative decision-making analysis, namely Structured Decision Making (SDM), in order to select the most appropriate WWTS, considering sustainability aspects?

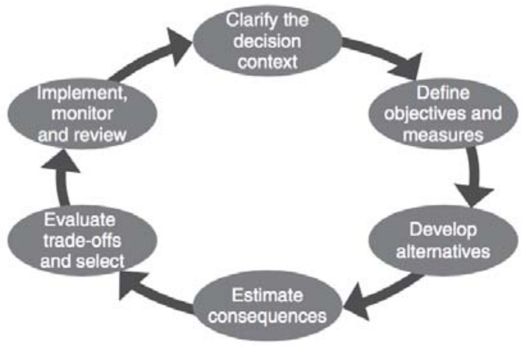

Fig. 1 Structured decision-making (SDM) process [17].

3. Material and Methods

As it will be seen on this section, the decision-making process of this research basically considers the principles of SDM. However, as it will also be seen, adaptions from the original framework depicted in Gregory et al. (2012) [17] were made.

3.1 Clarifying the Decision Context

In light of the problematic conjuncture, firstly the contextualization approaches the definition of the most suitable WWTS for the scenario elected, which is related to the areas that surround urbanized areas and also lack basic needs in the developing world.

3.2 Defining Indicators and Measures

Moving forward, the second step of the SDM is related to the definition of the indicators which will be used within the evaluation process. According to Muga and Mihelcic (2008) and Venkatesh et al. (2014) [20, 21], it is still consistent defining a set of the most commonly used indicators from other researches, for instance. In addition, the main group of indicators which have been recently elected within the field of study of this research acknowledge environmental, social and economic characteristics [16, 20]. For instance, in this investigation the set of indicators defined are organic matter (Biochemical Oxygen Demand and Chemical Oxygen Demand) and nutrients (Nitrogen and Phosphorus) removal efficiencies, and also implementation and operational and maintenance costs [22, 23]. Other important indicator to mention concerns land area requirements, which was discussed in Massoud et al. (2009) [5]. The last consideration is related to the energy spent in the treatment, which will be also analyzed ahead in this research. Thus, considering the data analyzed, the set of indicators selected to be part of the SDM process has agreed with the most widely indicators reported in recently researches.

This stage of the SDM hence was performed by analysing a matrix with different ranks regarding each indicator and previous defined values. In other words, it was created a weighing process as described on Table 1 (adapted from Ref. [24]).

As it is seen on Table 1, there are five different levels to rank and perform the decision analysis process. The Arabic numerals go from “1”, which indicates the lowest performance of each indicator, while “5” represents the highest, as well as the data which information, or consequences, could not be reached (for details see Tables 2 and 3). Thus, the Total Scores (TS) of each WWTS Configuration “n” (e.g., C.I, C.II, C.III, etc.) is equal to the sum of the given Ranks (R) of each Indicator (I), as follows:

$$TS(C.n) = \sum R(I) \tag{1}$$

In the next section it will be presented the results obtained with regards to economic criteria of the PP used as a case study in this research in order to achieve the comparison analysis.

Table 1 Ranking indicators [24].

Indicators		Approximately Values and Ranks				
		1	2	3	4	5
Area requirements		~ 1.25 m²/inhab.	~ 1.00 m²/inhab.	~ 0.75 m²/inhab.	~ 0.50 m²/inhab.	~ 0.25 m²/inhab.
Operation and maintenance costs		~ 14.00 $/inhab. year	~ 12.00 $/inhab. year	~ 9.00 $/inhab. year	~ 5.00 $/inhab. year	~ 3.00 $/inhab. year
Construction cost		~ 200 $/inhab.	~ 150 $/inhab.	~ 100 $/inhab.	~ 50 $/inhab.	~ 25 $/inhab.
Removals efficiency	BOD[1]	~ 40%	~ 50%	~ 60%	~ 70%	~80%
	COD[2]	~ 40%	~ 50%	~ 60%	~ 70%	~80%
	N[3]	~ 40%	~ 50%	~ 60%	~ 70%	~80%
	P[4]	~ 40%	~ 50%	~ 60%	~ 70%	~80%
Electricity consumption		16-20 kWh/inhab. year	11-20 kWh/inhab. year	6-10 kWh/inhab. year	1-5 kWh/inhab. year	None

[1] Biological Oxygen Demand; [2] Chemical Oxygen Demand; [3] Nitrogen; [4] Phosphorus

Table 2 Comparative rates of indicators between different WWTS solutions [7, 30].

Indicators		Centralized WWTS		Decentralized WWTS			
		C.I - Sewerage Network System + Biological Treatment (UASB + ASP)[1]	C.II - Septic Tank + Anaerobic Filter[1]	C.III - Septic Tank + Filter Strip[1]	C.IV - Septic Tank + Cesspool[1]	C.V - Septic Tank + Wetland[1]	C.VI (PP) - Septic Tank + Anaerobic Filter + Wetland[2]
Area requirements		0.08-0.20 m²/inhab.	0.20-0.35 m²/inhab.	1.25 m²/inhab. + 100% Basin Area	1.10-1.50 m²/inhab.	0.40-0.80 m²/inhab.+ 3-5% Basin Area	0.25-0.40 m² + 3-5% Basin Area
Operation and maintenance costs		2-7.5 $/inhab. year	2.00-4.00 $/inhab. year	*	3.00-5.00 $/inhab. year	8.50-14.00 $/inhab. year	3.00-5.00 $/inhab. year
Construction cost		250-300 $/inhab.	23-40 $/inhab.	*	17.5-29.5 $/inhab.	130-210 R$/inhab.	38-62 $/inhab.
Removals Efficiency	BOD[1]	83-93	40-75	50-85	90-98	70-90	80-95
	COD[2]	*	40-70	40-75	*	70-85	80-95
	N[3]	*	10-20	50-80	*	70-90	80-90
	P[4]	*	10-20	30-70	*	70-90	80-90
Electricity consumption		14-20 kWh/inhab. year	None	None	None	None	None

* Without Information;

[1] Biological Oxygen Demand; [2] Chemical Oxygen Demand; [3] Nitrogen; [4] Phosphorus

Table 3 Decision-making process rankings and total scores results.

		C.I	C.II	C.III	C.IV	C.V	C.VI
Area		5	5	1	1	2	3
Operation and maintenance costs		4	5	5	4	3	4
Construction costs		1	5	5	5	2	4
Removals Efficiency	BOD[1]	5	1	4	5	5	5
	COD[2]	5	1	3	5	5	5
	N[3]	5	1	4	5	5	5
	P[4]	5	1	2	5	5	5
Electricity consumption		1	5	5	5	5	5
Total Score		**31**	**24**	**29**	**35**	**32**	**36**

[1] Biological Oxygen Demand; [2] Chemical Oxygen Demand; [3] Nitrogen; [4] Phosphorus

3.3 Developing Alternatives

The third stage comprehend the definition of the WWTS alternatives.As it will be seen forward in this research, the comparison analysis will considerate not only traditional centralized WWTS commonly implemented worldwide, but also sustainable and decentralized solutions. According to Kalbar et al. (2012) [15], Activated Sludge Process (ASP), Upflow Anaerobic Sludge Blanket (UASB) reactors, among others, have been developed and satisfactorily used to treat wastewater with regards to the centralized approaches.

Consequently, in the selection of the distinct WWTS solutions to allow the comparison process, different systems were picked according to the most widely used in the developing world, as explained by Kalbar et al. (2012) [15]. Then, firstly it was selected one of the centralised WWTS widely used in the field of wastewater management in the developing world (UASB + ASP). Secondly, it was elected a set of four decentralized and traditional WWTS solutions which can be found in the Brazilian regulation (NBR 13969/1997). According to this regulation, in order to provide sufficient onsite treatment for domestic sewage, preliminary and complementary levels of treatment are required. The traditional set of onsite, or also called as individual treatment system, in Brazil is composed by a Septic Tank (ST), with reference to preliminary stages, followed by a secondary or complementary treatment, such as an Anaerobic Filter (AF), or other complementary devices. This sequence is also commonly and widely adopted in rural areas and peri-urban areas, especially in the developing world, due the favourable economical and functional features [25]. Thus, the other forth decentralized alternatives are: (i) Septic Tank plus Anaerobic Filter; (ii) Septic Tank plus Filter Strip; (iii) Septic Tank plus Cesspool; and finally Septic Tank plus Wetland.

Moreover, as a sixth alternative, and as a first exploratory step, this study proposes a Pilot Plant (PP) design, which acknowledges principles such as decentralization and sustainability, given the types of reactors involved. The overview of the conception of the PP is represented in the Fig. 2.

In fact, the configuration of the PP corroborates with Brazilian regulations. According to the NBR 7229/1993 and NBR 13969/1997.

Nevertheless, it is proposed an innovative concept since it considers a polish treatment characteristic. The PP is composed by a Septic Tank (ST) to the preliminary level of the treatment, followed by Anaerobic Filter (AF) in the complementary level, and subsequently there is a Wetland, which provides a supplementary process of treatment and enhance the performance of the system, especially regarding organic matter and TSS components [26]. Likewise, the illustrated PP also provides treatment to stormwater, where the flow collected on the roof of the building is conveyed to a perforated pipe, which soaks the buffer system and delays the surface runoff, whilst allowing for the treatment and removal of pathogens. Then, the runoff finally flows into the public drainage system. afterwards the traditional approach (ST plus AF).Thus, the design of the PP system defined to this research meets the local and standard regulations [27]. The comparison process was afterwards used to analyse the suitability with regards to these different solutions, and in the selection of the most appropriate option. The construction of the PP lasted approximately 120 days. The Fig. 3 shows the PP.

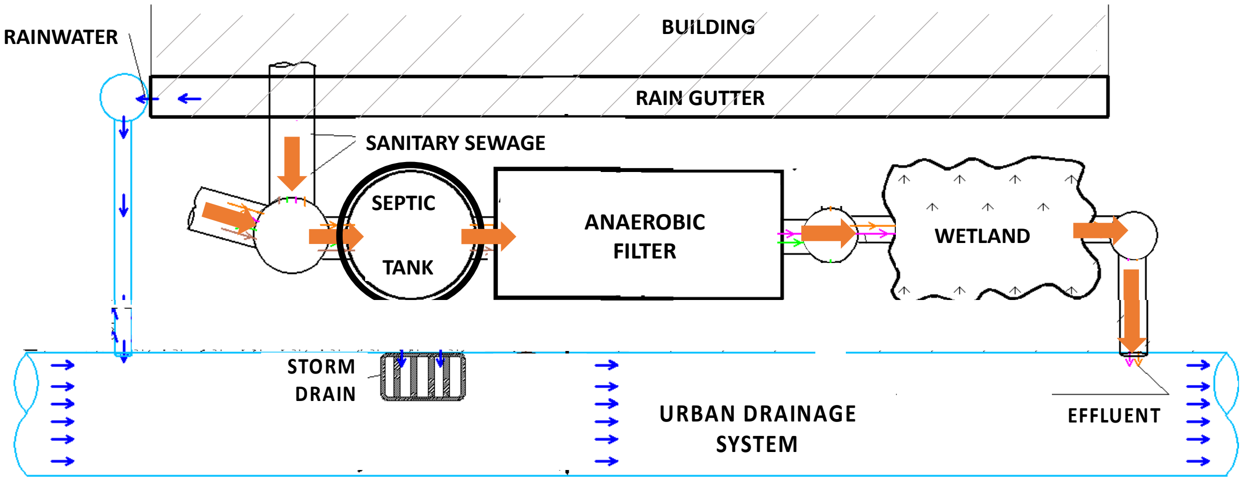

Fig. 2 Overall conception pilot plant (PP).

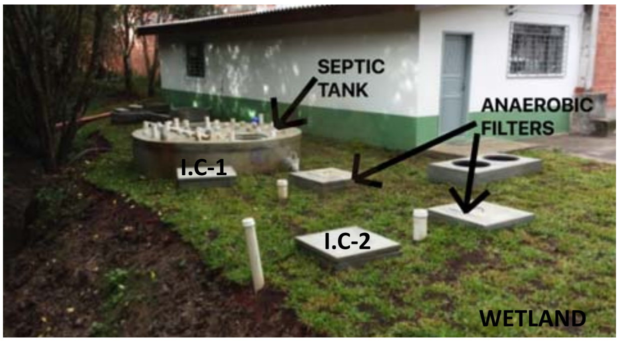

Fig. 3 Pilot plant.

Within the construction process of the PP, it was inserted two inspection chamber (I.C) in order to firstly provide easy access to collect samples to analyse after each reactor (e.g., ST, AF and Wetland).

Finally, in terms of WWTS solutions, a large number of alternative solutions have been developed over the years, and many of these have been recently tested as pilot plant or full scale [28]. Hence, constructed wetlands, or simply wetlands, contemplate principles of decentralization and sustainability, and has been emerging as a potential especially considering in combination with septic tanks, for instance [26].

3.4 Estimate Consequences

For the judgment context, the term sustainability is often mentioned when SDM is applied [29]. In this study, choosing the most sustainability solution will consider the balance between the three main criteria previous mentioned. In other words, the definition of the most sustainable option must consider the bottom-line trade-off between the strengths and weakness of the characteristics. The analysis also should corroborate with the decentralized WWTS approaches, in order to be suitable to solve the problem in the underserved urban areas. Therefore, the consequences related to each indicator and alternative was based both on data from literature and the experience of the PP, and it will be presented on the Table 2 on next section.

3.5 Evaluation Process and Analysis

For the stage of the evaluation process, as depicted in the section 3.2, each indicator of each alternative will receive a specific ranking value which go from 1 to 5, as detailed in Table 1. Afterwards, the total sum of each indicator, and hence the highest “score”, will reveal the most suitable solution with regards to the method selected for this study.

4. Results and Discussion

The Table 2 shows the compiled results with respect to the PP and literature review, which intends to organize the information and allow the application of the decision-making process.

The modelling described by the Eq. (1) has conducted to the matrix and data represented in Table 3.

With regards to the previous results, even though there are several different, and independent, outputs being evaluated, for instance organic matter removal, economic aspects, land requirements, the use of principles of SDM is a helpful procedure to orientate, or even, to select the most suitable alternative considering the elected indicators and the scenario defined.

Thus, as it can be seen at the Table 3, by applying the evaluation stage of the decision-making process, and by using the considerations of the Table 1 with respect to the efficiencies collected and depicted in Table 2, the Configuration “C.VI” (PP) represents the highest total score, hence the most sustainable balance of the indicators analyzed. For instance, the removals efficiencies with respect to organic matter and nutrients have reached the highest levels, and satisfactory data related to costs and area to implement the system. Moreover, even though the costs aspects evaluated are not the lowest, it could be seen that regarding this indicator the decentralized systems could represent advantages in comparison with centralized due the fact which serve high amounts of groups of people require extensive capital expenses related to pipes network to convey the wastewater to the treatment point. Thus, if the comparison just considers the indicator “area requirements” and “BOD removals”, for example, the centralized system may fit better as a solution. On the other hand, in terms of “construction costs” for instance, decentralized WWTS show more satisfactory values in comparison with the centralized alternative. Regarding these last aspect, the reason that the costs are elevated might be related to infrastructure regarding sewerage network and pumping stations, whereas decentralized systems generally consider gravity to convey the sewage.

It can be also pointed out from the results that there is an important conservation of natural resource (energy spent in the treatment), when it is compared any individual WWTS proposed to centralized systems. Since there is no use of electricity to operate, it results in reducing directly the operational and maintenance costs, and also the needs of technical support in case of necessity when the system fail, for example.

Finally, those analyses securely indicate the importance of performing a multi criteria analysis (SDM) to support complex decisions such as in the field of environmental engineering, since better alternatives should consider the analysis of different indicators within the same evaluation process.

5. Conclusions

The method applied has demonstrated that it is possible to use SDM in order to find sustainable solutions when comparing with different indicators and distinct WWTS configurations. Thus, it is a starter point to demonstrate to the public authorities that there are affordable WWTS solutions which can help to solve environment and social issues, especially in the urban areas which lack basic needs.

Regarding the data analyses, this paper has investigated performances among conventional and decentralized WWTS configurations to treat domestic sewage. As it has been seen, sustainable systems, for instance the PP, represent the best balances of consequences between the selected indicators for this research. Specifically about the PP efficiencies, the results also have shown for this system significant organic matter and nutrients removals. Although the implementation and maintenance costs may not be attractive if compared with traditional WWTS (Centralized and ST plus AF), the sustainable system represents also favourable results when it dismisses energy to operate.

Yet, recent studies have revealed that one of the low-term solutions for underserved urban areas in the developing world are decentralized treatment systems, due the lower financial investments to implement. Thus, it was found that the implementation of sustainable systems is highly suitable considering the financial reality of Brazil and, also, in the low-income countries. Regarding operation and maintenance costs, even though the system defined as the best solution of this research (PP) demonstrate some similar results when compared with the conventional one, it also appears to be attractive given the reason that there is low or null power consumption.

Regarding further studies, it is important to evaluate the acceptability of the sustainable WWTS obtained by their potential users. In other words, the decision-making analysis, and hence the evaluation process can be also applied with groups of people, who supposedly may give different weights for each specific indicator, for instance. Finally, the implementation of the system proposed (PP) can also contribute to other further studies, with regards to real scenarios, in order to evaluate other set of indicators and then have different analysis in the field of wastewater management.

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