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Framework of Sustainability Indicators for Public Water Systems

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Framework of Sustainability Indicators for Public Water Systems

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Abstract: Water infrastructure systems play a major part in developed cities and municipalities. They are the main infrastructure for providing safe and reliable drinking water. Challenges in the operation of water infrastructure systems occur when changes happen to these systems such as aging, demand increase, cost of providing service, etc., and decisions must be made about retrofit or replacement actions. This situation could be improved through developing a framework to analyse the sustainable operation and maintenance of this infrastructure while also focusing on the limited budget available. This framework should contain the different pillars of sustainability, i.e. technical, environment, economy; and society.

Our research showed that in order to achieve a sustainable water infrastructure system, the current state of sustainable infrastructure should be assessed. This work reviewed the state of the art in research and practice in Canada, USA and Australia and found sustainable indicators developed and used for the assessment of water systems. The research was followed by clustering all these indicators and developing a framework based on these indicators for sustainable assessment of water infrastructure. The research concluded that the sustainability of an infrastructure system can be shown by an overall sustainability score, which is based on the weighted sum of all contributing indicators.

1. Introduction

The topic of municipal infrastructure maintenance and operation has received considerable attention from both state-of-art and state-of-practice viewpoints during recent years. The volume of time, personnel and financial resources that are required for operation and maintenance of infrastructure is large, and the infrastructure's effect on the environment and society is substantial. This has made this field of study interesting for researchers, engineers, managers and other stakeholders involved in the activities.

One of the major concerns about infrastructure management is the shortage in annual funding resources for operation and maintenance activities. According to research by Canada West Foundation (CWF), the annual infrastructure deficit of the six big western cities in Canada ranged from \$87 to \$298 million dollars for the fiscal year of 2003 (Vander Ploegh, 2003).

Looking to the future, the Canadian Council of Professional Engineers (CCPE) estimated that 50 percent of Canada infrastructure will end its lifecycle in 2027, forecasting a steep increase in the gap between actual and necessary funding for infrastructure in the coming years (CCPE, 2004). In a more distressing estimation given by CCPE (2004), without any corrective action, "the required funds for the entire country's public infrastructure could reach as high as \$400 billion by 2015-2020". These numbers show the importance and necessity of having a sustainable operation and maintenance program based on available level of funding for infrastructure.

According to an InfraGuide Best Practice on an *Integrated Approach to Assessment and Evaluation of Municipal Roads, Sewer and Water Networks* (NRC, 2003), the major types of municipal infrastructure selected for investigation are: Potable Water, Storm and Wastewater, Transit, and Municipal Roads and Sidewalks. The focus of this report is to look at the first of these: Water Systems. The importance of water systems and their effect on the sustainability of a community is undeniable. The effect of drinking water on the health of the society, its availability to public, the cost of providing water for the society; and other social impacts makes any decision related to water and water systems crucial and important.

However, in the developed world the main concerns about water system infrastructure maintenance and operation relate to the aging of assets and the historical funding levels that are not sufficient to maintain safe and reliable water supply; the same is true of other types of infrastructure (Vander Ploegh, 2003). In the USA, according to a Water Infrastructure Network (WIN (2000)) report, from 2001 to 2021 there will be a gap of \$23 billion per year between necessary investment level and actual planned investment level in order to address different health and safety regulations.

This current situation in our society necessitates the sustainable management of operation and maintenance activities: deciding where, when and how to distribute limited resources. In the next section, the authors discuss a framework for sustainable operation and maintenance and the process of decision making to allocate limited financial resources to the operation and maintenance of water infrastructure systems.

2. Scope of the Work

2.1 Framework and related definitions

Based on the aforementioned gap between actual and desired levels of operation and maintenance budget for water infrastructure, there is need for a decision-making process to allocate budgets for sustainable operation and maintenance of water systems. For this decision-making process, the decision-makers should have clear understanding of the overall operation, maintenance and rehabilitation (O/M/R) actions. We have based our framework on a state-change model that includes the following elements:

- Current State: The current state of the infrastructure system and its characteristics, based on the evaluation of all available and suitable indicators.
- Event: An *O/M/R Event*, or some type of action that is performed on an infrastructure system, which needs external resources
- Future State: The future state of an infrastructure system after an *Event* and its new characteristics based on the predicted future performance.

These parts have been shown in Figure 1 and are the preliminary stage of developing a framework of sustainability indicators for public water system:



Figure 1 Preliminary framework of Operation, Maintenance and Rehabilitation

The following components are then added to this preliminary framework:

- **Sustainability Indicator:** Sustainability Indicators (SI) are a set of statistical parameters defined to give indications of different social, economical, technical; and environmental expectation of safe and sound sustainable infrastructure. These show how well the infrastructure meets present and future anticipation.
- **Data:** Data are values given to qualitative or quantitative indicators. Each indicator must be measured at the Current State to find the data related to it. Data will change during and after an O/M/R Event of and new data for the Future State will result.
- **Weight:** The importance of an indicator relative to each other. Each indicator has a relative weighting, which depends on the viewpoint of stakeholders and their idea about an indicator and its relative importance.
- **Score:** The result for Current State sustainable assessment is defined as a sustainability score. It is the sum of all indicators' data related to that specific score multiplied by the Weight of each Indicator. As weights are dependent on stakeholders' viewpoint, the final score is also dependent on the stakeholder performing the assessment. The O/M/R Event will result in change in of the score from Current State to the Future State.

These components are illustrated in Figure 2 for a single event option. A more comprehensive example would involve more than one option, which then leads to a number of different future states.

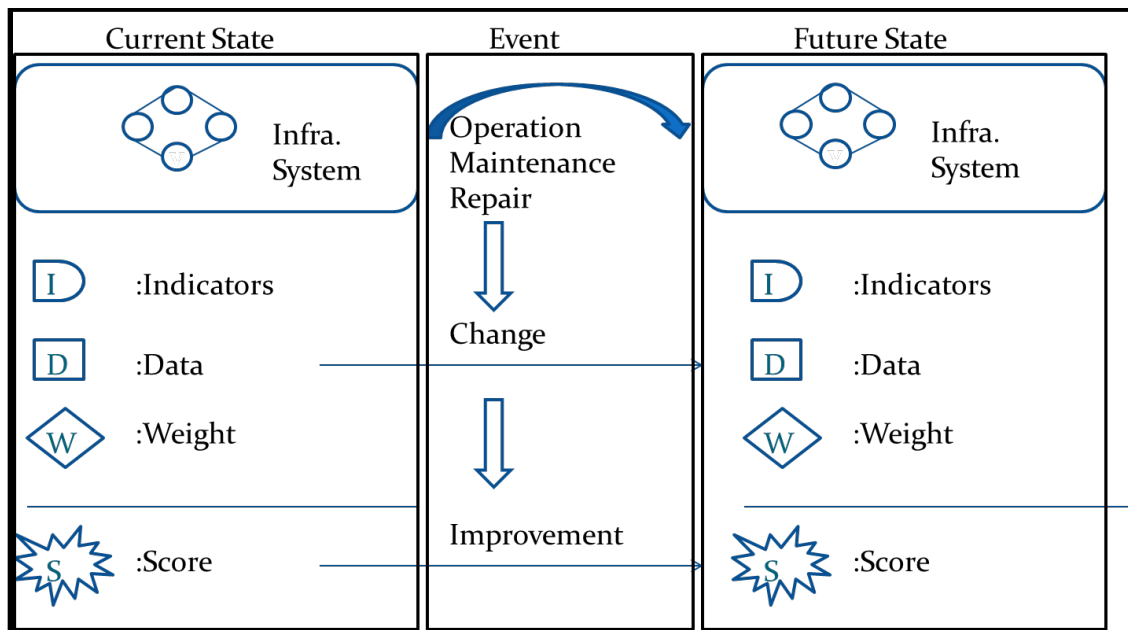


Figure 2 Expanded Framework of O/M/R

2.2 Problem Statement

Using the concepts shown in the framework, the following steps are involved in carrying out an assessment for infrastructure operations and maintenance decisions:

1. Define a set of *indicators* based on all important effects that an infrastructure system has related to the technical, social, economic and environmental aspects of a municipality.
2. Gather the *Data* for each indicator to describe the current state of infrastructure system.
3. Cluster the indicators into groups of Sustainability Categories.
4. Normalize the data related to sustainability indicators in order to aggregate them.
5. Calculate the 'Weight' of each indicator in order to derive the 'score' of the current state.
6. Define internal and external limitations of the Event, specifically the available budget to perform operation and maintenance activities on infrastructure systems.

7. Predict the *Change* of data that can occur after the event, in order to estimate the future state of infrastructure.
8. Estimate the future *Score* to evaluate the improvement caused by the event of operation and maintenance.
9. Perform decision-making practices to decide on priorities of O/M/R events based on related limitations of available sources, especially financial resources.

In summary, the proposed sustainable framework has the following steps:

Understand the current state

→ *Estimate the future state for defined O/M/R Event alternatives*

→ *Select and pursue the preferred Event*

Therefore, in order to have a better decision-making approach to operation and maintenance activities and to estimate the future state of infrastructure, the very first step is to understand the current state of the infrastructure system. In this research, the authors have concentrated on understanding the current state by defining what is important in assessing this state, particularly the “Sustainability Indicators” as used here.

2.3 Sections of Water system

Looking at potable water infrastructure, Figure 3 shows the typical sections of this system. For this research the authors focus on the sustainability indicators for the infrastructure systems that transfer the water from the source, treat the water; and distribute the potable water.

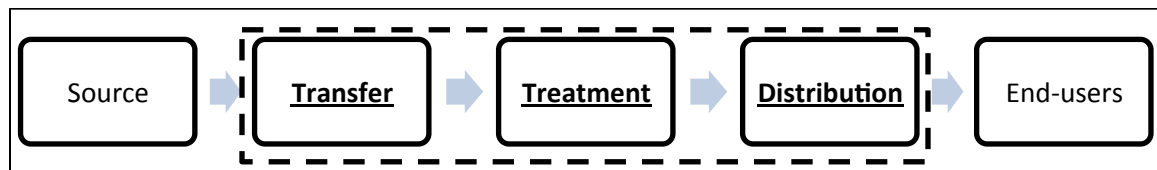


Figure 3 Water system sections

2.4 Objectives

The objectives of this research work are as follows:

- Identifying the sustainability indicators (SI) of the transfer system, treatment plant; and distribution system of a municipal water system based on a state-of-art and state-of-practice review of relative documents. Wherever possible, they should be quantifiable in order to be used in the following step.
- Developing the aggregation process to obtain a final sustainability score

3. Sustainability Indicators

3.1 Introduction

For the purpose of defining suitable sustainability indicators for the evaluation of water infrastructure systems, a comprehensive literature review was performed on available state-of-art and state-of-practice resources in order to understand how the water infrastructure is managed in different developed countries. According to the Canada West Foundation (CWF), the top ten countries in maintenance and development of infrastructure from the International institute for management are as follows: United States, Switzerland, Finland, Sweden, Australia, Canada, Germany, Iceland, Japan, and Denmark (Vander Ploegh, 2003). From these countries, three prominent counties have been chosen for the evaluation of their sustainability indicators (SI) of water systems. This selection was based on their ranking positions and also accessibility to the information about the SIs. These countries are: United States, Australia; and Canada. Table 1 shows the sources that have been used for each country to identify the SIs for water systems.

Table 1 Literature Review sources on Sustainability Indicators

Reference	Country
InfraGuide Best Practices (NRC.CNRC 2003, 2003a, 2003b, 2003c, 2003d, 2003e, 2003f, 2003g, 2003h, 2004, 2004a, 2004b, 2004c, 2005, 2005a, 2006, 2006a)	Canada
Greater Vancouver Water District (GVRD 2011)	Canada
Canadian Water and Wastewater Association (CWWA 1998, 2005, 2009)	Canada
Whistler 2020 Sustainability Program (Whistler 2011)	Canada
Health Canada Guidelines for Drinking Water (Health Canada 2008)	Canada
US Environment Protection Agency (EPA 2002, 2007, 2010, 2010a, 2011)	USA
Water Research Foundation (WRF 2011)	USA
American Water works Association (AWWA 2007, 2009)	USA
Governmental Accounting Standards Board (GASB 2011)	USA
Water Services Association of Australia (WSAA 2011)	Australia
University leaders for sustainable future (ULSF 2011)	International

These sources are typically the guidelines and practices that have been used at a national or international level, except for three sources that provide a municipal/regional perspective: the Greater Vancouver Water District (GVRD 2011), the Whistler 2020 sustainability program (Whistler 2011) and University leaders for sustainable future (ULSF 2011). In future research work, a more comprehensive set of municipality entities should be investigated from different types of municipalities and communities.

A total of 133 sustainability indicators have been gathered from the different references above. A full table of indicators is shown in the link provided at the end in the Appendix.

3.2 Clustering the indicators

In order to use these sustainability indicators to assess the current or future state of infrastructure, the first step is to cluster these indicators into suitable categories. The 133 sustainability indicators have been clustered in 10 categories for pragmatic reasons using classification from the original sources and the authors' experience. They are shown in Table 2, together with an example of one indicator for each category.

Table 2 Sustainability categories for clustering indicators

Sustainability Zones	Examples of indicators
Asset Condition	Length of water main that needed to be replaced annually
Economical Impact	% of water base flow to overall water consumption
Environmental Quality	Annual cubic metres of river water used for treatment system cooling
Financial Forecast	Reserve funds as a % of total presentvalue of infrastructure
Management of Assets	Quality of condition assessment data
Public Access to Water	Number of complaints about low pressure
Public Health & Safety	Risk of Security control failure at pump stations
Social Equity	% of total population connected to central water services
Water Quality	Average frequency of Boil Water Advisories issued per year
Water Resources	% of Purchased water (imported water) from other utility systems

4. Quantify and Normalization of SI

4.1 Quantification of subjective data

In this section, after identifying a suitable list of indicators, the next step was to quantify the data for any qualitative or subjective indicators. Although the focus of this research is to identify related quantifiable indicators in the literature, 13 of the 133 identified in the research were qualitative, and a quantification method was developed in order to assign a quantity value to these 13 SIs. Table 3 shows these indicators, most of these qualitative indicators are in the “Management of assets” category.

Table 3 Qualitative sustainability indicators

Sustainability Indicators (SI)	Sustainability Categories	Country
Percentage of distribution pipes in "Excellent" condition over total length of system	Asset Condition	USA
Vulnerability to environment violations, fines and penalties (likelihood)	Environmental Quality	USA
Effect of Water system on groundwater quality	Environmental Quality	Canada
Condition assessment strategies and protocols for water and wastewater assets	Management of assets	USA
Installation, condition assessment, and reliability of service lines	Management of assets	USA
Accessibility of condition assessment data	Management of assets	USA
Quality of condition assessment data	Management of assets	USA
Quality of assets	Management of assets	Canada
Increase in confidence and competence among operations and maintenance staff	Management of assets	Canada
Education of workers and public for new standards and regulation for sustainability	Management of assets	USA
Rate of importance of system in municipality	Management of assets	Canada
Risk of Security control failure at pump stations (likelihood x consequences)	Public Health& Safety	Canada
Engaging general public and informing about water main failure	Social Equity	Canada

The issue of quantifying socio-environmental problems and situations is not a new question in research and practice (EPA, 2010). Many detailed mathematical approaches have been presented for quantification logic and theory, which is out of the scope of this work. Looking specifically at the problems related to sustainability, a very detailed process has been developed by the U.S. Environmental Protection Agency (EPA), in *Guidelines for preparing Economic Analyses* (EPA 2010); accordingly, measuring benefit of an activity is generally challenging, whereas measuring its cost is relatively easy.

A method to the problem of quantifying these types of indicators, as described by EPA (2010), is to rate each of the above 13 indicator qualitatively based on the subjective evaluation of the available information. For example, for “Quality of condition assessment data” indicator, the indicator data will be subjective assigned by an expert a 0 for “extremely poor” to 5 for “excellent”, as is shown in Table 4. This method can be applied to all 13 qualitative indicators.

Table 4 Example of quantifying qualitative sustainability indicators

SI: Quality of Condition Assessment Data	
Condition	Rating
Extremely Poor	0
Poor	1
Fair	2
Above average	3
Good	4
Excellent	5

4.2 Normalization of data

The next step is to normalize the indicators. To aggregate indicators, they should be normalized before assigning weight to the indicators, which results in a dimensionless sustainability score of the current state. There are four types of indicators in the assessment of water systems:

- Indicators that are qualitative; as discussed above. (13 indicators). As these indicators are in the format of rating numbers, they do not need any normalization. For example, Quality of condition assessment data is one of the qualitative indicators; and data related to this indicator is reported as rating between 0 and 5.
- Indicators that are calculated as a percentage or ratio of an overall attribute (53 indicators). As these indicators are dimensionless, they can be used directly in the next step of assessment method. For example “% of length of water main that needed to be replaced annually” is one of indicators of this type.
- Indicators that are calculated and compared as “annual data” (60 indicators). For example “number of planned service interruption per year” is one of the indicators of this type. These data fluctuate annually; and as most of data do not have a constant trend of increasing or decreasing, a good statistical approach is to follow the pattern of “Normal distribution” probability function. If the function has mean of μ and variance of σ^2 , then normalization of the indicators is straightforward by using normalizing normal random variables function of: $Z = \frac{X-\mu}{\sigma}$ which can be interpreted as a dimensionless indicator.
- The last group contains indicators that generally relate to related health & public safety regulations (8 indicators). The reason they have been separated from the other group is that the standards and regulations change rarely during years of operation and they are relatively

constant. However, the data still can be modeled with Normal distribution function, with the normal value set to be as the mean of the model μ ; and can be normalized with the same process.

5. Assessment Method

Once we change all the indicators to dimensionless ones using different methods stated above, the next step in the framework is to find the sustainability score of the current state of water system. These indicators can be transformed to dimensionless scale data, the useful method here to assess the state of water system is the Multiple-attribute Utility Theory (MAUT). Based on this theory (Hobbs& Meier 2000, Coolen 2003), for assessment problem, the score can be found from:

$$[1] \quad S = \sum_{i=1}^n w_i * I_i \quad \sum_{i=1}^n w_i = 1$$

Where I_i is the i^{th} indicator of the sustainability and w_i is related to the indicators' relative weight. This will be the next proposed step in the development of the framework in order to find the score related to the state of water system. This is the future direction of our research in the field of sustainable infrastructure.

6. Conclusion and future works

This paper is preliminary research in the area of sustainable infrastructure. It introduces the concept of developing an assessment framework for sustainable municipal water infrastructure systems. The framework was described using 133 sustainability indicators derived from state-of-art and state-of-practice resources from around the world. It was also shown that all these indicators in the identified 10 different categories of sustainability can be normalized and be used in calculating the final dimensionless sustainability score for the state of a specific water system. The future step of this research is to develop and incorporate the framework in a real case study example, and see the applicability of the framework to a practical situation. Future research work can also include methods to establish the different weighting that is related to different stakeholders.

Appendix: List of the Sustainability Indicators

The complete spreadsheet containing all the gathered sustainability indicators and their reference can be found in the following Google.doc link: <https://docs.google.com/spreadsheet/ccc?key=0Ak59yFptZusxdElzcnh2ZjM5TWZDQ0paYkFMNXF4ZHc>

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