



# Using Qualitative Indicators in Infrastructure Assessment Using the Functionality–Resiliency–Sustainability Framework

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### Specialty section:

This article was submitted to  
Sustainable Infrastructure,  
a section of the journal  
Frontiers in Sustainable Cities

Received: 24 July 2021

Accepted: 24 September 2021

Published: 04 November 2021

### Citation:

Upadhyaya JK, Biswas N and  
Tam EKL (2021) Using Qualitative  
Indicators in Infrastructure  
Assessment Using the  
Functionality–Resiliency–Sustainability  
Framework.  
*Front. Sustain. Cities* 3:746537.  
doi: 10.3389/frsc.2021.746537

This paper presents the implementation of decision criteria template to incorporate qualitative indicators in functionality, resiliency and sustainability assessments of stormwater infrastructure using the Functionality–Resiliency–Sustainability Framework. Qualitative attributes, even though deemed important, are usually not included, or adequately considered because of their inherent subjectivity associated with assessing them. Whenever qualitative indicators are used in practice, an ordinal scale such as poor, fair, good, very good is frequently applied. However, depending on the understanding and priorities of the evaluator, the meaning of poor, fair, good and very good score can differ significantly. Such indicators were generally not intended to facilitate engineering solutions but rather management related concerns. However, understanding the issues behind using qualitative measures is critical for stormwater infrastructure because many non-conventional indicators—which are frequently non-technical measures—can be used to assess the resiliency and sustainability of stormwater system. Moreover, there are few resources to adapt specific qualitative factors to quantitative equivalents. To address this gap, a decision criteria template is developed to score qualitative indicators within a multi-criteria assessment approach so that consistency, transparency, and subjectivity in the assessment can be addressed. The indicator scoring template is illustrated in an example stormwater system in city of Windsor, Ontario, Canada. Based on the analysis done using the decision criteria matrix, it was found that city of Windsor's stormwater infrastructure resiliency is relatively better than its assessed functionality and sustainability.

**Keywords:** infrastructure, assessment, qualitative indicators, functionality, resiliency, sustainability, stormwater

## INTRODUCTION

Infrastructure resiliency is now center stage in the overall planning, design, and management of infrastructure. Assessing how resilient an infrastructure system is now more crucial than ever, and many decision frameworks has been developed recently to assist decision makers and operators manage infrastructure (Upadhyaya et al., 2018; Rehak et al., 2019; Argyroudis et al., 2020). The

Report Card of American Society of Civil Engineering. (2021) includes resiliency as one of the key parameters in assessing infrastructure. Assessing infrastructure in general—and particularly stormwater infrastructure—is complex because it involves multiple environmental, social and economic issues, and further requires thorough consideration of technical, financial, social and long-term aspects to be resilient and sustainable. For this reason, making decisions about whether a system is resilient and sustainable is increasingly challenging. However, qualitative attributes, despite being important, are generally not included in the assessment of infrastructure. To address this gap, a decision criteria template is developed to score qualitative indicators within a multi-criteria assessment approach so that consistency, transparency and subjectivity in the assessment can be addressed. The indicator scoring template is illustrated in an example stormwater system in city of Windsor, Ontario, Canada, to demonstrate how such qualitative indicators can be interpreted and assessed.

## Context and Literature Using Multi-Criteria Assessment

The overall approach of the scoring template uses multi-criteria assessment (MCA). When making decisions, MCA is popular for assessing infrastructure for sustainability (Hajkowicz and Collins, 2007; Lai et al., 2008; Upadhyaya and Moore, 2012; Suresh et al., 2016); risk and resiliency (Martin et al., 2007; Galarza-Molina et al., 2015; Kangas, 2016; Lounis and McAllister, 2016); asset management (Rasa, 2009); and performance assessment (Kabir et al., 2014), among many others. Although this research does not focus on MCA, it is discussed to provide the context for how indicators are incorporated. MCA is useful for a range of scenarios because of its capacity to include qualitative and quantitative indicators within the evaluation, but MCA also has shortcomings (Lai et al., 2008).

One of the main issues when applying MCA is the uncertainty associated with the scoring of the attributes (Hajkowicz and Collins, 2007; Lai et al., 2008; Steele et al., 2008; Alvarez-Guerra et al., 2009; Rasa, 2009; Yilmaz and Harmancioglu, 2010; Kabir et al., 2014; Brito and Evers, 2016; Kangas, 2016). Usually, a linear interpolation scheme is applied during scoring between the worst to best values (Martin et al., 2007; Jia et al., 2013). While many attributes may not truly exhibit a linear relationship, this straightforward approach to indicators provides an acceptable, understandable, and workable format for decision makers, even though it is imperfect, and thus is useful and adequate approach for the proposed template.

## Using Qualitative Indicators

Current assessment trends for infrastructure focus heavily on quantitative indicator summaries, such as seen in Infrastructure Report Cards or Benchmarking initiatives are useful for communicating broad themes that describe the state of infrastructure. However, these have not proven to be very effective (Upadhyaya et al., 2014, 2018) in addressing in-depth core issues related to resiliency and sustainability. Moreover, the Canada Infrastructure Report Card (The Association of Consulting Engineering Companies Canada, 2019) indicates that condition of stormwater assets is not largely known because in

the past collecting data on the status of these systems was not a priority. This presents a significant challenge: how to act on such issues with limited data, or even no data.

For indicators that are qualitative, an ordinal scale is typically applied, with descriptors such as poor, fair, good, very good, and so on. As a result, such scoring is inherently subjective (Yilmaz and Harmancioglu, 2010; Kangas, 2016). Depending on the characteristics of the system, the understanding and priorities of the evaluator, the meaning of poor, fair, good and very good score can differ significantly. There is also the concern that decision methods, in complex situations, can lose transparency: even decision makers might be uncertain of how their decisions are ultimately reached. This notion of a “black box” approach to scoring and the potential over or under estimation of some indicators (Lai et al., 2008; Kangas, 2016) often discourages the use of qualitative indicators.

Some type of uncertainty analysis has often been advocated to address such issues in the scoring process by using a probabilistic approach (Cinneli et al., 2014), fuzzy logic, or indicator approach (Rasa, 2009; Brito and Evers, 2016). However, using probabilistic and fuzzy logic can be complex, may need increased levels of resources, time and expertise, and do not necessarily produce improved results compared to long-standing methods such as MCA (Brito and Evers, 2016). There is also no specific evidence that a given method for addressing uncertainty can handle subjectivity more effectively than others in any specific scenario (Lai et al., 2008). The choice may also depend on the availability of data and information, timeline and resources (Lai et al., 2008). A review of papers by Huang et al. (2011) suggests that the recommendations were similar even if different methods of MCA were implemented for the same problem.

The challenge then is to not only develop decision frameworks, but a means to capably incorporate a variety of disparate qualitative indicators that may signal other issues not captured by quantitative indicators to better assess how an infrastructure system is faring in terms of resiliency and sustainability and day-to-day functionality. Qualitative attributes, despite being important, are generally not included in the assessment of infrastructure.

## Summary

To address this gap in practically using qualitative indicators, a decision criteria template is developed to score qualitative indicators within a multi-criteria assessment approach for upholding consistency and transparency. The indicator scoring template is illustrated later in an example stormwater system in the City of Windsor, Ontario, Canada that uses a mix of both qualitative and quantitative indicators.

## THE FUNCTIONALITY–RESILIENCY– SUSTAINABILITY FRAMEWORK

The Functionality–Resiliency–Sustainability (FRS) Framework [previously referred to as the Functionality–Survivability–Sustainability (FSS) Framework] clearly identified these issues and incorporated both qualitative and quantitative indicators to

reflect the performance of stormwater system (Upadhyaya, 2013; Upadhyaya et al., 2018). Upadhyaya et al. (2018) demonstrated how the FRS Framework could evaluate the City of Toronto's stormwater system utilizing a multi-criteria, weighted sum model to incorporate and assess indicators that describe functionality, resiliency, and sustainability.

Prior to developing the FRS framework to assess the functionality, resiliency (formerly called survivability), and sustainability of a stormwater system in a comprehensive manner, most conventional evaluations assessed operational performance, sustainability assessment, and risk assessment separately. A lack of connectivity among these issues was identified. The FRS Framework fulfills that gap by having three levels of assessment within a single framework. Assessing functionality, resiliency and sustainability is done hierarchically. The FRS Framework also addresses the complexity and interconnectedness of impacts on infrastructure while assessing the system.

In general, much infrastructure is often assessed using the triple bottom line (TBL) approach or similar variant where environmental, economic and social aspects form the main criteria for assessment. However, within these categories the range of factors considered is often relatively conventional. Instead, the FRS framework considers rapidly changing external impact factors, indirect and direct effects on public health and safety, and the increasing demand for resources to manage infrastructure: many of these are not explicitly considered in decisions that can affect infrastructure resiliency (Upadhyaya et al., 2014). To reflect these important but often overlooked factors, the issues of resource, public health, and change management (RPC) were proposed as the main determinants for assessing infrastructure (Upadhyaya et al., 2018). The FRS Framework assumes that unless a system is functioning well, it can ultimately not be resilient enough to survive climatic or other stressors, nor will it be sustainable in the long term. Details about the FRS Framework concept and implementation can be found in Upadhyaya et al. (2018).

In assessing the resiliency and sustainability of stormwater infrastructure, employing more straightforward methods for including both quantitative and qualitative indicators within the greater framework of functionality–resiliency–sustainability (FRS Framework) is useful and insightful (Upadhyaya et al., 2018). Such a straightforward approach is even more beneficial considering that evaluating stormwater resiliency is not common. As a result, within the FRS framework, a series of qualitative and quantitative indicators are selected, interpreted, and assessed using a weighted sum MCA model.

## Decision Criteria Template

A color coded decision criteria template, as shown in **Table 1** is developed for circumstances where the assessor may not be initially familiar with the system being evaluated, and furthermore, the template can help score the indicators without any prior knowledge of decision theory. The user essentially matches their system circumstances against the criteria provided in the table for the various, selected indicators. The framework demonstrates in a straightforward and unambiguous manner

how important qualitative data can be interpreted and then incorporated. This can reduce the hesitancy of decision makers to include them in infrastructure assessment and not omit them because they are perceived as difficult to understand or assess. More critically, **Table 1** was developed by assessing multiple literature and in-practice references to provide available points of reference (see Upadhyaya et al., 2014, 2018). The table can be used by the decision maker help assess their circumstances against a credible starting set of default criteria. This is particularly effective when staff responsible for managing infrastructure leave the organization, and new employees may not have prior in-depth, institutional knowledge, but must still make preliminary decisions. It should be noted that for efficiency, **Table 1** shows the decision criteria template generically, but also that the colors shown in specific cells are for the example discussed later in Using the Decision Criteria Template section.

A color coding scheme is adopted for scores ranging from zero to 5: 0 = red, 1 = orange, 2 = yellow, 3 = purple, 4 = blue, 5 = green. Alternate color schemes can of course be used provided they are used consistently. The color coding allows the assessor to visually analyze the information *across* all indicators; for example, if the majority of the indicators are represented by green or blue criteria, then that indicates the system being assessed is likely at an improved state as opposed to a state of disrepair or non-functionality. Overall, this provides a visual snapshot of how each indicator compares against each other without relying on the numerical score and before all items are aggregated. In this way, all the details are still available for the assessor to review even if the descriptions are all translated into proxy measures and then into one overall value that no longer possesses the original detail. The color coding provides a descriptive interpretation of how the system is performing on average using this table format but losing the individual data because the assessor can still view them.

## STORMWATER INFRASTRUCTURE CASE STUDY

A subsection of the stormwater infrastructure in Windsor, Canada is assessed using the FRS Framework to demonstrate how the decision matrix addresses subjectivity, transparency and “black box” issues in scoring, particularly with qualitative indicators, but also quantitative indicators. For clarity, the FRS Framework is briefly explained. Additional details about the FRS framework are available in other publications (Upadhyaya, 2013; Upadhyaya et al., 2018). This section outlines the decision criteria template for qualitative indicators and quantitative indicators, as well as the implementation of the FRS Framework in an example stormwater system in Windsor, Canada. Conclusions and recommendations are presented in the Using the Decision Criteria Template section.

The South Windsor (SW) area of the city is 633 ha and has a population of 22,996 serviced by a separate stormwater system built in 1960s. The 123 km separate storm sewer system was designed for a 1-in-5 years storm event. The network drains into Grand Marias drain, part of the Turkey creek, and was lined in concrete during the 1960s to rapidly remove

**TABLE 1** | Decision matrix analysis for qualitative indicators.

Indicators score	5	4	3	2	1	0
<b>Functionality</b>						
Demographic pattern	Demographic trend is monitored, effectively used in decision making, and how system responded is observed	Demographic trend is effectively used in decision making, but system response was not monitored	Monitoring has been done and trend is established but not utilized in decision making	Monitoring has been done but trend is not established	No monitoring of demographic pattern, but some provision in decision making on an <i>ad-hoc</i> basis	None of the previous
Peak flow	The peak flow is within pre-development value	The peak flow is within design value and no flooding is observed	The peak flow exceeds the design value but no flooding is observed	Flooding is observed regardless of peak flow but alternate arrangement is done to deal with flooding	Flooding is observed regardless of peak flow, no alternate arrangement, but residents are informed about risk and assisted	None of the previous
Change in impervious area	Impervious area was decreased by incorporating Innovative Stormwater Management (ISM) features or increasing the green cover (<0)	Impervious area was decreased by incorporating ISM features or increasing the green cover (zero)	Impervious area increased up to 25% but there is a valid reason (e.g., land use changed)	Impervious area increased from >25% up to 50% but there is a valid reason (e.g., land use changed)	Impervious area increased from >50% up to 75% but there is a valid reason (e.g., land use changed)	Impervious area increased upto 75% but there is no valid reason
Combined sewer replacement	100% of the combined sewer is replaced with separate storm sewer	75% to less than 100% combined sewer is replaced with separate storm sewer	50% to less than 75% combined sewer is replaced with separate storm sewer	25% to less than 50% combined sewer is replaced with separate storm sewer	Less than 25% combined sewer is replaced with separate storm sewer	No combined sewer is replaced with separate storm sewer
Type of Revenue Structure	The revenue structure is conservation oriented; users pay as per their runoff contribution and are encouraged to conserve water	The revenue structure is based on full cost recovery and reflective of the services available to the users	Stormwater contribution from users is not considered in the revenue structure, utility uses funding from other sources, e.g., budget allocated for water, wastewater or grants	No well defined revenue structure for stormwater infrastructure; decision about stormwater infrastructure is based on <i>ad hoc</i> basis	No consideration in revenue structure; no reliable source to fund stormwater infrastructure in long term	No consideration for stormwater issues, decisions are reactive, e.g., scramble to manage after a major flooding
Lifecycle cost consideration for capital <sup>a</sup> infrastructure	Future value of savings is higher than the costs during lifecycle of the system	Future value of savings is balanced with the costs during lifecycle of the system	No life cycle cost savings but system provides long term tangible/intangible benefit to society at large	No potential cost savings but infrastructure was necessary due to regulatory or system failure reasons	No assessment of lifecycle cost implication considered, decision on project made based on short term gain	No consideration of cost implications, reactive decision is made to build the infrastructure
Lifecycle Cost Consideration for Operation and Maintenance (O&M) <sup>a</sup>	Future value of savings is higher than the costs during lifecycle of the system	Future value of savings is balanced with the costs during lifecycle of the system	No life cycle cost savings but system provides long term tangible/intangible benefit to society at large	No potential cost savings but infrastructure was necessary due to regulatory or system failure reasons	No assessment of lifecycle cost implication considered, decision on project made based on short term gain	No consideration of cost implications, reactive decision is made to build the infrastructure
Operation and maintenance activity with respect to Service Level	O&M activities <sup>b</sup> and Service Level <sup>c</sup> requirements are defined. At least one or all O&M activities are going down while Service Level are maintained or improved	O&M activities and Service Level requirements are defined. At least one O&M activities remain stable while service levels are maintained or improved	O&M activities and Service Level requirements are defined. One or all O&M activities go up while at least one Service Level is improved	O&M activities and Service Level requirements are defined. One or all O&M activities go up while Service Level is maintained with more stringent regulations being met	O&M activities and Service Level requirements are defined. One or all O&M activities go up while Service Level is maintained with more stringent regulation being met	OandM activities and Service Level requirements are defined. All O&M activities go up while Service Level is lowered or unchanged with same regulations OR No consideration for Service Level in O&M decisions
Research and innovation	Research and Development (R&D) unit in the utility/municipality is responsible for identifying new solutions	There is a policy for the utility/municipality to fund in external research program and obtains new solutions	There is a policy for the utility/municipality to provide logistic support to carry external research and benefit from the new solutions	There is a policy to participate in research but new solutions are not necessarily implemented	There is no defined policy to participate in research but occasionally engage in research on <i>ad hoc</i> basis	New solutions/technologies are not a consideration

(Continued)

TABLE 1 | Continued

Indicators score	5	4	3	2	1	0
<b>Resiliency</b>						
Assessment of potential damage to infrastructure	Complete assessment of damage to all physical infrastructure <sup>d</sup> , public health impacts <sup>e</sup> and environmental impact <sup>f</sup> during an extreme event is done	Complete assessment of damage to all physical infrastructure and either of the two: public health and environment is done	Complete assessment of damage to affected stormwater system is done <i>but</i> all affected infrastructure is not done due to valid limitations (e.g., jurisdictional or limited capacity of the utility/municipality), and public health and environment impact is assessed	Assessment of physical damage either for all the affected infrastructure system or only the affected infrastructure system is done <i>but</i> the impact on people or environment is not assessed	Assessment of potential damage to infrastructure and impact on people and environment is done on <i>ad hoc</i> basis	No consideration of potential damage to infrastructure or impacts on environment, public health, reactive decision is made when issue comes up
Assessment of potential reconstruction need	Assessment of reconstruction cost for all physical infrastructure, <sup>g</sup> public health <sup>h</sup> and the environment <sup>i</sup> during an extreme event is done	Assessment of potential reconstruction cost for all physical infrastructure and public health OR physical infrastructure and the environment during an extreme event is done	Assessment of potential reconstruction cost for physical infrastructure, public health and the environment during an extreme event is done only for the current system but not the other related system	Assessment of potential reconstruction cost for physical infrastructure, public health and the environment during an extreme event is done only for the current system but is incomplete	Assessment of potential reconstruction cost is not well defined and done on an <i>ad hoc</i> basis	No assessment of potential reconstruction need is done, reactive decision is made as needed
Well-planned source, conveyance and end-of-pipe strategy for stormwater management and to eliminate root cause of problem	There is a comprehensive plan to mitigate the problem, (2) to adapt and (3) look into broader issues such as land use and water quality	There is a comprehensive plan but only plans to (1) mitigate the problem and (3) look into broader issues such as land use and water quality OR (2) to adapt and (3) look into broader issues such as land use and water quality	The plan is somewhat comprehensive but only looks into mitigating the issue and do not consider adaptation or broader issues	The utility/municipality does not have any plan; do provide support or information to deal with the issues regularly	The utility/municipality does not have any plan; do provide support or information to deal with the issues on <i>ad hoc</i> basis	The utility/municipality does not have any plan; reactive decision is made when an issue comes up
Emergency response plan	There is a comprehensive plan that considers people, infrastructure and environment with (1) coordinate response among stakeholders, (2) identifies resource personal, funds and provision for additional help (e.g. from other jurisdictions or other levels of government) and periodic training and exercise is conducted	There is a comprehensive plan that considers people, infrastructure and environment with coordinated response among stakeholders and periodic training and exercise is conducted OR identifies resource personal, funds and provision for additional help and periodic training and exercise is conducted	The plan is somewhat comprehensive but only considers people and infrastructure but <i>not</i> environment, and <i>may or may not</i> consider all the three aspects:  (1) coordinate response among stakeholders, (2) identifies resource personal, funds and provision for additional help and periodic training and exercise is conducted	The utility/municipality does not have any plan; do provide support or information to deal with the issues regularly	The utility/municipality does not have any plan; do provide support or information to deal with the issues on <i>ad hoc</i> basis	The utility/municipality does not have any plan; reactive decision is made when an issue comes up

(Continued)

TABLE 1 | Continued

Indicators Score	5	4	3	2	1	0
Recovery plan	There is a recovery plan to restore functionality of the affected infrastructure and disseminate information to people on (1) what to do after a flooding, (2) provide financial and other logistic support, (3) protect and manage data and information	There is a recovery plan restores functionality of the affected infrastructure and to disseminate information to people on (1) what to do after a flooding, (2) provide financial and other logistic support and	There is no structured recovery plan but the utility/municipality restores functionality of the affected infrastructure, disseminates information on what to do and provides funding support to deal with the flooding	There is no structured recovery plan, the utility/municipality restores functionality of the affected infrastructure and disseminates information on what to do <i>but</i> does not provide funding support to deal with the flooding	There is no structured recovery plan, the utility/municipality restores functionality of the affected infrastructure on an <i>ad hoc</i> basis	There is no structured recovery plan, reactive decision is made when an issue comes up
<b>Sustainability</b>						
Having an advance data collection and information management system	There is a central repository system and a standard procedure is followed; data is easily available to inform decision making	There is a central repository system <i>but</i> a standard procedure is not followed; data is not easily available to inform decision making	Data is collected and used but are not kept in a systematic way and are not easily available to inform decision making	Data is collected and somewhat used but not kept in a systematic way and is not available to inform decision making	Haphazard data collection, use and management; not useful for decision making	Data and information is gathered on a reactive basis when an issue comes up, decisions are not informed by data
Having a transparent information sharing policy	There is a central repository system and a standard procedure is followed; data is easily available to stakeholders	There is a central repository system <i>but</i> a standard procedure is not followed; data is not easily available to stakeholders	Data is collected and used but are not kept in a systematic way and are not easily available to stakeholders	Data is collected and somewhat used but not kept in a systematic way and is not available to stakeholders	Haphazard data collection, use and management, no intent to make it available to stakeholders	Data and information is gathered on a reactive basis when an issue comes up, stakeholder is not considered
Actions undertaken to achieve sustainability objectives are the main focus	There is a comprehensive plan that considered functionality, resiliency and sustainability that has: (1) provision for resource reduction, (2) Identify public health focus and (3) consider change management	There is a comprehensive plan that considered functionality, resiliency and sustainability <i>but</i> only: has provision for resource reduction and consider change management <i>OR</i> Identify public health focus and consider change management	The plan is somewhat comprehensive, only considers one or two of the functionality, resiliency and sustainability (FRS) <i>but</i> incorporates (1) provision for resource reduction, (2) Identify public health focus and (3) consider change management	The plan is somewhat comprehensive, only considers one or two of the functionality, resiliency and sustainability (FRS) <i>but</i> only incorporates provision for resource reduction and consider change management <i>OR</i> Identify public health focus and consider change management	There is a plan but not necessarily consider sustainability objectives, decisions are made on an <i>ad hoc</i> basis	There is no plan to consider for sustainability objectives, reactive decision is made and the issue is left unattended

<sup>a</sup>Same decision matrix analysis is used for the two indicators.  
<sup>b</sup>O&M activities indicators are: (1) roadside ditch and drain maintenance, (2) Km of storm sewer inspection and cleanup and (3) number of catch basin cleanup.  
<sup>c</sup>Service level indicators are: (1) kilometer of storm sewer, (2) kilometer of stormwater connections.  
<sup>d</sup>All physical infrastructure includes affected infrastructure in own and neighboring jurisdiction of the utility/municipality such as highways, bridges, electric cables, gas, telecommunication, etc.  
<sup>e</sup>Public health impacts include both long term and short term physical and mental health impacts.  
<sup>f</sup>Environmental impacts include impact in receiving water bodies, natural habitat, parks, etc.  
<sup>g</sup>Reconstruction cost of all physical infrastructure assessment indicators include (1) cost of restoration of infrastructure, (2) restoration cost of affected community infrastructure such as parks, play ground, etc. and (3) restoration cost of property. All affected infrastructure includes system road, bridges, electric cables, gas, telecommunication, etc.  
<sup>h</sup>Public health assessment indicators include (1) physical and (2) psychological health recovery costs.  
<sup>i</sup>Indicators for assessment of the environment include (1) clean up costs and (2) monitoring and sampling costs.

stormwater from the area. Part of the storm sewer also drains into the adjacent areas through 21 outlets. **Figure 1** shows the area. The system was assessed using FRS Framework. The 15 qualitative and 15 quantitative indicators are listed in **Tables 1, 2**.

The weights for each criterion indicated the relative importance, and the scores indicated how the individual indicators within the criteria performed. The respective indicator scoring templates for qualitative indicators and

selected composite indicators are provided within **Tables 1, 2** as explained previously.

## USING THE DECISION CRITERIA TEMPLATE

The criteria weights for resource (R), people’s health and well-being (P) and change management (C) were derived by



FIGURE 1 | South windsor area.

conducting a survey among professionals involved in municipal water management. On average, resources were weighted the highest, closely followed by change management and then public health. Normalizing the weights against the minimum of P resulted in the normalized weight values of 1.22, 1 and 1.04 for R, P and C respectively. The normalized weights were subdivided among the indicators. Scores were assigned according to the indicator scoring templates described earlier. The indicator weights and scores were then combined to produce individual indicator scores.

### Indicator Decision Matrix Analysis for Qualitative Indicators

An interval scale ranging from 0 to 5—with 0 being worst and 5 being the best performance—and a detailed step-by-step decision process was developed as outlined in **Table 1** for the following 17 indicators: 9 for functionality, 5 for resiliency, and 3 for sustainability. These include:

- **Functionality:** Monitoring of the demographic pattern; peak flow; change in impervious area; combined sewer replacement; type of revenue structure; lifecycle cost consideration for capital cost; lifecycle cost consideration for operation and maintenance (O&M); O&M activity with respect to level of service and research and innovation activity.
- **Resiliency:** Assessment of potential damage; assessment of reconstruction need; well-planned source control, conveyance and end-of-pipe measures for adaptation and mitigation, emergency response plan, and recovery plan.

- **Sustainability:** Continuously updated data and information system; transparent data and information sharing policy and actions undertaken to achieve sustainability goal are the main focus under sustainability. The indicator scoring analysis adopted for two of the indicators—*having an advance data collection and information system*, and *transparent data and information sharing policy*—are similar because it is assumed that the likelihood of sharing data with other parties is high only when there are well-recorded and managed data to assess.

Most of the scoring decision step is self-explanatory as shown in the table. Three of the indicators are composite indicators comprised of several factors and are intended to capture the cascading impacts on other infrastructure, for the environment and people's health: *operation and maintenance (O&M) activity with respect to service level*, *assessment of potential damage* and *assessment of reconstruction need* indicators.

For the *operation and maintenance (O&M) activity with respect to service level*—roadside ditch and drain maintenance, storm sewer clean-up and catch basin clean-up are considered as the three maintenance activities whereas the storm sewer length and number of storm sewer connections indicate the two underlying, actual level of service provided by the infrastructure. The detail scoring analysis provided in **Table 1** was followed to assign a score for this indicator. The scores are based on what activities resulted in the improvement in any one or more of the service levels. Depending on the types of system, these indicators could be slightly different, and the user can include their chosen representative indicators in their assessment. For

**TABLE 2 |** Scoring guide for quantitative indicators.

Indicators	Score assignment
<b>Functionality</b>	
Reduction in number of flooding event reported compared to similar event in previous year	>80–100% reduction or no flooding report = 5 >60–80% reduction = 4 >40–60% reduction = 3 >20–40% reduction = 2 >10–20% reduction = 1 No reduction or increased flooding = 0
Reduction in number of stormwater related complaints/100,000 population/year	>80–100% reduction or no complaints = 5 >60–80% reduction = 4 >40–60% reduction = 3 >20–40% reduction = 2 >10–20% reduction = 1 No reduction or increased complaints = 0
Cases of vector borne disease reported/100,000 population per year	0 = 5 >0–2 = 4 >2–4 = 3 >4–6 = 2 >6–8 = 1 > 8 or death = 0
Cases of waterborne disease reported/100,000 population/flooding event	0 = 5 >0–2 = 4 >2–4 = 3 >4–6 = 2 >6–8 = 1 > 8 or death = 0
Volume of stormwater replacing the demand of treated water for external use	100% of external demand replaced by using stormwater = 5 >80–<100% = 4 >60–80% = 3 >40–60% = 2 >20–40% = 1 <20% = 0
<b>Resiliency</b>	
Number of properties opting for source control (or other forms of adaptation) divided by total number of properties served	1 = 5 >0.8–<1 = 4 >0.6–0.8 = 3 >0.4–0.6 = 2 >0.2–0.4 = 1 <0.2 = 0
Death or injury caused by flooding event 100,000 population/year	0 = 5 >0–2 = 4 >2–4 = 3 >4–6 = 2 >6–2 = 1 >2 or death = 0
Death or injury caused by damage in infrastructure systems/100,000 population/year	0 = 5 >0–2 = 4 >2–4 = 3 >4–6 = 2 >6–2 = 1 >2 or death = 0

(Continued)

**TABLE 2 |** Continued

Indicators	Score assignment
<b>Sustainability</b>	
Having a water balance model for the catchment	100% pre-development peak flow is attenuated = 5 >80% to <100% stormwater infiltration = 4 >60–80% = 3 >40–60% = 2 >20–40% = 1 <20% = 0
Toxicity in receiving water sample (mercury)	0% of the time it was tested = 5 > 0–10% of the time it was tested = 4 >10–20% of the time it was tested = 3 >20–30% of the time it was tested = 2 >30–40% of the time it was tested = 1 >40% of the time it was tested = 0
Total phosphorus exceedance in receiving water body	0% of the time it was tested = 5 > 0–10% of the time it was tested = 4 >10–20% of the time it was tested = 3 >20–30% of the time it was tested = 2 >30–40% of the time it was tested = 1 >40% of the time it was tested = 0

example, for a stormwater system having Integrated Stormwater Management (ISM) features such as rain garden or bioswales, the number of cleanups of these features can be another indicator for O&M activities in the *O&M activity with respect to service level* indicator. Similarly, for the *assessment of potential damage* indicator, physical damage to infrastructure, health impacts (both physical and psychological) on people, and environmental impacts are considered and analysis is based on how these indicators are considered in combination. How flooding subsequently affects other infrastructure systems such as roads, water supply and wastewater systems, gas, electricity, and so on is considered as physical damage. In addition to assessing the physical damage, environmental impacts and long-term health impacts on people are also crucial.

For the indicator *assessment of reconstruction need* three factors are considered for scoring: (1) assessing the physical infrastructure restoration and repair need; (2) public health need; and (3) environmental restoration need. For physical infrastructure, the restoration cost of the affected system, public spaces such as parks, playgrounds, and properties are considered. For public health need, the costs of health recovery (e.g., estimated medical costs) are considered. Similarly, the cost associated with debris clean up, garbage pickup, sampling, and monitoring of water quality after the event are considered for the environmental restoration. Depending on the combination of these three aspects, a score is assigned as shown in the table.

Obtaining the future costs may need employing future cost forecasting. Typically, municipalities or utilities managing the infrastructure have this information available from infrastructure lifecycle costing. It is important to understand that this framework and the indicators are forward-looking



**TABLE 3 |** FRS assessment of the South Windsor Stormwater System.

	<b>Indicator</b>	<b>Indicator score</b>	<b>Criteria weight</b>	<b>Criteria weight for each indicator (Criteria weight divided by n# of indicators in each category)</b>	<b>Final indicator value (indicator score x criteria wt. for each indicator)</b>	<b>Average value for each criterion (total of final indicator value/number of indicators in each of R, P, C)</b>
<b>Functionality</b>						
	Monitoring of demographic pattern	1	1.22	0.136	0.136	0.422
Resource (R)	Peak flow reduction	3		0.136	0.407	
	Change in impervious area.	3		0.136	0.407	
	Storm sewer replacement	4		0.136	0.542	
	Type of pricing structure	3		0.136	0.407	
	Lifecycle cost savings on capital infrastructure = [(projected cost – actual cost)/projected cost] × 100%	3		0.136	0.407	
	Lifecycle cost savings on infrastructure O&M	3		0.136	0.407	
	Reduction in stormwater system related complaint	3		0.136	0.407	
	Number of reports of flooding by property owners/# of total properties	5		0.136	0.678	
Public health (P)	Cases of vector borne disease	5	1	0.500	2.500	2.500
	Cases of vector borne disease	5		0.500	2.500	
Change management (C)	O&M activity with respect to service delivery	4	1.04	0.347	1.387	0.693
	Volume of stormwater replacing the demand for treated water	1		0.347	0.347	
	Involvement in research and innovation	1		0.347	0.347	
Functionality value (average value of R, P and C)	<b>1.21</b>					
<b>Resiliency</b>						
Resource	Assessment of potential damage	2	1.22	0.407	0.813	1.08
	Assessment of reconstruction need	2		0.407	0.813	
	Having recovery plan	4		0.407	1.627	
P. Health	Death or injury caused by damage in infrastructure systems	5	1	0.5	2.5	2.5
	Death or injury caused by flood events	5		0.5	2.5	
Change management	Well planned source, conveyance and end of pipe control strategy for stormwater management (adaptation), and alleviation of the root cause (mitigation) of the problem	4	1.04	0.347	1.387	1.16
	Number of properties opting for source control/total properties served	1		0.347	0.347	
	Well developed emergency response plan	5		0.347	1.733	

(Continued)

TABLE 3 | Continued

	Indicator	Indicator score	Criteria weight	Criteria weight for each indicator (Criteria weight divided by n# of indicators in each category)	Final indicator value (indicator score x criteria wt. for each indicator)	Average value for each criterion (total of final indicator value/number of indicators in each of R, P, C)
Survivability value (Average value of R, P and C)	<b>1.58</b>					
<b>Sustainability</b>						
Resource	Having a water balance model for catchment	1	1.22	1.22	1.22	1.22
Public health	Heavy metal toxicity in receiving water sample	5	1	0.50	2.50	1.25
	Total Phosphorus exceedance in receiving water	0		0.50	0	
Change management	Having an updated data collection and Information Management System	3	1.04	0.347	1.04	1.04
	Transparent information sharing policy with all stakeholders	3		0.347	1.04	
	Actions undertaken to achieve sustainability are the main focus	3		0.347	1.04	
Sustainability value (average of R, P and C)	<b>1.170</b>					

in nature, and all the data need identified here may not be conventionally monitored or considered. For example, the Federal Emergency Management Agency (FEMA) of the USA has conducted studies on the comprehensive costs of a flood event, and interested readers are directed to FEMA’s website for further information.

While the *peak flow, combined sewer replacement, change in impervious area, and lifecycle cost savings indicators* are often quantifiable indicators, a scoring decision matrix analysis is still provided to capture the complexity from various scenarios. They are therefore grouped with qualitative indicators to better illustrate the process because of the comprehensive nature of such indicators.

### Scoring for Quantitative Indicators

For quantitative indicators, scores were generally assigned in linear increments of 20% for performance except for the *water quality related indicator*. Divisions every 20% were considered appropriate given how common scales for interpretation are constructed along similar interval bands. For the toxicity and phosphorus *indicators*, because the water quality guidelines suggest a minimum of 40% of the samples comply with the respective guidelines/objectives (MOECC 2010), the number of samples exceeding the standard value more than 40% of the time was assigned a score of zero, and the remaining scores were linearly divided. Overall, there are 11 quantitative indicators: 5 for functionality, 3 for resiliency, and 3 for sustainability are

adopted as listed with the scoring guide provided in **Table 2**. These include:

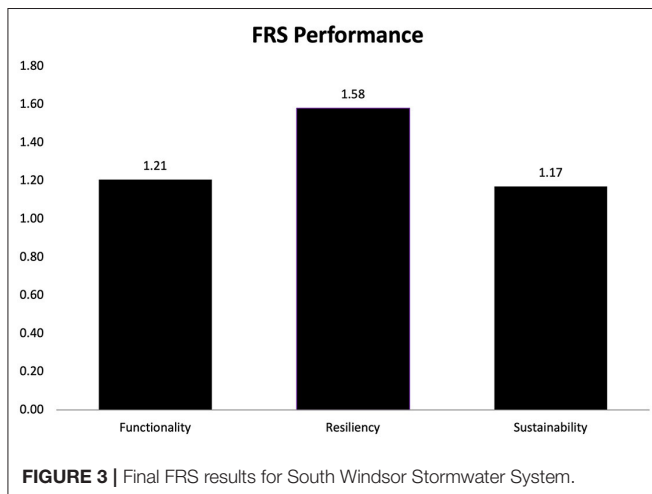
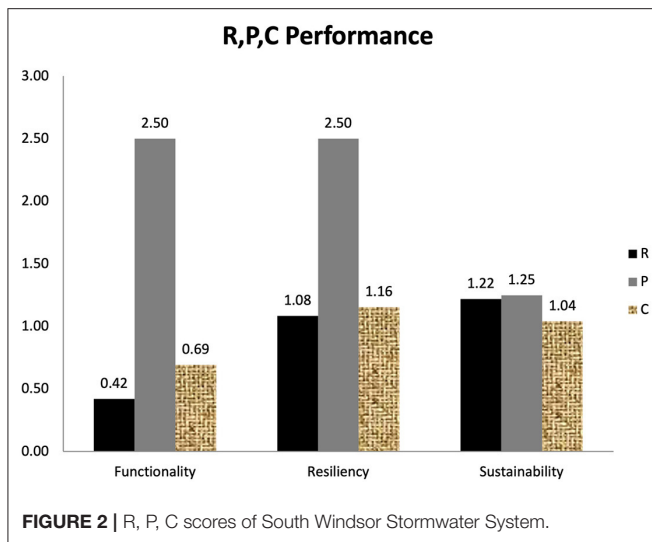
- **Functionality:** reduction in number of flooding event reported; reduction in number of complaints; cases of vector borne disease reported; cases of water borne disease reported; and volume of stormwater replacing the demand of treated water.
- **Resiliency:** number of properties opting for source control (or other forms of adaptation); death or injury caused by flooding event; and death and injury caused by damage in infrastructure.
- **Sustainability:** having a water balance model for the catchment; heavy metal toxicity in receiving water sample; and total phosphorus exceedance in receiving water body.

### Assessment

**Table 3** shows the calculations to determine how functional the stormwater system in South Windsor is using the three main criteria of resources (R), public health (P), and change management (C). Similarly, resiliency and sustainability of the South Windsor area were also evaluated.

Specifically, the indicator value is calculated by multiplying the indicator score based on the scoring guideline with the individual indicator criteria weight of each R, P and C category. The average of the indicator value provided the average value of each R, P and C. This breakdown is also illustrated in **Figure 2**.

The final value for each of the F, R and S categories are calculated by averaging the respective values of R, P and C as



shown individually in **Figure 2** prior to obtain three final values, one representing each of the system's functionality (F), resiliency (R), and sustainability (S). Although some detail is further lost by reducing the information to three values, the end result does represent a more efficient means to compare F, R, and S across systems or of the same system over time. These final values for a system's functionality, resiliency and sustainability of the system are shown in **Figure 3**.

The results from this evaluation were well received by the municipality and it was indicated that beside the usefulness of the functionality, resiliency and sustainability assessment, the municipality will also consider the decision matrix analysis in public outreach and information sessions to showcase the complexity of stormwater system and need for greater community participation and emphasis on "soft paths" such as source control among others. The use of this decision matrix analysis therefore helps reduce the subjectivity and inconsistency

in evaluating qualitative and complex indicators which are often omitted from assessments because they are perceived as being too difficult to measure. Moreover, the color coding in the decision matrix analysis table retains key elements of the rationale and decision process, while still aggregating the information into a numerical outcome. Updating and retaining these tables over time (e.g., annually) can therefore become a repository of information and provide institutional knowledge for future.

## CONCLUSIONS AND RECOMMENDATIONS

While the usefulness of addressing subjectivity associated with qualitative indicators has been recognized, a credible solution that is both comprehensive but workable on a practical level has been lacking. Much more detailed and complex approaches for including qualitative indicators exist but may require expertise or information that is not readily available nor widely embraced. However, ignoring such indicators however means that a meaningful but difficult-to-interpret amount of data is lost.

The main advantage of the decision matrix analysis presented is the structured stepwise process for guiding decision makers to arrive at a score for qualitative and complex indicators. The decision matrix analysis further provides a straightforward yet effective tool for decision makers for incorporating issues involving significant subjectivity. In the infrastructure sector, when there are many competing priorities, evolving challenges, and growing demands, using a template to assign score helps address the subjectivity in the decision process and renders the assessment more transparent, defensible, and consistent. Moreover, the presentation of how the information itself is presented and assessed is more readily understandable and useful for the assessor, decision-maker and by various stakeholders.

The decision matrix analysis can be a valuable tool for small and medium size municipalities which may not have the time, resources, or in-house expertise to use complex methods and tools to conduct independently derive custom values for assessing their infrastructure. The matrix for assessing the infrastructure system within the functionality-resiliency-sustainability (FRS) Framework should be applied periodically to reflect any changes over time to reveal a trend: is the infrastructure becoming more resilient and sustainable according to these more inclusive criteria, or is the infrastructure being overtaken by external events brought about by climate change or other forces?

Finally, the FRS Framework can be used to evaluate other types of infrastructure systems such as water-wastewater, transportation, buildings, and energy by modifying the decision matrix analysis to suit the specific parameters of any system.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

JU is the principle author of the manuscript. NB and ET substantially contributed in the review, revision, edits and finalizing the manuscript for publication. All authors contributed to the article and approved the submitted version.

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## FUNDING

The research described in this manuscript has been partially supported by Canadian Water Network, and partially by Natural Science and Engineering Research Council of Canada (NSERC).

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