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Practical Framework for Evaluation and Improvement of Drinking Water Treatment Robustness in Preparation for Extreme-Weather-Related Adverse Water Quality Events

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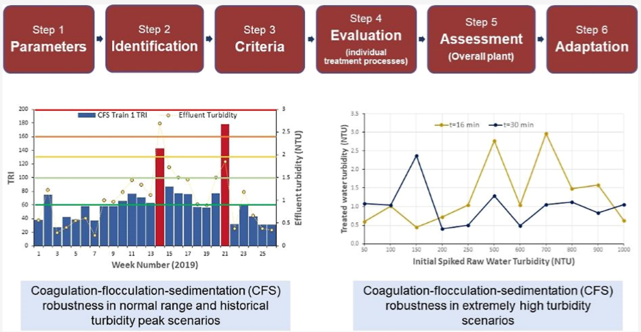
ABSTRACT: Robustness is the ability of a drinking water treatment plant (DWTP) to achieve the desired finished water quality even during adverse raw water quality events. Increasing the robustness of a DWTP is beneficial for regular operations and especially for extreme weather adaptation. This paper proposes three robustness frameworks: (a) a general framework outlining the main steps and methodology for systematic assessment and improvement of the robustness of a DWTP, (b) a parameter-specific framework applying the general framework to a water quality parameter (WQP), and (c) a plant-specific framework applying the parameter-specific framework to a DWTP. A parameter-specific framework for turbidity is presented using the turbidity robustness index (TRI) for evaluation and applied to a full-scale DWTP in Ontario, Canada. This evaluation was conducted with historical plant data, as well as bench-scale experimental data simulating extremely high-turbidity scenarios. The framework application is capable of identifying (i) less robust processes which are likely to be vulnerable during climate extremes, (ii) operational responses to increasing short-term robustness, and (iii) a critical WQP threshold beyond which capital improvements are necessary. The proposed framework provides insights into the current state of robustness of a DWTP and serves as a tool for climate adaptation planning.



KEYWORDS: *climate adaptation, turbidity robustness index, operational planning, water quality perturbations, capital planning*

1. INTRODUCTION

A robust drinking water treatment system can be defined as one that "provides excellent performance under normal conditions and deviates minimally during periods of upset or challenge".[1] Increases in extreme weather events due to climate change[2,3] can cause unprecedented changes in surface water quality parameters (WQPs) such as turbidity[4−10] and pose operational challenges to drinking water treatment plants (DWTPs).[11] Increasing the short-term robustness of DWTPs by changing operational conditions can be a viable adaptation option during a sudden event such as a turbidity spike. However, most DWTP designs only consider historical peaks, but not WQP extremes made more likely by the effects of climate change, and the plants may have aging infrastructure.[12,13] Therefore, it is important to understand the operational treatment limits by assessing robustness quantitatively and to increase robustness by improving treatment through a systematic change in operational conditions.

One metric that quantifies robustness is the turbidity robustness index (TRI),[14−16] which assesses the robustness of clarification and filtration processes in full-scale DWTPs.[17−20] These studies, however, have been limited to individual treatment steps rather than an entire DWTP, have only focused on historical data, without considering possible turbidity extremes, and were limited to relatively short time frames. Limited research studies have developed climate adaptation frameworks for entire DWTPs but were generally not able to quantitatively assess full-scale DWTPs.[21,22] In the gray literature, there are frameworks for improving the resilience of DWTPs during extreme weather events, which are only qualitative in nature and are targeted more toward restarting a DWTP after failure than on continuing operations to avoid a failure,[23−25] as is the focus of robustness.

The current study focuses on the robustness of DWTPs and proposes a framework to systematically evaluate individual treatment processes, assess the entire DWTP, and improve its robustness. The framework is then demonstrated on a full-scale DWTP to provide a proof of concept. The general robustness

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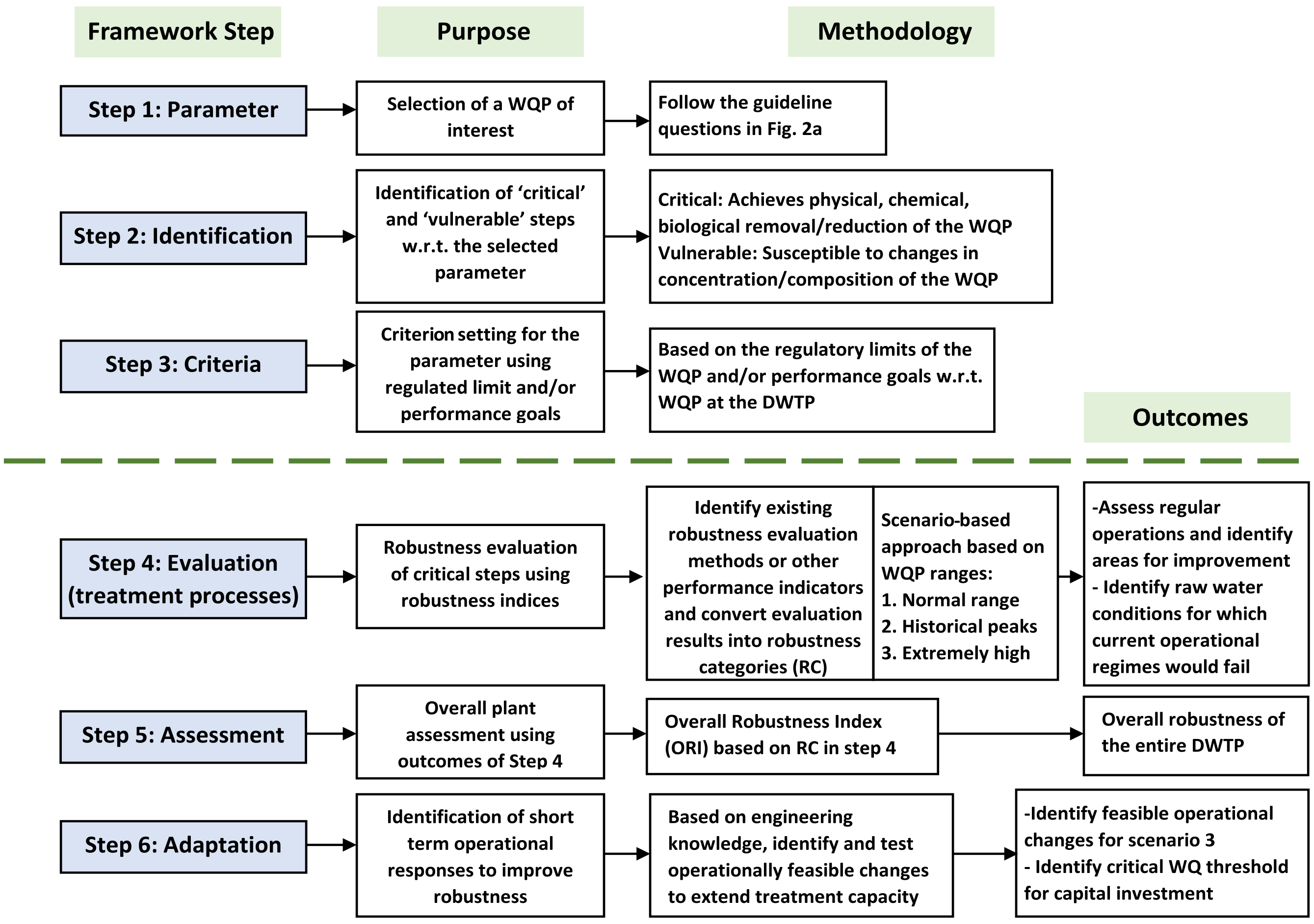

Figure 1. General Robustness Framework.

framework developed in this study can be applied to any WQP, and the current paper demonstrates it for turbidity, which is a regulated parameter in 80 countries and is of utmost importance for drinking water treatment operations.[26] Increases in raw water turbidity directly impact several treatment processes and the ability of a DWTP to produce safe drinking water. An increase in raw water turbidity has been correlated with an increase in pathogens such as *Giardia* and *Cryptosporidium*[1,5,9] and has a negative impact on the disinfection efficiency of chlorination, ozonation, and UV radiation.[5,6,27] The turbidity framework provides steps and tools to identify critical treatment steps and performs a quantitative evaluation of the robustness of these critical steps and the overall plant. This evaluation typically uses historical online data and also simulates extremely high-turbidity scenarios at bench scale. The next step of the framework is the optimization of critical treatment steps for such high-turbidity scenarios, which is not usually carried out at DWTPs. Finally, the developed turbidity framework was applied to a full-scale DWTP in southern Ontario, Canada.

2. APPROACH AND METHODOLOGY

2.1. Conceptual Framework Development. A good conceptual framework is flexible, has the capacity for modification, and provides an understanding of the phenomenon being studied.[28] The approach followed for constructing the robustness frameworks in this study had two goals: (1) to provide a generally applicable sequence of steps, which can be expanded to any WQP following the proposed methodology, and (2) to provide a specific and detailed expansion of these steps to one WQP that can be readily applied to a full-scale DWTP.

To develop the current framework, both the academic and gray pieces of literature were surveyed for previous examples of robustness and resilience frameworks with a focus on drinking water treatment. There was little or no direct application of existing resilience models in the development of the current framework, but the general idea about conceptual frameworks for water was taken from the various EPA resilience models and other resources.[23−25,29]

2.2. Full-Scale Data Collection and Analysis (Plant Framework, Step 4: Evaluation, Scenarios 1 and 2). Full-scale plant data from Plant A were collected for 6 months (weeks 1−26 of 2019) from different process locations (Figure SI1) for train 1 [coagulation−flocculation−sedimentation (CFS) unit 1 and filters 1 and 2]. It should be noted that while Plant A has the flexibility to operate trains 1 and 2 separately, water is typically blended after CFS and then distributed to the 4 filters. Filters 1 and 2 were chosen to represent roughly 50% of the water treatment along with CFS unit 1 for demonstrating the framework application. This included online turbidity and flow rate data in 5 min intervals. Since the online data set was large, MATLAB by MathWorks was used for processing and computations. Before analyzing the data, data as described below were identified and removed after consultation with plant personnel so that the data set only reflected the readings when the processes were fully operational for water production. This

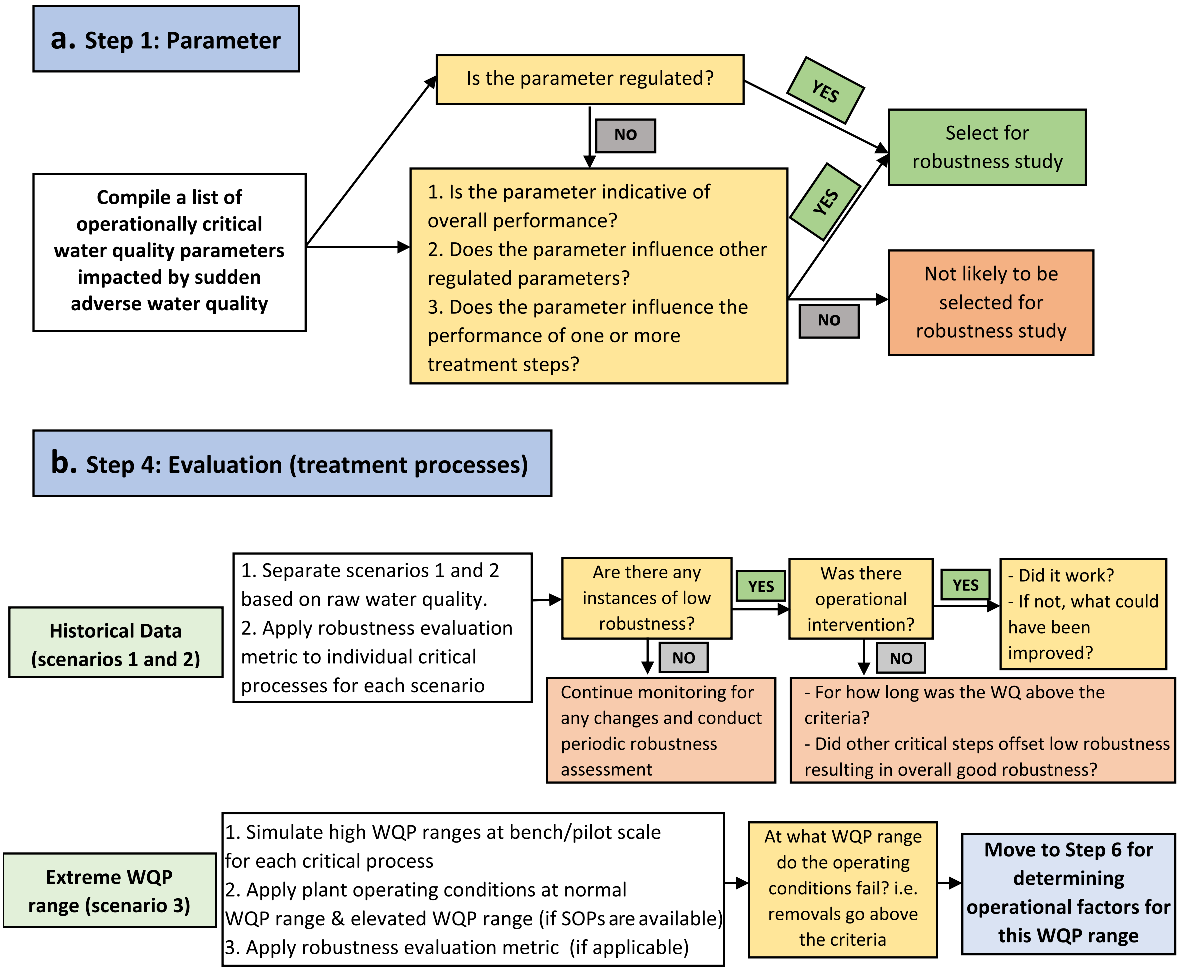

Figure 2. Detailed methodology for steps 1 and 4 of general robustness framework; (a) presents a guideline for selection of a WQP for robustness framework application; (b) shows the steps for robustness evaluation of critical treatment processes for three scenarios. The questions provided here serve as a guideline so that each DWTP can tailor its investigation based on the evaluation results.

was done for all three critical treatment steps using turbidity and corresponding flow rates. For the intake, the influent and effluent data below a flow-rate threshold of 1 L/s were removed as this indicated that the intake was shut off. For CFS, the following criteria were adopted.

1 Turbidity values above 8 NTU were removed as these values were deemed unreliable by Plant A staff because they were approaching the upper bound of reliable quantification of the turbidimeter setting which was 10 NTU.

2 Turbidity values corresponding to flow rates less than 100 L/s were removed as flows below this threshold indicate that the blenders were taken offline for cleaning or other operational interventions.

3 Sudden jumps were removed using the “hampel” function in MATLAB for both flow rate and turbidity data in 30 min time windows (10 data points). These sudden jumps were either due to instrumentation still stabilizing or general instrumentation errors.

For filtration, effluent turbidity data during backwash were removed by setting a flow-rate threshold of 1 L/s. MATLAB codes for identifying valid data and TRI calculations based on the index in ref 16 are provided in the Supporting Information, Section 2.2.1.

2.3. Extremely High-Turbidity Bench-Scale Jar Tests Simulating CFS (Plant Framework, Step 4: Evaluation, Scenario 3).

Raw water entering Plant A was used to generate water of extremely high turbidity ranging from 50 to 1000 NTU by adding kaolin (K1512, Sigma-Aldrich) in amounts ranging from 0.07 to 0.65 g/L. Coagulant [STERN PAC (Kemira), 40% strength] and polymer, that is, coagulant aid (Magnafloc LT22s, 0.2% strength), stock solutions were obtained from Plant A. The coagulant was dosed at 30 mg/L and the polymer at 0.3 mg/L.

A standard jar test apparatus (Phipps & Bird) was used, and the test procedure for a 400−500 L/s flow scenario developed by Plant A personnel was adopted (Table SI4). This lower-flow scenario was chosen to account for a possible flow reduction the plant might employ during an elevated turbidity event.

2.4. Factorial Design Bench-Scale Experiment for Adaptation (Plant Framework, Step 6: Adaptation).

A 2^3 full factorial design with two center-point replicates was chosen as the experimental design to study the effect of three optimization factors, that is, coagulant dose, polymer (coagulant aid) dose, and settling time. The levels of the three factors and corresponding dosages can be found in Table SI7. The reagent preparation and jar test procedures used for this experiment are the same as in Section 2.3.

3. RESULTS AND DISCUSSION

3.1. Development of Robustness Frameworks. Three frameworks were developed for DWTP robustness evaluation, overall assessment, and improvement.

1. General: outlines the main steps and defines the methodology for developing parameter-specific details.
2. Parameter-specific: general framework tailored to a specific WQP of importance.
3. Plant-specific framework: parameter-specific framework tailored to the processes and surface water quality of a specific DWTP.

3.1.1. General Framework. There are six main steps in the general framework, as outlined in Figure 1.

3.1.1.1. Step 1: Parameter. This step involves the selection of a WQP which is impacted by extreme weather and is of operational importance to a DWTP. This WQP will be the basis of the robustness evaluation. Figure 2a provides a guideline for this process. It is important to note here that equal importance is given to WQPs that are regulated and WQPs which are not regulated but can impact other regulated parameters and other treatment processes. An example of such a WQP is background organic matter (natural organic matter—NOM) as it can impact the levels of other regulated parameters such as disinfection byproducts (DBP) and the performance of treatment steps such as coagulation, filtration, disinfection, and adsorption.

3.1.1.2. Step 2: Identification. This step involves the classification of treatment processes at a DWTP as critical and/or vulnerable. Critical processes are defined as steps achieving physical, chemical, and/or biological reduction (removal) of the chosen WQP. Vulnerable processes are defined as steps that are susceptible to an increase in the concentration or a change in the nature of the WQP. The robustness evaluation in the next steps of the framework is done for the critical treatment processes, whereas the identification of vulnerable processes highlights the impact sudden WQP perturbations may have on DWTP operations.

3.1.1.3. Step 3: Criteria. In this step, a criterion for the selected WQP is set for each critical step based on the regulated values and/or treatment performance goals associated with the parameter at the selected DWTP. This step sets a treatment goal as a threshold beyond which the robustness of a step would decrease and potentially cause operational challenges.

3.1.1.4. Step 4: Evaluation (Individual Treatment Processes). The goal of this step is to conduct a quantitative robustness evaluation of each critical process for the selected WQP. For this, any existing robustness methodology applicable to the WQP will be identified. If there are none, other existing evaluation methods may be used or tailored. In some cases, new methods will need to be developed. This evaluation will be conducted for three raw water scenarios of the WQP.

- Scenario 1: normal range
- Scenario 2: historical peaks
- Scenario 3: extreme values not yet experienced but that may be encountered during future extreme weather events.

Quantification of treatment robustness in scenarios 1 and 2 allows an assessment of the historical performance of the DWTP and can serve as a diagnostic tool to narrow down patterns of low robustness, possible causes, and whether any operational adjustments were made to overcome periods of low robustness. This retroactive assessment could also be potentially included in a water quality management plan alongside other periodic assessments such as filter run time and filter index analysis.

Scenario 3 evaluation focuses on identification of raw water conditions in which climate adaptation measures for critical treatment processes become necessary for treatment to remain robust. In a way, this is to give an early indication of the "failure point" or threshold of a treatment process beyond which operational intervention (short-term measures) or capital investment (long-term measures) becomes inevitable.

The first two scenarios can be evaluated based on the historical data available at the plant over a certain duration. The third scenario can be evaluated using water samples and simulating, for example, extremely high turbidities in bench-scale setups. The detailed steps for evaluation are shown in Figure 2b.

Table 2 shows the proposed robustness categories (RCs) to be assigned to each critical treatment process based on the

Table 1. Guidance List for Identifying Critical and Vulnerable Drinking Water Treatment Steps with Respect to Turbidity

	critical		vulnerable
process	yes/no	nature of control on the turbidity removal process	yes/no
intake (including any storage units)	varies	natural, maybe operational	yes
coagulation	yes	operational	yes
flocculation	yes	operational	yes
sedimentation	yes	design, operational	yes
dissolved air flotation	yes	operational	yes
filtration	yes	operational, design	yes
rapid granular media filtration			
membrane filtration			
biological filtration			
adsorption	no		varies
powdered activated carbon			depends on point of usage
granular activated carbon			yes
ozonation	no		yes
disinfection	no		yes
distribution system	no		yes

Table 2. Demonstration of the Proposed RC Assignment to a Robustness Metric[a]

TRI value	effluent WQP range corresponding to TRI	category description	RC/ORI number
<60	0.1−0.5 × criterion	very stable	1
60−100	0.6−0.8 × criterion	stable	2
100−130	0.9−1.2 × criterion	slightly disturbed	3
130−160	1.3−1.5 × criterion	moderately disturbed	4
160−200	1.6−1.8 × criterion	upset	5
>200	>2 × criterion	severely upset	6

[a] TRI values reflect the effluent turbidity ranges and have originally been assigned to six RCs. The description of these categories has also been used to describe the RC and ORI categories for overall treatment assessment.

evaluation outcomes. The goal is to link the robustness metric to the effluent WQP from that step and convert the results into six categories of system robustness (adapted from ref 31). An example of how this was done for the turbidity robustness metric, that is, the TRI, is shown in Table 2. This conversion to RCs will make evaluation results consistent across different WQPs and treatment processes and their evaluation methodologies.

3.1.1.5. Step 5: Assessment (Overall Plant). Based on the evaluation outcomes of individual critical treatment processes from step 4, an overall assessment of the selected DWTP will be done using an overall robustness index (ORI) (equation 1). This overall assessment will be conducted for each scenario where possible.

$$\text{ORI} = \frac{W_1 \times \text{RC}_1 + \ldots + W_n \times \text{RC}_n}{\sum_1^n W_i} \tag{1}$$

ORI: overall robustness index, W_1: weight of critical process 1, RC_1: RC of critical process 1, W_n: weight of critical process n, RC_n: RC of critical process n, and $\sum_1^n W_i$: sum of weights.

The ORI is based on a weighted average approach incorporating the evaluation results for all individual critical processes. This approach is similar to the simple additive robustness concept presented in ref 30 which defines the overall robustness of a water supply system as the sum of the robustness of its individual elements (source, treatment, distribution, monitoring, and response) and indicates that because lower robustness of one element can be compensated for by greater robustness of one or more other elements, the concept of a "chain being only as strong as its weakest link" does not apply.

General guidelines for assigning weights are given below:

Step 1: Rank the treatment processes in the order of their importance.

Step 2: Assign a higher weight (0.5 and above) to the more or most important process. For example, filtration or the final treatment process would be ranked highest for the turbidity framework since filtered or finished water turbidity is regulated. The sum of all the weights is equal to 1.

Step 3: Conduct a sensitivity analysis of the index with different weights to evaluate how the weighting scenarios influence the outcome of the ORI and the overall plant assessment.

The actual value of the weights will be determined together with the utility carrying out the robustness framework assessment, based on the experiential knowledge specific to their DWTP. This step is intended as a self-assessment of the DWTP.

Once the weights for each critical treatment step are determined, the ORI can be calculated using equation 1. The naming of the ORI categories follows the naming convention of the RCs (as will be seen in Table 2).

3.1.1.6. Step 6: Adaptation. The goal of this step is to identify and apply short-term operational responses to improve the robustness of the system beyond the initial failure point identified during evaluation of scenario 3 (extremely high WQP range) in step 4. This step includes testing short-term responses, initially at the bench scale and maybe later at the pilot scale, to determine their feasibility and effectiveness. This step may result in identifying (a) a successful operational regime for scenario 3, resulting in extreme-weather standard operating procedures (SOPs) and (b) the critical threshold beyond which capital investments may be required.

3.1.2. Parameter-Specific Framework for Turbidity.

3.1.2.1. Steps 1 and 2 (Parameter and Identification). Turbidity was chosen for this study as turbidity is a regulated parameter and is of utmost importance for DWTP operations, impacting the treatment effectiveness of several processes. Commonly used drinking water treatment processes were categorized as "critical" and/or "vulnerable" with respect to turbidity based on engineering knowledge (Table 1). In addition, the nature of control on the turbidity removal process was also identified for the critical treatment processes. This is meant to guide a DWTP in choosing the critical treatment processes for their robustness assessment with respect to turbidity. The criticality of an intake system for turbidity would vary depending on its design and placement in the source water. As such, intakes are not designed for turbidity removal apart from screening larger debris, but there may be some particulate reduction due to intake design such as a raw water reservoir or variable-depth intake systems.

As CFS units are designed primarily for turbidity removal, they are categorized as critical processes. Operational parameters for coagulation and flocculation, such as coagulant type and dosage, coagulant aid use, pH, and mixing speed, can be adjusted, whereas operational control of sedimentation can only be achieved through an overall change in flow rate, which would affect residence time.

Filter performance is mostly dependent on the efficacy of pretreatment achieved by CFS, which is normally included, although direct filtration may involve only coagulant addition and no flocculation−sedimentation steps. Operational control in the filtration step includes changing the hydraulic loading rates, filter run length, backwash duration, backwash rate, and air scouring conditions. Other factors such as filter media and bed depth are part of the filter design and cannot be controlled operationally.

While all critical steps would be inherently vulnerable, all vulnerable steps may or may not be critical, that is, contribute to the removal/reduction of the WQP. For example, disinfection is not a critical step for turbidity, but it is a vulnerable step because increased turbidity can increase pathogen loading, thereby increasing the disinfectant demand for chlorine and ozone and also interfering with the actual disinfection/inactivation. Similarly, distribution systems are also vulnerable to turbidity changes, which can contribute both to particulate matter deposition and to potential microbiological growth and transport.

3.1.2.2. Step 3 (Criteria). The criterion for finished water quality was set as 0.3 NTU as per drinking water regulations in the province of Ontario, Canada.[32] In addition, performance goals for turbidity at the selected DWTP for different treatment steps were considered and will be discussed in more detail in Section 3.2.

3.1.2.3. Step 4 (Evaluation). For evaluating scenarios 1 (normal range) and 2 (historical peaks) from historical data, the TRI was identified as a suitable robustness metric.[14−16] While the TRI has been previously used only for evaluating filtration performance and for limited durations (e.g., a few filter-run cycles), it was determined that the index can be expanded to any critical process with online turbidity data acquisition and for any desirable length of time. This expansion is an innovative contribution of the present research. Scenario 2 should be evaluated separately from scenario 1 by distinguishing the two cases based on the raw water turbidity. For scenario 2, it is also important to review any high-turbidity SOPs at the DWTP and review the operational response of the plant during a previous turbidity event.

Scenario 3 (extremely high turbidities) evaluation can be carried out by simulating high-turbidity raw water using synthetic clay such as kaolin or by collecting raw water during a storm event and concentrating the particulate matter. The typical plant operational parameters can then be applied in bench-/pilot-scale experiments to determine the performance of the treatment steps for the simulated water quality. As a first step, jar tests are recommended for CFS and bench-scale filters for the filtration step evaluation. If a plant has an SOP for high-turbidity events, it should be used in scenario 3 testing. If not, typical plant operational parameters should be employed. It should be noted that TRI is only applicable to scenarios 1 and 2, and scenario 3 is evaluated by whether a treatment process is able to reduce elevated turbidities below the set criterion.

3.1.2.4. Step 5 (Assessment). Since the RCs originally defined for TRI (Table SI2) correspond to the RC proposed in Table 1, the ORI proposed in Section 3.1.1 can be easily applied to a turbidity-specific overall assessment for scenarios 1 and 2. The assessment of historical data as TRIs for individual treatment processes can be interpreted for the overall plant with ORI for scenarios 1 and 2. This in conjunction with the insights derived from the bench-scale experiments for scenario 3 gives a complete assessment of the DWTP robustness.

3.1.2.5. Step 6 (Adaptation). Based on the robustness assessment outcomes, once it is determined which critical treatment steps at a DWTP are low in robustness, short-term adaptation options (Table 3) can be tested at bench scale or pilot scale (if available) to obtain at least an initial assessment of their effectiveness and feasibility. A factorial experimental design is recommended to determine the most significant factors.

Table 3. Critical Steps and Possible Operational Adaptation Options

critical step	potential operational responses
intake	intake can be shut off beyond a certain raw water turbidity level
	intake depth can be changed for variable-depth systems
coagulation	coagulant dose
	coagulant type
	pH adjustment
	additional chemicals such as coagulant aid
	zeta potential can be used as a tool to monitor and control coagulant dosage
flocculation	mixing speed, *G*
	mixing duration, *t*
sedimentation	surface loading rate of the system
filtration	hydraulic loading rate
	filter run time
	backwash duration
	modified backwash techniques
	addition of filter aid polymers

3.2. Application of the Turbidity Robustness Framework to Plant A (Plant-Specific Framework). *3.2.1. Steps 1−3 (Selection, Identification, and Criteria).* To demonstrate the application of the turbidity framework, a full-scale DWTP in southern Ontario, Canada (referred to as Plant A), was chosen (Figure SI1). One of the unique features of Plant A is its raw water storage reservoir with four cells in series at the intake, with about 48 h of residence time. This reservoir was included in the robustness evaluation as some turbidity removal by natural settling occurs (Figure SI2).

Following the steps of the parameter-specific framework for turbidity, the critical treatment steps were identified as the intake (reservoir), CFS, and filtration (Figure SI1). Next, the criteria for robustness evaluation were set for each critical step as 25 NTU for intake (reservoir), 2 NTU for CFS, and 0.1 NTU for filtration, which is below the regulatory limit of 0.3 NTU.[32] This was done after discussions with Plant A personnel about the expected performance goals with respect to turbidity.

3.2.2. Step 4: Evaluation. 3.2.2.1. Evaluation of Critical Process 1: Intake (Reservoir) for Historical Data (Scenarios 1 and 2). Scenarios 1 and 2 for Plant A could not be evaluated separately due to the intake-shut-off protocol which was set at 50 NTU. Hence, higher turbidity values, which would classify as historical peaks, were never experienced by the plant over the duration of this study. The TRI values for the intake (reservoir) show robust performance, with most of the values falling in the "very stable" category and only two values falling in the "stable" category (Figure 3a). The effluent turbidity was always below 17 NTU even for raw water turbidities higher than 30 NTU. In addition, higher raw water turbidities (>20 NTU) corresponded to a higher percentage of removals in the reservoir due to natural settling (Figure SI2).

3.2.2.2. Evaluation of Critical Process 2: CFS for Historical Data (Scenarios 1 and 2). Figure 3b shows that most of the TRI values lie in the "very stable" and "stable" category. However, the exceptions were week 14 (TRI 143, "moderately disturbed") and week 21 (TRI 178, "upset"). In both weeks, the daily average effluent turbidities were higher than T_{goal} (2 NTU) with values as high as 3.7 NTU for week 14 and 3.1 NTU for week 21 (Table SI3). In addition, the TRI for week 21 is higher than for week 14 even though week 14 had higher daily average effluent turbidities. One possible reason is that the TRI incorporates not only the average performance but also the variability of the performance (first term in Supporting Information equation 1). Week 21 has less uniformity, meaning a higher range of turbidity values, which resulted in a higher weighting on the first term, therefore leading to a higher TRI. The lower CFS robustness in those 2 weeks was noted by plant staff as the corresponding higher effluent turbidities were tagged in the monitoring data. However, there was operational intervention only for week 21 where the polymer dosage increased from 0.26 to 0.31 mg/L. While this was a larger change than usual, the dosage was well within the operational ranges (Plant A staff, personal communication, November 9, 2022).

3.2.2.3. Evaluation of Critical Step 2: Filtration for Historical Data (Scenarios 1 and 2). TRI was calculated for train 1, that is, filters 1 and 2. For the duration of the study, these filters were very robust, with most of the values in the "very stable" range and a few values in the "stable" range (Figure 3c,d). The effluent turbidities for both filters were close to 0.05 NTU, that is, half the T_{goal}. The low robustness of the CFS process in weeks 14 and 21 was offset by the robust filtration, indicating that filters at Plant A may be able to handle turbidities higher than 2 NTU during a high-turbidity event.

3.2.2.4. Evaluation of Critical Process 2: CFS for Scenario 3 (Extremely High Turbidity Values). Since Plant A did not have any specific SOPs for high-turbidity events, typical plant dosages for coagulant (30 mg/L) and coagulant aid (0.3 mg/L) were used for scenario 3 evaluation. Jar tests for spiked raw water turbidities of 50−1000 NTU showed that the plant chemical dosages were able to achieve high removal well below T_{goal} (2

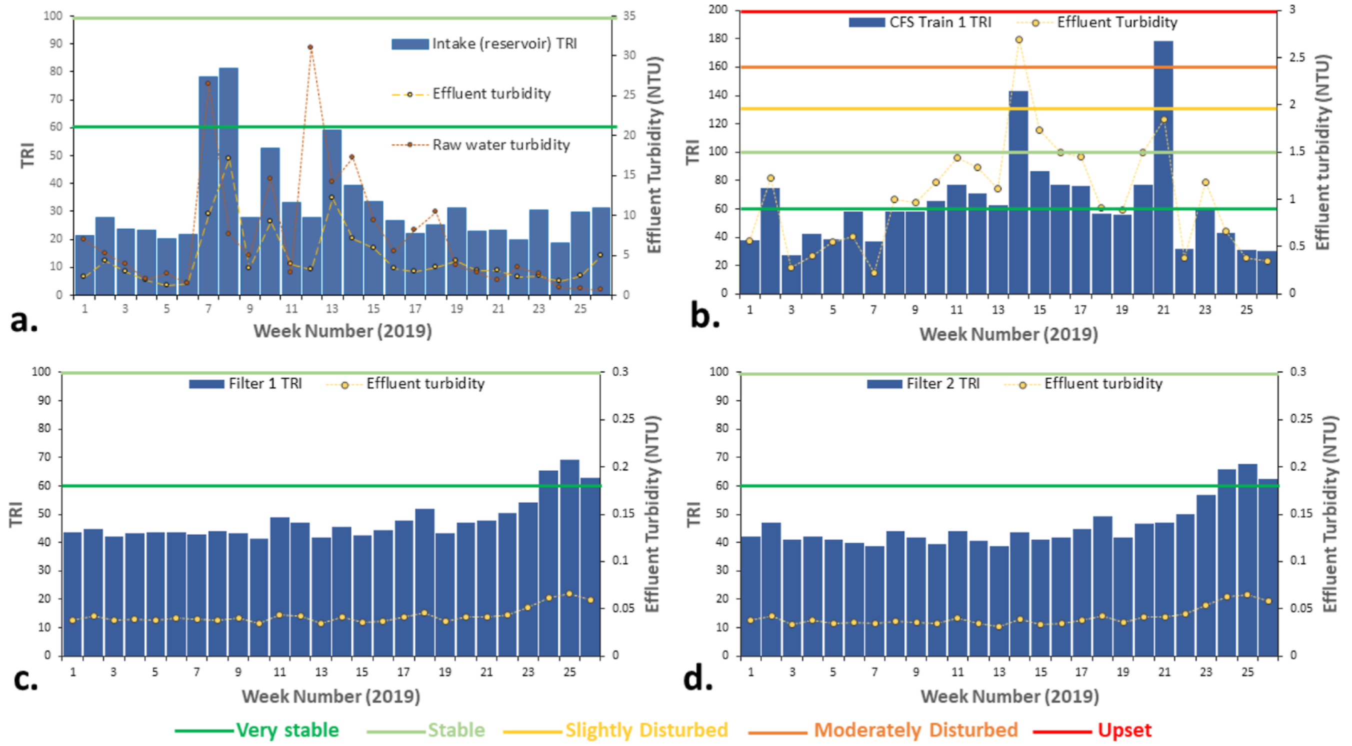

Figure 3. TRI evaluation of critical treatment steps at Plant A: (a) intake (reservoir) TRI values with raw water and effluent turbidities at T_{goal} = 25 NTU, (b) CFS train 1 TRI values and effluent turbidities at T_{goal} = 2 NTU, (c) train 1 filter 1 TRI values and effluent turbidities at T_{goal} = 0.1 NTU, and (d) train 1 filter 2 TRI values and effluent turbidities at T_{goal} = 0.1 NTU.

NTU), even for extremely high raw water turbidities for settling times of 16 and 30 min (Figure SI3). This suggests, within the limitations of bench-scale results, that current plant dosages may work very well even for high raw water turbidities.

3.2.3. Step 5: Assessment. To calculate the ORI for historical data (scenarios 1 and 2), where TRI categories correspond to RCs, four weighting approaches were applied to measure the sensitivity of the index.

i Case 1: equal weight of 0.33 for all processes

ii Case 2: low weight for intake (0.1) and high weight for filtration (0.5)

iii Case 3: high weight for intake (0.25) and high weight for filtration (0.5)

iv Case 4: combination weight based on raw water turbidity range. High weight (0.25) for intake for raw water turbidity >25 NTU, low weight (0.1) for raw water turbidity <25 NTU, and constant high weight (0.5) for filtration.

Filtration was given higher importance as filter effluent is regulated, and weights for the intake were changed due to observed higher percentage removal for higher raw water turbidities (Figure SI2). Regardless of the weighting approach, the overall robustness of Plant A lies in the "stable" or "very stable" categories for the assessment period, with only one instance of "slightly disturbed" for week 21 based on the weighting cases 2 and 4 (Figure SI4). The four weighting approaches are shown to demonstrate the application of the ORI by considering several factors. The decision of which weights to assign is based on the judgment of the DWTP applying the framework.

For extremely high turbidities (scenario 3), since the current CFS operational regime is quite robust, that is, it performed very well in bench-scale tests even for extremely high-turbidity scenarios, the current CFS dosages may serve plant A well during sudden turbidity spikes. Ideally, this could be confirmed by pilot testing.

3.2.4. Step 6: Adaptation. Testing of operational adaptation options builds on the results of the evaluation (Section 3.2.2) and is applied to critical treatment processes identified as having low robustness, most likely in scenario 3. Plant A operational parameters for CFS were robust even for extremely high turbidity ranges. However, since this study intends to demonstrate a complete application of the proposed framework, bench-scale jar tests using simulated 700 NTU raw water and a full factorial design were used to test three short-term operational responses: change in coagulant and polymer dose and change in settling time. While there was a slight lowering of final turbidity with increased settling time, there were not any significant factors upon performing ANOVA with the data (α = 0.05) (Table SI8). This may be because the original chemical dosages were sufficient to treat the high turbidity and did not require higher dosages. However, this method demonstrates how a utility can perform bench-scale tests to provide an initial assessment of short-term responses in case of low robustness of a treatment process.

3.3. Discussion of the Turbidity Robustness Framework and Its Application to Plant A. The turbidity robustness framework demonstrates how the general framework can be tailored to a specific WQP. The quantitative robustness evaluation of individual critical treatment steps using the TRI is a key feature of the turbidity framework. This study also extended the application of the TRI to treatment processes other than filtration and for a prolonged period, which has not been done in previous studies.

Based on the evaluation of the historical data (scenarios 1 and 2), the Plant A intake reservoir functioned as a natural sedimentation basin, which significantly reduced higher raw water turbidities, presumably providing a natural cushion for future extreme-turbidity events. CFS was found to be low in robustness for 2 out of 26 weeks, but this was offset by operational intervention and robust filter performance as even when the water quality after CFS was not within the expected range, that is, <2 NTU, the filters were producing finished water of <0.1 NTU turbidity. The consistent overall performance of Plant A is further evidenced by the ORI, which remained "stable" and "very stable" throughout the assessment period except in week 21 which was "slightly disturbed" based on the weighting approach.

A concern raised by the plant personnel was the reliability of turbidimeter data for CFS which emphasizes not only the need for robust treatment and operations but also for robust instrumentation to aid in monitoring and response. For scenario 3 (extreme future weather events), current CFS operational parameters seem to be robust based on the high-turbidity experiment, but this is limited by the applicability of bench-scale results and the use of synthetic clay, kaolin, which may not represent the particle characteristics entering the system during extreme weather. Further investigation for scenario 3 is recommended not only for CFS but also for filtration. These additional investigations may identify a critical turbidity threshold beyond which operational interventions will not be successful and capital improvements to the plant will become necessary. Going forward, the assessment demonstrated here could be incorporated into a water quality management plan, thereby documenting past plant performance quantitively and highlighting process scenarios where interventions are needed and can be planned for in the future. Though Plant A's performance could not be evaluated separately for normal raw water turbidity (scenario 1) and past turbidity peaks (scenario 2), other plants may wish to do so, thus giving them a better indication of plant performances during turbidity spikes.

The TRI concept may be extended to other WQPs, which are monitored online, but it may have limited application to parameters less frequently monitored. Though the latter may hinder the evaluation step of the general robustness framework for other WQPs, it provides an incentive for developing robustness metrics for other WQPs of importance and for increased water quality monitoring at DWTPs.

4. CONCLUSIONS AND WHY IS THIS IMPORTANT FOR THE WATER TREATMENT INDUSTRY?

This study proposes a framework that provides steps for a systematic robustness evaluation of individual treatment processes as well as the overall DWTP and demonstrates its application to a full-scale DWTP. The framework can be used to develop evaluation and adaptation methodologies for any WQP. This is useful not only for evaluating regular operations and performance during past water quality disturbances but also for more extreme weather situations that may impact the raw water quality and threaten DWTP operations in the future, making this a potential climate adaptation tool.

One of the important features of this framework is the quantitative evaluation of treatment performance during extreme water quality events for which plant operations may not be prepared. While recognizing the limitations of bench-scale experiments, by performing such simple experiments simulating extreme raw water qualities, an initial indication of the robustness of the critical treatment processes can be obtained, and the raw water conditions in which current treatment procedures might fail can be provisionally assessed. Beyond this point, operational changes can be tested for effectiveness as short-term adaptation options. It takes planning and effort to implement such changes; therefore, having a sense of whether such a measure is useful in advance helps in climate preparedness. Another crucial feature of the framework is the interaction with the plant personnel to understand the nuances of plant operation during normal and extreme weather events. This helped in developing the framework as a practical tool rather than a desktop exercise.

Application of the robustness framework can help a DWTP in developing SOPs for an extreme weather event, which can guide operators in making operational changes in a systematic manner. This can potentially be incorporated into drinking water safety plans which are periodically assessed in Canadian provinces like Alberta.[33] If it is identified that none of the short-term operational changes are successful in treating the WQP to acceptable values, a DWTP may consider long-term options as a part of climate adaptation planning such as infrastructure modifications to increase its treatment robustness.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestwater.2c00627.

> Additional details about the framework application, experiment, TRI theory and calculation, and ORI calculation, including figures and tables (PDF)

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Notes

The authors declare no competing financial interest.

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