Optimized Maintenance Model for Wastewater Treatment Plants

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ABSTRACT

Wastewater treatment plants (WWTPs) are facing significant deterioration due to aging and improper maintenance. Statistics Canada reported that 22% and 14% of the wastewater treatment plants in Alberta and Ontario, respectively, are in poor and very poor conditions. Because of the non-capital and capital improvements' requirements for any WWTP, intervention decision-making tools are paramount. The objectives of this research were to develop an integrated condition rating model for the WWTP and an optimized maintenance, rehabilitation, and replacement (MR&R) intervention model. The condition assessment model was applied on case studies and the indices supplied by the operators were used to compare the results of model through the mean absolute error (MAE) calculation which was minimal. To optimize the intervention decisions for various units of the WWTP, the binary integer programming was used. These models are expected to enhance the evaluation of WWTPs and facilitate intervention plans based on an optimized methodology.

Key words: Asset management, Condition rating, Wastewater treatment plants, Optimized rehabilitation, Infrastructure deterioration

INTRODUCTION

Meeting the increased wastewater treatment demands and compliance with the amplified stringent environmental standards using the equipment, controls, and structures of aging wastewater treatment plants (WWTPs) is currently the largest challenges of municipalities and decision-makers in Canada and the United States (US). Statistics in both countries have shown that WWTPs are prone to deterioration and approaching the end of their service lives (Canadian Water Network [CWN] 2018; Statistics Canada 2018; American Society of Civil Engineers [ASCE] 2017). Ignoring any capital and non-capital improvements and interventions to these assets would result in expedited degradation of their physical and functional states, leading to failure. Statistics Canada (2018) reported that 21.5% and 13.7% of the wastewater treatment plants in Alberta and Ontario, respectively, are in poor and very poor conditions. In the US, the status of publicly-owned sewage treatment facilities had a grade of D+, in which $271-billion would be required to upgrade the facilities and meet local regulations in the next 25 years (ASCE 2017).

Finding feasible and economical maintenance, rehabilitation, and replacement (MR&R) solutions for such aging facilities require reliable methodologies to calculate their conditions. Accordingly, informed decisions can then be deduced to help decision-makers allocate their resources towards the most vulnerable ones. Although WWTP is considered one of the most core assets in North America, the research in this field is still rather limited and does not attract sufficient attention from researchers. Therefore, the main objective of this research was to develop an integrated condition rating model for WWTPs, which could be used as a decision support tool. This tool can later be utilized and extended by decision-makers in developing their short- and long-term MR&R plans. The following sub-objectives were used to achieve the main objective:

1- Design an integrated WWTP condition assessment model by considering the elements' physical states and the treatment's performance; and
2- Develop a model to optimize the MR&R interventions for the WWTPs' infrastructure units.

BACKGROUND

There are no clear or standard methods followed by North American municipalities to manage the WWTPs' infrastructure facilities. A survey conducted by the US Government Accountability Office (GAO 2004) concluded that there is no proper regulation or plan to manage the WWTPs infrastructure facilities. Due to scarce funding resources by some of the North American municipalities, wastewater and water infrastructures maintenance are neglected (Kaddoura and Zayed 2018a; Angkasuwansiri and Sinha 2014; Vanier 2001; US Environmental Protection Agency [EPA] 2002). The US GAO (2004) survey claimed that more than 25% of water and WWTPs infrastructure had shortfalls in constructive of capital asset management plans. Nevertheless, the same study stated that some facility managers had strategies that account for future capital improvement needs; yet, their plans did not consider the essential factors in their assets such as the physical condition assessments. In addition, the survey reported that 65% of the maintenance and rehabilitation action plans were below the requirements to improve the conditions due to lack of funds. Although asset management practices improved over the years, many cities in the US, with a declining population, confront significant obstacles in allocating budgets due to reduced wastewater ratepayers and some political influence (Bipartisan Policy Centre 2017). Given the constraints that would prevent the MR&R interventions, the WWTPs conditions would not attain their required performance.

Disregarding this fact without any immediate condition assessment models followed by optimized intervention decisions could lead to collapse or malfunction of the infrastructure units. Therefore, there is a pressing need to improve the constructed facilities' conditions to maintain the required performance. These plans need informative, accurate, and economical models that evaluate their states. Some field measurements and specialized tests can be conducted to measure the performance or condition of the infrastructure asset. However, these techniques require time and budget, which are constraints for many municipalities. Thus, decision-makers have to seek for the most cost-effective solutions due to the scarcity of resources. One solution is to use decision-making tools to overcome the aforementioned limitation as they clinically allow decisions makers to assess the condition of the assets (Kleiner and Rajani 2001). Broadly, these tools are used after pre-defining certain criteria and metrics along with experts' judgement inputs (Angkasuwansiri and Sinha 2014). To overcome inconsistencies in some of the experts' opinions, the responses should be evaluated to measure based on some metrics (Kaddoura and Zayed 2018b).

These Decision-making tools have been deployed in different infrastructure asset management fields. Their applications were supported by implementations and validations which proved their reliabilities in estimating the performance of infrastructure assets (Kaddoura and Zayed 2018a). In the assessment of wastewater assets, some researchers applied different techniques to evaluate such components. Daher (2015) proposed an assessment of sewer pipelines deploying fuzzy expert system and Evidential Reasoning (ER) methods. The assessment initiated by defining defect groups and sub-groups. Later, the author aggregated the indexes of each defect group and sub-defect group utilizing the Analytical Network Process (ANP). In a similar work, Angkasuwansiri and Sinha (2014) proposed two models that evaluated sewer pipelines employing the weighted factors' method and fuzzy expert system. The authors defined several structural and operational modules that were aggregated to define an overall grade for sewer pipelines. In addition, Kaddoura et al. (2017) proposed a model that assessed linear sewer assets considering four sewer defects. The authors relied on the Multi-Attribute Utility Theory (MAUT) application and some relative weights to suggest an overall grade for sewer pipelines.

In work related to wastewater treatment plants assessment, Zayed et al. (2015) developed a condition-rating index (CRI) model for the WWTP infrastructures. The CRI was developed utilizing an integrated approach of the Analytical Hierarchy Process (AHP) with the MAUT. The authors relied on experts' opinions in defining the attribute values of the factors considered as well as in the calculation of the relative importance weights of each main factor and sub-factor. Their model was able to assess the condition of the essential components of the primary, secondary, and tertiary treatment phases and integrated their conditions in a single index. In another work, Qasem et al. (2009) presented a framework that rated the performance of each treatment phase (primary, secondary and tertiary) based on some proposed equations and the condition index for each phase was calculated. Later, the three indexes were aggregated using relative importance weights.

Previous works pertinent to condition index calculations for facilities were essential as they are considered the main inputs for future decisions related to performance improvements. These improvements can be accomplished by optimized solutions considering single- or multi-objective models subject to one or many constraints. Therefore, many decision-support systems were proposed to assist decision-makers in planning for MR&R activities (Abraham et al. 1998 and Santis et al., 2017). Abraham et al. (1998) proposed an optimization technique for maximizing benefit/cost ratio over a planning horizon and in order to identify appropriate sewer rehabilitation techniques, the deterministic dynamic programming was employed. Yang and Su (2006) suggested a rehabilitation framework that was based on Genetic Algorithm (GA). The authors considered three rehabilitation methods (renovation, excavation replacement and trenchless replacement) and four substitute materials (glassfiber reinforced plastics, reinforced concrete, high density polyethylene and vitrified clay). The main output of the model was achieving longer service life with lower rehabilitation costs. In addition, Ward and Savić (2012) designed a multi-objective optimization model, using the GA method, for sewer rehabilitation. The conflicting objectives, in their methodology, were maximizing the structural condition improvement, reducing construction costs and minimizing critical asset risk of failure. Similarly, the GA was also adopted by Marzouk and Omar (2013) to propose a lifecycle cost analysis for sewers. Their multi-objective optimization problem treated sewer network condition, service life and life-cycle maintenance cost as separate objective functions. The methodology was able to locate appropriate maintenance scenarios considering the conflicting objectives. Additionally, there were multiple rehabilitation and optimization models for infrastructure assets in which interested readers could review (Tagherouit et al. 2011; Hahn et al. 2002; Wright et al. 2006; Goldberg and Kuo 1987; Fenner and Sweeting 1999; Hastak et al. 2004, Gazso et al., 2017, Lee et al., 2017 and Asadi et al., 2017). Lately, Gazso et al., (2017) studied real-time optimization using full-scale wastewater treatment plant simulation. Seungchul et al., (2017) studied the optimization of an integrated wastewater treatment plant with a combined heat and power generation system and Asadi et al., (2017) studied the wastewater treatment aeration process optimization using a data mining approach.

Despite the enormous efforts achieved in optimizing the rehabilitation problems for infrastructures' assets, minimal attention was granted to WWTPs' MR&R decisions. In the available literature, there is a significant scarcity in optimizing WWTP infrastructure units based on their conditions and performance. Based on the literature, several researches were conducted to evaluate either a single process or an equipment in WWTPs, disregarding other essential components. Disregarding this fact could decrease the overall state of the ignored infrastructures and increase corrective actions. In addition, such practices would not aid decision-makers in allocating the required budget to enhance the assets. Therefore, this study aimed at developing an informative condition index that would assist decision-makers in addressing the state of the treatment plants. To better allocate budgets, this study designed an optimized model to select the proper interventions to the infrastructures available in WWTPs.

RESEARCH METHODOLOGY

A simple, practical, and straightforward approach was selected as a research methodology to identify the WWTP infrastructure and operational malfunctions. Fig. 1 shows the flowchart of the research's framework and the steps that were followed, which could summarized as follows: (1) review the literature in many aspects related to the problem in hand; (2) develop a combined condition assessment model for WWTP asset, considering the performance of the three-stage treatments (Qasem et al. 2009) and the condition of the infrastructure units (Zayed et al. 2015), and 4) optimize the MR&R interventions for various units.

[Figure 1 near here]

This study considered the activated sludge wastewater treatment systems because they are among the most widely-used ones in North America (Qasem 2011). In this study, the treatment plant was divided into three phases: primary (PTP), secondary (STP), and tertiary (TTP). In general, the PTP uses certain processes that separate solids from the wastewater and the STP is designed to remove dissolved organic matter. However, the treatments performed in the TTP, are coagulation, flocculation, adsorption, oxidation, electrochemical processes and others for disinfection purposes. Given the complex infrastructures in each process, this study selected the main infrastructure units which were related to tanks, pipes, pumps, and blowers.

INFRASTRUCTURE CONDITION RATING

The infrastructure condition rating index of the WWTP (CRI_{WWTP}) was based on the computed CRI of each infrastructure unit in the three treatment phases. The infrastructure units considered in the treatment phases were pipes, tanks, pumps, and blowers. According to Zayed et al. (2015), the CRI of all infrastructure units (CRI_{INF}) was calculated using predefined factors (e.g. physical, environmental, and operational) and sub-factors along with their preference values using Equation 1.

$$CRI_{INF} = \sum_{i=1}^{n} \sum_{j=1}^{m} w_i v_{ij} Pv_{ij} \qquad (1)$$

Where w_i is the relative importance weight of criteria *i* (environmental, operational, and physical); v_{ij} is the weight of sub-factor *j* (e.g. age) within the i factor (e.g. pipes' physical attribute); and Pv_{ij} is the sub-factor's preference value, which ranges between 1 (critical condition) and 10 (excellent condition). For instance, a pipe that is less than five years old would have a score of 10 (excellent), as per Zayed et al. (2015). For each phase, all the CRI_{INF} were aggregated using the relative importance weights (θ_{kl}) that described the condition of the infrastructure (k) in each phase (l). Accordingly, the condition rating indexes of the primary (CRI_{PTP}), secondary (CRI_{STP}), and tertiary (CRI_{TTP}) phases were computed. The overall representation of the CRI_{WWTP} is expressed in Equation 2.

$$CRI_{WWTP} = \sum_{l}^{p} \varpi_l \sum_{k=1}^{o} \theta_{kl} \sum_{i=1}^{n} \sum_{j=1}^{m} w_i v_{ij} P v_{ij} \quad (2)$$

TREATMENT PERFORMANCE INDEX

The methodology of calculating the performance index was based on Qasem et al. (2009). According to the authors, a treatment performance index (TPI) for each phase was developed by scaling its performance over a (0-10) scale, where 10 representing 100% compliance and (0) as no compliance. As per Equation (3), the TPI_{PTP} was measured based on the sedimentation tank's efficiency in removing the total suspended solids (TSS_{rem}) as well as the partial removal of the five-day Biochemical Oxygen Demand (BOD_{5rem}). Since the scores were associated with the removal efficiencies and based on the methodology's scale convention, lower scores of lower removal efficiencies were used in the computations.

$$TPI_{PTP} = \alpha TSS_{rem} + \beta BOD_{5rem} \quad (3)$$

Equation 4, however, was used to calculate the TPI_{STP}. As this phase is responsible for the biological treatment processes in the WWTP, the equation is a function of soluble organic compounds. In the first tank in this phase, called the reactor, microorganisms oxidize the soluble organic compounds and convert them to solids. Therefore, the TPI would measure the ability of this phase in transferring the soluble organic matter into solids.

$$TPI_{STP} = BOD_{5rem} \beta_1 \gamma_{SVI} \quad (4)$$

Where β_1 is the Mixed Liquor Volatile Suspended Solids (MLVSS)-dependent factor, reflecting the biomass production balance; and γ_{SVI} is a sludge volume index (SVI)-dependent factor.

In the TTP, the disinfection process occurs where the pathogenic microorganisms are destroyed. Therefore, the performance measurement of this phase was based on the total coliform count present in the treated wastewater effluent since such a measurement would reflect the reduction of the pathogenic microorganisms (Decol et al. 2019). Therefore, Equation 5 was used to measure the efficiency of the disinfection phase for the TTP. The performance of this phase is heavily impacted by the medium resulting from the STP. In case the STP produced higher BOD_5, due to operational problems, there is a higher risk of producing disinfection by-products that would decrease the efficiency of the TTP product. Additional insights on the TPI_{TTP} calculations can be found in Qasem et al. (2009).

$$TPI_{TTP} = \omega \left(1 - \frac{\sum_1^{12} vi}{12}\right) x\ 10 \qquad (5)$$

Where ω is the chlorination by-products formation potential reduction factor; vi is a binary variable with a value of [0 or 1]; v = 0 when the colony forming unit (CFU) is less than 25, and the CFU is greater than 25, V = 1.

After calculating the TPI_{PTP}, TPI_{STP}, and TPI_{TTP}, the TPI would be computed by aggregating all these indices through computed relative importance weights suggested by Qasem et al. (2009) as per Equation (6)

$$TP\mathrm{I} = w_p TPI_{PTP} + w_s TPI_{STP} + w_t TPI_{TTP} \qquad (6)$$

Where w_p, w_s, and w_t are the relative weights of PTP, STP, and TTP, respectively.

WWTP INTEGRATED CONDITION

The state of the WWTP's operation and infrastructure was mapped into different management levels by combining the CRI_{WWTP} and TPI indices, as shown in Fig. 2 to compute the WWTP integrated CRI ($WWTP_{INT}$). The score-based matrix shows the rows and the columns representing the CRI_{WWTP} and TPI, respectively. From the figure, the criticality of the WWTP's condition increases as the score values decreases. Since each parameter provides a unitless index, the maximum integrated computed score will be 20 (Equation 7).

$$WWTP_{INT} = CRI_{WWTP} + TPI \quad (7)$$

If the values of the $WWTP_{INT}$ are between 16 and 20, the infrastructure units and treatment performance of the WWTP are classified as excellent. Adversely, if the values are in the range of 2 to 6, the infrastructure and treatment performance of the WWTP are classified as critical. In case other values are concluded, decision-makers can interpret the $WWTP_{INT}$ by performing a backward analysis to determine the parameter that requires more attention (an infrastructure or a treatment process). Through the bottom-up approach, detailed condition rating of each unit and treatment phase can be addressed.

[Figure 2 near here]

OPTIMIZED INTERVENTION MODEL FOR CRI_{WWTP}

Environmental performance and infrastructure needs of WWTP affect its required MR&R actions. In order to increase the treatment performance to the desired level of service (LoS), corrective measures should be defined in order to enhance the WWTP's existing condition and therefore, its performance. These corrective actions can be either operation-related needing operational modifications, infrastructure-related requiring infrastructure upgrades, or can be operation- and infrastructure-related. Each intervention is associated with certain cost along with a condition rating recovery (improvement). Therefore, this research incorporated four different intervention actions: do nothing, maintain, rehabilitate, and replace. Many factors such as the minimum and allowable CRI thresholds, current treatment levels and infrastructure CRIs, and the remaining service life of each WWTP infrastructure unit should be considered by decision-makers in order to select the optimum MR&R for WWTP infrastructures. Additionally, the cost of different MR&R interventions and their condition recovery impacts must be defined by engineers.

In general, lifecycle cost analysis is developed by considering either short- or long-term study periods that will result in capital- and non-capital improvement plans. Such a practice finds the deterioration of the infrastructures during the service lives and optimally selects the intervention actions but will increase the optimization computational efforts and complexity. Therefore, the developed model optimized the selection of an intervention action based on a one-year analysis. The same approach can be further applied by extending the one-year plan to multiple years (time [t] = varies).

This study developed two separate optimization approaches that were constrained by specific predefined criteria (available budget and minimum CRI) as per Fig. 3. The integer programming with binary variables was used to solve the optimization functions for the two problems. The advantage of using this method was that the intervention action variable could be set either 1 or 0 if selected or unselected, respectively. The first optimization approach was to minimize the MR&R intervention costs that was solved by setting a constraint related to a minimum CRI threshold. Due to this constraint, the approach would maintain the CRI of all infrastructures to be either higher than or equal to the designated minimum CRI threshold.

[Figure 3 near here]

By considering the four major intervention categories mentioned earlier, there was only one action that could be applied to a given infrastructure unit. It should be noted that the MR&R action had an effect on the infrastructure unit's future condition rating (CRI_{t+1}). The value of CRI_{t+1} must be either greater than or equal to the current condition rating (CRI_t). The purpose of the first optimization was to minimize the intervention costs of the MR&R that was constrained by the minimum required MR&R budget and the CRI as illustrated in Equation 8.

$$Minimize\ Y = \sum_{p=1}^{l} \sum_{k=1}^{o} \sum_{a=1}^{z} x_{pa}^{k} C_{pa}^{k} \qquad (8)$$

Where x is the decision variable that simulates the intervention action a and this variable can be either 0 (no action) or 1 for (action); C is the cost of an MR&R intervention MR&R action; p is the treatment phase; and Y is the total MR&R intervention cost that must be either less than or equal to the available budget. The constraint associated with the first optimization takes the minimum allowable CRI threshold defined by a decision-maker as shows in Equation 9. This equation is expressed in terms of time (t) and therefore, it takes the deterioration or recovery, of the infrastructure unit, into account.

$$CRI_{l(t+1)}^{k} = CRI_{lt}^{k} + x_{lta}^{k}(I_{la}^{k} * CRI_{lt}^{k}) \geq CRI_{l(min)}^{k} \qquad (9)$$

Where $CRI_{l(t+1)}^{k}$ is the CRI of k infrastructure unit after implementing a certain MR&R action at $t+1$; CRI_{lt}^{k} is the current CRI of k infrastructure unit (before applying any MR&R action); $CRI_{l(min)}^{k}$ is the minimum desired CRI for the infrastructure unit (k); I_{la}^{k} is the percentage improvement or deterioration taken from Table 1. These values were assumed to be consistent for all the infrastructures in all treatment processes. Also, the maximum improvements or deterioration should not exceed or bypass the minimum and maximum conditions of CRI and TPI. According to the table, the "do nothing" option will decrease a pump's CR of 6 at t to 5.7 at t+1. On the contrary, an improvement of the condition will occur when the other options are applied.

[Table 1 near here]

The second optimization approach considered in this study was to maximize the CRI_{WWTP} (Equation 10) through the MR&R performed on the infrastructures within a certain budget (Equation 11).

$$Maximize\ CRI_{WWTP} = \sum_{l}^{p} \varpi_l \sum_{k=1}^{o} \theta_{kl} \sum_{i=1}^{n} \sum_{j=1}^{m} w_i v_{ij} Pv_{ij} \, [1 + x_{la}^{k} \left(I_{la}^{k} * CRI_{la}^{k}\right) \quad (10)$$

Subject to:

$$\sum_{l=1}^{p} \sum_{k=1}^{o} \sum_{a=1}^{z} x_{lpa}^{k} C_{lpa}^{k} \leq Budget \quad (11)$$

The guidelines by Canada's Municipal Affairs (CMMA) were reviewed. In these guidelines, the yearly intervention costs of WWTP infrastructure unit was estimated as a percentage of the replacement cost of the different infrastructure assets of WWTPs. In the guidelines, the intervention cost was calculated using the ratio between the cost of capital replacement and the asset's remaining service life. The average numbers presented by CMMA were used for the optimization model and are shown in Table 2. The costs displayed in the table were based on 2009 rates since the case study and condition used in the following section were received in the same year.

[Table 2 near here]

DATA COLLECTION

Data were collected from three different municipalities in North America; where the USA, Quebec and Ontario's WWTPs were referred as PU, SQ and HO, respectively. The names were kept confidential based on the providers' requests. The PU WWTP receives an average daily flow rate of 171, 000 cubic meters. After treating the effluent, the medium is discharged into the Miami River. The PU WWTP utilizes a conventional activated sludge system with a chlorine disinfection infrastructure. The SQ WWTP, however, receives an average daily flow rate of approximately 49,500 cubic meters from both industrial and domestic resources. Before dumping the treated effluent into the river, the SQ WWTP uses a conventional activated sludge system. The HO WWTP is considered one of the largest WWTP in Ontario as it receives approximately 500,000 cubic meters a day. Similar to the previous WWTPs, this treatment plant utilizes the conventional activated sludge system in the chlorination phase.

These three WWTPs were significant in the application of the proposed integrated model. The collected data involved several inputs required to compute the $WWTP_{INT}$ for the three plants. As the providers did not have records of several condition ratings, they provided general indices that would describe their WWTP, including the TPI_{PTP}, TPI_{STP}, TPI_{TTP}, TPI, and CRI_{WWTP} as per Table 3. According to the table, the operators provided higher ratings for most of their treatment processes. A condition of "0" was given to the SQ WWTP's TPI_{TTP} as this plant disposes its treated effluent into the rivers without any disinfection. The conditions provided in the table were used as a benchmark to compare the outcomes of the model with the operators' judgements.

[Table 3 near here]

Nevertheless, the detailed maintenance and other intervention actions were difficult to obtain due to the scarcity of the information. Generally, all three WWTP adopted age-based and visual inspection methodologies to plan for intervention actions.

MODEL IMPLEMENTATION AND FINDINGS

$WWTP_{INT}$ Model

The $WWTP_{INT}$ condition index was calculated using the models developed earlier by Zayed et al. (2015) and Qasem et al. (2009). Later, the outcomes of the two models were combined for each WWTP. The results of the $WWTP_{INT}$ findings are shown in Table 4.

[Table 4 near here]

The matrix, shown in Fig. 2, was used to interpret the concluded indices. Based on the matrix, the HO WWTP had an "excellent" CRI_{WWTP} and TPI and the PU WWTP had a "very good" CRI_{WWTP} and TPI. However, the SQ WWTP had a lower $WWTP_{INT}$ due to missing disinfection phase. Subsequently, the computed $WWTP_{INT}$ results were shared with each WWTP operators in order to receive their feedback.

The proposed methodology highlighted important operational factors in both PU WWTP and HO WWTP and was discussed with the decision-makers who accepted the results and the evaluation criteria. Nevertheless, the operators of the SQ WWTP expected a higher $WWTP_{INT}$ as they believed that the treatment plant was performing as expected. After performing a backward analysis using the model's methodology, the operators realized that the resulting low $WWTP_{INT}$ rate was because of the missing disinfection phase in the PTP and STP. Further, the method was supported by the officials since the causes of the operational problems were shared by the authors and identified by the operators during the early phases of this study. The proposed methodology helped the decision-makers to address not only the vital operational malfunctions but also the future needs of the WWTP. Since the implemented data was collected in 2009, these findings coincided with the study accomplished by the Comité des Citoyens et Citoyennes Pour La Protection de L'nvironnement Maskoutain (CCCPEM) (2009). It was concluded by all operators that the developed methodology could confidently be used to support their upgrading plans and the strategic developments.

Although this study collected three samples of the WWTP along with the expert-based condition indices, the Mean Absolute Error (MAE), in Equation 12, was used to compare the $WWTP_{INT}$ results. In general, closer MAE values to zero signify accurate results with minimal errors. The equation is based on three variables, which are the actual (C), estimated (E), and the number of samples (s) implemented.

$$MAE = \frac{\sum_{i=1}^{n} |C_i - E_i|}{s} \tag{12}$$

The values of the TPI and CRI_{WWTP}, supplied by the experts, were aggregated and used as C values of the $WWTP_{INT}$; however, *E* was considered to be the results computed using the proposed model; *s*, in this case, was three which represented the number of the WWTPs. The calculated MAE was 2.67 due to the difference between the results calculated and predicted by the experts in the SQ WWTP. However, to deduce robust conclusions regarding the developed model, accurate condition data and larger samples would be required.

CRI_{WWTP} Optimized Intervention Models

The MR&R interventions (do nothing, maintain, rehabilitate, and replace) for each infrastructure unit in the three treatment phases were used in the developed optimization model. A specific condition recovery effect and a cost for each intervention were identified as indicated previously in Table 1 and Table 2, respectively. Only one MR&R intervention for any infrastructure unit was allowed in each treatment phase. In the first optimization problem, the objective function to be optimized was to minimize the cost of MR&R interventions, given a minimum acceptable CRI_{INF}.

The MR&R decision variables considered were in the form of x_{la}^{k}. Therefore, for the primary treatment process, the decision variables of the tanks were x_{11}^{1} or x_{12}^{1} or x_{13}^{1} or x_{14}^{1}; x_{11}^{2} or x_{12}^{2} or x_{13}^{2} or x_{14}^{2} for the pipes; and x_{11}^{3} or x_{12}^{3} or x_{13}^{3} or x_{14}^{3} for the pumps. Each decision variable could only be assigned once annually for each infrastructure unit in each treatment phase.

Only one of the MR&R decision variables was set to 1 for tanks, pumps and pipes', while all the other variables were set to 0. By repeating the optimization options for the STP and PTP, a total of 44 decision variables would be obtained as listed in Table 5, Table 6, and Table 7.

[Table 5,6, and 7 near here]

In order to calculate the decision variables for each infrastructure unit in each treatment phase, the costs displayed in Table 2 were incorporated. Equations 13-15 show the examples of the primary treatment's infrastructure units in which the decision variables could be determined. As one intervention action was allowed for each infrastructure unit in this optimization, each equation was constrained as indicated below.

$PTP\_tank = 0 * x_{11}^{1} + 90{,}000 * x_{12}^{1} + 200{,}000 * x_{13}^{1} + 900{,}000 * x_{14}^{1};\ \sum_{a=1}^{z} x_{1a}^{1} \leq 1$

(13)

$PTP\_pipe = 0 * x_{11}^{2} + 2{,}700 * x_{12}^{2} + 25{,}000 * x_{13}^{2} + 40{,}000 * x_{14}^{2};\ \sum_{a=1}^{z} x_{1a}^{2} \leq 1$

(14)

$PTP\_pump = 0 * x_{11}^{3} + 8{,}000 * x_{12}^{3} + 25{,}000 * x_{13}^{3} + 40{,}000 * x_{14}^{3};\ \sum_{a=1}^{z} x_{1a}^{3} \leq 1$

(15)

where *PTP_tank*, *PTP_pipe*, *PTP_pump* are the PTP intervention costs for the tanks, pipes and pumps, respectively. The same approach was implemented to determine the MR&R costs for the STP and TTP.

Minimize MR&R Intervention Costs (Y)

In this case, the minimum allowable condition rating was a constraint for all infrastructure units in all three treatment phases. As the main purpose was to minimize the costs, all variables tended to be "0" and the variable with the least cost would tend to be "1" to satisfy the objective function. After comparing the cost of interventions, the model was forced to select the second lowest cost at all times; thus, satisfying the constraint and the lowest cost requirements. For each infrastructure unit, the objective function was affected by the minimum desired condition rating but used the MR&R intervention with the most economical cost. This means that the lower the minimum allowable condition rating, the lower the MR&R cost, as long as it met the minimum allowable level. When using the integer programming technique with binary variables, the minimum desired value of the CRI and the intervention cost were adjusted to overcome infeasible solutions as illustrated in the MR&R decisions for the HO WWTP. If the CRI was greater or equal to 7.0 for all infrastructure units of HO WWTP, the MR&R cost would be $368,100. This was due to the different MR&R interventions that were applied over different infrastructures, as presented in Table 8. The optimized MR&R decisions clearly showed that, in order to increase the condition of any infrastructure asset, the regular maintenance was needed with the minimum cost. For example, in order to increase the score of the PTP sedimentation tank's condition from 6.7 to 7.4, the MR&R cost for the PTP would be $90,000. A similar MR&R action was chosen for the pipes which raised the CRI from 7.1 to 7.8 but without any action for the PTP tank. Since the "do nothing" option resulted in degrading the asset, the tank's condition dropped to 7.9. However, minimal changes to the CRI_{STP} occurred after performing the interventions. In general, the HO CRI_{WWTP} increased from 7.4 to 7.8.

[Table 8 near here]

A similar approach was also performed by considering a minimum threshold of 6.0, and the results are shown in Table 9. The minimum CRIs of different infrastructure units in the WWTP highly influenced the MR&R selections. Since "do nothing" option was the optimum solution to minimize the MR&R cost and if the condition ratings of all infrastructure units were allowed to be as low as 6.0, the MR&R cost would be zero for the HO WWTP. Although the "do nothing" option reduced the infrastructure units' conditions, they would still be above the desired threshold level of 6.0.

[Table 9 near here]

Maximize CRI_{WWTP}

The second optimization approach was to maximize the CRI_{WWTP} within an available MR&R budget. The constraints for this objective function were the minimum allowable condition. The MR&R budget would be the first allocated to the most important infrastructure units. In order to illustrate this optimization approach, the data from HO WWTP were used. Before applying the optimization model the current condition rating, the cost of different MR&R interventions and their condition recovery effects must be identified, similar to the first approach.

Keeping all infrastructure units' CRI greater than or equal to 6.0 and keeping an MR&R budget of $100,000, the first optimization option was performed to maximize the CRI_{INF}. Table 10 shows all MR&R decisions associated with this optimization option. From the table, the optimization resulted in a cost of $99,700 that would be used to upgrade the CRI_{INF} of the HO WWTP from 7.4 to 9.0; where the enhanced CRI_{PTP}, CRI_{STP}, and CRI_{TTP} were 8.4, 9.3 and 8.7, respectively.

[Table 10 near here]

The same objective function was utilized but with a lower budget of $50,000 and a minimum desired CRI value of 6.0 As shown in Table 11, the CRI_{INF} improved to 8.2 from 7.4. Based on the two trials, the higher the budget, the better was the improved condition for multiple components in the three phases. However, the cost of these improvements would cost double.

[Table 11 near here]

Discussion

In the first objective function, the optimization model selected the optimized MR&R interventions and based on the minimum incurred costs. There were 4,194,304 different MR&R actions on all infrastructure units for each WWTP. This optimization approach considered the deterioration of each infrastructure unit and the intervention with the lowest costs that would keep the CRI_{INF} above the minimum condition threshold. By restraining the CRI at 7.0 for each infrastructure unit, the optimization model selected the "do nothing" and "maintain" decision variables to keep the costs minimized and in the same time satisfying the minimum requirements. By reducing the CRI requirements for each infrastructure at 6.0, all decisions were "do nothing" for the same WWTP. The one index difference between the two approaches would save the decision-makers $368,100, as per Fig. 4.

Considering the second optimization approach, which aimed at maximizing the CRI_{INF}, the model tended to consider the decision variables that would drastically improve the CRI_{INF} subject to the maximum allowable budget. After running the tool on the HO WWTP and considering a maximum budget of $100,000, the decision variables that enhanced the CRI_{WWTP} were selected and allocated on the most important infrastructure units (based on the relative importance weights). Among all decision variables selected, one replacement and two rehabilitations were considered. These two decisions had a significant impact when calculating the CRI_{INF}. With a maximum budget of $100,000, the decision-maker could enhance the CRI_{INF} to 9.0 with a total budget of $99,700, as shown in Fig. 4. After decreasing the maximum allowable budget to 50,000, one rehabilitation option was selected and the rest were the "do nothing" and "maintain" options with a total incurred cost equal to $49,000. As the main objective of this second optimization was to maximize the CRI_{INF}, the total incurred cost would mostly be close to the maximum allowable budgets.

Although the discussed optimization models solved two separate objective functions, it would still aid decision-makers in justifying their demands of budgets to enhance the existing built WWTPs. In general and due to budget constraints, many of the decision-makers would tend to minimize the incurred costs while keeping the minimum requirements as per the regulations Tee et al. (2014). Based on Fig. 4, the second approach (maximizing the CRI) produced better results as it enhanced the CRI_{INF} with lower costs when compared with the first approach (minimizing the costs). Since the main objective of the first approach was to minimize the costs subject to a predefined CRI, the tool explored the decision variables that would change the CRI equal to or greater than the CRI threshold. Therefore, the most selected decision variable was "maintain". However, the second approach explored the decision variables that would maximize the CRI given a predefined budget. Thus, it can be observed that the decision variables varied and the overall computations surpassed the first optimization approach. In case decision-makers were concerned with the existing conditions and would require increasing the current LoS, the second optimization approach would be recommended for utilization.

Although the optimization tool was implemented on all three treatment phases, this model can further be applied to optimize each phase separately. Therefore, the MR&R possibilities would be 4^3, 4^5 and 4^3. In this case, the CRI of each treatment phase would rely solely on its infrastructure units. As the CRI of each treatment phase would be calculated based on the relative importance weights, the most significant assets would be prioritized for interventions.

[Fig. 4 near here]

CONCLUSIONS

WWTPs are considered one of the main critical and core assets in North America. Therefore, it is significant to maintain their functionality to treat wastewater. Due to aging and other influencing factors, these assets are prone to deterioration. Knowing their conditions is essential to plan ahead for interventions. In this study, the $WWTP_{INT}$ index was calculated and interpreted for the WWTPs. The combined index was computed considering the CRI_{WWTP} and TPI. The CRI_{WWTP} studied the infrastructure conditions while the TPI considered the three treatments performance. The developed model was applied on three WWTPs and based on the results, the SQ WWTP condition was 9.0, referring to a “critical” performance due to missing disinfection phase. However, the PU WWTP condition was 15, describing a “very good” infrastructure condition and a treatment performance and the HO WWTP grade was 17, suggesting an “excellent” condition for both infrastructure and treatment performance. After comparing the conditions provided by the operators with the estimated ones, the errors were minimal as per the MAE value (2.67).

In addition, the research developed a binary integer optimization tool for the MR&R options for the three WWTPs. Four different options were considered: do nothing, maintain, rehabilitate and replace. Considering the most significant assets in the three treatment phases, 44 decision variables were investigated. The first optimization option, in which the MR&R decisions were highly affected by the minimum condition ratings, was to minimize the MR&R costs. However, the second optimization approach was to maximize the CRI within an available MR&R budget. Upon sharing the results with the decision-makers, it was believed the developed rating and optimization models can confidently be used to provide the appropriate decisions to justify and modify asset management plans.

This model can be further extended by applying a multi-objective evolutionary-based optimization model that would solve the non-linear deterioration of the infrastructure units. Despite the near optimum solutions these models will produce, complex problems can be solved considering short- and long-term lifecycle analysis. Additionally, it would be necessary to apply this model on a larger sample to conclude the accuracy of the proposed condition assessment model.

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Table 1. MR&R Intervention and CRI Recovery Effects

MR&R Intervention	I_{Tank}	I_{Pipes}	$I_{Pumps\ and\ Blowers}$
Do nothing	-1%	- 2%	-5%
Maintain	+10%	+10%	+15%
Rehabilitate	+60%	+40%	+50 %
Replace	+100 %	+100%	+100 %

Table 2. WWTP MR&R Cost Estimates

Infrastructure Units	Replacement Cost ($)	Annual Maintenance Cost ($)	Rehabilitation Cost ($)
Cast Iron Pipes	40,000 $ *	2,700	25,000
Tanks	900,000 $	90,000	200,000
Pumps	40,000 $	8,000	25,000
Blowers	40,000 $	8,000	25,000

*Based on 400$/m assuming 100 m

Table 3. Experts-based Conditions

WWTP	**TPI_{PTP}**	**TPI_{STP}**	**TPI_{TTP}**	**TPI**	**CRI_{WWTP}**	**$WWTP_{INT}$**
HO	9	9	9	9	8	17
PU	8	8	9	8	9	17
SQ	8	9	0	8	7	15

Table 4. The Calculated $WWTP_{INT}$ for the Studied WWTPs

WWTP	**TPI**	**CRI_{WWTP}**	**$WWTP_{INT}$ (Rounded up)**
HO	9	8	17
PU	7	8	15
SQ	4	5	9

Table 5**.** MR&R Intervention Variables for the PTP

MR&R Intervention	**PTP (*l*=1)**		
	Tanks (*k*=1) CRI$_{t+1}$	**Pipes (*k*=2) CRI$_{t+1}$**	**Pumps (*k*=4) CRI$_{t+1}$**
Do nothing (*a*=1)	x_{11}^{1}	x_{11}^{2}	x_{11}^{3}
Maintain (*a*=2)	x_{12}^{1}	x_{12}^{2}	x_{12}^{3}
Rehabilitate (*a*=3)	x_{13}^{1}	x_{13}^{2}	x_{13}^{3}
Replace (*a*=4)	x_{14}^{1}	x_{14}^{2}	x_{14}^{3}

Table 6. MR&R Intervention Variables for the STP

MR&R Intervention	**STP (*l*=2)**				
	Tanks (*k*=1) CRI$_{t+1}$	**Reactor (*k*=2) CRI$_{t+1}$**	**Pipes (*k*=3) CRI$_{t+1}$**	**Pumps (*k*=4) CRI$_{t+1}$**	**Blower (*k*=5) CRI$_{t+1}$**
Do nothing (*a*=1)	x_{21}^{1}	x_{21}^{2}	x_{21}^{3}	x_{21}^{4}	x_{21}^{5}
Maintain (*a*=2)	x_{22}^{1}	x_{22}^{2}	x_{22}^{3}	x_{22}^{4}	x_{22}^{5}
Rehabilitate (*a*=3)	x_{23}^{1}	x_{23}^{2}	x_{23}^{3}	x_{23}^{4}	x_{23}^{5}
Replace (*a*=4)	x_{24}^{1}	x_{24}^{2}	x_{24}^{3}	x_{24}^{4}	x_{24}^{5}

Table 7. MR&R Intervention Variables for the TTP

MR&R Intervention	**TTP (*l*=3)**		
	Tanks (*k*=1) CRI$_{t+1}$	**Pipes (*k*=2) CRI$_{t+1}$**	**Pumps (*k*=3) CRI$_{t+1}$**
Do nothing (*a*=1)	x_{31}^{1}	x_{31}^{2}	x_{31}^{3}
Maintain (*a*=2)	x_{32}^{1}	x_{32}^{2}	x_{32}^{3}
Rehabilitate (*a*=3)	x_{33}^{1}	x_{33}^{2}	x_{33}^{3}
Replace (*a*=4)	x_{34}^{1}	x_{34}^{2}	x_{34}^{3}

Table 8. MR&R Decisions for HO WWTP for a Minimum CRI Value of 7.0

Treatment Phase	Infrastructure Unit	CRI_t	Min CRI	MR&R Selected	MR&R Cost ($)	CRI_{t+1}
PTP	Tank	6.7	7.0	Maintain	90,000	7.4
	Pipes	7.1	7.0	Maintain	2,700	7.8
	Pump	8.3	7.0	Do nothing	0	7.9
	CRI_{PTP}	7.6				7.7
STP	Tank	6.9	7.0	Maintain	90,000	7.6
	Reactor	6.9	7.0	Maintain	90,000	7.6
	Pipes	6.5	7.0	Maintain	2,700	7.2
	Pump	8.6	7.0	Do nothing	0	8.2
	Reactor Blower	8.4	7.0	Do nothing	0	8.0
	CRI_{STP}	7.8				7.8
TTP	Tank	6.6	7.0	Maintain	90,000	7.3
	Pipes	6.5	7.0	Maintain	2,700	7.2
	Pump	8.6	7.0	Do nothing	0	8.2
	CRI_{TTP}	7.4				7.6
	CRI_{INF}	7.4				7.8
Budget					368,100	

Table 9. MR&R Decisions for HO WWTP for a Minimum CRI Value of 6.0

Treatment Phase	Infrastructure Unit	CRI_t	Min CRI	MR&R Selected	MR&R Cost ($)	CRI_{t+1}
PTP	Tank	6.7	6.0	Do nothing	0	6.6
	Pipes	7.1	6.0	Do nothing	0	7.0
	Pump	8.3	6.0	Do nothing	0	7.9
	CRI_{PTP}	7.6	6.0			7.4
STP	Tank	6.9	6.0	Do nothing	0	6.8
	Reactor	6.9	6.0	Do nothing	0	6.8
	Pipes	6.5	6.0	Do nothing	0	6.4
	Pump	8.6	6.0	Do nothing	0	8.2
	Reactor Blower	8.4	6.0	Do nothing	0	8.0
	CRI_{STP}	7.8	6.0			7.5
TTP	Tank	6.6	6.0	Do nothing	0	6.5
	Pipes	6.5	6.0	Do nothing	0	6.4
	Pump	8.6	6.0	Do nothing	0	8.2
	CRI_{TTP}	7.4	6.0		0	7.2
	CRI_{INF}	7.4	6.0			7.4
Budget					0	

Table 10. MR&R Decisions for HO WWTP for a Budget of $100,000

Treatment Phase	Infrastructure unit	CRI_t	Min CRI	MR&R Selected	MR&R Cost ($)	CRI_{t+1}
PTP	Tank	6.7	6.0	Do nothing	0	6.6
	Pipes	7.1	6.0	Maintain	2,700	7.8
	Pump	8.3	6.0	Maintain	8,000	9.6
	CRI_{PTP}	7.6	6.0			8.4
STP	Tank	6.9	6.0	Do nothing	0	6.8
	Reactor	6.9	6.0	Do nothing	0	6.8
	Pipes	6.5	6.0	Replace	40,000	10.0
	Pump	8.6	6.0	Maintain	8,000	9.9
	Reactor Blower	8.4	6.0	Maintain	8,000	9.7
	CRI_{STP}	7.8	6.0			9.3
TTP	Tank	6.6	6.0	Do nothing	0	6.5
	Pipes	6.5	6.0	Rehabilitate	25,000	9.1
	Pump	8.6	6.0	Maintain	8,000	9.9
	CRI_{TTP}	7.4	6.0			8.7
	CRI_{INF}	7.4	6.0			9.0
Budget					99,700	

Table 11. MR&R Decisions for HO WWTP for a Budget of $50,000

Treatment Phase	**Infrastructure unit**	**CRI_t**	**Min CRI**	**MR&R Selected**	**MR&R Cost ($)**	**CRI_{t+1}**
PTP	Tank	6.7	6.0	Do nothing	0	6.6
	Pipes	7.1	6.0	Do nothing	0	7.0
	Pump	8.3	6.0	Do nothing	0	7.9
	CRI_{PTP}	7.6	6.0			7.4
STP	Tank	6.9	6.0	Do nothing	0	6.8
	Reactor	6.9	6.0	Do nothing	0	6.8
	Pipes	6.5	6.0	Rehabilitate	25,000	9.1
	Pump	8.6	6.0	Maintain	8,000	9.9
	Reactor Blower	8.4	6.0	Maintain	8,000	9.7
	CRI_{STP}	7.79	6.0			9.1
TTP	Tank	6.6	6.0	Do nothing	0	6.5
	Pipes	6.5	6.0	Do nothing	0	6.4
	Pump	8.6	6.0	Maintain	8,000	9.9
	CRI_{TTP}	7.432	6.0			8.3
	CRI_{INF}	7.372	6.0			8.6
Budget					49,000	