*Int. J. Environ. Res., 9(1):1-8,Winter 2015*
*ISSN: 1735-6865*

# An Efficiency-Centred Hierarchical Method to Assess Performance of Wastewater Treatment Plants

**Chen, Z.*, Zayed, T. and Qasem, A.**

[1]Department of Building, Civil, and Environmental Engineering, Concordia University, Montreal, Quebec,Canada H3G 1M8

Received 12 March 2014; Revised 26 Aug. 2014; Accepted 18 Oct. 2014

**ABSTRACT:** An efficiency-centred hierarchical model is developed to assess the performance of wastewater treatment plants (WWTPs). Specifically, a new treatment performance index (TPI) has been proposed to determine the overall treatment performance of WWTP by analysing the TPI values and the weights of individual treatment phase for overall treatment performance. Three modules have been developed to examine the performance of the primary, secondary, and tertiary treatment units of a WWTP. The model is applied to three WWTPs with different scale, loading rate, capacity, and process phases. The case study results indicate that the developed tool is useful in assessing the WWTP system in terms of treatment efficiency, operating conditions, and cost-effectiveness of its management schemes. The model can be also combined with an infrastructure condition rating index model to form a condition rating model for a WWTP, and used as a cost-effective tool to evaluate current and future needs in operation and management.

**Key words:** Condition rating, Infrastructure, Model, Performance index, Wastewater treatment

## INTRODUCTION

Wastewater treatment plants (WWTPs) are the major infrastructure important to safeguard the environment and human facilities. They have the highest age among other infrastructure facilities, followed by bridges and overpasses (Gagnon *et al.*, 2008), and ageing facilities are failing prematurely and need costly rehabilitation and maintenance plans (Vanier and Danylo, 2003). Hence, finding feasible and economical solutions for performance evaluation is important to maintain, rehabilitate, or replace aging WWTPs, in addition to locating innovative technologies for cost-effective rehabilitation (Guild, 2000). However, evaluating processes in a full-scale WWTP is a difficult task. Although several evaluation approaches are available, they are tend to be based on narrow assessment and inadequate neglecting the overall adverse effects on the environment (Puig *et al.*, 2010).

A performance index is part of a necessary decision making model for the design and operation of water treatment system (Olsson and Newell, 1999), and integrated performance index is a valuable tool for the design and operation of WWTPs (Matos *et al.*, 2004). Several performance index models and criteria have been proposed previously as a tool for comparison of plant design and operation performance of WWTP. European Cooperation in the field of Scientific and Technical Research (COST) benchmark protocol (Copp, 2002) have been used for large number of studies (e.g. Vanrolleghem and Gillot, 2002; Pons and Corriou, 2002) due to its ability to compare different control strategies (Ingildsen, 2002). However, the results from the benchmark model are not directly transferable to a full scale plant working under different situation (Abusam *et al.*, 2002). Vanrolleghem and Gillot (2001) attempted to solve this problem by proposing the robustness index that allows transferability of control strategy evaluation results to situations different than typical conditions. The flexibility index model was proposed by Hopkins et al. (2001) to compare continuous and batch activated sludge plant design and operation performance. Many simulation tools and software are also available to predict or evaluate the system performance of WWTPs. For instance, the benchmark simulation model no. 1 (BSM1) can simulate a five-reactor activated sludge plant configuration with a non-reactive secondary

*Corresponding author E-mail: zhichen@alcor.concordia.ca

clarifier, However, evaluation is performed using only an effluent quality index (a weighted sum of effluent TSS, COD, BOD, TKN and nitrate) (Jeppsson *et al.*, 2006). Such simple evaluation using a removal efficiency based on the concentration difference between inflow and outflow may not be considered as a proper model to evaluate overall performance of a WWTP (Puig *et al.*, 2010).

The evaluation of overall treatment performance of WWTP has become drastically difficult as the complexity of combinations of unit processes has been increased to meet the demanding environmental standards for WWTPs. Also, most treatment performance index model only considers the single-sludge continuous-flow activated sludge process rather than enlarged plant layout and phases involving all aspects of a plant including primary sedimentation, sludge thickening, sludge dewatering, flow equalisation and anaerobic digestion processes (Jeppsson and Pons, 2004). The complex interactions among the processes in a WWTP should be evaluated considering a WWTP as a single unit. Otherwise, sub-optimisation will be an unavoidable outcome leading to reduced effluent quality and/or higher operational costs (Jeppsson *et al.*, 2006). Hence, it is required to develop a comprehensive treatment performance index model that can include the critical processes in WWTPs to evaluate the system performance using broader criteria that just effluent concentrations.

The objective of the present study is to identify and study the different factors that affect the treatment performance of each phase in WWTPs. The identified factors are adopted to develop a treatment performance index model to quantify the overall treatment performance of WWTPs considering the various treatment phases of WWTP. Finally, the model is applied to a case study to demonstrate the accuracy and effectiveness of the model. The developed index model aims to provide decision makers and plant operators with a management tool to assess and evaluate the capabilities of their WWTPs, and also to help them to identify current and future operation and rehabilitation needs.

## MATERIALS & METHODS

The overall treatment performance of a WWTP can be assessed based on the performance of individual treatment of phase. Hence, it is critical to determine proper parameters to assess the treatment performance of each treatment phase. As shown in Figure 1, typical wastewater treatment system for WWTPs has three treatment phases (AWC, 2008; USEPA, 2004): primary treatment phase for solids removal from wastewater using settling, flotation, and sedimentation; secondary treatment phase for biological treatment using microorganisms; and tertiary treatment phase for disinfection. The treatment performance of each phase is assessed using a treatment performance index (TPI) developed to measure its treatment efficiency and the robustness of its treatment indicators. The treatment performance of the entire WWTP is determined by integrating the condition ratings of its three treatment phases (Fig. 1). The proposed model in this study determines the treatment performance of WWTPs by measuring the compliance of each phase against its treatment requirements. A treatment performance index (TPI) for each treatment phase is developed by scaling its performance over a 0 - 10 scale, with 10 representing 100 % compliance and 0 for no compliance. The developed TPI equations also include reduction factors to lower the TPI score if any essential treatment indicator is out of the acceptable range. This approach it to draw the operator's attention to possible causes of current or future treatment problems ahead of time and provide the required time to fix problems before they severely affect performance. Finally, the overall treatment performance of a WWTP is evaluated summing TPI values of each phase considering the weight of each phase on overall performance determined using the analytic hierarchy process (AHP) technique. The primary treatment phase (PTP) in a WWTP pertains to the removal of bulky suspended solids that settled by gravity with a specific time. Although this phase incorporates other treatment units, the primary sedimentation tank remains the main unit. The key concern here is the removal of the total suspended solids (TSS). The sedimentation tanks remove more than 35% of the influent Biochemical Oxygen Demand ($BOD_5$) (Warren, 2009). Therefore, treatment performance index of the primary treatment phase $TPI_{PTP}$ is developed to measure the TSS removal efficiency and the partial removal of $BOD_5$, as Equation 1.

$$TPI_{PTP} = \alpha\, TSS_{rem} + \beta\, BOD_{5rem} \qquad (1)$$

where $TSS_{rem}$ is the total suspended solids removal efficiency, $BOD_{5rem}$ is the BOD removal efficiency (based on the 35% portion only), $\alpha$ is a constant representing the weight of TSS removal in the primary phase, and $\beta$ is a constant representing the weight of the $BOD_5$ removal in the primary phase. $\alpha$ and $\beta$ depend on the WWTP's design and the expected performance of the primary treatment phase. For the typical activated sludge system used in this study, the main function of the primary treatment phase is to remove the suspended solids, not the BOD, from the treated wastewater influent. $\alpha$ is to be larger than 0.6 and the sum of $\alpha$ and $\beta$ is to be 1.0. The recommended values by wastewater treatment experts for $\alpha$ and $\beta$ are 0.7 and 0.3, respectively, as BOD is mainly removed in the secondary treatment phase (Viessman and Hammer, 2005). The proposed $TPI_{PTP}$ in this phase is used as a treatment performance

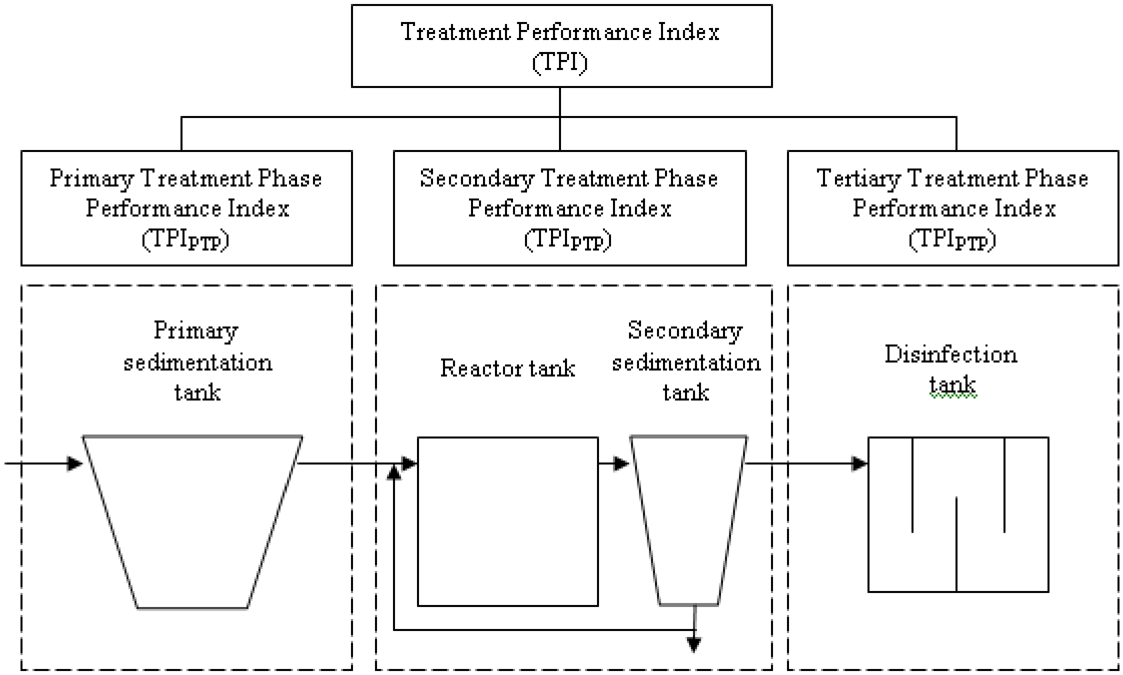


**Fig. 1. Treatment Performance Index (TPI) for a WWTP with three treatment phases**

indicator showing the TSS removal efficiency level. Many chemical, hydraulic and physical factors affect the TSS removal efficiency including influent flow rates, tank's hydraulic retention time, and PH.

The secondary treatment phase considered in this study is the activated sludge system which is responsible for biological treatment processes in the WWTP. It consists of a two-tank system illustrated in a schematic diagram in Figure 1. In the first tank, called the reactor, microorganisms oxidize soluble organic compounds converting soluble organic matter ($BOD_5$) into suspended and settleable solids (new microorganisms). To maintain a stable, continuous process, oxygen and other nutrients must be provided to the microorganisms. The amount of required oxygen is determined based on the Food/Microorganism (F/M) ratio and the food utilization rate. The microorganisms produced in the first tank settle in the secondary sedimentation tank that is the second tank (Figure 1). The required amount of microorganisms for biological oxidation in the reactor is assessed and returned from the secondary sedimentation tank to the reactor, and the excess is disposed. Two key indicators of the robustness of the treatment process and its performance chosen for this study are: Mixed Liquor Volatile Suspended Solids (MLVSS) and Sludge Volume Index (SVI). Using the MLVSS, the bio-oxidation process in the reactor and secondary sedimentation tank is evaluated. The MLVSS concentrations in the reactor tank typically range from 2500 mg/L to 3500 mg/L, and the values in the secondary sedimentation tank are ten times the values in the reactor. The value of SVI reflects the robustness of biological treatment and indicate possible problems such as presence of filamentous bacteria, sludge rising and sludge buckling. The SVI value between 100 ml/g and 150 ml/g indicates good settling of suspended solids (Zhang *et al.*, 2006). The TPI of the secondary treatment phase ($TPI_{STP}$) is determined mainly based on the influent $BOD_5$ removal efficiency as shown in Equation 2. In Equation 2, two reduction factors, $\gamma_{SVI}$ and $\beta_1$, are used to reflect the impact of SVI, MLVSS and ($MLVSS_s$)/$MLVSS_R$ ratios. Here, the subscripts S and R stand for the secondary sedimentation tank and the reactor.

$$TPI_{STP} = BOD_{5REM} \bullet \beta_1 \bullet \gamma_{SVI} \quad (2)$$

where $BOD_{5REM}$ is the BOD removal efficiency of the secondary phase, $\gamma_{SVI}$ is a sludge volume index (SVI) dependent factor that reflects sludge settleability (Giokas *et al.*, 2003), and $\beta_1$ is an MLVSS dependent factor.

$\beta_1$ is determined using Equation 3 to reflect the biomass production balance in the reactor.

In the tertiary treatment phase, pathogenic microorganisms present in the treated wastewater are destroyed. However, if a significant amount of organic compounds reaches this phase, a reaction with chlorine could produce harmful and carcinogenic disinfection by-products. This issue can be minimized through high $BOD_5$ removal efficiency in the secondary treatment. The proposed TPI for the disinfection phase reflects disinfection efficiency and the generation of hazardous by-products, as illustrated in Fig. 1.

$$\beta_1 = \begin{cases} 1 & \text{for } MLVSS_S / MLVSS_R \quad 5 \\ (MLVSS_S / MLVSS_R)/5 & \text{for } MLVSS_S / MLVSS_R \gtrless 5 \end{cases} \qquad (3)$$

Disinfection efficiency is measured by the total coliform count present in the treated wastewater effluent. The total coliform count must not exceed the standard coliform forming unit number (CFU), which is d┐ 25.00 per 100 ml for general-use treated effluent. High organic matter concentrations in the chlorination basin are associated with a high formation of harmful disinfection by-products which have a dangerous, adverse impact on health and the environment. Hence, the treatment performance index for the tertiary treatment phase ($TPI_{TTP}$) is determined based on the number of coliform count number violations per month for the disinfected effluent as per the environmental regulations of Ontario's ministry of environment using Equation 4:

$$TPI_{TTP} = \omega\left(1 - \frac{\sum_1^{12} vi}{12}\right) x10 \qquad (4)$$

where ω is the chlorination by-products formation potential reduction factor, and *vi* is a binary variable with a value of 0 or 1 for coliform forming unit number (CFU) less or greater than 25, respectively. The values of ω depend on the $BOD_5$ of the effluent from the secondary treatment phase: the higher the $BOD_5$, the higher the risk of disinfection by-products formation. ω values assigned for $BOD_5$ values are provided in Qasem (2011). The treatment performance index of the whole WWTP is determined using the weighted sum of the of the treatment performances of the three treatment phases as illustrated in Equation 5.

$$TPI = w_p TPI_{PTP} + w_s TPI_{STP} + w_t TPI_{TTP} \qquad (5)$$

where $w_p$, $w_s$, and $w_t$ are the relative weight of primary treatment phase, secondary treatment phase, and tertiary treatment phase, respectively. The analytic hierarchy process (AHP) technique, developed by Satty (1991), is widely used to determine the weighting factors (Belton and Stewart, 2002). The weight of each treatment phase for overall treatment performance is determined using the Eigen vector approach, which is a part of AHP. The hierarchy to determine the attribute weights and further details to determine the weighing factors for this study are found in Qasem (2011). The interpretation of the $TPI_{TP}$ values is based on these ranges: 8-10 (Excellent condition); 6-8(Good Condition); 4-6 (Bad to acceptable condition); 2–4 (Very bad condition); and <2(Critical condition) (Qasem, 2011).

Two WWTPs in Canada (WWTP 1 in Quebec and WWTP 3 in Ontario) and one in the US (WWTP 2) are selected and analyzed using the model to show the impact of different jurisdictions over the performance of these WWTPs. The overall treatment performance of WWTP is determined using different tests in each municipality, and the collected data for these WWTPs are reorganized to satisfy the phase based approach adopted in this study. The data are used to assess TPI values for each WWTP.

The values of TPI for the primary and secondary treatment phase are shown in Table 1. In the primary treatment phase of WWTP 1, the removal efficiencies for suspended solid (SS) and the BOD5 are low, and the phase is not functioning well and requires upgrading. The TSS removal efficiency for this phase is around 20 % for most of the year with variation between 20 % and 50 %. The BOD removal efficiency is also low reaching 35 % only for two months. This low removal efficiency may be the result of factors such as poor design, high flow rates, or an insufficient retention time in the primary sedimentation tank. Therefore, all possible causes must be identified by decision-makers before applying any corrective measurements. The results are also need to be compared with the state of the infrastructure in this treatment phase to determine the most efficient and cost effective solution.

The TPI for the secondary treatment phase ($TPI_{STP}$) is developed to reflect the condition of the main and vital operational factors that affect the biological treatment processes. This approach serves as an alarm for the decision-makers, notifying them of current and possible future operational problems. The TPI of the secondary treatment phase ($TPI_{STP}$) is determined using Equations 2 and 3. As shown in Table 2, the $BOD_5$ removal efficiency in the secondary treatment phase of WWTTP 1 is excellent and ranges between 92 % and 94 %. However, the SVI index values are higher than 50 ml/g which may indicate settling problems and unstable treatment process that may lead to future operational problems. Possible causes of the settling problem may include sludge rising and must be investigated by the WWTP operators. Also, the ratio of the $MLVSS_S$ concentration in the secondary sedimentation tanks to the $MLVSS_R$ in the reactor tank ranges between 2.5 and 3.5 for WWTP 1. This also may indicate another operational problem in this phase as the ratio of greater than 5 is recommended to provide

**Table 1. Treatment performance of the primary and second treatment phase of WWTP 1**

| | Primary Treatment Phase | | | | | | Secondary Treatment Phase | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $BOD_{Rem}$ % | $TSS_{Rem}$ % | CR $BOD_{Rem}$ | CR $BOD_{Adj}$ | CR TSS | $TPI_{PTP}$ | $MLVSS_S$/ $MLVSS_S$ | β1 | γSVI | $BOD_{Rem}$ % | CR $BOD_{Rem}$ | $TPI_{STP}$ |
| Jan | 11 | 21 | 3.2 | 3.2 | 2.1 | 2.4 | 3.4 | 0.68 | 0.9 | 92 | 9.25 | 5.82 |
| Feb | 19 | 31 | 5.3 | 5.3 | 3 | 3.7 | 2.53 | 0.51 | 0.7 | 92 | 9.24 | 4.33 |
| Mar | 10 | 35 | 2.7 | 2.7 | 3.4 | 3.2 | 2.63 | 0.53 | 0.8 | 88 | 8.8 | 4.08 |
| Apr | 16 | 19 | 4.4 | 4.4 | 1.9 | 2.6 | 3.72 | 0.74 | 0.8 | 91 | 9.14 | 6.22 |
| May | 27 | 45 | 7.7 | 7.7 | 4.5 | 5.4 | 2.84 | 0.57 | 0.8 | 93 | 9.34 | 4.96 |
| June | 26 | 51 | 7.4 | 7.4 | 5 | 5.7 | 2.9 | 0.58 | 0.9 | 94 | 9.39 | 5.11 |
| July | 25 | 48 | 7.1 | 7.1 | 4.7 | 5.4 | 2.86 | 0.57 | 0.8 | 95 | 9.53 | 5.18 |
| Aug | 41 | 28 | 11.6 | 10 | 2.8 | 4.9 | 3.02 | 0.6 | 0.6 | 92 | 9.21 | 5.12 |
| Sep | 32 | 43 | 9.1 | 9.1 | 4.3 | 5.7 | 2.88 | 0.58 | 0.8 | 94 | 9.39 | 5.08 |
| Oct | 30 | 45 | 8.5 | 8.5 | 4.4 | 5.6 | 3.13 | 0.63 | 0.8 | 94 | 9.4 | 5.52 |
| Nov | 36 | 35 | 10.3 | 10 | 3.4 | 5.4 | 3.95 | 0.79 | 0.9 | 94 | 9.4 | 6.99 |
| Dec | 23 | 24 | 6.61 | 6.61 | 2.3 | 3.6 | 3.59 | 0.72 | 0.8 | 92 | 9.16 | 6.02 |
| Average | | | | | $TPI_{PTP}$ | 4.5 | | | | | $TPI_{PTP}$ | 5.37 |

the operator with the needed flexibility to deal with sudden fluctuations in the hydraulic and biological loadings. The TPI for the tertiary treatment phase is determined using Equation 4, which takes into the consideration of coliform bacteria presence and potential disinfection by-product formation.

WWTP 1 disposes its treated effluent into rivers without disinfection because the restricted usage of treated effluent from WWTP 1. In order to apply the developed TPI to the tertiary treatment phase, wastewater samples from the secondary effluent were taken from the WWTP 2 and tested to see the potential of disinfection by-product (DBP) formation. Unfortunately, the collected samples tested positive for coliform bacteria, and the potential formation of disinfection by-products was also high. Therefore, the value of zero was specified for the $TPI_{TTP}$ of WWTP 1. The overall treatment performance index (TPI) is determined using the weighted sum of the TPI of each treatment phase as seen in Equation 5. These weights *wp*, *ws*, and *wt*, determined using the Eigen-vector techniques, are 0.14, 0.6, and 0.26, respectively. For WWTP 1, the overall TPI is 3.85 (= 0.14 x 4.53 + 0.6 x 5.37 + 9.26 x 0.0).

The $BOD_5$ removal efficiency for the primary treatment phase of WWTP 2 is excellent as shown in Table 3. However, the SS removal efficiency needs improvement since it ranges between 39 % and 64 %. The removal efficiency during certain months exceeded 60 %, which is acceptable by many operators. The monthly $TPI_{PTP}$ of WWTP 2 is shown in Table 2.

The assessed values of $TPI_{STP}$ for WWTP 2 is also shown in Table 2. The data indicate that its $BOD_5$ removal is excellent with the removal efficiency ranging between 96% and 98%. However, similarly to WWTP 1, the SVI index values for this treatment plant are higher than the optimum value (50 ml/g) indicating that there may be a sludge settling problem in the WWTP. On the other hand, the values of $MLVSS_S/MLVSS_R$ ratio range between 4 and 5 being near the recommended range that can provide the required operating flexibility described previously.

The TPI for tertiary treatment phase for WWTP 2 is determined based on the coliform test results measured in CFU and the secondary phase $BOD_5$ effluent (Equation 4). The $TPI_{TTP}$ values for WWTP 2 are presented in Table 3.

The effluent data for WWTP 2 show that the maximum coliform count numbers are violated in five months of the year, while $BOD_5$ values are within the acceptable levels. Hence, the reduction factor ω ranging from 1 to 0.7 is used. The $TPI_{TTP}$ of WWTP 2 is 5.2, so better control is required to use the treated effluent for general purposes. However, the treated effluent of WWTP 2 is sufficient for a restricted usage that allows higher coliform concentrations. The overall TPI calculated for WWTP 2 using Equation 5 is 6.85 (= 0.14 × 6.26 + 0.6 × 7.71 + 0.26 × 5.2). This value is higher than the value for WWTP 1.

The monthly $TPI_{PTP}$ values of WWTP 3 are shown in Table 4. The SS removal efficiency of the first treatment phase for WWTP 3 is very good, ranging between 62 % and 72 %. In addition, the $BOD_5$ removal efficiency of this phase is excellent as it ranges between 29 % and 45 %, which is approximately the desired removal level for this phase.The $BOD_5$ removal efficiency in the secondary phase of WWTP 3 ranges between 96 % and 98 % (Table 4). In addition, the SVI values range between 60 mg/s and 100 mg/s demonstrating that WWTP 3 has good sludge settling characteristics. Moreover, the $MLVSS_S/MLVSS_R$ ratio in this WWTP is around the target value of 5. The performance of the secondary treatment phase of WWTP 3 is the best among the three treatment plants studied.

**Table 2. Treatment performance of the primary and second treatment phase of WWTP 2**

| | Primary Treatment Phase | | | | | | Secondary Treatment Phase | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $BOD_{Rem}$ % | $TSS_{Rem}$ % | CR $BOD_{Rem}$ | CR $BOD_{Adj}$ | CR TSS | $TPI_{PTP}$ | $MLVSS_S$/ $MLVSS_S$ | β1 | γSVI | $BOD_{Rem}$ % | CR $BOD_{Rem}$ | $TPI_{STP}$ |
| Jan | 34 | 39 | 9.7 | 9.7 | 3.9 | 5.6 | 4.4 | 0.9 | 0.6 | 97 | 9.7 | 5.9 |
| Feb | 41 | 55 | 11.6 | 10.0 | 5.5 | 6.9 | 5.7 | 1.0 | 0.6 | 98 | 9.8 | 3.8 |
| Mar | 28 | 17 | 8.1 | 8.1 | 1.7 | 3.6 | 2.8 | 0.6 | 0.7 | 96 | 9.6 | 5.5 |
| Apr | 32 | 30 | 9.1 | 9.1 | 3.0 | 4.9 | 3.9 | 0.8 | 0.7 | 97 | 9.7 | 4.7 |
| May | 42 | 43 | 11.9 | 10.0 | 4.3 | 6.0 | 3.9 | 0.8 | 0.6 | 98 | 9.8 | 4.3 |
| June | 40 | 43 | 11.5 | 10.0 | 4.3 | 6.0 | 3.6 | 0.7 | 0.6 | 97 | 9.7 | 5.2 |
| July | 36 | 43 | 10.4 | 10.0 | 4.3 | 6.0 | 3.8 | 0.8 | 0.7 | 98 | 9.8 | 6.3 |
| Aug | 45 | 57 | 13.0 | 10.0 | 5.7 | 7.0 | 4.0 | 0.8 | 0.8 | 98 | 9.8 | 6.9 |
| Sep | 45 | 63 | 12.9 | 10.0 | 6.3 | 7.4 | 4.4 | 0.9 | 0.8 | 97 | 9.7 | 8.6 |
| Oct | 42 | 64 | 12.0 | 10.0 | 6.4 | 7.5 | 4.9 | 1.0 | 0.9 | 96 | 9.6 | 6.8 |
| Nov | 40 | 61 | 11.6 | 10.0 | 6.1 | 7.3 | 4.2 | 0.9 | 0.8 | 98 | 9.8 | 6.2 |
| Dec | 32 | 60 | 9.1 | 9.1 | 6.0 | 7.0 | 3.9 | 0.8 | 0.8 | 98 | 9.8 | 5.9 |
| Average | | | | $TPI_{PTP}$ | | 6.3 | | | | | $TPI_{PTP}$ | 5.8 |

**Table 3. Treatment performance of the tertiary treatment phase of WWTP 2**

| Month | Effluent BOD | CFU / 100 mlColiform Count | ω | *vi* |
|---|---|---|---|---|
| Jan | 3.4 | 0 | 1.0 | 0 |
| Feb | 3.6 | 0 | 1.0 | 0 |
| March | 25 | 0 | 0.8 | 0 |
| April | 36 | 0 | 0.7 | 0 |
| May | 40 | 10.6 | 0.7 | 0 |
| June | 30 | 34.1 | 0.8 | 1 |
| July | 10 | 35.8 | 1.0 | 1 |
| Aug | 10 | 47.4 | 1.0 | 1 |
| Sep | 4.6 | 132.2 | 1.0 | 1 |
| Oct | 40 | 174.9 | 0.7 | 1 |
| Nov | 4 | 0 | 1.0 | 0 |
| Dec | 3 | 0 | 1.0 | 0 |
| Average ω= 0.89 | | | | |
| # of CFU exceeding allowable limit V | | | | 5 |
| $TPI_{TTP}$ | | | | 5.2 |

As shown in Table 5, the $BOD_5$ of the tertiary treatment phase of WWTP 3 ranges between 6 and 9. These values reflect excellent treatment efficiency and minimize the possibility of DBP formulation potential (DBPFP). Hence, the value of 1 is specified as the reduction factor **ω**. The coliform forming units (CFU) ranged between 0 and 14, which is far below the allowable CFU of 25 indicating that the coliform count is never violated in the year. The value of *vi* is 0. Hence, the $TPI_{TTP}$ for WWTP 3 is 10/10. The calculation of the $TPI_{TTP}$ of WWTP 3 is shown in Table 5.The overall TPI calculated for WWTP 3 using Equation 5 is 8.51 (= 0.14 × 7.09 + 0.6 × 8.20 + 0.26 × 10.0). This value is the highest among all three WWTPs compared.

## RESULTS & DISCUSSIONS

The 3 WWTPs operates have different capacity, loading rate, treatment phases and operating conditions, and the developed treatment performance index model was applied to compare the treatment performance of them. The results show that the TPI value of WWTP 3 is the highest value among the studied WWTPs, while WWTP 1 has the lowest TPI value due to absence of tertiary (disinfection) treatment phase.

The model assessed the all three main treatment phases of WWTP instead of considering only the activated sludge process. It allows identification of critical processes affecting the overall treatment of WWTP. This can be helpful for developing sub-optimisation and a successful control strategy considering all aspects of a plant (Jeppsson and Pons, 2004). There are uncertainties in selecting treatment performance parameters and the assignment of weights for each treatment phase in relation to overall performance since they rely on experts' judgments. Those uncertainties in the model can be treated using a method such as fuzzy set theory (Sii *et al.*, 1999). The developed TPI model can be seamlessly combined with the infrastructure condition rating index (CRI) model forming a combined condition rating index (CCRI)

**Table 4. Treatment performance of the primary and second treatment phase WWTP 3**

| | Primary Treatment Phase | | | | | | Secondary Treatment Phase | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $BOD_{Rem}$ % | $TSS_{Rem}$ % | $^{CR}BOD_{Rem}$ | $^{CR}BOD_{Adj}$ | $^{CR}TSS$ | $TPI_{PTP}$ | $MLVSS_S/MLVSS_S$ | β1 | γSVI | $BOD_{Rem}$ % | $^{CR}BOD_{Rem}$ | $TPI_{STP}$ |
| Jan | 29 | 68 | 8.2 | 8.2 | 6.8 | 7.2 | 4.4 | 0.9 | 0.9 | 96 | 9.6 | 7.6 |
| Feb | 35 | 64 | 10.1 | 10.0 | 6.4 | 7.5 | 5.2 | 1.0 | 0.9 | 97 | 9.7 | 8.7 |
| Mar | 45 | 72 | 12.8 | 10.0 | 7.2 | 8.1 | 3.4 | 0.7 | 0.9 | 96 | 9.6 | 5.8 |
| Apr | 33 | 73 | 9.5 | 9.5 | 7.3 | 8.0 | 4.6 | 0.9 | 0.9 | 96 | 9.6 | 8.0 |
| May | 32 | 62 | 9.1 | 9.1 | 6.2 | 7.1 | 4.4 | 0.9 | 0.9 | 96 | 9.6 | 7.5 |
| June | 25 | 70 | 7.1 | 7.1 | 7.0 | 7.1 | 4.3 | 0.9 | 0.9 | 96 | 9.6 | 7.3 |
| July | 34 | 65 | 9.8 | 9.8 | 6.5 | 7.5 | 4.0 | 0.8 | 0.9 | 95 | 9.5 | 6.8 |
| Aug | 34 | 66 | 9.8 | 9.8 | 6.6 | 7.6 | 4.5 | 0.9 | 0.9 | 98 | 9.8 | 8.0 |
| Sep | 31 | 66 | 8.9 | 8.9 | 6.7 | 7.3 | 4.2 | 0.9 | 0.9 | 96 | 9.7 | 7.4 |
| Oct | 30 | 69 | 8.6 | 8.6 | 6.9 | 7.4 | 5.0 | 1.0 | 0.9 | 96 | 9.6 | 8.6 |
| Nov | 31 | 67 | 8.9 | 8.9 | 6.7 | 7.4 | 4.5 | 0.9 | 0.9 | 95 | 9.5 | 7.7 |
| Dec | 27 | 68 | 7.6 | 7.6 | 6.8 | 7.0 | 5.2 | 1.0 | 0.9 | 94 | 9.4 | 8.5 |
| Average | | | | $TPI_{PTP}$ | | 7.4 | | | | | $TPI_{PTP}$ | 7.7 |

**Table 5. Treatment performance of the tertiary treatment phase of WWTP 3**

| Month | BODEff. | CFU / 100 mlColiform Count | ω | *vi* |
|---|---|---|---|---|
| Jan | 6.0 | 14.0 | 1.0 | 0 |
| Feb | 5.0 | 8.0 | 1.0 | 0 |
| March | 7.1 | 0.0 | 1.0 | 0 |
| April | 6.0 | 15.0 | 1.0 | 0 |
| May | 6.5 | 4.0 | 1.0 | 0 |
| June | 7.0 | 0.0 | 1.0 | 0 |
| July | 9.0 | 8.0 | 1.0 | 0 |
| Aug | 3.0 | 14.0 | 1.0 | 0 |
| Sep | 6.0 | 13.0 | 1.0 | 0 |
| Oct | 6.0 | 2.0 | 1.0 | 0 |
| Nov | 9.0 | 0.0 | 1.0 | 0 |
| Dec | 9.0 | 0.0 | 1.0 | 0 |
| Average ω = 1 | | | 1.0 | |
| # of CFU exceeding allowable limit | | | | 0 |
| $TPI_{TTP}$ | | | | 10.00 |

model to assess the operating cost performance of WWTPs (Qasem *et al.,* 2010). The CRI for each WWTP infrastructure unit (e.g. tanks, pipes, and pumps) can be determined mathematically by summing the products of the weight of each factor using the AHP technique and their associated utility values. The CCRI model will be able to help different levels of management to communicate and to map the state of a WWTP's operation and infrastructure. It will also greatly facilitate the classification of rehabilitation demands for a WWTP.

## CONCLUSION

In this study, a model is developed to assess the treatment performance of wastewater treatment plant using a systematic and planned approach. The developed model can assess the overall treatment performance of a WWTP based on the treatment performance index (TPI) to measure its treatment efficiency of each treatment phases adopted in WWTP. The model determines the overall treatment performance of WWTP by integrating the TPI values of all treatment phases and applying different weights of each phase for overall treatment performance. The developed model was applied to three WWTPs that have different scales, loading rates, capacities, and process phases. The results indicate that the model is capable of assessing the performance of WWTAs with different treatment scenarios without the requirement of excessive computing time and data processing. The developed treatment performance index model can be used as a standardized tool to measure the treatment performance of typical WWTPs and to help plant operators properly to assess and evaluate current and future needs in operation and rehabilitation of WWTP.

## REFERENCES

Abusam, A., Keesman, K. J., Spanjers, H., van Straten, G. and Meinema, K. (2002). Evaluation of control strategies using an oxidation ditch benchmark. Water Sci. Technol., **45 (4-5)**, 151-158.

AWC, (2008). Alberta Wastewater Commission, Alberta Capital Region Wastewater Treatment Plant. Retrieved April, 2008, from http://www.acrwc.ab.ca/Brochure.pdf.

Andrews, J. F. (1992). Dynamics and Control of the Activated Sludge Process. (USA, Pennsylvania, Lancaster: Technomic Publishing Co.).

method (Belton, V. and Stewart, T. (1982). Multiple Criteria Decision Analysis – An Integrated Approach. Boston: Kluwer Academic Press.

Gagnon, M., Gaudreault, V. and Overton, D. (2008). Age of Public Infrastructure: A Provincial Perspective. Ottawa: Statistics Canada. 11-621-MIE2008067, 1-27.

Giokas, D. L., Daigger, G. T., Sperling, Mv, Kim, Y. and Paraskevas, P. A. (2003). Comparison and evaluation of empirical zone settling velocity parameters based on sludge volume index using a unified settling characteristics database. Water Res., **37 (16)**, 3821-3836.

Copp, J. B. (2002). The COST simulation benchmark: description and simulator manual. Office for Official Publications of the European Community, Luxembourg, ISBN 92-894-1658-0.

Guild, R. L. (2000). Infrastructure investment and interregional development: theory, evidence, and implications for planning. Public Works Management and Policy, **4 (4)**, 274-285.

Henze, H., Grady, C. P. L., Gujer, W., Marais, G. V. R. and Matsuo, T. (1987). Activated Sludge Model No. 1. UK, London: IWA Publishing.

Hopkins, L. N., Lant, P. A. and Newell, R. B. (2001). Using the flexibility index to compare batch and continuous activated sludge processes. Water Sci. Technol., **43**, 35-43.

Ingildsen, P. (2002). Realising full-scale control in wastewater treatment systems using in situ nutrient sensors. Ph D thesis, Lund University, Sweden.

Jeppson, U. and Pons, M. N. (2004). The COST benchmark simulation model-current state and future perspective. Control Eng. Practice, **12 (3)**, 299-304.

Jeppsson, U., Rosen, C., Alex, C., Copp, J., Gernaey, K. V., Pons, M. N. and Vanrolleghem, P. A. (2006). Towards a benchmark simulation model for plant-wide control strategy performance evaluation of WWTPs. Water Sci. Technol., **53 (1)**, 287-295.

Luccarini, L., Pulcini, D., Mello, P., Bragaglia, S. and Sottara, D. (2012). Monitoring the performance of Soft Sensors used in WWTPs by means of Formal Verification. iEMSs 2012 6th International Congress on Environmental Model. and Software, Leipzig, Germany, 1-5 July 2012.

Matos, R., Cardoso, A., Ashley, R., Molinari, A. and Schulz, A. (2002). Performance indicators for wastewater services-on the way to a manual of best practice and its implementation. ASCE, 2004 Urban drainage.

Olsson, G. and Newell, B. (1999). Wastewater Treatment Systems: Modelling, Diagnosis and Control. IWA publishing.
Peng, H., Ozaki, T., Toyoda, Y. and Oda, K. (2001). Modeling and control of systems with signal dependent nonlinear dynamics. Proceedings of the European Control Conference, Porto, Portugal, 42-47.

Pons, M. N. and Corriou, J. P. (2002). Implementation of storage tanks on the COST 624 benchmark. Water Sci. Technol., **45 (4/5)**, 159-166.

Puig, S., van Loosdrecht, M. C. M., Flameling, A. G., Colprim, J. and Meijer, S. C. F. (2010). The effect of primary sedimentation on full-scale WWTP nutrient removal performance. Water Res., **44 (11)**, 3375-3384.

Qasem, A. (2011). Performance Assessment Model for Wastewater Treatment Plants. PhD thesis, Concordia University, Montreal, Quebec.

Qasem, A., Zayed, T. and Chen, Z. (2010). A condition rating system for wastewater treatment plants infrastructures. Int. J. Civil Environ. Eng., 2-3.

Ráduly, B., Gernaey, K. V., Capodaglio, A. G., Mikkelsen, P. S. and Henzed, M. (2007). Artificial neural networks for rapid WWTP performance evaluation: methodology and case study. Environ. Model. Softw., **22 (8)**, 1208-1216.

Saaty, T. (1991). Decision Making with Dependence and Feedback: The Analytic Network Process. Pittsburgh, PA: RWS Publications.

Sii, H. I., Sherrard, J. H. and Wilson, T. E. (1993). A water quality index based on fuzzy sets theory. Joint ASCE/CSCE National Conf. on Environmental Engineering (ENJN93), ASCE-CSCE, Montreal, 253-259.

Takacs, I., Patry, G. G. and Nolasco, D. (1991). A dynamic model of the clarification thickening process. Water Res., **25 (10)**, 1263-1271.

USEPA, (2004). United States Environmental Protection Agency, Primer for Municipal Wastewater Treatment Systems, from www.epa.gov.owm.

Vanier, D. and Danylo, N. (2003). Municipal Infrastructure Investment Planning, asset Management. MIIP report, Institute for Research in Construction, National Research Council Canada.

Vanrolleghem, P. A. and Gillot, S. (2001). Robustness and economic measures as control benchmark performance criteria. Proceedings of 1st IWA Conference on Instrumentation, Control and Automation, Malmo, Sweden, **1**, 213-220.

Vanrolleghem, P. A. and Gillot, S. (2002). Robustness and economic measures as control benchmark performance criteria. Water Sci. Technol., **45 (4/5)**, 117-126.

Viessman, W. and Hammer, J. (2005). Water supply and pollution control, 7th edition. (Upper Saddle River, NJ : Pearson Prentice Hall, ISBN 0131409700.

Warren, V. (2009). Water supply and pollution control. (Upper Saddle River, NJ: Pearson Prentice Hall. ISPN 9780132337175).

Zhang, Q., Suidan, M. T., Zhang, K., Oerther, D. B. and Venosa, A. D. (2006). Comparison of biomass selection between a novel membrane bioreactor and activated sludge process. WEFTEC. 06, Conference Proceedings, Annual Technology Exhibition and Conference, 79th, Dallas, TX, the United States.