Performance Assessment Model for Wastewater Treatment Plants

Altayeb Qasem

A Thesis

In the Department

of

Building, Civil and Environmental Engineering

Presented in Partial Fulfillment of the Requirements

For the Degree of

Doctor of Philosophy (Civil and Environmental Engineering) at

Concordia University

Montreal, Quebec, Canada

April 2011

CONCORDIA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

This is to certify that the thesis prepared

By: Altayeb Qasem

Entitled: Performance Assessment Model for Wastewater Treatment Plants

and submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY (Civil Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

______________________________________ Chair
Dr. Y.R. Shayan

______________________________________ External Examiner
Dr. Y. Kleiner

______________________________________ External to Program.
Dr. Y. Zeng

______________________________________ Examiner
Dr. M. Nokken

______________________________________ Examiner
Dr. S. Alkass

______________________________________ Thesis Co-Supervisor
Dr. T. Zayed

______________________________________ Thesis Co-Supervisor
Dr. Z. Chen

Approved by ______________________________________
Dr. K. Ha-Huy, Graduate Program Director

April 26, 2011

____
Dr. Robin A.L. Drew, Dean
Faculty of Engineering & Computer Science

Abstract

Performance Assessment Model for Wastewater Treatment Plants

Altayeb Qasem, Ph.D.

Concordia University, 2011

Management of wastewater treatment plants has become a major environmental and economic concern in North America because of the unprecedented deterioration of these facilities. This situation is aggravated by the lack of adequate funds for upgrading and maintenance. In 2008, Statistics Canada estimated that wastewater treatment assets have exceeded 63% of their useful life, the highest level among public infrastructure facilities. Similar studies in the United States found current wastewater treatment facilities with a near-failure average grade of *D-*. These facts show the urgent need for rehabilitation decision tools to keep these facilities running effectively. This dissertation aims to respond to such a pressing need by developing a performance assessment model (PAM) for the maintenance and rehabilitation of wastewater treatment plants (WWTPs) that depends on various treatment and infrastructure aspects.

The developed PAM is based on the evaluation of both treatment and infrastructure performance for the main treatment phases of a WWTP. The treatment performance of each phase is based on efficiency of treatment and robustness of its parameters as set by design standards. The infrastructure performance of each treatment phase is determined using infrastructure condition rating models developed by integrating the multi-attribute utility theory (MAUT) and the analytic hierarchy process (AHP).The required data for these models were collected via questionnaires from, site visits to, and interviews with experts in Canada and the United States. The results reveal that physical factors have the highest impact on deterioration of WWTP infrastructure and that pumps are the most vulnerable infrastructure unit. Deterioration curves for different infrastructure units in a WWTP are generated using sensitivity analysis, which shows the effect of age over their condition rating indexes. The treatment and infrastructure performance indexes are merged and presented in a combined condition rating index. Integer programming approach is used to optimize the rehabilitation interventions within available budget constraints with a minimum desired condition rating for each infrastructure unit.

The developed PAM is validated using data of three WWTPs from Canada and the United States. Managers of these WWTPs acknowledged the efficacy of the developed model outputs and deemed it systematic, straightforward, and valuable for clearly pinpointing the main problems in these WWTPs.

Acknowledgement

I would like to express my deepest gratitude and sincere appreciation to my supervisors, Dr. Tarek Zayed and Dr. Zhi Chen for their keen support and guidance. I would like also to thank Dr. Sabah Alkass and Dr. Michelle Nokken for their help and support.

I am indebted to my colleagues in the Construction Automation lab for their brotherly help and support throughout my work.

I owe my deepest gratitude to Mrs. Debbie Walker from the BCEE For her endless help and support.

I dedicate my thesis to my Mother & my Father for their continuous love and support.

Finally, my appreciation goes to my little angle Amal and my two princes Mohammad and Abdullah for their patients and scarifies.

Contents

List of Figures

List of Tables

List of Abbreviations

ACI	American Concrete Institute
AHP	Analytical Hierarchy Process
ANN	Artificial Neural Network
ASCE	American Society of Civil Engineering
ASM	Activated Sludge Modeling
ASTM	American Standard Testing Measurement
BOD_5	Biochemical Oxygen Demand
BPNN	Back Propagation Neural Network
C.I	Consistency Index
C.R	Consistency Ration
CCRI	Combined Condition Rating Index
CCTV	Closed Circuit Television
CFU	Coliform Forming Units
CIS	Canadian Infrastructure Systems
CRI	Condition Rating Index
CRI_{PTP}	Primary Treatment Phase Condition Rating
CRI_{STP}	Secondary Treatment Phase Condition Rating
CRI_{TTP}	Tertiary Treatment Phase Condition Rating
CRI_{pip}	Pipe Condition Rating
CRI_{tnk}	Tank condition Rating
CRI_{pmp}	Pump condition Rating
CRI_{IP}	Infrastructure Performance Condition Rating
CWWA	Canadian Water Works Association
DBCM	Dibromochloromethane
DBP	Disinfection By Product
DBPFP	Disinfection By Product Formation Potential
DCBM	Dichlorobromomethane
EPA	Environment Protection Agency

EPE	Environmental performance Evaluation
F/M	Food to Microorganisms Ratio
FCM	Federation of Canadian Municipalities
GAO	Government Accounting Board
HAAS	HaloAcitic Acids
IP	Infrastructure Performance
ISO	International Standard Organization
LCCA	Life Cycle Cost Analysis
MAC	Maximum Acceptable Concentration
MAUT	Multi Attribute Utility Theory
MLVSS	Mixed Liquor Volatile Suspended Solids
MR&R	Maintenance Rehabilitation and Replacement
NDT	Non Destructive Testing
NN	Neural Network
NOM	Natural Organic Matter
PAM	Performance Assessment Model
PST	Primary Sedimentation Tank
PST	Primary sedimentation Tank
PTP	Primary Treatment Phase
R.I	Random Consistency Index
RAS	Returned Activated Sludge
R.T	Reactor Tank
SST	Secondary Sedimentation Tank
STP	Secondary Treatment Phase
SVI	Sludge Volume Index
THM	Tri Halo Methane
TOC	Total Organic Carbon
TP	Treatment Performance
TPI	Treatment Performance Index of the WWTP
TPI_{PPT}	Treatment Performance Index of the PTP
TPI_{SPT}	Treatment Performance Index of the STP

TPI_{TPT}	Treatment Performance Index of the TTP
TSS	Total Suspended Solids
TTP	Tertiary Treatment Phase
USEPA	United States Environmental Protection Agency
UVA	Ultra Violate Absorbance
WAS	Wasted Activated Sludge
WHO	World Health Organization
WWTP	Waste Water Treatment Plant
$WWTP_{CCRI}$	Combined Condition rating Index for WWTP

Ch I. Introduction

1.1 Problem Statement and Research Motivation

The main function of wastewater treatment plants is to protect human health and the environment from excessive overloading of various pollutants. Wastewater treatment plants (WWTPs) are considered one of the major infrastructure assets on both federal and municipal levels. Meeting the increasingly stringent wastewater treatment demands, which must comply with environmental standards, using aging WWTP is currently among the most challenging aspects of wastewater treatment operations facing decision makers in municipalities.

Unfortunately, many studies have shown that infrastructure assets in the US and Canada are deteriorating and approaching the end of their projected service lives (Vanier, 2004). In addition, these studies show that these facilities, including wastewater treatment plants, are failing prematurely and need costly rehabilitation and maintenance to keep functioning at an acceptable performance level. This situation has arisen mainly because most municipalities have placed more emphasis on new construction for the past three decades, which has allowed major deterioration to occur in old facilities (Vanier and Danylo, 2003). This process has led to a maintenance-accumulated shortfall of $44 billion, which is the sum necessary to regain the assets' acceptable conditions (FCM, 1995). The Canadian Water and Wastewater Association’s (CWWA’s) investment assessment for 1998-2012 reported that water and wastewater section in Canada requires $90 billion to maintain the functionality of these facilities, of which $14 billion is required for wastewater treatment plants (CWWA, 1997). The American Society of Civil

Engineers ASCE (2009) stated that federal government had directly invested more than $72 billion in the construction of publicly owned sewage treatment works and their related facilities since 1979. However, the physical condition of many US wastewater treatment systems is in very poor conditions with an overall [D-] grade (ASCE, 2009). The US Environmental Protection Agency (EPA) stated that, in 2004, most wastewater treatment plants and sewer collection facilities were tattered, old and worn. Thus, they required immediate improvements, repairs, and maintenance, or even replacement to maintain their useful life.

A recent study conducted by Statistics Canada (2008) reported that the average age of Canada's wastewater treatment facilities has been increasing steadily since the 1970s. On the national scale, wastewater treatment facilities exceeded their service life by 63% at the end of 2007. This is the highest percentage among other public infrastructure assets (i.e. roads, bridges, water supply systems, and sewer systems). The report also stated that the average age of wastewater treatment facilities increased from 17.4 years in 2001 to 17.8 years in 2007. Prince Edward Island had the worst situation, followed by Quebec, where the average age went from 16.9 years in 2001 to 19.1 years in 2007 (Mychèle et al., 2008). Another study conducted by Environment Canada (2007) reviewed the different practices and treatment performances in plants across Canada and found that more than 50% of all wastewater treatment plants have a high risk of failure within the coming 10 years.

Finding feasible and economical maintenance rehabilitation and replacement (MR&R) solutions for such aging facilities requires accurate methods for assessing their conditions and innovative technologies for cost-effective rehabilitation alternatives to keep these facilities functioning within their required serviceability period (Guild, 2000). Developing a condition index for wastewater treatment facilities is a key factor in assessing treatment operations and relative performance (Matos et al., 2004).A well-structured performance assessment model (PAM) for wastewater treatment plants, reflecting the physical integrity and treatment efficiency of each phase, is a key factor in the asset management and decision-making processes for these aging facilities. The PAM can provide appropriate information on a treatment plant's physical integrity and treatment efficiency. The PAM evaluates, characterizes and prioritizes different maintenance, rehabilitation and replacement (MR&R) plans for wastewater treatment facilities.

Based upon the available literature, there is a lack of research in this field. There are some condition rating systems for wastewater treatment plants. However, these systems are not standardized and do not reflect the physical integrity and treatment performance of these plants.

1.2 OBJECTIVES

The main objective of this research is to develop a Performance Assessment Model (PAM) for maintenance, rehabilitation and/or replacement of WWTPs. This main objective can be achieved through the following sub-objectives:

1- Identify and study the different factors that affect infrastructure and treatment performances of WWTPs.
2- Design condition rating and treatment performance models for various elements of WWTP.
3- Design an integrated condition rating model for wastewater treatment plants

4- Develop deterioration curves for the major elements of WWTP (tanks, pipes & pumps), treatment phases and the WWTP in general.

5- Develop a model to optimize MR&R interventions.

1.3 RESEARCH METHODOLOGY

The research methodology is based on analyzing treatment performance and infrastructure state of wastewater treatment plants (WWTPs). This approach enables decision makers to accurately identify rehabilitation needs for their WWTP and to pinpoint the main causes of ill performance. The developed methodology assesses the performance of WWTPs through its three treatment phases and evaluates the treatment and infrastructure performance of each phase. The treatment performance of each phase is performed using a condition rating index (CRI) 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. The relative weight of each phase is determined using the analytic hierarch process (AHP) technique. On the other hand, the infrastructure state of each treatment phase is determined by integrating the condition ratings of its tanks, pipes, pumps and blowers, which are the main WWTP units.

The condition rating of each infrastructure unit is determined using condition rating models developed by the integration of multi attribute utility theory and the analytical hierarchy process (MAUT-AHP). The treatment performance and infrastructure condition ratings are presented in a combined condition rating index ($WWTP_{CCRI}$). Based on the combined index, decision makers will be able to decide whether the treatment malfunction is due to poor infrastructure conditions or to deprived treatment and operational practices.

Deterioration curves for different infrastructure units are developed using sensitivity analysis approach by evaluating the effect of age on CRI of each infrastructure unit. The deterioration curves in addition to minimum desired and allowable CRI thresholds are used to develop and schedule the appropriate maintenance and rehabilitation (MR&R) interventions. These interventions along with their costs and condition recovery effect are optimized within the available MR&R budget using the integer programming technique.

The research methodology adopted in this dissertation has the advantage of identifying WWTP infrastructure and operational malfunctions using simple, practical and straightforward approach. This approach, if appropriately applied, can provide a proactive decision tool for WWTP operators and decision makers. The research framework and steps followed in this study are shown in Figure I.1.

1.4 THESIS OVERVIEW

This thesis consists of seven chapters as follows. Chapter I contains the problem statement and research motivations. Chapter II provides a detailed literature review that describes the previous work done in this field and the different approaches and techniques currently used. A detailed description of the developed methodology adopted in this study is presented in Chapter III. Data collection is presented in Chapter IV. Chapter V presents the data analysis and a case study that provides a systematic numerical illustration of the developed methodology. A software prototype of the developed performance assessment model is presented in chapter VI. Chapter VII presents the research's conclusions, contributions and limitations, as well as suggestions for future work.

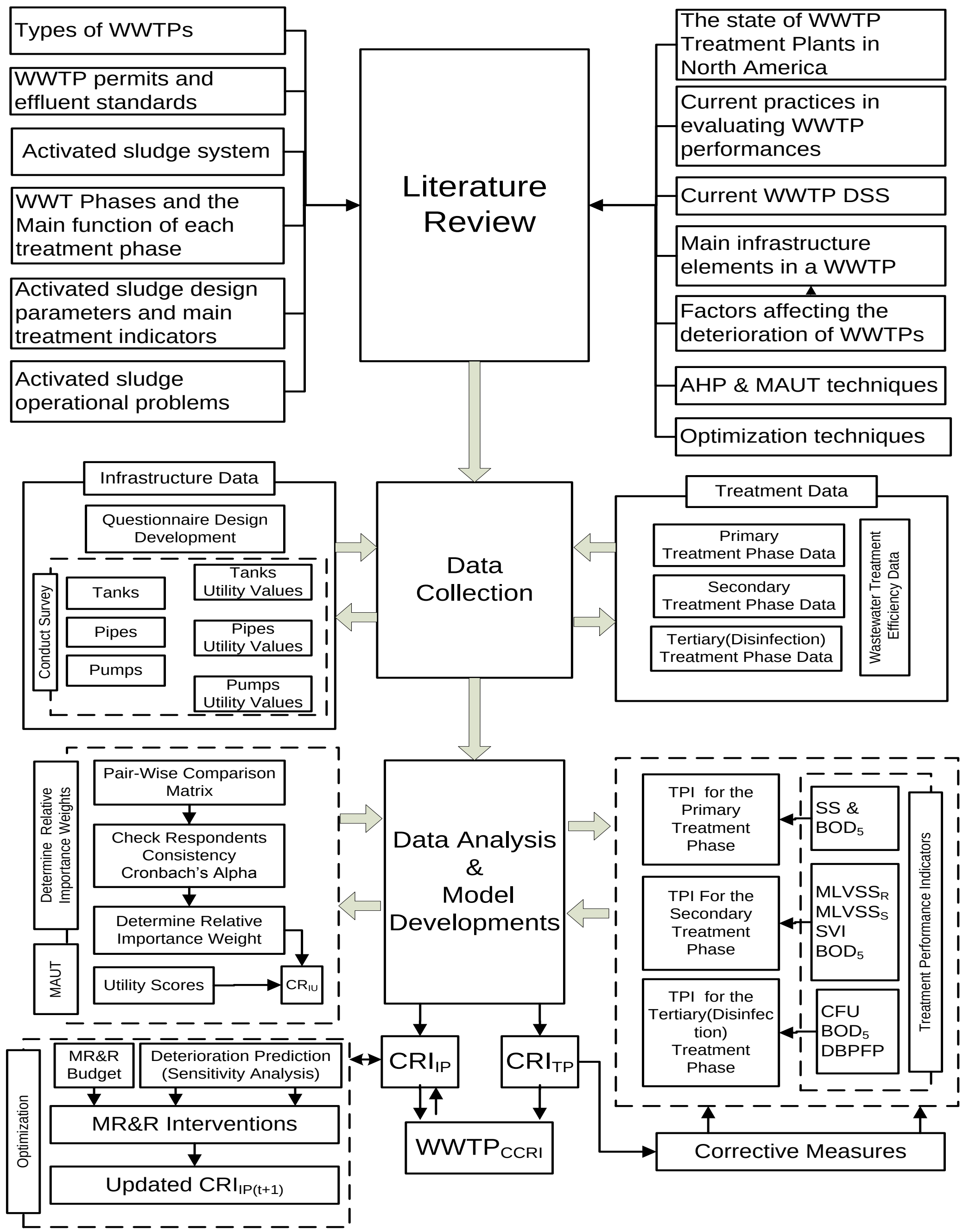


FIGURE I-1: Research Framework

Ch II. Literature Review

2.1 CHAPTER OVERVIEW

The main aim of this chapter is to provide a comprehensive literature review about the state of wastewater infrastructure in Canada and the US and to cover different topics in asset management and infrastructure deterioration, especially in the sewer environment. This chapter also highlights the main wastewater treatment plant condition assessment techniques used so far. Different decision support techniques, such as the Analytical Hierarchy Process (AHP), Multi-Attribute Utility Theory (MAUT), Artificial Neural Networks (ANN), regression analysis and others commonly used in asset management and condition rating developments, are also explained. The main sources of this literature review are journals, books, research papers, the Internet and wastewater.

2.2 THE STATE OF WASTEWATER INFRASTRUCTURE FACILITIES IN CANADA AND THE US

The main function of wastewater treatment plants (WWTP) is to protect the environment and human health human health from excessive overloading from different types of pollutants. Wastewater treatment plants are considered one of the major infrastructure assets on both federal and municipal levels. Unfortunately, many studies have shown that the US and Canada's infrastructures are deteriorating and approaching their projected service life (Vanier and Rahman, 2004). Statistics Canada (2008) emphasised that wastewater treatment plants all over Canada are approaching their projected service life and urgent upgrading plans are needed to keep them functioning within the required standards. Figure II.1 shows that wastewater treatment facilities have the highest age among other infrastructure facilities, followed by bridges and overpasses (Mychèle et al., 2008).

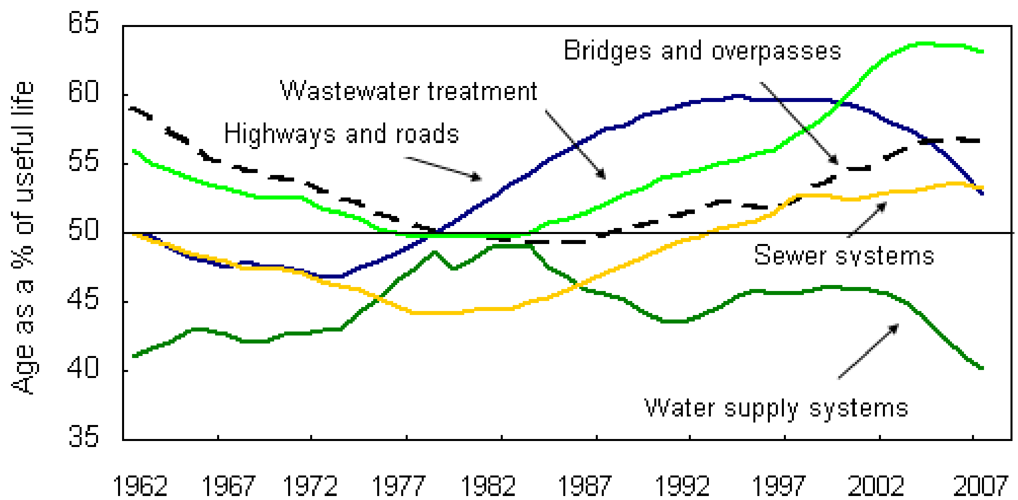


FIGURE II-1: Infrastructures' Remaining Service Life (Statistics Canada, 2008)

Many studies have shown that infrastructure facilities in North America are deteriorating dramatically as most infrastructures are approaching their projected service life (Vanier, 2003). The Technology Roadmap (2003-2013) indicated that the value of Canada's Civil Infrastructure Systems (CIS), including highways, roads and airports, as well as systems for water supply, storm water management and wastewater treatment, are deteriorating. Infrastructures cost Canadian municipalities CAD$15 billion per year, of which 80% is spent on the repair and renewal of aging infrastructures.

A survey conducted by the Federation of Canadian Municipalities (FCM) showed that 58% of the sewage treatment systems and 68% of the sanitary and combined sewers are not operating at an acceptable level (Mirza and Haidar, 2003).

Unfortunately, North American municipalities are not managing their infrastructure facilities based on clear or standard methods. A survey conducted by the US Government Accountability Office (GAO, 2004) showed that water and wastewater infrastructures in the US either do not have plans for managing their assets or have plans that are not adequate in scope or content. Most North American municipalities suffer from funding problems, which have caused remarkable maintenance shortfalls that now require major investments, especially for water and wastewater infrastructure (Burns et al.,1999; CERF, 1996; Vanier, 1999; USEPA,2002). The US GAO's (2002) survey found that more than a quarter of water and wastewater treatment infrastructure facilities lacked plans for the management of capital assets. The survey also showed that although facility managers have plans that identify future capital improvement needs, unfortunately more than half of these plans do not cover all of their assets and lack key plan elements such as physical condition assessments. The survey also showed that 65% of wastewater treatment facilities and maintenance and rehabilitation actions are far below the minimum required levels due to lack of funds. This finding is confirmed by the infrastructure report card published by the ASCE (2009), which shows that the wastewater sector grade had dropped from grade [C] in 1988 to [D-] by 2009. A grade this poor makes it clear that urgent actions are needed, just to maintain the functionality of these facilities.

The CWWA's 1998-2012 assessment report states that the water and wastewater sectors in Canada will require $90 billion to maintain a proper functionality of these facilities, of which CAD$14 billion is required for wastewater treatment facilities alone. The US needs to invest 12 billion dollars in sewer and wastewater treatment facilities to keep them operating within the desired functional level (ASCE, 2005). The USEPA (2002b)

Gap Analysis estimated that, over the next two decades, the United States must spend nearly $390 billion to replace existing wastewater infrastructure systems and to build new ones. This situation and these huge numbers emphasize the importance of finding accurate, feasible and economical solutions for assessing the conditions of infrastructure facilities which require new and innovative technologies to develop cost-effective maintenance and rehabilitation plans (HAPM, 1995; Guild, 2000).

The treatment performance of Canadian wastewater treatment plants varies drastically between provinces because these facilities have shared jurisdictions among different municipalities and follow different provincial and federal regulations. Environment Canada (2007) reviewed different practices and treatment performances in plants across Canada and found that more than 50% have a high risk of failure within the next 10 years. The total number of WWTPs that need to meet the national effluent quality standards and their associated risk rankings are summarized Table II.1.

TABLE II-1: National Ranking of Wastewater Facilities in Canada (Environment Canada, 2007)

Provence	Low Risk 2040	Medium Risk 2030	High Risk 2020
Alberta	6	40	2
British Columbia	0	5	8
Manitoba	0	81	0
New Brunswick	13	44	0
Newfoundland and Labrador	0	1	185
Nova Scotia	9	37	16
Ontario	102	4	3
Prince Edward Island	17	7	0
Quebec	0	154	33
Saskatchewan	0	29	1
Yukon	0	1	1
Federal	0	0	150
Total	147	403	399

The table shows that Ontario's WWTPs are in better condition than those of Quebec, since most of their WWTP have a low risk, while WWTPs in Quebec lie within the medium to high-risk ranges. Such a high risk of failure emphasizes the urgent need for tools that can evaluate the treatment performances of WWTPs using standardized tools, providing operators and decision makers with the needed information to know when and how to upgrade the treatment performances of their WWTPs.

2.3 ASSET MANAGEMENT

"Asset management is a business process and a decision-making framework that covers an extended time horizon, draws from economics as well as engineering, and considers a broad range of assets" (USFHA, 2004). Infrastructure asset management plans help municipalities focus on what is essential for different municipal infrastructure systems. These demands are then prioritized and optimized according to the available resources. The prioritization process relies on solid knowledge of the serviceability and the deterioration level of different infrastructure facilities. A study conducted by Urquhart et al., in 2005 stated that proper asset management is based on a condition assessment that reflects the asset's current serviceability and failure risk.

Vanier, (2000) recommended that good asset management systems have to include six implementation levels that were referred to as the *six 'what's' asset management levels.* In this approach, asset management starts with the first asset management level by building "your assets inventory", which is achievable by answering the first question: *What do you own?* The second level is to evaluate its worth by answering the second question: *What is it worth?* The value of different municipal assets is required for different maintenance aspects; currently required by the Government Accounting

Standard Board (GASB); in which municipalities in the U.S and Canada need to evaluate the value of their infrastructure assets over time. The third level defines the condition of these assets, which is done by answering the third question: *What is its condition?* Defining asset conditions can be associated with different thresholds that can be used to decide what to maintain first and how. Knowing the condition rating of different assets will affect maintenance decisions and thus will make it possible to predict the consequences of maintenance delays. This will also answer the fourth question: *What is the deferred maintenance*? and it's complement, *How will it affect the asset's future functionality?* These answers will make it possible to answer the fifth question: *What is the asset's remaining service life?* After answering these, the sixth and last level would be: *What should be fixed first?* Unfortunately, the answer to this last question is not a simple one, and requires the application of many sophisticated prioritization and optimization techniques (Vanier, 1999). A well-structured performance assessment model based on solving these questions will be a beneficial tool for decision makers in managing their assets. In addition, this asset management tool should contain the generic components of a good management system provided by the American federal highway agency (FHWA) presented in Figure II.2.

2.4 INFRASTRUCTURE CONDITION RATING AND DETERIORATION

Loss of serviceability over time is the simplest definition of deterioration. Infrastructure deterioration can be a result of the interaction of several factors that affect the infrastructure itself. Many studies have categorized these factors into physical, environmental and operational factors (Hudson et al. 1997; Kleiner and Rajani 2001; NRC Best Practices 2003a; Albarqawi 2006; Albarqawi and Zayed 2006; and Urhaman

2007). These factors and their interactions are responsible for the deterioration rate of infrastructure facilities. Infrastructure deterioration is a function of many variables that

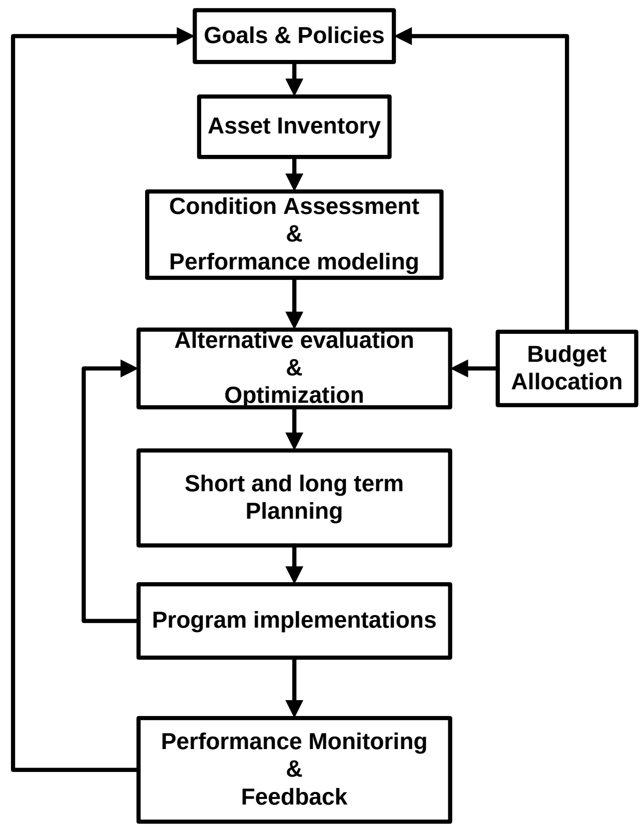


FIGURE II-2: Generic Asset Management Framework (FHWA, 1999)

have a number of unclear and uncertain factors, which adds to the complexity of predicting deterioration. These factors can also be classified into the categories of static, dynamic and operational (Al-Barqawi and Zayed (2008 & 2006) and Rajani and Kleiner, 2002).

Concrete deterioration depends on many factors, such as concrete quality (established during the construction phase, when it was poured (i.e. quality of material used, quality control procedures, specifications, etc.)), and on the operational environment to which the concrete is subjected to during its operational lifespan (Greg, 1998). In most treatment facilities, both plain and reinforced concrete is used to build different types of water pipes and water and wastewater tanks. The steel reinforcement in concrete corrodes if it is subjected to humidity, acids, salts or other chemicals, and corroded reinforcements increase in volume, causing the concrete to crack. If they are not treated in time by the appropriate MR&R measures, these cracks widen over time, which causes spalling and further deterioration (ACI, 1993). Concrete deterioration and its mechanisms are an important aspect of this research because most wastewater treatment plant tanks are made of concrete.

i- Concrete Deterioration in a Sewer Environment

Several studies have found significant evidence that corrosion is present in many concrete structures within wastewater treatment plants and that these facilities are significantly deteriorated after less than a decade in service. However, the deterioration mechanisms associated with these facilities are not widely understood since little detailed research has been conducted in that field (Connell et al., 2010; Neville, 2004). There are many other factors that contribute to the durability of concrete in wastewater treatment plants, such as abrasion, chemical attack and microbiological activities, and seasonal freeze and thaw forces. Such destructive forces can significantly reduce the service life of these structures. The durability of concrete structures in sewer environments such as wastewater treatment plants can be enhanced using high-quality concrete, proper insulation, and the application of a regular preventive maintenance plan. Such precautions can be applied based on appropriate design codes, high-quality material, and with good quality control during the construction phase. The best time to protect concrete is when it is new and before harsh chemicals such as acids, salts and sulfates have a chance to penetrate the concrete and cause damage (Hengst, 1994). Concrete is the main material used in WWTP tanks, which accommodate microbial activities in various treatment phases. The impacts of typical microbial activities on hardened concrete play a major role in concrete deterioration. Microbial activities, especially under anaerobic conditions, may have a remarkable effect due to acid formation. Acid formation in wastewater environments can occur in several ways; the main two are by the action of sulphuric acid that generates bacteria and through the production of hydrogen sulphide gas (H_2S), which is produced when anaerobic conditions prevail. The hydrogen sulphides produced usually transform into sulphuric acid (H_2SO_4) in a moist environment (Mori et al., 1992; Milde et al., 1983). This acid plays a major role in WWTP infrastructure deterioration. This acid reacts with concrete, decreasing its structural strength and durability, thus increasing permeability, which in turn causes concrete reinforcements to corrode and swell causing massive cracks (Crites and Tchobanoglous, 1998).

ii- Biogenic Sulphuric Corrosion Mechanism and Modeling

Sulphuric acid is a very aggressive acid that reacts with the free calcium hydroxide ($Ca(OH)_2$) in concrete-forming gypsum ($CaSO_4 \cdot 2H_2O$). With continuous corrosion, the corroded concrete structure loses its mechanical strength, causing more reactions to occur, leading to volume changes that create internal pressure and generate cracks (Vipulanandan and Liu, 2002). Predictive models usually cannot exactly predict the degree of corrosion due to the complexity of such reactions and the variety of different concrete types, mixes and installation conditions (Liu and Vipulanandan, 2003). Most predictive measures have been based on estimating the useful service life with respect to the corrosion rate, as illustrated in Equation 2.1 where L is the useful life in years, Z is the wall thickness of the concrete before reaching the reinforcement (mm), and C is the corrosion rate in mm/year. Modeling this form of corrosion depends on many factors such as concrete mixes, different types of cements, coating materials, biochemical oxygen demand (BOD) loadings, tank depth, etc. (Monteny et al., 2000; Lui, 2008).

$$L = Z/C \qquad (2.1)$$

2.5 CONCRETE TANK INSPECTION AND CONDITION ASSESSMENT

Tank condition assessment is performed to evaluate a tank's structural condition and different MR&R needs, which can be evaluated through different techniques such as visual, external and internal inspections. This assessment is done based on expert inspection or by using different visual technologies (ACI, 1989). Interior tank inspection involves applying several ASTM-approved methods to determine a tank's physical and structural condition, such as the concrete strength and the level of sulfate, chloride or other chemical penetration (Trovato, 2008).

2.6 PIPE DETERIORATION

The physical, chemical, and biological characteristics of wastewater are expected to have a significant impact on the deterioration of wastewater treatment plant pipes. These pipes are of different types, made with different materials and in different sizes. All types of pipes typically deteriorate and may fail over time, but the rate of deterioration and failure is a function of the various physical operational and environmental conditions that affect them (Makar, 1999; Makar et al., 2000). Many studies have classified pipe deterioration into external, internal or structural deterioration. Internal deterioration affects the pipe's hydraulic capacity and water quality (Rajani and Kleiner, 2004). Structural deterioration affects a pipe's structural integrity, which is a pipe's ability to resist different internal and external stresses. Most studies that have been implemented on water mains and sewer collection systems have focused mainly on structural deterioration. Although sewer pipes have some similarity with WWTP pipes, these two pipe systems have different operational parameters and therefore are expected to have different deterioration patterns. There are a few studies, however, that have dealt with pipes within wastewater treatment plants.

2.7 TREATMENT LEVELS AND PLANT DETERIORATION

Water and wastewater treatment infrastructure facilities are increasingly being challenged with the continuous upgrade in discharged effluent regulations decreed by regulatory bodies such as the EPA and the World Health Organization (WHO). These regulations require changes to treatment processes that can actually accelerate infrastructure deterioration. For example, achieving new optimum removal efficiencies may require a lower pH or higher chemical doses which can lead to significant degradation of treatment plant infrastructure (Lauris et al., 2003).

2.8 INFRASTRUCTURE CONDITION ASSESSMENT AND CONDITION RATING MODELS

The condition assessment of infrastructure facilities can be determined either by applying certain direct inspection techniques or by using condition rating assessment techniques. Direct inspection techniques are typically used to evaluate the exact condition of various infrastructures; however, due to budget limitations, only selected elements of these infrastructures can be inspected.

Condition rating models can be used to prioritize the infrastructure elements to be physically tested. Al-Barqawi and Zayed (2006) developed a condition rating system for water mains based on Artificial Neural Networks (ANN). The city of Edmonton developed a model to predict the condition rating of the sewer network using rule-based simulation. The developed model is designed to be part of a budgeting allocation system which depends on the condition rating model to prioritize MR&R needs (Ruwanpura et al., 2003). Rahman (2007) developed a condition rating model for tanks and pumps in a water treatment plant using the analytical hierarchy process (AHP). Water quality in water and sewer networks and in treatment plants is another important factor that should be taken into consideration, and which unfortunately has not been considered in these studies.

Even though condition rating models are considered to be a powerful tool for infrastructure condition assessment, and they are the backbone for the integrated infrastructure management concept, the research in this field is still very limited.

Typically, infrastructure inspection techniques are divided into destructive and non-destructive techniques, which are further classified into mechanical, mathematical, statistical, and soft computing techniques (Waaserman,1989; NRC, 2003b). The following sections give a brief discussion of each type.

2.8.1. Direct Inspection Techniques

Many inspection techniques are based on direct vision, such as closed-circuit television (CCTV) inspection, or on remote sensing and non-destructive testing (NDT), such as radar, sonar, ultrasound, sound emission, and eddy current, which can indicate various distresses in different facilities. Each technique has its own standards to define the condition of different infrastructure assets. However, the interpretation of NDT inspection results is often complex and involves many uncertainties that must be based on scientific analysis (Kleiner, 2001).

2.8.2. Statistical Regression Analysis Technique

One of the most-used statistical approaches is regression analysis. Regression analysis has often been used to correlate historical data due to its simplicity, effectiveness and practicality. Regression analysis is a statistical tool for defining the relationships or correlations between dependent and independent variables based on statistical data. The regression analysis approach can deduce the relationship between different variables that are then used to describe the problem. The dependent variable in the regression equation is modeled as a function of the independent variables. The equation developed for the dependent variables is expected to give a best fit curve, which is anticipated to have certain variation errors based on the following assumptions: (1)The error around a regression line is independent for each value of x; (2) The errors around a regression line are assumed constant for all x values; and (3) The errors arround a regression line are assumed to be normally distributed at each value of x (Levine et al., 2002). Researchers usually compare the true values of a problem with one generated by the regression model to find the confidence level of a regression model (Andreu et al., 1987; Zahedi, 1991; Chouinardet et al., 1996).

The least-square method is typically used to evaluate the best fit, in addition to other methods. Regression analysis has been used in many studies for prediction, forecasting, inference, hypothesis testing, and modeling of causal relationships (Montgomery et al., 2006). The regression will formulate an equation for the dependent variable (Y) modeled on the independent variable (*x*). In multiple regression analysis, more than one independent variable is used to predict the function value.

Other statistical techniques have been used to develop condition assessment techniques, for example Corotis et al., (2004) used Markov decision processes to develop deterioration curves for steel. Papadimitriou (2004) also used statistical techniques, based on the Bayesian method to model the deterioration damage in structures using dynamic data.

2.8.3. SOFT COMPUTING TECHNIQUES

This term is used to refer to various artificial intelligence techniques. Artificial Neural Networks (ANN), Fuzzy logic systems, and genetic algorithm techniques are classified among these techniques, which were originally developed and used in the industrial, engineering and computer science fields. These techniques were used for a wide variety of civil engineering applications.

Artificial neural network (ANN) technology is a robust artificial intelligence technology that can deal with the complexity and dynamic nature of many real-life systems. Artificial neural networks are structured based on the functions of human brain learning mechanisms. Sawhney and Mund, (2002) stated that the ANN technique is an effective tool due to its ability to learn by example, that can be used for data modeling and which can overcome data-related problems (Hrycej, 1992; Sadiq and Rajani, 2004; Du and Swamy, 2006). ANNs were used to develop a multitude of models and they have been used in many studies as an alternative to regression analysis, following the development of the back propagation algorithm (Karunaanithi et al., 1994; Faghir and Hua, 1995; Chua et al., 1997; Baxter et al., 2002). The ANN technique has been used effectively in many studies as a predictive tool. Najafi and Kulandaivel, (2005) used ANN to develop a CR model for sewers based on historic condition assessment data. Kulandaivel, (2004) developed a sewer pipe condition prediction using ANNs. Farouq et al., (2007) used an ANN to model water and wastewater applications, while Rádulya et al., (2007) developed an ANN model that predicts the BOD and COD in treated WWTP effluent.

2.8.4. THE ANALYTICAL HIERARCHY PROCESS (AHP)

The analytic hierarchy process (AHP) is defined as a general theory of measurement (Saaty, 1991). The AHP is one of the decision models used to evaluate different decision alternatives by introducing qualitative and quantitative factors. The AHP has been widely used and applied in various fields due to its ability to rate the relative weight of different alternatives, and thus provide an overall ranking for each alternative. The AHP is therefore a suitable approach to multi-criteria decision making (Elmisalami, 2001; Saaty, 1980).

Applying the AHP to the decision-making process starts with building the hierarchical structure of the problem, which presents the relationships between the goal, criteria, and sub-criteria, as illustrated in Figure II.3.

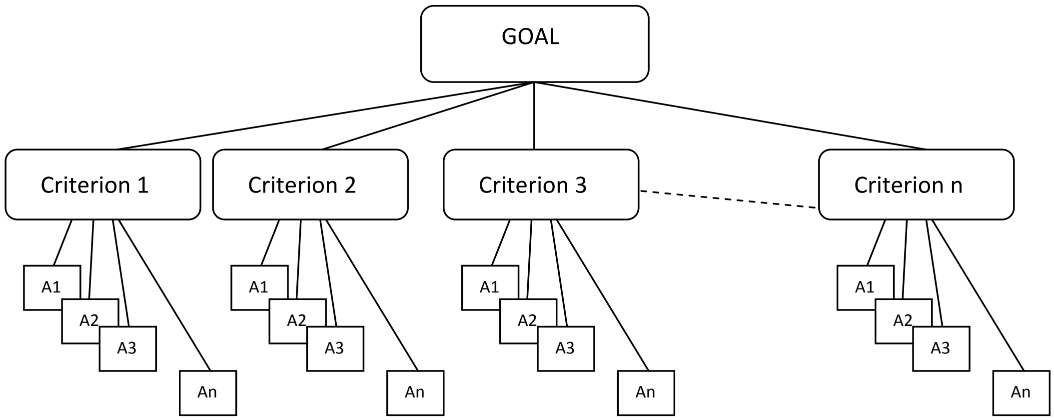


FIGURE II-3: AHP Structure

The hierarchical structure simplifies the problem and clearly illustrates the goals. The weights of the various elements are determined at each hierarchical level. The decision on the final goal is made after considering the weights of all of the criteria and the alternatives. Comparing these alternatives and defining their importance relative to each other is done using the pair-wise comparison matrix. The AHP uses pair-wise comparison matrices composed of various factors. The pair-wise comparison matrix gives the importance ratio for each pair of alternatives. Each matrix is a reciprocal matrix in which the main diagonal elements are one and the values above the diagonal are reciprocal to those below.

The elements of a pair-wise comparison matrix are mutual importance ratios between the criteria, which are decided on the basis of how well each criterion serves its purpose and how important it is in reaching the final goal.

Saaty (1980) developed a system of numbers to indicate by how much a certain criterion is more important than another. Saaty's numerical scale values and their corresponding interpretations are listed in Table II.2.

TABLE II-2: Pair-Wise Comparison Scales (Saaty, 1980)

Intensity of importance	Verbal judgment of preference
1	Equal Importance
3	Moderate importance
5	Strong importance
7	Extreme importance
9	Extremely more important
2,4,6,8	Intermediate values between adjacent scale values

i. Calculating weights

There are many techniques to calculate the AHP's final weights. However, the Lambda Max (λ_{max}) is the main technique used in most studies. The Lambda Max technique determines the weights of the criteria in the pair-wise comparison method. Saaty's method considers that every matrix has a set of Eigen values and for each Eigen value, there is a corresponding eigenvector. In Saaty's Lambda Max technique, a vector of weights is the normalized eigenvector corresponding to the largest Eigen value, termed λ_{max}. The vector weights w_i are determined using Equation 2.8.

$$C \times w = \lambda \times w \quad \text{......} \quad 2.8$$

where:

C is the pair-wise comparison matrix of the criteria

w is the weight vector

λ is the maximum Eigenvalue λ_{max}.

The Lambda Max technique requires special mathematical conditions to guarantee that a unique answer is obtained, which has led to the use of an approximation to the Lambda Max method in which the maximum Eigen-value is determined using a simple approach called the *mean of normalized value*. This approximation has been applied by most researchers using the AHP technique. The *mean of normalized values method* implementation is summarized in the following steps:

Step1: The sum of the elements in each column in a pair-wise comparison matrix is determined.

Step2: Each column element is then divided by the sum determined at the previous step.

Step3: The arithmetic average of each row of the normalized matrix gives the weight of the corresponding criterion or alternative.

To insure the accuracy of the *mean of normalized values method*, the pair-wise comparison matrix consistency ratio must be determined. A lower consistency ratio reflects better accuracy. The Consistency Ratio (C.R.) measures how far a matrix is from being consistent. The C.R. is defined as the ratio of the consistency index (C.I.) to the random consistency index (R.I) for a particular set of judgments (Malczewski, 1999). The C.R is determined using Equation 2.9.

$$C.R. = C.I./R.I \qquad 2.9$$

where:

C.R. is the Consistency Ratio

C.I. is the Consistency Index, and

R.I. is the Random Consistency Index

The Random Index (R.I.) is the random consistency index of a pair-wise comparison matrix, and depends on the number of elements in the pair-wise matrix. R.I values are shown in Table II.3.

TABLE II-3: Random Inconsistency Index (R.I) (Saaty, 1980)

n	1	2	3	4	5	6	7	8	9	10	11	12
R.I	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

If the consistency ratio (C.R.) is ≤ 10 % the results are acceptable and considered consistent. However, results that are >10% indicate inconsistent judgments and so the data is rejected or is sent back to the experts to be modified (Zayed and Chang, 2002; Zayed and Halpin, (2004& 2005); Ali et al., (2007)).

The consistency index (C.I.) is defined as the degree of deviation from consistency (Saaty, 1980). This is obtained by calculating the matrix product of the pair-wise comparison matrix and the weight vectors and then adding together all of the elements of the resulting vector. The consistency of each matrix is checked by calculating its C.I. and its C.R. The C.I. is determined using Equation 2.10 (Han & Tsay, 1998).

$$C.I. = (\lambda_{max} - n)/(n-1) \quad \text{.................................. 2.10}$$

where:

n is the number of criteria (matrix elements)

λ_{max} is the largest Eigenvalue (Han &Tsay, 1998; Malczewski, 1999)

ii. AHP Uncertainty

Saaty (2008) and Buckley (1985) stated that uncertainty lies in the nature of the AHP method. Their concerns were primarily regarding the certainty of the comparison ratios used in the AHP pair-wise comparison matrices. They observed that the decision maker has feelings of uncertainty while he/she is ranking or comparing different alternatives or criteria. They also stated that these uncertainties can be addressed by using fuzzy numbers instead of crisp numbers to compare the importance between the alternatives or criteria.

2.8.5. Multi-Attribute Utility Theory (MAUT)

The multi-attribute utility theory (MAUT) is a useful method for formulizing and analyzing decision-making problems. Some researchers use different terminologies to describe MAUT; sometimes MAUT is referred to as multi-attribute utility measurements (MAUM) or multi-attribute utility analysis (MAUA) (Winterfeldt and Ward, 2007). MAUT is used in this research because it provides a systematic, solid approach for evaluating different alternatives and attributes that affect WWTP infrastructure performance. The MAUT approach helps decision makers compare complex alternatives (Geoffrion et al., 1972). MAUT, similar to the AHP, functions by subdividing or breaking down problems into sublevels. The attributes of each alternative are evaluated accordingly and the overall evaluation of an option is achieved by combining different single attributes into an aggregate function. The AHP is generally used to evaluate different weights that are used in the aggregation process (Misalami, 2001). MAUT provides a logical and tractable means to make tradeoffs among conflicting objectives (Keeney and Raiffa, 1976). The MAUT approach is based on breaking down the problem into alternatives with measurable attributes. Experts are thus required to assign tradeoffs among these attributes. A certain weight reflecting an attribute's importance is provided and quantified into a single attribute. The MAUT method is summarized into the following three steps: the first step is to obtain a multi-attribute utility function that describes the problem; the second step is to find the weight for each of these utility functions, as these weights reflect the attributes' importance. Finally, the attributes or attribute utilities are aggregated in a single utility index for each alternative (Winterfeldt and Ward, 2007).

i- MAUT Structure

The MAUT model is based on showing how much each attribute for each alternative will contribute to achieving the problem's goals. A hierarchical structure is a standard approach to define the different levels of objectives. The high-level objectives represent overall objectives, while the other levels in the hierarchy branch out into a number of lower-level objectives. The lowest level contains the alternative attributes. These attributes are the indicators that are used to measure how each alternative contributes to meeting the objectives. Each alternative should have at least one unique attribute that makes a major contribution to the evaluation objectives (Pitz, 1984).

ii- Attribute Utility Function

Utility is a value that measures risk and that quantifies the value of an attribute's worth. The utility theory reflects experts' opinion in decision models that aid decision makers by providing relative quantifiable values (Keeney and Raiffa, 1976). The function performed by a single utility function, which is an element of a multi-attribute utility function, must be determined. First, single utility functions are checked as to whether they are increasing or decreasing functions. In this research, the function of each utility will be evaluated statistically using best fit curves or discrete values, depending on the attributes obtained from experts. A general utility function is shown in Equation 2.11 (Elmaslamani, 2001).

$$u(x_1, x_2, x_3,...x_n) = f(u_1(x_1), u_2(x_3),...u_n(x_n)) \quad \text{.........................} \ 2.11$$

where :

u(x) single attribute utility function.

iii- Attribute Characteristics

Experts define different attributes that contribute to the evaluation of a problem's objectives. Thompson, (1982) stated that, to avoid cumbersome analysis, it is recommended to have less than 20 attributes. Each attribute must be quantifiable by a suitable attribute measurement. However, non-quantifiable attributes can be defined subjectively, based on expert judgment(s). These subjective attribute scales are expected to have systematic errors, which affect their reliability. However, these are appropriate for certain problems (Campbell, 1975). Upper and lower attribute scope limits are determined using experience or through scientific analysis. Experts need to determine and calculate the weight factors for each attribute that reflects its importance and contribution to the overall utility index (Goicoechea et al. 1982). The AHP is widely used to determine the weighting factors (Belton and Stewart 2002; Weber and Borcherding 1993) and in this research, it is used to calculate the attribute weights using the Eigenvector approach.

iv- Aggregation Utility Value

The additive and multiplicative aggregation rules are the simplest aggregation rules and are typically used to combine attributes' utilities (Winterfeldt and Ward, 2007). In the additive aggregation rule, attribute utilities (scores) are multiplied by the attribute weights (obtained by the Eigenvector approach) and then summed. The additive function is typically used when there is no clear relationship among the various factors that affect the deterioration of different infrastructure units, which is the case in this research. However, if these factors have direct and clear relationships, the additive function will not be able to describe interactions among them. The multiplicative utility function can be used to show such interactions; different interaction methods are extensively discussed by Keeney and Raiffa (1976).

2.9 WASTEWATER TREATMENT PLANTS

Wastewater treatment plants are constructed to protect the environment from excessive overloading from different kinds of pollutants. These plants must meet the appropriate effluent standards. If a plant's operation managers do not respond correctly to plant conditions, environmental damage resulting in the deterioration of human health may occur (David and Paul, 2000). A wastewater treatment plant (WWTP) consists of several systems designed to remove various pollutants from wastewater. Abnormal process conditions at wastewater treatment plants result in the release of water that may contain toxins and unacceptably high levels of dangerous organic and inorganic materials into various water bodies and the general environment (David and Paul, 2000).This study is based on activated sludge wastewater treatment systems because they are among the most widely-used systems; an example of this system is illustrated in Figure II.4.

Wastewater sources can be municipal, industrial or agricultural. Typically, WWTPs are designed to treat wastewater from various sources, such as municipal and industrial wastewater. Municipal wastewater treatment plants are traditionally designed to remove suspended solids, dissolved organic materials, nitrogen, phosphorus and some metals.

WWTP operations and processes must satisfy effluent legislation and requirements, as stated by the relevant health and municipal agencies.

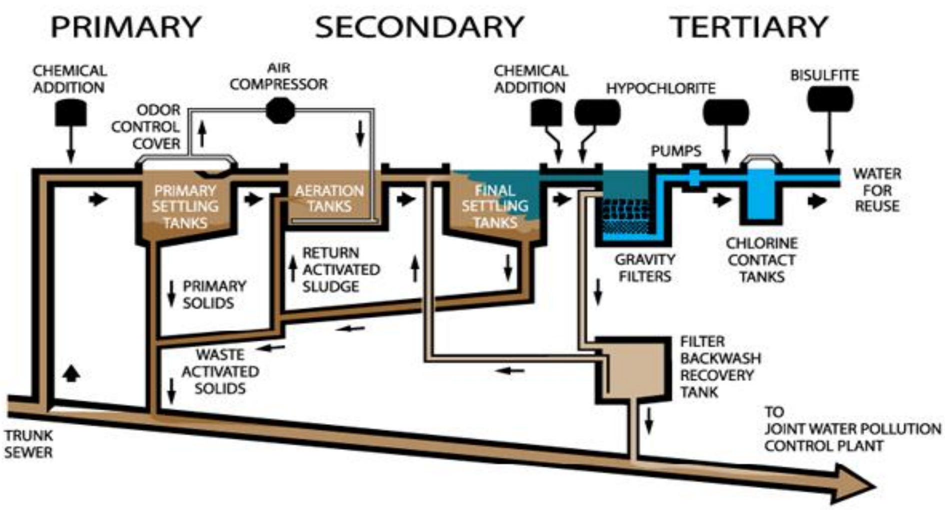


FIGURE II-4: Main Systems of an Activated Sludge WWTP (LACSD, 2007)

2.9.1. Wastewater Treatment Processes

Numerous technologies are used to differentially remove undesirable substances contained in wastewater. Wastewater treatment processes, however, are generally classified into the following three treatment phases (Alberta wastewater commission, 2008; USEPA, 2004).

i. Primary Treatment Phase

Primary treatment processes, or physical treatment processes, in wastewater treatment are processes used to separate solids from wastewater. Solids removal in WWTPs can be achieved by different means such as screening, grit chambers and primary sedimentation tanks. The primary treatment phase removes the heavier solids by gravity. These methods include settling, flotation, filtration and sedimentation. The primary sedimentation tank is the main infrastructure unit in this phase and typically has a removal efficiency of 60% to 70%. A schematic figure of a sedimentation tank is shown in Figure II.5.

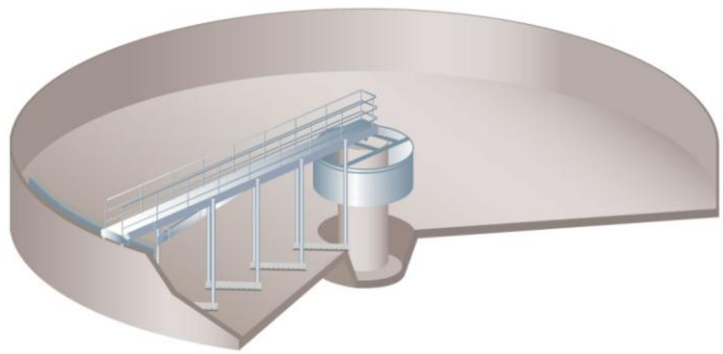


Figure II-5: Primary Sedimentation Tank (Pumpen Engineering, 2009)

ii. Secondary Treatment Phase

The secondary treatment phase in a WWTP is typically known as the biological treatment phase. It is designed for the removal of dissolved organic matter. Microorganisms, mainly bacteria, are used to oxidize dissolved organic matter, resulting in new bacterial cells and other by-products depending on the reaction type, which can be aerobic or anaerobic. In this process, dissolved organic matter is converted into suspended solids, which can then be settled. The oxygen demand for the oxidation process indicates the concentration of the dissolved organic material present in the water.

This oxygen demand is commonly known as the biochemical oxygen demand (BOD) and reflects the strength of the treated wastewater. WWTP efficiency is usually measured by its BOD removal efficiency. Activated sludge, aerated lagoon, bacterial bed, bio-filtration and anaerobic treatments are among the different biological treatment methods. Most treatment plants use the activated sludge system. A schematic diagram for an activated sludge system is shown in Figure II.6.

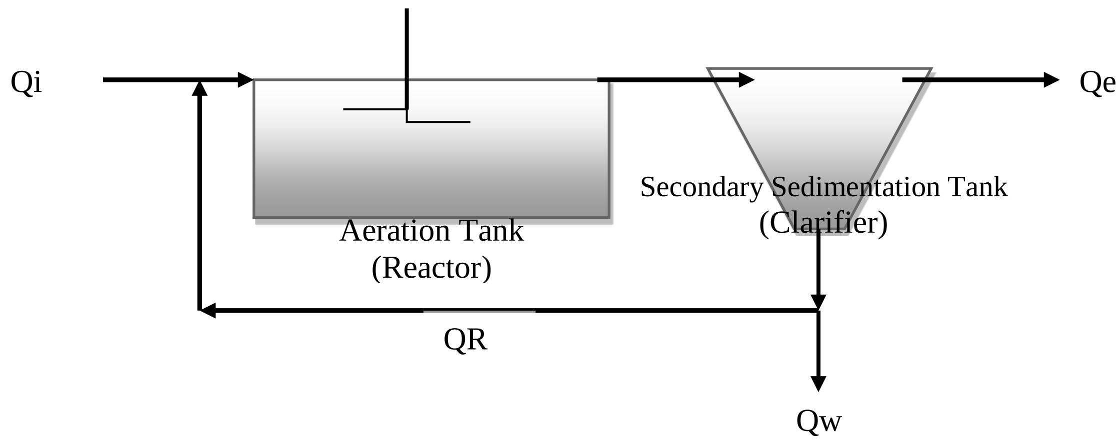


Figure II-6: Activated Sludge System

iii. Tertiary Treatment Phase (Disinfection)

Tertiary treatment typically refers to the chemical and physiochemical treatment processes typically found in water treatment plants. These treatments include coagulation, flocculation, adsorption, oxidation, electrochemical processes and others. In wastewater treatment plants, this phase corresponds to disinfection processes, which are applied to destroy pathogenic microorganisms. Chlorination, Ozonation and ultraviolet rays are the techniques commonly used for disinfection; however, for economic reasons chlorination is the most widely used technique (Communaute Urbaine de Montréal, 2008).

iv. Disinfection By-Products

Chlorine is one of the most reliable disinfectants typically used in water and wastewater treatment processes to destroy pathogens. Unfortunately, during the disinfection process, chlorine reacts with natural organic matter (NOM) in the treated wastewater, resulting in the formation of various disinfection by-products (DBP). These products are found in many forms and compounds. One major group of these disinfection by-products is the trihalomethanes (THMs) and the haloacetic acids (HAAs). THM is typically used to describe four compounds: Chloroform, Dichlorobromomethane (DCBM), Dibromochloromethane (DBCM) and Bromoform. These compounds are typically found in water and wastewater discharges.

THM compounds are known for their adverse health impacts and many studies have demonstrated that THMs are potentially carcinogenic (King and Marret, 1996; Levallois, 1997; Rodriguez et al., 1998; Richardson, 2003). Typical disinfection by-products and their corresponding health impact(s) are shown in Table II.4.

TABLE II-4: Major DBP and Their Health Impacts (US EPA, 1996).

Class of DBP's	Compound	Rating	Detrimental effect
Trihalomethanes (THM)	-Chloroform -Dibromochloromethane -Bromodichloromethane -Bromoform	B2 C B2 B2	Cancer, liver, kidney, and reproductive effects Nervous system, liver, kidney and reproductive effects Cancer, liver, kidney, and reproductive effects Cancer, nervous system, liver and kidney effects
Haloacetonitrile (HAN)	Trichloroacetonitrile	C	Cancer, mutagenic and clastogenic effects
Halogenated aldehydes and ketones	Formaldehyde	B1	Mutagenic b
Halophenol	-Chlorophenol	D	Cancer, tumour promoter
Haloacetic acids (HAA)	Dichloroacetic acid Trichloroacetic acid	B2 C	Cancer, reproductive and developmental effects Liver, kidney, spleen and developmental effects
Inorganic compounds	Bromate Chlorite	B2 D	Cancer Developmental and reproductive effects

B1: Probable human carcinogen (with some epidemiological evidence); B2: Probable human carcinogen (sufficient laboratory evidence); C: Possible human carcinogen; D: Non classifiable; b: Inhalation exposure.

Since chloroform is the most likely THM to form, in addition to its severe health impacts, many studies have based their evaluations on chloroform levels instead of total THM levels (Teksoy et al., 2008). The maximum acceptable concentration (MAC) levels of total THMs stated by the US EPA is 80 - 100 µg/l based on an annual running average (Health Canada, 1996; Sharfenaker, 2001; Rodriguez et al., 2003). THM compounds and their relative concentrations are shown in Table II.5.

TABLE II-5: THM Compounds in Chlorinated Water (Teksoy et al., 2008)

THM Compound	Mean concentration
Chloroform (CHCl3	82.4
Bromodichloromethane (CHBrCl2)	18
Dibromochloromethane (CHBr2Cl)	12
Bromoform (CHBr3)	-

Several studies have shown that THM formation depends on its precursors, mainly total organic carbon TOC, chlorine dose, chlorine residual, pH and reaction time (Trussell and Umphres, 1978; Moore et al., 1979; Kavanaugh et al., 1980; Engerholm and Amy, 1983).

v. Chloroform as THM Indicator

Predicting the formation of THM has been addressed by many studies, and they have shown that it requires very complicated procedures, making them impractical to be applied by WWTP operators. One simple and easy approach with an acceptable accuracy is done using a spectrophotometer test with light of a wavelength of 254 λ nanometres (nm) because THM precursors absorb this light. The THM formation can be determined by multiplying the total organic carbon (TOC) content with the adsorbed light of the wavelength of 254 λ, which is the THM precursor reactivity (UVA) (Amy et al.

1990; Luong et al., 1982). This approach is used in this research to build the disinfection phase condition rating model.

2.10 WASTEWATER TREATMENT PLANT PERFORMANCE EVALUATION

The main function of wastewater treatment plants is to remove or reduce different types of pollutants from the wastewater influent so as to comply with environmental standards for wastewater effluent before discharging it into the environment. WWTPs are designed to achieve these goals by having the proper tools and infrastructures. Therefore, WWTP performance depends on the state of WWTPs infrastructure and the treatment performances of their treatment units.

Wastewater treatment plant infrastructures are designed to support the plant's treatment goals; therefore, any failure in the WWTP infrastructure is expected to affect the WWTP's treatment performance. Efficient inspection of and maintenance procedures for these facilities are the key factors for an acceptable performance.

There are many studies that have measured WWTP treatment performance; however, there is a remarkable lack of studies that deal with WWTP infrastructure evaluation and management. Environmental regulations are always concerned with the characteristics of the effluent discharged from treatment plants, as these regulations are usually a set of restrictions on the quality of effluent that must be met by any WWTP. Wastewater treatment characteristics vary from one WWTP to another on a daily and seasonal basis, which makes the standardization of evaluation procedures for all plants very difficult (Hamed et al., 2004) and their performances are usually evaluated based on local expertise and using non-standard techniques (Hong et al., 2003).

2.10.1. WWTP PERFORMANCE INDICATORS

A performance indicator measures or quantifies a feature of a particular service that can be used to compare performance historically, or against some pre-defined targets. A performance indicator helps to assess, monitor and evaluate the effectiveness of a service (Mussati et al., 2002). Performance measurements indicate the level of service performance and whether it is achieving its goals or not. Performance indicators help managers assess different services, providing managers with proper information on how to allocate efforts and resources (OMB, 2003). Matos et al., (2002) categorized performance indicators into six categories: environmental, personnel, physical, operational, quality of service, and financial. These indicators need to be embedded in the models used to evaluate WWTP performance.

2.10.2. ENVIRONMENTAL PERFORMANCE EVALUATION STANDARDS

Environmental Performance Evaluation (EPE) is a term used to describe the process of measuring, analyzing, reporting, and communicating the environmental performance of a service against specific criteria set by its management (Putnam, 2002). EPE provides a reliable management tool to evaluate the level of a service. ISO-14031 provides guidelines to establish these levels.

i. ISO Standards for Water and Wastewater Facilities

The International Organization for Standardization (ISO) developed and published three standards that deal with water and wastewater systems. These standards are ISO-24510, ISO-24511, and ISO-24512, and they provide standard guidelines to help water and wastewater authorities achieve a desired quality level for their services. In addition, they provide standard guidelines for managing and assessing wastewater services and utilities (IHS, 2008).

2.10.3. WWTP Performance Limiting Factors

WWTP performance evaluation is a complex task that consists of evaluating many separate processes, a task which is not achievable through straightforward procedures. WWTP evaluation and optimization processes can best be described as a philosophy that depends on sustainability and goal achievement (NRC, 2003c). These goals are achieved based on the desired level of treatment with respect to the available expertise and technology. WWTP performance evaluation is a function of a very large number of factors that affect the overall performance of a WWTP. The key factors are called the WWTP performance limiting factors, and they are categorized into operation, design, maintenance, and administration practices, as presented in Table II.6.

The WWTP performance evaluation process aims to identify and prioritize different performance-limiting factors that affect WWTP infrastructure and treatment performances. Various corrective measures are suggested and assessed. The Canadian National Research Council (NRC, 2003c) developed a best practice report that provides a specific approach for optimizing existing WWTPs. Applying best practice tools to existing infrastructure facilities is expected to increase capacity, improve performance, and reduce operating and maintenance costs. Furthermore, the NRC highlights the capacity of the WWTP infrastructure to accommodate the required measures (Kiracofe, 2000; USAID, 2005).

TABLE II-6: WWTP Performance Limiting Factors (NRC, 2003)

Category	Factors
Operation	• Process monitoring • Sludge wasting and disposal • Knowledge of operating staff • Manual and technical support • Availability of equipment • Proper chemical selection and use
Design	• Hydraulic load • Organic load • Oxygen transfer • Inflow and infiltration (I/I) • Instrumentation and control (I&C) • Industrial load • Lack of flexibility • Sludge treatment capacity • Sludge storage capacity • Sludge disposal capacity • Process equipment • Non-modular design • Configuration of process tankage
Maintenance	• Scheduling and recording • Equipment malfunction • Availability of equipment • Skilled manpower • Age of equipment • Knowledge/training of staff
Administration	• Level of staffing • Support from administrative bodies • Financial • Policies • Record keeping • Operator training

2.10.1. WWTP Treatment Performance Modeling &Simulation

Consistent performance evaluation of wastewater treatment plants (WWTPs) can be done by simulating plant performance over a wide range of operational variables, such as influent disturbances, intensity, flows, temperature and other factors. WWTP mechanistic models are able to predict performance to an acceptable level. However, these simulation models require a considerable amount of time and are sensitive to different variables that can affect the simulation's outcome (Rádulya et al., 2007).

In practice, WWTP performance depends on knowing the exact characteristics of the wastewater influent. Unfortunately, the physical, chemical and biological influent characteristics vary dramatically, making their simulation very difficult. Therefore, most WWTP simulation software packages operate under predefined conditions and for specific scenarios. There are many well-developed simulation tools and software that were specifically designed to simulate the behaviour of different elements in WWTPs. Some examples of these tools are BioWin, EFOR, GPS-X, MATLAB & Simulink, SIMBA, STOAT, and WEST.

Each of these software tools has various limitations and shortcomings; therefore, they must be used for specific goals and under controlled parameters. Most WWTP simulation and modelling tools have been used in a variety of studies; mainly, they are used for evaluating the performance of different WWTPs and their compliance with design and effluent standards and regulations. These tools can also be used to optimize the performance of existing WWTPs, to predict future plant expansion requirements, and to accurately design new treatment facilities or upgrades in light of changing wastewater treatment effluent regulations (Desjardins et al., 2001).

i. Activated Sludge Modeling

Activated sludge modeling (ASMs) tools model biomass growth and substrate utilization in the activated sludge systems. These models were developed by the

International Association on Water Pollution Research and Control (IAWPRC) in the early 1980's. Complicated mathematical processes were used in their development. These models, known as ASM1 and ASM2, were each developed and modified to model higher treatment levels, such as phosphorus and nitrogen removal. Unfortunately, due to their complexity, these models have never been used in actual operation modeling and they are typically used only for WWTP design (Henz et al., 2000).

2.11 SUMMARY OF THE LITERATURE REVIEW

Even though many studies have shown the urgent need for management tools, the literature review showed that the research work on WWTP has not been adequate. More specific, the literature review shows lack of research in assessing condition ratings for. This chapter provided an extensive review of the different PAM tools, their applications, benefits and limitations. Despite the fact that several studies have indicated that WWTPs are currently in the worst state among other infrastructure facilities (Statistics Canada, 2008; ASCE, 2009; GAO, 2002; GAO, 2004), little progress has been made to help decision makers evaluate and prioritize the rehabilitation needs of WWTPs.

Typically, WWTP infrastructure deterioration is directly related to the treatment processes conducted in these plants. However, most studies have focused on a specific aspect of the WWTP treatment process or on specific factors that affect the durability of certain infrastructure within a WWTP. There is a remarkable lack of research on WWTP infrastructure deterioration as a whole and its impact over WWTP treatment performance (Connell et al. 2010). This shows a sincere need for effective management tools to manage and upgrade these facilities within the available budgets.

Ch III. Research Methodology and Model Development

3.1 METHODOLOGY OVERVIEW

The WWTP malfunction can be attributed to either operational or infrastructural failure. Firstly, an operational failure occurs when the WWTP cannot satisfy the environmental standards and specifications. This could be due to aging infrastructure or other operational dynamics. This failure can also be due to new, more stringent environmental standards beyond the capabilities of the treatment plant. Secondly, an infrastructure failure occurs when specific infrastructure components deteriorate to unacceptable levels. This often results in loss of serviceability as various treatment operations are affected or even halted.

The methodology of this research is based on developing a PAM for WWTP infrastructure maintenance and rehabilitation. This PAM methodology involves quantifying the performance of the physical state of a WWTP's main infrastructure units in addition to the treatment performance of the WWTP. The developed PAM aims to provide decision makers and plant operators with a management tool to assess and evaluate the capabilities of their WWTPs. This enables them to identify current and future operation and rehabilitation needs.

3.2 RESEARCH STAGES

The PAM methodology followed in this research consists of five stages as shown in Figure III.1. The first stage deals with collecting WWTP data. The developed PAM relies on two types of data: infrastructure and treatment performance. Tanks, pipes and pumps are the WWTP infrastructure units that are considered in the presented research. As for treatment performance, it deals with WWTP pollutant removal efficiencies. The second stage is the development of condition rating indexes for WWTP treatment performance and infrastructures. The third stage of the methodology is to develop deterioration curves for various infrastructure units in a WWTP based on sensitivity analysis. These curves show the relation of condition rating of each infrastructure unit with age over its estimated useful service life. The condition rating of different treatment phases within a WWTP, in addition to their deterioration curves are developed using the weighted sum of these condition ratings of various infrastructures (i.e. tanks, pipes pumps). The fourth stage focuses on developing the repair and rehabilitation alternatives. The objective is to put forward solutions that keep the WWTP functioning within a desired treatment and infrastructure condition rating level. The fifth and final stage optimizes alternatives generated in stage four. At this point, the best interventions are selected for different infrastructure units considering the WWTP's current maintenance and rehabilitation budget.

3.2.1. STAGE I: WWTP TREATMENT AND INFRASTRUCTURE PERFORMANCE DATA

As stated earlier, the first stage in this methodology is data collection. Most WWTPs have good operational and treatment data needed to verify compliance with permits and environmental regulations. The WWTPs infrastructure data (e.g., soil type, geology, ground water levels, construction methods, and materials) are important to predict and analyze WWTP deterioration levels. This stage is the first step toward identifying the WWTP's infrastructure and operational conditions as shown in Figure III-2.

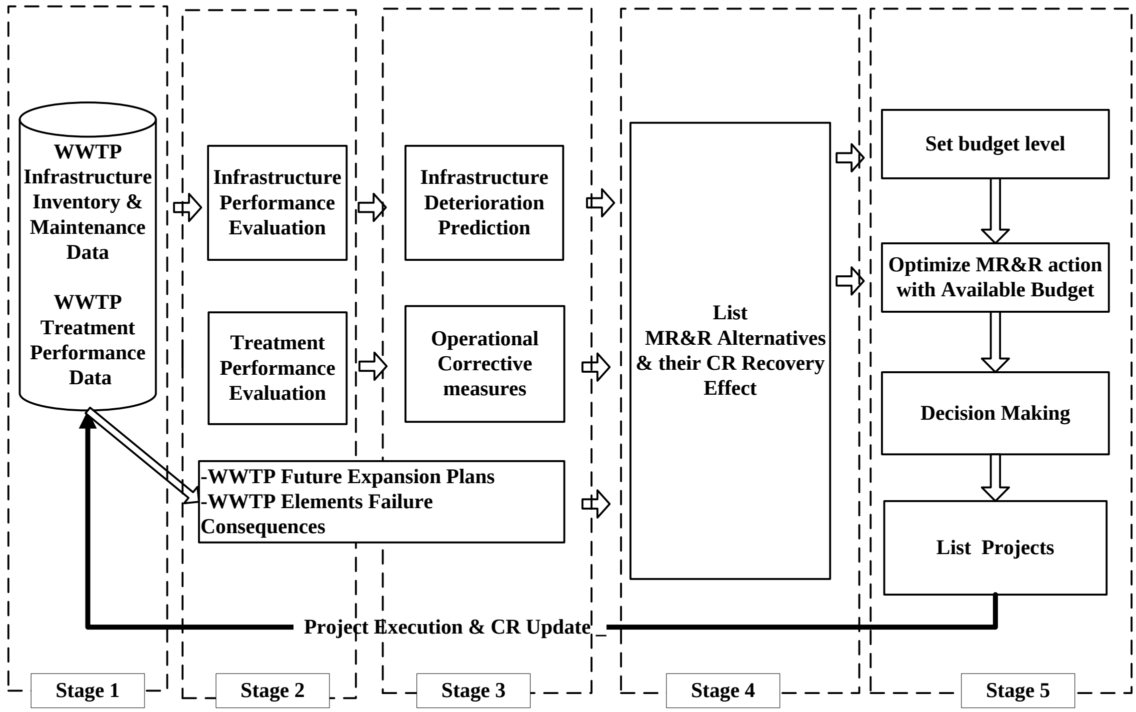


FIGURE III-1: PAM Methodology for WWTP

3.2.2. SAGE II: DEVELOPMENT OF CONDITION RATING MODELS FOR WWTP

The second stage is the WWTP identification or characterization stage. This is where the condition rating models for a WWTP's infrastructure and operational condition are developed. The utilized methodology to develop these models is shown in Figure III.2. Typically, wastewater treatment is divided into three phases: primary, secondary and tertiary. Each treatment phase addresses the removal of specific pollutants. To achieve this, each treatment phase has its own infrastructure elements that are needed for the required treatment. The developed methodology is based on a typical activated sludge system and its treatment phases. The infrastructure units, which are considered in this study, are tanks, pipes, pumps, and blowers.

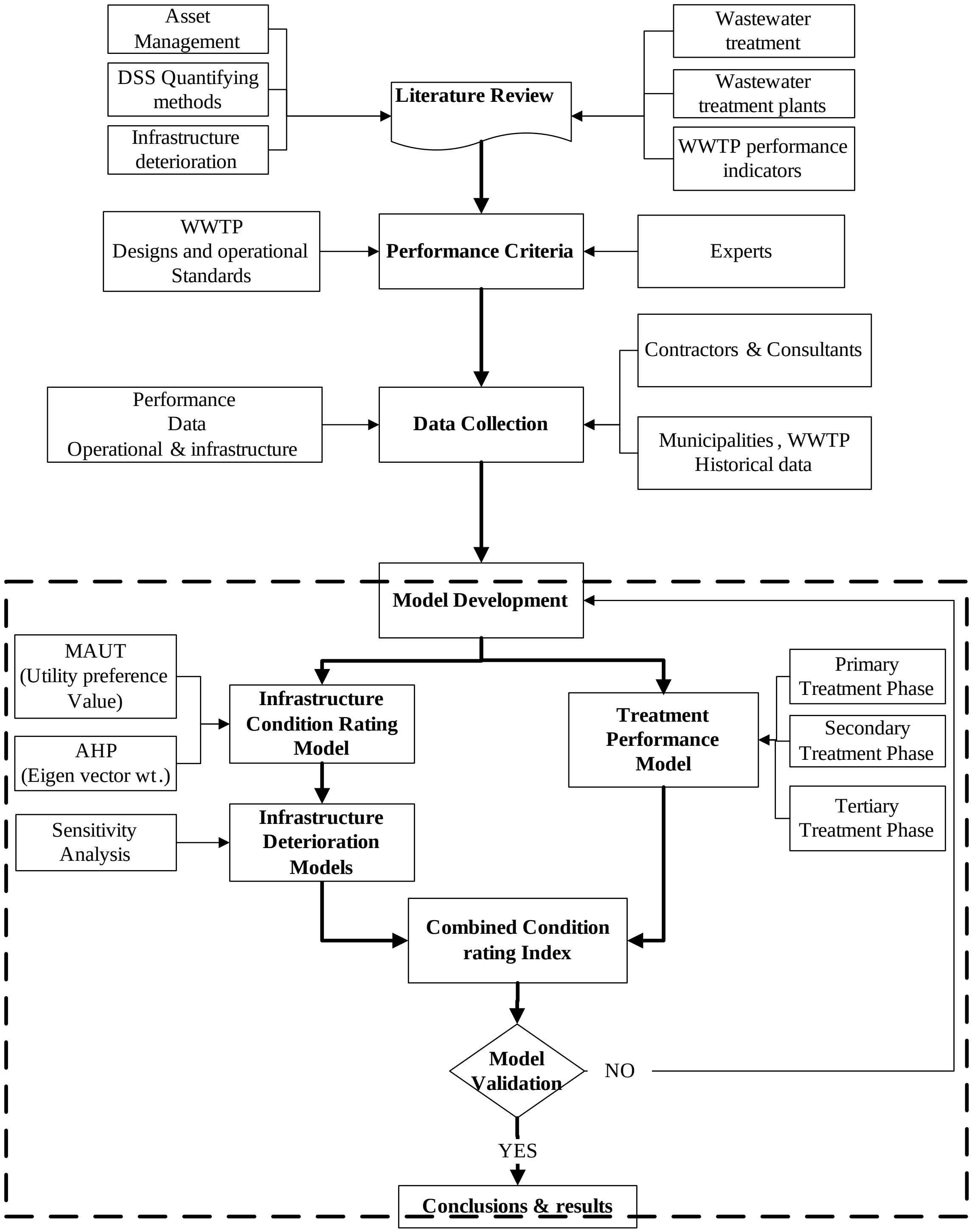


FIGURE III-2: Development Methodology of WWTP CRI

In this study, a WWTP is divided into three treatment phases as shown in Figure III.3. The condition rating models are developed for each phase, where each treatment phase is evaluated by measuring its treatment and infrastructure performances, as illustrated in Figure III.4. The next sections describe how these models are developed. The condition assessment adopted for all phases uses a 0-10 scale, where 10 and 0 represent excellent and failure, respectively. Each condition rating value corresponds to a certain MR&R action that improves the WWTP's operational and infrastructure performances.

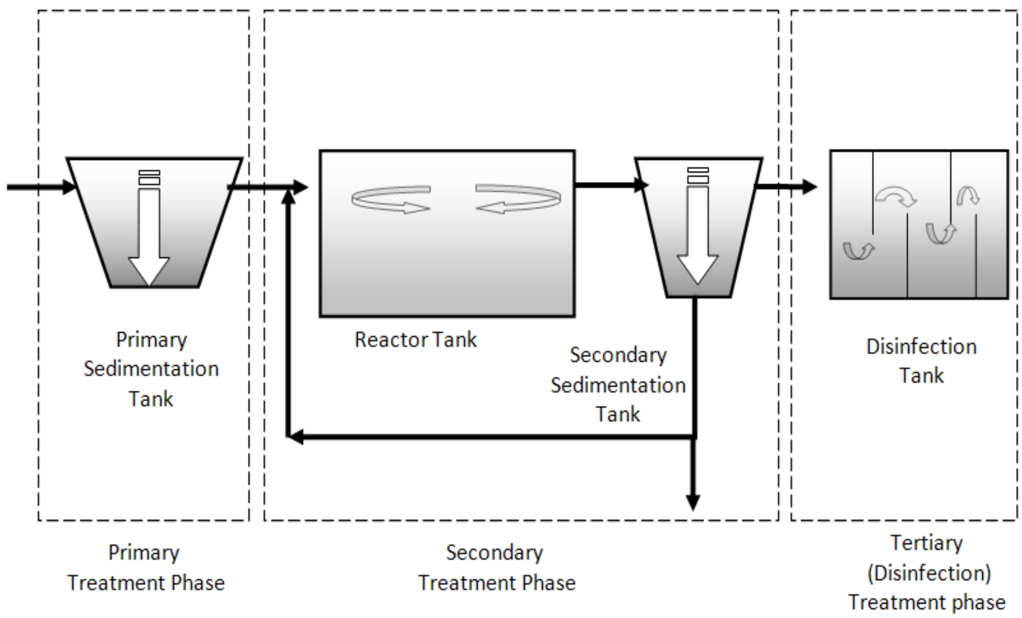


Figure III-3: Typical Treatment Phases of A WWTP

3.3 TREATMENT PERFORMANCE INDEX (TPI) FOR WWTP

The treatment performance of a WWTP is evaluated by measuring the compliance of each phase against its treatment requirements as shown in Figure III-4 .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) no compliance. Moreover, the developed TPI equations introduce reduction factors, which will lower the TPI score if any essential treatment indicator is out of the acceptable range. This approach will 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.

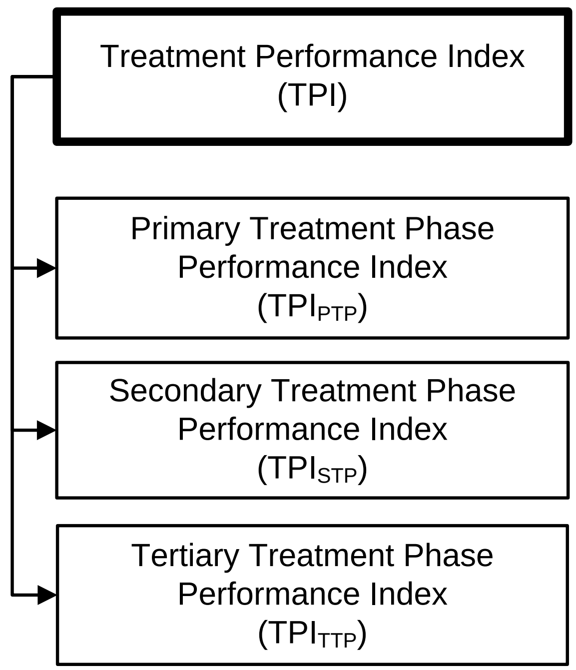


FIGURE III-4: Treatment Performance Index (TPI) WWTP

3.3.1. PRIMARY TREATMENT PHASE PERFORMANCE INDEX (TPI$_{PTP}$)

The primary treatment phase (PTP) in a WWTP pertains to the removal of bulky suspended solids that settle by gravity with a specific time. Although this phase incorporates many small treatment units (e.g., screens grit chambers), the primary sedimentation tank remains the main unit. Thus, this study considers only the primary sedimentation tank illustrated in a schematic diagram in Figure III.5. The effect of other elements in this phase is integrated into the overall performance of this treatment phase.

The key concern here is the removal of the total suspended solids (TSS). As stated in most wastewater treatment literature, the sedimentation tanks remove more than 35% of the influent Biochemical Oxygen Demand (BOD_5) (Warren, 2009). Therefore, the developed TPI_{PTP} for the primary treatment phase equation measures the TSS removal efficiency and the partial removal of BOD_5, as per Equation 3.1 below.

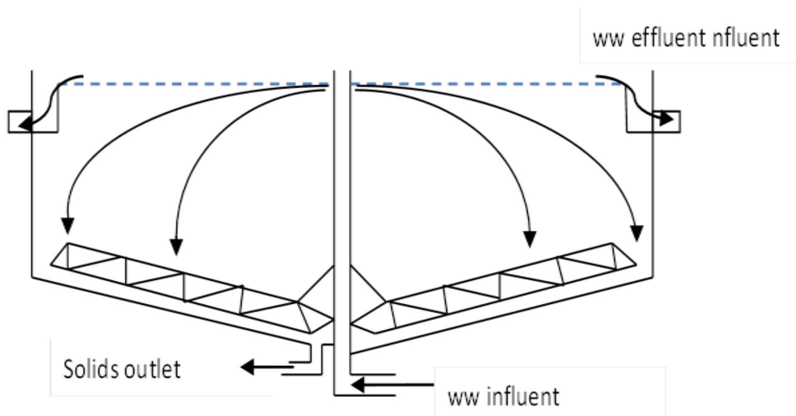


FIGURE III-5: Typical Primary Sedimentation Tank

$$TPI_{PTP} = \alpha TSS_{rem} + \beta BOD_{5rem} \quad \text{……………………………………} \quad 3.1$$

where:

TPI_{PTP} is the treatment performance index of the primary treatment phase

TSS_{rem} is the total Suspended Solids removal efficiency

BOD_{5rem} is the BOD removal efficiency (based on the 35% portion only)

α is a constant representing the weight of TSS removal in the primary phase

β is a constant representing the weight of the BOD_5 removal in the primary phase

The values of the constants α and β depend on the WWTP's design and on 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. Wastewater treatment experts recommend 0.7and 0.3 values for α and β, respectively. In addition, they generally recommend that $\alpha + \beta = 1$ *and* $\alpha \geq 0.6$. Clearly, SS removal takes priority over BOD removal at this stage. The latter is mainly removed in the secondary treatment phase (Tchobanoglouset al. 2002; Syed 1999; Viessman and Hammer 2005). The proposed TPI_{PTP} in this phase is used as a treatment performance 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 WWTP operators need to analyze these factors, as well as other design parameters, to determine the required corrective measures to increase TSS removal efficiency.

3.3.2. SECONDARY TREATMENT PHASE PERFORMANCE INDEX (TPI_{STP})

The secondary treatment phase considered in this research 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 III.6. The first tank, called the reactor, is where microorganisms oxidize soluble organic compounds. In this process, soluble organic matter (BOD_5) is converted into suspended and settleable solids (new microorganisms). To maintain a stable, continuous process, oxygen and other nutrients must be provided to the microorganisms.

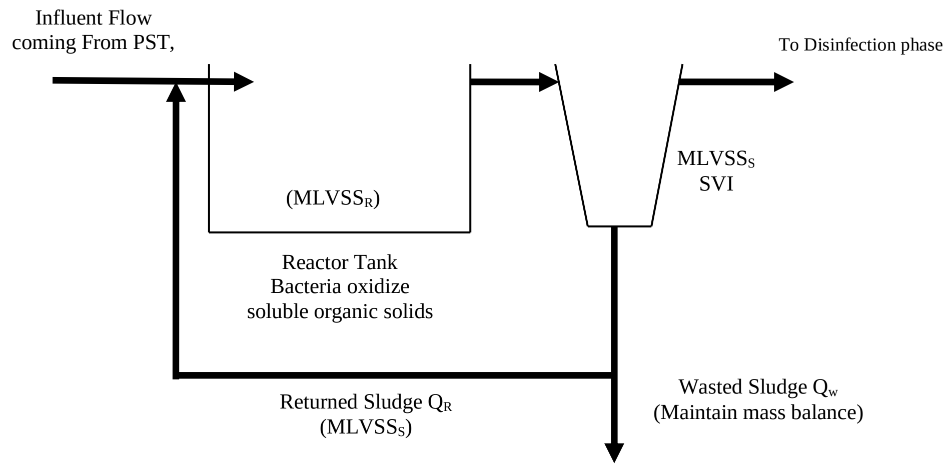


FIGURE III-6: Main Sections of the Activated Sludge System

Oxygen is supplied by either surface or diffused aeration systems in the reactor tank. 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, the second tank in this treatment phase, where microorganisms are stored. The amount of microorganisms sufficient for the biological oxidation is determined based on mass balance and a set F/M ratio. The required amount of microorganisms is transferred to the reactor tank through the returned activated sludge (RAS), and the produced excess is disposed of. This biological treatment process depends on numerous interrelated factors linked in complex ways. Nonetheless, key indicators of the robustness of the treatment process and its performance can be highlighted. This study uses two such indicators: Mixed Liquor Volatile Suspended Solids (MLVSS) and Sludge Volume Index (SVI).

Using the MLVSS in the reactor and in secondary sedimentation tank, the bio-oxidation process is evaluated. This process is the key in any biological treatment. It controls the required F/M ratio and gives WWTP operators the flexibility to control biomass production, storage and disposal. Typically, the MLVSS concentrations in the reactor range from 2500mg/L to 3500mg/L. The MLVSS concentrations in the secondary sedimentation tank range between 25000mg/L and 35000mg/L, ten times the concentration in the reactor. WWTP operators adjust to inevitable fluctuations in the influent concentrations by controlling the F/M ratio. They recommend keeping the F/M ratio conveniently as low as 5, given the relatively low BOD_5 level of the sludge. This research adheres to this suggestion and sets to 5 the targeted value in the developed CRI.

The value of sludge volume index (SVI) reflects the robustness of biological treatment and indicate possible problems associated with this type of treatment, such as presence of filamentous bacteria, sludge rising and sludge buckling. Measuring SVI is an experimentally proven approach to monitor the settling characteristics of activated sludge. The SVI value between 100ml/g and 150ml/g indicates good settling of suspended solids. Table III.1 illustrates SVI values and their possible treatment impacts (Janczukowicz et al., 2001; Qiang et al., 2006). The proposed CRI of the secondary treatment phase aims to provide WWTP operators a proactive tool to control the treatment performance of this treatment phase. The proposed CR measures treatment performance and operational parameters. These elements then indicate the corrective measures required to avoid affecting effluent characteristics. The treatment performance index TPI of the secondary treatment phase (TPI_{STP}) is determined based on its efficiency in removing the influent BOD_5. This is further assessed by looking at the state of the sludge volume index (SVI) and the Mixed Liquor Volatile Suspended Solids (MLVSS) values as well as the $(MLVSS_s)$ $/MLVSS_R$ ratios.

TABLE III-1: SVI and Its Treatment Interpretations

SVI value	Possible Impact
SVI < 50	No impact (excellent)
50 < SVI <100	Acceptable (check nutrients)
100 < SVI <150	Filament growth
150 < SVI <200	Sludge Buckling at high flows
200 < SVI <300	Sludge Buckling
SVI > 300	Severe Buckling

Two reduction factors, γ_{SVI} and β_1, are introduced to reflect the impact of these values on the CRI of this phase. The values of γ_{SVI} depend on the SVI values, as illustrated in Table 3.2. The value of β_1 depends on the value of the $MLVSS_S/MLVSS_R$ ratio. The value of β_1 is equal to 1 if the [$MLVSS_S/MLVSS_R$] ratio is greater or equal to 5, but if the [MLVSSS/$MLVSS_R$] ratio is less than 5, then β_1 is equal to [$MLVSS_S/MLVSS_R$]/5. The CRI_{STP} is determined using Equation III.2.

TABLE III-2: Activated Sludge Settleability & SVI Values (Dimosthenis et al., 2003)

Settleability	SVI (range)	SVI(typical)	γSVI
Very good	0 -50	25	1.00
Good	50 - 100	75	0.90
Fair	100 - 200	150	0.75
Poor	200 -300	250	0.50
Very poor	300 - 400	350	0.25

$$TPI_{STP} = BOD_{5REM}.\beta_1.\gamma_{SVI} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. \ 3.2$$

where:

BOD_{5REM} is the BOD removal efficiency of the secondary phase

β_1 is an MLVSS-dependent factor that reflects the biomass production balance and is based on the MLVSS concentrations in the SST and in the reactor, determined as follows.

$$\beta_1 = \begin{cases} 1 & \text{If } (MLVSS_S / MLVSS_R \geq 5 \\ [(MLVSS_S / MLVSS_R)] / 5 & \text{If } (MLVSS_S / MLVSS_R < 5 \end{cases}$$

γ_{SVI} is a sludge volume index (SVI)-dependent factor that reflects sludge settle-ability; its values can be obtained from Table III-2.

3.3.3. Tertiary Treatment phase Performance index (TPI_{TTP})

In this 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 treatment performance for the disinfection phase reflects disinfection efficiency and the generation of hazardous by-products, as illustrated in Figure III.7.

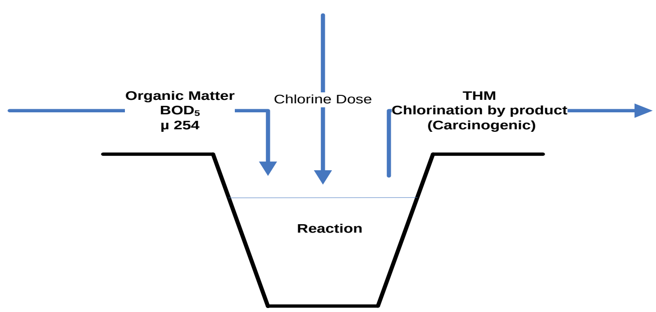


Figure III-7: Disinfection By-Product Formation

Disinfection efficiency is measured by the total coliform count present in the treated wastewater effluent, as this reflects the destruction of pathogenic microorganisms. The total coliform count must not exceed the standard coliform forming unit number (CFU), which is ≤ 25.00 per 100 ml for general-use treated effluent. Studies have shown that high organic matter concentrations in the chlorination basin are associated with a high formation of harmful disinfection by-products. It has also been proven that these compounds have a dangerous, adverse impact on health and the environment and therefore must be included in assessing the performance of this phase.

Studies presented in the literature review have proven that humic organic substances are the main precursors of these disinfection by-products, which can be detected by spectrophotometer at a wavelength of 245 λ. Unfortunately, this simple test is not performed in most of the treatment plants that are part of this study. To validate this approach, samples from S WWTP were tested in the Concordia University environmental labs. Test results indicated that 30% of the BOD_5 influent reacts with free chlorine to form hazardous DBP. A reduction factor for the potential formation of disinfection by-product, ω, is introduced to reflect this possibility. The value of ω depends on the BOD_5 influent values: the higher the BOD_5 entering the disinfection phase, the higher the risk of generating these compounds. Environment Canada recommends a value of 10 mg/l for the treated effluent of WWTP. Therefore, if the BOD_5 concentration is less than 10 mg/l this means fewer chances to form the DBP. BOD_5 values greater than 20 mg/l indicate problems in the secondary treatment phase. However, if the TTP influent BOD_5 is greater than 60mg/l this indicates treatment failure in the STP. In this research the BOD_5 values considered ranges from 10 – 90 mg/l. If the TTP influent BOD_5 is greater than 90mg/l this indicates untreated wastewater. The treatment performance index for the tertiary treatment phase (TPI_{TTP}) is determined based on the number of colony forming unit

(CFU) number violations per month for the disinfected effluent as per the environmental regulations of Ontario's ministry of environment. The TPI_{TTP} calculation is outlined in Equation 3.3. The value of ω depends on the BOD_5 value. The standard BOD_5 effluent must be less or equal to 10 mg/l, therefore if the BOD_5 was less than this value the DBPFP will be minimal, and the value of ω will be 1. Higher BOD_5 values are associated with lower ω values to reduce the CRI_{TTP}. Usually, high influent BOD_5 entering the TTP indicate operational problems in the STP. Hua and Yeats (2009) showed that THM formation has a linear relationship chlorine does. Another study performed by Fuji et al., (1998) found that THM formation potential has a linear relationship with dissolved organic carbon. The BOD_5 influent for the TTP is expected to have linear relationship with THM formation potential in this phase. Therefore the proposed values of ω in this study are linearly proportioned with the BOD_5 as shown in Table III.3.

TABLE III-3: BOD_5 and the Associated Values of ω

BOD_5	ω
$BOD_5 < 10.0$	1.0
$10 < BOD_5 \leq 20$	0.9
$20 < BOD_5 \leq 30$	0.8
$30 < BOD_5 \leq 40$	0.7
$40 < BOD_5 \leq 50$	0.6
$50 < BOD_5 \leq 60$	0.5
$60 < BOD_5 \leq 70$	0.4
$70 < BOD_5 \leq 80$	0.3
$80 < BOD_5 \leq 90$	0.2
$BOD_5 \geq 90$	0.1

$$TPI_{TTP} = \omega . \left(1 - \frac{\sum_{1}^{12} vi}{12}\right) x\ 10 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.3$$

where:

TPI_{TTP} is the treatment performance the (tertiary) disinfection phase

ω is the chlorination by-products formation potential reduction factor with a value of less than 1 depending on the BOD_5 effluent of the secondary treatment phase. The values of ω depend on the BOD_5 of the influent: the higher the BOD_5, the higher the risk of disinfection by-products formation. The BOD_5 values and their ω values are shown in Table III.3.

vi is a binary variable with a value of [0 or 1] depending on the allowable colony forming unit (CFU) value. V = 0 if the CFU is less than 25, and V=1 if the CFU is greater than 25

3.3.4. Overall Treatment Performance Index (TPI) of WWTP

The methodology followed in this research to determine the overall treatment performance index for the WWTP (TPI) is shown in Figure III-8. The weighted sum of the treatment performances of the three treatment phases is used here as explained earlier. The interpretation of the TPI values and the required operational actions are shown in Table III-4.

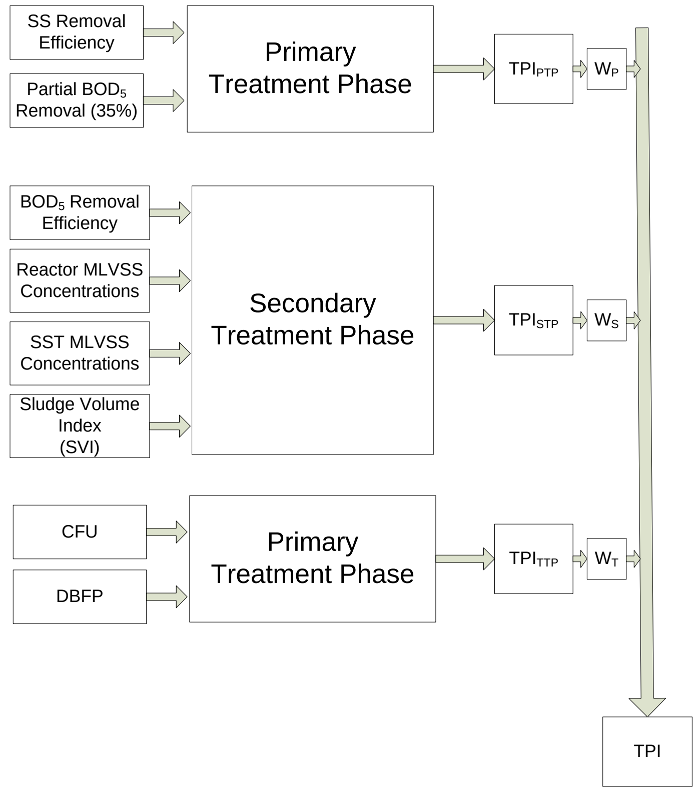


FIGURE III-8: Methodology of TPI Development

Equation 3.4 illustrates how the WWTP TPI is developed. The weights reflect the importance and the level of contribution of each phase to the overall treatment process. The Eigen-vector method is used to define these weights, according to the hierarchy shown in Figure III.9.

$$TPI = w_p TPI_{PTP} + w_s TPI_{STP} + w_t TPI_{TTP} \qquad \text{3.4}$$

where:

TPI	WWTP treatment performance index
TPI_{PTP}	primary treatment phase condition rating
TPI_{STP}	secondary treatment phase condition rating
TPI_{TTP}	tertiary (disinfection) phase condition rating

w_p	relative weight of the primary treatment phase
w_s	relative weight of the secondary treatment phase
w_t	relative weight of the tertiary treatment phase

Table III-4: The TPI Scale and its Interpretations

TPI_{TP}	**Grade Explanation**	**Action Required**
8-10	Excellent condition	No specific action is required, only typical daily routine inspections.
6 - 8	Good Condition	Good condition, minor operational changes required application of some lab tests.
4- 6	Bad to acceptable condition	Bad condition, major operational changes are required.
2– 4	Very bad condition	New operational procedures are required.
<2	Critical condition	Immediate action is required. System re-initialization is required.

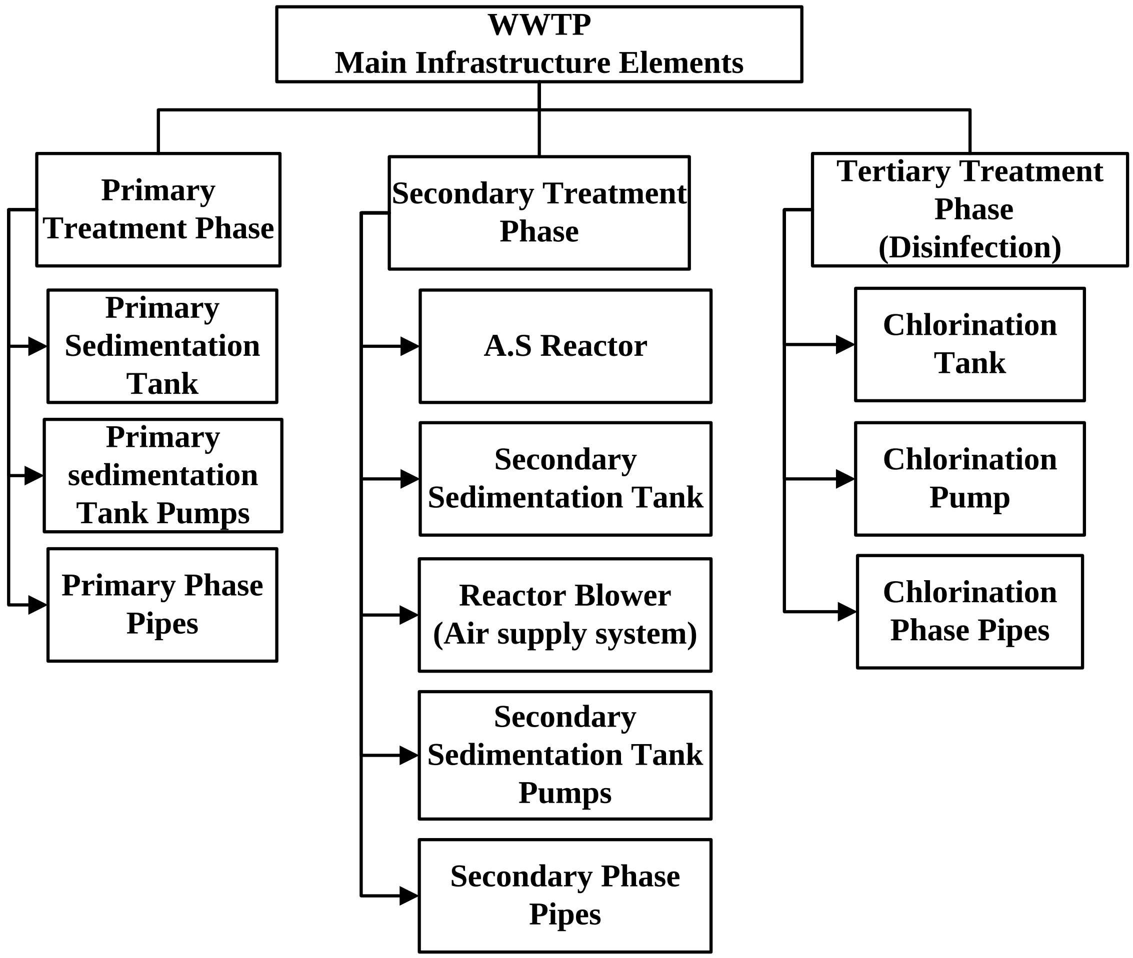


FIGURE III-9: WWTP Hierarchy for Infrastructure Elements

3.4 DEVELOPMENT OF WWTP INFRASTRUCTURE CONDITION RATING INDEX (CRI_{IP})

A WWTP infrastructure condition rating is developed for tanks, pipes, and pumps in each of the three treatment phases as shown in Figure III-10. The proposed CRI for each of these infrastructure elements is based on expert assessment. The AHP-MAUT technique is adopted as per the methodology shown in Figure III.11. The weight of each factor and sub-factor for each infrastructure element is determined using the AHP technique. The AHP weights are obtained from the questionnaire shown in Appendix A. The attributes for these factors are then evaluated using the MAUT technique, as presented in the second part of the survey. The description of different factors and sub-factors for each WWTP infrastructure unit (tanks, pipes, and pumps) is shown in Appendix B. Experts provide their preferred utilities (scores) for these attributes, which are then used to determine the CR. The CR of each infrastructure unit in all treatment phases is the sum of the product of each factor weight and its preference value (score). The proposed condition rating scale is divided into six different categories, ranging numerically from 1to 10, and linguistically from critical to excellent. These six categories and their MR&R counterparts are developed using WWTP experts' inputs and recommendations as presented in Table III.5. The WWTP infrastructure condition rating (CRI_{IP}) is determined using the weighted sums of the infrastructure CRI's of the primary, secondary and tertiary treatment phases.

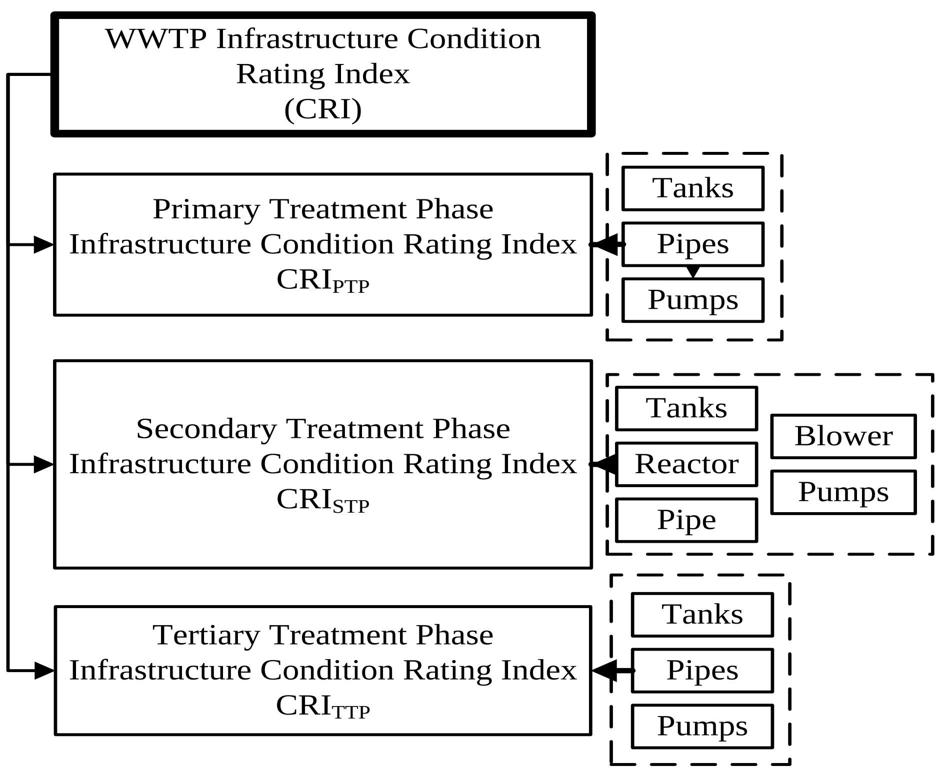


Figure III-10: WWTP Infrastructure Condition Rating Index (CRI_{IP})

TABLE III-5: CRI_{IP} Scale and Its MR&R Interpretations

CRI Numeric Value	CRI Linguistic	Deterioration Level	Maintenance and Rehabilitation Requirements
8-10	Excellent condition	1	No specific maintenance is required, only typical daily routine maintenance
6 - 8	Good Condition	2	Good condition, minor rehabilitation is required
6 - 4	Bad to acceptable condition	3	Bad condition, major rehabilitation action is required but not immediately necessary
4 – 2	Very bad condition	4	Immediate major rehabilitation action is required
<2	Critical condition	5	Immediate and urgent major rehabilitation action is required or immediate replacement is necessary

3.5 WWTP INFRASTRUCTURE CONDITION RATING

The CR for each WWTP infrastructure unit is determined mathematically by summing the products of the weight of each factor, obtained from the AHP, and their associated utility value, as shown in Equation 3.5. The AHP assumes no direct relationship between different factors and it is up to the decision maker to refer to these relations while selecting different attributes.

$$CR_{INF} = \sum_{i=1}^{n}\sum_{j=1}^{m} w_i . v_{ij} . Pv_{ij} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \; 3.5$$

where:

CR_{INF} is the condition rating of a certain infrastructure unit

wi is the relative weight of criteria i

vij is the weight of sub-factor *j* within the *i* factor

Pvij is the sub-factor preference value

3.5.1. WWTP TANK CONDITION RATING DEVELOPMENT

Tanks are the main visible infrastructure units in wastewater treatment plants. They vary in size and shape and have a significant impact on a treatment plant's overall performance. Most WWTP infrastructure tanks are made of concrete. Factors that contribute to the degradation of concrete in a WWTP include abrasion, chemical attack, and freeze-thaw. These forces can significantly reduce the service life of these structures. The WWTP tanks considered in this study are primary sedimentation tanks (PST), reactor tanks (RT), secondary sedimentation tanks (SST) and disinfection or chlorination tanks (CT). The hierarchy of factors and sub-factors for the WWTP tanks are shown in Figure III.12. These factors are associated with different attributes that contribute to the CRI's infrastructure unit depending on their preference values.

The preference value of each attribute is given a utility value for each factor expressing the most and least favourable utility level. Experts are required to assign this utility value ($Pv_{(ij)}$) on a 1 to 10 scale, where 1 is the least preferable and 10 is the most preferable utility level. These values are then used to develop the utility curves for each parameter, which in turn is used to calculate the CR of various infrastructure units. The description of different tank factors and sub-factors shown in Figure III-12 and explained in details in Appendix B.

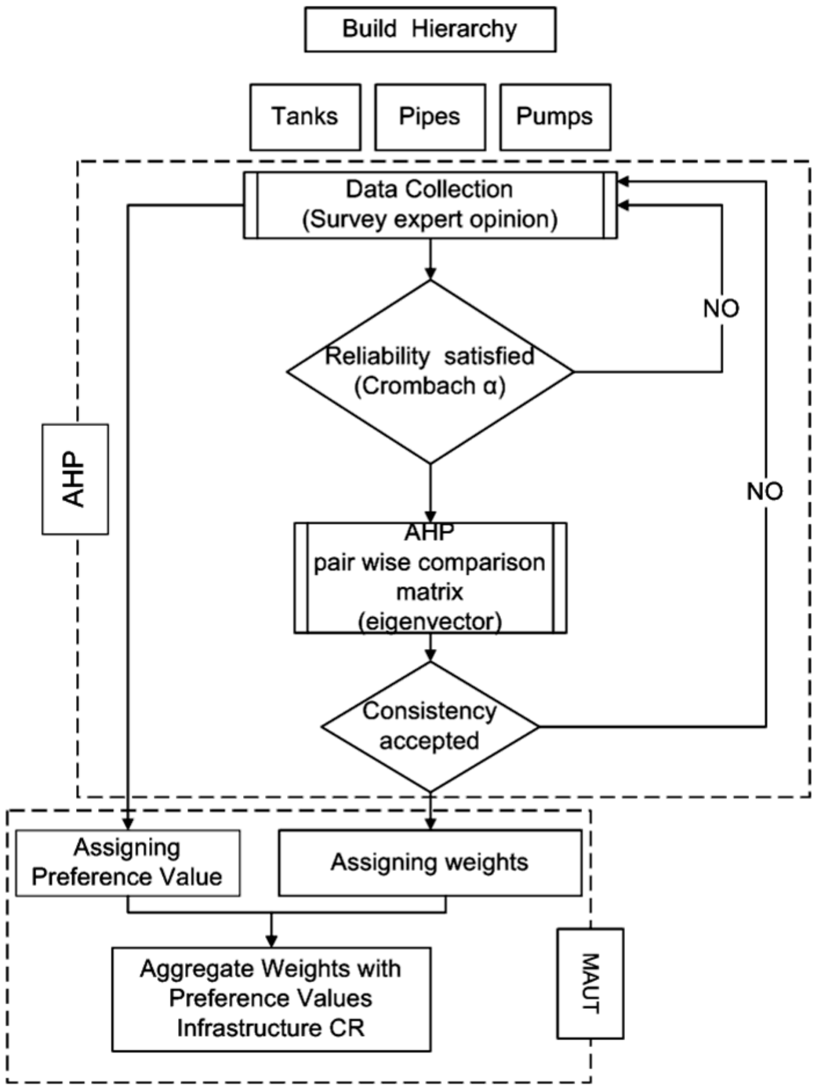


FIGURE III-11: Methodology of Infrastructure CR Model(s) Development

3.5.2. WWTP Pipe Condition Rating

Various factors affect the condition at which pipes deteriorate and fail over time. Deterioration rates for sewer pipes differ from those of WWTP pipes because the latter are flowing full. Other sewer collection systems are designed as open-channel flow. This phenomenon affects pipe degradation due to sulfate attacks that is presumed to form in sewers.

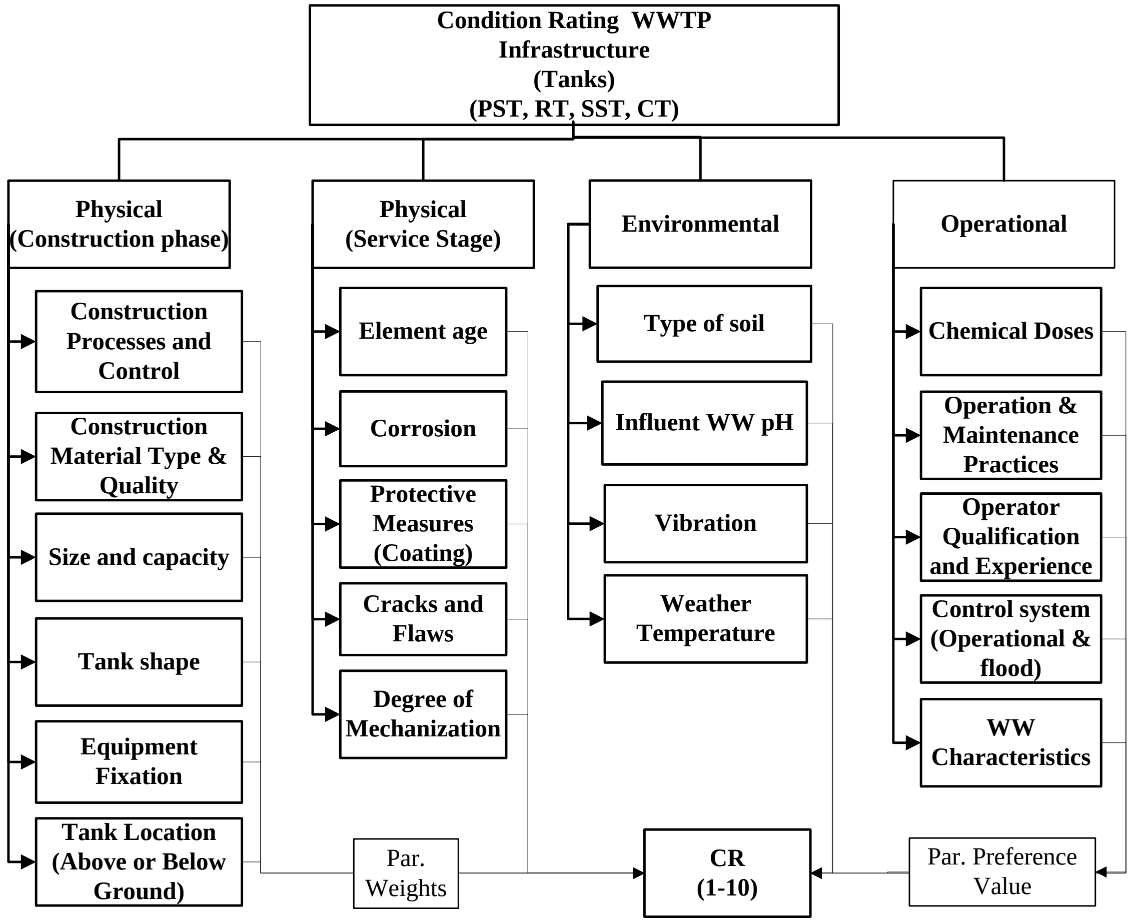


FIGURE III-12: Hierarchal Structure of Factors Affecting WWTP Tank Deterioration

The factors affecting WWTP pipe deterioration is indeed a function of various physical, operational and environmental conditions. The hierarchical structure considered in this study for WWTP pipes is illustrated in Figure III.13.

Similar to tanks, Equation 3.4is used to determine the condition rating of WWTP pipe CRI considering their weights and utility preference values. Factors affecting WWTP pipe deterioration examined in this research, their description and preference utility values are shown in Appendix B.

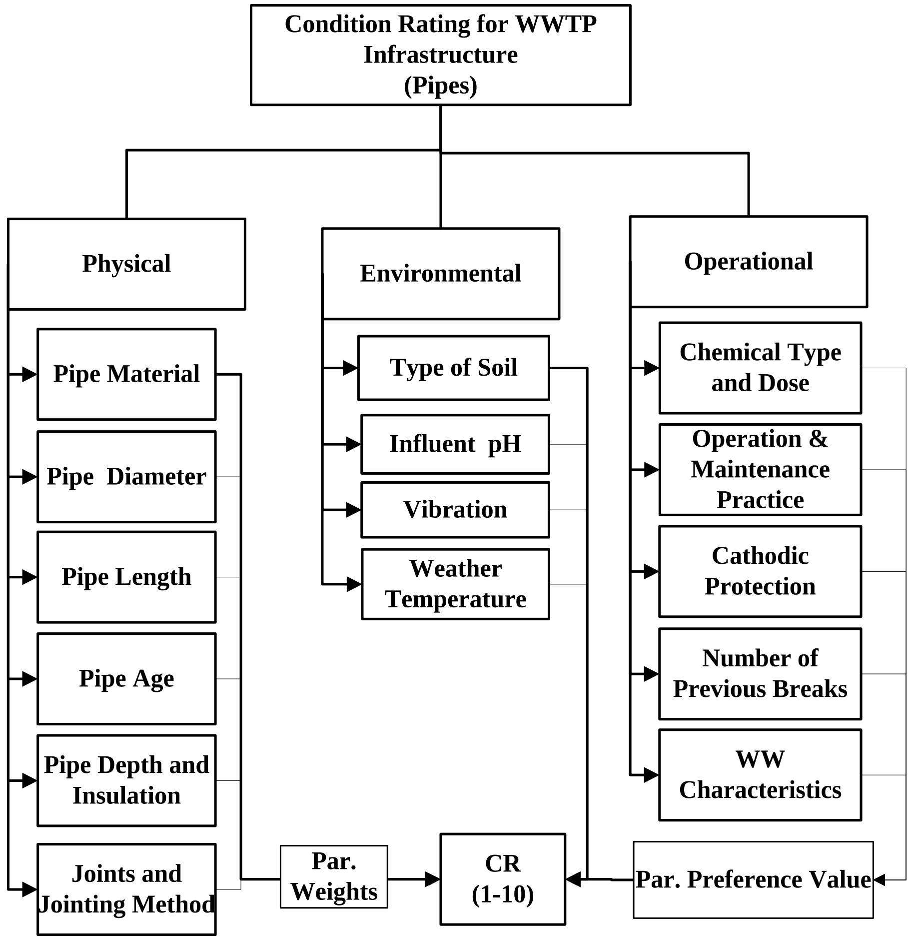


FIGURE III-13: Hierarchal Structure of Factors Affecting WWTP Pipe Deterioration

3.5.3. WWTP PUMP/BLOWER CONDITION RATING

WWTP pumps play a major role in treatment processes; their failure or malfunction affects the whole treatment process. Their performance depends on physical, operational and environmental factors, the hierarchy of which is shown in Figure III.14. The description and significance of these factors are summarized in Appendix B. A WWTP pump's CRI is determined using Equation 3.4, which is the same approach used to calculate the CR of WWTP tanks and pipes. The preference utility levels of the factors affecting WWTP pumps need to be identified in order to apply Equation 3.5; which are also shown in Appendix B.

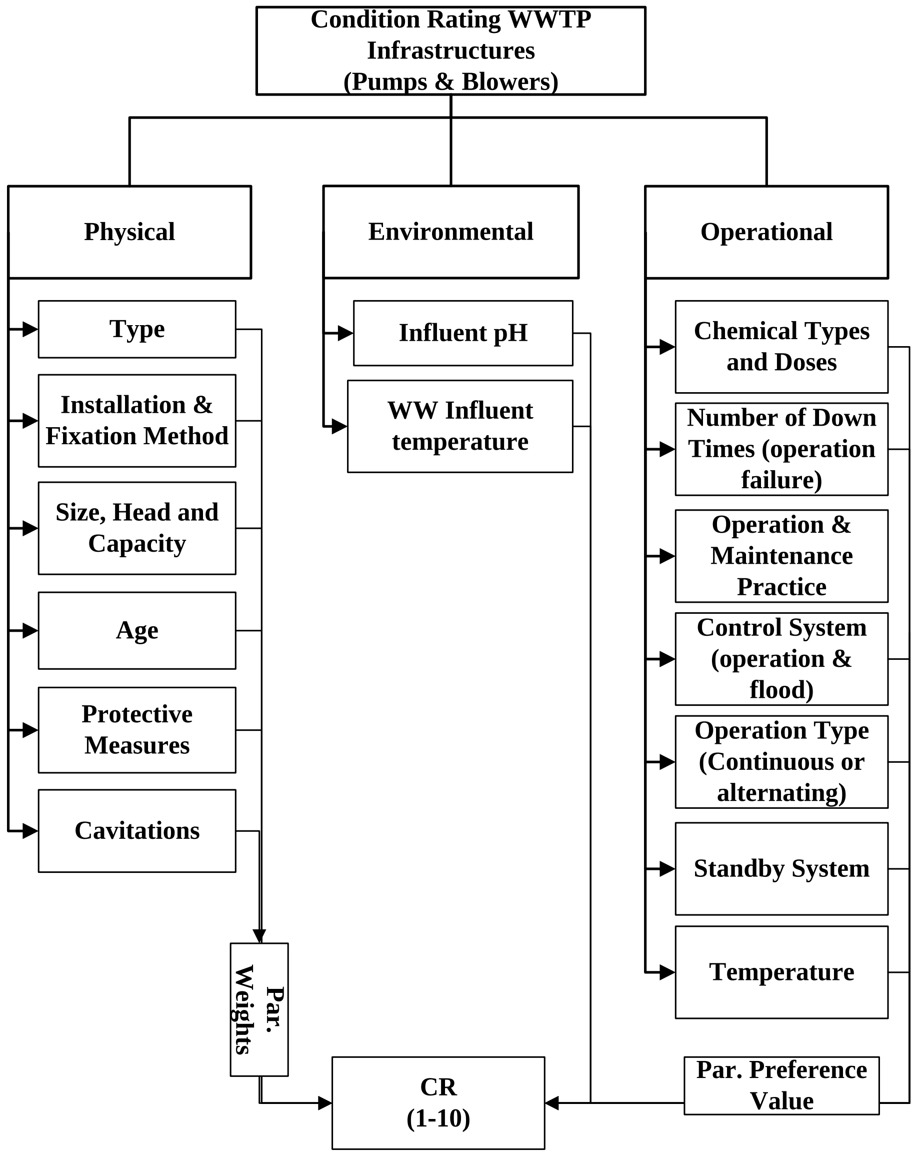


FIGURE III-14: Hierarchical Structure of Factors Affecting WWTP Pumps Deterioration

3.5.4. WWTP INFRASTRUCTURE CRI (CRI_{IP})

The condition rating of a WWTP infrastructure (CRI_{IP}) is a score that reflects the overall condition of the WWTP by quantifying its overall infrastructure performance. The methodology to determine CRI_{IP} is shown in Figure III.15. The integrated condition rating of each treatment phase is used as per Equation 3.6.

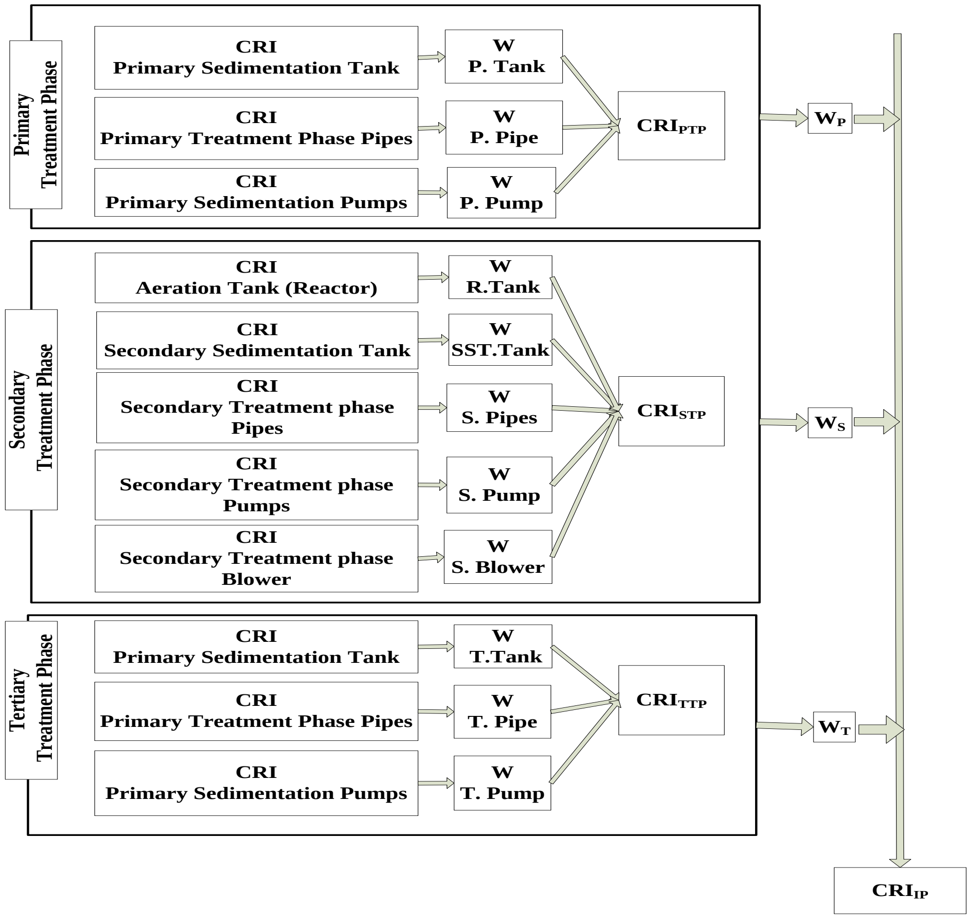


FIGURE III-15: WWTP Infrastructures Condition Rating (CRI_{IP})

$$CRI_{IP} = \sum_{l}^{p} \varpi_l \sum_{k=1}^{o} \theta_{kl} \sum_{i=1}^{n} \sum_{j=1}^{m} w_i . v_{ij} . Pv_{ij} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 3.6$$

where

CRI_{IP} is the condition rating of all of the wastewater treatment plant infrastructures,

ϖ_l is the weight of each treatment phase (see Figure 3.7), and

θ_{kl} is the weight of each infrastructure element in each treatment phase.

3.6 WWTP COMBINED CRI ($WWTP_{CCRI}$)

The WWTP combined condition rating index ($WWTP_{CCRI}$) concerns both the WWTP infrastructure CR (CRI_{IP}) and treatment performance index (TPI). This $WWTP_{CCRI}$ quantifies the overall performance of a WWTP. Figure III.16 is mapping the overall performance of a WWTP through the CCRI matrix. The WWTP infrastructure CRI_{IP} is in the rows, while the WWTP treatment performance CRI_{TP} is in the columns, as illustrated in Figure III.16a. The CCRI matrix makes it easy to communicate and map the state of a WWTP's operation and infrastructure to different management levels. It also greatly facilitates the classification of rehabilitation demands for a WWTP. The $WWTP_{CCRI}$ cells located above the main diagonal of the matrix have better treatment conditions, while cells located below it have better infrastructure conditions. The bigger the difference between rows and columns of the $WWTP_{CCRI}$ matrix, the bigger the difference between the WWTP's infrastructure conditions and treatment performance. The developed $WWTP_{CCRI}$ is an additive function of the WWTP treatment performance index (TPI) and infrastructure condition rating (CRI_{IP}), determined using Equation 3.7. The $WWTP_{CCRI}$ matrix is shown in Figure III.16b.

$$WWTP_{CCRI} = CRI_{IP} + TPI \qquad \text{3.7}$$

The additive equation 3.7 makes it easy to interpret the extreme values. For example, if the $WWTP_{CCRI}$ has values between 16 and 20, the WWTP infrastructure and treatment performance are excellent. Similarly, for the extreme lower values in the range of 2 to 6, the WWTP infrastructure's and treatment performance are critical. However, other values will not be easily interpreted unless they are presented in the combined condition rating index matrix (CCRI). This matrix can easily reflect the treatment and infrastructure performances of a WWTP and therefore can help communicate and interpret this among different management levels. The $WWTP_{CCRI}$ values are shown in Figure III.16b and the interpretation of $WWTP_{CCRI}$ is shown in Figure III.16c.

WWTP Treatment Performance Index (TPI) (T) →

WWTP Infrastructure CR I_{IP}(I) ↓

	1	2	3	4	5	6	7	8	9	10
1	I_1T_1	I_1T_2	I_1T_3	I_1T_4	I_1T_5	I_1T_6	I_1T_7	I_1T_8	I_1T_9	I_1T_{10}
2	I_2T_1	I_2T_2	I_2T_3	I_2T_4	I_2T_5	I_2T_6	I_2T_7	I_2T_8	I_2T_9	I_2T_{10}
3	I_3T_1	I_3T_2	I_3T_3	I_3T_4	I_3T_5	I_3T_6	I_3T_7	I_3T_8	I_3T_9	I_3T_{10}
4	I_3T_1	I_4T_2	I_4T_3	I_4T_4	I_4T_5	I_4T_6	I_4T_7	I_4T_8	I_4T_9	I_4T_{10}
5	I_3T_1	I_5T_2	I_5T_3	I_5T_4	I_5T_5	I_5T_6	I_5T_7	I_5T_8	I_5T_9	I_5T_{10}
6	I_3T_1	I_6T_2	I_6T_3	I_6T_4	I_6T_5	I_6T_6	I_6T_7	I_6T_8	I_6T_9	I_6T_{10}
7	I_3T_1	I_7T_2	I_7T_3	I_7T_4	I_7T_5	I_7T_6	I_7T_7	I_7T_8	I_7T_9	I_7T_{10}
8	I_3T_1	I_8T_2	I_8T_3	I_8T_4	I_8T_5	I_8T_6	I_8T_7	I_8T_8	I_8T_9	I_8T_{10}
9	I_3T_1	I_9T_2	I_9T_3	I_9T_4	I_9T_5	I_9T_6	I_9T_7	I_9T_8	I_9T_9	I_9T_{10}
10	I_3T_1	$I_{10}T_2$	$I_{10}T_3$	$I_{10}T_4$	$I_{10}T_5$	$I_{10}T_6$	$I_{10}T_7$	$I_{10}T_8$	$I_{10}T_9$	$I_{10}T_{10}$

FIGURE III-16a: $WWTP_{CCRI}$ Matrix

WWTP Treatment Performance Index (TPI) (T) →

WWTP Infrastructure CRI_{IP} (I) ↓

	1	2	3	4	5	6	7	8	9	10
1	2	3	4	5	6	7	8	9	10	11
2	3	4	5	6	7	8	9	10	11	12
3	4	5	6	7	8	9	10	11	12	13
4	5	6	7	8	9	10	11	12	13	14
5	6	7	8	9	10	11	12	13	14	15
6	7	8	9	10	11	12	13	14	15	16
7	8	9	10	11	12	13	14	15	16	17
8	9	10	11	12	13	14	15	16	17	18
9	10	11	12	13	14	15	16	17	18	19
10	11	12	13	14	15	16	17	18	19	20

FIGURE III.16b: $WWTP_{CCRI}$ VALUES

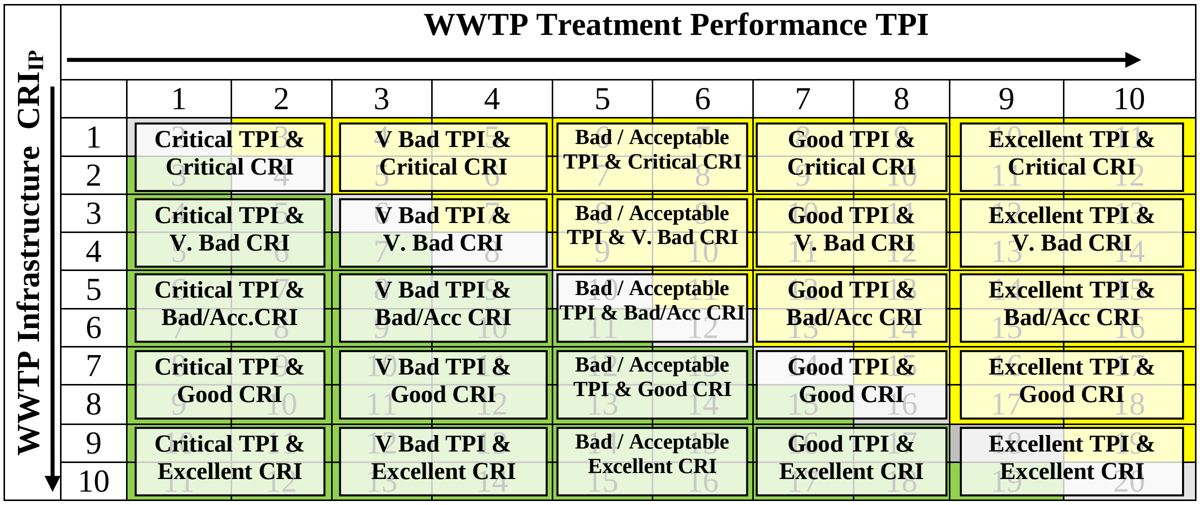


FIGURE III.16c: WWTP$_{CCRI}$ Value Interpretation

3.7 STAGE III: MR&R ACTIONS AND SERVICEABILITY LEVELS

The condition rating of different infrastructure elements in a WWTP is associated with specific MR&R rehabilitation actions. For each infrastructure unit (tanks, pipes and pumps) a CR threshold is defined to establish priorities of MR&R interventions in the WWTP**.** Thresholds indicate minimum-allowable and -acceptable levels of service. Once a CR of any infrastructure unit approaches or falls below these thresholds, a suitable MR&R action is enforced to prevent this element from further deterioration. The conceptual use of infrastructure deterioration curves as a MR&R planning tool is shown in Figure III.17, and is further addressed in the optimization model.

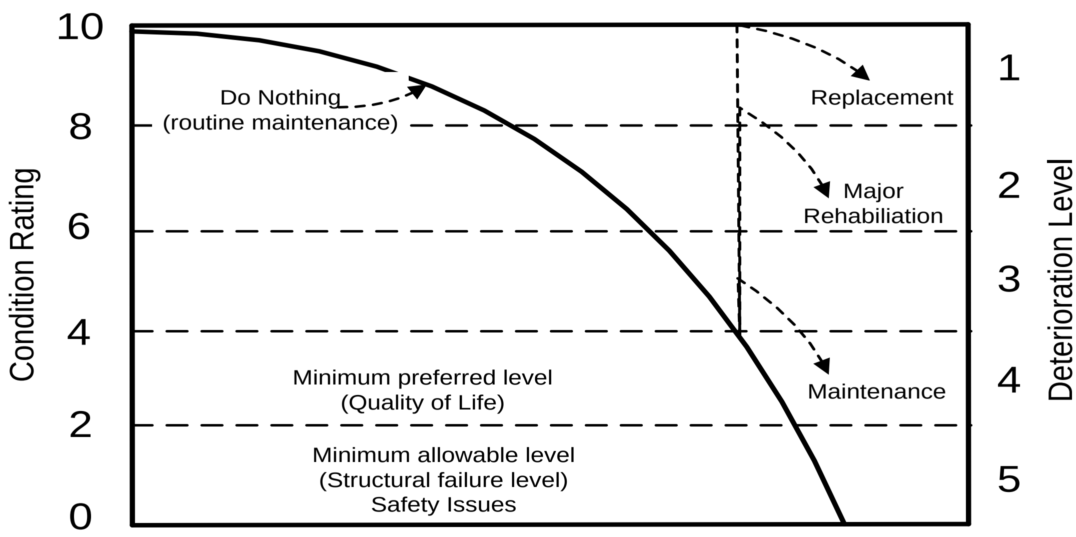


FIGURE III-17: CR Threshold and MR&R Actions

3.8 STAGE IV: WWTP MR&R ACTION TYPES AND THEIR RECOVERY EFFECTS

Defining the required MR&R actions for a WWTP depends on its environmental performance and its infrastructure needs. Based on the WWTP's current treatment levels, for each treatment phase, corrective measures are defined to raise the treatment performance to the desired level. These corrective measures can be operation dependent requiring only some operational modifications. They can be both operation and infrastructure dependent, where the required operational modifications depend on certain upgrades in the infrastructure facility. They can also be only infrastructure dependent, requiring solely an infrastructure upgrade. The procedure to define different WWTP MR&R lists and their corrective measures depending on their CR is illustrated in the flow chart shown in Figure III.18.

In this research, different MR&Rs are classified into four action groups. Each action group contributes to the CR by a certain percentage, which is proportional to its implementation cost. The MR&R groups considered in this study are do nothing, minor rehabilitation, major rehabilitation and replacement. These groups were adopted in previous studies because it simplifies the implementation of different maintenance and rehabilitation practices. Each group will change the condition rating with a certain percentage. The condition rating and their recovery percentages are shown in Table III.6 (Chunlu et al., 1997; Wu, 2008).

TABLE III-6: MR&Rs and their CR Recovery

MR&R action	**Recovery Factor**
Do nothing	-5 % to 0 %
Minor Rehabilitation	10 % to 25 %
Major Rehabilitation	26 % to 60%
Replacement	61 % to 100 %

The deterioration curve of each infrastructure unit is used to define the infrastructure MR&R alternatives, restricted by the minimum required CR threshold. These MR&R alternatives are optimized based on the available MR&R budget and constrained by the desired serviceability level of each infrastructure unit, as shown in Figure III.19.

3.5.1. MR&R Cost and CR Recovery

Determining the rehabilitation cost is a vital step in selecting the best MR&R alternative. Four major rehabilitation options are considered in this research: do nothing, maintain, rehabilitate, and replace. MR&R interventions are categorized based on their CR recovery effect and their cost. The rehabilitation cost and its associated CR recovery for each MR&R group must be proportional to the replacement cost assuming 100%

recovery of the CR. This approach is used to accept or reject MR&R interventions and to ensure the cost is consistent with the expected CR recovery.

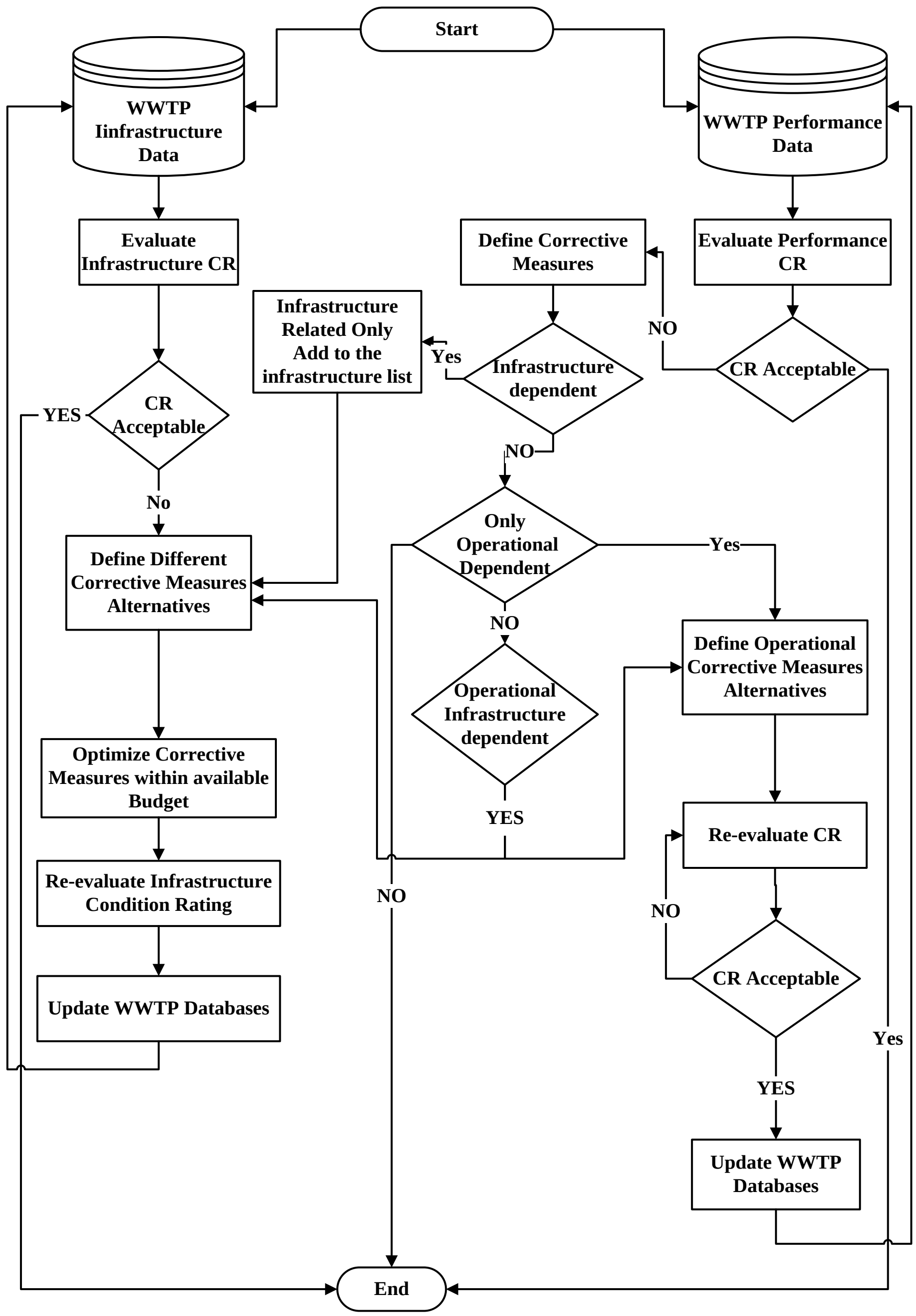


FIGURE III-18: WWTP Corrective Measures

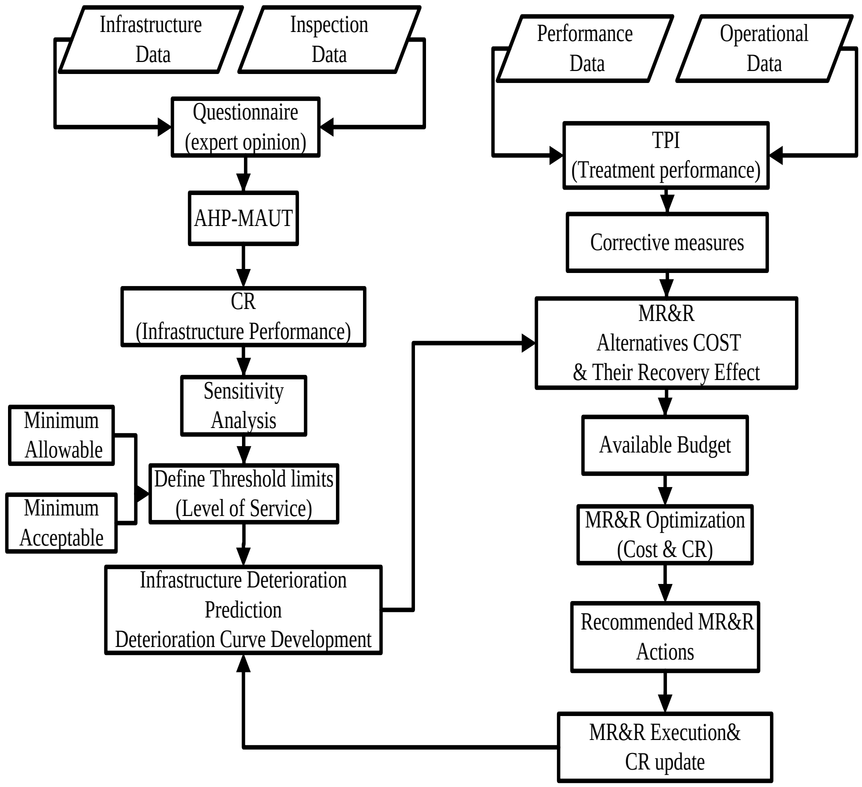


FIGURE III-19: WWTP Rehabilitation Alternatives

3.9 STAGE V: WWTP MR&R OPTIMIZATION APPROACHES

To select the optimal MR&R for a WWTP, decision makers need to consider many factors. These include current treatment levels and infrastructure CRs, minimum and allowable CR thresholds, and the remaining service life of each WWTP infrastructure unit. In addition, experts need to define the cost of different MR&R interventions and their condition recovery effects. Two practical optimization approaches based on these factors are considered in this study. This section shows the development of these optimization approaches, their objective functions and their constraints. The methodology for these approaches is shown in Figure III.20.

3.9.1. Minimize MR&R Intervention Cost

The first optimization approach is to minimize the MR&R intervention cost keeping the CR of all infrastructure units higher than or equal to the designated threshold. This approach answers the question: What is the minimum cost needed to achieve the required WWTP CRI? Each treatment phase has infrastructure units (i.e., tanks, pipes, and pumps) that are subject to certain MR&R interventions. Considering the four major rehabilitation categories mentioned above, only one action can be applied to a given infrastructure unit. The selection of a certain MR&R action is based on the level of service desired, represented by the desired CRI. The MR&R action applied to each unit has, however, an effect over its future condition rating (CRI_{t+1}), which must be greater than or equal to the current condition rating (CRI_t). The only exception is the do-nothing option, which allows further deterioration and will lower its future condition rating value with no cost, as shown in Table III.4. To maintain the entire WWTP, (4^9= 262144) MR&R possibilities are considered.

The objective function for this optimization is to minimize the MR&R intervention cost, as illustrated in Equation 3.7, constrained by the minimum required CR and the MR&R budget.

$$Minimize\ Y = \sum_{u=1}^{o}\sum_{p=1}^{n}\sum_{a=1}^{m} x_{pa}^{u} C_{pa}^{u} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 3.7$$

where:

x_{pa}^{u} is the decision variable that simulates the intervention action [a]; this variable can be either 0 [no action] or 1 for [action]

C is the cost of an intervention MR&R action p	is the treatment phase (primary, secondary, tertiary)

a	represents the MR&R intervention actions (four actions are considered)

u	represents the infrastructure unit (Tanks, Pipes, or Pumps)

Y	MR&R intervention cost, must be ≤ the available budget

The objective function shown in Equation 3.7 is constrained by the available MR&R budget and the minimum desired CRI for each infrastructure unit in the three treatment phases, as illustrated in Equation 3.8.

$$CRI_{t+1}^{u} = CRI_{t}^{u} + x_{sta}^{u}\Delta CRI_{a}^{u} \geq CRI_{\min}^{u} \quad \text{....................3.8}$$

where:

CRI^{u}_{t+1}	is the CRI of the infrastructure unit after implementing a certain MR&R action
CRI^{u}_{t}	is the current CRI of the infrastructure unit (before applying any MR&R action)
CRI^{u}_{min}	is the minimum desired CRI for the infrastructure unit [u]

3.9.2. MAXIMIZE THE WWTP INFRASTRUCTURE CR (MAX CRI_{IP})

The second optimization approach adopted in this study is to maximize the CR rating of the WWTP's infrastructures without exceeding the MR&R budget. This approach determines the maximum achievable condition rating for the WWTP infrastructures (CRI_{IP}) within a certain rehabilitation budget. The objective function for this optimization approach is shown in Equation 3.9. This equation is simply the weighted sum of the infrastructure condition ratings of the three treatment phases of a WWTP presented in Figure III-15.

$$Maximize\ CRI_{IP} = \sum_{l}^{p} \varpi_l \sum_{k=1}^{o} \theta_{kl} \sum_{i=1}^{n} \sum_{j=1}^{m} w_i . v_{ij} . Pv_{ij} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 3.9$$

where:

CRI_{IP} is the condition rating index of the WWTP infrastructures (see equation 3.5 and 3.6)

ϖ_l is the weight of each treatment phase (see Figure 3.7), and

θ_{kl} is the weight of each infrastructure element in each treatment phase.

This objective function is constrained by available MR&R budget, as expressed in Equation 3.10, as well as the minimum desired CR threshold for each infrastructure unit, as per Equation 3.8.

$$\sum_{u=1}^{o} \sum_{p=1}^{n} \sum_{a=1}^{m} x_{pa}^{u} C_{pa}^{u} \le budget \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.10$$

Binary integer programming is selected as the ideal approach to solve the optimization objective functions since the MR&R decision can only be 1 or 0 for each MR&R alternative. The optimization functions are coded and solved using the Lingo program, as illustrated through a case study in Chapter 5.

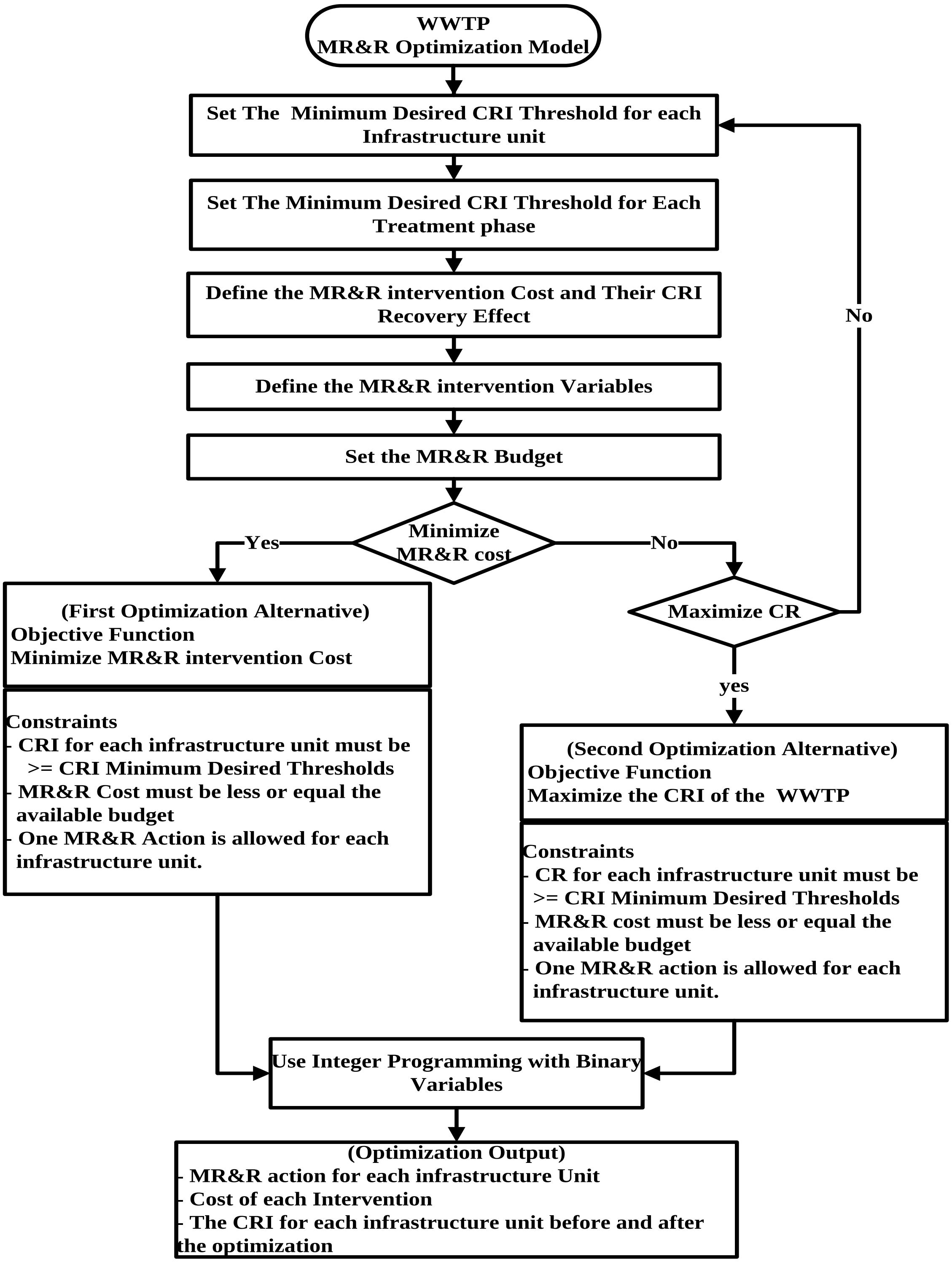


Figure III-20: MR&R Optimization Methodology

Ch IV. Data Collection

4.1 WWTP Data Collection

In order to develop the CRI models for WWTP, a lot of data is required. The necessary data can be classified into two types. The first data type is the wastewater treatment plant infrastructure's historical data, which is needed to develop the condition rating models of the WWTP infrastructure. The second data type is the treatment performance data, which is needed to develop the WWTP treatment performance. The required infrastructure data includes materials used, material quality, year of installation, size, soil types, pipe diameters, installation procedures and standards, and maintenance records. However, most of the required data and maintenance records were not found for most of the contacted wastewater treatment plants. Due to this fact, an expert based system is adopted in this research to develop the condition rating models for main WWTP infrastructure units (tanks, pipes, pumps and blowers), as discussed in the previous chapter. The necessary information was collected through a survey sent to municipal experts, contractors, WWTP operators, and environmental engineers in Canada and the United States. The questionnaire was designed after intense consultation with WWTP researchers and then reviewed by wastewater treatment plant experts. It was designed to collect the opinion of practitioners regarding different factors and sub-factors that affect the deterioration of the different infrastructure units considered in this study. Fortunately, most WWTPs have good historical treatment performance records, as they are used to demonstrate the plants' compliance with different environmental regulations. Therefore, in this study, an expert based approach using the AHP is adopted to collect the needed data to develop the condition rating for the WWTP infrastructure performance (CRI_{IP}), while the historical records of treatment performance are used to develop the condition rating models for the WWTP treatment performance (TPI). The data collection framework adopted in this study is shown in Figure IV.1.

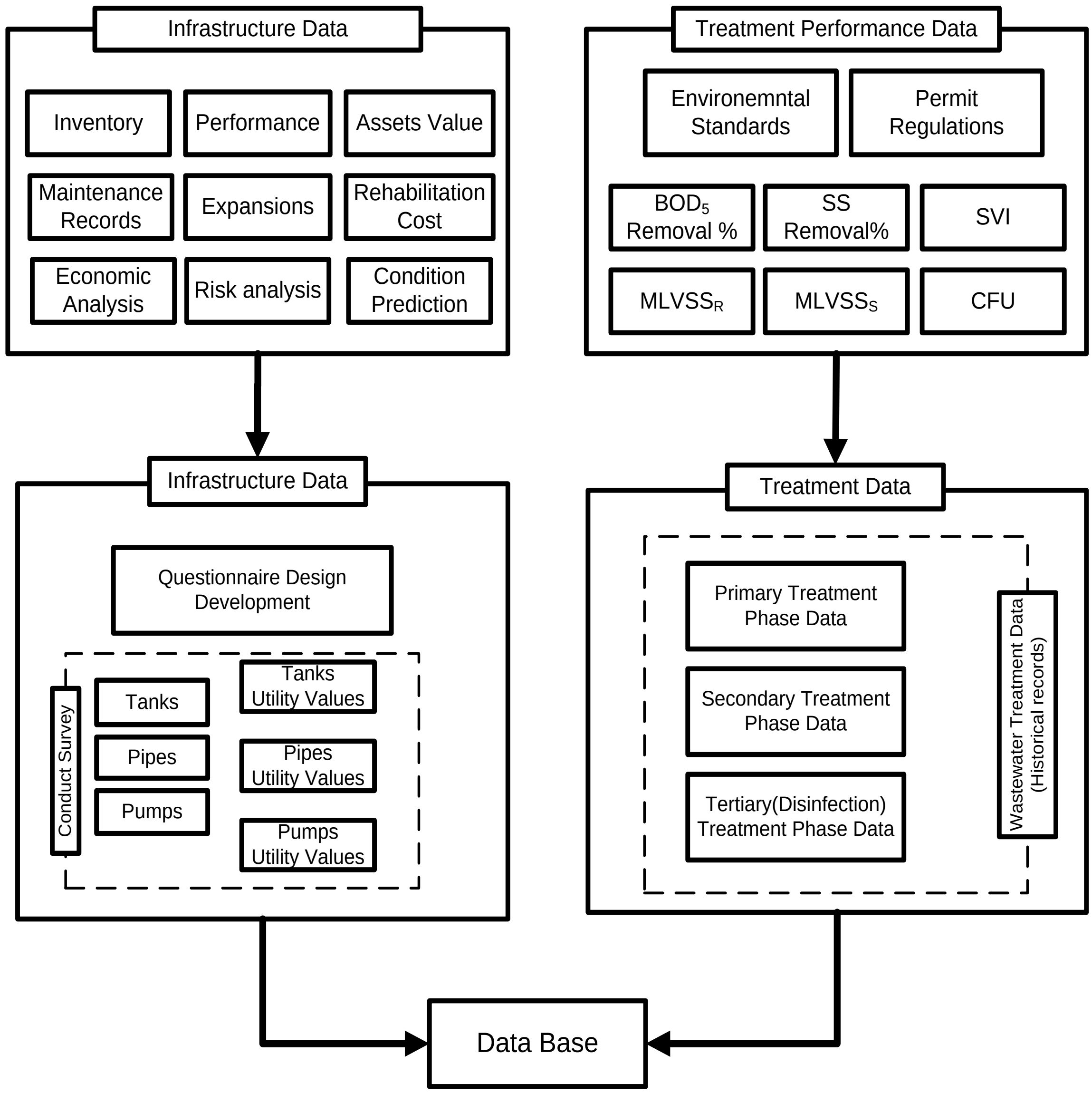


FIGURE IV-1: Data Collection Framework

4.2 WWTP INFRASTRUCTURE DATA

The WWTP infrastructure data in this research is collected through a survey sent to WWTP experts in the form of a questionnaire. The survey has two main objectives. The first objective is to collect the needed data to determine the relative weight for different factors and sub factors that affect the deterioration of various infrastructure units in WWTPs. These weights are determined using the Eigen-vector technique developed by Thomas Saaty (1991). The second objective of the survey is to determine the preference utility values for the different attributes of these factors required to apply the MAUT approach in this research. The basic principal of MAUT is the use of utility functions that transform different criteria to a dimensionless scale, (0 to 1) or (1 to 10) or (0 to 100), known as the multi attribute "utility". Utility functions are usually applied to quantitative and subjective data that can be converted to a certain score (Edwards and Barron, 1994).

The surveys were modified many times to accommodate the comments and feedback provided by different experts. These modifications made the questionnaires simpler and easier to fill out. The first questionnaire's responses were highly inconsistent because experts working in that domain have little knowledge about management issues and have little or no previous exposure to the AHP technique used in the survey, so they did not feel comfortable with the AHP (1-9) scale. In addition, many experts showed a lot of confusion in dealing with the pair-wise matrix since they were unable to achieve the required consistency. To overcome these problems, a simpler version of the questionnaire was developed based on recent studies. Experts showed a positive response towards the new version of the survey and showed more confidence when responding to different questions. Nevertheless, six experts' answers were inconsistent with other respondents and therefore were discarded from the study. A copy of this questionnaire is presented in Appendix A. The responses were collected from experts through emails, telephone interviews and site visits. Seventy-five questionnaires were sent to different wastewater treatment plant experts throughout Canada and the United States. Only thirty-two experts answered the survey. The expert responses showed reliable values for the importance of each treatment phase within WWTPs. However, most expert responses reflected a lower reliability level when deciding the relative weight of various infrastructure elements within each treatment phase.

4.3 Data Reliability

The reliability of expert responses is verified using Cronbach's alpha approach. Cronbach's alpha is a coefficient typically known as the coefficient of reliability that measures internal consistency. It measures how well a set of variables measures a single uni-dimensional latent construct. Cronbach's alpha is the most widely applied estimator of reliability. If data have a multidimensional structure, Cronbach's alpha will usually be low. Cronbach's alpha is the ratio of the true variance to the total variance of the measurement and a function of a number of observations, variance and covariance and it is determined using Equation 4.1.

$$C\alpha = \frac{n}{n-1}\left(1 - \frac{\Sigma Vi}{\overline{V}}\right) \qquad \text{4.1}$$

where:

n = number of points

Vi = variance of scores for each point

$\overline{V}$ = total variance of overall points

Cronbach's alpha coefficient of reliability has (0-1) scale value. The higher the score, the more reliable the data is. A value of (0.70) or greater is typically considered to be acceptable. Typical values for Cronbach's alpha and their interpretations are summarized in Table IV.1 (Pison and Aelst, 2004).

TABLE IV-1: Cronbach's Alpha and Its Interpretation (Pison and Aelst, 2004)

Cronbach's Alpha	Interpretation
0.9 and greater	High reliability
0.80 – 0.89	Good reliability
0.70 – 0.79	Acceptable reliability
0.65 – 0.69	Marginal reliability
0.50 – 0.64	Minimal reliability

4.4 RELATIVE WEIGHT DATA

The survey sent to experts contains two sections, of which the first section contains four parts and collects the required data to determine the relative weight of WWTP treatment phases and their infrastructure units according to the hierarchy presented in Chapter 3. The average relative weight and their reliability for each treatment phase and its infrastructure units are presented in Table IV-2. Similarly, the second, third and fourth parts of the survey collect the needed data to determine the relative weight for different factors and sub-factors affecting WWTP tank, pipe and pump deterioration following the hierarchy presented in Chapter III. The average relative weight for factors and sub-factors affecting the deterioration of WWTP tanks, pipes and pumps and their reliabilities are presented in Table IV-3,Table IV-4 and Table IV-5, respectively. These weights are determined using the Eigen-vector approach presented in Appendix C.

The following tables (Table IV-2 to Table IV-3) summarize relative weights based on the pair-wise comparison approach obtained from experts. To verify a respondent's reliability, each variance is measured against the overall variance using Cronbach's alpha. The 15 most reliable respondents—the ones with the highest Cronbach's alpha values—are presented in the tables. These experts hold similar views on the different treatment phases and their infrastructure units.

TABLE IV-2: Relative Weights for Each Treatment Phase and Its Infrastructure Units.

Factors & Sub Factors	Respondents														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg.
Primary Treatment phase	0.09	0.08	0.08	0.09	0.11	0.12	0.09	0.07	0.09	0.76	0.47	0.11	0.10	0.08	0.08	0.16
Secondary Treatment Phase	0.82	0.61	0.54	0.64	0.78	0.86	0.82	0.36	0.37	0.13	0.47	0.88	0.87	0.38	0.54	0.60
Tertiary Treatment Phase	0.09	0.32	0.38	0.27	0.11	0.02	0.09	0.57	0.54	0.11	0.07	0.02	0.03	0.54	0.38	0.24
Cronbach's Alpha	0.84															
Primary Phase Pump	0.07	0.75	0.07	0.55	0.11	0.79	0.07	0.76	0.75	0.76	0.67	0.82	0.82	0.45	0.07	0.50
Primary Sedimentation Tank	0.40	0.15	0.33	0.18	0.78	0.10	0.40	0.13	0.15	0.13	0.17	0.09	0.09	0.09	0.33	0.23
Primary phase Pipes	0.53	0.09	0.60	0.27	0.11	0.11	0.53	0.11	0.09	0.11	0.17	0.09	0.09	0.45	0.60	0.26
Cronbach's Alpha	0.52															
Secondary Phase Reactor Blower	0.04	0.24	0.07	0.69	0.69	0.50	0.04	0.61	0.43	0.64	0.37	0.07	0.60	0.44	0.07	0.37
Secondary Sedimentation tank	0.04	0.06	0.01	0.08	0.08	0.13	0.04	0.12	0.21	0.11	0.07	0.01	0.07	0.11	0.01	0.08
A.S Reactor	0.33	0.24	0.01	0.08	0.08	0.13	0.33	0.10	0.14	0.09	0.19	0.01	0.10	0.15	0.01	0.13
Secondary Sedimentation Pump	0.25	0.24	0.45	0.08	0.08	0.13	0.25	0.09	0.11	0.08	0.19	0.45	0.12	0.15	0.45	0.21
Secondary Phase pipes	0.33	0.24	0.45	0.08	0.08	0.13	0.33	0.08	0.11	0.08	0.19	0.45	0.12	0.15	0.45	0.22
Cronbach's Alpha	0.56															
Chlorination Phase Pump	0.07	0.45	0.75	0.60	0.33	0.80	0.07	0.77	0.74	0.75	0.33	0.08	0.33	0.33	0.08	0.43
Chlorination Phase Tank	0.40	0.45	0.13	0.20	0.33	0.10	0.40	0.13	0.15	0.13	0.33	0.46	0.33	0.33	0.46	0.29
Chlorination Phase Pipes	0.53	0.09	0.13	0.20	0.33	0.10	0.53	0.10	0.11	0.13	0.33	0.46	0.33	0.33	0.46	0.28
Cronbach's Alpha	0.56															

TABLE IV-3: Relative Weights for Factors and Sub-Factors Affecting WWTP Tank Deterioration.

Factors & Sub Factors	Respondent															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg.
Physical Construction Phase	0.67	0.44	0.70	0.69	0.73	0.25	0.62	0.69	0.43	0.56	0.67	0.66	0.62	0.42	0.62	0.58
Physical service stage	0.10	0.44	0.08	0.14	0.09	0.25	0.15	0.09	0.43	0.11	0.10	0.11	0.15	0.42	0.15	0.19
Environmental	0.12	0.06	0.11	0.09	0.09	0.25	0.11	0.11	0.07	0.16	0.12	0.11	0.11	0.08	0.11	0.11
Operational	0.12	0.06	0.11	0.09	0.09	0.25	0.11	0.11	0.07	0.16	0.12	0.11	0.11	0.08	0.11	0.11
Cronbach's Alpha	0.67															
Construction Processes & control	0.36	0.57	0.28	0.32	0.54	0.14	0.38	0.58	0.33	0.45	0.53	0.57	0.38	0.35	0.38	0.41
Construction Material Quality	0.36	0.07	0.28	0.32	0.06	0.14	0.38	0.07	0.17	0.15	0.08	0.08	0.38	0.35	0.38	0.22
Size & Capacity	0.05	0.07	0.04	0.06	0.07	0.02	0.05	0.08	0.04	0.05	0.07	0.08	0.05	0.12	0.05	0.06
Tank Shape	0.06	0.08	0.04	0.08	0.11	0.42	0.05	0.07	0.05	0.11	0.09	0.09	0.05	0.06	0.05	0.10
Equipment Fixation Method	0.07	0.11	0.28	0.05	0.11	0.14	0.06	0.08	0.33	0.09	0.11	0.08	0.06	0.06	0.06	0.11
Tank location (Above or below Surface)	0.09	0.09	0.07	0.16	0.11	0.14	0.06	0.12	0.08	0.15	0.13	0.09	0.06	0.06	0.06	0.10
Cronbach's Alpha	0.89															
Element Age	0.25	0.11	0.08	0.08	0.29	0.15	0.05	0.67	0.08	0.15	0.25	0.54	0.19	0.10	0.05	0.20
Corrosion	0.04	0.65	0.08	0.08	0.03	0.15	0.05	0.08	0.08	0.47	0.04	0.11	0.19	0.31	0.05	0.16
Protective Measures	0.06	0.02	0.08	0.08	0.03	0.29	0.05	0.07	0.08	0.05	0.06	0.18	0.19	0.10	0.05	0.09
Cracks & Flaws	0.44	0.15	0.38	0.38	0.45	0.22	0.42	0.08	0.38	0.22	0.44	0.08	0.29	0.28	0.42	0.31
Degree of Mechanization	0.21	0.08	0.38	0.38	0.19	0.19	0.42	0.09	0.38	0.11	0.21	0.09	0.13	0.20	0.42	0.23
Cronbach's Alpha	0.94															

TABLE IV-3: Relative Weights for Factors and Sub-Factors Affecting WWTP Tank Deterioration (Cont.),

Factors & Sub Factors	Respondents (Cont.)															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
Type of Soil	0.05	0.11	0.30	0.06	0.08	0.24	0.10	0.66	0.10	0.06	0.07	0.61	0.05	0.06	0.10	0.18
Influent pH	0.36	0.11	0.30	0.13	0.08	0.04	0.10	0.08	0.10	0.01	0.03	0.09	0.05	0.06	0.10	0.11
Vibration	0.23	0.65	0.05	0.31	0.41	0.24	0.02	0.08	0.02	0.35	0.48	0.08	0.27	0.19	0.02	0.23
Vibration (Operational)	0.36	0.02	0.05	0.31	0.41	0.24	0.02	0.09	0.02	0.35	0.39	0.12	0.27	0.19	0.02	0.19
Weather Conditions	0.01	0.11	0.30	0.19	0.01	0.24	0.77	0.08	0.77	0.24	0.03	0.10	0.36	0.50	0.77	0.30
Cronbach's Alpha	0.93															
Chemical Doses	0.03	0.06	0.06	0.05	0.04	0.09	0.04	0.04	0.06	0.05	0.04	0.52	0.04	0.06	0.04	0.08
Operational & Maintenance practices	0.23	0.44	0.44	0.38	0.30	0.27	0.35	0.23	0.44	0.27	0.30	0.09	0.35	0.31	0.35	0.32
Operator Qualification & Experience	0.16	0.17	0.17	0.24	0.30	0.42	0.23	0.22	0.17	0.35	0.37	0.07	0.23	0.25	0.23	0.24
Control System (Flood & operational control)	0.25	0.22	0.22	0.29	0.30	0.19	0.31	0.20	0.22	0.24	0.25	0.10	0.31	0.25	0.31	0.24
WW characteristics(PST, SST, CT)[1]	0.32	0.12	0.12	0.04	0.08	0.02	0.08	0.31	0.12	0.10	0.04	0.20	0.08	0.12	0.08	0.12
Aeration Type (RT)[2]	0.09	0.09	0.07	0.13	0.11	0.1	0.06	0.1	0.6	0.15	0.1	0.1	0.06	0.06	0.06	0.12
Cronbach's Alpha	0.88															

[1]Used for Primary sedimentation tank (PST), secondary sedimentation tank (SST), and Chlorination tank (CT)

[2] Used Only for reactor tank (RT)

TABLE IV-4: Relative Weights for Factors and Sub-Factors Affecting WWTP Pipe Deterioration.

Factors & Sub Factors	Respondents															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg.
Physical factors	0.60	0.80	0.79	0.79	0.55	0.80	0.60	0.78	0.79	0.73	0.63	0.81	0.76	0.79	0.79	0.74
Operational	0.20	0.10	0.10	0.10	0.21	0.10	0.20	0.11	0.10	0.13	0.19	0.10	0.11	0.10	0.10	0.13
Environmental	0.20	0.10	0.11	0.11	0.24	0.10	0.20	0.12	0.11	0.14	0.17	0.09	0.12	0.11	0.11	0.13
Cronbach's Alpha	0.70															
Pipe Material	0.37	0.11	0.38	0.10	0.19	0.56	0.37	0.10	0.50	0.51	0.43	0.41	0.55	0.38	0.10	0.34
Pipe Diameter	0.05	0.06	0.08	0.02	0.19	0.08	0.05	0.02	0.08	0.10	0.06	0.05	0.08	0.08	0.02	0.07
Pipe Length	0.04	0.06	0.05	0.02	0.19	0.08	0.04	0.02	0.10	0.09	0.14	0.05	0.08	0.05	0.02	0.07
Pipe Age	0.12	0.11	0.05	0.74	0.19	0.06	0.12	0.81	0.13	0.07	0.11	0.14	0.07	0.05	0.74	0.23
Pipe Depth	0.05	0.33	0.06	0.02	0.19	0.11	0.05	0.03	0.10	0.13	0.14	0.21	0.11	0.06	0.02	0.11
Joints &J. Methods	0.37	0.33	0.38	0.10	0.05	0.11	0.37	0.02	0.08	0.10	0.11	0.14	0.11	0.38	0.10	0.18
Cronbach's Alpha	0.82															
Soil Type	0.25	0.09	0.25	0.07	0.31	0.08	0.09	0.06	0.14	0.13	0.11	0.13	0.09	0.25	0.07	0.14
Ground Water Level	0.25	0.09	0.25	0.48	0.31	0.08	0.09	0.37	0.07	0.06	0.11	0.13	0.04	0.25	0.48	0.20
Vibration	0.25	0.64	0.25	0.39	0.31	0.67	0.73	0.31	0.71	0.77	0.67	0.63	0.43	0.25	0.39	0.49
Weather Condition	0.25	0.18	0.25	0.07	0.08	0.17	0.09	0.25	0.07	0.04	0.11	0.13	0.43	0.25	0.07	0.16
Cronbach's Alpha	0.85															
Chemical Type &Dose	0.09	0.05	0.04	0.05	0.09	0.09	0.05	0.05	0.05	0.05	0.05	0.04	0.05	0.04	0.05	0.05
O&M Practices	0.02	0.18	0.26	0.29	0.36	0.36	0.24	0.23	0.28	0.34	0.30	0.33	0.24	0.26	0.29	0.26
Cathodic Protection	0.02	0.23	0.30	0.29	0.36	0.36	0.24	0.32	0.28	0.24	0.30	0.37	0.24	0.30	0.29	0.28
Number of Previous Breaks	0.79	0.41	0.35	0.33	0.09	0.09	0.43	0.36	0.34	0.34	0.30	0.24	0.24	0.35	0.33	0.33
WW Characteristics	0.09	0.14	0.04	0.05	0.09	0.09	0.05	0.05	0.05	0.02	0.05	0.02	0.24	0.04	0.05	0.07
Cronbach's Alpha	0.96															

TABLE IV-5: Relative Weights for Factors and Sub-Factors Affecting WWTP Pump Deterioration.

Factors & Sub Factors	Respondents															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Avg
Physical	0.76	0.80	0.80	0.60	0.44	0.76	0.77	0.80	0.76	0.80	0.81	0.77	0.80	0.80	0.78	0.75
Operational	0.15	0.10	0.10	0.30	0.44	0.15	0.13	0.11	0.13	0.10	0.09	0.13	0.10	0.09	0.11	0.15
Environmental	0.08	0.10	0.10	0.10	0.11	0.08	0.10	0.09	0.11	0.10	0.10	0.10	0.10	0.11	0.11	0.10
Cronbach's Alpha	0.84															
Pump Type	0.35	0.15	0.15	0.06	0.28	0.35	0.08	0.15	0.07	0.15	0.59	0.06	0.15	0.06	0.05	0.18
Fixation Method	0.07	0.02	0.02	0.06	0.06	0.07	0.01	0.02	0.01	0.02	0.07	0.01	0.02	0.01	0.01	0.03
Size & Capacity	0.04	0.02	0.02	0.12	0.06	0.04	0.02	0.04	0.01	0.02	0.07	0.01	0.02	0.01	0.01	0.03
Age	0.35	0.02	0.02	0.01	0.28	0.35	0.44	0.74	0.49	0.02	0.10	0.02	0.02	0.01	0.01	0.19
Protective measures	0.07	0.03	0.03	0.23	0.05	0.07	0.02	0.02	0.01	0.03	0.07	0.45	0.03	0.50	0.49	0.14
Cavitations	0.12	0.75	0.75	0.52	0.28	0.12	0.44	0.02	0.40	0.75	0.10	0.45	0.75	0.42	0.43	0.42
Cronbach's Alpha	0.90															
pH	0.7	0.6	0.8	0.7	0.5	0.8	0.7	0.9	0.8	0.7	0.6	0.7	0.6	0.5	0.6	0.70
Weather temperature	0.3	0.4	0.2	0.3	0.5	0.2	0.3	0.1	0.2	0.3	0.4	0.3	0.4	0.5	0.4	0.30
Cronbach's Alpha	0.97															
Chemical Types	0.34	0.03	0.04	0.04	0.06	0.34	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.08
No. of Failure	0.07	0.20	0.13	0.13	0.19	0.07	0.17	0.17	0.18	0.20	0.30	0.19	0.21	0.32	0.31	0.18
O&M	0.34	0.17	0.38	0.38	0.19	0.34	0.24	0.20	0.22	0.17	0.20	0.13	0.17	0.32	0.31	0.25
Control System	0.11	0.20	0.08	0.08	0.19	0.11	0.17	0.24	0.16	0.20	0.27	0.16	0.21	0.02	0.03	0.15
Operation Type	0.06	0.20	0.17	0.17	0.06	0.06	0.17	0.17	0.16	0.20	0.02	0.13	0.21	0.03	0.03	0.12
Standby System	0.06	0.17	0.17	0.17	0.31	0.06	0.20	0.17	0.18	0.17	0.17	0.23	0.17	0.25	0.24	0.18
WW temperature	0.04	0.02	0.04	0.04	0.01	0.04	0.03	0.03	0.06	0.03	0.01	0.13	0.00	0.03	0.03	0.04
Cronbach's Alpha	0.89															

4.5 PREFERENCE UTILITY VALUES

The second section of the survey is designed to measure preference utility values for the attributes of the factors defined in the first part of the survey; thus, this part will provide the required scores for each factor described in the first part of the survey. In this part, experts are asked to give a preference utility value on a scale of (1 - 10) for different attributes of the factors affecting the deterioration of each infrastructure unit in WWTPs. A preference utility value of (10) indicates the highest preference score, while a preference utility value of (1) reflects the lowest preference score. These scores will be used to develop the utility curves for the various factors considered in this study. The attributes considered in this study and the interpretations of different factors affecting the deterioration of the different infrastructure units are discussed in Appendix B. Only five experts familiar with WWTP construction and operation processes completely answered this part of the survey. The preference utility values for factors affecting the deterioration of WWTP tanks, pipes and pumps are shown in Table IV.6, Table IV.7 and Table IV.8, respectively.

TABLE IV-6: Preference Utility Values for Attributes of Tanks Factors

Factors	**Attribute**	**Respondents**					
		1	2	3	4	5	Avg.
Const. Pros. & Control							
	- Typical standard	5	6	7	5	6	5.8
	- High standard	8	8	8	8	7	7.8
	- Specific Standard	10	9	10	10	10	9.8
Construct. Material							
	- Typical material	6	6	6	7	6	6.2
	- High quality	8	8	8	8	9	8.2
	- Very high quality	10	10	10	10	10	10
Size & Capacity							
	-Small	5	5	5	5	6	5.2
	- Medium	5	8	7	7	8	7.0
	- Large	5	6	8	5	5	5.8
Tank Shape							
	- Rectangular	7	6	8	8	5	6.8
	- Square	6	6	8	8	5	6.6
	- Circular	8	8	8	8	5	7.4
Fixation Method							
	- Built In	10	10	10	8	10	9.6
	- Surface fixed	5	5	6	5	5	5.2
Tank Location							
	-Totally above the	5	5	5	5	5	5.0
	- Partially Below the	4	6	4	5	5	4.8
	- Totally below the	8	10	10	9	8	9.0
Element Age							
	age < 5yrs	10	10	10	10	10	10
	age>5yrs<10	8	9	8	8	8	8.2
	age>10yrs<15	7	6	7	7	7	6.8
	age>15yrs<20	6	5	6	6	5	5.6
	age>20yrs	5	5	5	3	2	4.0
Corrosion							
	non	10	10	10	10	10	10
	<5%	9	9	8	9	8	8.6
	>5%<10%	6	7	7	7	6	6.6
	>10%<20%	5	4	5	6	5	5.0
	>20%<25%	4	3	4	4	5	4.0
	>25%<30%	4	2	3	3	4	3.2
	>30%<40%	3	2	2	2	3	2.4
	>40%	0	0	0	2	2	0.8

TABLE IV-6: Preference Utility Values for Attributes of Tanks Factors (Cont.)

Factors	**Attributes**	**Respondents**					
		1	2	3	4	5	Avg.
Cracks and Flaws							
	1 - non	10	10	10	10	10	10
	2 - mild	4	5	5	5	4	4.6
	3 - sever	0	2	0	0	0	0.4
Protective Measures							
	1-Waterrepellant	8	9	10	10	7	8.8
	2-Water& sulfate	10	10	10	10	10	10
	3- No coating	5	5	5	5	5	5.0
Automation Level							
	1- Full automation	10	10	10	10	10	10
	2- 50% automation	7	7	8	6	9	7.4
	3- Not automated	5	5	5	6	6	5.4
Type of Soil							
	1-Silt	8	8	6	7	6	7.0
	2-Clay	6	5	6	5	6	5.6
	3-Sand	4	4	5	5	4	4.4
	4-Rocks	6	6	6	8	8	6.8
WW Influent pH Value							
	1- acidic pH< 7	3	4	3	2	2	2.8
	2- neutral pH= 7	10	10	10	10	10	10
	3- alkaline pH >7	8	8	7	9	8	8.0
Vibration							
	1- Non	10	10	10	10	10	10
	2- Low	8	9	8	7	8	8.0
	4- Mild	5	6	5	5	5	5.2
	3- Sever	2	3	2	0	2	1.8
Weather Temp							
	-40 to -20	3	2	5	4	3	3.4
	-20 to 0	4	5	6	5	5	5.0
	0 to 20	6	8	8	7	8	7.4
	20 to 40	7	7	8	8	8	7.6

TABLE IV-6: Preference Utility Values for Attributes of Tanks Factors (Cont.)

Factors	**Attributes**	**Respondents**					
		1	2	3	4	5	Avg.
Chemical Types & Doses							
	1 - Chlorine	3	4	5	5	5	4.4
	2 - Alum	6	6	6	6	6	6
	3 - polymers	7	7	9	8	8	7.8
	4 - Nutrients	8	9	8	8	8	8.2
	5 -others	-	-	-	-	-	
Aeration Type (RT only)1							
	1- Surface aeration	5	5	6	6	5	5.4
	2- Diffused aeration	7	5	8	9	8	7.4
WW Characteristics	1-Abrasive	4	3	5	4	5	4.2
	2-Non Abrasive	8	9	8	7	9	8.2
Operation & Maintenance							
	1-Short term M&O	5	8	8	10	9	8
	2- Log term M&O	10	4	7	8	8	7.4
	3- Reactive M&O	4	5	4	4	6	4.6
Operator Experience							
	1- E.>10	5	5	8	10	10	7.6
	2- 5 >E.<10	5	5	7	6	7	6
	3- E. <5	5	5	3	3	5	4.2
Control Systems (Operation & Flood Control)							
	1- Full automatic	8	9	10	8	8	8.6
	2 - Semi automatic	7	7	6	9	7	7.2
	3- Manual	6	5	7	6	5	5.8

[1]Used Only for reactor tank (RT)
[2]Used for Primary sedimentation tank (PST), secondary sedimentation tank (SST), and Chlorination tank (CT)

TABLE IV-7: Preference Utility Values for Attributes of Pipes Factors

Factors	**Attributes**	**Respondents Preference Value**					
		1	2	3	4	5	AVG.
Pipe Material	1-Cast Iron	8	9	10	10	8	9.00
	2-Ductile Iron	7	7	5	8	7	6.80
	3-Asbestos	5	7	5	7	7	6.20
	4-Concrete Pipes	7	6	7	7	8	7.00
	5-P.V.C	10	10	9	9	10	9.60
Pipe Diameters							
	dia. < 100 mm	6	6	5	5	5	5.33
	150< dia< 250 mm	7	7	6	6	6	6.33
	250<dia< 350 mm	7	7	6	7	6	6.67
	350 <dia< 450 mm	8	6	7	7	6	7.00
	dia> 500 mm	7	7	8	9	10	8.67
Pipe Length							
	L < 50 m	8	9	10	8	8	8.60
	50 m < L ≤ 100 m	5	6	8	8	6	6.60
	100 m< L ≤150 m	5	6	8	7	6	6.40
	150 m< L ≤ 300 m	5	6	7	7	5	6.00
	L > 300 m	3	6	8	7	5	5.80
Pipe Age (Years)	age<5	10	10	9	9	10	9.60
	5 < age < 10	7	8	7	7	8	7.40
	10 < age <15	5	5	5	5	7	5.40
	15 < age <20	5	4	4	4	6	4.60
	20 < age <25	5	5	4	4	5	4.67
	25 < age < 30	5	3	4	3	4	4.00
	30 < age <35	5	5	3	3	4	4.00
	35 < age <40	5	3	3	3	3	3.67
	40 <age <45	0	2	0	3	3	2.00
	age >50	2	0	2	2	0	1.20
Pipe Insulation							
	1- heavily insulated	10	9	10	10	10	9.80
	2- moderately insulated	5	7	8	7	8	7.00
	3- non insulated	3	5	5	6	6	5.00

TABLE IV-7: Preference Utility Values for attributes of Pipes Factors(Cont.)

Factors	**Attribute**	**Respondents Preference Value**					
		1	2	3	4	5	Avg.
Joint Types	1- standard welded	6	8	8	8	7	7.40
	2- standard bolted	7	9	8	9	9	8.40
	3- high quality joints	10	10	10	10	11	10.20
	4- poor welded joints	0	0	2	2	2	1.20
	5- poor bolted joints	0	0	2	2	2	1.20
Chemical Type	1- Lime	7	8	8	7	8	7.60
	2-Alums	7	5	5	5	5	5.40
	3-Polymers	7	5	5	5	5	5.40
	4-chlorine	5	5	5	5	5	5.00
O& M Practices							
	1- Preventive	10	10	10	10	10	10.0
	2- Reactive	5	5	5	5	5	5.00
Cathodic Protection							
	1-available	10	10	10	10	10	10.00
	2-non-available	5	5	5	5	5	5.00

TABLE IV-7: Preference Utility Values for attributes of Pipes Factors (Cont.)

Factors	**Attribute**	**Respondents Preference Value**					
		1	2	3	4	5	Avg.
Breakage Rate	1- Frequent	1	2	2	2	3	2.00
	2- High	4	4	3	3	5	3.80
	3- Moderate	6	5	7	6	6	6.00
	4 - Rare	8	8	9	9	8	8.40
	5- Non	10	10	10	10	10	10.00
Soil Type	1- Highly reactive	3	3	2	2	4	2.80
	2- Reactive aggressive	4	3	4	4	4	3.80
	3- Slightly reactive	7	6	8	7	8	7.20
	4- Non- reactive	10	10	10	10	10	10.00
WW Influent (pH)							
	1- pH < 7 acidic	3	3	3	2	2	2.60
	2- pH= 7 neutral	10	10	10	10	10	10.00
	3- pH > 7 alkaline	7	10	10	8	7	8.40
Vibration							
	1- high	2	2	3	3	4	2.80
	2- moderate	4	5	5	5	6	5.00
	3- low	8	9	8	9	8	8.40
Weather Temp.	-40	2	0	1	2	3	1.60
	-30	3	2	3	4	3	3.00
	-10	4	4	5	3	3	3.80
	0	5	4	4	5	5	4.60
	10	7	6	8	7	8	7.20
	20	8	7	7	9	8	7.80
	30	8	8	9	8	9	8.40
	40	6	5	7	5	7	6.00
GW Table							
	1- high	5	4	5	6	5	5.00
	2- moderate	6	6	6	7	8	6.60
	3- low	8	10	10	10	10	9.6

TABLE IV-8: Preference Utility Values for attributes of Pumps Factors

Factors	**Attribute**	**Respondents**					
		1	**2**	**3**	**4**	**5**	Avg.
Pump Type	1-Axial	4	2	3	4	3	3.2
	2- Centrifugal	9	10	10	8	10	9.4
	3- Radial	3	4	4	4	4	3.8
	4-Reciprocating	5	5	5	6	6	5.4
Fixation Method							
	1-Pre- fixation	10	10	10	10	10	10
	2-post-fixation	6	5	6	6	7	6
Size & Capacity m^3/d							
	cap <100	4	5	5	4	5	4.6
	100 > cap < 200	6	6	6	5	6	5.8
	200 >cap < 300	5	7	7	7	7	6.6
	300 > cap < 500	7	8	7	9	8	7.8
	500 > cap < 1000	8	9	8	9	9	8.6
	cap > 1000	9	10	10	8	8	9.0
Age (as a Function of Service Life)	age< 10% of Service Life	10	9	10	10	10	9.8
	10% >age < 25%	8	8	9	7	9	8.2
	25% > age < 50 %	6	6	5	6	7	6.0
	50% > age < 75 %	5	4	5	5	4	4.6
	75% > age < Service life	4	3	4	3	4	3.6
	age > Service life	0	0	0	0	1	0.2
Coating	1-Specialized	10	10	10	10	10	10
	2-Typical	6	5	5	7	7	6
	3-Non	3	3	3	3	3	3
Cavitations							
	1-Non	10	10	10	10	10	10
	2-Mild	5	6	6	5	5	5.4
	3-severe	2	2	0	2	4	2.0

TABLE IV-8: Preference Utility Values for attributes of Pumps Factors (Cont.)

Factors	**Attribute**	**Respondents**					
		1	2	3	4	5	Avg.
Chemical Types	1-No effect on pH	10	10	9	10	9	9.6
	2-Increase pH	6	6	6	6	5	5.8
	3-Decrease pH	4	4	5	3	2	3.6
Number of Operation Failure (Monthly)	no failure	10	10	10	10	10	10
	2 > failure ≤ 5	5	5	5	5	5	5
	6 > failure ≤ 10	2	2	2	2	2	2
	failure > 10	0	0	0	0	0	0
Operation & Maintenance Procedures	1-short term	6	6	6	6	5	5.8
	2-long term	6	5	5	5	5	5.2
	3-both	10	10	10	10	10	10
	4-reactive	2	2	2	4	0	2
Control System	1-fully automated	10	10	10	10	10	10
	2-semi automated	5	6	7	5	8	6.2
	3-Non automated	4	4	6	4	5	4.6
Operation Type							
	1-continuous	7	7	6	8	6	6.8
	2-alternating	8	9	9	8	8	8.4
Standby System							
	1-available	10	10	10	10	10	10
	2-not available	0	0	0	0	0	0

TABLE IV-8: Preference Utility Values for attributes of Pumps Factors (Cont.)

Factors	**Attribute**	**Respondents**					
		1	**2**	**3**	**4**	**5**	**Avg.**
WW pH	1- 3 (acidic)	3	3	2	5	4	**3.4**
	2- 5 (acidic)	4	5	5	5	5	**4.8**
	3- 7 (neutral)	10	10	10	10	10	**10**
	4- 9 (alkaline)	8	7	8	7	6	**7.2**
	5- 11 (alkaline)	8	7	8	6	5	**6.8**
	6- 13 (alkaline)	9	6	7	5	5	**6.4**
WW Temperature							
	T< 4	5	6	4	5	5	**5**
	4>T< 20	8	6	8	8	7	**7.4**
	20>T< 30	6	7	8	8	9	**7.6**
	T> 30	5	5	6	7	6	**5.8**
Weather Temperature							
	-40 to -20	4	5	4	5	4	**4.4**
	-20 to 0	5	5	5	6	7	**5.6**
	0 to 20	7	8	6	8	8	**7.4**
	20 to 40	7	6	6	6	8	**6.6**

The utility function of WWTP pipe diameters considered in this study is shown in Figure IV-2. This graph shows that experts prefer large pipe diameters; therefore, they assigned higher preference utility values for larger pipe diameters. This indicates that smaller diameter pipes deteriorate faster than larger pipes; therefore, smaller pipes diameters were assigned lower preference utility values.

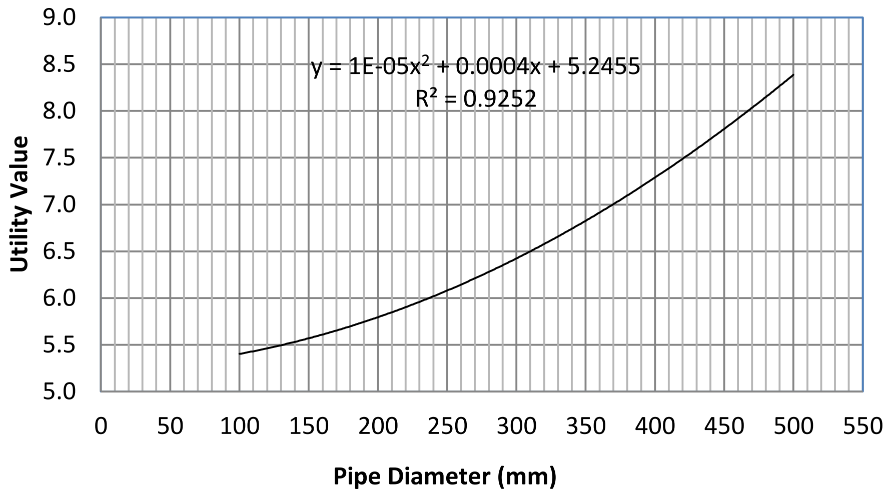


FIGURE IV-2: Utility Values for Pipe Diameter

The utility function values of WWTP pipe lengths are illustrated in Figure IV-3, where experts apparently prefer smaller pipe segments, and thus these were assigned higher Preference values.

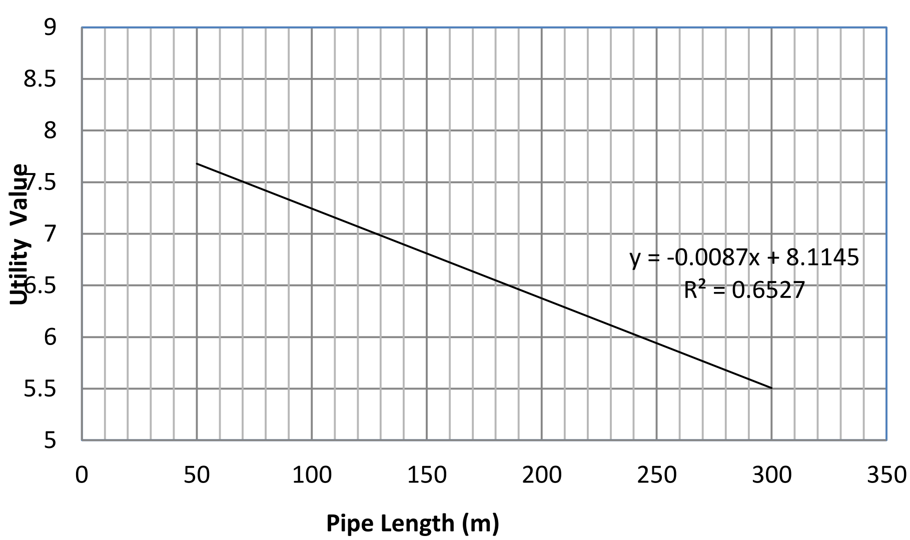


Figure IV-3: Utility Values for Pipe Length

Figure IV-4 shows the utility values for WWTP pipes. New pipes are preferred by most experts and therefore higher preference utility values were assigned to new pipes. In addition to that, pipe age is considered the main factor in this study when it comes to predicting the deterioration curves of various types of WWTP pipes.

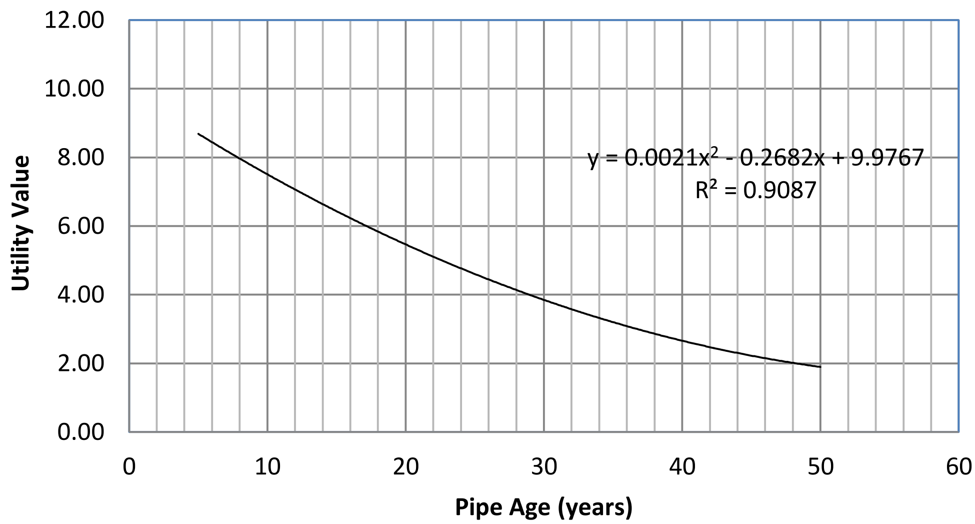


Figure IV-4: Utility Values for Pipe Age

Apparently weather, specifically temperature, has a significant effect on pipe deterioration due to freeze/thaw cycles and other environmental factors. Experts prefer temperatures above zero, as illustrated in Figure IV-5.

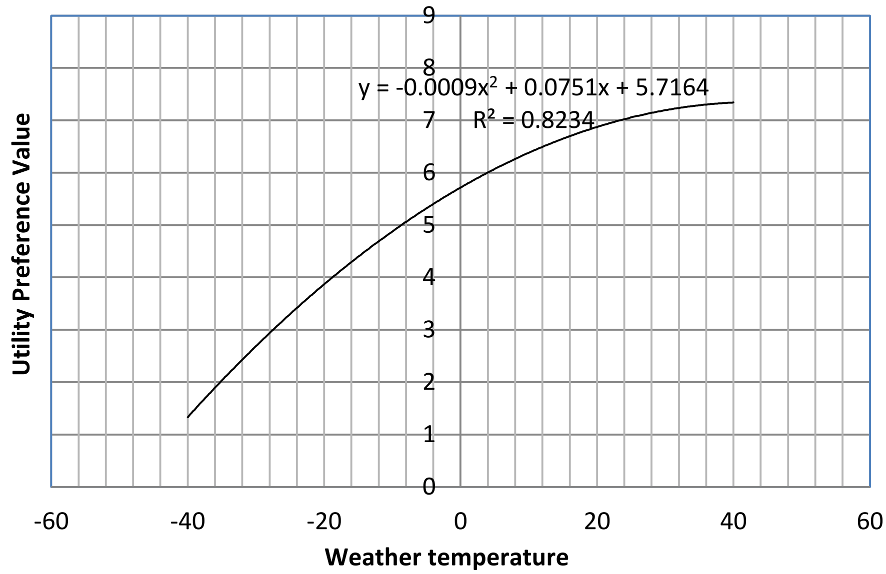


Figure IV-5: Utility Values for Weather Temperature

The Hazen-William coefficient known as the C factor is an indicator that reflects the pipe's internal friction. The C factor changes with time and reflects the degree of deterioration of these pipes. Experts do not recommend the use of this factor in the assessment model because it is very difficult to identify its value within different wastewater treatment plants' hydraulic systems. Thus, the C factor will not be used throughout the rest of this study.

Pumps are considered one of the major infrastructure units in wastewater treatment plants, thus a failure of these pumps critically affects the overall performance of the WWTP. The preference utility values for pump failures are shown in Figure IV-6.

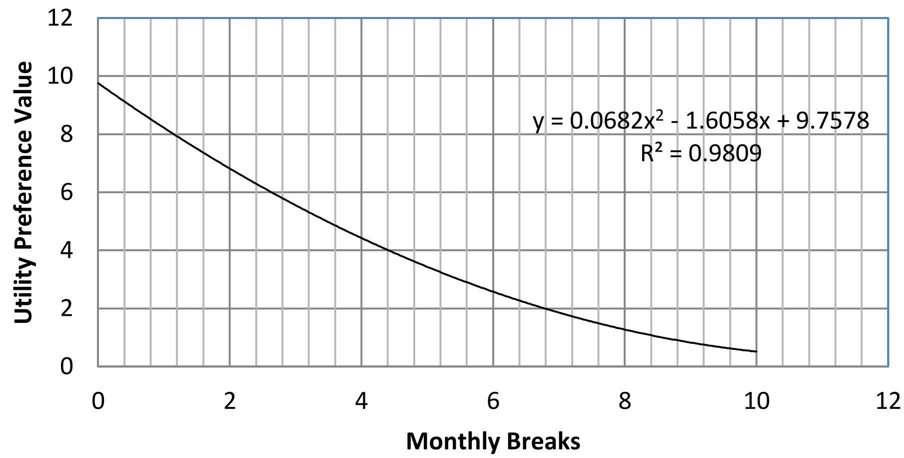


FIGURE IV-6: Utility Values for Monthly Failures of Pumps

Wastewater (WW) acidity has a significant impact on tank deterioration, especially concrete tanks, so the WW acidity value, or pH, is among the important factors affecting the deterioration of WWTP infrastructures. Experts prefer neutral to slightly alkaline WW over acidic WW. This preference is illustrated in Figure IV-7.

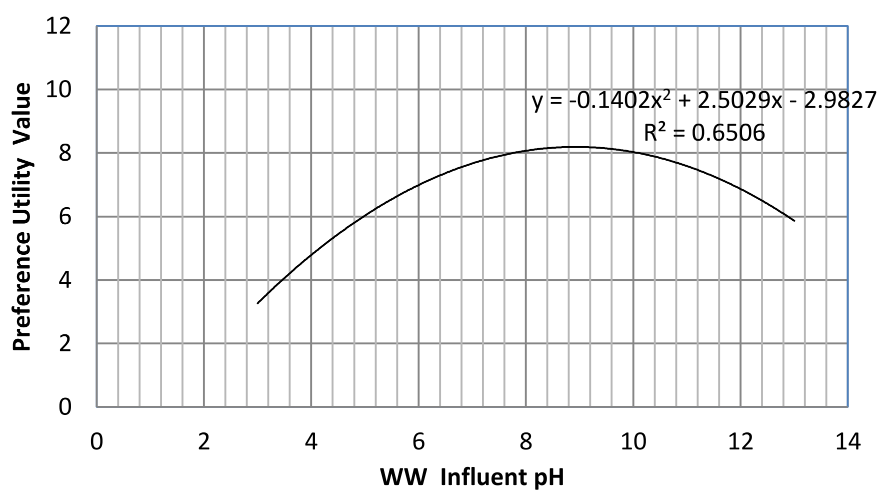


Figure IV-7: Utility Values for Wastewater pH

Age is the most apparent factor that causes infrastructure deterioration. Since experts prefer new facilities over old ones, high utility values were given to newer pumps as shown in Figure IV-8.

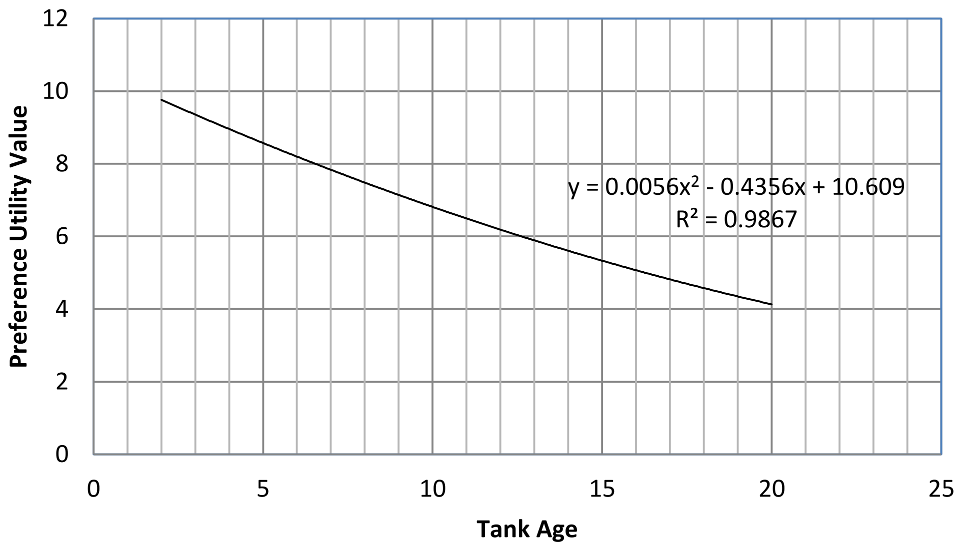


FIGURE IV-8: Utility Values for WWTP Tanks' Age

4.6 WWTP TREATMENT DATA

The management of wastewater involves several levels of government in Canada. However, municipalities own and operate the majority of wastewater systems in Canada. Treated wastewater (WW) effluent from wastewater treatment plants must comply with the environmental standards and regulations stated by Canadian Environmental Protection Acts. In order to comply with these regulations, WWTP needs to test and report the quality of the treated wastewater effluent to local and federal environmental authorities. This explains why most WWTPs keep good records of various tests performed over their treaded wastewaters. However, these results are reported using different tests to measure and report the WWTP's overall treatment performance. In this study, treatment data for three WWTPs from Canada and the US are presented in the case study section to demonstrate the implementation of the developed methodology. These WWTPs are referred to as S from Quebec, H from Ontario and P from the United States. The names of these WWTPs are kept confidential upon their request. These WWTP are selected to show the impact of different jurisdictions over the performance of these WWTPs. The collected data for these WWTPs are reorganized to satisfy the phase based approach adopted in this study. The treatment data of these WWTPs are presented and discussed in Appendix D.

4.7 WWTP MAINTENANCE DATA

The WWTP maintenance data was extremely difficult to obtain due to the fact that it is not available within most contacted WWTPs. Also, these plants are controlled and managed by different municipalities which operate under different provincial bylaws and thus they usually have different budgets and follow different operation and maintenance procedures. The designs of WWTPs are typically based on the ideal that the failure of any single WWTP component should not prevent the whole WWTP from meeting the required effluent quality. This can only be achieved by having redundant infrastructure units, which will operate automatically during emergencies or when the main components fail. On the other hand, these redundancies influence the plant's infrastructure operations and maintenance strategies. Usually, different municipalities have different budget values and different short and long term financial plans that affect WWTP maintenance and rehabilitation plans as well as rehabilitation decisions.

The Ministry of environment of Ontario (MOE) developed design and maintenance guidelines for WWTPs that require them to have a stand by equipment that ensures the WWTP's treatment functionality and the protection of public health and environment.

These guidelines indicate that WWTPs must be designed to meet current and projected needs, including hydraulic and contaminant loadings to eliminate bypasses and overflows for at least 30 years. This projected capacity of the plant is larger than the initial demand and it can therefore provide decision makers with the required maintenance flexibility measures to maintain various infrastructure units. However, there is a standard reporting system used to report the level of service for different infrastructures found in wastewater treatment plants. Therefore, there is no way to measure the effect of the maintenance and rehabilitation interventions carried out at these facilities, nor is there a way to link it with the intervention expenditures. All contacted WWTPs are supplied with standby redundant equipment, mainly pumps and other electromechanical devices, which give the plant operator the needed flexibility to maintain or replace the instruments without affecting the overall performance of the WWTP.

4.9.1. Maintenance and Rehabilitation Data for S WWTP

The maintenance procedures followed in S WWTP depends on locally developed time based inspection procedures. The electromechanical equipments in the WWTP are repaired if they seize to work or if they have negative visual inspection results. This procedure is a combination of the two maintenance philosophies of run to fail and condition based maintenance. The municipality engineers and the equipment suppliers make the rehabilitation decisions for pumps and other electromechanical equipment. Tank and pipe maintenance is usually performed following preventive time based maintenance, in which every tank is inspected and maintained at least once a year. Unfortunately, this WWTP it is managed by more than one department of this municipality. This perhaps explains the inconsistency and the confusion found in most of the maintenance records of this WWTP. This WWTP operate with two budgets. This is due to the reactive management approach followed by the managers of this WWTP. Most of WWTP's MR&R expenditures are funded through the municipality emergency funds because power, chemicals, waste handling and other operational issues consume most of the WWTP's budget.

4.9.1. MAINTENANCE AND REHABILITATION DATA FOR P WWTP

P WWTP follows time based and condition based maintenance philosophies, which are performed following routine inspection procedures. The majority of P's maintenance budget is spent on rebuilding and/or replacing different types of pumps and other electrometrical devices. This confirms the finding of this research that WWTP pumps are the infrastructure units with the highest relative importance. P- Maintenance expenditures are shown in Figure IV-9.

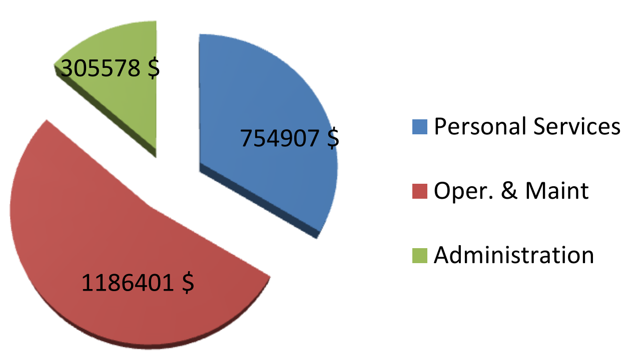


FIGURE IV-9: WWTP Maintenance Expenses for P WWTP

4.9.1. MAINTENANCE AND REHABILITATION DATA FOR H WWTP

HWWTP maintenance can be described as preventative, predictive and breakdown for a wide range of equipment, mainly pumps, in different phases. These findings also confirm that pumps and WWTP electromechanical devices have the highest relative weight of WWTP infrastructures. There is a separate maintenance department in this WWTP; however, it follows certain maintenance procedures governed by the municipality's financial regulations and spending policies. The main objectives of such maintenance procedures are to ensure equipment availability to meet the plant's process operations. H-WWTP maintenance expenditures are shown in Figure IV-10.

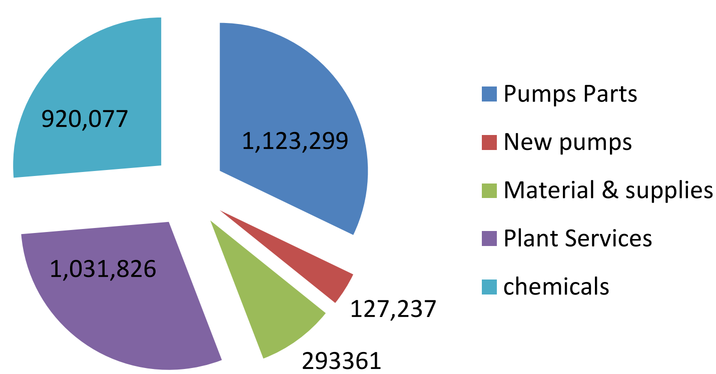


Figure IV-10: Maintenance Expenses for H WWTP

Ch V. Data Analysis & Model Implementation

5.1 CHAPTER OVERVIEW

In this chapter, the relative weights for the different treatment phases in WWTPs and for different infrastructure units within each treatment phase are determined using the AHP technique. The relative weights for different physical, operational and environmental factors that affect the deterioration of WWTP tanks, pipes, pumps and blowers are also determined using this approach. The condition ratings of different infrastructure units within WWTPs are determined using an integrated AHP-MAUT approach, as explained in Chapter III. Deterioration prediction curves for the various infrastructure units within a WWTP are developed using sensitivity analysis, showing the effect of age on the condition rating of each infrastructure unit (CR_{INFU}). The condition rating of a WWTP infrastructure's performance in the primary treatment phase (CRI_{PTP}), the secondary treatment phase (CRI_{STP}) and the tertiary treatment phase (CRI_{TTP}) are determined using the weighted sum of the condition ratings of each phase's infrastructure units throughout their service lives. Finally, the condition rating of the overall infrastructure performance of a WWTP (CRI_{IP}) is determined using the weighted sum of the of the condition rating of the three treatment phases of the WWTP.

The deterioration of various infrastructure units throughout a WWTP's service life depends on many factors, including various maintenance and rehabilitation actions applied to its infrastructure units. Therefore, it is expected to have different deterioration levels for different WWTPs, even if they were constructed and operated in similar environments and under similar conditions. In this chapter, six deterioration and rehabilitation scenarios are presented. Each scenario shows the effect of certain rehabilitation actions on specific infrastructure units and their effects on the condition rating of each treatment phase, and finally their effect on the overall condition rating of the WWTP (CRI_{IP}). The treatment performances of WWTPs are determined using the condition rating equations presented in Chapter III. Therefore, the treatment performance data for WWTPs are re-organized to satisfy the phase-based methodology adopted in this study. The framework for the data analysis followed in this study is shown in Figure V.1.

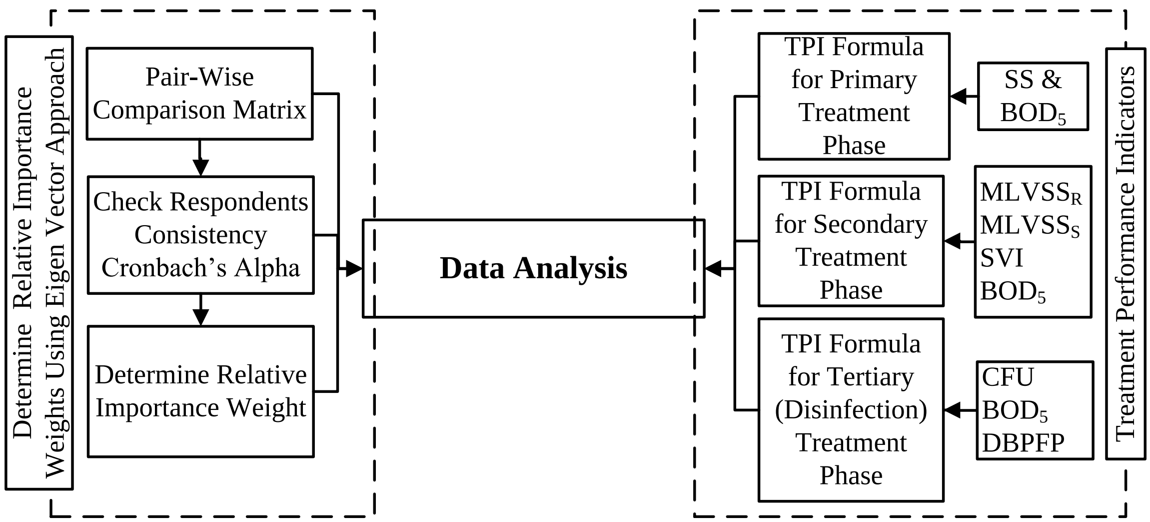


FIGURE V-1: Data Analysis Framework

Finally, a case study based on data collected from three WWTPs in Canada and the US is presented in this chapter to show the implementation of the developed methodology.

5.2 DETERMINING RELATIVE WEIGHTS

The AHP technique is used to develop the relative weights of different factors and sub-factors affecting the deterioration of WWTP infrastructure units (tanks, pipes and pumps) in the three treatment phases considered in this study. The hierarchy presented in Chapter 3 for each infrastructure unit is now presented using two levels. The first level classifies these factors into physical, operational and environmental factors, while the second level deals with the sub-factors. The relative weights for the factors and sub-factors affecting the deterioration of various infrastructure units in WWTPs are determined using the Eigen-vector approach, which is part of the AHP technique developed by Saaty (1991). A detailed explanation of the AHP method used in this research is presented in Appendix C.

5.2.1. RELATIVE WEIGHTS FOR WWTP TREATMENT PHASES

This part of the study is dedicated to determining the importance and the weight of each treatment phase in WWTPs, as well as the relative weight of each infrastructure unit within each treatment phase, as per the hierarchy presented in Chapter III.

The relative weight of the secondary treatment phase in WWTPs was determined to be (0.6), the highest among the three treatment phases. This phase is the main treatment unit in an activated sludge treatment system and it is at this stage that oxidation of soluble organic matter occurs through the biological treatment processes. The tertiary treatment phase, responsible for the disinfection of the treated wastewater, had a relative weight of (0.24). As for the primary treatment phase, responsible for the removal of suspended solids, it showed the smallest relative weight at (0.16). The relative weights of the three treatment phases and their infrastructure units are shown in Table V-1.

TABLE V-1: Relative Weights for WWTP Phases and Their Infrastructure Units

Main Factors	Sub factor	Level 1	Level 2	Final weight
Primary Treatment Phase	Primary Sedimentation Tank	0.14	0.23	0.03
	Primary Phase Pump		0.51	0.07
	Primary phase Pipes		0.26	0.04
Secondary Treatment Phase	Secondary Phase Reactor Blower	0.60	0.37	0.22
	Secondary Sedimentation tank		0.08	0.05
	A.S Reactor		0.13	0.08
	Secondary Sedimentation Pump		0.20	0.12
	Secondary Phase pipes		0.22	0.13
Tertiary Treatment Phase	Chlorination Phase Tank	0.26	0.29	0.08
	Chlorination Phase Pump		0.43	0.11
	Chlorination Phase Pipes		0.28	0.07

i. Relative Weights for the PTP Infrastructure Units

In the primary treatment phase, the pump boasted the highest relative weight (0.5) compared to the primary sedimentation tank (0.23) and the primary treatment phase pipes (0.26). These results reflect the vital role of pumps in this phase and stress the importance of their maintenance, relative to that of other infrastructure units.

ii. Relative Weights for the STP Infrastructure Units

The secondary treatment phase showed the highest relative weight among all treatment phases. The main parts of this phase are the reactor and the secondary sedimentation tank. The relative weight of the reactor blower was (0.37) and that of the secondary phase pump was (0.22), the highest among the five infrastructures, thereby confirming the vital role of the blower and the returned sludge pump in the biological treatment process.

iii. Relative Weights for the TTP Infrastructure Units

The tertiary phase in WWTPs involves WW disinfection, followed by the disposal of the treated effluent into water bodies or its reuse for other applications. Usually, disinfection efficiency depends on chlorine dosage and contact time provided respectively by the TTP pump and the TTP tank. The TTP pump had the highest relative weight (0.43), compared to the tanks (0.29) and the pipes (0.28).

5.3 RELATIVE WEIGHTS FOR FACTORS AFFECTING WWTP TANKS DETERIORATION

The relative weight of different factors and sub-factors affecting the deterioration of tanks in WWTPs are also determined by the Eigen-vector technique.

The relative weights of these factors and sub-factors are summarized in Table V-2 and illustrated in Figure V-2.

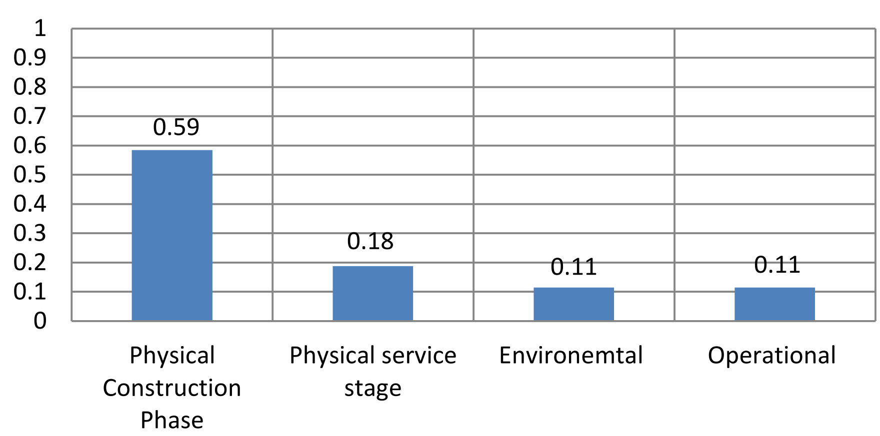


FIGURE V-2: Relative Weights for Main Factors Affecting WWTP Tank Deterioration

TABLE V-2: Relative Weights for Factors Affecting WWTP Tank Deterioration

Main Factors	Sub factors	Level 1	Level 2	Final weight
Physical Construction Phase	Construction Processes & control	0.59	0.41	0.24
	Construction Material Quality		0.22	0.13
	Size & Capacity		0.06	0.03
	Tank Shape		0.10	0.06
	Equipment Fixation Method		0.11	0.07
	Tank location (Above or below Surface)		0.10	0.06
Physical Service stage	Element Age	0.19	0.20	0.04
	Corrosion		0.16	0.03
	Protective Measures		0.09	0.02
	Cracks & Flaws		0.31	0.06
	Degree of Mechanization		0.23	0.04
Environmental	Type of Soil	0.11	0.18	0.02
	Influent pH		0.11	0.01
	Vibration		0.35	0.04
	Weather Conditions		0.30	0.03
Operational	Chemical Doses	0.11	0.08	0.01
	Operational & Maintenance practices		0.32	0.03
	Operator Qualification & Experience		0.24	0.03
	Control System (Flood & operational control)		0.24	0.03
	WW Characteristics[1] or Aeration Type[2]		0.12	002

[1] For Primary Sedimentation Tank (PST), Secondary Sedimentation Tank (SST), & Chlorination Tank (CT)
[2] For Reactor Tank Only

The construction processes, during the construction phase, had the highest relative weight among the factors with a weight of (0.41), while the cracks and flaws factor had a value of (0.31).

5.4 RELATIVE WEIGHTS FOR FACTORS AFFECTING WWTP PIPE DETERIORATION

The relative weight of different factors and sub-factors affecting the deterioration of pipes in WWTPs are determined using the same approach used to calculate the relative weights of different factors and sub-factors affecting the deterioration of WWTP tanks, using the Eigen-vector approach. The relative weights of these factors are summarized in Table V-3.

TABLE V-3: Relative Weights for Factors and Sub-Factors Affecting WWTP Pipe Deterioration

Main Factors	Sub-factors	Level 1	Level 2	Final weight
Physical Factors	Pipe Material	0.73	0.34	0.25
	Pipe Diameter		0.07	0.05
	Pipe Length		0.07	0.05
	Pipe Age		0.23	0.17
	Pipe Depth & insulation		0.11	0.08
	Joints & jointing Methods		0.18	0.13
Environmental Factors	Soil Type	0.13	0.14	0.02
	Influent pH		0.2	0.03
	Vibration		0.49	0.07
	Weather Condition		0.16	0.02
Operational Factors	Chemical Type & Dose	0.13	0.05	0.01
	Operation & Maintenance Practice		0.26	0.03
	Cathodic Protection		0.28	0.04
	Number of Previous Breaks		0.33	0.04
	WW Characteristics		0.07	0.01

Vibration caused by machinery and other sources had the highest relative weight as the major sub-factor of the operational factors affecting pipe deterioration, followed by the number of breaks sub-factor. Many experts considered vibration as the main cause of pipe breakage in WWTPs.

5.5 RELATIVE WEIGHTS FOR FACTORS AFFECTING WWTP PUMPS

Pumps are the most important infrastructure elements in WWTPs due to their vital role in the treatment process continuity.The relative weight of different factors and sub-factors affecting the deterioration of WWTP pumps are determined using the Eigen-vector technique. The relative weights for these factors are presented in Table V-4.

TABLE V-4: Relative Weights for Factors and Sub-Factors Affecting WWTP Pump Deterioration

Main Factors	Sub-factors	Level 1	Level 2	Final weight
Physical	Pump Type	0.75	0.18	0.13
	Fixation Method		0.03	0.02
	Size & Capacity		0.03	0.03
	Age		0.19	0.15
	Protective measures		0.14	0.10
	Cavitations		0.42	0.31
Operational	Chemical Types & Doses	0.15	0.08	0.01
	Number of Operation Failure		0.19	0.03
	Operation & Maintenance Practices		0.25	0.04
	Control System		0.15	0.02
	Operation type (Continuous or alternating)		0.12	0.02
	Standby System		0.18	0.03
	WW temperature		0.04	0.01
Env.	pH	0.10	0.80	0.080
	WW temperature		0.20	0.020

Pump cavitation is an important factor that reflects pump deterioration. It has the highest relative weight among the factors with a value of (0.31).

5.6 THE DEVELOPMENT OF WWTP DETERIORATION CURVES

Deterioration curves for WWTP infrastructure units can be used to assist decision makers in prioritizing their maintenance and rehabilitation procedures. The developed CRI for each infrastructure unit needs to be integrated with WWTP infrastructure maintenance data to ensure the development of accurate deterioration curves for WWTP infrastructure units. However, because this data is not available for most WWTPs contacted, sensitivity analysis was used to develop the deterioration curves by showing the effect of age on the developed CRI. The deterioration curves developed using this approach were discussed with and approved by WWTP experts.

The proposed deterioration curves presented in this chapter are based on the change in CRI of each infrastructure unit with time. As explained in Chapter III, this study divides WWTPs into three phases, with each phase responsible for the removal of specific pollutants from the WW influent. Each treatment phase in a WWTP has infrastructure units necessary to achieve the required treatment level. Therefore, the CRI of each infrastructure unit will affect the CRI of the treatment phase and eventually also the overall CRI of the WWTP. The infrastructure CRI of each treatment phase is determined using the weighted sum of its infrastructure CRI. Similarly, the condition rating index (CRI) of the whole WWTP is determined using the weighted sum of the CRI of the WWTP's three treatment phases.

5.6.1. WWTP TANK DETERIORATION PREDICTION

In this study, the deterioration curves of WWTP tanks are developed using sensitivity analysis after calculating the CRI. Three CRIs for tanks are determined using best, average and minimum utility values. The best CRI is determined based on selecting the best utility value score for all attributes considered in the CRI model, while the minimum CRI is determined using the lowest utility score for all attribute considered in the CRI. Similarly, the average CRI is determined using the average score for each model obtained using the average utility score for all attributes. The maximum and average CRIs are used to show different deterioration scenarios for WWTP tanks.

The minimum CRI is used as the minimum threshold for the WWTP, represented by the minimum CRI determined. The deterioration curves are developed by showing the effect of the element's age using sensitivity analysis over (25 – 30) years, the estimated service life of WWTPs. The deterioration curve for WWTP tanks is shown in Figure V-3, assuming best utility values for all attributes, while Figure V-4 shows WWTP tank deterioration curves assuming an average utility value for all attributes.

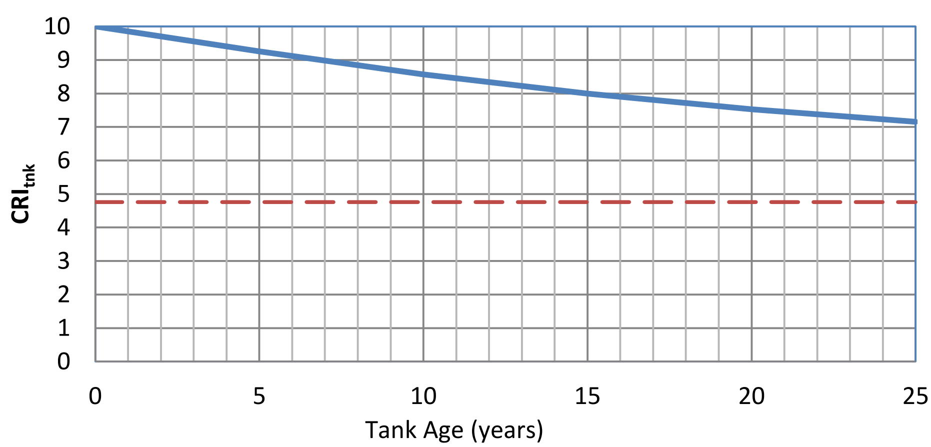


Figure V-3: Tank Deterioration Curve Based On Best Utility Values

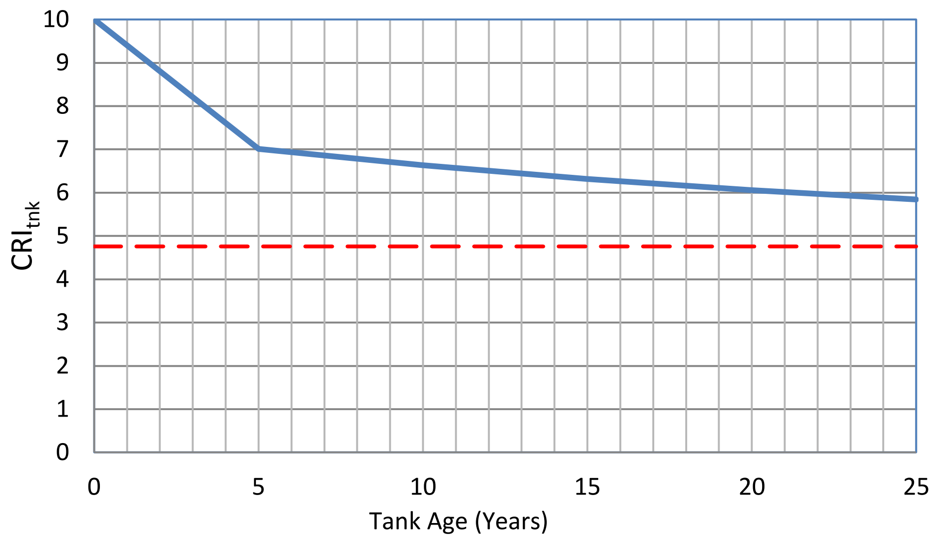


FIGURE V-4: Tank Deterioration Curve Based On Average Utility Values

5.6.2. WWTP Aeration Tank Deterioration Prediction

The aeration tanks in WWTPs, also called reactor tanks, are mainly found in the secondary treatment phase, where all biological oxidation processes take place. The deterioration curves for these tanks are developed using the same approach followed to develop the WWTP tank deterioration curves after adding the aeration attribute alternatives among the overall attributes considered in the aerated tank CRI. The maximum and average CRIs are used to develop two deterioration curves for aeration tanks, as shown in Figure V-5. and Figure V-6, respectively. The minimum condition rating is used to determine the minimum allowable CRI threshold.

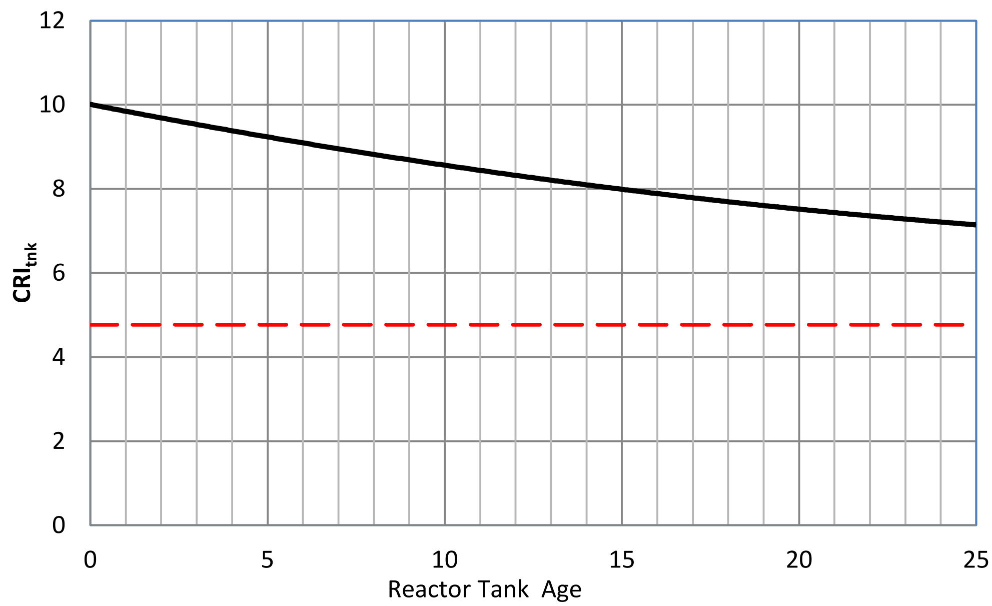


FIGURE V-5: Reactor Tank Deterioration Curve Based On Best Utility Value

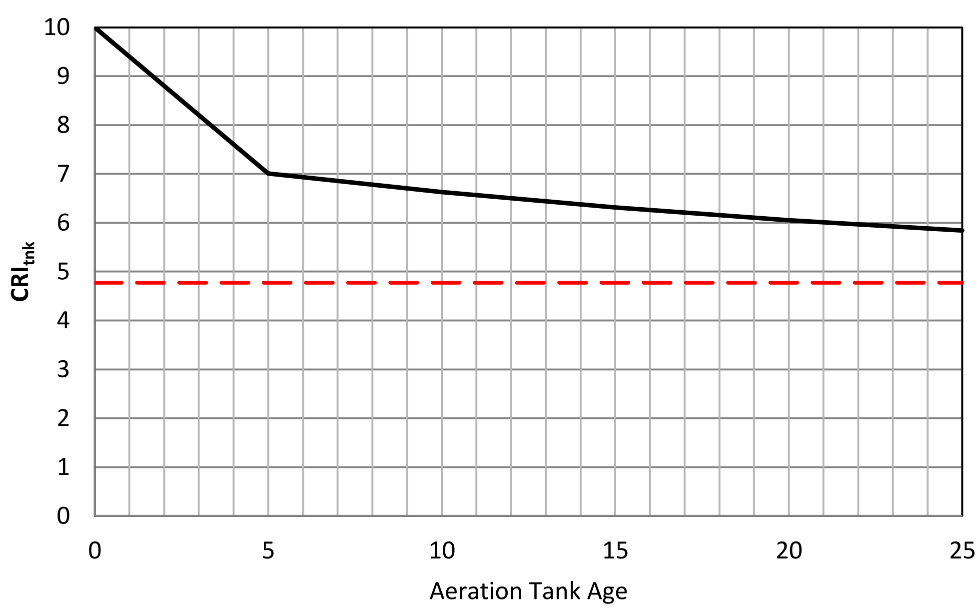


FIGURE V-6: Aeration Tank Deterioration Curve Based on Average Utility Value

5.6.3. WWTP Pipes Deterioration Prediction

The WWTP pipe system is used to transfer WW influent to the different treatment units in different treatment phases. Typically, pipes of different materials are used in different treatment plants. Although concrete and cast iron are widely used in WWTPs, PVC pipes are also used in new WWTPs due to their durability and flexibility. The service life of pipes considered in this study is 30 years, the estimated service life of WWTPs; however, WWTP pipes can last much longer and they have the longest service life among all WWTP infrastructure. The deterioration curve for WWTP pipes is obtained in this study by using the sensitivity analysis approach and showing the cumulative effect of pipe age over the pipes' overall CRI. Three CRI values for different pipe materials (PVC, cast iron, and concrete) are determined along with best operating conditions. The minimum utility value is used to calculate the minimum CRI needed for the minimum allowable threshold. This approach generates an acceptable estimate for pipe deterioration curves, although it only reflects the cumulative effect of age on the CRI and neglects other immeasurable time-dependent factors. The deterioration curves for PVC, cast iron and concrete pipes are shown in Figure V-7, Figure V-8 and Figure V-9, respectively.

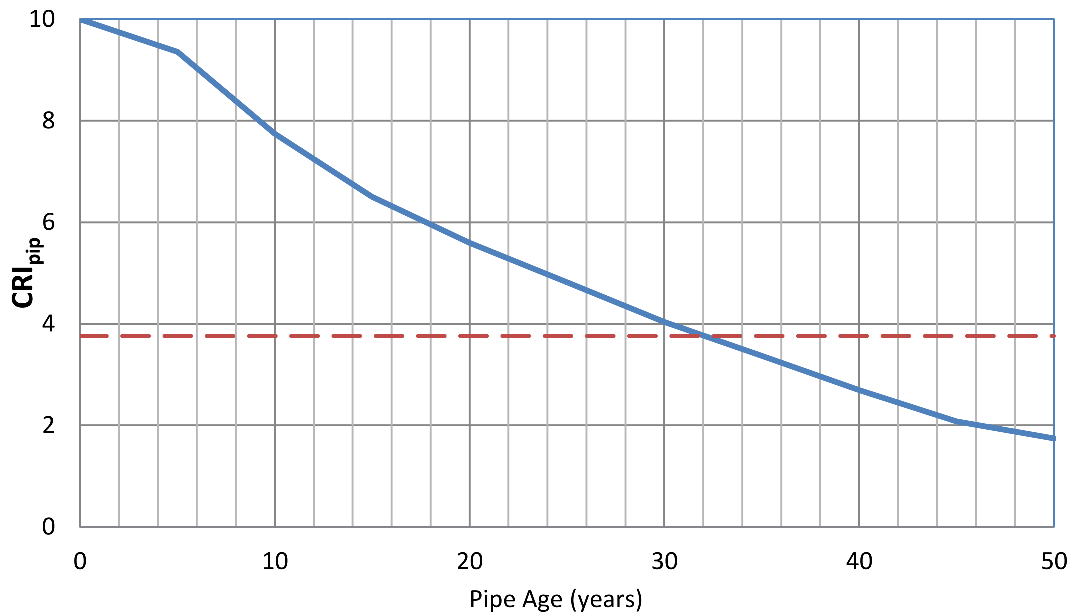


FIGURE V-7: Deterioration Curve for WWTP PVC Pipes

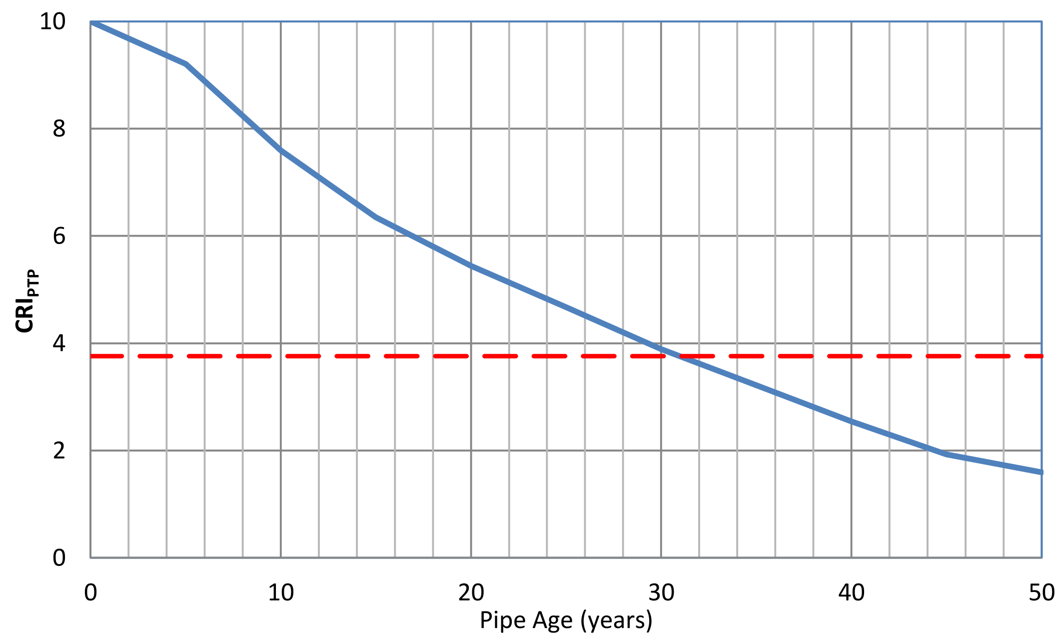


FIGURE V-8: Deterioration Curve for WWTP Cast Iron Pipes

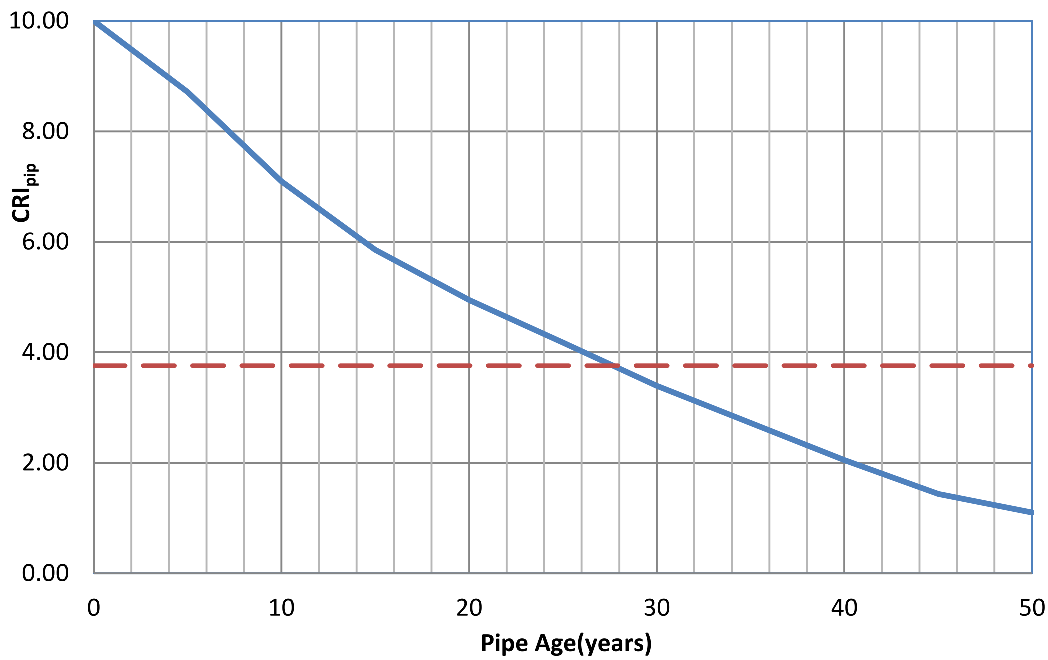


FIGURE V-9: Deterioration Curve for WWTP Concrete Pipes

5.6.4. WWTP PUMPS & BLOWERS DETERIORATION PREDICTION

WWTP pumps play a major role in the WW treatment processes in each phase. This is emphasized by the fact that pumps had the highest relative weight among all infrastructures. Many studies have shown that WWTP pump service life is 15 years, the lowest service life of WWTP infrastructure units. This fact is expected to affect the CRI of each treatment phase and eventually the CRI of the whole treatment plant.

The ministry of environment of Ontario (MOE 2008) developed strict guidelines for the design and maintenance of WWTPs, which accept only a single failure every five years for WWTP pumps. The guidelines also recommend redundancy for different electromechanical equipment, including pumps, to ensure the WWTP's reliability. The five-year period is a conservative value for the pump replacement period (MOE 2008). The developed model shows that pumps would reach their minimum CRI threshold in year six if they operate continuously. However, the CRI of pumps and other electromechanical equipment is highly affected by the operational environment and maintenance practices. Alternating operational practices and periodical rehabilitation plans will significantly affect the CRI of pumps and therefore extend their service lives.

In this research, the deterioration curves are developed for centrifugal pumps because this is the most used pump type in wastewater treatment plants. Three CRIs are determined for centrifugal pumps. The first CRI is determined using the maximum score value which assumes the best attribute for each factor. However, the second CRI is determined using the average score, based on the average utility value for the attributes considered for each factor. The third CRI is determined using the minimum utility value for the attributes considered. This minimum CRI is used to show the minimum threshold value on the deterioration curve, below which the pump's CRI should not drop. However, the maximum and average utility values are used to calculate WWTP pump deterioration scenarios adopted in this study. The deterioration curve for WWTP pumps using maximum attribute values is shown in Figure V-10, while the pump deterioration curve based on average CRI is shown in Figure V-11.

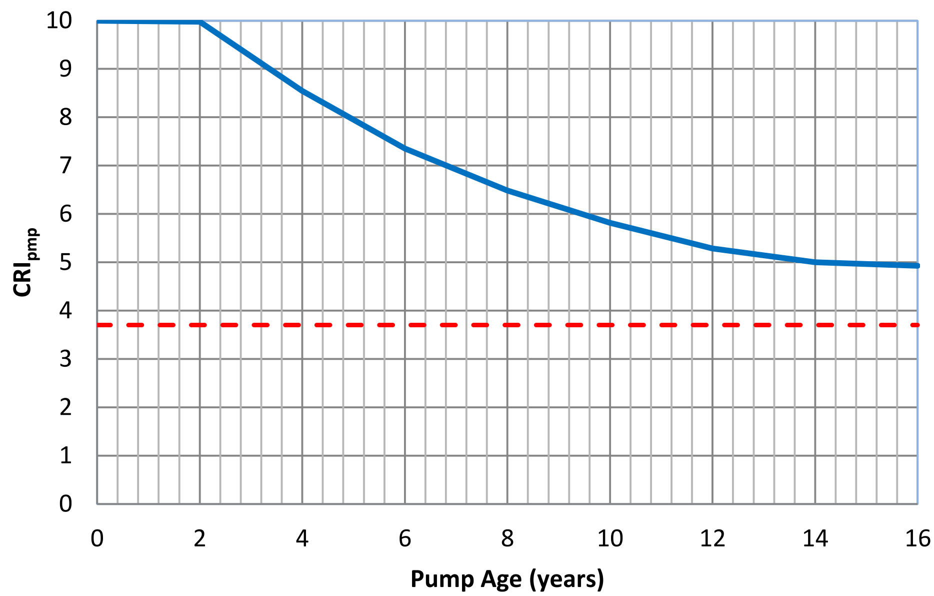


FIGURE V-10: Pump Deterioration Curve Based On Best Utility Values

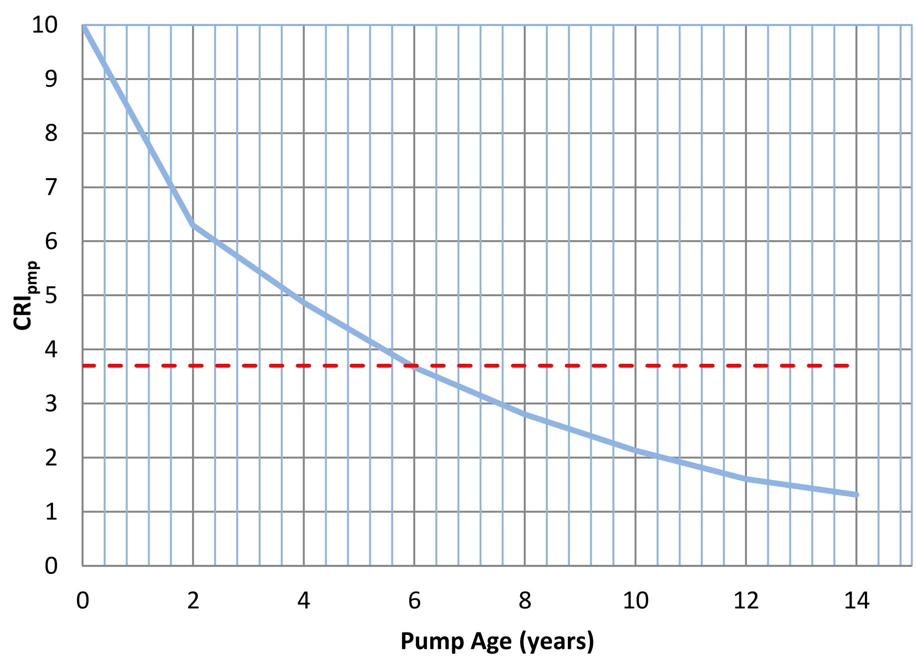


FIGURE V-11: Pump Deterioration Curve Based On Average Utility Values

5.7 **WWTP CRI**

Typically, treatment performance and compliance with environmental regulations and permits are key factors for decision makers. However, due to drastic changes in environmental regulations and WW dynamics, this compliance varies over time, requiring continuous WWTP upgrades. Therefore, it is important to know the WWTP's infrastructure performance level to figure out whether it can accommodate the required operational modifications and upgrades. This can be done by developing condition rating models for different infrastructure units in WWTPs, in addition to a condition rating for each treatment phase. These ratings will provide decision makers with the needed proactive assessment tool to plan their short and long-term rehabilitation resources and keep their WWTP functioning at the desired level.

5.7.1. CRI AND DETERIORATION SCENARIOS

Typically, WWTPs have different designs, different infrastructure types, different material qualities and even different operational and maintenance practices. This means that each infrastructure unit is expected to have different deterioration rates and therefore a different deterioration curve. However, all WWTPs have three treatment phases and each treatment phase has a similar relative weight and similar infrastructure units. Therefore, the CRI of each treatment phase is determined by the weighted sum of the CRI of its infrastructure units. Because different WWTPs have different material qualities, pipe material, and pump types, in addition to different operational and maintenance practices, it is expected that the infrastructures of different WWTPs will have different deterioration rates over their life spans. Therefore, to reflect these variations, the deterioration curves for wastewater treatment plants are presented using six scenarios.

Each scenario reflects the material used and the operational and maintenance practices. The best preference utility value obtained using the MAUT discussed in Chapter IV is used to reflect best material and best operating quality, while the average utility values are used to reflect typical material and operational quality.

The first CRI scenario considers the maximum utility value for various attributes to determine the CRI for tanks and pumps. However, the pipe CRI is determined using PVC type material. Also, this scenario assumes best utility values for different infrastructure units within a WWTP. The second scenario uses the same approach for tanks and pumps, but its CRI for pipes is determined based on cast iron pipes. The third CRI scenario uses the same approach for tanks and pumps, but the CRI for pipes is determined for concrete material. The fourth scenario uses average utility values for all attributes to determine the CRI for tanks and pumps and uses the PVC pipe material's CRI. The fifth scenario is the same as the fourth, using the average utility values for all attributes, but it uses cast iron to calculate the CRI for pipes. The sixth and the final scenario is also similar to the fourth and fifth scenario in using the average attribute utility values to calculate the CRI for tanks and pumps, but it uses concrete to calculate the CRI for pipes. The CRI for each treatment phase and for the WWTP using the first scenario is presented in this chapter. The other five scenarios are presented in Appendix E.

5.8 THE CRI OF EACH TREATMENT PHASE

The condition rating index for each treatment phase in WWTPs is determined using the weighted sum of the condition rating index of its tanks, pipes and pumps, as illustrated in Figure V-12. The relative weight of each treatment phase of a WWTP and the relative weights of its infrastructure units are presented in Table V-1. This table shows that the PTP tank and pipes have relative weights of (0.23) and (0.26), while the pump in this phase has the highest relative weight of (0.5). Similarly, the relative weights of the STP show that the blower and pumps have the highest relative weight of (0.37) and (0.21), respectively. However, the STP reactors and secondary sedimentation tanks have relative weights of (0.13) and (0.08), respectively. The relative weight of pipes in the STP is almost the same as for the PTP with a relative weight of (0.22). Finally, the relative weights for tanks and pipes for the TTP are almost equal with values of (0.29) and (0.28), respectively, while the pump in this phase has the highest relative weight of (0.43).

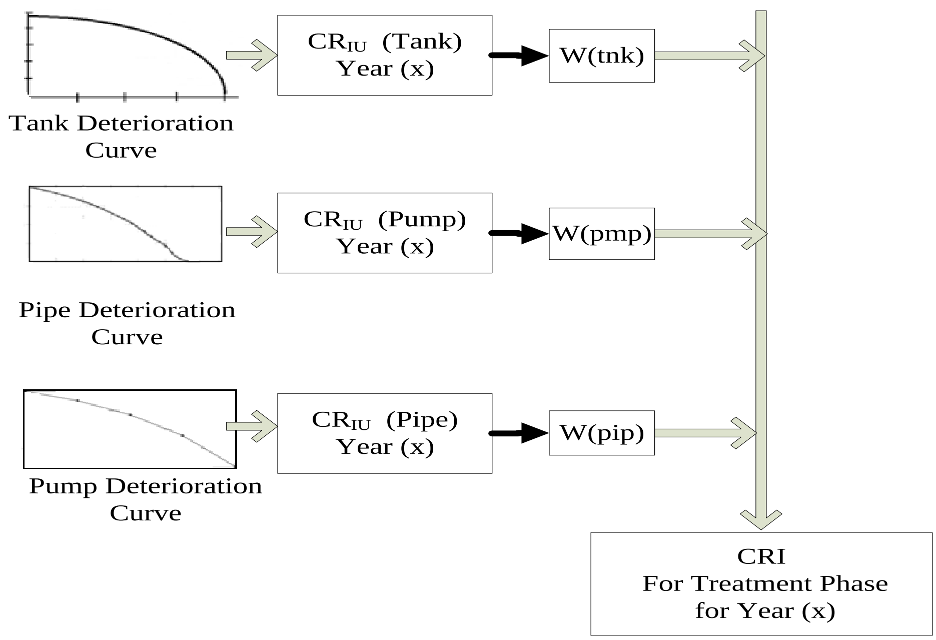


FIGURE V-12: CRI Development Framework for Treatment Phases

5.8.1. Primary Treatment Phase condition rating (CRI_{PTP}) for different scenarios

The condition rating for the primary treatment phase (CRI_{PTP}) of a WWTP is determined using the weighted sum of the condition rating of its infrastructure units, as discussed in previous chapters. However, because there are many possible combinations for different infrastructure types, the condition rating for the primary treatment phase is determined in this section using the assumed infrastructure types in the six scenarios described in the previous section. These scenarios show the effect of different factors and their attributes over wastewater treatment plant deterioration. The condition ratings of a WWTP's infrastructure units depend on their preference utility values, which provide the condition rating score needed for the AHP-MAUT model adopted in this research. The six scenarios are used to illustrate the best, average and lowest infrastructure qualities that can be found in different WWTPs and their predicted deterioration. The first deterioration scenario shows the deterioration curve of the primary treatment phase of a WWTP having the best quality tanks and PVC pipes, in addition to using centrifugal pumps. The CRI_{PTP} is determined using the weighted sum of the condition ratings of the infrastructure units, as shown in Table V-5. The deterioration curve for the PTP is developed by showing the effect of time over its infrastructures following the first scenario, as shown in Figure V-13.

Table V-5: Primary Treatment Phase CR (CRI_{PTP}) for Scenario (1)

Tanks Max. Utility Value			Pipe PVC		Pump Max. Utility Value		CRI_{PTP}
Age	CRI	w Tanks	CRI	w Pipe	CRI	w Pump	
0	10.00	0.24	10.00	0.26	10.00	0.50	10.0
5	9.26	0.24	9.35	0.26	8.10	0.50	8.7
10	8.57	0.24	7.74	0.26	6.90	0.50	7.5
15	8.00	0.24	6.50	0.26	5.30	0.50	6.3
20	7.52	0.24	5.59	0.26	4.80	0.50	5.6
25	7.16	0.24	4.82	0.26	4.80	0.50	5.4

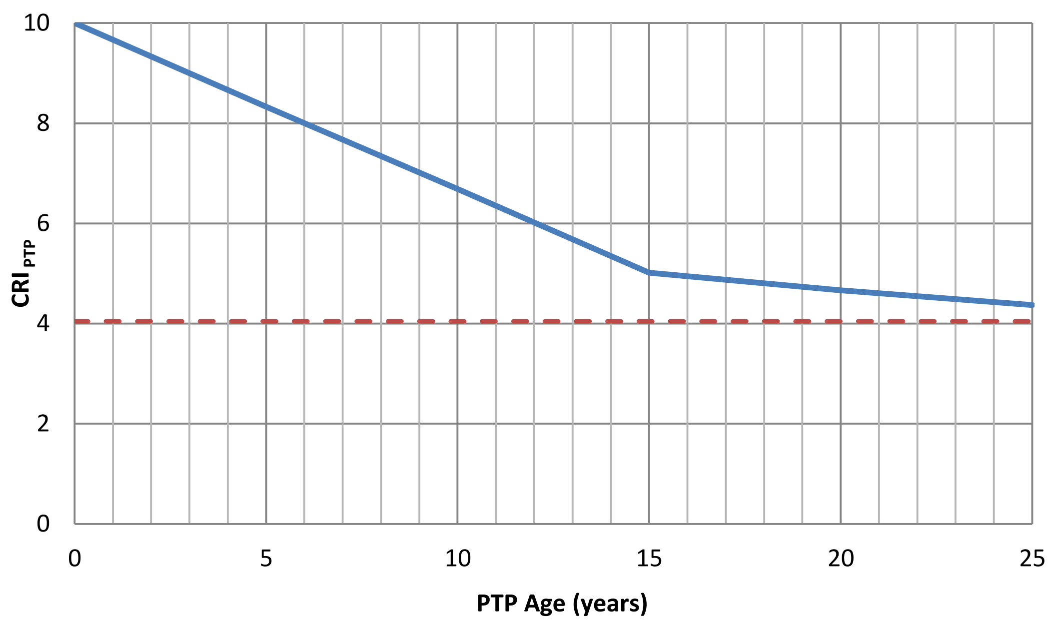


FIGURE V-13: PTP Deterioration Curve for Scenario 1

5.8.2. THE CRI FOR THE SECONDARY TREATMENT PHASE

The CRI for WWTP STP (CRI_{STP}) is determined using the same six-scenario approach used to calculate the CRI of the primary phase (CRI_{PTP}). Using the first scenario, the CRI_{STP} is determined using the weighted sum of the condition ratings of the secondary sedimentation tank, the reactor tank, the secondary phase pump and the secondary phase blower, as shown in Table V-6. The deterioration curve of this phase, based on the first scenario, is shown in Figure V-14. This curve illustrates that this phase has low deterioration rates, because of its mild operational conditions and excellent material quality.

TABLE V-6: Secondary Treatment Phase CR (CRI_{STP}) for Scenario (1)

Sedimentation tank Max. Utility Values			Reactor tank Max. Utility Values		Pipe PVC		Pump Max. Utility Value		Blower Max. Utility Value		CRI_{STP}
Age	CRI	w Tank	CRI	w Reactor	CRI	w Pipe	CRI	w Pump	CRI	w Blower	
0.00	10.00	0.08	10.00	0.13	10.00	0.22	10	0.21	10	0.37	10.00
5.00	9.26	0.08	9.25	0.13	9.35	0.22	8.1	0.21	8.1	0.37	8.61
10.00	8.57	0.08	8.56	0.13	7.74	0.22	6.9	0.21	6.9	0.37	7.43
15.00	8.00	0.08	7.99	0.13	6.50	0.22	5.3	0.21	5.3	0.37	6.12
20.00	7.52	0.08	7.51	0.13	5.59	0.22	4.8	0.21	4.8	0.37	5.54
25.00	7.16	0.08	7.15	0.13	4.82	0.22	4.8	0.21	4.8	0.37	5.30

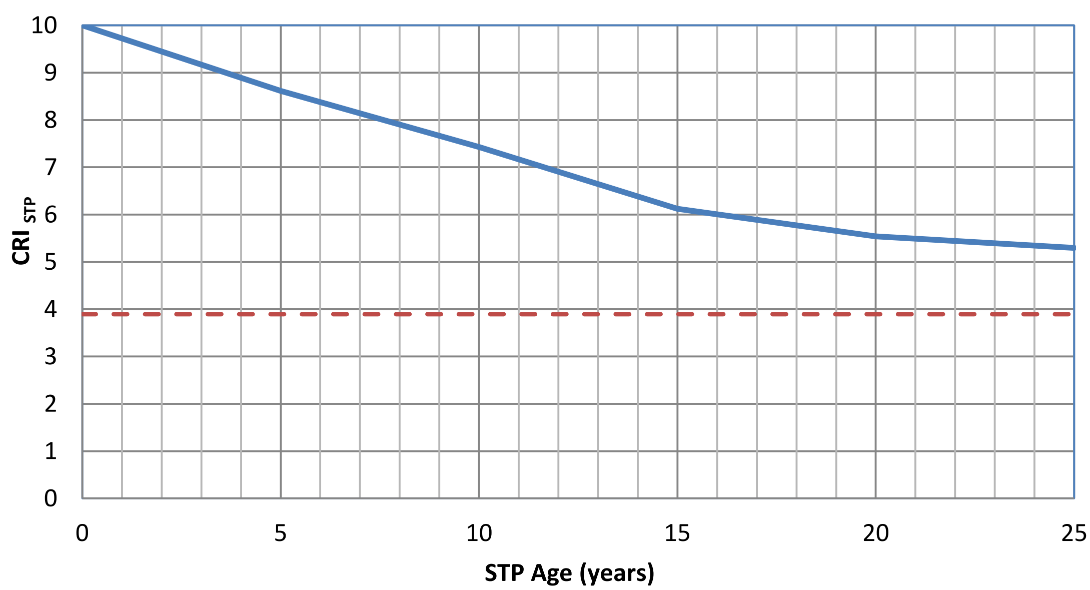


FIGURE V-14: STP Deterioration Curve (Scenario 1)

5.8.3. CRI for the Tertiary Treatment Phase

The CRI of the tertiary treatment phase (CRI_{TTP}) is determined using the weighted sum of the condition ratings of its infrastructure units, based on the previously mentioned deterioration scenarios. The deterioration of this phase is relatively lower than for the other treatment phases for different pipe types for the first three scenarios; however, the deterioration is higher for the fourth, fifth and sixth scenarios because of the pump state. The values of CRI_{TTP} using the first scenario are shown in Table V-7. The deterioration curve for this phase, also based on the first scenario, is shown in Figure V-15.

TABLE V-7: Tertiary Treatment Phase CR (CRI_{TTP}) for Scenario (1)

Tank Max Utility Value			Pipe PVC		Pump Max Utility Value		
Age	CRI	w Tank	CRI	w Pipe	CRI	w Pump	CRI_{TTP}
0	10.00	0.29	10.00	0.28	10	0.43	10.00
5	9.26	0.29	9.35	0.28	8.1	0.43	8.95
10	8.57	0.29	7.74	0.28	6.9	0.43	7.86
15	8.00	0.29	6.50	0.28	5.3	0.43	6.80
20	7.52	0.29	5.59	0.28	4.8	0.43	6.20
25	7.16	0.29	4.82	0.28	4.8	0.43	5.83

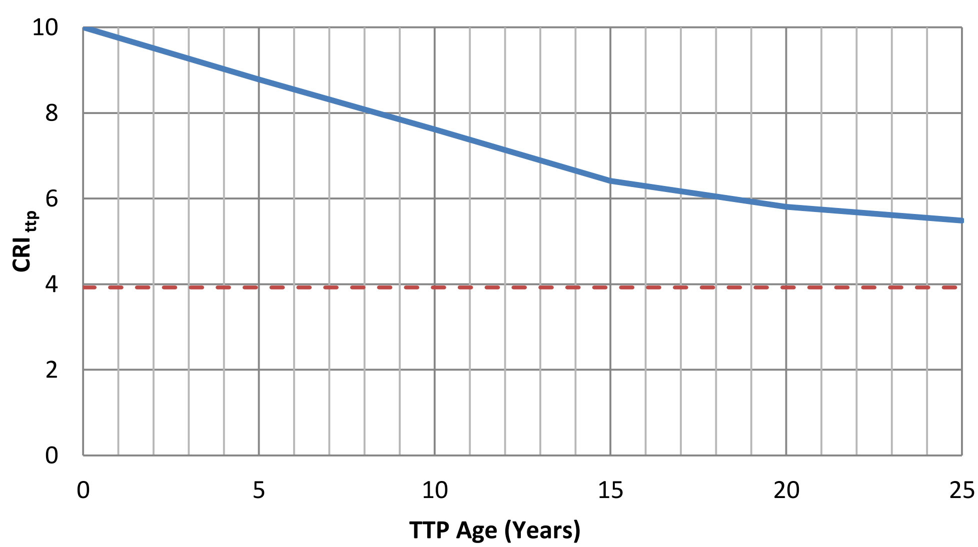


FIGURE V-15: TTP Deterioration Curve (Scenario 1)

5.9 THE CRI FOR WWTP INFRASTRUCTURES (CRI_{IP})

The CRIs of the three treatment phases within a WWTP give the condition rating index of the WWTP infrastructure performance (CRI_{IP}). Therefore, the infrastructure determines the performance of the three treatment phases of the WWTP. The CRI_{IP} is determined using the weighted sum of the condition rating index of the three treatment phases (primary, secondary and tertiary). The weights of each treatment phase were presented in Table IV-.4. The relative weight of the primary treatment phase is (0.16), the lowest among the three treatment phases, while the secondary treatment phase has the highest relative weight at (0.6). Finally, the tertiary treatment phase has a relative weight of (0.24). The deterioration curve for WWTPs is developed using the weighted sum of the CRI of each treatment phase at different WWTP ages until the estimated service life. The CRI_{IP} presented in this section is determined using the six scenarios previously discussed. The CRI_{IP} values using the first scenario are shown in Table V-8. The WWTP deterioration curve using this scenario is shown in Figure V-16.

TABLE V-8: WWTP Infrastructure Condition Rating (CRI_{IP}) for Scenario (1)

Age	Primary Treatment Phase		Secondary Treatment Phase		Tertiary Treatment Phase		CRI_{IP}
	CRI	*wp*	CRI	*ws*	CRI	*wt*	
0	10.0	0.16	10.00	0.6	10.00	0.24	10.00
5	9.0	0.16	8.88	0.6	8.95	0.24	8.92
10	8.0	0.16	7.82	0.6	7.86	0.24	7.85
15	7.0	0.16	6.76	0.6	6.80	0.24	6.80
20	6.4	0.16	6.18	0.6	6.20	0.24	6.22
25	6.0	0.16	5.85	0.6	5.83	0.24	5.87

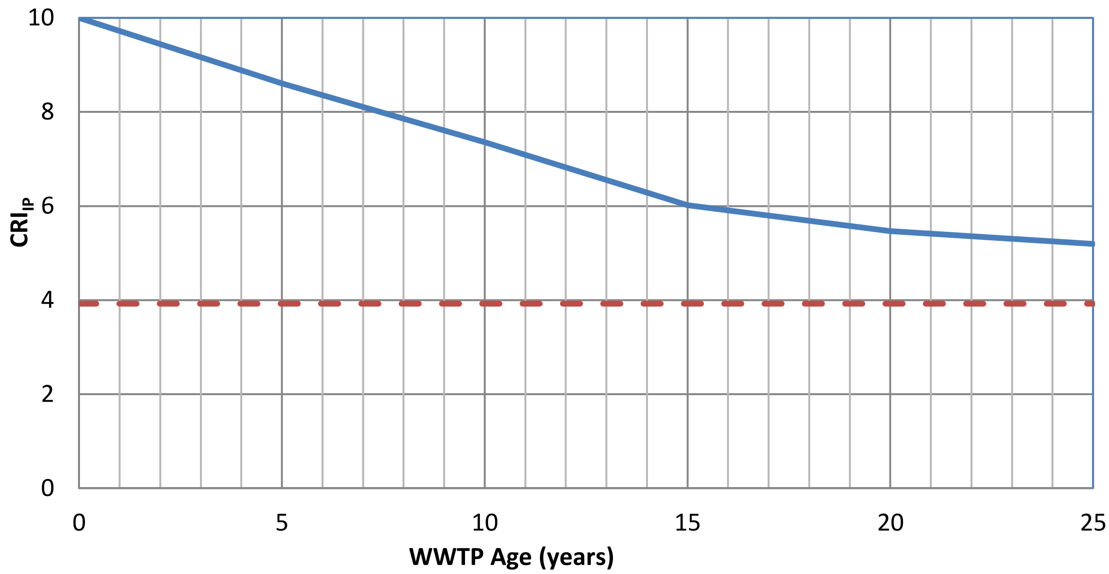


FIGURE V-16: WWTP Deterioration Curve (Scenario 1)

5.10 Deterioration Curves and Rehabilitation Decisions

The WWTP CRI and its deterioration curves will reflect the overall performance of the WWTP infrastructure and can be used to plan maintenance and rehabilitation procedures. The following section will demonstrate the application of the developed deterioration curves toward various WWTP rehabilitation plans.

5.11 Rehabilitation Scenarios

The rehabilitation scenario presented in this section is based on the assumption that all infrastructure units (tanks, pipes, and pumps have the same characteristics in the three treatment phases and are subjected to the same operational conditions. As presented in earlier sections, WWTP pumps and blowers have the highest relative weight among other infrastructure units and, at the same time, the shortest service life. The deterioration of these units will thus have a noticeable effect on the CRI of each treatment phase, as well as the CRI of the whole WWTP. Two rehabilitation scenarios are presented in this section. The first rehabilitation scenario is based on the assumption that pumps in all treatment phases, along with blowers in the secondary treatment phase, are replaced when they reach their projected service life of 15 years. The second rehabilitation scenario, however, is based on the assumption that pumps are replaced when their CRI reaches the minimum acceptable threshold. These rehabilitation scenarios were chosen based on real operational and maintenance practices commonly applied to these units, as discussed in earlier sections. Pumps can reach their projected service life if they are maintained and rehabilitated according to the manufacturer's specifications; however, they can only last six years if they operate continuously.

Two CRIs for pumps are considered in this section. The first CRI is determined using the maximum utility value, which represents the best operational conditions. These conditions will allow the pump to serve all of its estimated service life of 15 years, at which point it will be replaced. This is shown in Figure V-17. The second CRI for pumps is determined using the average utility values, representing harsher operating and maintenance conditions that cause more rapid deterioration. According to this deterioration pattern, the pumps will be replaced after just 6 years, so the pumps will be replaced five times during the service life of the WWTP which ranges from 25 to 30 years, as shown in Figure V-18.

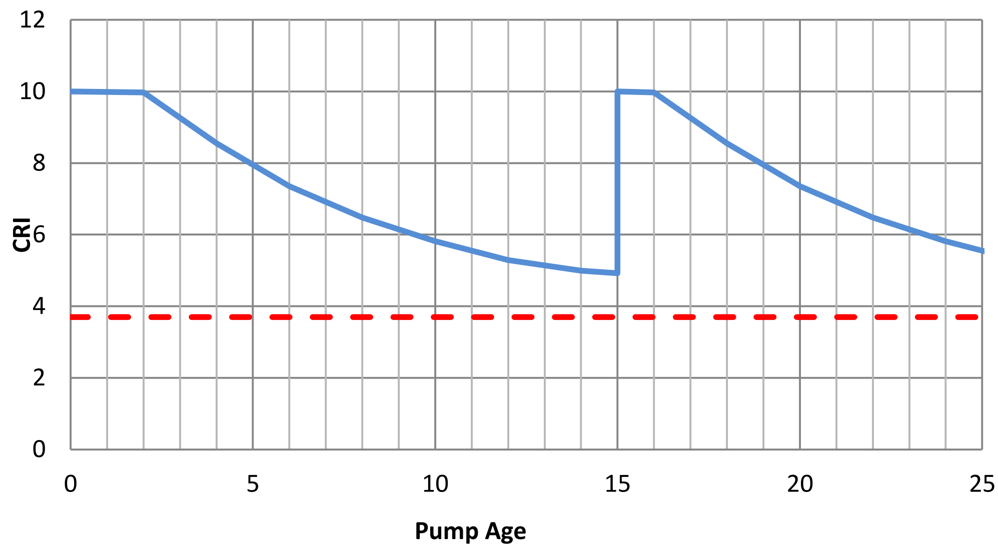


Figure V-17: Pump Replacement at End of Service Life

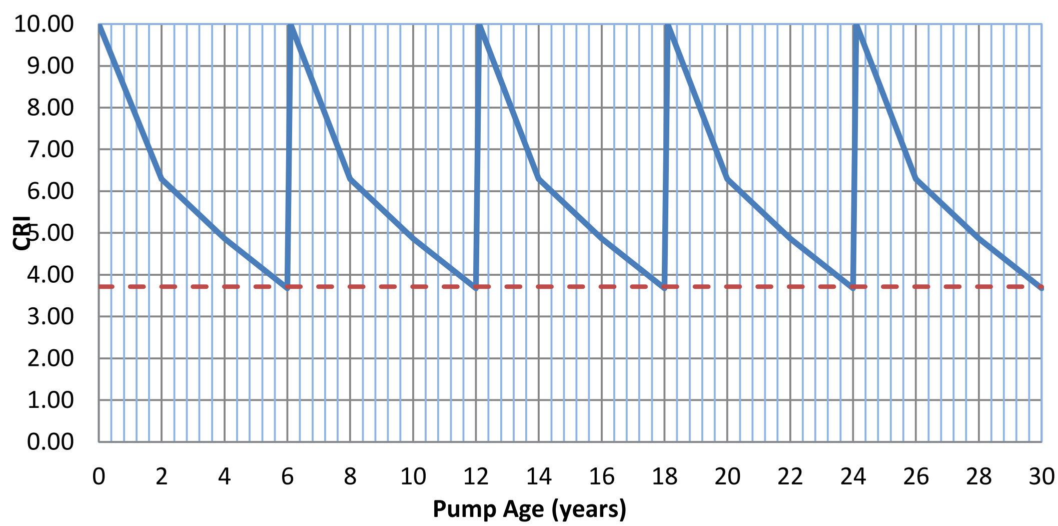


FIGURE V-18: Pump Replacement When Minimum CRI is Reached

5.12 Rehabilitation Effects over the CRI of each Treatment Phase

Decision makers are continuously challenged to comply with new, more stringent effluent standards using aging WWTP infrastructure. By studying and comparing different rehabilitation alternatives for different infrastructure units, this research provides decision makers with appropriate tools to support their decisions. Each rehabilitation alternative has a specific cost and a specific impact over the CRI of certain infrastructure units. These alternatives affect the CRI of different treatment phases and thus the CRI of the whole WWTP. This section will illustrate the effect of certain rehabilitation actions on the CRI of each treatment phase and on the CRI of the whole WWTP.

The rehabilitation action presented in this section is pump replacement in each treatment phase and the corresponding CRI recovery effect for each treatment phase and on the whole plant. The rehabilitation actions presented in this section are based on the deterioration curves of scenarios (3) and (6).

5.12.1. THE IMPACT OF PUMP REPLACEMENT ON CRI_{PTP}

Pump replacement will upgrade the pump's CRI to 10; however, since the assumption is "do nothing" for other infrastructure units (tanks and pipes), the CRI of the PTP will recover only partially.

FIGURE V-19: Effect of Pump Replacement at End of Service Life on PTP

Figure V-19 shows the recovery effect of the CRI_{PTP} when pumps are replaced at the end of their projected service life, while Figure V-20 shows the recovery effect of the CRI_{PTP} when pumps are replaced when they reach their minimum CRI threshold.

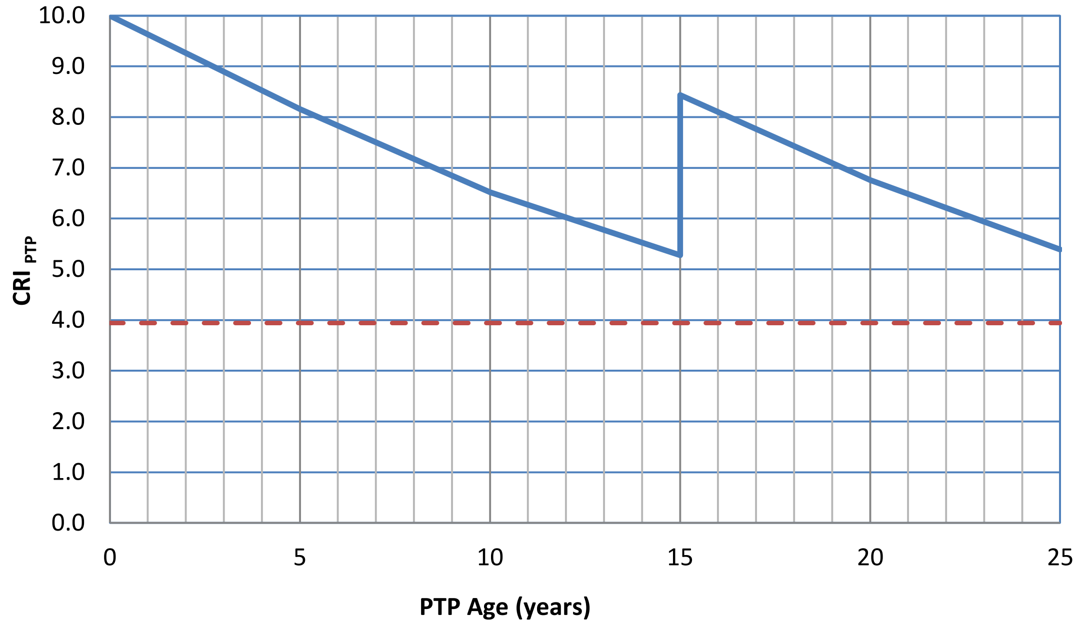


FIGURE V-19: Effect of Pump Replacement at End of Service Life on PTP

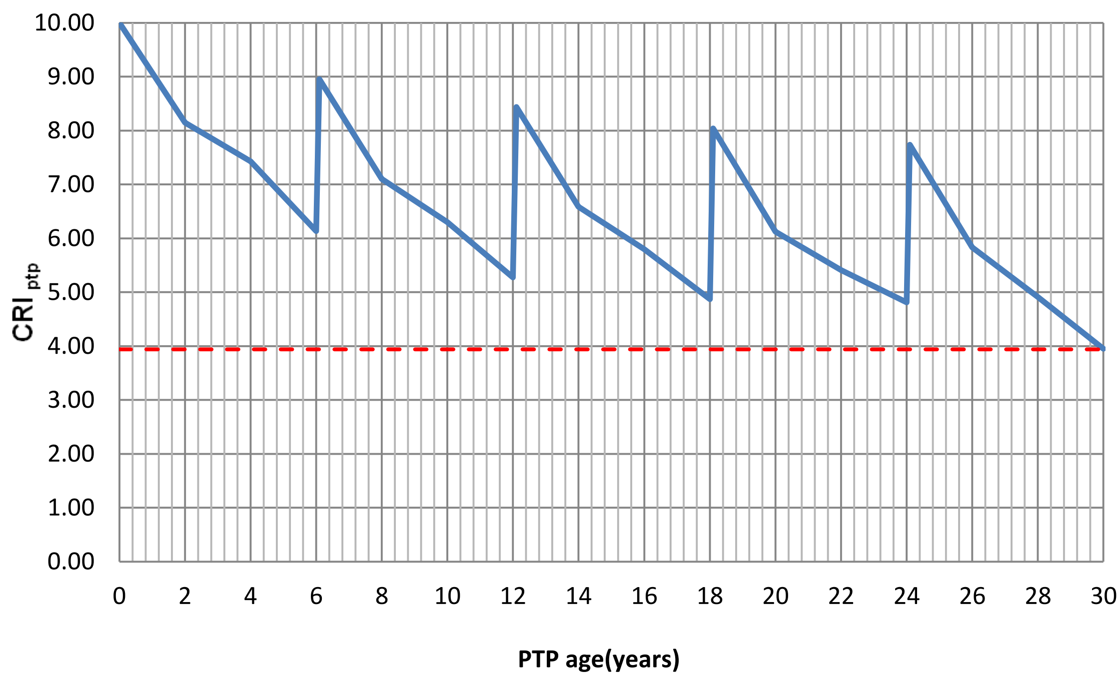


FIGURE V-20: Effect of Pump Replacement at Minimum Threshold on PTP

5.12.2. Effect of Pump Replacement on CRI_{STP}

This section shows the CRI recovery effect for replacing the pumps and blowers in the secondary treament phase of a WWTP. Figure V-21 shows the recovery effect on the CRI_{STP} when the pumps and blower are replaced at the end of their service life, estimated at 15 years, which will boost their CRI to 10. However, because the "do nothing" option is assumed for the other infrastructure (pipes and tanks), the CRI recovery for this phase will be increased but partially. The second rehabilitation option is to replace the pumps and blowers when they reach their minimum CR thresholds (scenario 6). This effect is illustrated in Figure V-22, which shows the recovery effect on CRI_{STP} when pumps and blowers are replaced when they reach their minimum thresholds. The deterioration effect of pipes and tanks is more apparent for years 12 and 18 than for year 6.

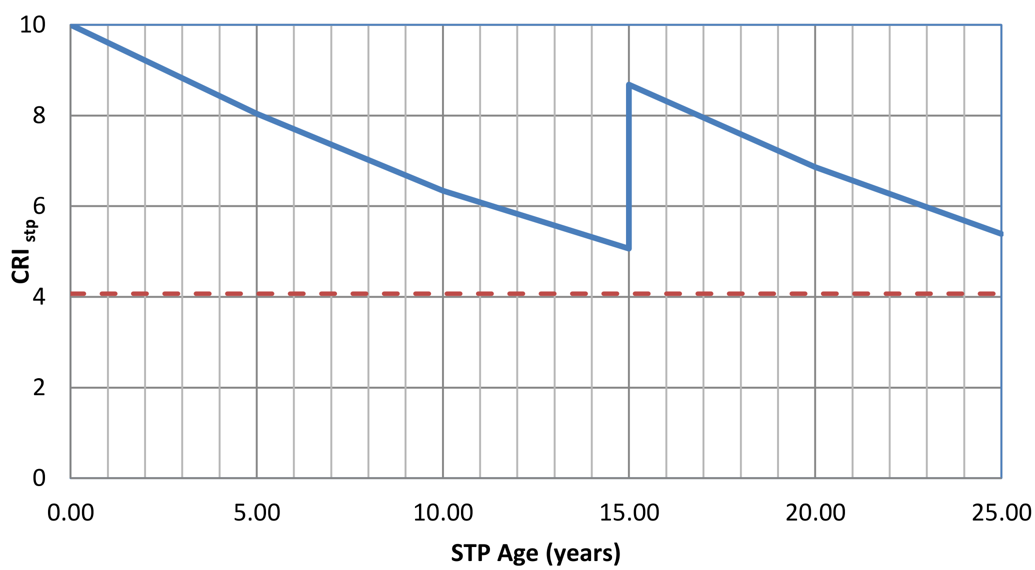


FIGURE V-21: Pump Replacement Effect at End of Service Life on STP

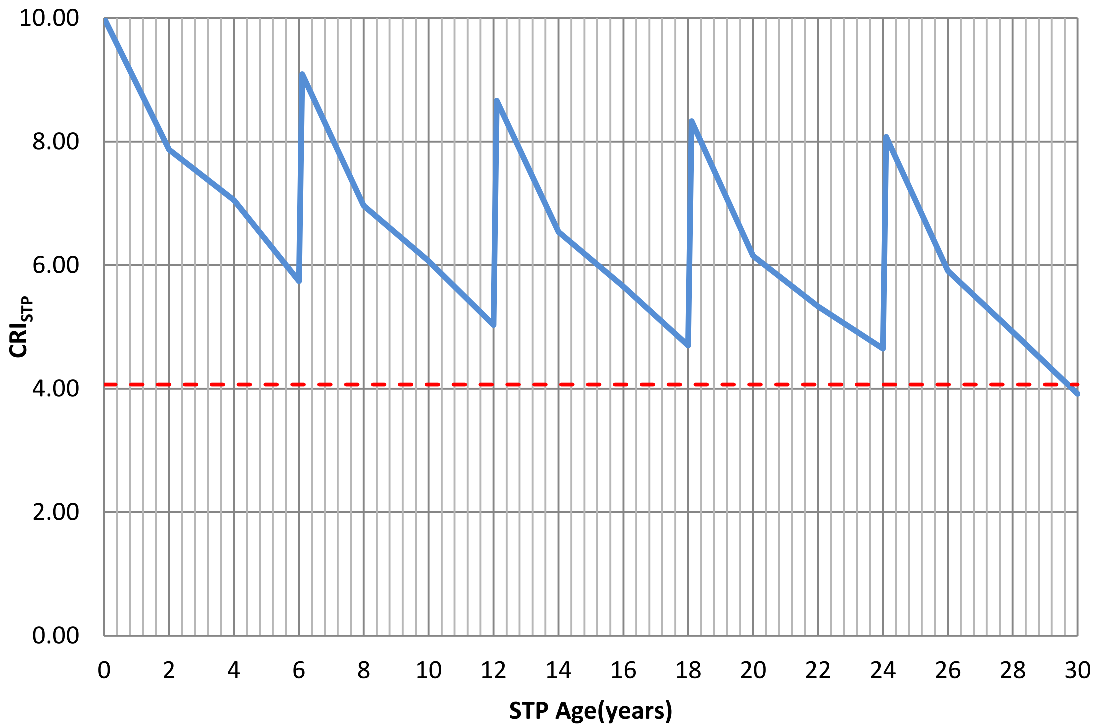


FIGURE V-22: Pump Replacement Effect at Minimum Threshold on STP

5.12.3. Effect of Pump Replacement On CRI_{TTP}

The effect of pump replacement on the tertiary treatment phase is similar to the effect on the primary treatment phase. Pump replacement will upgrade the pump's CRI to 10, while the CRI of the other infrastructure units will keep declining because no rehabilitation actions are applied to them. Therefore, the CRI of the TTP will partially recover when pumps are replaced at year 15 when they reach their projected service life, as shown in Figure V-23. On the other hand, Figure V-24 shows the recovery effect on the CRI_{TTP} when pumps are replaced upon reaching their minimum CRI threshold after six years.

FIGURE V-23: Effect of Pump Replacement at End of Service Life on CRI_{TTP}

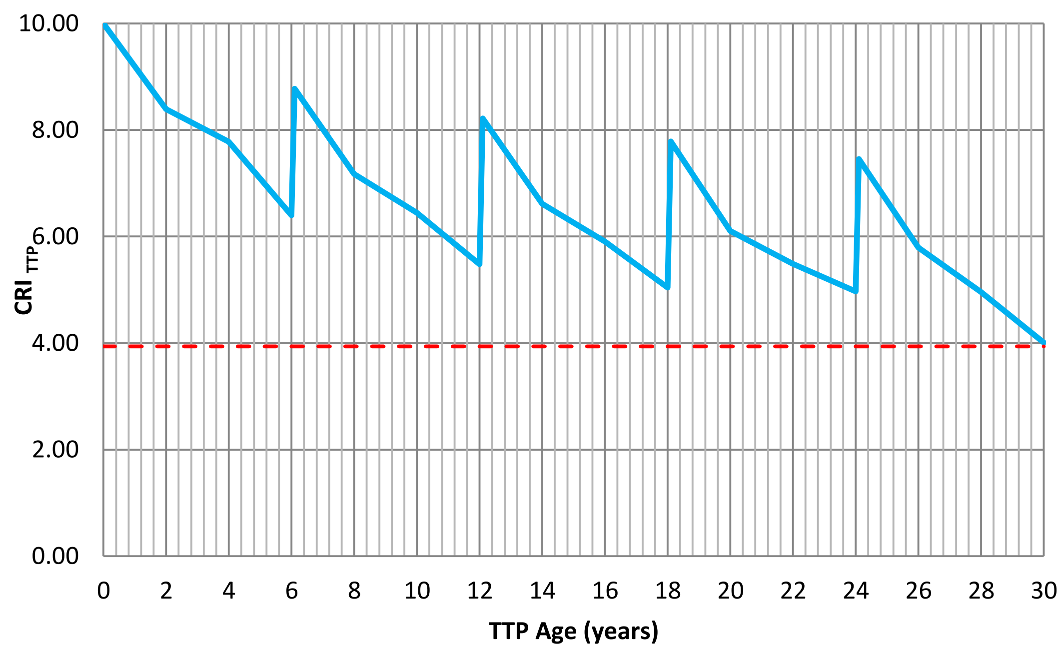


FIGURE V-24: Effect of Pump Replacement at Minimum Threshold on TTP

5.13 EFFECT OF PUMP REPLACEMENT ON WWTP CRI

The pump replacement scenarios presented in the previous sections affect the infrastructure CRI of the whole WWTP (CRI_{IP}), as it is determined based on the weighted sum of the CRI of each of the three treatment phases. Figure V-25 shows the effect on CRI_{IP} of pump replacement at the end of service life for all treatment phases. Figure V-26 shows the effect on CRI_{IP} of pump replacement when minimum CRI thresholds are reached for all treatment phases.

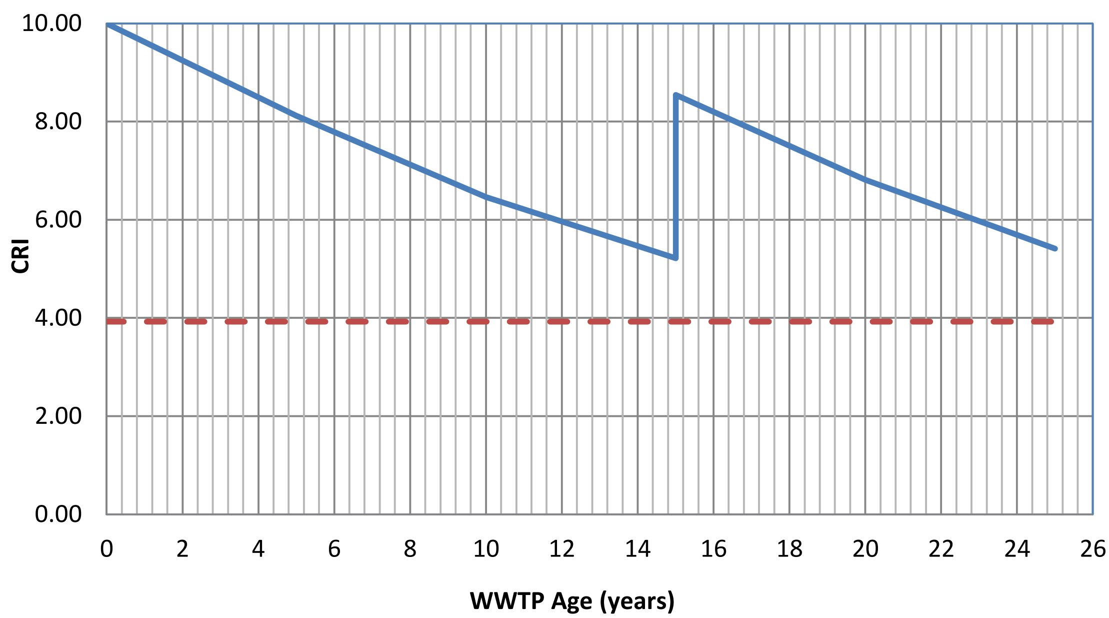


FIGURE V-25: Effect of Pump Replacement on CRI_{IP} at End of Service Life

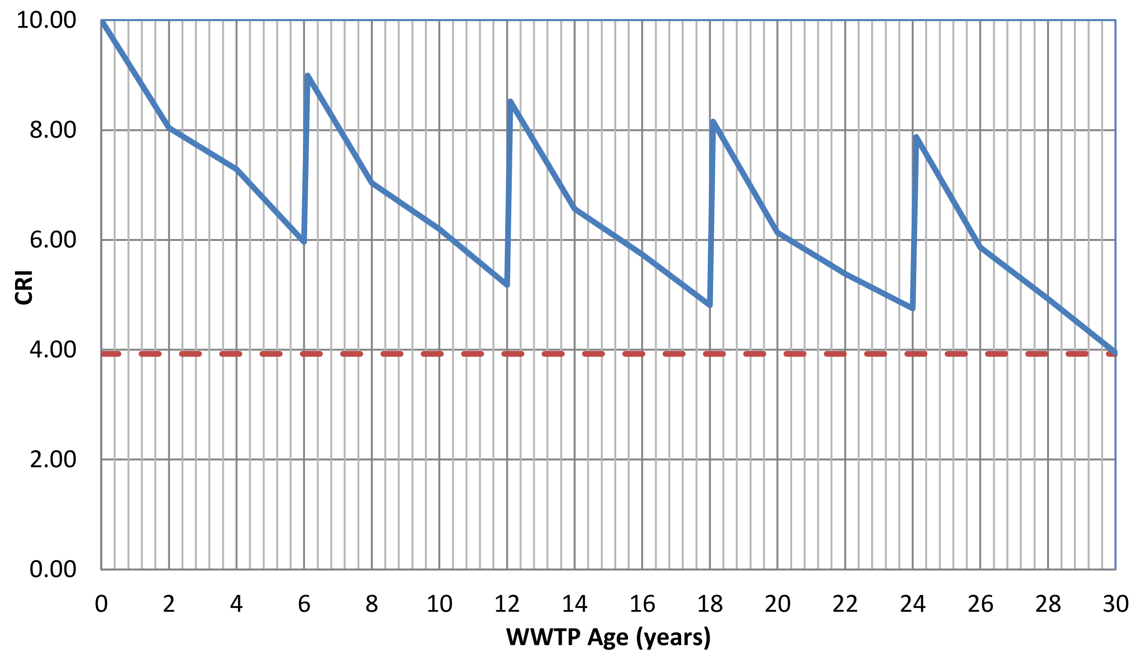


FIGURE V-26: Effect of Pump Replacement on CRI_{IP} at Minimum Threshold

5.14 CASE STUDY

To illustrate the implementation of the developed PAM, a case study using data obtained from three wastewater treatment plants in Canada and the U.S is presented in this section. Due to an agreement between the researcher and the WWTP officials, the names of these WWTPs are kept confidential. (P), (S) and (H) are used to signify these three WWTPs. These plants were chosen particularly because they operate under different jurisdictions and because they have good treatment records that suit the developed phase-based methodology. The results presented in this section is a single year data presented to illustrate the implementation of the developed PAM. Thankfully, officials in these plants were cooperative and provided the needed information and feedback for the developed PAM.

In this case study, the condition ratings of each treatment phase are determined using the developed methodology presented in Chapter III. The following sections show the implementation of the developed condition rating models to the measure treatment and infrastructure performances of the three treatment phases of the selected plants.

The condition rating system for the treatment performance developed in this research measures the treatment contribution of each phase to the overall WWTP treatment. Therefore, this system can detect and diagnose the exact source of treatment malfunction. The infrastructure condition ratings developed in this research are used to indicate the service level of each infrastructure unit and therefore encourage the required maintenance and rehabilitation actions for various infrastructure units within the WWTP.

The deterioration curves for WWTPs presented in this chapter are developed based on a sensitivity analysis of the ages of infrastructure units. The implementation of the developed condition rating models and their interpretations are presented in a detailed manner to show the current and future operational and/or rehabilitation needs.

The CRI for different infrastructure units presented in this case study are determined using the expert feedback provided through survey responses.

The presented case study results were thoroughly discussed with the operators and decision-makers of the WWTPs involved in this study. For validation purposes, the results obtained by the developed PAM are compared to the results obtained by WWTP officials, as presented in the validation section below. The engineers and operators of the studied WWTPs recommended the implementation of the developed PAM and they were highly appreciative of its systematic approach to identifying treatment performance levels, in addition to the serviceability level of the WWTP infrastructure. This part is also further discussed in the validation section.

5.14.1. P Wastewater Treatment Plant

The P WWTP treats wastewater before discharging it into the Miami River. The treatment plant has a capacity of 171,000 cubic meters of wastewater per day. P WWTP uses a conventional activated sludge system with a chlorine disinfection unit. This treatment plant was selected because the inspection, sampling and analysis procedures followed by the plant can be easily adjusted to follow the proposed condition rating model. The WWTP removes 97.45% of the influent BOD_5 and 95.93% of the influent TSS; although these numbers show that the treatment efficiency of this WWTP is high, the developed condition rating model was able to pinpoint many treatment problems. These problems are discussed in the coming sections.

5.14.2. S Wastewater Treatment Plant

S WWTP is a wastewater treatment plant in Quebec. The water treatment program in Quebec was launched in 1978 and requires that every municipality in the province treat its wastewater before dumping it into water bodies. However, the Quebec regulations are in need of many amendments to come to the level of other provinces. Many studies blame bylaws for the deteriorated state of various water bodies in Quebec. S WWTP was commissioned in 1987. The average flow rate of this WWTP is 49,500 cubic meters a day from both domestic and industrial sources. Since 1988, the treatment plant S has maintained a percentage of removal of BOD_5 and TSS above 90%. This WWTP also uses a conventional activated sludge system before dumping the treated effluent into the river.

5.14.3. H Wastewater Treatment Plant

The H WWTP is one of the largest wastewater treatment plants in Ontario, treating a flow of almost 500,000 cubic meters per day. The H treatment plant discharges its effluent into Lake Ontario and operates under the strict monitoring of the MOE of Ontario. H WWTP treats wastewater effluent of 164mg/l BOD_5 and 323mg/l SS. The H Treatment Plant meets or exceeds all required effluent quality standards dictated by the WWTP operation permit and uses a conventional activated sludge system with a chlorination phase.

5.15 Treatment Performance of the Primary Treatment Phase in The WWTPs

The treatment performance of the primary treatment phase in the three WWTPs is measured by the ability to remove suspended solids and at least 35% of the influent BOD_5, as discussed in Chapter III. The CRI_{PTP} is determined using Equation 3.1 and substituting the values of 0.7 and 0.3 into the variables α and β, respectively. All contacted experts agree that the PTP's main function is the removal of SS, which is why they gave α higher values than β, and the majority recommended these values specifically.

5.15.1. Primary Treatment Phase CRI of S WWTP

The primary treatment phase influent and effluent flow characteristics data and the CRI_{PTP} of S WWTP are shown in Table V-9 and illustrated in Figure V-27. The table shows that neither the SS nor the BOD_5 removal efficiencies are appropriate. This means that this phase is not functioning well and requires upgrading, while the CRI for this phase shows that the efficiency varies between 20% and 50%. However, it was around

20% for most of the year. The BOD removal efficiency was also low and only reached the proposed 35% for two months. Many operators typically accept an SS removal efficiency of 60% to 70% because these sediments can be removed in other treatment phases. However, this low removal efficiency may be a result of such factors as poor design, high flow rates, or an insufficient retention time in the primary sedimentation tank. Therefore, before applying any corrective measurements, all possible causes must be addressed by decision-makers and the results compared with the state of the infrastructure in this treatment phase to determine the most efficient and cost effective solution.

TABLE V-9: Treatment Performance of the Primary Treatment Phase of S WWTP

Month	**Influent**		**Effluent**		**BOD Removal %**	**TSS Removal %**	**CR BOD Removal**	**Removal**		**CRI_{PTP}**
	BOD_5 mg/l	SS mg//l	BOD_5 mg/l	SS mg/l				CR BOD Adjusted	CR TSS	
Jan	152	143	135	113	11	21	3.2	3.2	2.1	2.4
Feb	250	157	203	109	19	31	5.3	5.3	3.0	3.7
Mar	216	168	195	110	10	35	2.7	2.7	3.4	3.2
April	148	116	125	94	16	19	4.4	4.4	1.9	2.6
May	261	173	190	95	27	45	7.7	7.7	4.5	5.4
June	308	172	228	85	26	51	7.4	7.4	5.0	5.7
July	228	142	171	74	25	48	7.1	7.1	4.7	5.4
Aug.	228	144	135	103	41	28	11.6	10.0	2.8	4.9
Sept.	288	201	196	114	32	43	9.1	9.1	4.3	5.7
Oct	258	179	181	99	30	45	8.5	8.5	4.4	5.6
Nov	190	158	121	103	36	35	10.3	10.0	3.4	5.4
Dec	186	148	143	113	23	24	6.61	6.61	2.3	3.6
Average TPI_{PTP}										4.5

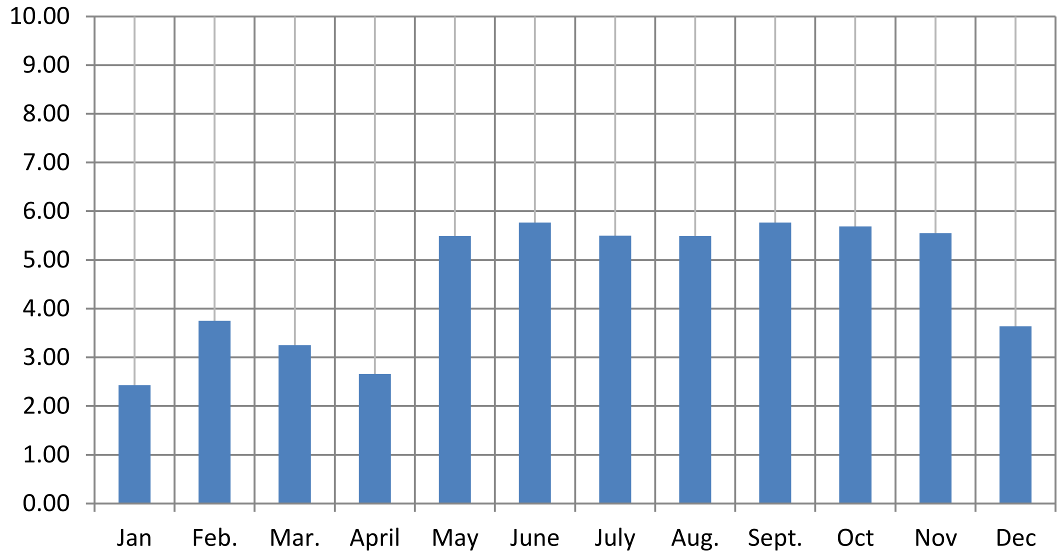


FIGURE V-27: Monthly TPI_{PTP} of the Primary Treatment Phase of S WWTP

5.15.2. PRIMARY TREATMENT PHASE CRI OF P WWTP

The CRI_{PTP} of the primary treatment phase of P WWTP shows that the BOD_5 removal efficiency is excellent; 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 CRI_{PTP} of P-WWTP is shown in Table V-10 and illustrated in Figure V-28.

TABLE V-10: Treatment Performance of the Primary Treatment Phase of P WWTP

Month	Influent		Effluent		Removal				CR TSS Removal	CRI_{PTP}
	BOD5 mg/l	SS mg//l	BOD5 mg/l	SS mg/l	BOD %	TSS Removal %	CR BOD	CR BOD Adjusted		
Jan	110.4	68.7	73	42	34	39	9.68	9.68	3.89	5.62
Feb.	174.2	148	103.3	66.3	41	55	11.63	10.0	5.52	6.86
Mar.	165.8	115.8	119.1	96.2	28	17	8.05	8.05	1.69	3.60
April	155	105.7	105.6	73.7	32	30	9.11	9.1	3.03	4.85
May	185.7	161.6	108.2	91.6	42	43	11.92	10.0	4.33	6.03
June	200.7	183.3	119.9	104	40	43	11.50	10.0	4.33	6.03
July	203.1	167.3	129.2	95.5	36	43	10.40	10.0	4.29	6.00
Aug.	179.6	140.4	98	60.3	45	57	12.98	10.0	5.71	6.99
Sept.	174.4	149.2	95.9	54.7	45	63	12.86	10.0	6.33	7.43
Oct	210.1	173.7	122.1	62.1	42	64	11.97	10.0	6.42	7.50
Nov	205.8	141.5	122.5	54.9	40	61	11.56	10.0	6.12	7.28
Dec	129.2	114.2	88.1	45.3	32	60	9.09	9.09	6.03	6.95
									Average TPI_{PTP}	6.26

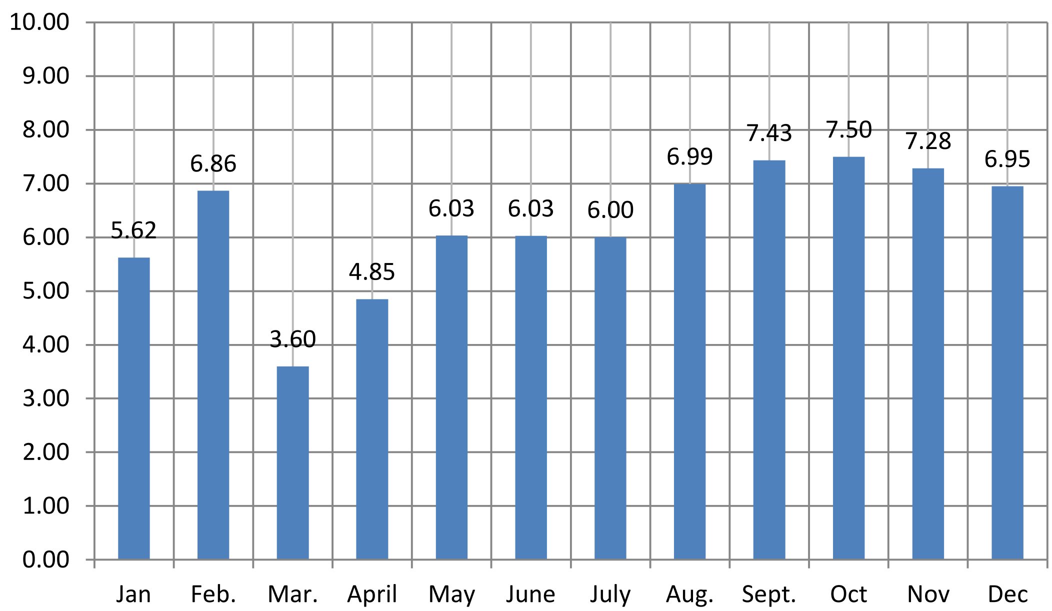


FIGURE V-28: Monthly TPI_{PTP} of the Primary Treatment Phase of P WWTP

5.15.3. Primary Treatment Phase CRI For H WWTP

The TPI_{PTP} of H WWTP shows that the SS removal efficiency of the first treatment phase is very good, ranging between 62% and 72%, although further improvements can be made. 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 TPIPTP values of H-WWTP are shown in Table V-11 and its monthly TPIPTP is graphically presented in Figure V-29.

TABLE V-11: Treatment Performance of the Primary Treatment Phase of H WWTP

Month	Influent		Effluent		Removal				CR TSS Removal	TPI_{PTP}
	BOD_5 mg/l	SS mg//l	BOD_5 mg/l	SS mg/l	BOD Removal %	TSS Removal %	CR BOD Removal	CR BOD Removal Adjusted		
Jan	164	322	117	104	29	68	8.19	8.19	6.77	7.20
Feb.	170	280	110	100	35	64	10.08	10.00	6.43	7.50
Mar.	190	380	105	105	45	72	12.78	10.00	7.24	8.07
April	180	400	120	109	33	73	9.52	9.52	7.28	7.95
May	175	290	119	110	32	62	9.14	9.14	6.21	7.09
June	160	350	120	104	25	70	7.14	7.14	7.03	7.06
July	180	300	118	104	34	65	9.84	9.84	6.53	7.52
Aug.	190	322	125	109	34	66	9.77	9.77	6.61	7.56
Sept.	160	325	110	109	31	66	8.93	8.93	6.65	7.33
Oct.	150	340	105	106	30	69	8.57	8.57	6.88	7.39
Nov.	160	300	110	100	31	67	8.93	8.93	6.67	7.35
Dec.	150	333	110	105	27	68	7.62	7.62	6.8	7.04
									Average TPI_{PTP}	7.42

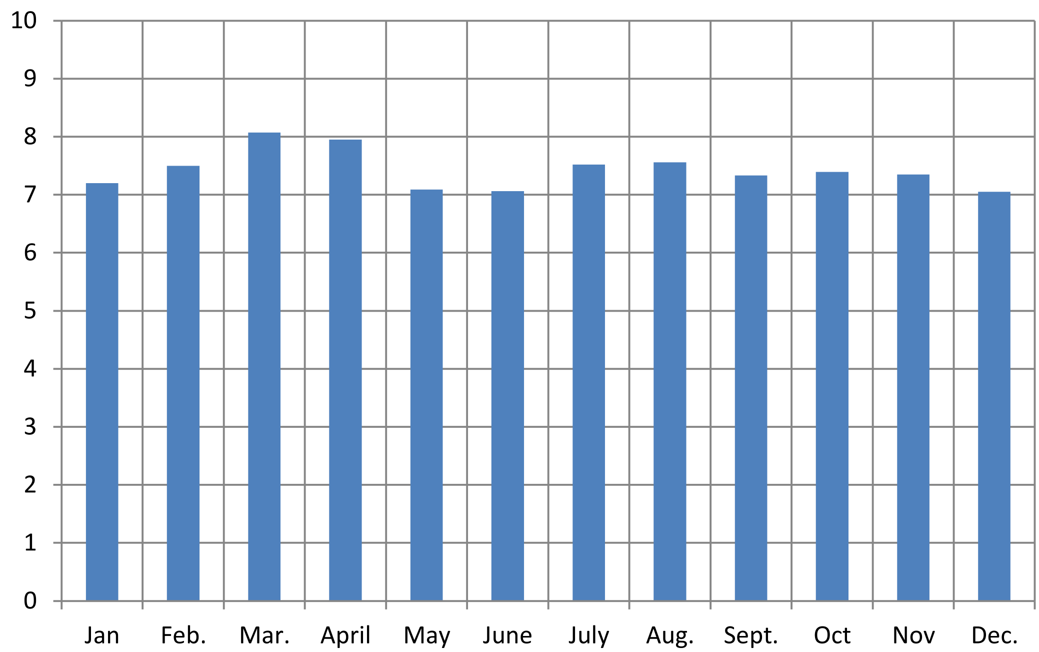


FIGURE V-29: Monthly TPI_{PTP} of P WWTP

5.16 Treatment Performance of the Secondary Treatment Phase in the WWTPs

The secondary treatment phase in WWTPs using an activated sludge system is the main treatment unit in the WWTP. Designed to accommodate the biological treatment processes, it consists of two main tanks: the reactor (the aerated tank), in which microorganisms oxidize the soluble organic compounds, and the secondary sedimentation tank, which is used to store the produced microorganisms needed for treatment. The CRI of the secondary treatment phase (CRI_{STP}) is developed to reflect the condition of the main, vital operational factors that affect the biological treatment processes. This approach will serve as an alarm for the decision-makers, notifying them of current and possible future operational problems. The CRI of the secondary treatment phase (CRI_{STP}) is determined using Equation 3.2.

5.16.1. Secondary Treatment Phase Performance of S WWTP

The values of TPI_{STP} for S-WWTP show that the BOD_5 removal efficiency is excellent and ranges between 92% and 94% percent. However, the treatment indicators of the secondary phase indicate that the treatment process is not stable and is expected to have future operational problems. This is because the SVI index values are higher than the 50ml/g level that indicates settling problems. Possible causes include sludge rising and must be investigated by the WWTP operators. Another operational problem in this phase is illustrated by the ratio of the $MLVSS_S$ concentration available in the secondary sedimentation tanks to the $MLVSS_R$ available in the reactor tank. It is recommended that this ratio be greater than 5 to provide the operator with the needed flexibility to deal with sudden fluctuations in the hydraulic and biological loadings. Unfortunately, the ratio for S-WWTP ranges between 2.5 and 3.5. The values of CRI_{STP} are tabulated in Table V-12 and the monthly TPI_{STP} values are illustrated in Figure V-30.

TABLE V-12: Treatment Performance of the Secondary Treatment Phase of S WWTP

Month	Inf. BOD_5 mg/l	Eff. BOD5 mg/l	$MLVSS_R$ mg/l	SVI ml/g	$MLVSS_S$ mg/l	$MLVSS_S$ / $MLVSS_R$	β_1	γ_{SVI}	BOD Rem.	CR BOD	TPI_{STP}
Jan	158	11.9	2380	84	8103	3.40	0.68	0.90	0.92	9.25	5.82
Feb.	203	15.4	2797	187	7086	2.53	0.51	0.70	0.92	9.24	4.33
Mar.	195	23.4	2252	122	5934	2.63	0.53	0.80	0.88	8.80	4.08
April	161	13.8	1920	125	7144	3.72	0.74	0.80	0.91	9.14	6.22
May	190	12.5	2080	103	5912	2.84	0.57	0.80	0.93	9.34	4.96
June	228	13.9	2157	75	6252	2.90	0.58	0.90	0.94	9.39	5.11
July	171	8.1	1900	136	5427	2.86	0.57	0.80	0.95	9.53	5.18
Aug.	135	10.7	1812	268	5477	3.02	0.60	0.60	0.92	9.21	5.12
Sept.	196	12	2062	107	5940	2.88	0.58	0.80	0.94	9.39	5.08
Oct	181	10.9	2082	110	6509	3.13	0.63	0.80	0.94	9.40	5.52
Nov	121	7.2	1910	78	7544	3.95	0.79	0.90	0.94	9.40	6.99
Dec	143	12	2219	129	7961	3.59	0.72	0.80	0.92	9.16	6.02
										TPI_{STP}	5.37

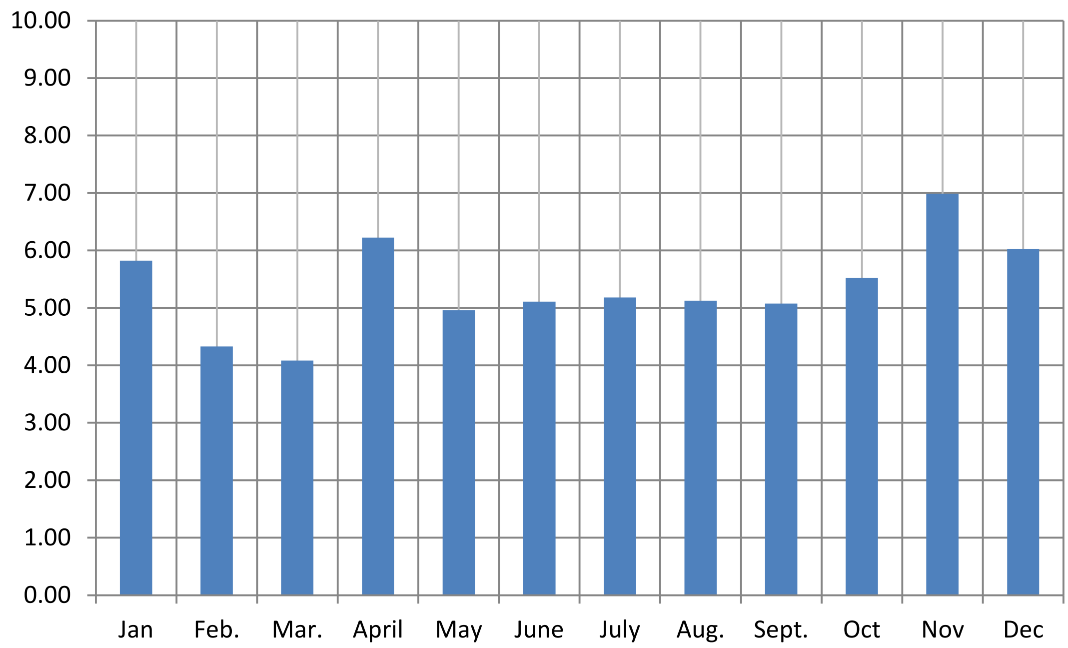


FIGURE V-30: Monthly TPI_{STP} of the Secondary Treatment Phase of S WWTP

5.16.2. Secondary Treatment Phase Performance of P WWTP

The TPI_{STP} of P WWTP shows that its BOD_5 removal ranges between 96% and 98%, which is excellent. However, similarly to S-WWTP, the SVI index values for this treatment plant are higher than the 50ml/g optimum value, which serves as a warning that there may be a sludge settling problem in the WWTP. On the other hand, the $MLVSS_S/MLVSS_R$ ratio ranges between 4 and 5, near the recommended range to provide the required flexibility to deal with expected fluctuations in the hydraulic and organic loadings of the treated wastewater influent. The TPI_{STP} calculations are tabulated in Table V-13 and the monthly TPI_{STP} is illustrated in Figure V-31.

TABLE V-13: Treatment Performance of the Secondary Treatment Phase of P WWTP

Month	Inf. BOD_5 mg/l	Eff. BOD_5 mg/l	$MLVSS_R$ mg/l	SVI ml/g	$MLVSS_S$ mg/l	MLVSSS / MLVSSR	β1	γSVI	BOD_{REM}	CR BOD_{REM}	TPI_{STP}
Jan	110	3.4	1736	224	7703	4.4	0.89	0.6	0.97	9.69	5.87
Feb	174	3.6	1692	258	9716	5.7	1.0	0.6	0.98	9.79	3.75
Mar	165	7.1	2021	153	5662	2.8	0.56	0.7	0.96	9.57	5.45
April	155	4	1856	156	7389	3.9	0.80	0.7	0.97	9.74	4.65
May	185	3.7	1418	229	5635	3.9	0.79	0.6	0.98	9.80	4.25
June	200	6	1667	226	6095	3.6	0.73	0.6	0.97	9.70	5.19
July	203	5	1899	166	7244	3.8	0.76	0.7	0.98	9.75	6.27
Aug	179	3.8	1839	136	7392	4.0	0.80	0.8	0.98	9.79	6.86
Sept	174	4.6	1700	121	7493	4.4	0.88	0.8	0.97	9.74	8.59
Oct	210	7.5	1612	91	7991	4.9	0.99	0.9	0.96	9.64	6.75
Nov	205	4	1916	139	8200	4.2	0.86	0.8	0.98	9.81	6.17
Dec	129	3	2216	143	8772	3.9	0.79	0.8	0.98	9.77	5.87
										TPI_{STP}	5.80

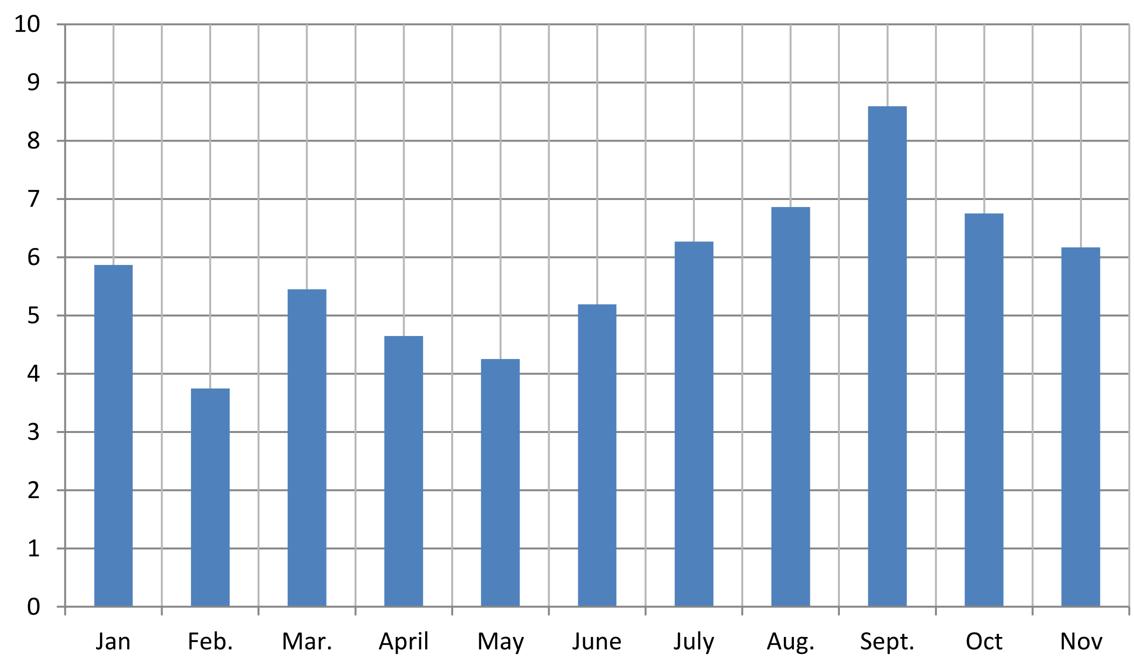


FIGURE V-31: Monthly TPI_{STP} of the Secondary Treatment Phase of P WWTP

5.16.3. Secondary Treatment Phase Performance of H WWTP

The BOD_5 removal efficiency of H WWTP ranges between 96% and 98%. In addition, the SVI values range between 60 and 100ml/g, which means that this WWTP 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 H-WWTP is the best among the three treatment plants studied. The TPISTP calculations for H WWTP are shown in Table V-14 and the monthly TPI_{STP} are illustrated in Figure V-32.

TABLE V-14: Treatment Performance of the Secondary Treatment Phase of H WWTP

Month	Inf. BOD5 mg/l	Eff. BOD5 mg/l	MLVSSR mg/l	SVI ml/g	MLVSSS mg/l	MLVSSS / MLVSSR	β1	γSVI	BOD REM	CR BOD	TPI_{STP}
Jan	164	6	1292	60	5676	4.39	0.88	0.9	0.96	9.63	7.6
Feb	170	5	1300	80	6700	5.15	1.00	0.9	0.97	9.71	8.7
Mar	166	7.1	1500	70	5040	3.36	0.67	0.9	0.96	9.57	5.8
April	155	6	1300	90	5990	4.61	0.92	0.9	0.96	9.61	8.0
May	180	6.5	1400	78	6112	4.37	0.87	0.9	0.96	9.64	7.5
June	160	7	1450	90	6196	4.27	0.85	0.9	0.96	9.56	7.3
July	168	9	1650	100	6608	4.00	0.80	0.9	0.95	9.46	6.8
Aug.	170	3	1500	90	6781	4.52	0.90	0.9	0.98	9.82	8.0
Sept.	170	6	1600	70	6770	4.23	0.85	0.9	0.96	9.65	7.4
Oct	150	6	1800	60	9026	5.01	1.00	0.9	0.96	9.60	8.6
Nov	170	9	1916	80	8596	4.49	0.90	0.9	0.95	9.47	7.7
Dec	160	9	1700	90	8772	5.16	1.03	0.9	0.94	9.44	8.5
										TPI_{STP}	7.7

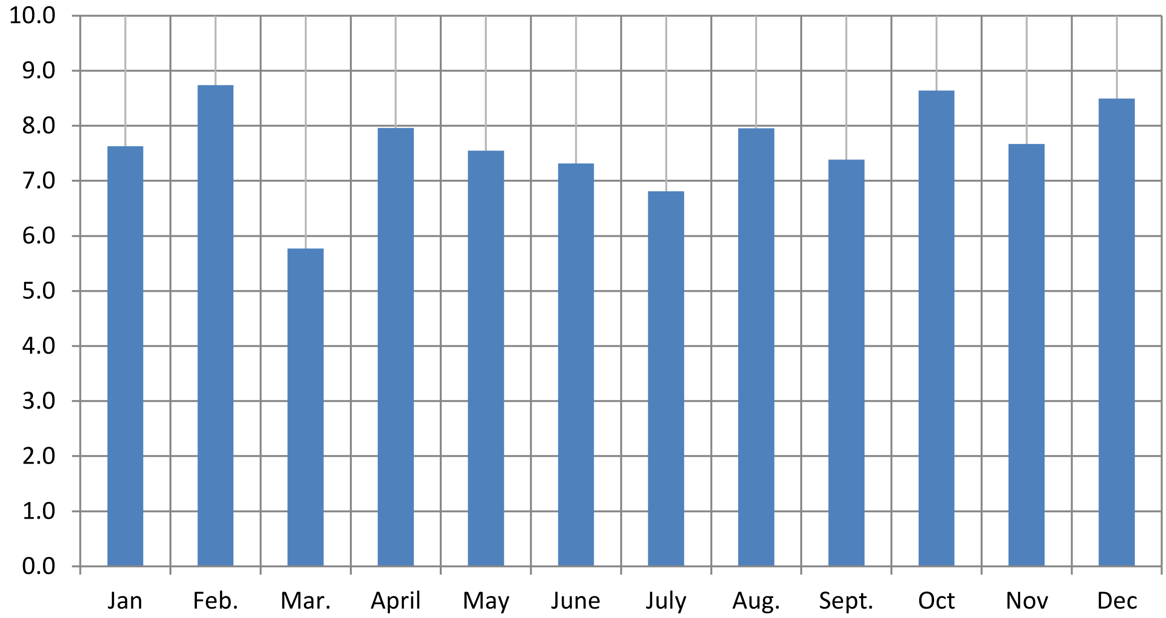


FIGURE V-32: Monthly TPI_{STP} of the Secondary Treatment Phase of H WWTP

5.17 Treatment Performance of the Tertiary Treatment Phase in the WWTPs

The tertiary treatment phase of wastewater treatment plants is responsible for disinfection and other chemical and physiochemical treatment processes. For a typical activated sludge system, this phase is mainly responsible for effluent disinfection before its release to the environment and into water bodies. The effluent must satisfy the environmental regulations for disinfection, which are based on the presence of coliform bacteria and hazardous disinfection byproducts. The condition rating index for the tertiary treatment phase (CRI_{TTP}) for different wastewater treatment plants is determined based on the annual performance of each WWTP because most environmental regulations for wastewater effluents, concerning unrestricted usage, are based on the number of violations in the coliform count test per year. The CRI_{TTP} is determined using Equation

3.3, which takes into consideration the presence of coliform bacteria and potential disinfection byproduct formation, as discussed in Chapter III.

5.17.1. Tertiary Treatment Phase Performance of S WWTP

Unfortunately, S WWTP disposes its treated effluent into rivers without disinfection. After investigating the issue, it appears that this action is taken because the permit for the treatment effluent for this WWTP is for restricted water usage only. In order to apply the developed CRI to the tertiary treatment phase, WW samples from the secondary effluent were taken from the S WWTP plant and tested to see the potential of DBP formation. Unfortunately, the collected samples tested positive for coliform bacteria, and the potential formation of disinfection byproducts was also high. Therefore, the CRI_{TTP} of S-WWTP was given a value of zero.

5.17.2. Tertiary Treatment Phase Performance of P WWTP

The TPI_{TTP} P-WWTP is determined based on the coliform test results measured in CFU and based on the secondary phase BOD_5 effluent, as shown in Equation 3.3. The value of $\boldsymbol{v}$ depends on the coliform count, specifically whether it is more or less than 25. In addition, the value of $\boldsymbol{\omega}$ depends on the secondary phase BOD_5 effluent and its value ranges between 1 and 0.1, as discussed in Chapter III. The TPI_{TTP} values for P-WWTP are presented in Table V-15.

TABLE V-15: Treatment Performance of the Tertiary Treatment Phase of P WWTP

Month	BOD Eff.	CFU / 100 ml Coliform Count	ω	v
Jan.	3.4	0	1.00	0
Feb.	3.6	0	1.00	0
March	25	0	0.80	0
April	36	0	0.70	0
May	40	10.6	0.70	0
June	30	34.1	0.80	1
July	10	35.8	1.00	1
Aug.	10	47.4	1.00	1
Sept.	4.6	132.2	1.00	1
Oct.	40	174.9	0.70	1
Nov.	4	0	1.00	0
Dec.	3	0	1.00	0
Average ω= 0.89				
# of CFU exceeding allowable limit V				5
			TPI_{TTP}	5.20

P WWTP effluent shows that the maximum coliform count numbers was violated in five months of the year, while BOD_5 values were within the acceptable levels and were penalized by the reduction factor ω with values ranging from 1 to 0.7, which indicates good performance. The TPI_{TTP} of this WWTP was 5.2, so better control is required to use the treated effluent for general purposes. However, the treated effluent of P is sufficient for a restricted usage that allows higher coliform concentrations.

5.17.3. Tertiary Treatment Phase Performance of H WWTP

The BOD_5 of the secondary treatment phase of H WWTP ranged between 6 and 9. These values reflect excellent treatment efficiency and minimize the possibility of DBPFP. This is reflected in the reduction factor **ω**, which was 1 for all months. The coliform forming units (CFU) ranged between 0 and 14, which is far below the allowable CFU of 25. This means that the coliform count was never violated in this year, and the value of ***v*** was 0 for the 12 test months; therefore, the TPI_{TTP} for H-WWTP is 10/10. The calculation of the CRI_{TTP} of H-WWTP is shown in Table V-16.

TABLE V-16: Treatment Performance of the Tertiary Treatment Phase of H WWTP

Month	$BOD_{Eff.}$	CFU / 100 ml Coliform Count	ω	***v***
Jan.	6.00	14.00	1.00	0
Feb.	5.00	8.00	1.00	0
March	7.10	0.00	1.00	0
April	6.00	15.00	1.00	0
May	6.50	4.00	1.00	0
June	7.00	0.00	1.00	0
July	9.00	8.00	1.00	0
Aug.	3.00	14.00	1.00	0
Sept.	6.00	13.00	1.00	0
Oct.	6.00	2.00	1.00	0
Nov.	9.00	0.00	1.00	0
Dec.	9.00	0.00	1.00	0
Average ω = 1			1.00	
# of CFU exceeding allowable limit				0
TPI_{TTP}				10.00

5.18 THE OVERALL TREATMENT PERFORMANCE (TPI)

The overall treatment performance index (TPI) of the studied WWTPs is determined using the weighted sum of the CRI of each treatment phase. These weights are determined using the Eigen-vector techniques explained in Chapter III, where w_p=0.14, w_s=0.6 and w_t=0.26. The TPI is determined using Equation 3.4. The CRI_{TP} of the studied WWTPs are shown in Table V-17 and the CRI of each treatment phase, in addition to its overall treatment performance, are shown in Figure V-33.

TABLE V-17: The TPI of the Studied WWTPs

WWTP	TPI_{PTP}	TPI_{STP}	TPI_{TTP}	$TPI = 0.14\ TPI_{PTP} + 0.6 TPI_{STP} + 0.26\ TPI_{TTP}$
H-WWTP	7.09	8.20	10	8.51
P-WWTP	6.26	7.71	5.2	6.85
S-WWTP	4.53	5.37	-	3.85

The TPI of H WWTP had the highest value among the studied WWTPs, while S had the lowest value since S-WWTP lacks the tertiary (disinfection) treatment phase, which affected its overall CRI_{TP} as shown in Figure V-53.

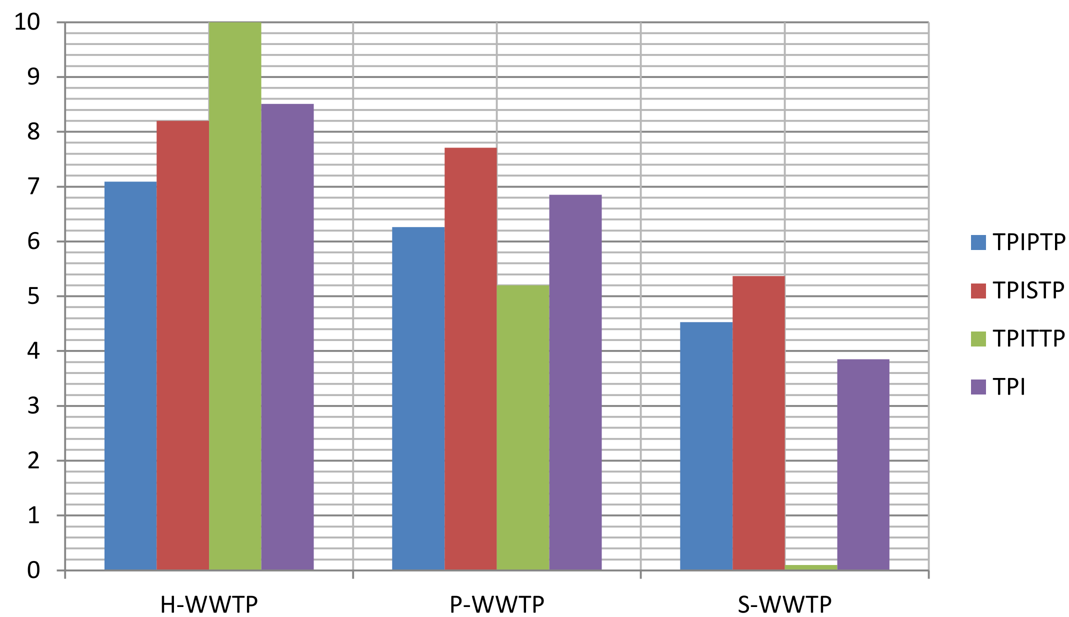


Figure V-33: The CRI_{TP} for the Studied WWTPs

The CRI for different infrastructure units in the three treatment phases of the WWTPs were determined using the developed AHP-MAUT model after asking their respective experts to provide the required data. Experts in these WWTPs were given a form containing different physical, operational and environmental factors that affect the deterioration of different infrastructure units in the WWTP. The experts were asked to select the most suitable situation for describing their WWTP's infrastructure. These selections were then transformed into the appropriate scores and weights to calculate the CRI of different infrastructure units, as explained in the research methodology.

5.19.1. CRI of WWTP Tanks

The CRI of the tanks in different treatment phases are determined for the selected WWTP and the results are summarized in Table V-18. The CRI of the tanks in the three treatment phases were similar to each other, ranging between 7 and 9. These values indicate a very good to excellent physical condition of the different tanks in these WWTPs, likely because tanks are examined and maintained on a timely basis. This maintenance approach was the main factor in extending the service life of these tanks. The CRIs of the different tanks in the three treatment phases are shown in Figure V-34.

TABLE V-18: The CRI of WWTP Tanks

WWTP	Primary phase	Secondary Phase		Tertiary Phase
		Reactor	SST	
H - Ontario	6.71	6.91	6.98	6.59
P - USA	6.83	7.07	6.86	6.89
S - Quebec	7.11	7.08	6.76	0.00

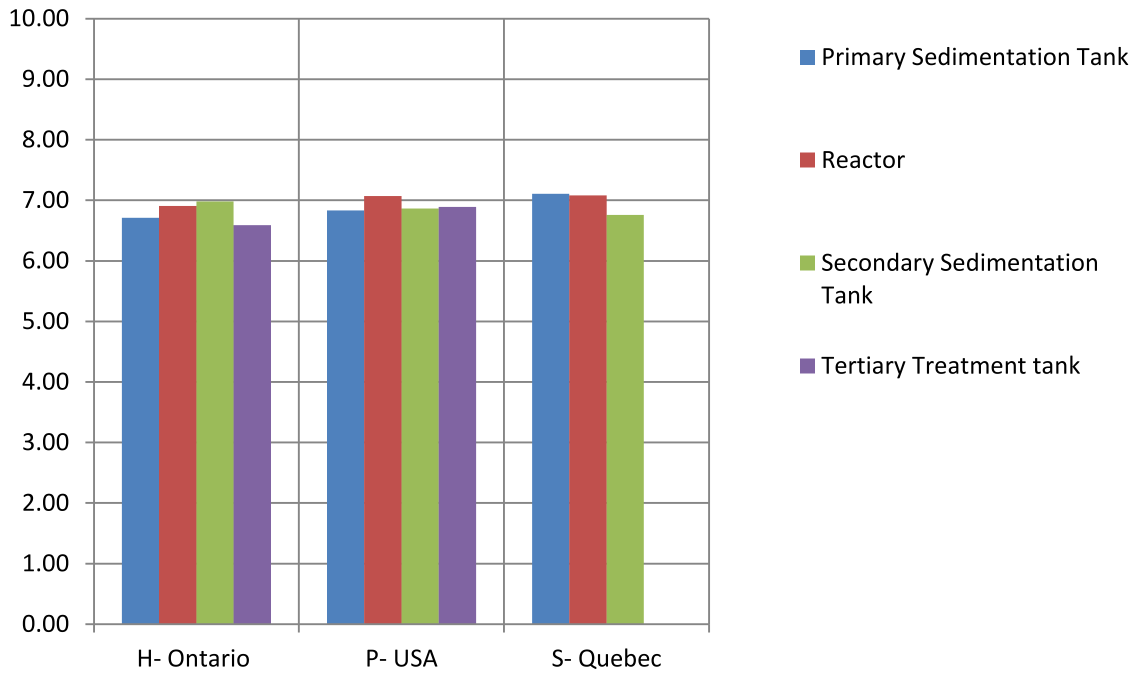


FIGURE V-34: The CRI of WWTP Tanks In Different Treatment Phases

5.19.2. WWTP PIPES CRI

The CRIs for WWTP pipes for the three treatment phases are determined using the same approach followed to calculate the CRI of WWTP tanks. Although experts were asked to select the situation that best matches their WWTP pipes, most of them mentioned that exact information regarding pipes in the WWTP is not available for various reasons. Most experts mentioned that since WWTP pipes are usually flowing full, deterioration caused by crown corrosion as a result of sulfate attacks is reduced, as well as other deterioration factors. The determined CRIs for the pipes of the three WWTPs studied are shown in Table V-19 and illustrated in Figure V-35.

TABLE V-19: The CRI of WWTP Pipes

WWTP	Primary Phase	Secondary Phase	Tertiary Phase
H- Ontario	7.14	6.57	6.55
P- USA	8.50	8.52	8.09
S- Quebec	7.11	7.34	0.00 *

*The value for the tertiary (disinfection) treatment phase in S-WWTP is given a zero value because there is no tertiary phase in this WWTP.

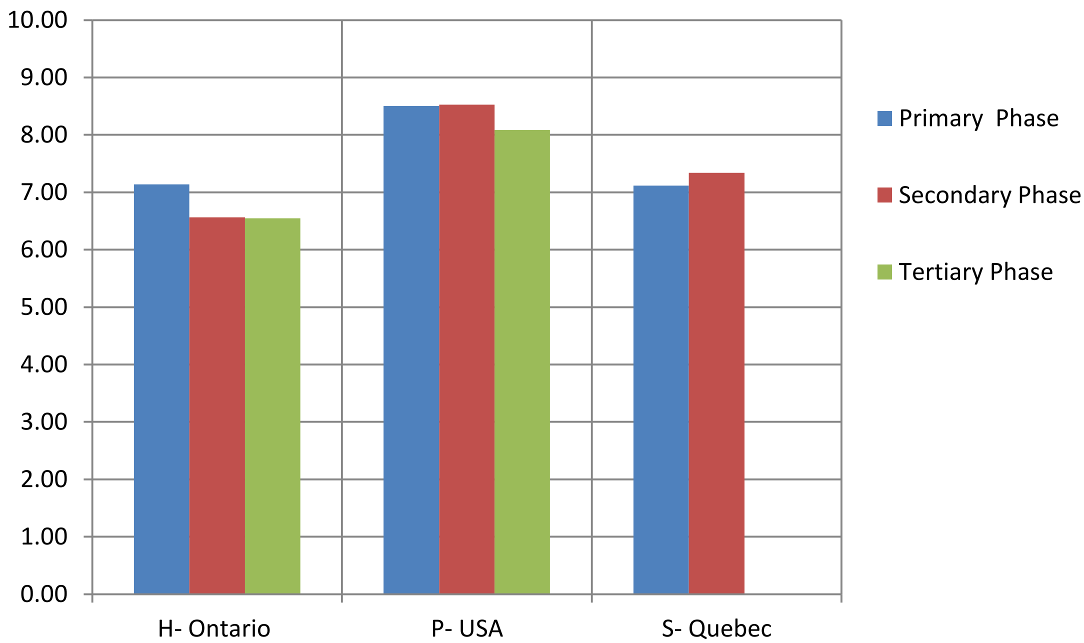


FIGURE V-35: The CRI of Pipes in Different Treatment Phases of WWTPs

5.19.3. CRI OF WWTP PUMPS AND BLOWERS

Pumps and blowers are the most important infrastructure units in any WWTP due to their major role in the treatment processes. WWTP operators rely on pumps to react to changes in hydraulic and organic loadings. Pumps in all studied WWTPs are operated based on the alternating approach, which means that there are redundancies in the available pumps in every treatment phase. In addition, some WWTPs have complete emergency standby pumping systems to deal with any sudden failures. Having many alternating pumps in each treatment phase helps extend the service life of each pump. However, experts provided the required information to calculate the CRI of pumps and blowers assuming no redundancy, which hypothetically reflects the actual pump service life. The CRIs of the pumps for the three WWTPs studies are summarized in Table V-20 and illustrated in Figure V-36.

TABLE V-20: CRI for WWTP Pumps and Blowers

WWTP	Primary Phase	Secondary Phase		Tertiary Phase
		Reactor Blower	SST Pump	
H- Ontario	8.32	8.4	8.6	8.86
P- Ohio	7.68	8.67	8.67	7.77
S- Quebec	5.11	7.20	5.14	0.00 N/A

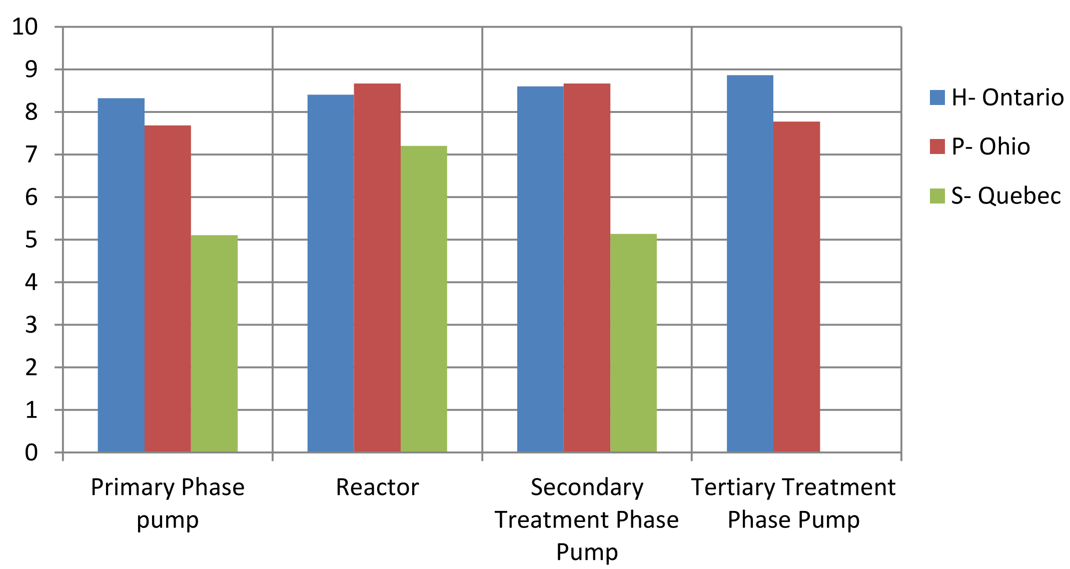


FIGURE V-36: CRIs FOR Pumps and Blowers in the Studied WWTPS

5.19 WWTP INFRASTRUCTURE CONDITION RATING (CRI_{IP})

The CRI of WWTP infrastructure performance (CRI_{IP}) is determined using the weighted sum of the condition rating index of its infrastructure units (CRI_{IU}).The weight of each infrastructure unit in a WWTP is determined using the Eigen-vector techniques explained in Chapter III. The CRI_{IP} values for H, P and S WWTPs are shown in Table V-21, Table V-22 and Table V-23, respectively.

TABLE V-21: CRI_{IP} for H WWTP

Main Factors	Sub factor	1st level w1	2nd Level w2	w1 x w2 W	CRI_{IU}	W x CRI_{IU}
Primary Treatment Phase	Primary Phase Pump	0.14	0.51	0.07	8.32	0.58
	Primary Sedimentation Tank		0.23	0.04	6.71	0.27
	Primary phase Pipes		0.26	0.04	7.14	0.29
Secondary Treatment Phase	Secondary Phase Reactor Blower	0.60	0.37	0.21	8.40	1.76
	Secondary Sedimentation tank		0.08	0.05	6.98	0.35
	A.S Reactor		0.13	0.08	6.91	0.55
	Secondary Sedimentation Pump		0.21	0.12	8.6	1.03
	Secondary Phase pipes		0.22	0.13	6.55	0.85
Tertiary Treatment Phase	Chlorination Phase Pump	0.26	0.43	0.11	8.66	0.95
	Chlorination Phase Tank		0.29	0.08	6.59	0.53
	Chlorination Phase Pipes		0.28	0.07	6.55	0.46
H - WWTP Infrastructures CRI_{IP} = CRI ($\sum$w x CRI_{IU})						7.62

TABLE V-22: CRI_{IP} for P WWTP

Main Factors	Sub factor	1st level w1	2nd Level w2	W	CRI_{IU}	W x CRI_{IU}
Primary Treatment Phase	Primary Phase Pump	0.14	0.51	0.07	7.68	0.54
	Primary Sedimentation Tank		0.23	0.04	6.83	0.27
	Primary phase Pipes		0.26	0.04	8.5	0.34
Secondary Treatment Phase	Secondary Phase Reactor Blower	0.60	0.37	0.21	8.67	1.82
	Secondary Sedimentation tank		0.08	0.05	6.86	0.34
	A.S Reactor		0.13	0.08	7.07	0.57
	Secondary Sedimentation Pump		0.21	0.12	8.67	1.04
	Secondary Phase pipes		0.22	0.13	8.52	1.11
Tertiary Treatment Phase	Chlorination Phase Pump	0.26	0.43	0.11	7.77	0.85
	Chlorination Phase Tank		0.29	0.08	6.86	0.55
	Chlorination Phase Pipes		0.28	0.07	8.09	0.57
P WWTP Infrastructures (CRI_{IP})= ($\sum$x CRI_{IU})						8.00

The CRI_{IP} of the H and P plants were within the same range and had a value of 8, which indicates excellent infrastructure performance. However, the CRI_{IP} value for S-WWTP was around 5since this WWTP has no infrastructure for the tertiary (disinfection) phase. The CRI_{IP} of the studied WWTPs are shown in Table V-24.

TABLE V-23: CRI_{IP} for S WWTP

Main Factors	Sub factor	1st level w1	2nd Level w2	w1 x w2 W	CRI_{IU}	$W x CRI_{IU}$
Primary Treatment Phase	Primary Phase Pump	0.14	0.51	0.07	5.11	0.36
	Primary Sedimentation Tank		0.23	0.04	7.11	0.28
	Primary phase Pipes		0.26	0.04	7.11	0.28
Secondary Treatment Phase	Secondary Phase Reactor Blower	0.60	0.37	0.21	7.2	1.51
	Secondary Sedimentation tank		0.08	0.05	6.76	0.34
	A.S Reactor		0.13	0.08	7.08	0.57
	Secondary Sedimentation Pump		0.21	0.12	5.14	0.62
	Secondary Phase pipes		0.22	0.13	7.34	0.95
Tertiary Treatment Phase	Chlorination Phase Pump	0.26	0.43	0.11	N/A	-
	Chlorination Phase Tank		0.29	0.08	N/A	-
	Chlorination Phase Pipes		0.28	0.07	N/A	-
S- Infrastructures Condition Rating Index (CRIIP)= (∑W x CRIIU)						4.91

TABLE V-24: The CRI_{IP} of H, P and S WWTPs

WWTP	(CRI_{IP})
H - Ontario WWTP	7.62
P - USA WWTP	8.00
S - Quebec WWTP	4.91

5.20 WWTP COMBINED CONDITION RATING INDEX

The combined condition rating index for a WWTP ($WWTP_{CCRI}$) is determined using a simple additive function of the treatment performance index (TPI) of the WWTP and the infrastructure performance (CRI_{IP}) using Equation 3.5. The combined condition rating index ($WWTP_{CCRI}$) for the studied WWTPs are listed in Table V-25.

TABLE V-25: $WWTP_{CCRI}$ for the Studied WWTPs

WWTP	TPI	CRI_{IP}	$WWTP_{CCRI}$ (Rounded up)
H- Ontario WWTP	9	8	17
P-USA WWTP	7	8	15
S- Quebec WWTP	4	5	9

5.21 COMBINED CRI MATRIX

The combined CRI values need to be presented in the combined condition rating index matrix (CCRIM) to interpret the MR&R needs for the studied WWTPs. In this matrix, the rows represent the treatment performance condition rating of the studied WWTP (CRI_{TP}), while the columns show its infrastructure performance condition rating (CRI_{IP}). The value of each cell in this matrix is simply the summation of its row and column values. The $WWTP_{CCRI}$ of the studied WWTPs and their interpretations are shown in Figure V-37.

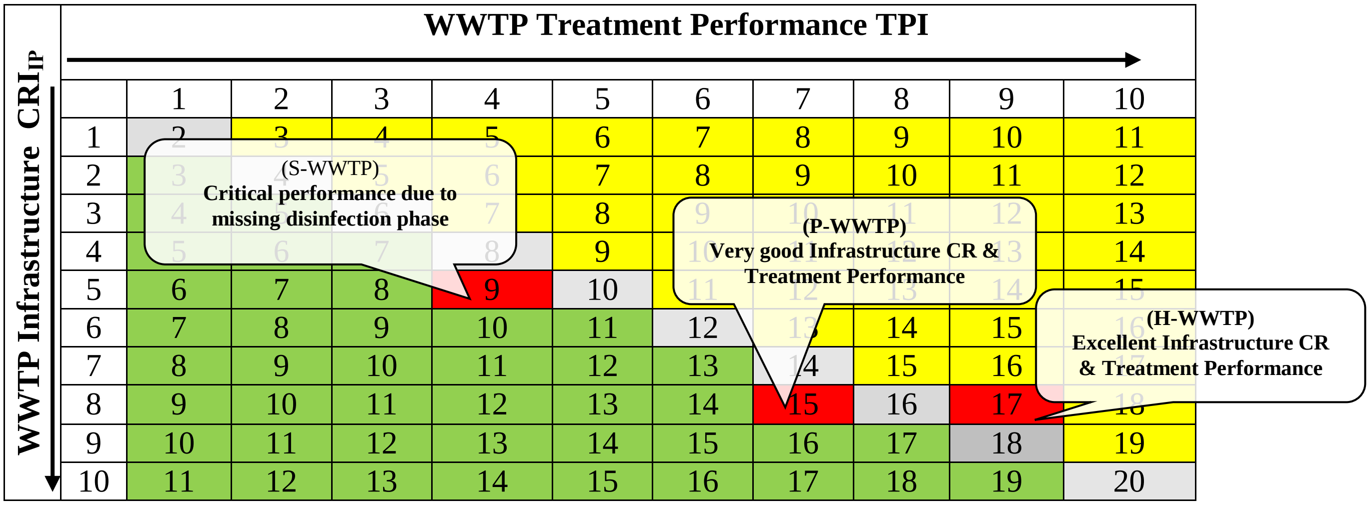


FIGURE V-37: WWTP$_{CCRI}$ & Their Interpretations

5.22 RESULTS & VALIDATIONS

The results obtained by the model are compared with the condition rating provided by the studied WWTP to see the compatibility of the developed model with the experts' feedback. Experts seem to have higher expectations about their treatment plants compared with the developed model. The results were first discussed with S WWTP operators and decision-makers. They did not approve of the final condition rating of their WWTP, which was low because this WWTP has no disinfection phase and operates under jurisdictions that have comparatively low environmental regulations. However, these officials supported the PAM system's methodology because it was able to pinpoint the causes of operational problems during the early phases of this study. The developed PAM was able to address vital operational malfunctions in this WWTP and addressed the future needs of this plant. Furthermore, these findings were also supported by a study conducted by the CCCPEM (2009), formed of environmental specialists whose analysis of the environmental needs of this WWTP were similar to ours.

S WWTP operators' main argument in support of the plant's treatment efficiency was that the removal efficiency is very high; however the condition rating of their WWTP is very low. After explaining the results and informing them that the low rating was due to the missing disinfection phase, in addition to the state of their primary and secondary treatment phases, they were convinced of the results and they appreciated the model outcomes and included the findings in their annual report.

The developed models were explained to decision-makers working in the studied WWTPs. After presenting how the models work and how they can use them to improve treatment efficiency and to predict possible errors in every treatment phase and reviewing the design and operational standards, the operators were asked to provide their estimated CR for each treatment phase and compare it to the CR determined using this study. The results are shown in Table V-26. This table compares the Model (M) results with the Experts' (E) condition ratings. Figure V-38 shows a comparison of the two values. After discussing the results, these officials were convinced of the results and recommended to introduce this PAM to the municipality for possible future implementation, as it can provide a better tool for communication among different management levels.

The decision-makers of P WWTP and H WWTP were satisfied with the results and the evaluation criteria because it was able to highlight important factors in their WWTP operations. They also appreciated the fact that the developed methodology can be used to support their strategic development and the upgrading plans for their WWTPs.

Table V-26: Model and Expert Based CRI Values

WWTP	PTP (M)	PTP (E)	STP (M)	STP (E)	TTP (M)	TTP (E)	TP (M)	TP (E)	IP (M)	IP (E)	CCRI (M)	CCRI (E)
H	7.0	9	8.2	9	10	9	8.5	9	7.6	8	16	17
P	6.2	8	7.7	8	5.	9	6.8	8	8	9	15	17
S	4.5	8	5.3	9	0	0	3.8	8	4.9	7	9	15

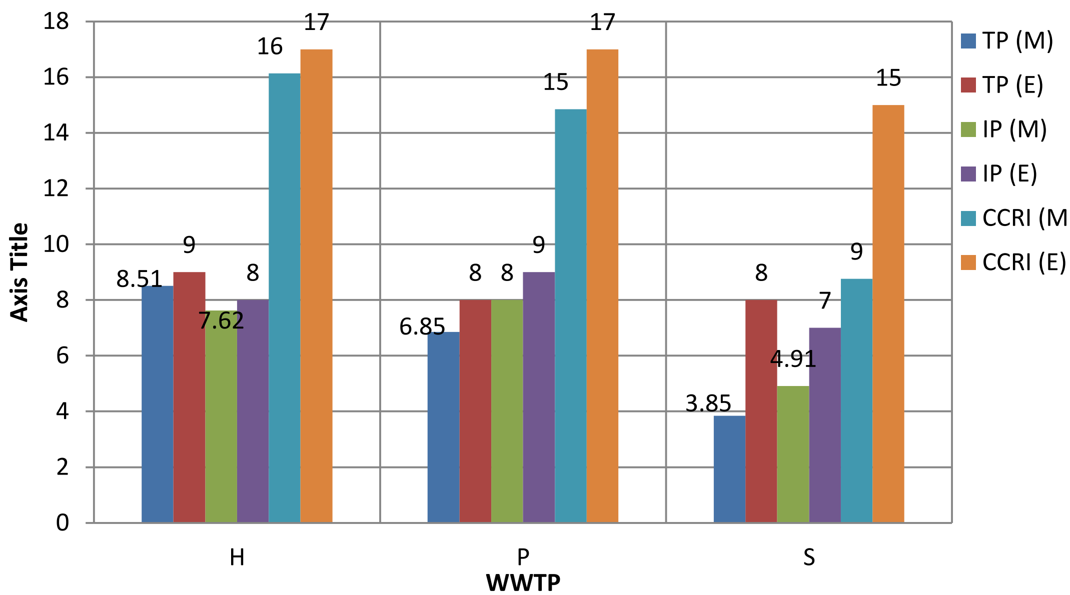


FIGURE V-38: CRI Model and Expert Based Comparison

5.23 WWTP MR&R Optimization Options

This section demonstrates how to implement the developed optimization models. The developed optimization model uses MR&R interventions for each infrastructure unit in the three treatment phases. These MR&R interventions are: (1) do nothing; (2) maintain; (3) rehabilitate; or (4) replace. Each intervention has a specific cost and specific condition recovery effect that must be identified. The optimization model allows only one MR&R intervention for any one infrastructure unit. The optimization model can be applied to the three treatment phases at the same time or can be applied to each treatment phase separately.

Two optimization options are considered in this research: in the first optimization option, the objective function to be optimized is minimizing the cost of maintenance and rehabilitation and the constraints for this option are the minimum acceptable CRI of each infrastructure unit and the available rehabilitation budget. This option answers the question of “how much it will cost to keep all infrastructure units within the required serviceability level?” The second optimization option is based on maximizing the condition rating of the wastewater treatment plant. This second objective function is constrained by the budget and by the minimum allowable CRI for each infrastructure unit. This optimization option answers the question of “by how much can the condition rating be improved within the plant’s budget?” The optimization functions for the two options are solved using integer programming with binary variables. This method is used because the intervention action variable (*x*) can be either (1) if the rehabilitation option is selected or (0) if the variable is not selected.

Only one of the tanks’ MR&R decision variables X_1 or X_2 or X_3 or X_4 is equal to 1; only one of the pipes’ MR&R decisions of X_5 or X_6 or X_7 or X_8 is equal to1; and only one of the pumps’ MR&R decisions X_9 or X_{10} or X_{11} or X_{12} is equal to 1, while all the other variables will be 0. Repeating the same equations for the secondary and tertiary treatment phases will yield 44 decision variables. These variables are listed in Table V-27 for the primary treatment phase, Table V-28 for the secondary treatment phase and in Table V-29 for the tertiary treatment phase.

TABLE V-27: MR&R Intervention Variables for the Primary Treatment Phase

MR&R Intervention	Primary Treatment Phase		
	Tanks CRI_{IUt+1}	Pipes CRI_{IUt+1}	Pumps CRI_{IUt+1}
Do nothing	x_1	x_5	x_9
Maintain	x_2	x_6	x_{10}
Rehabilitate	x_3	x_7	x_{11}
Replace	x_4	x_8	x_{12}

TABLE V-28: MR&R Intervention Variables for the Secondary Treatment Phase

MR&R Intervention	Secondary Treatment Phase				
	Tanks CRI_{IUt+1}	Reactor CRI_{IUt+1}	Pipes CRI_{IUt+1}	Pumps CRI_{IUt+1}	Blower CRI_{IUt+1}
Do nothing	x_{13}	x_{17}	x_{21}	x_{25}	x_{29}
Maintain	x_{14}	x_{18}	x_{22}	x_{26}	x_{30}
Rehabilitate	x_{15}	x_{19}	x_{23}	x_{27}	x_{31}
Replace	x_{16}	x_{20}	x_{24}	x_{28}	x_{32}

TABLE V-29: MR&R Intervention Variables for the Tertiary Treatment Phase

MR&R Intervention	Tertiary Treatment phase		
	Tanks CRI_{IUt+1}	Pipes CRI_{IUt+1}	Pumps CRI_{IUt+1}
Do nothing	x_{33}	x_{37}	x_{41}
Maintain	x_{34}	x_{38}	x_{42}
Rehabilitate	x_{35}	x_{39}	x_{43}
Replace	x_{36}	x_{40}	x_{44}

To illustrate the implementation of the optimization process, four MR&R interventions are assumed in this research. Each MR&R intervention will have an impact over the condition rating of each infrastructure unit, as shown in Table V-30. These impacts are used in the constraint equations and are assumed to be the same for different infrastructures found in different treatment phases.

TABLE V-30: MR&R Intervention and CRI Recovery Effect

MR&R Intervention	(Tanks) CRI_{IUt+1}	(Pipes) CRI_{IUt+1}	(Pumps& Blowers) CRI_{IUt+1}
Do nothing	- 1 %	- 2 %	- 5 %
Maintain	+ 10 %	+ 10 %	+ 15 %
Rehabilitate	+ 60 %	+ 40 %	+ 50 %
Replace	+ 100 %	+ 100 %	+ 100 %

Table V-30 shows that doing nothing will reduce the tank's condition rating by 1%, the minimum maintenance intervention will increase the tank's CR by 10%, the major rehabilitation intervention will increase the tank's CR by 60%, and the replacement intervention option will increase the CR by 100%.

The cost and the condition rating (CRI_{t+1}) recovery effect of each MR&R intervention method needs to be identified to apply the optimization model. These costs are calculated using the guidelines stated by Canada's Ministry of Municipal Affairs (CMMA), which estimates the yearly maintenance cost of WWTP infrastructure units as a percentage of the replacement cost of the different infrastructure assets of WWTPs. The maintenance cost is calculated by dividing the cost of capital replacement by the asset's remaining service life. Thus, the remaining service life and the capital replacement cost of such units needs to be assessed. However, most municipalities lack the appropriate methods and tools to provide these numbers and therefore the optimization model presented here is based on the average numbers presented by CMMA. These costs are presented in Table V-31.

TABLE V-31: WWTP MR&R Cost Estimates

Infrastructure Units	Remaining Years of Service Life(Yrs)	Replacement Cost ($)	Annual Maintenance Cost ($)	Rehabilitation Cost ($)
Cast Iron Pipes	15	40,000 $ *	2700	25000
Treatment Tanks	10	900,000 $	90000	200000
Pumps	5	40000 $	8000	25000
Blowers	5	40000 $	8000	25000

*Based on 400$/m assuming 100 m

Decision variables, intervention cost and condition recovery effect are used to determine the rehabilitation option. The MR&R costs for the primary treatment phase are illustrated using Equations 5.1, 5.2, and 5.3, where pmin_tank, pmin_pipe, pmin_pump are the primary treatment phase intervention costs for the PTP tank, PTP pipes and PTP pumps, respectively.

$$pmin\_tank = 0 * X1 + 90000 * X2 + 200000 * X3 + 900000 * X4 \quad \ldots\ldots\ldots\ldots\ldots 5.1$$
$$pmin\_pipe = 0 * X5 + 2700 * X6 + 25000 * X7 + 40000 * X8 \quad \ldots\ldots\ldots\ldots\ldots 5.2$$
$$pmin\_pump = 0 * X9 + 8000 * X10 + 25000 * X11 + 40000 * X12 \quad \ldots\ldots\ldots\ldots\ldots 5.3$$

The same approach is used for the secondary treatment phase. The decision variables for this phase include decision variables for the tank, reactor, pipe, pump, and blower decision variables. These variables are used to determine the rehabilitation cost for the secondary treatment phase, using Equations 5.4, 5.5, 5.5, 5.6, 5.7 and 5.8, respectively.

smin_tank =0 * X13 + 90000 * X14 + 200000 * X15 + 900000 * X16 ……..…5.4
smin_reactor =0 * X17 + 90000 * X18 + 200000 * X19 + 900000 * X20 ……..…5.5
smin_pipe = 0 * X21 + 2700 * X22 + 25000 * X23 + 40000 * X24 ...…...5.6
smin_pump = 0 * X25 + 8000 * X26 + 25000 * X27 + 40000 * X28 ………....5.7
smin_blower =0 * X29 + 8000 * X30 + 25000 * X31 + 40000 * X32 ……...…5.8

where smin_tank, smin_reactor, smin_spipe, smin_pump, and smin_blower are the secondary treatment phase intervention costs for the STP tank, reactor, pipes, pump and blower, respectively.

A similar approach is used to find the MR&R intervention cost for the tertiary treatment phase using the variables presented in Table V-29. These variables are demonstrated in Equations 5.9, 5.10 and 5.11. The variables tmin_tank, tmin_pipe, and tmin_pump are the tertiary treatment phase MR&R intervention costs for the TTP tank, pipes and pumps, respectively.

tmin_tank = 0 * X33 + 90000 * X34 + 200000 * X35 + 900000 * X36 ………. 5.9
tmin_pipe = 0 * X37 + 2700 * X38 + 25000 * X39 + 40000 * X40 ……. 5.10
tmin_pump = 0 * X41 + 8000 * X42 + 25000 * X43 + 40000 * X44 ……….. 5.11

The optimization model presented in this research assumes that the intervention cost for an infrastructure unit will be the same in the three treatment phases and will have the same condition recovery effect in these phases. The cost of each MR&R intervention and its recovery effect, presented in the coming sections, is estimated using the guidelines developed by the CMMA.

The presented optimization models allow only one MR&R intervention for each infrastructure unit in each treatment phase. The optimization problem is solved using the integer programming with binary variables technique. This technique is used because the MR&R decision X can either be (1) if the MR&R is implemented or (0) if the MR&R alternative is not implemented. Lingo software is used to solve the optimization algorithm with its constraints. Lingo input coding and the output given for this section are shown in Appendix F.

5.23.1. Minimize WWTP MR&R Intervention Cost

The first optimization option is to minimize the WWTP MR&R cost, which must be less than or equal to the available budget and is constrained by the minimum required CRI for each infrastructure unit in the three treatment phases. The objective function of this approach is to minimize the MR&R intervention cost using Equation 3.7, where *x* is the MR&R intervention (do nothing, maintain, rehabilitate or replace) and *C* is the MR&R intervention cost. The objective function in this case is to minimize the MR&R cost which is represented by Equations 5.1, 5.2, 5.3, 5.4, 5.5, 5.6,5.7, 5.8, 5.9, 5.10, and 5.11. The optimization is constrained by the minimum allowable condition ratings for all infrastructure units in all treatment phases.

To satisfy the objective function, all variables tend to "0"; however, this will violate one or more constraints. The variable with the least cost will tend to be "1"; however, this will not satisfy one or more constraints, which forces the model to select the second lowest cost, thus satisfying the constraints. This will insure the selection of the lowest cost solution that will also satisfy the minimum requirements. The constraints are illustrated in Equation 3.8. The main constraints for this approach are the minimum required condition rating threshold (CRI) for each infrastructure unit in each treatment phase and the available budget.

The optimization model will select the optimized rehabilitation interventions with the lowest cost that satisfies all constraints. This means that the model will select different

MR&R actions over all infrastructure units in a WWTP. There are 4^{11} (4194304) MR&R possibilities for the whole WWTP. The optimization model will select the best MR&R action for each infrastructure unit. However, the MR&R rehabilitation interventions for each treatment phase can be optimized separately. Therefore the MR&R possibilities for this option will be 4^3 (64), 4^5 (1025) and 4^3 (64). However, in this study the optimization model consider the three treatment phases combined.

Each MR&R alternative will affect the infrastructure unit condition rating (CRI $_{(t+1)}$) and is determined using Equation 3.8. The minimum desired value of (CRI $_{(t+1)}$) for each infrastructure unit are the constraints in the optimization process. The objective function and its constraints are presented in Appendix F.

The objective function used to minimize the cost of the MR&R intervention is affected by the minimum allowable condition rating for each infrastructure unit. This means that the decision-maker can reduce the minimum desired condition rating to reduce the MR&R cost, as long as it is above the minimum allowable level. The rehabilitation cost and the minimum CRI desired are adjusted to overcome infeasible solutions typically obtained when using the integer programming technique, especially when it is used with binary variables. This is illustrated in the rehabilitation decisions for H-WWTP. The rehabilitation cost to keep the CR of all infrastructure units of H-WWTP greater or equal to 7 will cost 368,100 CAD because different rehabilitation interventions are to be applied over different infrastructure, as shown in Table V-32. The optimized MR&R decisions show that, in order to increase the CR of the primary sedimentation tank from 6.7 to 7.4, the PTP tank needs to be maintained with a cost of 90,000 CAD. A similar rehabilitation action is chosen for the primary treatment phase pipes, which raises their

CR from 7.1 to 7.8, while no action is chosen for the PTP tank, which lowers its CR from 8.3 to 7.9. The rehabilitation decisions for the secondary treatment phase, shown in the table, will cause a slight change in the CR, from 7.7 to 7.8. The infrastructure performance CRI_{IP} for H-WWTP will be upgraded from 7.3 to 7.8. Although this increase appears marginal, it is determined using a CRI greater or equal to 7 for all infrastructure units.

TABLE V-32: MR&R Decisions for H WWTP for a minimum CR Value of 7

Treatment Phase	Infrastructure unit	CRI_{IUt}	Min CRI	MR&R Selected	MR&R Cost	CRI_{IUt+1}
Primary Treatment Phase	Primary Sedimentation Tank	6.7	7	maintain	90000	7.4
	Primary phase Pipes	7.1	7	maintain	2700	7.8
	Primary Phase Pump	8.3	7	nothing	0	7.9
	CRI_{PTP}	**7.6**				**7.7**
Secondary Treatment Phase	Secondary Sedimentation tank	6.9	7	maintain	90000	7.6
	A.S Reactor	6.9	7	maintain	90000	7.6
	Secondary Phase pipes	6.5	7	maintain	2700	7.2
	Secondary Sedimentation Pump	8.6	7	nothing	0	8.2
	Secondary Phase Reactor Blower	8.4	7	nothing	0	8.0
	CRI_{STP}	**7.79**				**7.8**
Tertiary Treatment Phase	Chlorination Phase Tank	6.6	7	maintain	90000	7.3
	Chlorination Phase Pipes	6.5	7	maintain	2700	7.2
	Chlorination Phase Pump	8.6	7	nothing	0	8.2
	CRI_{TTP}	**7.432**				**7.6**
	CRI_{IP}	**7.372**				**7.8**
Budget					**368100**	

The rehabilitation decisions in this optimization option are highly affected by the minimum condition ratings of different infrastructure units in the WWTP. For H-WWTP, the rehabilitation cost will go to zero if the condition ratings of all infrastructure units are allowed to go as low as 6. This is because the do nothing option will be the optimum solution to minimize the rehabilitation cost, as shown in Table V-33.

TABLE V-33: MR&R Decisions for H WWTP for a minimum CR Value of 6

Treatment Phase	Infrastructure unit	CRI_{IUt}	Min CRI	MR&R Selected	MR&R Cost	CRI_{IUt+1}
Primary Treatment Phase	Primary Sedimentation Tank	6.7	6	Nothing	0	6.63
	Primary phase Pipes	7.1	6	Nothing	0	6.96
	Primary Phase Pump	8.3	6	Nothing	0	7.89
	CRI_{PTP}	**7.6**	**6**			**7.36**
Secondary Treatment Phase	Secondary Sedimentation tank	6.9	6	Nothing	0	6.83
	A.S Reactor	6.9	6	Nothing	0	6.83
	Secondary Phase pipes	6.5	6	Nothing	0	6.37
	Secondary Sedimentation Pump	8.6	6	Nothing	0	8.17
	Secondary Phase Reactor Blower	8.4	6	Nothing	0	7.98
	CRI_{STP}	**7.79**	**6**			**7.50**
Tertiary Treatment Phase	Chlorination Phase Tank	6.6	6	Nothing	0	6.53
	Chlorination Phase Pipes	6.5	6	Nothing	0	6.37
	Chlorination Phase Pump	8.6	6	Nothing	0	8.17
	CRI_{TTP}	**7.432**	**6**		0	**7.19**
	CRI_{IP}	**7.372**	**6**			**7.40**
Budget					0	

This option will reduce the CRs of all infrastructure units, but they will still be above the desired CR threshold of 6. This shows that this optimization model can give decision-makers the needed tools to be aware of the consequences of all their decisions, which will better equip them to defend and justify their decisions.

5.23.2. MAXIMIZE WWTP CRI

The second optimization approach is based on maximizing the CRI for the WWTP within a defined MR&R budget. This optimization approach will answer the question of "how much improvement in the WWTP's CRI is possible for a certain MR&R budget?" The objective function in this case is maximizing the CRI_{IP}, as shown in Equation 3.9.

The optimization of this objective function is constrained by the minimum allowable CR for each infrastructure unit, as illustrated in the first optimization approach using equation 3.8, and constrained by the available MR&R budget. The MR&R budget will highly affect the rehabilitation because it will be first allocated to the most important infrastructure units. This optimization approach will inform decision-makers of how much improvement can be achieved within a certain rehabilitation budget.

To illustrate this optimization approach, H-WWTP infrastructure data is used. Similarly to the first approach, the current condition rating for all infrastructure units and the cost of different MR&R interventions and their condition recovery effects must be identified before applying the optimization model, as presented in Table V-34 and Table V-35.

The first optimization option is performed to maximize the CRI_{IP} with a MR&R budget of 100,000 CAD, while keeping all infrastructure units' condition ratings greater or equal to 6. This means that the CR of all infrastructure units of H-WWTP can go as low as 6. The MR&R decision associated with this optimization option is presented in Table V-34. This optimization alternative will cost 99,700 CAD and will upgrade the CRI_{IP} of H-WWTP from 7.37 to 9.0. Furthermore, it will upgrade the CRI_{PTP} from 7.6 to 8.42, the CRI_{STP} from 7.79 to 9.29 and the CRI_{TTP} from 7.4 to 8.7.

TABLE V-34: MR&R Decisions for H WWTP for an MR&R Budget of $100,000

Treatment Phase	Infrastructure unit	CRI_{IUt}	Min CRI	MR&R Selected	MR&R Cost	CRI_{IUt+1}
Primary Treatment Phase	Primary Sedimentation Tank	6.7	6	Nothing	0	6.63
	Primary phase Pipes	7.1	6	maintain	2700	7.81
	Primary Phase Pump	8.3	6	maintain	8000	9.55
	CRI_{PTP}	**7.6**				**8.42**
Secondary Treatment Phase	Secondary Sedimentation tank	6.9	6	nothing	0	6.83
	A.S Reactor	6.9	6	nothing	0	6.83
	Secondary Phase pipes	6.5	6	replace	40000	10.00
	Secondary Sedimentation Pump	8.6	6	maintain	8000	9.89
	Secondary Phase Reactor Blower	8.4	6	maintain	8000	9.66
	CRI_{STP}	**7.79**				**9.29**
Tertiary Treatment Phase	Chlorination Phase Tank	6.6	6	nothing	0	6.53
	Chlorination Phase Pipes	6.5	6	rehabilitate	25000	9.10
	Chlorination Phase Pump	8.6	6	maintain	8000	9.89
	CRI_{TTP}	**7.432**				**8.70**
	CRI_{IP}	**7.372**				**9.01**
Budget					**99700**	

These results show that this optimization option targeted the most important infrastructure units in each phase and focused most of the resources towards the STP since it has the highest relative importance.

The same rehabilitation option is repeated for a lower budget of 50,000 CAD and keeping the minimum desired CRI value of 6 for all infrastructure units. The optimization output is shown in Table V-35.

TABLE V-35: MR&R Decisions For H WWTP for MR&R Budget of $100,000

Treatment Phase	Infrastructure unit	CRI_{IUt}	Min CRI	MR&R Selected	MR&R Cost	CRI_{IUt+1}
Primary Treatment Phase	Primary Sedimentation Tank	6.7	6	nothing	0	6.633
	Primary phase Pipes	7.1	6	nothing	0	6.958
	Primary Phase Pump	8.3	6	nothing	0	7.885
	CRI_{PTP}	**7.6**				**7.36**
Secondary Treatment Phase	Secondary Sedimentation tank	6.9	6	nothing	0	6.831
	A.S Reactor	6.9	6	nothing	0	6.831
	Secondary Phase pipes	6.5	6	rehabilitate	25000	9.1
	Secondary Sedimentation Pump	8.6	6	maintain	8000	9.89
	Secondary Phase Reactor Blower	8.4	6	maintain	8000	9.66
	CRI_{STP}	**7.79**				**9.09**
Tertiary Treatment Phase	Chlorination Phase Tank	6.6	6	nothing	0	6.534
	Chlorination Phase Pipes	6.5	6	nothing	0	6.37
	Chlorination Phase Pump	8.6	6	maintain	8000	9.89
	CRI_{TTP}	**7.432**				**8.29**
	CRI_{IP}	**7.372**				**8.64**
Budget					**49000**	

This optimization approach will upgrade the CRI_{IP} from 7.4 to 8.2; however, it will have no MR&R action for most infrastructure units, which will allow their CR to drop, though still above the acceptable limit of 6. Similar optimization options for P-WWTP and other optimization options are presented in Appendix F.

The developed optimization options can provide decision-makers with the appropriate tools to justify and modify their MR&R plans according to many decision variables.

However, in order to have good, flexible results, WWTP operators and decision-makers must have accurate data. The more accurate the information they provide, the better the optimization outcomes, which can be used in their planning and to support their current and future financial demands.

Ch VI. Automated Tool Development

6.1 PROTOTYPE SOFTWARE

In order to make it easy for decision makers to use and implement the developed performance assessment model (PAM), it is automated by converting the developed methodology into a user-friendly prototype software. This software is developed using the visual basic applications (VBA) programming language, as this is an object-oriented programming language that is easy and flexible to use. The VBA is developed based on the traditional Visual Basic, but VBA runs through a host application, while VB runs as a standalone application. Therefore, the VBA allows programmers to develop user-defined functions that can be run through different Microsoft Office Applications. The prototype software in this research is developed using the research methodology presented in Chapter III. The main menu of the software is shown in Figure VI-1.

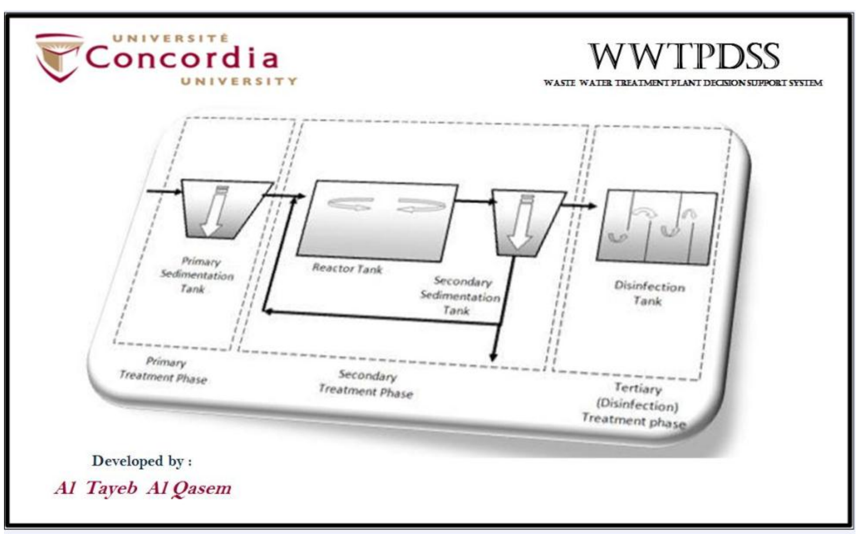


Figure VI-1: Software Main Menu

The main menu of the software enables the user to choose the desired treatment phase, in addition to the overall condition assessment for the whole WWTP. The main menu will always appear on the upper part of the screen. Once the user chooses the desired treatment phase, he or she will be able to either determine the treatment performance index, the infrastructure performance index or the deterioration curve for each infrastructure or for the whole WWTP. Once one of these options is selected, the user is asked to fill in the required data for that selection. The computer will then automatically show the results based on the input data.

6.2 Primary Treatment Phase Performance

For each treatment phase, the user will choose the treatment performance index menu or the infrastructure condition rating menu. Figure VI-2 shows the screen used to determine the TPI of the primary treatment phase. This TPI_{PTP} is determined using its BOD and TSS removal efficiency.

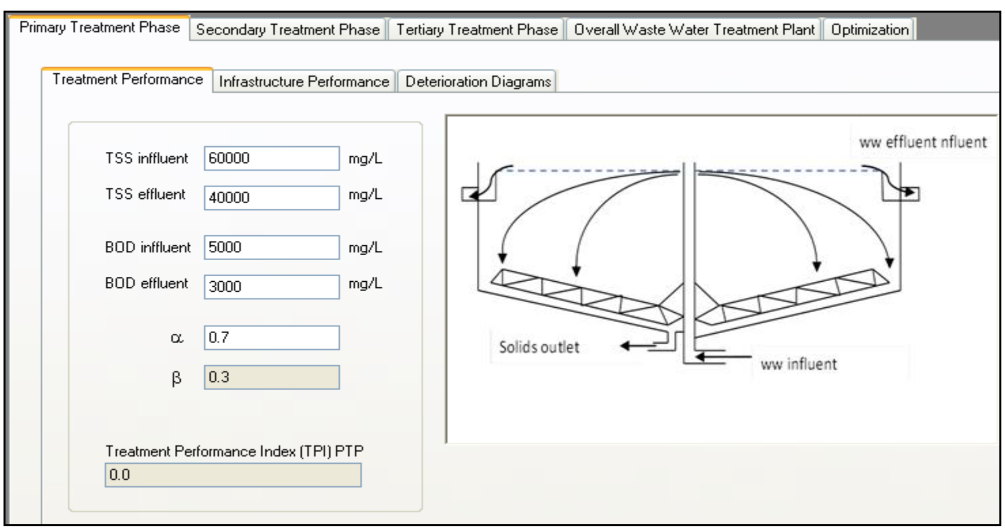


Figure VI-2: Treatment Performance Menu of the PTP

The second part of the primary treatment phase menu is the infrastructure performance menu. When the user selects that option, another screen will appear and ask the user to enter the attributes needed to determine the infrastructure condition ratings of the primary treatment phase, as shown in FigureVI-3. The user can select the required infrastructure by pressing on the calculate button located in front of it. Once the calculate button is pressed, another menu will be shown on the top part of this screen. This will let the user choose the factors category (physical, operational or environmental). Once the category is chosen, the user will be able to select the attributes of the different factors (discussed in Chapter III) in the user-friendly menus. FigureVI-4 shows the tanks attributes used to determine the tanks condition rating.

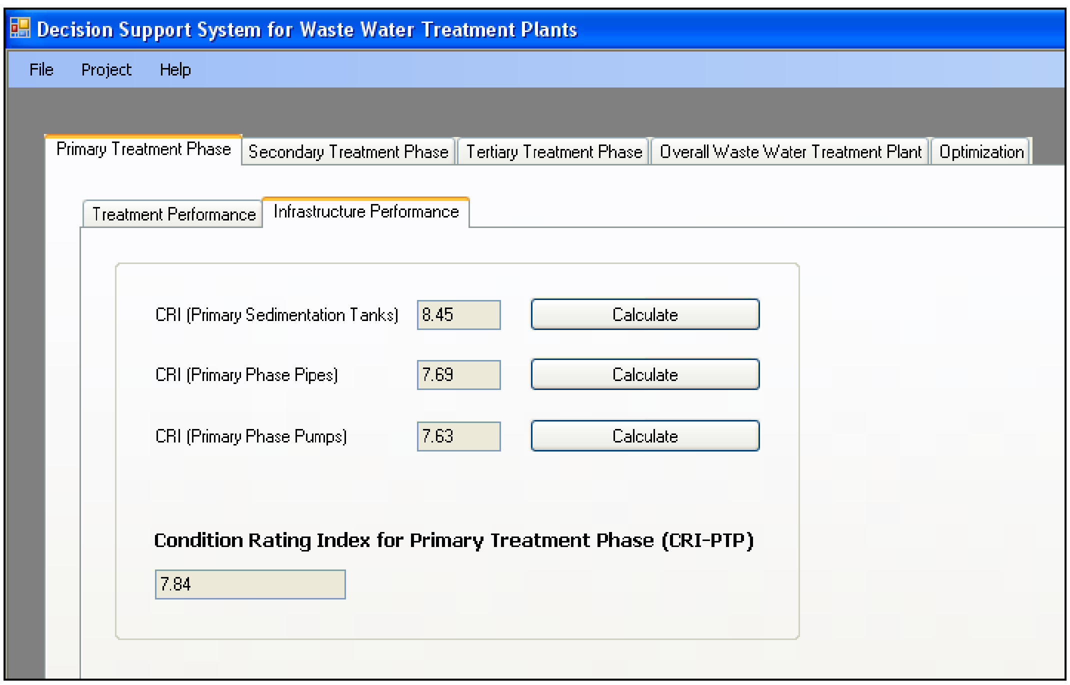


Figure VI-3: PTP Infrastructure Performance Menu

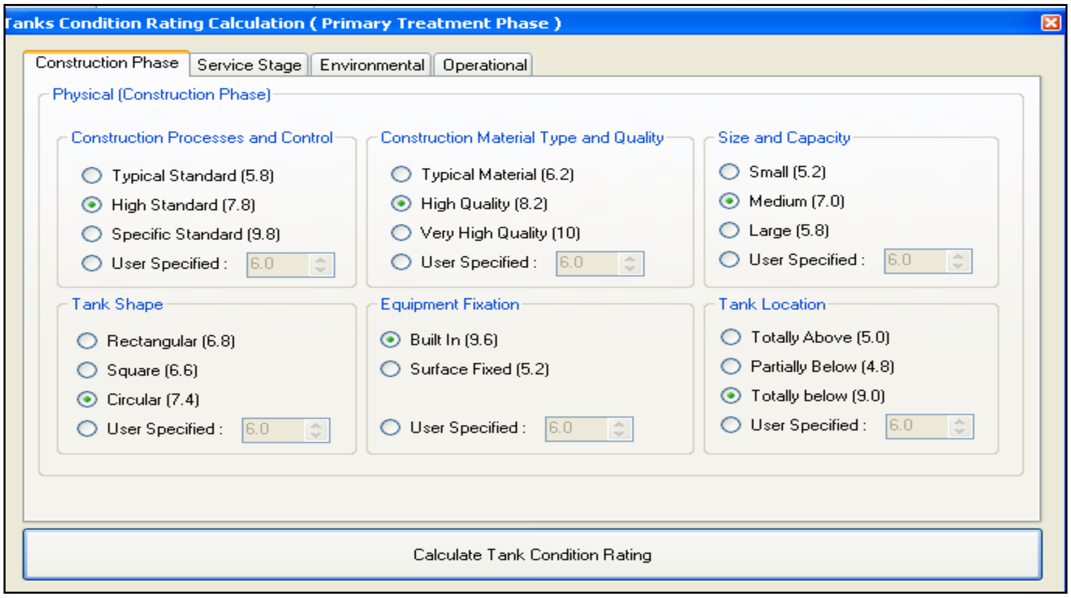


FIGURE VI-4: Attributes of Factors Affecting Tanks Condition Rating

Similar menus to determine the condition ratings of primary treatment phase pipes and pumps are shown in Figure VI-5 and Figure VI-6, respectively, and will appear once selected from the screen shown in Figure VI-3.

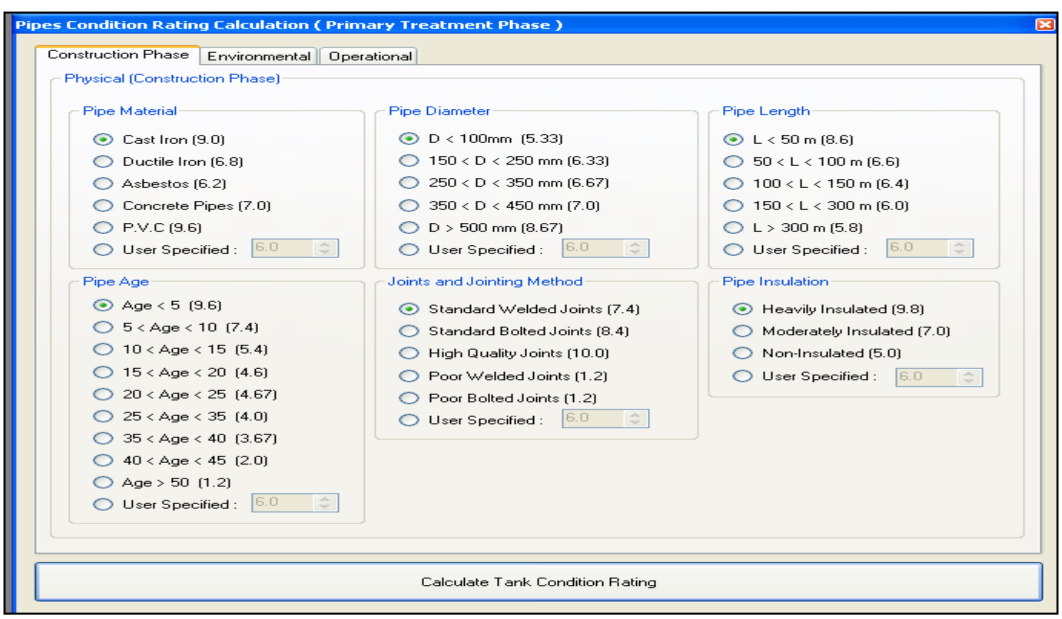


Figure VI-5: Attributes of Factors Affecting Pipes Condition Rating

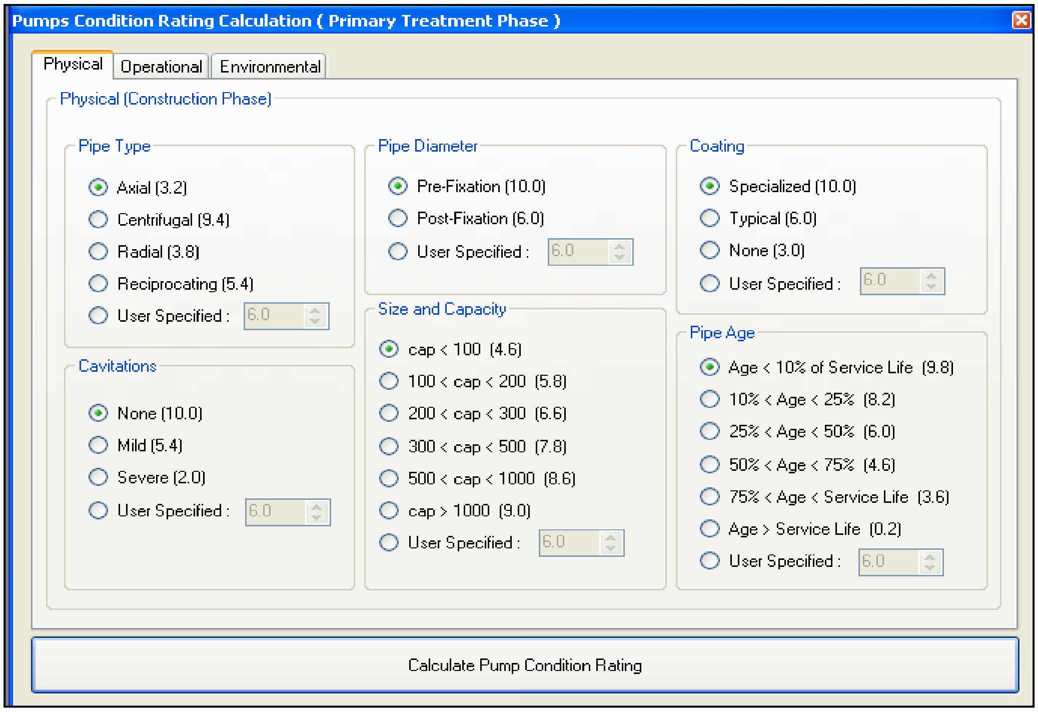


FIGURE VI-6: Attributes of Factors Affecting Pumps Condition Rating

The third option of the primary treatment phase menu is the deterioration diagram. When the user selects this option, the deterioration curve of the selected infrastructure unit will be automatically generated and displayed as shown in Figure VI-7. These graphs are dynamic graphs, which mean that the user can zoom in and out or can expand and shrink the figure as needed.

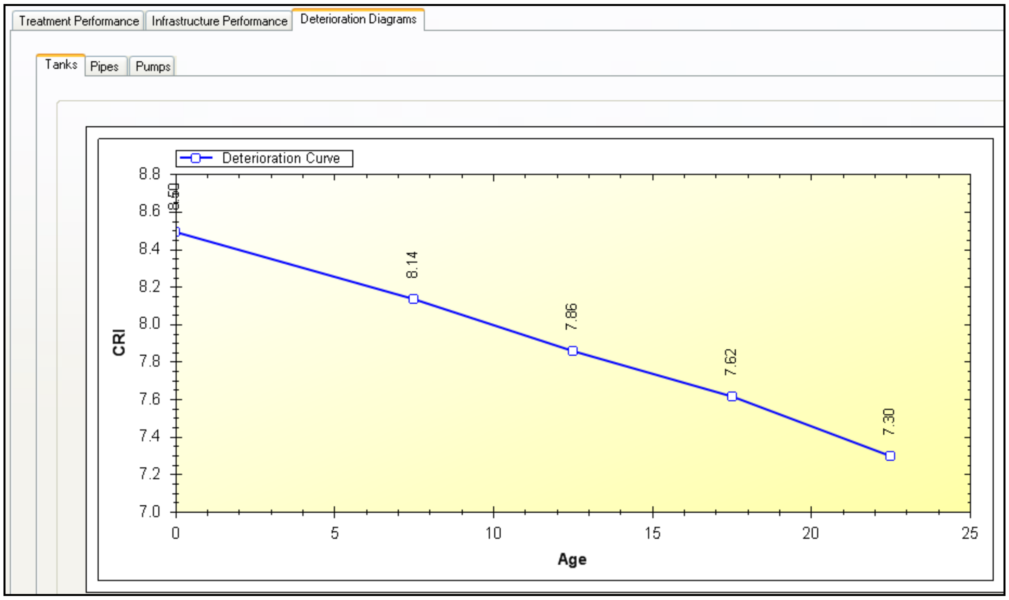


FIGURE VI-7: Tank Deterioration Curve Sample

6.3 SECONDARY TREATMENT PHASE PERFORMANCE

The treatment performance and the condition ratings of the secondary treatment phase will be determined using the menu shown in Figure VI-2; however, the user will choose the secondary treatment phase option, as shown in FigureVI-8. This menu has three options: the treatment performance, the infrastructure performance and the deterioration curve. The treatment performance option, which measures the treatment performance of this phase using its removal efficiency and the state of the MLVSS and SVI as explained in Chapter III.

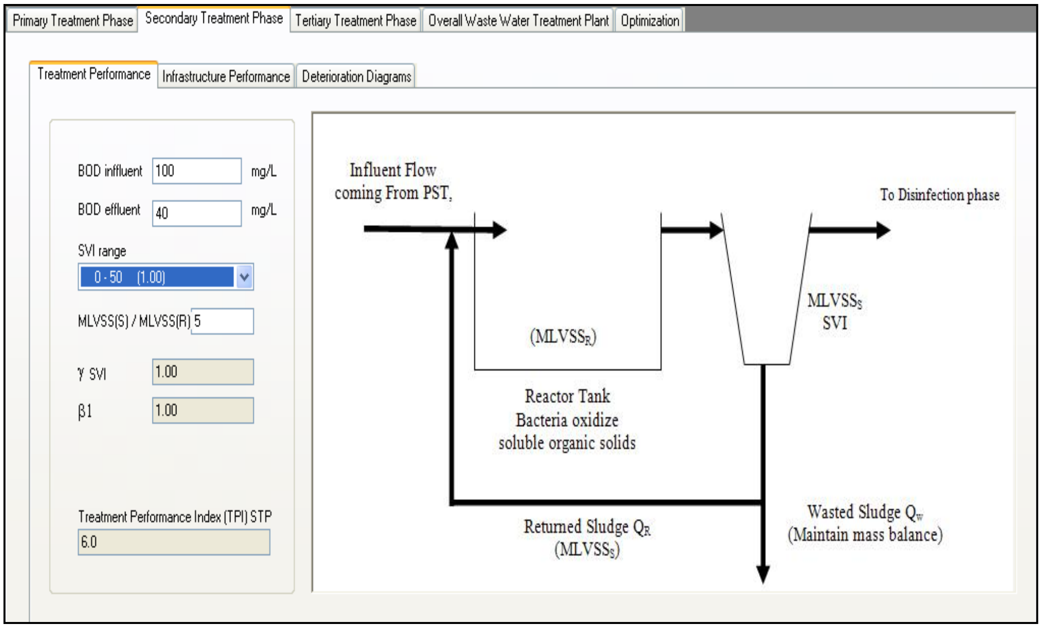


FIGURE VI-8: Treatment Performance Menu of the STP

The condition rating of the secondary treatment phase infrastructures (secondary sedimentation tank, reactor, pumps and blower) will be determined using the infrastructure performance. This option will open the STP infrastructure menu shown in Figure VI-9. Once the calculate button located in front of each infrastructure unit is selected, the user will select the attributes needed to calculate its condition rating. Then, the condition rating of each infrastructure unit will be determined depending on its selected attributes, as shown in FigureV-10.

The deterioration curves of the secondary treatment phase infrastructures (tanks, reactor, pipe, pump and blower) are automatically shown on the screen when the user selects the deterioration curves menu shown in the secondary treatment phase options menu.

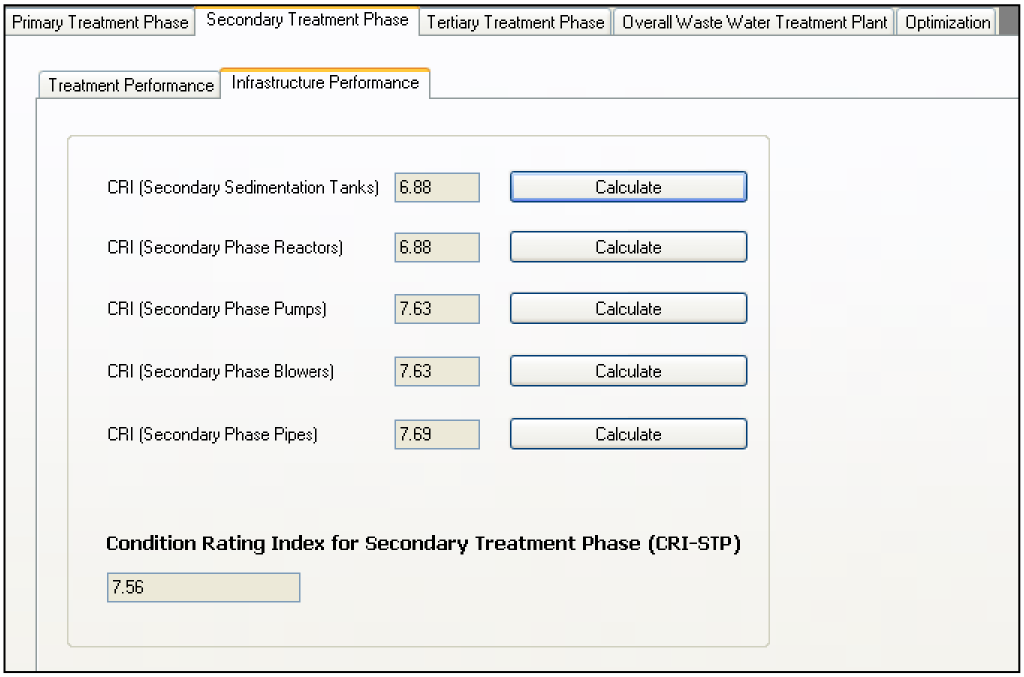


FIGURE VI-9: Infrastructure Performance Menu for the STP

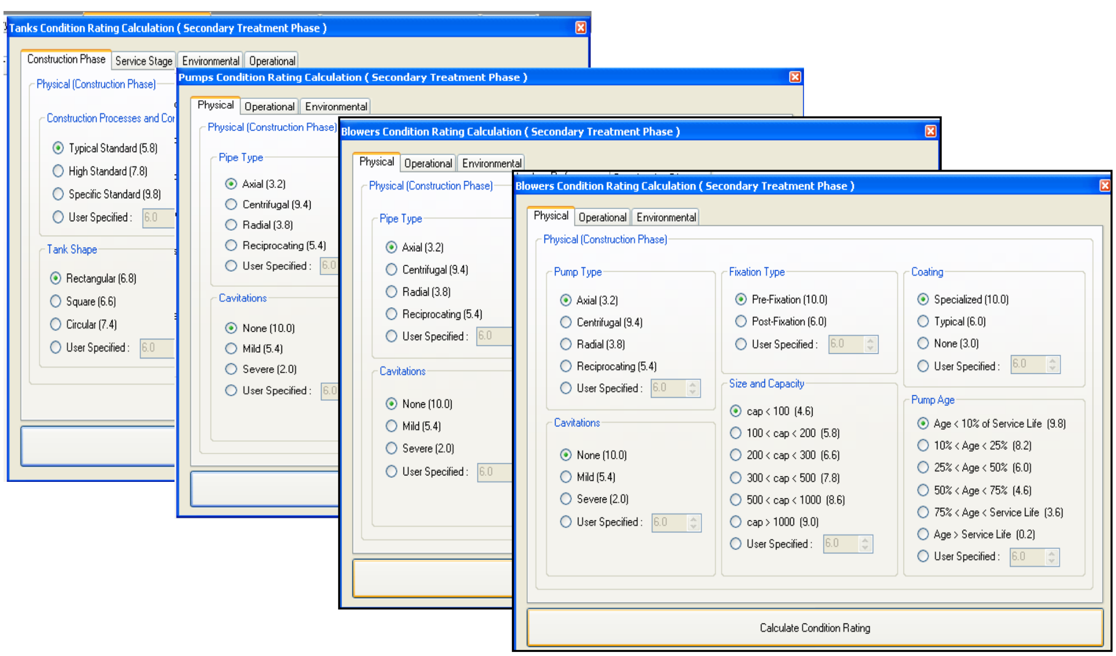


FIGURE VI-10: Tanks, Pipes, Pumps & Blower Attributes Menus for STP

6.4 TERTIARY TREATMENT PHASE PERFORMANCE ASSESSMENT

The treatment performances and the condition ratings of the tertiary treatment phase are determined using similar approach to the one followed for the primary treatment phase, as presented in Figure VI-11.

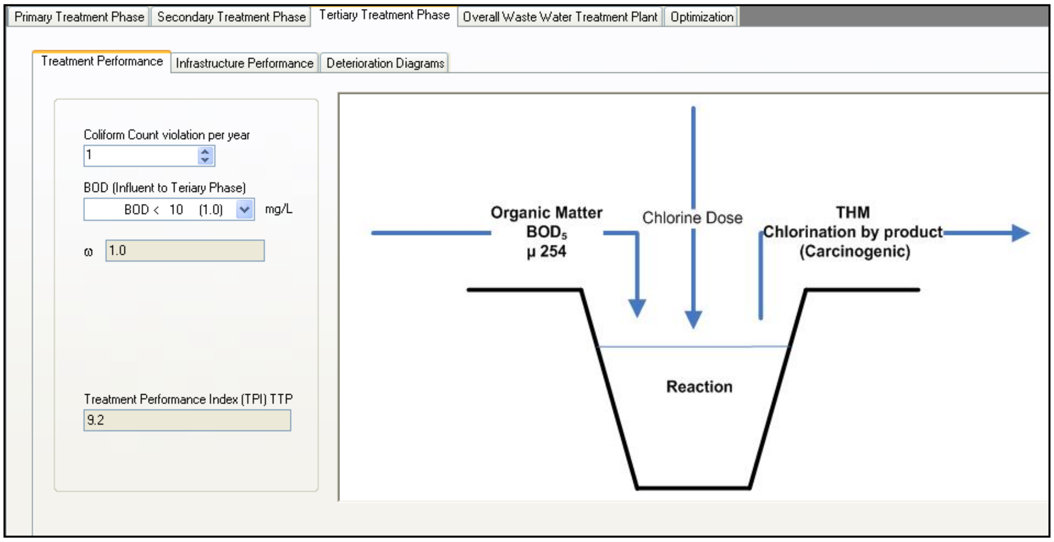


FIGURE VI-11: Treatment Performance Menu of the TTP

6.5 WWTP OVERALL PERFORMANCE ASSESSMENT

The overall WWTP performance menu allows the user to see the overall treatment and infrastructure performance for the studied WWTP. The condition ratings of each treatment phase and its treatment performance are determined automatically using the weighted sum of its infrastructure condition ratings. These condition ratings are shown on the screen after selecting the overall wastewater treatment plants option from the main menu. The condition rating of each treatment phase will be shown when the user presses the CRI option, while the treatment performance indexes for the three treatment phases will be shown when the user selects the TPI option, as shown in Figure V-12 and Figure V-13, respectively.

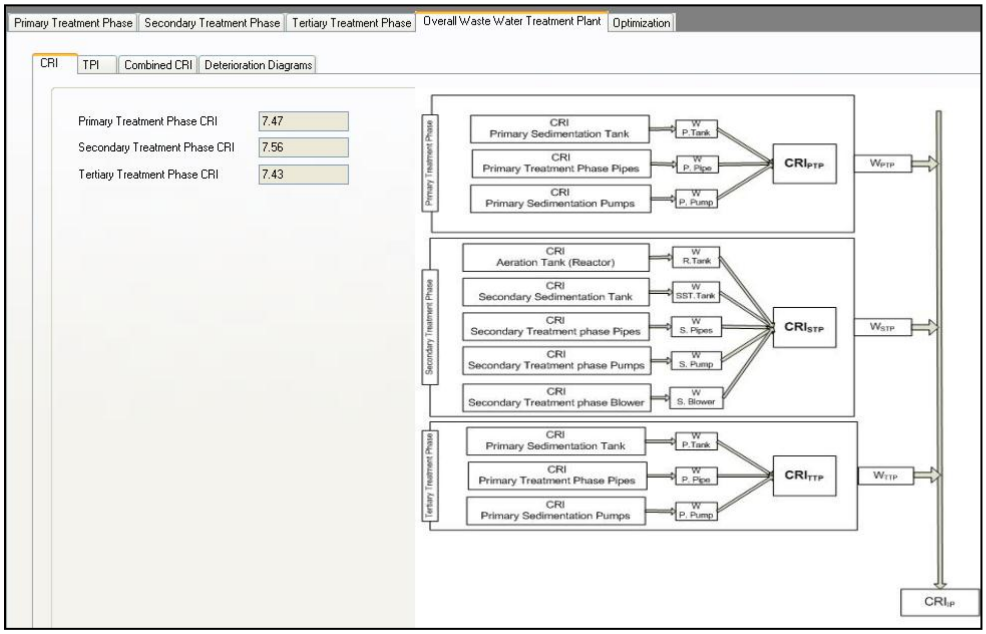


FIGURE VI-12: The Condition Rating of Each Treatment Phase

The third option in this menu is the combined condition rating index (CCRI) option, in which the treatment performance index and the condition rating index of the whole WWTP are presented using the combined condition rating index matrix, as shown in Figure V-14. This option will also summarize the overall state of the WWTP and provide the user with an interpretation of the CCRI value.

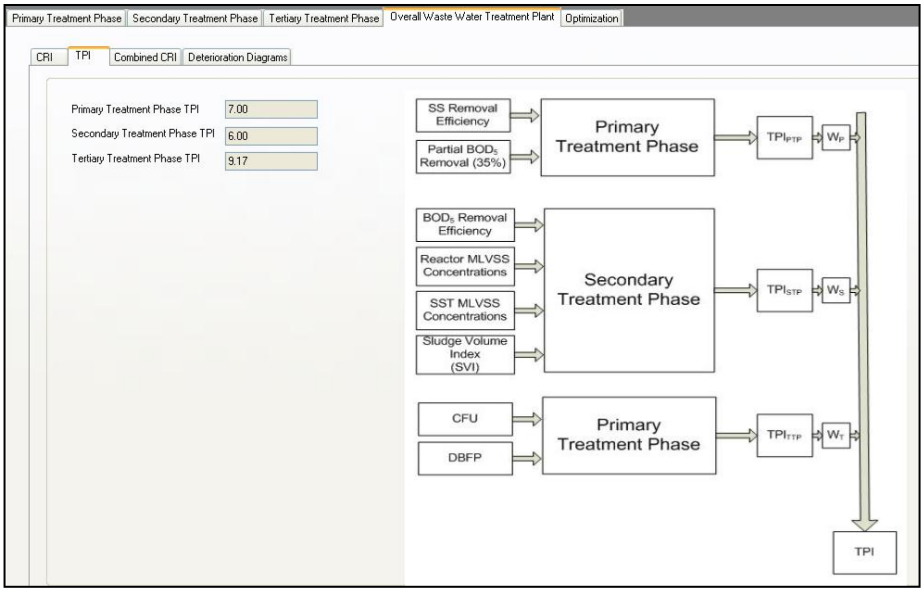


FIGURE VI-13: The Treatment Performance Index of Each Treatment Phase

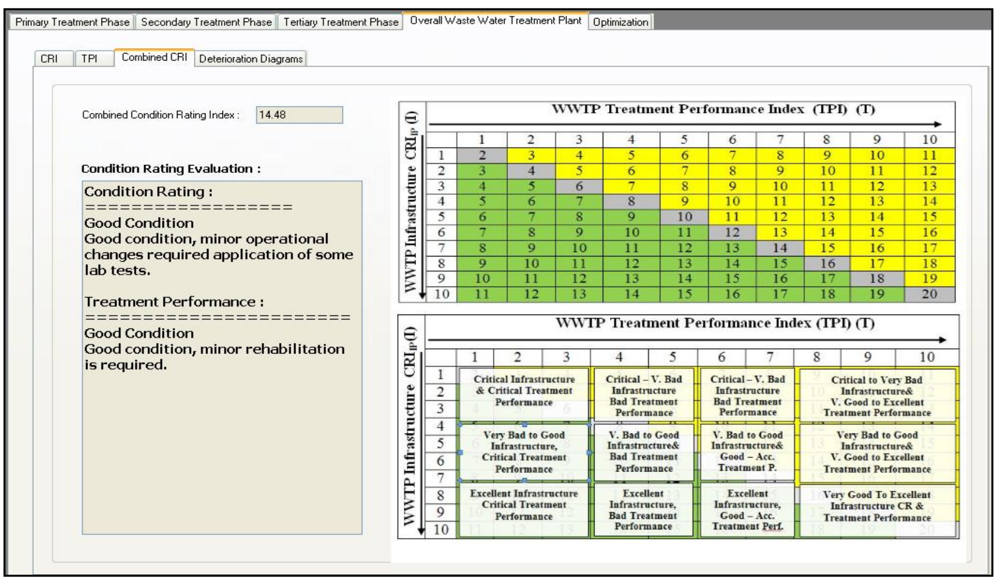


FIGURE VI-14: The Treatment Performance Index of Each Treatment Phase

The deterioration curve for the whole WWTP infrastructure is shown when the user selects the deterioration curve option from this menu. The deterioration curve of the whole WWTP is determined by the weighted sum of the condition rating of each treatment phase infrastructure condition rating, as shown in FigureV-15.

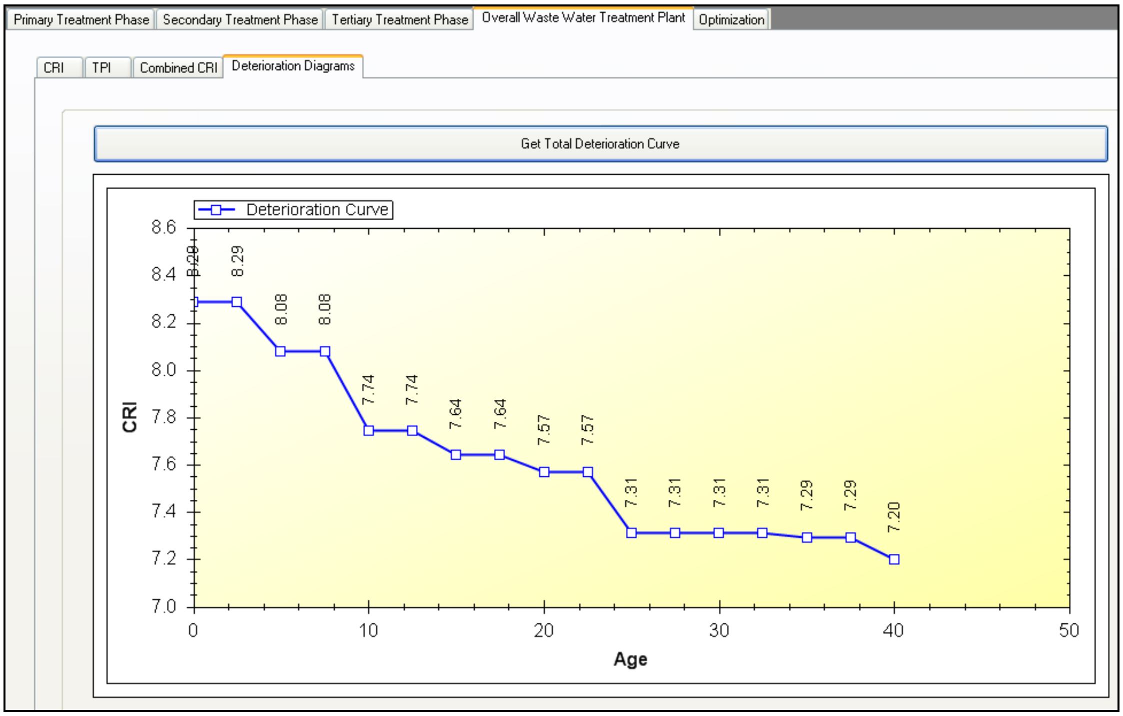


FIGURE VI-15: The Deterioration Curve of the WWTP

6.6 MR&R OPTIMIZATION

The last part of the software is optimization. In this part, the user can select one of two options: to maximize the condition rating of the WWTP infrastructures for a given rehabilitation budget or to minimize the rehabilitation budget while maintaining a minimum desired condition rating for each infrastructure unit. These optimization options were discussed in Chapter III.

The optimization option will link to the Lingo optimization software and our developed software will write the input file. The cost of each intervention must be provided by the user, in addition to the minimum desired condition rating for each infrastructure facility, as shown in FigureV16. The developed software will run the Lingo optimization tool and it will read the output file for each optimization alternative. The developed software will then translate Lingo's output files into rehabilitation actions over each infrastructure unit in the WWTP and their costs. In addition, the current and updated condition ratings for each infrastructure unit will be determined by reading and interpreting the Lingo output file.

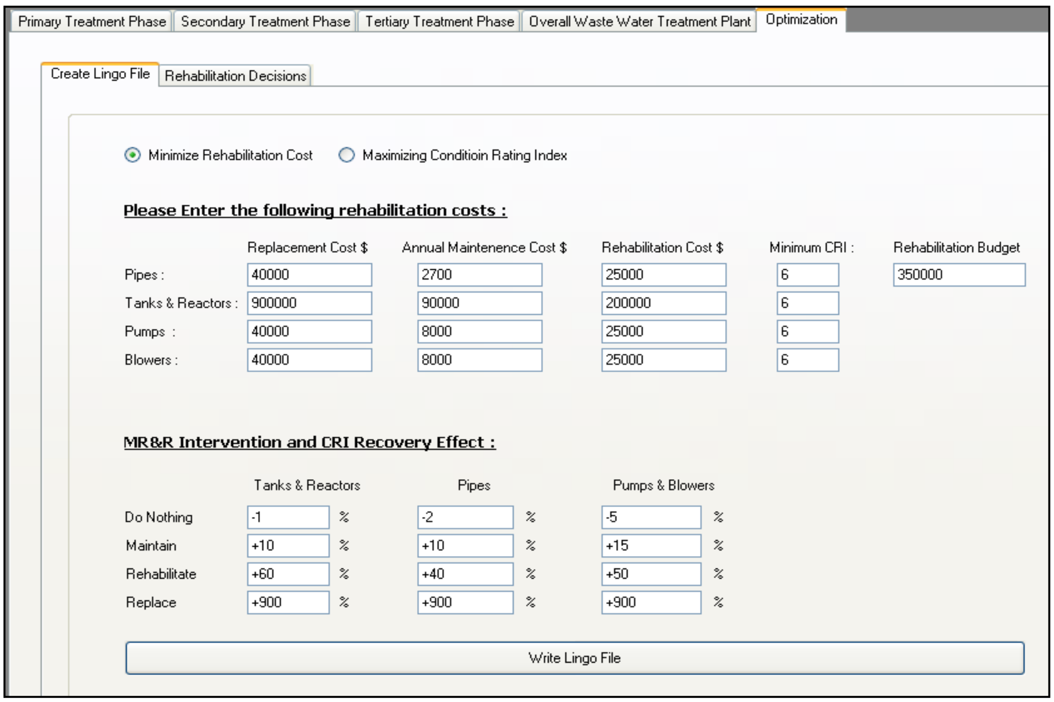


FIGURE VI-16: MR&R Optimization Input Menu

To run the optimization option, Lingo software version 10 or higher must be installed on the computer to be able to generate and read the optimization files.

Ch VII. Conclusions, Contributions, Limitations & Recommendations for Future Work

7.1 CONCLUSION

The literature review showed a tremendous need for a performance assessment tool for managing WWTPs. The conducted research demonstrated that such a performance assessment model (PAM) for wastewater treatment plant maintenance and rehabilitation is possible and it can be the backbone of a WWTP decision support system. The developed PAM provides decision makers with the best time to implement various rehabilitation interventions over the most vulnerable infrastructure units within a specific rehabilitation budget to keep their WWTPs running within desired performances levels. Based on the research and its outcomes, the conclusions are summarized as follows:

- A new PAM for wastewater treatment plant maintenance and rehabilitation was developed following a systematic, planned approach. This new model evaluates the infrastructure conditions and treatment performance of wastewater treatment plants.

- New budget optimization models were developed. They satisfy the requirement of decision makers to minimize the cost of WWTP maintenance and rehabilitation while keeping the WWTP performance within the desired conditions. In addition, they respond to upper management's need for linking maintenance budget to WWTP performance enhancement.

- The physical factors during the construction phase have the highest impact over tanks deterioration with a relative weight of (59%) while the physical factors during service stage has the second significant impact with a relative weight of (19%). The operational and environmental factors have less impact over tanks deterioration with a relative weight of (11%) for both factors. The results also showed that the physical factors for pipes have the highest relative weight of (73%). However, the operational and environmental factors have less impact over pipes deterioration with a relative weight of (13%). Similarly, the physical factors in pumps have the highest relative weights of (75%) among other factors, which are (15%) and (10%) for operational and environmental factors respectively.

- This research showed that the secondary treatment phase of a WWTP has the highest relative weight of (60%), followed by the tertiary treatment phase, which has a relative weight of (26%), while the primary treatment phase had a relative weight of (14%).

- The conducted research also led to the development of condition rating models quantifying the state of different infrastructure units typically found in wastewater treatment plants. A condition rating scale for WWTP infrastructure was developed. It is divided into six categories: excellent, very good, good, bad, very bad, and critical. Each category is associated with a certain rehabilitation action or operational modification.

- The developed condition-rating models are best used as condition-prediction models to identify the most vulnerable infrastructure units, thereby constituting valuable cost-saving measures that focus the inspection on these units.

- A minimum condition-rating threshold was established for the different infrastructure units considered in this research using the minimum preference value for the developed AHP-MAUT models. The minimum condition-rating threshold for tanks is 4.7, while that for pipes is 3.7, and it is 3.8 for pumps. These minimum thresholds were used in the constraint equations in the developed optimization models.

- The condition ratings of each treatment phase and its minimum threshold value was determined in this research using the weighted sum of the condition ratings of its infrastructure. The minimum threshold for each infrastructure unit of each treatment phase was used to define the minimum condition rating of each phase. These minimum thresholds were4.0 for the primary, 3.8 for the secondary and 3.9 for the tertiary treatment phase.

- The condition rating describing the state of the overall condition rating of a WWTP was developed using three condition-rating equations were developed to measure the treatment performance of each treatment phase. The framework followed to develop these equations has the ability to detect the exact causes of treatment malfunctions, providing WWTP operators with the information and justification needed to perform the required corrective measurements.

- The conducted research showed that suspended solids and BOD_5 removal efficiencies are good indicators to measure the treatment performance of the primary treatment phase in a simple and straightforward approach.

- This research showed that the biological treatment process of the secondary treatment phase, although a highly complicated process, can be evaluated using its treatment indicators. The biochemical oxygen demand (BOD_5) removal efficiency, the sludge volume index (SVI), and the mixed liquor volatile suspended solids (MLVSS) concentrations in the reactor and the secondary treatment phases, all reflect the treatment performance of the secondary phase.

- The coliform counting units test (CFU) and potential production of harmful disinfection byproducts (DBFP) were used to develop the condition-rating model to evaluate the tertiary treatment phase. This new approach measures the ability of this phase to destroy pathogenic microorganisms as well as its ability to prevent the production of DBP.

- This research showed that the main WWTP design factors used by environmental engineers, in addition to other WWTP performance requirement factors stated by the Canadian National Research Council, can be used effectively to measure the treatment performance of WWTPs. The developed treatment performance equations can be used as a standardized tool to measure the treatment performance of different WWTPs.

- The conducted research showed the development of an integrated WWTP condition-rating model that combines the treatment performance and infrastructure state of WWTPs and can be used as a WWTP network-ranking tool to prioritize and grade the rehabilitation needs for different WWTPs.

7.2 RESEARCH CONTRIBUTIONS

The contribution of this research to the body of knowledge in the field of wastewater treatment plant management lies in developing a comprehensive tool for the maintenance and rehabilitation of WWTPs. A tool that can be used on network and project levels. More specifically, key contributions of the developed PAM are as follows:-

- Identify and study the different factors that affect infrastructure and treatment performances of WWTPs.
- Design an integrated condition rating and treatment performance models for various elements of WWTP using AHP and MAUT techniques.
- Develop a condition rating scale to interpret the values generated by the developed models.
- Design an integrated performance model for the entire wastewater treatment plant considering treatment and infrastructure aspects.
- Develop deterioration curves for the major elements of WWTP (tanks, pipes & pumps), treatment phases and the entire WWTP.
- Develop a model to optimize MR&R interventions in order to maximize the performance of a WWTP subject to rehabilitation budget.

7.3 LIMITATIONS & RECOMMENDATIONS FOR FUTURE WORK

The developed PAM used a comprehensive approach that evaluated the treatment entails the following limitations:-

- The developed CRI models require data that are either not available in most municipalities or scattered and inconsistent and therefore the model is developed using relatively small data samples.

- The CRI models for WWTP infrastructure units are expert-based to address data related problems. They, thus, depend on the experts' personal judgments that include some uncertainty.

- The PAM presented in this research is applicable only for an activated sludge system as the secondary treatment phase in WWTPs. It also considers only the main activated sludge phases and it does not include other treatment units such as phosphorus and nitrogen removal.

- The developed PAM is best used to evaluate the current performance of WWTP. Therefore, it cannot be used for long term planning unless the developed condition rating index for various infrastructure units are integrated with life cycle cost analysis (LCCA) models.

The recommendations for future work can be categorized into two parts as follows:

<u>Research enhancement areas:</u>

- Enhance the developed CRI models by showing the relationship between different fcators using Analytical Network Process (ANP). In addition, the insignificant factors should be eliminated. This will make the developed models more effective and easier to implement.

- Fuzzy techniques can be integrated in developing the performance models to reduce the risk of uncertainty associated with the subjectivity of different factors.

- Experimental-based techniques can be used to better evaluate and predict the deterioration curves of different WWTP infrastructure units.

- Use more specific rehabilitation intervention in the optimization models to replace the four rehabilitation categories. This will give more realistic outcome and interventions that are more specific.

<u>Research Extension areas:</u>

- One important extension to this research is to apply the life cycle cost analysis (LCCA) as the base to select the best rehabilitation intervention over different infrastructure units. The LCCA will provide a powerful tool to estimate the overall costs of different infrastructure units in a WWTP consistent with its quality and functionality.

- The Current research focuses only on the main treatment units typically found in an activated sludge system. The research can be extended to include other important treatment phases found in a WWTP such as sludge handling and disposal units.

- The research can be extended to include different wastewater treatment technologies such as trickling filter, RBC and other biological treatment processes.

- Data related problems were among the main challenges of this research. Therefore, an important research extension of this research would be the development of a standardized data acquisition system for municipal assets. This will provide a powerful tool towards better municipal asset management and better communication between different municipalities to manage their shared infrastructure assets. This will also benefit different municipalities to satisfy the PSAB and GASB34 requirements.

- The research showed that there is tremendous lack of research in the field of concrete deterioration in sewer environments. This makes it a fertile field of research in all aspects. Mainly the development of destructive and non-destructive techniques to predict the deterioration of different municipal assets present in such environment.

References

ACI, (1989).“Corrosion of Metals in Concrete” (ACI 222R-89), American Concrete Institute, Detroit, USA.

ACI, (1993), “Erosion of Concrete in Hydraulic Structures”, (ACI 210R-93), American Concrete Institute, Committee 210, Detroit, MI, USA.

ASCE, (2009). “Report Card for American Infrastructures”, <http://www.asce.org/reportcard/2009/grades.cfm>.

Al-Barqawi, H., Zayed, T., (2008). “Infrastructure Management: Integrated AHP/ANN Model to Evaluate Municipal Water Mains’ Performance”, Journal of Infrastructure Systems, ASCE, Vol. 14, No. 4, pp. 305-318.

Al-Barqawi, H., Zayed, T., (2006). “Condition Rating Models for Underground Infrastructure: Sustainable Water Mains”, Journal of performance of construction facilities, ASCE, pp.126-135.

Alberta Wastewater Commission, (2008). “Alberta Capital Region Wastewater Treatment Plant”, available on http://www.acrwc.ab.ca/Brochure.pdf, surfed on April 2008.

Ali, S., Zayed, T., Hegab, M.,(2007).“Modeling the Effect of Subjective Factors on Productivity of Trenchless Technology Application to Buried Infrastructure Systems”, Journal of Construction Engineering and Management, ASCE, October 2007.

Amy, G., L., Thompson, J. M., Tan, L., Davis, M. K., Krasner, W., (1990). “Evaluation of THM precursor contributions from agricultural drains”, AWWA, 82(1), 57-64.

Amy, G., Siddiqui M, Ozekin, K., Zhu, H-W., Wang, C., (1998). “Empirical Based Models For Predicting Chlorination and Ozonation Byproducts: Haloacetic Acids, Chloral Hydrate, and Bromate”, EPA report CX 819579, 1998.

Baxter, C., Stanley, J., Zhang, Q., Smith, W., (2002). “Developing Artificial Neural Network Models of Water Treatment Processes: A Guide for Utilities”, Journal of Environmental engineering Science, Volume, pp 201-211.

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

Buckley, J., (1985). “Fuzzy hierarchical analysis”, Fuzzy Sets and Systems, Vol,17, pp 233-247.

Burns, P., Hope, D., Roorda, J., (1999). “Managing Infrastructure for the Next Generation”, Automation in Construction, Vol. 8, 689-703.

Canadian Water and Wastewater Association (CWWA), (1997). “Municipal Water and Wastewater Infrastructure Estimated Investment Needs 1997-2012”, <http://www.ccpe.ca/e/files/TRMReporteng.pdf>.

Campbell, D., T., (1975). “Degrees of freedom -the case study-”, Comparative Political Studies, pp.178- 193.

Carlos, A., Coello, G., Lamont, D., Van, V., (2007). “Evolutionary Algorithms For Solving Multi-Objective Problems”, second edition, Springer.

CCCPEM, (2009). “Pour Une Ville Durable”, a report presented and prepared by the advisory committee citizens for the protection of the environment of Maskoutain.

CERF, (1996). “Level of Investment Study: Facility and Infrastructure Maintenance and Repair”, Civil Engineering Research Foundation, Washington, D.C.

Chouinard, E., Andersen, G., Torrey, V., (1996). “Ranking Models Used for Condition Assessment of Civil Infrastructure Systems”, Journal of infrastructure systems. March 1996.

Corotis, R., Ellis, J., Jiang, M., (2004). “Modeling of Risk Based Inspection, Maintenance and Life Cycle Cost With Partially Observed Markov Decision Processes”, ASCE 9th conference on probabilistic mechanics and structural reliability, July 2004.

Communaute Urbaine de Montréal, (2008). “Wastewater Treatment Plant”, publication of Treatment Process,<http://services.ville.montreal.qc.ca/station/an/pdf/process.pdf>.

Connell, M., McNally, C., Richardson, M., (2010). “Biochemical Attack on Concrete In Wastewater Applications: A State of the Art Review”, Journal of Cement & Concrete Composites, Vol. 32, pp 479–485.

Crites, R., Tchobanoglous, G., (1998). “Small and Decentralized Wastewater Management Systems”, WCB McGraw-Hill Companies Inc, New York.

Chunlu, L., Hammad, A., Itoh, Y., (1997). “Maintenance Strategy Optimization of Bridges desks using Genetic Algorithms”. Journal of transportation Engineering, ASCE March/April, pp 91- 100.

David, W., Paul, M., (2000). “Identifying Process Conditions In An Urban Wastewater Treatment Plant”. International Journal of Operations & Production Management, Vol. 20 No. 5, 2000, pp. 573-590.

Dimosthenis, G., Glen, D., Marcos, S., Youngchul, P., Paraskevasa, K., (2003). “Comparison and Evaluation of Empirical Zone Settling Velocity Parameters Based on Sludge Volume Index Using a Unified Settling Characteristics Database”, Water Research Journal vol. 37 (2003), PP 3821–3836.

Desjardins, M., Gino, B., Elmonayeri, D., Stephenson, J., (2001). "Wastewater Treatment Plant Optimization Using a Dynamic Model Approach", Sixth International Water Technology Conference, IWTC 2001, Alexandria, Egypt.

Du, K., Swamy, M., (2006). "Neural Networks In A Soft-Computing framework", Publisher: London Springer.

Elmisalami, T., (2001). "Developing a Multi-Attribute Utility Model for Selecting Information Technologies In The Construction Industry", Ph.D. thesis, Iowa State University.

Edwards, W., Barron, F., (1994). "SMARTS and SMARTER: Improved Simple Methods for Multi attribute Utility Measurement", Organizational Behavior and Human Decision Processes 60: 306–325.

Environment Canada, (2007). "National Ranking of Wastewater Facilities in Canada". Government of Canada Wastewater Rules. < http://www.ec.gc.ca/eu-ww/default.asp?lang=En&n=BC799641-1>.

Farouq, M., Al-Asheh, S., Alfadala, H., (2007). "Use of Artificial Neural Network Black-Box Modeling for The Prediction of Wastewater Treatment Plants Performance", Journal of Environmental Management Volume 83, Issue 3, May, pp 329-338.

Faghir, A., Hua, J., (1995). "Roadway Seasonal Classification Using Neural Networks", Journal of Computing in civil engineering, ASCE 9 (3), pp. 209-215

FCM, (1995). "The State of Municipal Infrastructure", report for the federation of Canadian municipalities. Federation of Canadian Municipalities publications, Ottawa Canada, available at McGill University, Montreal Canada.

Fujii, R., Ranalli, A., Aiken, G., Bergamaschi, B., (1998). "Dissolved Organic Carbon Concentrations and Compositions, and Trihalomethane Formation Potentials in Waters from Agricultural Peat Soils, Sacramento-San Joaquin Delta, California: Implications for Drinking-Water Quality", US U.S. Geological Survey, Water-Resources Investigations Report 98–4147.

GAO, the US Government Accountability Office (2002). "Water Infrastructure Information on Financing, Capital Planning, and Privatization", Report to Congressional Requesters, Ref. GAO-02-764.

GAO, the US Government Accountability Office, (2004). "Water Infrastructure, Comprehensive Asset Management Has Potential to Help Utilities Better Identify Needs and Plan Future Investments", Report to the Ranking Minority Member, Committee on Environment and Public Works, U.S. Senate, Ref.GAO-04-46.

Greg, I., (1998). "Protecting Concrete Tanks in Water and Wastewater Treatment Plants", water engineering and management.<http://www.wwdmag.com/Protecting-Concrete-Tanks-in-Water-and-Wastewater-Treatment-Plants-article1180>.

Guild, R., (2000). “Infrastructure Investment and Interregional Development: Theory, Evidence, and Implications for Planning”, Public Works Management& Policy, Vol. 4, pp. 274-285.

Goicoechea, A., Hansen, D., Duckstein,L., (1982). “Multi-Objective Decision Analysis with Engineering and Business Applications”, John Wiley & Sons, New York.

HAPM, (1995). “Lifespan of Building Components”, Technical Note 6, Housing Association Property Manual, June 1995, London (http://www.hapm.co.uk).

Hamed, M., Khalafallah, M., and Hassanein, E., (2004). “Prediction of Wastewater Treatment Plant Performance Using Artificial Neural Network”, Environmental Modeling and Software, Volume.19, pp 919–928.

Han, W., Tsay, W., (1998). “Formulation of Quality Strategy Using Analytic Hierarchy Process”, Twenty Seven Annual Meeting of the Western Decision Science Institute, University of Northern Colorado, USA, pp. 580–583.

Henze, M., Gujer,W., Mino, T., Loosdrecht, M., (2000). “Activated Sludge Models Asm1, Asm2, Asm2d and Asm3”, IWA, UK. (http://www.iwapublishing.com/pdf/contents/isbn1900222248_contents.pdf)

Hong, Y., Rosen, M., Bhamidimarri, R., (2003). “Analysis of A Municipal Wastewater Treatment Plant Using a Neural Network-Based Pattern Analysis”, Water Research 37, 1608–1618.

Hengst, R., (1994). “Concrete Watertight Structures and Hazardous Liquid Containment”, ASCE Press, New York.

Hoff, J., (1986). “Inactivation of microbial agents by chemical disinfectants”, United States Environmental Protection Agency, EPA 600-2-86-067.

Hudson, R., Hass, R., Waheed, U., (1997). “Infrastructure Management, Integrating Design Construction Maintenance Rehabilitation and Renovation”, McGraw Hill, New York, USA.

Hrycej, T., (1992). “Modular learning in Neural Networks”, JohnWiley and Sons Inc., USA.

Hua, G., Yeats, S., (2010). “Control of Trihalomethanes in Wastewater Treatment”, Floridawater Resources Journal April, 2010.

IHS, (2008). “ISO: Standards Aim to Improve Quality of Water Services to Consumers - ISO 24510, 24511, 24512”, January 13, 2008, Published as a news service by IHS. (http://engineers.ihs.com/news/2008/iso-water-services.htm) surfed on May 2008.

Janczukowicz, W., Szewczyk, M., Krzemieniewski, P., (2001). “Settling Properties of Activated Sludge from a Sequencing Batch Reactor (SBR)”, Polish Journal of Environmental Studies Vol. 10, No. 1 (2001), 15-20.

Jin, Y., (2003). "Advanced Fuzzy Systems Design and Applications", A Springer-Verlag Company, New York.

Karunanithi, N., Grenney, W., Whitley, D., Bovee, K., (1994). "Neural Networks for River Flow Prediction", Journal of Computing in civil engineering, ASCE 8(2), pp. 201 -220.

Kleiner, Y., (2001). "Optimal Scheduling of Rehabilitation and Inspection Condition Assessment In Large Buried Pipes", NRCC-44487,fourth international conference on water pipeline systems - managing pipeline assets in an evolving market, pp. 181-197.

Kleiner, Y., Rajani, B., (2002). "Modeling the Deterioration of Water Mains and Planning their Renewal", Infra 2002 International Conference on Urban Infrastructure, Montreal, Quebec.

Keeney, L., Raiffa, H., (1976). "Decision With Multiple Objectives: Preferences and Values Tradeoffs", John Wiley, New York, ISBN: 0521438837.

Kulandaivel, G., (2004). "Sewer Pipeline Condition Prediction using Neural Network Models".M.Sc. theses, Michigan State University, USA.

Kiracofe, B., (2005). "Performance Evaluation of the Town of Monterey Wastewater Treatment Plant Utilizing Subsurface Flow Constructed Wetlands", M.Sc. theses, Faculty of Virginia Polytechnic Institute and State University.

King, W., Marrett, L., (1996). "Case–Control Study of Bladder Cancer and Chlorination By-Products In Treated Water", Cancer Causes Control, 7(6): 596–604.

Kavanaugh, M., Trussell, A., Cromer, J., Trussell, R., (1980). "An Empirical Kinetic Model of Trihalomethane Formation -, an application to meet the proposed THM Standards", AWWA Journal, 72(10) 578-582.

Laurie, S., McNeill, A., Marc, E., (2003). "Degradation of Drinking Water Treatment Plant Infrastructure from Enhanced Coagulation", Journal of Infrastructure Systems, ASCE, December 2003.

Levine, D., (2008). "Statistics for Managers Using Microsoft Excel", Publisher Upper Saddle River, N.J. : Pearson Prentice Hall, c2008.

Liu, J., andVipulanandan, C., (2003). "Modeling Water and Sulfuric Acid Transport through Coated Cement Concrete", ASCE, Journal of Engineering Mechanics, April 2003.

Luong, T., Peters, C., Perry, R., (1982). "Influence of Bromide and Ammonia Upon The Formation of Trihalomethanes Under Water Treatment Conditions", Environment Science technology, 16(8), 473-479.

Matos, R., Cardoso, D., Ashley, R., Molinari, A., Schulz, A., (2002).“Performance Indicators for Wastewater Services- On the Way to a Manual of Best Practice and Its Implementation”, ASCE, 2004 Urban drainage.

Malczewski, J., (1999). “GIS and Multi-criteria Decision Analysis”, New York: John Willey and Sons, Inc.

Mirza, S., Haider, M., (2003). “The State of Infrastructure in Canada: Implications for Infrastructure Planning and Policy”, Infrastructure Canada.

Milde, K., S., W., Wolff, W., Bock E., (1983). “Thiobacilli of the Corroded Concrete Walls of the Hamburg Sewer System”, Journal of general microbiology, London, 129, 1327–133.

Mussati, M., Gernaey, K., Gani R., Jorgensen, S., (2002). “Performance Analysis of A Denitrifying Wastewater Treatment Plant”, Clean Tech. Environment Policy Vol. 4 2002, pp. 171–182.

MOE, Ontario, (2008).“Design Guidelines for Sewage Works”, ISBN 978-1-4249-8438-1, Ministry of the Environment, Ontario, PIBS 6879.

Monteny, J., Vincke, E., Beeldens, A., De Belie, N., Taerwe, L., Van Gemert, D., Verstraete, W., (2000). “Chemical, Microbiological, and In Situ Test Methods for Biogenic Sulfuric Acid Corrosion of Concrete”, Cement and Concrete Research 30, pp. 623- 634.

Montgomery, D., Peck, E., Vining, G., (2006). “Introduction To Linear Regression Analysis”, 4th edition Hoboken, publisher NJ : J. Wiley & Sons.

Mori, T., Nonaka, T., Tazaki, K., Koga, M., Hikosaka, Y.,Noda, S., (1992). “Interactions of Nutrients, Moisture and pHon Microbial Corrosion of Concrete Sewer Pipes”, Water Res. 26 (1) pp. 29– 37.

Mychèle, G., Valérie, G., Donald, O., (2008). “Age of Public Infrastructure -A Provincial Perspective-”, Statistics Canada Report – No. 11-621-MIE2008067.

Najafi, M., Kulandaivel, G., (2005). “Pipeline Condition Predicting Using Neural Network Models”. ASCE Conference Proceeding, Pipelines 2005: Optimizing pipeline Design, Operations, and Maintenance in Today’s Economy, Aug. 21-24, pp.767-781.

Neville, A., (2004). “The Confused World of Sulfate Attack on Concrete”, Cem. Concrete Research; 34(8):1275–96.

NRC, National research Council, (2003a). “Deterioration and Inspection of Water Distribution Systems” - National Guide to Sustainable Municipal Infrastructure, Infra-guide best practice report No. 1.1, April 2003.

NRC, National research Council, (2003b). “Selection of Technologies for Sewer Rehabilitation and Replacement, National guide report, Infraguide best practice report.

NRC, National research Council, (2003c). “Wastewater Treatment Plant Optimization”, best practice publication. Infraguide best practice report.

OMB, (2003). “Performance Measurement Challenges and Strategies”, Program Assessment Rating Tool (PART), Report, presented to the USA government.(June 18, 2003). <http://www.whitehouse.gov/omb/part/challenges_strategies.pdf>.

Papadimitriou, C., (2004). “Bayesian inference applied to structural model updating and damage detection”, ASCE 9th Conference on Probabilistic Mechanics and structural reliability, July 2004.

Pison, G., and Van S., (2004). “Diagnostic Plots for Robust Multivariate Methods”, Journal of Computational and Graphical Statistics, Vol.13, pp. 310–329.

Putnam, D., (2002). “ISO 14031: Environmental Performance Evaluation” .CEA, Altech Environmental Consulting Ltd. Journal of Confederation of Indian Industry.(http://www.altech-group.com/ftp/EPEarticle.pdf).

Pumpen Enginnering, (2009). “Pumping Engineering Group”, an engineering company specialized in water and sewage water management, <http://www.pumpengroup.com/>.

Rajani, B., Kleiner, Y. (2004). “Alternative Strategies for Pipeline Maintenance & Renewal”, AWWA Annual Conference, Orlando, Florida, June 13-17, pp. 1-16.

Pitz, G., McWip, J., (1984). “Decision Analysis for Program Evaluators”, Sage Publications, Beverly Hills.

Qiang, Z., Makram, S., Kai, Z., Daniel, O., Albert, V.,(2006). “Comparison of Biomass Selection Between a Nove Membrane Bioreactor and Activated sludge Process”, Water Environment Foundation. <http://www.environmentalexpert.com/Files%5C5306%5Carticles%5C12679%5C402.pdf>.

Rahman, S., (2007). “Condition Assessment Tool for elements of Drinking Water Treatment Plant”, Master thesis, Building Civil & Environmental Engineering, Concordia University.

Rádulya, B., Gernaeyb, K., Capodaglioa, A.,Mikkelsend, P., Henzed, M., (2007). “Artificial Neural Networks For Rapid WWTP Performance Evaluation: Methodology and Case Study”, Environmental Modeling & Software Volume 22, Issue 8, August 2007, Pages 1208-1216.

Rodriguez, M., Milot, J.,Serodes, J., (2003). “Predicting Trihalomethanes in Chlorinated waters Using Multivariate regression and Neural Networks”, Journal of water Supply Research and Technology- Aqua, 52 (3): 199-215.

Rodriguez, M., S´erodes J., Morin, M., (1998). “Models for THM Formation in Distribution Systems: Development, Evaluation and Application to Quebec Water Utilities”. National forum sur l’eau potable et les eaux us´ees, Ville de Quebec, Canada.

Richardson, S., (2003). “Disinfection By-Products and Other Emerging Contaminants in Drinking Water”, Trends in Analytical Chemistry, Vol. 22, No. 10, 2003.

Ruwanpura, J., Ariaratnam, S., El-Asslay, A., (2003). “Rule Based Simulation Models for Sewer Infrastructure”, Construction research, pp. 1-8.

Saaty, T., (1980). “The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation”, McGraw-Hill, New York.

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

Saaty, T., (1994). “Highlights and Critical Points in the Theory and Application of the Analytical Hierarchy Processes”, European Journal of Operation Research, Vol. 74 pp.426- 447.

Sadiq, R., Kleiner, Y., Rajani, B., (2004). “Fuzzy cognitive maps for decision support to maintain water quality in ageing water mains”,NRCC-47305, DMUCE 4, 4th International Conference on Decision-Making in Urban and Civil Engineering, Porto, Portugal, Oct. 28-30, pp. 1-10.

Salem, S., Berends, D., Heijnen, J., Van L., (2002). “Model-Based Evaluation of a New Upgrading Concept for N-Removal”, Water Science and Technology Volume 45, pp. 169-176.

Sawhney, A., Mund, A., (2002). “Adaptive Probabilistic Neural Network-based Crane Type Selection System”, ASCE, Journal of Construction Engineering and Management, Vol. 128 (3), June 1.

Sharfenaker, M., (2001). “USEPA Offers First Glimpse of Stage 2 D/DBPR”. AWWA Journal, 93(12), 20-34.

Syed, R., (1999). “Wastewater treatment plants: planning, design, and operation”, 2nd edition, publisher: Lancaster, Pa.: Technomic Pub. Co, ISBN 1566766885.

Teksoy, A., Alkan, U., Savas, H., Kaya, B., (2008). “Influence of the Treatment Process Combinations on the Formation of THM Species in Water”, Separation and Purification Technology, 61, 2008, 447–454.

Technology Road Map (2003–2013). “Civil Infrastructure Systems”, a national consensus on preserving Canadian community lifelines.<http://www.engineerscanada.ca /e/files/ TRMReporteng.pdf>.

Thompson, M., (1982). “Decision analysis for program evaluation”, Ballinger publishing company, Massachusetts

Trovato, N., (2008). “Evaluation and Repair of the Deterioration in a Liquid Sulphur Holding Tank”, Case Study.<http://www.rjc.ca/cms/files/Case%20Study%20-%20Evaluation%20and%20Repair%20of%20Deterioration%20in%20a%20Liquid%20Sulphur%20Holding%20Tank.pdf>.

Trussell, R., Umphres, M., (1978). “The Formation of Trihalomethanes”, American Water Works Association Journal (AWWA), 70(11), 604-612.

Tchobanoglous, G., Burton,F., Stensel,H., (2002). “Wastewater Engineering: Treatment and Reuse”, by Metcalf & Eddy Inc, Publisher: McGraw-Hill Education, ISBN 13: 9780071241403 fourth edition, May 1, 2002.

Urquhatr, T., Marlow, D., Burn, S., (2005). “Incorporating Condition Assessment into a Comprehensive Asset Management Program”. <http://www.uimonline.com/index/webapp-stories-action?id=28>.

U.S.F.H.A Department of Transportation, (1999). “Asset Management Primer”, a report submitted to U.S. Department of Transportation, Federal Highway Administration Office of Asset Management.

USFHA, United States Federal Highway Administration, (2002). “Road conditions”, Condition and performance report, USFHA publication. <http://www.fhwa.dot.gov/policy/1999cpr/ch_03/cpm03_3.htm>.

USEPA, (1996).“National Primary Drinking Water Regulations: Disinfectants - Disinfection By-products Proposed Rule”, Federal Register, 59:145:38667

USEPA, United States Environmental Protection Agency, (2002a). “Deteriorating Buried Infrastructure Management Challenges and Strategies”, report prepared for USEPA. <http://www.epa.gov/ogwdw/disinfection/tcr/pdfs/whitepaper_tcr_infrastructure.pdf>.

USEPA, United States Environmental Protection Agency, (2002b). “The Clean Water and Drinking Water Infrastructure Gap Analysis”, EPA publication. http://www.epa.gov/waterinfrastructure/pdfs/report_si_infrastructuregap.pdf.

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

USAID, Jordan, WAJ, (2005). “Assessment of the Upgrading of the Mafraq WWTP-Feasibility Report”. <http://epiq2admin.web.aplus.net/pubs/mafraq_wastewater_assessment.pdf>.

USFHA,United States Federal Highway Administration, (1998). “National Strategic Plan”, <http://www.fhwa.dot.gov/policy/fhplan.html>.

Vanier, D., (1999). “Why Industry Needs Asset Management Tools”, Innovations in Urban Infrastructure. Seminar of the APWA International Public Works Congress, Denver, U.S.A, pp. 11-25.

Vanier, D., (2000). “Asset Management 101: A Primer, Innovations in Urban Infrastructure”, Seminar of the APWA International Public Works Congress, Louisville, KY, U.S.A, pp. 1-14. <http://www.nrc.ca/irc/uir/apwa/apwa2000>.

Vanier, D., Rahman, S., (2004). “Survey on Municipal Infrastructure Assets”, MIIP Report. <http://irc.nrc-cnrc.gc.ca/pubs/fulltext/b5123.2/b5123.2.pdf>.

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

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

Vipulanandan, C., Liu J.,(2002). “Glass-fiber mat-reinforced epoxy coating for concrete in sulfuric acid environment”, Cement and Concrete Research 32, pp.205–210.

Wassermann, P., (1989). “Neural computing: Theory and Practice”, Van Nostrand Reinhold, New York.

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

Weber, M., Borcherding, K., (1993). “Behavioral Problems in Weight Judgments”, European Journal of Operational Research 67 (1993), pp. 1–12.

West, D., and Mangiameli P., (2000), “Identifying process conditions in an urban wastewater treatment plant”, International Journal of Operations & Production Management, Vol. 20 No. 5, 2000, pp. 573-590.

Winterfeldt, D., Ward E., (2007).“ Defining a Decision Analytic Structure”, Cambridge Press, ISBN: 9780511611308, pp. 81-103.

Winnipeg City, (1998). “Strategic Infrastructure Reinvestment Policy”, Report and recommendations, on Strategic Infrastructure Reinvestment Policy, City of Winnipeg, 100 Main Street, Winnipeg, Manitoba, Canada R3C 1A4.

Wu, H., (2008). “A Multi-Objective Decision Support Model for Maintenance and Repair Strategies in Bridges Networks”, PhD Thesis, Columbia University, Graduate School of Art and Science.

Zahidi, F., (1991).“An Introduction to Neural Networks and Comparison with Expert Systems”, Interftices. 21(2), pp. 25-38.

Zayed, T., Halpin, D., (2005).“Pile Construction Productivity Assessment”, ASCE Journal of Construction Engineering and Management, Vol. 131 (6), June 1, pp.705– 714.

Zayed, T., and Halpin, D., (2004). “Quantitative Assessment For Piles Productivity Factors”, ASCE, Journal of Construction Engineering and Management, May 2004.

Zayed, T., Chang L., (2002).“Prototype Model for Build Operate-Transfer Risk Assessment”, ASCE, Journal of Management in Engineering, January 2002.

Appendix A

UNIVERSITÉ Concordia UNIVERSITY — Building, Civil and Environmental Engineering

Survey of Factors Affecting Wastewater Treatment Plant Infrastructure (Tanks, Pipes & Pumps)

Wastewater treatment plant (WWTP) infrastructure deterioration is a function of many interrelated factors.

The objective of this survey is to evaluate and quantify these factors, which will then be used to develop a comprehensive condition rating model for WWTP infrastructure.

Your help in completing this survey will greatly assist in the creation of this new model. I sincerely appreciate the investment of your time and effort.

Altayeb Qasem:
Phd Student
E-mail
a_qasem@encs.concordia.ca

Dr. Tarek Zayed:
Supervisor
Associate Professor
E-mail
zayed@bcee.concordia.ca

Dr. Zhi Chen
Supervisor
Associate Professor
e-mail
zhichen@bcee.concordia.ca

Contact Name (Optional) [ ]

Occupation [ ]

Years of experience [ ]

If you are working in a treatment plant please answer the following (optional)

On a [1- 10] scale how would you rate the plants treatment performance [ ]

On a [1- 10] scale how would you rate the plants infrastructure performance [ ]

Part one : wastewater treament plant main elements

Example

	B	C	D
A	9	1	1 / 7

A is Extremely preferred To

A is Equally preferred to C

D is strongly preferred to A

	Secondary Treatment Phase	Tertiary Treatment Phase
Primary Treatment phase		

	Primary Phase Pump	Primary phase Pipes
Primary Sedimentation Tank		

	Secondary Sedimentation tank	Secondary Phase Reactor Blower	Secondary Sedimentation Pump	Secondary Phase pipes
A.S Reactor				

	Chlorination Phase Tank	Chlorination Phase Pump	Chlorination Phase Pipes
Chlorination Tank			

Part Two : Wastewater Treatment Plant Tanks CR development

This part is used to find out the relative importance of different Factors that affects WWTP Tanks deterioration.

	Physical service stage	Environmental	Operational
Physical Construction Phase			

	Construction Material Quality	Size & Capacity	Tank Shape	Equipment Fixation Method	Tank location (Above or below Surface)
Construction Processes & control					

	Corrosion	Protective Measures	Cracks & Flaws	Degree Of Mechanization
Element Age				

	Influent pH	Vibration	Vibration (Operational)	Weather Conditions
Type of Soil				

	Operational & Maintenance practices	Operator Qualification & Experience	Control System (Flood & operational control)	Treatment Efficiency	WW Influent & Effluent characteristics
Chemical Doses					

Part Three :Wastewater Treatment Plant Pipes CR Development

	Operational	Environmental			
Physical					
	Pipe Diameter	Pipe Length	Pipe Age	Pipe Depth & insulation	Joints & jointing Methods
Pipe Material					
	Influent pH	Vibration	Weather Condition		
Soil Type					
	Operation & Maintenance Practice	Cathodic Protection	Number of Pervious Breaks	WW Characteristics	
Chemical Type & Dose					

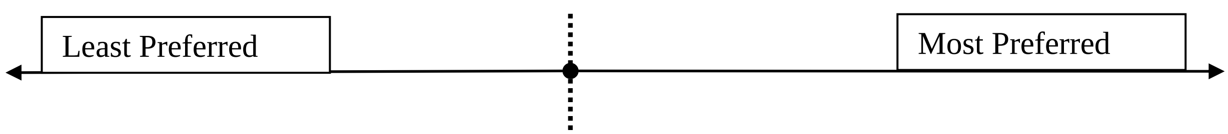
Part Four : Wastewater Treatment Plant Pumps CR development

	Operational	Environmental				
Physical						
	Fixation Method	Size & Capacity	Age	Protective measures	Cavitations	
Pump Type						
	WW Influent Temperature					
Influent pH						
	Number of Operation Failure	Operation & Maintenance Practices	Control System	Operation type (Continuous or	Standby System	WW temperature
Chemical Types & Doses						

Preference Utility value

Part II

In this part while scoring, you are requested to consider all options (consequences) order each of the parameters separately identify the most preferred and the least preferred options for the parameter ***i*** terms of its contribution toward the condition of the element under service life. The most p referred option will be given maximums score on a (**1** to 10) scale the leas preferred one will be given minimum score of **1** on a scale (1-10). Different parameters are assigned different states which are used to measure each parameter preference, the preference measured scale has the values of [1 to 10] where 1 represent the worst state and 10 represent the best state of each parameter. Depending on the nature of selected parameters



1	2	3	4	5	6	7	8	9	10
Extremely Unexpected	*Unexpected*	*Almost unexpected*	*Moderately Unexpected*	*Slightly unexpected*	*Neither Expected nor Unexpected*	*Slightly Expected*	*Moderately Expected*	*Almost Expected*	*Extremely expected*

Preference Utility Level

Preference values (attribute score)

PST Primary sedimentation tank

RT Reaction Tank of the secondary treatment phase

SST Secondary sedimentation tank of the secondary treatment phase

CT Chlorination tank

Tanks $Pv_{(ij)}$ *Values (1-10)*

Factor $w_{(i)}$	**Sub-Factor** $V_{(ij)}$	**Preference Attribute Value (1-10)** $Pv_{(ij)}$ *PST*	*RT*	*SST*	*CT*
Physical (Construction phase)	-Construction processes & control				
	- Typical standard				
	- High standard				
	- Specific Standard				
	-Construction material				
	- Typical material				
	- High quality				
	- Very high quality				
	-Size and capacity				
	- large				
	- Medium				
	- High				
	-Tank shape				
	- Rectangular				
	- Square				
	- Circular				
	-Equipment fixation				
	- Built In				
	- Surface fixed				
	-Tank Location				
	-Totally above the ground				
	- Partially Below the ground				
	- Totally below the ground				
Physical (Service Stage)	-Element age				
	age < 5				
	age>5<10				
	age>10<15				
	age>15<20				
	age>20				
	-Corrosion				
	<5%				
	>5%<10%				
	>10%<20%				
	>20%<25%				
	>25%<30%				
	>30%<40%				
	>40%				

	-Cracks and flaws - non - mild - sever	
	-Protective Measures 1- Water repellant coatings 2- Water repellant and sulfate resisting coatings 3- No coating	
	-Automation level 1- Full automation 2- 50% automation 3- Non automated	
Environment	-Type of soil 1-Silt 2-Clay 3-Sand 4-Rocks	
	- WW influent pH value 1- acidic pH< 7 2- neutral pH= 7 3- alkaline ph>7	
	-Vibration 1- very low 2- low 3- mild	
	-Weather temp 1- -40 to -20 2- -20 to 0 3- 0 to 20 4- 20 to 40	
Operational	-Chemical types and doses 1 - Chlorine 2 - Alum 3 - polymers 4 - Nutrients 5 -others chemicals (please specify)	
	- Aeration Type 1- Surface aeration 2- Diffused aeration	

	- Operation & maintenance 1- Standard short term O&M 2- Log term O&M 3- Reactive M&O	
	- Operator experience 1- >10 years 2- > 5<10 experience 3- <5	
	- Control systems (Operation & flood control) 1 - automatic 2 - semi automatic 3 - manual	

Pumps $Pv_{(ij)}$*Values (1-10)*

Factor $w_{(i)}$	**Sub-Factor** $V_{(ij)}$	**Preference Attribute Value (1-10)** $Pv_{(ij)}$ *PST*	*RT*	*SST*	*CT*
Physical	-Pump type				
	1- Axial				
	2- Centrifugal				
	3- Radial				
	4- Mixed				
	-Installation and Fixation Method				
	1- Pre- fixation				
	2- post-fixation				
	-Size power and capacity				
	1- 500 – 1000 m^3/h				
	2- 1000 – 5000 m^3/h				
	3- >5000 m^3/h				
	-Age (of design life)				
	1- < 25%				
	2- > 25 % < 50 %				
	3- >50%< 75%				
	4- > 75%< 100				
	5- > design age				
	-Coating				
	1- specialized				
	2- Typical				
	3- Non				
	-Cavitations				
	1- Non				
	2- Mild				
	3- severe				
Operational	-Chemical types and doses				
	1-Alum				
	2-Chlorine				
	3-other please specify				
	-Number of operation failure (monthly)				
	1- <5				
	2- >5 <10				
	3- >10				

	- Operation and maintenance procedures 1- short term 2- long term 3- reactive	
	-Control system 1- fully automated 2- semi automated 3- Non automated	
	-Operation type 1- continuous 2- alternating	
	-Stand by system 1- available 2- non available	
Environmental	-Wastewater Influent pH 1- acidic <7 2- neutral =7 3- alkaline >7	
	-WW temperature 1- <4 2- >4<20 3->20<30 4>30	
	-Weather temperature 1- -40 to -20 2- -20 to 0 3- 0 to 20 4- 20 to 40	

Pipes $Pv_{(ij)}$ *Values (1-10)*

Factor $w_{(i)}$	Sub-Factor $V_{(ij)}$	Preference Attribute Value (1-10) $Pv_{(ij)}$ *PST*	*RT*	*SST*	*CT*
Physical	-Pipe material				
	1-Cast Iron				
	2-Ductile Iron				
	3-Asbestos				
	4-Concrete Pipes				
	5-P.V.C				
	6-Polyethylene Pip				
	-Pipe diameters				
	1-<100 mm				
	2- >150 <250mm				
	3- > 250<350mm				
	4- >350 <450mm				
	5- >500 mm				
	-Pipe length				
	1- ≤50 m				
	2- >50 m ≤100 m				
	3- >100 m≤150 m				
	4- >150 m≤300 m				
	5- >300 m				
	-Pipe age				
	1- < 10				
	2- > 10 ≤ 20				
	3- > 20 ≤30				
	4- > 30 ≤ 40				
	5- > 40 ≤ 50				
	6- > 50				
	-Pipe insulation				
	1- heavily insulated				
	2- moderately insulated				
	3 non insulated				
	- Joint types				
	1- standard welded				
	2- standard bolted				
	3- high quality joints				
	4- poor welded joints				
	5- poor bolted joints				

Operational	-Chemical type 1- Lime 2-Alums 3-Polymers 4-chlorine	
	-C factor 1- CF < 40 2- 40 > CF ≤ 60 3- 60 > CF ≤ 80 4- 80 > CF ≤ 100 5- CF > 100	
	- Operation and maintenance practices 1- Preventive 2- Reactive	
	-Cathodic protection 1-available 2-non-available	
	- Number of breaks 1- Frequent 2- High 3- Moderate 4 - Rare	
Environment	- Soil type 1- Highly reactive 2-Reactive aggressive 3- Slightly reactive 4- Non- reactive	
	-WW Influent pH 1- pH < 7 acidic 2- pH= 7 neutral 3- pH > alkaline	
	-Vibration 1- high 2- moderate 3- low	

	-Weather temp. 1- -40 to -20 2- -20 to 0 3- 0 to 20 4- 20 to 40	
	-Ground water table 1- high 2- moderate 3- low	

Appendix B

WWTP Infrastructure Parameter Significance & Preference

Table B-1: WWTP Tanks' Physical (Construction Phase) Parameter Significance and Their Preferences

Category	Parameter	Significant	Preference Value Considered $V_{(ij)}$
Physical (Construction phase)	-Construction processes & control	- Water and wastewater structures must follow specific construction and control codes to enforce their durability.	-Construction processes & control - Typical - High Control - Specific Standard
	-Construction material	- The quality of used construction material is expected to play a major role in the structure durability.	-Construction material - Typical material - High quality - Very high quality
	-Size & capacity	- The structure size affects its construction method and therefore it is expected to be a factor that may affect its durability.	-Size and capacity - large - Medium - High
	-Tank shape	- The shape affects the construction method and material placement. Therefore, the shape can be a factor that affects the durability of the structure and its deterioration.	-Tank shape - Rectangular - Square - Circular
	-Equipment fixation	- Fixation method may affect the durability of the structure and its deterioration.	-Equipment fixation - Built In - Surface fixed
	- Tank Location	-Tanks located above and below the ground surface are subjected to different deterioration mechanisms.	-Tank Location -Totally above the round - Partially Below the ground - Totally below the ground

Table B-2: WWTP Tanks' Physical (Service Stage) Parameter Significance and Their Preferences

Category	Parameter	Significant	Preference Value Considered $V_{(ij)}$
Physical (Service Stage)	-Element age	-Aging is the main deterioration factor.	-Element age age < 5 age>5<10 age>10<15 age>15<20 age>20
	- Corrosion	-Steel corrosion is a serious sign of deterioration, which requires fast remediation action.	-Corrosion <5% >5%<10% >10%<20% >20%<25% >25%<30% >30%<40% >40%
	-Cracks and flaws	-Concrete cracks and its significant is a clear sign of deterioration degree and it may reflect the structure serviceability.	-Cracks and flaws - non - mild - sever
	-Protective Measures	-Applying protection procedures, such as special water repellant and other coating material affect the structure service life.	-Protective Measures 1- Water repellant coatings 2- Water repellant and sulfate resisting coatings 3- No coating
	-Degree of mechanization	- Mechanical equipment and its vibration may affect the durability of the tanks.	-Automation level 1- Full automation 2- 50% automation 3- Non automated

Table B-3: WWTP Tanks' Environmental Parameter Significance and Their Preferences

Category	Parameter	Significant	Preference Value Considered $V_{(ij)}$
Environment	- Type of soil	- Soils physical and chemical and structural characteristics will affect the construction method and will affect the deterioration level of the tanks.	-Type of soil 1-Silt 2-Clay 3-Sand 4-Rocks
	- Vibration	-Vibration caused by pumps, blowers and hydraulic flow can affect the rate of deterioration.	-Vibration 1- very low 2- low 3- mild
	-Weather condition	-Weather temperature cycles and variation affects the durability of tanks specially freeze and thaw attacks.	-Weather temp 1- -40 to -20 2- -20 to 0 3- 0 to 20 4- 20 to 40

Table B-4: WWTP Tanks' Operational Parameter Significance and Their Preferences

Category	Parameter	Significant	Preference Value Considered $V_{(ij)}$
Operational	-Chemical types and doses	-Chemical attacks such as sulfates and chlorine affect the rate deterioration significantly.	-Chemical types and doses 1 - Chlorine 2 - Coagulats 3 - polymers 4 - Nutrients 5 -others chemicals (please specify)
	- Operational and maintenance procedures.	- Maintenance practices and procedures can slow the deterioration rate if applied in the right manner.	- Aeration Type 1- Surface aeration 2- Diffused aeration
	- Operator qualifications	- The operator qualification & experience is a key factor that is related to all operational parameters.	- Operation & maintenance 1- Standard short term O&M 2- Log term O&M 3- Reactive M&O
	- Control systems (Operation & flood control)	- The availability of control systems such as SCADA systems that works on the right time to control the plants main operations and to control floods due to weather variation significantly affects the tanks durability and its performance.	- Operator experience 1- >10 years 2- > 5<10 experience 3- <5
	-Treatment and treatment efficiency	- The treatment process and its efficiency may be a factor that affects the tanks deterioration.	- Control systems (Operation & flood control) 1 - automatic 2 - semi automatic 3 - manual
	- WW influent characteristics	-The chemical composition of the treated water (pH, BOD_5, etc.) will affect the deterioration rate of the tanks mainly pH.	- WW influent pH value 1- acidic pH< 7 2- neutral pH= 7 3- alkaline pH>7

TableB-5: WWTP Pumps' Physical Parameter Significance and Their Preferences

Category	Parameter	Significant	Sub-Factor $V_{(ij)}$
Physical	- Type	-Different pumps types affect the performance and its condition	-Pump type 1- Axial 2- Centrifugal 3- Radial 4- Mixed
	- Installation and Fixation Method	- The fixation method may affect the long-term serviceability of the pump	-Installation and Fixation Method 1- Pre- fixation 2- post-fixation
	- Size power and capacity	- The size and capacity of the pumps must be proportion to the expected hydraulic loads under different conditions.	-Size power and capacity 1- 500 – 1000 m^3/h 2- 1000 – 5000 m^3/h 3- >5000 m^3/h
	- Age	- The pump age is a main factor in its deterioration.	-Age (of design life) 1- < 25% 2- > 25 % < 50 % 3- >50%< 75% 4- > 75%< 100 5- > design age
	- Protective measures	- Protective measures such as power protection and protective coating materials reduce the effect of cavitations	-Coating 1-Specialized 2-Typical 3-Non

TableB-6: WWTP Pumps' Operational Parameter Significance and Their Preferences

Category	Parameter	Significant	Sub-Factor $V_{(ij)}$
Operational	- Number of operation failure	- Number of operation failure reflect the condition of the pumps and may reflect the performance of other parameters too.	-Number of operation failure (monthly) 1- <5 2- >5 <10 3- >10
	- Operation and maintenance procedures	- Proactive maintenance procedures is expected to reduce number of major failures and therefore extend the pump serviceability	- Operation and maintenance procedures 1- short term 2- long term 3- reactive
	- Control system	- Good control systems can help in reducing the impacts of operational sudden variation such as coping with sudden high hydraulic loadings.	-Control system 1- fully automated 2- semi automated 3- Non automated
	- Operation type	- Continuous or alternating operation types have impacts on pumps performance and maintenance procedures.	-Operation type 1- continuous 2- alternating
	- Stand by system	The availability of standby system will give more flexibility for maintenance and operation practices.	-Stand by system 1- available 2- not available

Table B-7: WWTP Pumps' Environmental Parameter Significance and Their Preferences

Category	Parameter	Significant	Sub-Factor $V_{(ij)}$
Environmental	-WW Influent pH	-WW Acidity affects the deterioration rate of pumps due to their corrosive effect over metals	-WW pH 1- acidic <7 2- neutral =7 3- alkaline >7
	- WW influent temperature	-WW influent temperature may influence the cavitation processes in pumps and therefore affect the rate of its deterioration	-WW temperature 1- <4 2- >4<20 3->20<30 4>30
	- Weather temperature	- Weather condition may cause pumps overheating and therefore reduce its efficiency and its service life.	-Weather temperature 1- -40 to -20 2- -20 to 0 3- 0 to 20 4- 20 to 40

Table B-8: WWTP Pipes' Physical Parameter Significance and Their Preferences

Category	Parameter	Significant	Preference Value Considered $V_{(ij)}$
Physical	- Pipe material	- Different type of pipe materials has different deterioration rates.	-Pipe material 1-Cast Iron 2-Ductile Iron 3-Asbestos 4-Concrete Pipes 5-P.V.C 6-Polyethylene Pip
	- Pipe diameters	- Pipes of same material and different diameters have different deterioration rates.	-Pipe diameters 1- dia < 100 mm 2- 150 > dia < 250mm 3- 250 > dia < 350mm 4- 350 > dia < 450mm 5- dia > 500 mm
	- Pipe length	- Pipe length segments can be a factor in pipes deterioration rates.	-Pipe length 1- $l \leq 50$ m 2- $l > 50$ m ≤ 100 m 3- $l > 100$ m ≤ 150 m 4- $l > 150$ m ≤ 300 m 5->300 m
	- Pipe age	- Age is the expected to be a main factor in pipes deterioration	-Pipe age 1- age < 10 2- 10 > age $\leq$ 20 3- 20> age $\leq$ 30 4- 30 > age $\leq$ 40 5- 40> age $\leq$ 50 6- age > 50
	- Pipe depth and insulation	- Pipes depth and insulation has a significant impact in protecting the pipe and therefore reduce its deteriorating rate,	-Pipe insulation 1- heavily insulated 2-moderately insulated 3- non insulated
	- Joint types	-Welded or bolted joints affect the pipes deterioration rates.	- Joint types1- standard welded 2- standard bolted 3- high quality joints 4- poor welded joints 5- poor bolted joints

Table B-9: WWTP Pipes' Operational Parameter Significance and Their Preferences

Category	Parameter	Significant	Preference Value Considered $V_{(ij)}$
Operational	- Chemical type and dose	- Reactive chemicals react with pipe material with time, and therefore affect the pipe deterioration rate.	-Chemical type 1- Lime 2-Alums 3-Polymers 4-chlorine
	- C factor	-The Hazen William coefficient represents the pipe roughness, which reflects the pipe internal condition and its deterioration.	-C factor 1- CF < 40 2- $40 > CF \leq 60$ 3- $60 > CF \leq 80$ 4- $80 > CF \leq 100$ 5- CF > 100
	- Operation and maintenance practices	- Pipes inspection in addition to routine and proactive maintenance procedures expedite pipes deterioration rate.	- Operation and maintenance practices 1- Preventive 2- Reactive
	- Cathodic protection	- The availability of a cathodic protection system, reduce steel pipes deterioration rates significantly.	-Cathodic protection 1-available 2-non-available
	- Number of breaks	- Number of breaks in a pipe segment reflects the interaction of different parameters and the pipe condition.	- Number of breaks 1- Frequent 2- High 3- Moderate 4 - Rare

TableB-10: WWTP Pipes' Environmental Parameter Significance and Their Preferences

Category	Parameter	Significant	Preference Value Considered$V_{(ij)}$
Environment	- Soil type	- Soil types textures and chemical composition is expected to affect the pipes deterioration rate.	- Soil type 1- Highly reactive 2-Reactive aggressive 3- Slightly reactive 4- Non- reactive
	- WW Influent characteristics	- WW influent characteristics is expected to influence the rate of pipes physical and deterioration rates.	-WW pH 1- pH < 7 acidic 2- pH= 7 neutral 3- pH > alkaline
	- Vibration	- Vibration resulted from mechanical equipments may affect pipes joints and therefore affect the breakage rate.	-Vibration 1- high 2- moderate 3- low
	- Weather conditions	- Weather conditions and temperature variations are expected to affect pipe deterioration.	-Weather temp. 1- -40 to -20 2- -20 to 0 3- 0 to 20 4- 20 to 40

Appendix C

THE AHP TECHNIQUE

The Analytical Hierarchy Process (AHP) is a decision making method developed by Saaty (1990). It aims at quantifying relative priorities for a given set of alternatives on a (1 to 9) scale radio, based on the judgment of the experts or decision maker. The consistency of the decisions provided is as important as their decisions, since the consistency of the decisions will show the level of confidence of these decisions to differentiate them from randomness.

The AHP provides a structured simple solution to the decision making problems and quantifies tangible and intangible factors in a systematic way using the pair wise comparison approach.

Saaty (1980) developed the following steps for applying the AHP:

1. Define the problem and determine its goal.

2. Structure the hierarchy from the top (the objectives from a decision-makers viewpoint) through the intermediate levels (criteria on which sub-sequent levels depend) to the lowest level that usually contains the list of alternatives.

3. Construct a set of pair-wise comparison matrices(size n _ n) for each of the lower levels with one matrix for each element in the level immediately above by using the relative scale measurement shown in Table C.1. The pair-wise comparisons are done in terms of which element dominates the other.

Table C.1

1	Equally preferred
2	Equally to moderately
3	Moderately preferred
4	Moderately to strongly
5	Strongly preferred
6	Strongly to very strongly
7	Very strongly preferred
8	Very strongly to extremely
9	Extremely preferred

4. There are n(n-1) judgments (experts decisions to fill the matrix) required to develop the set of matrices in step 3. Reciprocals are automatically assigned in each pair-wise comparison.

5. Based on the pair wise matrix and the scales provided by experts the relative weights are calculated. A sample calculation is presented in Table C.2. The table has the following data: part (I) represent the pair-wise comparison matrix of ABCD alternatives, part (II) shows the calculation of the geometric mean for the values in the rows in the pair-wise comparison matrix. Part (III) shows the calculation of the relative weights of alternatives A, B, C, and D. Parts (IV) and (V) are used to calculate the value of λ_{max}, which is used to calculate the consistency ration shown in the coming step.

Table C.2

	(I)				(II)	(III) Eigenvector (Relative weight)	(IV)	(V)	(VI)
	A	B	C	D	n^{th} root of(ABCD) product values	n^{th} root value / n^{th} root Sum	(I)*(III)	(IV) / (III)	AVG (V) λ_{max}
A	**1**	**1/3**	**1/9**	**1/5**	0.29	0.05	0.20	4.13	4.3
B	**3**	**1**	**1/4**	**1/7**	0.57	0.10	0.42	4.41	
C	**9**	**4**	**1**	**3**	3.22	0.54	2.31	4.25	
D	**5**	**7**	**1/3**	**1**	1.85	0.31	1.41	4.54	
					5.94				

6. Having made all the pair-wise comparisons the next step is to calculate the consistency ratio which is calculated by dividing the consistency index value (CI) by the random consistency index value (CR = CI/RI) ,the RI value is obtained from Table C.3 using the matrix size n. While the CI is calculated using this equation CI =(λmax – n)/ (n -1) where n is the matrix size.

   The CR is acceptable, if it does not exceed 0.10. If it is more, the judgment matrix is inconsistent. To obtain a consistent matrix, judgments should be reviewed and improved accordingly.

Table C.3.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.00	0.00	0.50	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

8. Steps 3 to 6 are repeated to all hierarchy levels

Appendix D

WASTEWATER TREATMENT PERFORMANCE DATA

D.1 Introduction

The following section presents the data collected from three wastewater treatment plants from Canada and the US. These treatment plants are S from Quebec, H from Ontario and P from the US. The treatment performances data of these WWTPs is reorganized in order to satisfy the phase based procedures adopted in this research.

D.2. S WWTP Primary Phase Data

The collected data from S-WWTP presented in this section reorganized to satisfy the phase based approach followed in this study. The first treatment phase is the primary phase; many environmental references refer to this phase as the physical treatment phase which is responsible for the physical removal of suspended solids that can settle by gravity in addition to the removal of floating scum. The primary treatment phase is also responsible for partial BOD_5 removal. Many researchers estimate this partial removal by 35% of the influent BOD_5. The primary treatment phase data of S WWTP is shown in Table D.1

TABLE D.1: Primary Treatment Phase Data

Month	Avg. Flow m^3/d	Avg. pH	Rain (mm)	Influent BOD_5mg/l	Influent SS mg//l	Temp. ºC	Effluent BOD_5mg/l	Effluent SS mg/l
Jan	51853	7.5	47.7	152.0	143	10.8	-	113
Feb.	43989	7.4	13.6	250.0	157	10.9	203	109
Mar.	45903	7.5	18.6	216.0	168	9.9	195	
April	64234	7.5	73.6	148.0	116	10.4	-	94
May	50527	7.6	74.1	261.0	173	15.4	190	95
June	48078	7.6	96.5	308.0	172	19.2	228	85
July	49057	7.6	130.5	228.0	142	21.8	171	74
Aug.	51769	7.7	178.1	228.0	144	21.7	135	103
Sept.	44099	7.6	68.5	288.0	201	22.3	196	114
Oct	44675	7.5	72.6	258.0	179	19.4	181	99
Nov	44217	7.6	56.7	190.0	158	16	121	103
Dec	47257	7.6	63.4	186.0	148	12.2	143	113

D.2.1 S-WWTP Secondary Treatment Phase Data

The secondary treatment phase consists of two main tanks, the reactor (the aerated tank) and the secondary sedimentation tank. In this phase the soluble organic (BOD_5) compounds are oxidized by the microorganisms found in this phase. The secondary treatment phase in an activated sludge system that must maintain F/M balances in the reactor tank to achieve the required oxidation. The secondary sedimentation tank in this phase is designed to store sufficient concentrations of the MLVSS to maintain a specific F/M ratio. The WWTP operator usually controls the F/M ratio by controlling the returned and wasted sludge from the secondary sedimentation tank. The SVI value indicates sludge robustness and settleability, which are used by WWTP operator to control treatment related problems. This data is shown in Table D.2 and Table D.3.

TABLE D.2: Secondary Treatment Phase Data

Month	Avg. Flow m^3/d	pH	Inf. SS mg/l	Inf. VS mg/l	Inf. BOD_5 mg/l	Inf. COD mg/l	Eff. BOD_5 mg/l	Eff. COD mg/l	Eff. SS mg/l	Eff. VS mg/l
Jan	51853	-	113	101	-	-	11.9	52	16.5	13.3
Feb.	43989	7.1	109	121	203	351	15.4	60	14	11.4
Mar.	45903	7.2		125	195	266	23.4	52	13.7	11.7
April	64234	-	94	80	-	-	13.8	56	12.2	10.1
May	50527	7.2	95	121	190	251	12.5	42	13.4	10.7
June	48078	7.3	85	132	228	288	13.9	47	11.9	9.4
July	49057	7.3	74	103	171	244	8.1	44	10.5	7.5
Aug.	51769	7.4	103	111	135	203	10.7	41	14.5	12.1
Sept.	44099	7.3	114	159	196	294	12	42	11.7	8.9
Oct	44675	7.4	99	136	181	282	10.9	44	14.4	10.6
Nov	44217	7.4	103	121	121	241	7.2	43	10.4	7.7
Dec	47257	7.4	113	113	143	257	12	44	8	7.1

TABLE D.3: Reactor and Secondary Sedimentation Tank Data

Settled flow			**Reactor**			**Secondary Sedimentation tank**				
Month	Avg. Flow m3/d	pH	MLSS mg/l	MLVSS mg/l	F/M	SVI ml/g	Qr m3/d	Qw m3/d	MLSSr mg/l	MLVSSr mg/l
Jan	51853	7.0	2965	2380	-	84	22902	28951	8103	6464
Feb.	43989	7.0	3289	2797	0.41	187	22876	21113	7086	6020
Mar.	45903	7.0	2650	2252	0.52	122	22934	22969	5934	5028
April	64234	7.2	2374	1920	-	125	22803	41431	7144	5732
May	50527	7.0	2535	2080	0.6	103	22542	27985	5912	4818
June	48078	6.9	2661	2157	0.65	75	22790	25288	6252	5068
July	49057	7.0	2394	1900	0.57	136	22785	26272	5427	4281
Aug.	51769	7.1	2217	1812	0.5	268	21949	29820	5477	4255
Sept.	44099	7.0	2552	2062	0.57	107	20386	23713	5940	4739
Oct	44675	6.8	2617	2082	0.49	110	18034	26641	6509	5184
Nov	44217	7.0	2318	1910	0.37	78	15843	28374	7544	6125
Dec	47257	7.1	2575	2219	0.39	129	17600	29657	7961	6785

D.2.2 S WWTP Tertiary Treatment Phase Data

Many WWTP dispose their treated effluent into rivers without disinfection it with chlorine since they cannot control the chlorination disinfection byproducts formation, which has a huge impact over marine life. In order to apply the developed CRI for the Tertiary treatment phase, WW samples taken from the secondary effluent from saint Hyacinths WWTP plants were tested in the lab and the results are used to calculate the tertiary treatment phase CRI. These results are shown in the case study section.

D.3 P WWTP Data

The P WWTP is one of the US treatment plants; this WWTP treats wastewater before it is discharged to the Great Miami River. This treatment plant was selected because it is one of the few WWTP that follow the phase based testing approach adopted in this research. The plant reports recorded the removal of 97.45% of the BOD_5, and 95.93 % of the TSS. Although these numbers show that the overall treatment plant' efficiency is high; the developed condition rating methodology showed that the actual treatment performance of each treatment phase has some problems which are discussed in the coming sections. The provided data was reorganized to satisfy the treatment phase's methodology developed in this research.

D.3.1 P- WWTP Primary Treatment Phase Data

The primary treatment phase performance data for P WWTP is shown in Table D.4. Although the rain intensity is provided in the table, however it is has slight impact over the WWTP.

Table D.4: P- WWTP Primary Treatment Phase Data

Month	Avg. Flow m^3/d	Avg. pH	Rain (mm)	Influent BOD_5 mg/l	Influent SS mg//l	Temp. ºC	Effluent BOD_5 mg/l	Effluent SS mg/l
Jan	23258.70	7.4	2.3	110.4	68.7	13.33	73.0	42.0
Feb.	14706.00	7.3	2	174.2	148	11.89	103.3	66.3
Mar.	24032.70	7.1	2.3	165.8	115.8	10.95	119.1	96.2
April	19233.90	7	3.0	155	105.7	12.84	105.6	73.7
May	12577.50	7	3.6	185.7	161.6	15.33	108.2	91.6
June	10603.80	7	3.6	200.7	183.3	18.08	119.9	104.0
July	10487.70	6.9	3.3	203.1	167.3	19.89	129.2	95.5
Aug.	12654.90	6.9	3.0	179.6	140.4	21.38	98.0	60.3
Sept.	11803.50	7	2.5	174.4	149.2	21.41	95.9	54.7
Oct	10216.80	7	2	210.1	173.7	20.59	122.1	62.1
Nov	12306.60	7.1	2.5	205.8	141.5	17.72	122.5	54.9
Dec	20511.00	7.2	2.8	129.2	114.2	14.78	88.1	45.3

D.3.2 P- WWTP Secondary Treatment Phase Data

The secondary treatment phase in P- WWTP is also considered as an activated sludge system. The plants' performance and reports of different tests reflect good operational control concerning various treatment phases within the WWTP. The secondary treatment phase data for P- WWTP are presented in Table D.5 and Table D.6 respectively.

TABLE D.5: P- WWTP Secondary Treatment Phase Data

Month	Avg. Flow m^3/d	pH	Inf. SS mg/l	Inf. BOD5 mg/l	Eff. BOD_5 mg/l	Eff.SS mg/l
Jan	23258.70	7.4	42.0	110.4	3.4	5
Feb.	14706.00	7.3	66.3	174.2	3.6	5.3
Mar.	24032.70	7.1	96.2	165.8	7.1	8.6
April	19233.90	7.0	73.7	155	4	3.4
May	12577.50	7.0	91.6	185.7	3.7	3.8
June	10603.80	7.0	104.0	200.7	6	7.3
July	10487.70	6.9	95.5	203.1	5	7.5
Aug.	12654.90	6.9	60.3	179.6	3.8	3.4
Sept.	11803.50	7.0	54.7	174.4	4.6	3.4
Oct	10216.80	7.0	62.1	210.1	7.5	7.9
Nov	12306.60	7.1	54.9	205.8	4	4.5
Dec	20511.00	7.2	45.3	129.2	3	5

TABLE D.6: P-WWTP Secondary Treatment Phase Data (Cont.)

Settled flow			**Reactor**			**Secondary Sedimentation tank**		
Month	Avg. Flow m^3/d	pH	$MLSS_R$ mg/l	F/M	SVI ml/g	Qr m^3/d	Qw m^3/d	MLSSs mg/l
Jan	23258.70	7.4	1736	0.17	224	8958.60	195408	7703
Feb.	14706.00	7.3	1692	0.16	258	7144.20	196704	9716
Mar.	24032.70	7.1	2021	0.28	153	9072.00	207504	5662
April	19233.90	7.0	1856	0.24	156	7106.40	241776	7389
May	12577.50	7.0	1418	0.19	229	4725.00	240048	5635
June	10603.80	7.0	1667	0.14	226	4309.20	150048	6096
July	10487.70	6.9	1899	0.13	166	5065.20	112176	7244
Aug.	12654.90	6.9	1839	0.12	136	6237.00	113472	7393
Sept.	11803.50	7.0	1700	0.12	121	5896.80	107424	7494
Oct	10216.80	7.0	1612	0.14	91	5443.20	106272	7992
Nov	12306.60	7.1	1916	0.16	139	6728.40	101520	8201
Dec	20511.00	7.2	2216	0.17	143	8996.40	110160	8772

D.3.3 WWTP Tertiary Treatment Phase Data

The Tertiary treatment phase in P- WWTP is used to disinfect the treated effluent before it is discharged into Miami River. The E-coli test, which has the value of coliform forming unit (CFU), is used to test the efficiency of disinfection. The disinfection data for P- WWTP are shown in table D.7

TABLE D.7: WWTP Tertiary Treatment Phase Data

Month	Flow m^3/d	pH	Inf. Temp ^oC	BOD_5 Eff. mg/l	TSS mg/l	Total coliform / 100 ml
Jan.	23258.70	7.4	12.97	3.4	5	0
Feb.	14706.00	7.3	11.05	3.6	5.3	0
March	24032.70	7.1	11.26	25	8.6	0
April	19233.90	7.0	13.25	36	3.4	0
May	12577.50	7.0	16.49	40	3.8	10.6
June	10603.80	7.0	19.8	30	7.3	34.1
July	10487.70	6.9	21.68	10	7.5	35.8
Aug.	12654.90	6.9	23.05	10	3.4	47.4
Sept.	11803.50	7.0	22.35	4.6	3.4	132.2
Oct.	10216.80	7.0	20.97	40	7.9	174.9
Nov.	12306.60	7.1	17.51	4	4.5	0
Dec.	20511.00	7.2	14.23	3	5	0

D.4 H -WWTP Data

H-WWTP is one of Ontario's largest wastewater treatment plants. It was established in the year 1960 with initial capacity of 227,000 m^3/d. The plant was expanded and rehabilitated over the years to its current capacity of 473,000 m^3/d serving a population of 651,000. The plant works under the strict Ontario's MEO environmental rules and regulations because its effluent is released to Lake Ontario which has swimming quality levels.

D.4.1 H-WWTP Primary Treatment Phase Data

The Primary treatment phase of H-WWTP is reorganized to satisfy the phase based methodology developed in this research. The primary treatment date for H-WWTP is show in Table D.8.

Table D8: H-WWTP Primary Treatment Phase Data Summary

Month	**Influent BOD_5 mg/l**	**Influent SS mg//l**	**Effluent BOD_5 mg/l**	**Effluent SS mg/l**
Jan	164	322	117	104
Feb.	170	280	110	100
Mar.	190	380	105	105
April	180	400	120	109
May	175	290	119	110
June	160	350	120	104
July	180	300	118	104
Aug.	190	322	125	109
Sept.	160	325	110	109
Oct.	150	340	105	106
Nov.	160	300	110	100
Dec.	165	150	105	110

D.4.2 H-WWTP Secondary Treatment Phase Data

In order to use the developed equations which are used to calculate the treatment performance of the secondary treatment phase of H-WWTP, the collected data for this phase is illustrated in Table D.9.

D.4.3 H-WWTP Tertiary Treatment Phase Data

The treatment performance of the tertiary (disinfection) treatment phase of H WWTP is determined based on its disinfection efficiency measured by the CFU number in addition to its potential to develop hazardous DBPFP. Therefore, the H WWTP TTP data is reorganized as shown in Table D.10.

Table D.9: H-WWTP Secondary Treatment Phase Data Summary

Month	Influent BOD_5 mg/l	Effluent BOD5 mg/l	$MLVSS_R$ mg/l	SVI ml/g	$MLVSS_S$ mg/l
Jan	164.1	6	1292	60	5676
Feb.	170	5	1300	80	6700
Mar.	166	7.1	1500	70	5040
April	155	6	1300	90	5990
May	180	6.5	1400	78	6112
June	160	7	1450	90	6196
July	168	9	1650	100	6608
Aug.	170	3	1500	90	6781
Sept.	170	6	1600	70	6770
Oct	150	6	1800	60	9026
Nov	170	9	1916	80	8596
Dec	160	9	1700	90	8772

Table D.10: H-WWTP Tertiary Treatment Phase Data

Month	Effluent BOD5 mg/l	CFU / 100 ml Coliform Count
Jan.	6.00	14.00
Feb.	5.00	8.00
March	7.10	0.00
April	6.00	15.00
May	6.50	4.00
June	7.00	0.00
July	9.00	8.00
Aug.	3.00	14.00
Sept.	6.00	13.00
Oct.	6.00	2.00
Nov.	9.00	0.00
Dec.	9.00	0.00

Appendix E

WWTP DETERIORATION SCENARIOS

E.1 Introduction

This section present the deterioration prediction for WWTPs infrastructure units using the different scenarios presented in Chapter V to show the effect of different factors over the WWTP deteriorations.

E.2 Condition Rating of the PTP

PTP CRI .1The deteriorations of different infrastructure units using the second scenario is based on having best utility values for tanks and pumps using PVC pipes in the WWTPS. As shown in Table E.1. The deterioration curve based on this table is shown in figure E.1.

Table E.1: Primary Treatment Phase CR (CRI_{PTP}) For Scenario 2

Tanks Max. Utility Value			**Pipe PVC**		**Pump Max. Utility Value**		**CRI_{PTP}**
Age	CRI	w Tanks	CRI	w Pipe	CRI	w Pump	
0	10.00	0.23	10.00	0.26	10.00	0.50	10.00
5	9.26	0.23	9.21	0.26	8.10	0.50	8.67
10	8.57	0.23	7.59	0.26	6.90	0.50	7.48
15	8.00	0.23	6.35	0.26	5.30	0.50	6.21
20	7.52	0.23	5.44	0.26	4.80	0.50	5.61
25	7.16	0.23	4.67	0.26	4.80	0.50	5.32

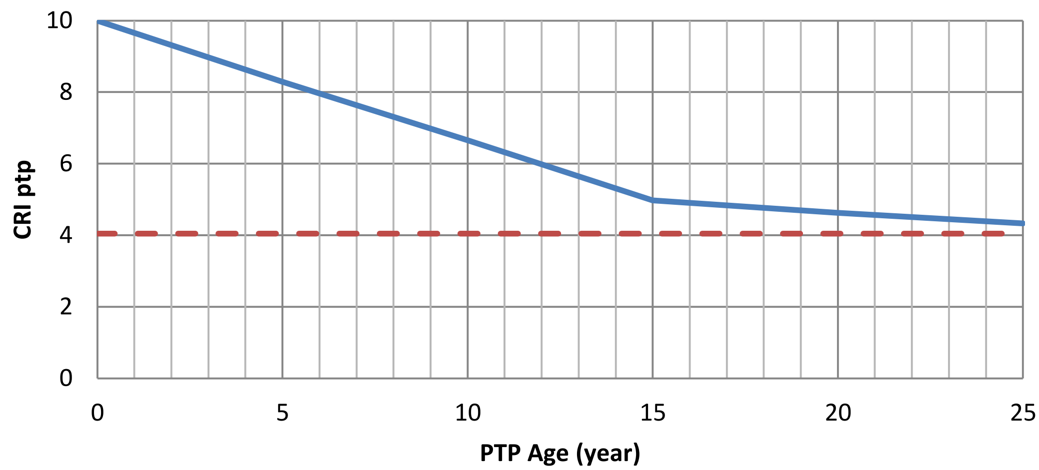


Figure E.1 PTP Deterioration Curve for Scenario 2

The CRI for PTP (CRI_{PTP}) using the third scenario is determined using the maximum utility value for tank CRI and for concrete pipes to calculate the pipes' CRI. The CRI calculations used for this scenario are obtained using the weighted sum as shown in Table E.2. The deterioration curve for this phase using the third scenario is shown in Figure E.2.

TABLE E.2 Primary Treatment Phase CR (CRI_{PTP}) For Scenario3

Tanks Max. Utility Value			**Pipe PVC**		**Pump Max. Utility Value**		**CRI_{PTP}**
Age	CRI	w Tanks	CRI	w Pipe	CRI	w Pump	
0	10.00	0.23	10.00	0.26	10.00	0.50	10.00
5	9.26	0.23	8.71	0.26	8.10	0.50	8.53
10	8.57	0.23	7.10	0.26	6.90	0.50	7.34
15	8.00	0.23	5.85	0.26	5.30	0.50	6.08
20	7.52	0.23	4.95	0.26	4.80	0.50	5.48
25	7.16	0.23	4.18	0.26	4.80	0.50	5.19

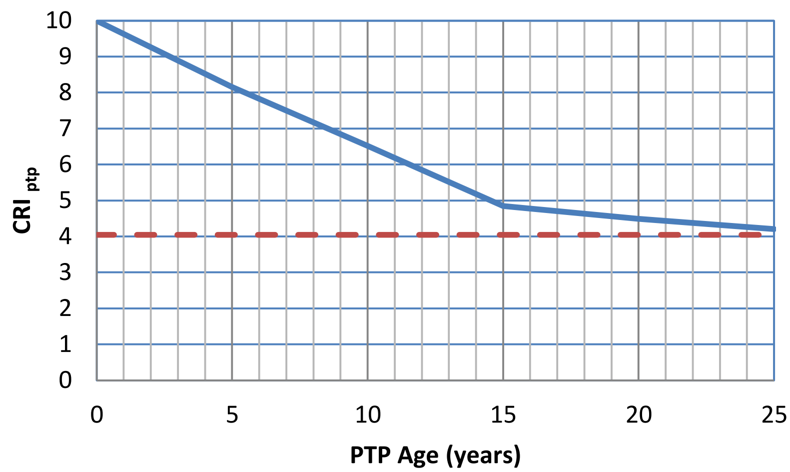


Figure E.2 PTP Deterioration Curve for Scenario 3

The CRI for the PTP (CRI_{PTP}) using the fourth scenario is shown in Table E.3. It is determined using the weighted sum of the CRI of tanks and pumps using the average utility values and using the CRI of PVC pipes. The deterioration curve for this phase using the fourth scenario is shown in Figure E.4

TABLE E.3: Primary Treatment Phase CR (CRI_{PTP}) for Scenario4

Tanks Avg. Utility Value			**Pipe (PVC)**		**Pump Avg. Utility Value**		**CRI_{PTP}**
Age	Score	w tank	Score	w pipe	Score	w pump	
0	10.00	0.23	10.00	0.26	10.00	0.50	10.00
5	7.01	0.23	9.35	0.26	6.20	0.50	7.23
10	6.63	0.23	7.74	0.26	3.60	0.50	5.41
15	6.32	0.23	6.50	0.26	2.10	0.50	4.26
20	6.06	0.23	5.59	0.26	1.60	0.50	3.70
25	5.85	0.23	4.82	0.26	1.50	0.50	3.40

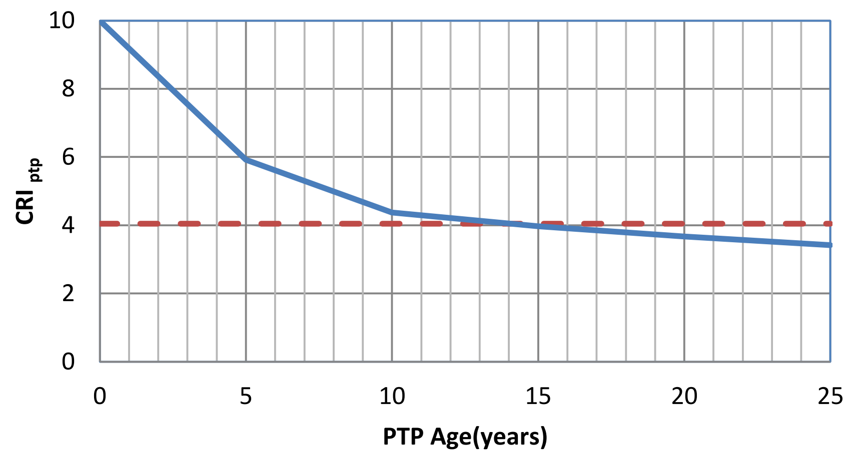


Figure E.4 Ptp Deterioration Curve (Scenario 4)

The CRI for the PTP (CRI_{PTP}) using the fifth scenario is shown in Table E.5.In this scenario, the CRI for tanks and pumps are determined using the average utility values, while the CRI for pipes is determined for cast iron pipes. The deterioration curve for this phase using the fifth scenario is shown in Figure E.5. The graph shows that the CRI of this phase will reach the minimum threshold in year (15). Therefore, WWTP decision makers to plan for WWTP rehabilitation needs can use this information.

TABLE E.5 Primary Treatment Phase CR (CRI_{PTP}) for Scenario5

Tanks Avg. Utility Value			**Pipe Cast Iron**		**Pump Avg. Utility Value**		**CRI_{PTP}**
Age	Score	w. tanks	Score	w. pipe	Score	w. pump	
0	10.00	0.23	10.00	0.26	10.00	0.50	10.00
5	7.01	0.23	9.21	0.26	6.20	0.50	7.19
10	6.63	0.23	7.59	0.26	3.60	0.50	5.37
15	6.32	0.23	6.35	0.26	2.10	0.50	4.22
20	6.06	0.23	5.44	0.26	1.60	0.50	3.67
25	5.85	0.23	4.67	0.26	1.50	0.50	3.36

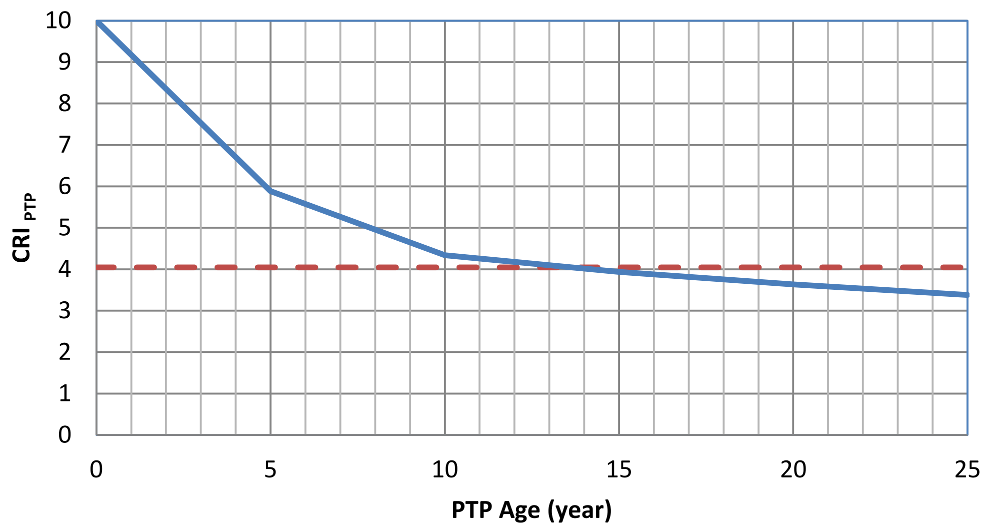


FIGURE E.5: PTP Deterioration Curve for Scenario 5

The CRI for the PTP (CRI_{PTP}) using the sixth scenario is shown in Table E.6 In this scenario, the CRI for tanks and pumps is determined using the average utility values, while the CRI for pipes is determined for concrete pipes. This scenario represents most WWTP conditions preferred by WWTP operators, as most WWTPs need to have major rehabilitation plans for their WWTP in year ten of their operation. The deterioration curve for this phase using the sixth scenario is shown in Figure E.6.

TABLE E.6: Primary Treatment Phase CR (CRI_{PTP}) for Scenario 6

Tanks Avg. Utility Value			**Pipe (Concrete)**		**Pump Avg. Utility Value**		**CRI_{PTP}**
Age	Score	w tanks	Score	w pipe	Score	w pump	
0	10	0.23	10.00	0.26	10.00	0.50	10.00
5	7.01	0.23	8.71	0.26	6.20	0.50	7.06
10	6.63	0.23	7.10	0.26	3.60	0.50	5.24
15	6.32	0.23	5.85	0.26	2.10	0.50	4.08
20	6.06	0.23	4.95	0.26	1.60	0.50	3.53
25	5.85	0.23	4.18	0.26	1.50	0.50	3.23

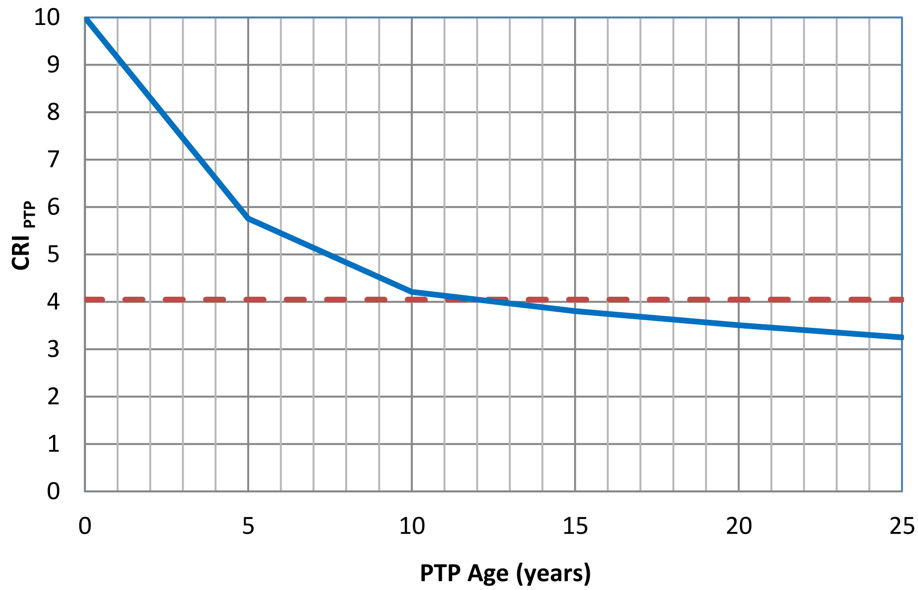


Figure E.6: PTP Deterioration Curve for Scenario 6

E.3 CRI for the Secondary Treatment Phase

The CRI for WWTP STP (CRI_{STP}) is determined using the same six-scenario approach used to calculate the CRI of the primary phase (CRI_{PTP}). Using the first scenario, the CRI_{STP} is determined using the weighted sum of the condition ratings of the secondary sedimentation tank, the reactor tank, the secondary phase pump and secondary phase blower. This is shown in Table E.7. The deterioration curve of this phase based on the first scenario is shown in Figure E.7. This curve shows that this phase will have low deterioration rates because of mild operational conditions with excellent material quality.

TABLE E.7 Secondary Treatment Phase CR (CRI_{STP}) for Scenario (1)

Sedimentation tank Max. Utility Values			Reactor tank Max. Utility Values		Pipe PVC		Pump Max. Utility Value		Blower Max. Utility Value		CRI_{STP}
Age	CRI	w Tank	CRI	w Reactor	CRI	w Pipe	CRI	w Pump	CRI	w Blower	
0.00	10.00	0.08	10.00	0.13	10.00	0.22	10	0.21	10	0.37	10.00
5.00	9.26	0.08	9.25	0.13	9.35	0.22	8.1	0.21	8.1	0.37	8.61
10.00	8.57	0.08	8.56	0.13	7.74	0.22	6.9	0.21	6.9	0.37	7.43
15.00	8.00	0.08	7.99	0.13	6.50	0.22	5.3	0.21	5.3	0.37	6.12
20.00	7.52	0.08	7.51	0.13	5.59	0.22	4.8	0.21	4.8	0.37	5.54
25.00	7.16	0.08	7.15	0.13	4.82	0.22	4.8	0.21	4.8	0.37	5.30

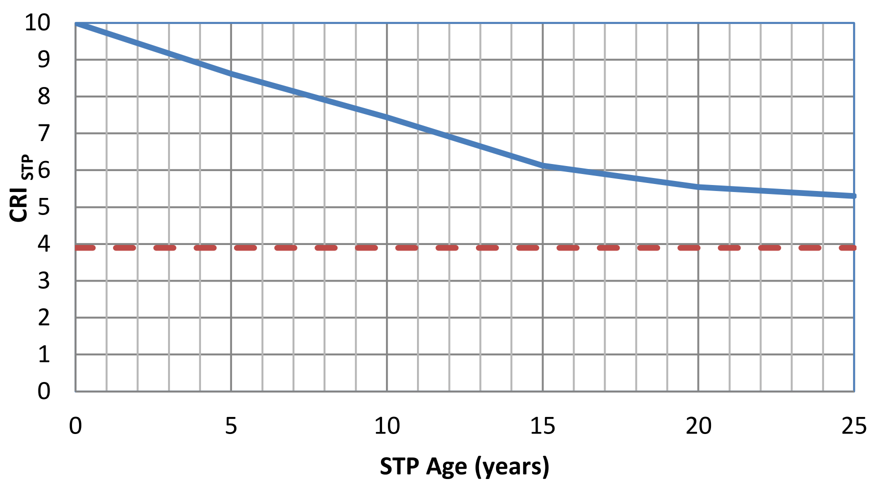


Figure E.7: STP Deterioration Curve (Scenario 1)

Using the second scenario, the CRI_{STP} calculations are shown in Table E.8. The deterioration curve for the second scenario is shown in Figure E.8.This curve shows that the condition rating for this phase will reach the minimum threshold within 25 years, which needs to be addressed by decision makers. This is due to the relatively higher deterioration rates of pipes in this phase.

TABLE E.8: Secondary Treatment Phase CR (CRI_{STP}) for Scenario (2)

Sedimentation tank Max. Utility Values			Reactor tank Max. Utility Values		Cast Iron pipe		Pump Max. utility value		Blower Max. utility value		CRI_{STP}
Age	CRI	w Tank	CRI	w Reactor	CRI	w Pipe	CRI	w Pump	CRI	w Blower	
0	10.00	0.08	10.00	0.13	10.00	0.22	10	0.21	10	0.37	10.00
5	9.26	0.08	9.25	0.13	9.21	0.22	8.1	0.21	8.1	0.37	8.58
10	8.57	0.08	8.56	0.13	7.59	0.22	6.9	0.21	6.9	0.37	7.40
15	8.00	0.08	7.99	0.13	6.35	0.22	5.3	0.21	5.3	0.37	6.09
20	7.52	0.08	7.51	0.13	5.44	0.22	4.8	0.21	4.8	0.37	5.51
25	7.16	0.08	7.15	0.13	4.67	0.22	4.8	0.21	4.8	0.37	5.27

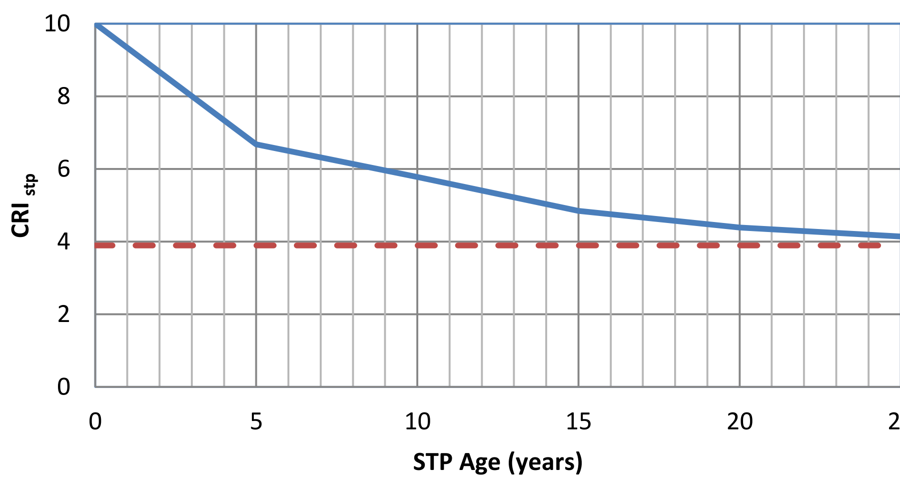


FIGURE E.8 STP Deterioration Curve (Scenario 2)

The CRI for the STP (CRI_{STP}) using the third scenario is determined using the weighted sum of its infrastructure units, as shown in Table E.9The deterioration curve for this phase following the second scenario is shown in Figure E.9.

TABLE E.9: Secondary Treatment Phase CR (CRI_{STP}) for Scenario (3)

Sedimentation Tank Max. Utility Values			Reactor Tank Max. Utility Values		Concrete Pipe		Pump Max. Utility Value		Blower Max. Utility Value		CRI_{STP}
Age	CRI	w Tank	CRI	w Reactor	CRI	w Pipe	CRI	w Pump	CRI	w Blower	
0	10.00	0.08	10.00	0.13	10.00	0.22	10	0.21	10	0.37	10.00
5	9.26	0.08	9.25	0.13	8.71	0.22	8.1	0.21	8.1	0.37	8.47
10	8.57	0.08	8.56	0.13	7.10	0.22	6.9	0.21	6.9	0.37	7.29
15	8.00	0.08	7.99	0.13	5.85	0.22	5.3	0.21	5.3	0.37	5.98
20	7.52	0.08	7.51	0.13	4.95	0.22	4.8	0.21	4.8	0.37	5.40
25	7.16	0.08	7.15	0.13	4.18	0.22	4.8	0.21	4.8	0.37	5.16

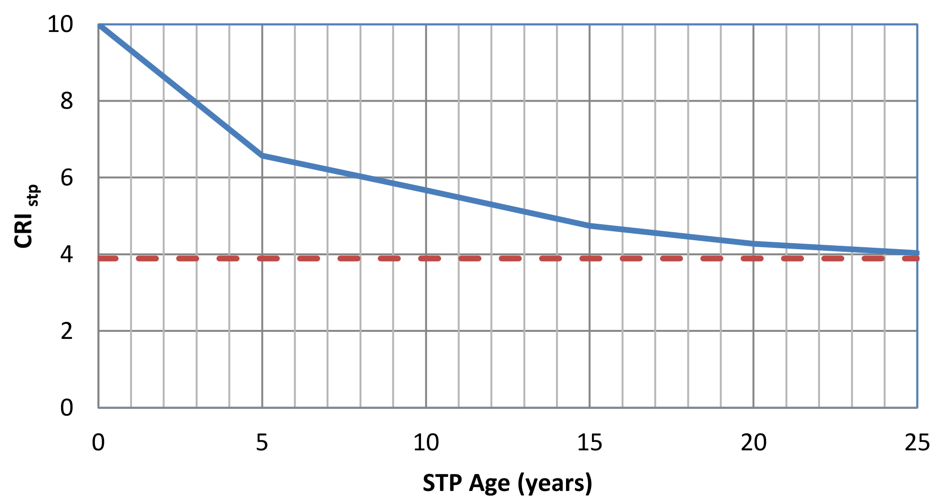


Figure E.9: STP Deterioration Curve (Scenario 3)

The fourth, fifth and the sixth scenarios are based on average utility values for tanks and pumps, but with different pipe materials. The CRI_{STP} calculation for the fourth scenario is shown in Table E.10.The deterioration curve for this phase, following the fourth scenario, is shown in Figure E.10. The concrete pipes affect the deterioration for this scenario, the deterioration of which shows that these concrete pipes need to be rehabilitated or maintained within 20 to 25 years.

TABLE E.10 Secondary Treatment Phase CR (CRI_{STP}) for Scenario (4)

Sedimentation Tank Avg. Utility Value			Reactor Tank Avg. Utility Value		PVC Pipe		Pump Avg. Utility Value		Blower Avg. Utility Value		CRI_{STP}
Age	CRI	w Tank	CRI	w Reactor	CRI	w Pipe	CRI	w Pump	CRI	w Blower	
0	10.00	0.08	10.00	0.13	10.00	0.22	10	0.21	10	0.37	10.00
5	7.01	0.08	9.25	0.13	9.35	0.22	6.2	0.21	8.1	0.37	8.05
10	6.63	0.08	8.56	0.13	7.74	0.22	3.6	0.21	6.9	0.37	6.60
15	6.32	0.08	7.99	0.13	6.50	0.22	2.1	0.21	5.3	0.37	5.34
20	6.06	0.08	7.51	0.13	5.59	0.22	1.6	0.21	4.8	0.37	4.77
25	5.85	0.08	7.15	0.13	4.82	0.22	1.5	0.21	4.8	0.37	4.52

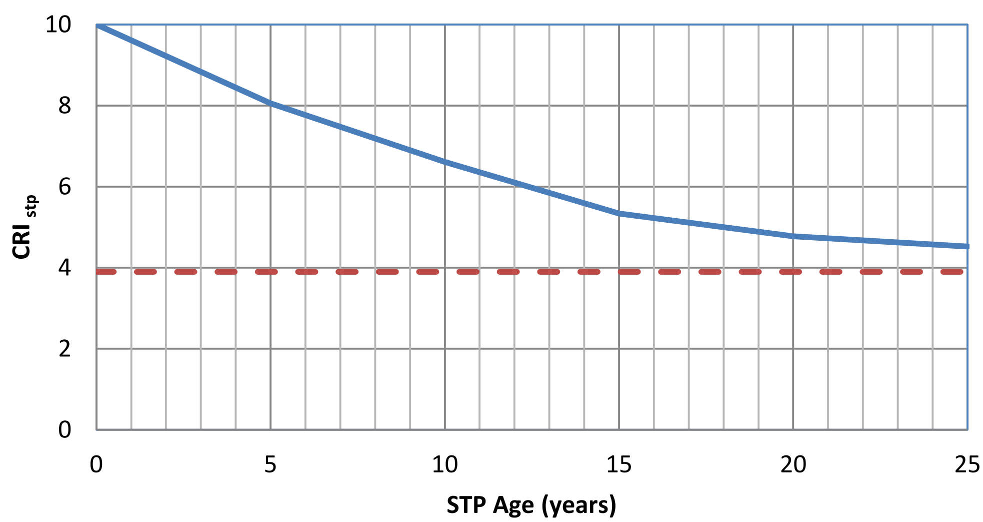


Figure E.10STP Deterioration Curve (Scenario 4)

The CRI_{STP} calculations for the fifth scenario are shown in Table E.11. The deterioration curve for this phase following the fifth scenario is shown in Figure E.11.

TABLE E.11 Secondary Treatment Phase CR (CRI_{STP}) for Scenario (5)

Sedimentation Tank Avg. Utility Value			Reactor Tank Avg. Utility Value		Pipe Cast Iron		Pump Avg. Utility Value		Blower Avg. Utility Value		CRI_{STP}
Age	CRI	w Tank	CRI	w Reactor	CRI	w Pipe	CRI	w Pump	CRI	w Blower	
0	10.00	0.08	10.00	0.13	10.00	0.22	10	0.21	10	0.37	10.00
5	7.01	0.08	9.25	0.13	9.21	0.22	6.2	0.21	8.1	0.37	8.02
10	6.63	0.08	8.56	0.13	7.59	0.22	3.6	0.21	6.9	0.37	6.57
15	6.32	0.08	7.99	0.13	6.35	0.22	2.1	0.21	5.3	0.37	5.30
20	6.06	0.08	7.51	0.13	5.44	0.22	1.6	0.21	4.8	0.37	4.74
25	5.85	0.08	7.15	0.13	4.67	0.22	1.5	0.21	4.8	0.37	4.49

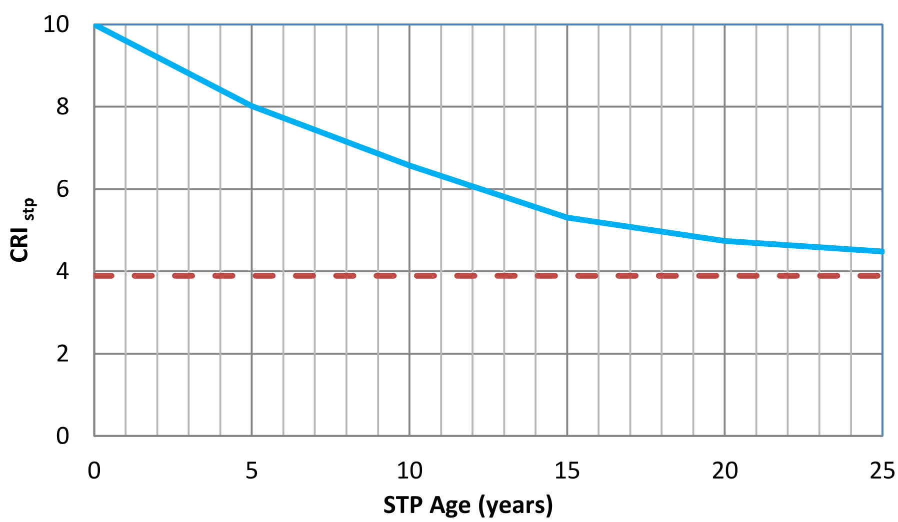


Figure E.11 STP Deterioration Curve (Scenario 5)

The CRI_{STP} calculation for the sixth scenario is shown in Table E.12.The deterioration curve for this phase following the sixth scenario is shown in Figure E.12.

TABLE E.12 Secondary Treatment Phase CR (CRI_{STP}) for Scenario (6)

Sedimentation Tank Avg. Utility Value			Reactor Tank Avg. Utility Value		Concrete Pipe		Pump Avg. Utility Value		Blower Avg. Utility Value		CRI_{STP}
Age	CRI	w Tank	CRI	w Reactor	CRI	w Pipe	CRI	w Pump	CRI	w Blower	
0	10.0	0.08	10.0	0.13	10.00	0.22	10	0.21	10	0.37	10.00
5	7.01	0.08	9.25	0.13	8.71	0.22	6.2	0.21	8.1	0.37	7.91
10	6.63	0.08	8.56	0.13	7.10	0.22	3.6	0.21	6.9	0.37	6.46
15	6.32	0.08	7.99	0.13	5.85	0.22	2.1	0.21	5.3	0.37	5.20
20	6.06	0.08	7.51	0.13	4.95	0.22	1.6	0.21	4.8	0.37	4.63
25	5.85	0.08	7.15	0.13	4.18	0.22	1.5	0.21	4.8	0.37	4.38

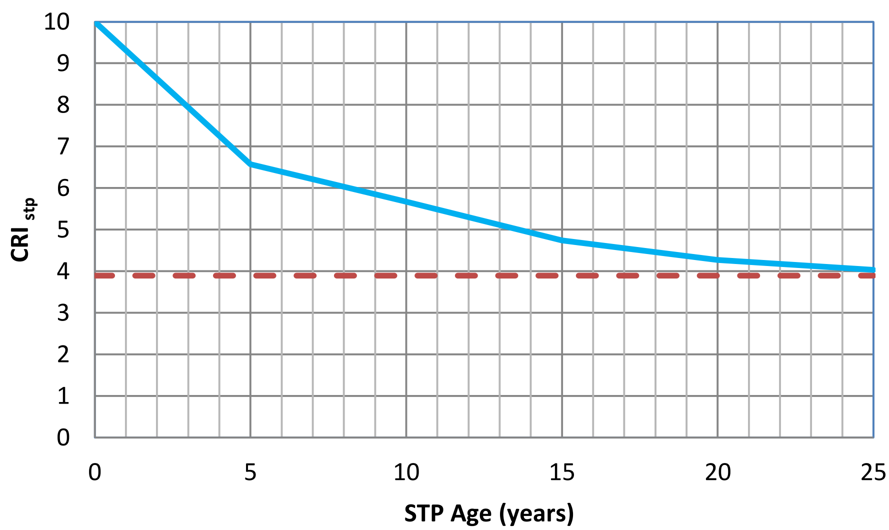


FIGURE E.12: STP Deterioration Curve (Scenario 6)

E.3 CRI for the Tertiary Treatment Phase

The CRI of the tertiary treatment phase (**CRI_{TTP}**)is determined using the weighted sum of its infrastructure units based on the previously mentioned deterioration scenarios. The deterioration of this phase in the presented scenarios is relatively lower than for the other treatment phases for different pipe types for the first three scenarios; however, the deterioration is higher for the fourth, fifth and sixth scenarios because of the pump state. The values of CRI_{TTP} using the first scenario are shown in Table E.13. The deterioration curve for this phase, based on the first scenario, is shown in Figure E.13.

TABLE E.13 Tertiary Treatment Phase CR (CRI_{TTP}) for Scenario (1)

Tank Max Utility Value			Pipe PVC		Pump Max Utility Value		
Age	CRI	w Tank	CRI	w Pipe	CRI	w Pump	CRI_{TTP}
0	10.00	0.29	10.00	0.28	10	0.43	10.00
5	9.26	0.29	9.35	0.28	8.1	0.43	8.95
10	8.57	0.29	7.74	0.28	6.9	0.43	7.86
15	8.00	0.29	6.50	0.28	5.3	0.43	6.80
20	7.52	0.29	5.59	0.28	4.8	0.43	6.20
25	7.16	0.29	4.82	0.28	4.8	0.43	5.83

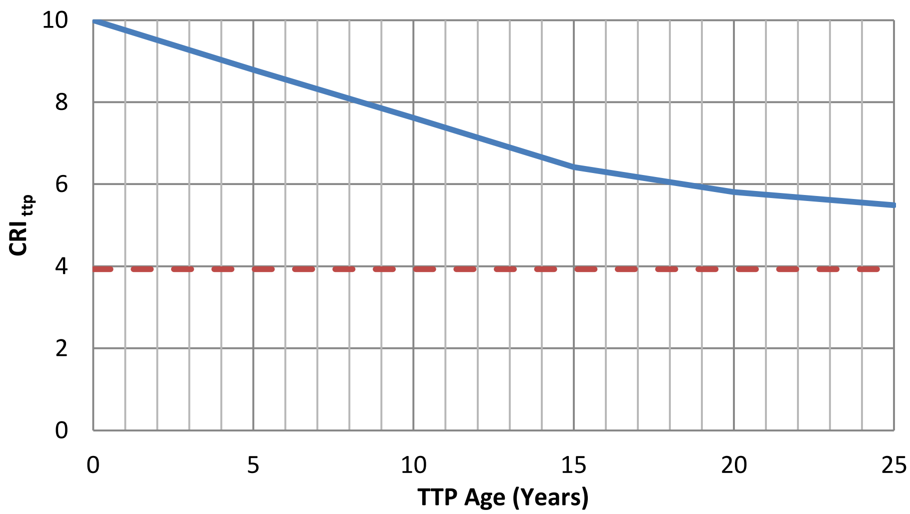


FIGURE E.13: TTP Deterioration Curve (Scenario 1)

The CRI_{TTP} determined using the second scenario is shown in Table E.15. The deterioration curve of this phase using the second scenario is shown in Figure E.15.

TABLE E.15 Tertiary Treatment Phase CR (CRI_{TTP}) for Scenario (2)

Tank Max Utility Value			Pipe Cast Iron		Pump Max Utility Value		
Age	CRI	w Tank	CRI	w Pipe	CRI	w Pump	CRI_{TTP}
0	10.00	0.29	10.00	0.28	10	0.43	10.00
5	9.26	0.29	9.21	0.28	8.1	0.43	8.74
10	8.57	0.29	7.59	0.28	6.9	0.43	7.57
15	8.00	0.29	6.35	0.28	5.3	0.43	6.37
20	7.52	0.29	5.44	0.28	4.8	0.43	5.77
25	7.16	0.29	4.67	0.28	4.8	0.43	5.45

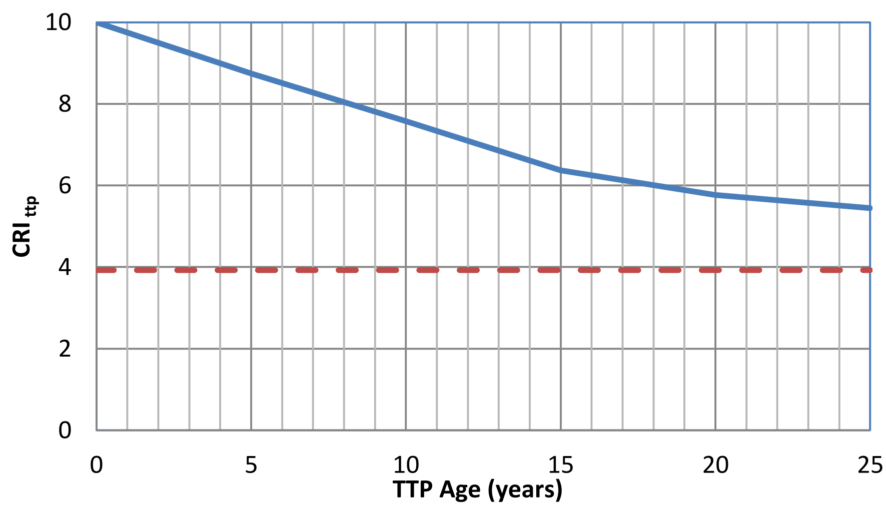


FIGURE E.15 TTP Deterioration Curve (Scenario 2)

The CRI_{ttp} calculations using the third scenario are shown in Table E.16. The deterioration curve for this phase using the third scenario is shown in Figure E.16.

TABLE E.16.Tertiary Treatment Phase CR (CRI_{TTP}) for Scenario (3)

Tank Max Utility Value			**Concrete Pipe**		**Pump Max Utility Value**		
Age	CRI	w Tanks	CRI	w Pipe	CRI	w Pump	CRI_{TTP}
0	10.00	0.29	10.00	0.28	10	0.43	10.00
5	9.26	0.29	8.71	0.28	8.1	0.43	8.60
10	8.57	0.29	7.10	0.28	6.9	0.43	7.44
15	8.00	0.29	5.85	0.28	5.3	0.43	6.23
20	7.52	0.29	4.95	0.28	4.8	0.43	5.63
25	7.16	0.29	4.18	0.28	4.8	0.43	5.31

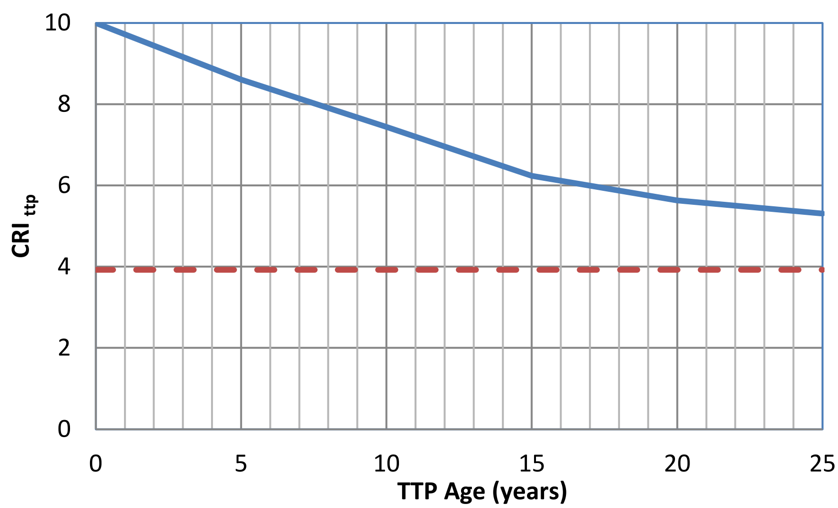


FIGURE E.16: TTP Deterioration Curve (Scenario 3)

The CRI_{ttp} calculations using the fourth scenario are shown in Table E.17. The deterioration curve for this phase using the fourth scenario is shown in Figure E.17.

TABLE E.17 Tertiary Treatment Phase CR (CRI_{TTP}) for Scenario (4)

Tank Avg. Utility Value			**PVC Pipe**		**Pump Avg. Utility Value**		
Age	CRI	w tanks	CRI	w pipe	CRI	w Pump	CRI_{TTP}
0	10.00	0.29	10.00	0.28	10	0.43	10.00
5	7.01	0.29	9.35	0.28	6.2	0.43	7.31
10	6.63	0.29	7.74	0.28	3.6	0.43	5.63
15	6.32	0.29	6.50	0.28	2.1	0.43	4.54
20	6.06	0.29	5.59	0.28	1.6	0.43	4.00
25	5.85	0.29	4.82	0.28	1.5	0.43	3.68

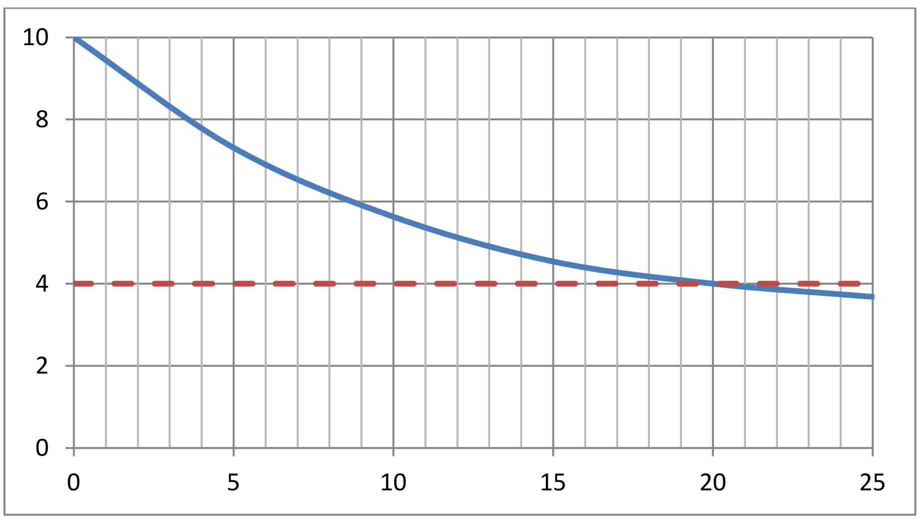


FIGURE E.17: TTP Deterioration Curve for Scenario 4

The CRI_{TTP} calculations using the fifth scenario are shown in Table E.18The deterioration curve for this phase using the fifth scenario is shown in Figure E.18.

TBALE E.18: Tertiary Treatment Phase CR (CRI_{TTP}) for Scenario (5)

Tank Avg. Utility Value			Pipe Cast Iron		Pump Avg. Utility Value		
Age	CRI	w tanks	CRI	w pipe	CRI	w Pump	CRI_{TTP}
0	10.00	0.29	10.00	0.28	10	0.43	10.00
5	7.01	0.29	9.21	0.28	6.2	0.43	7.27
10	6.63	0.29	7.59	0.28	3.6	0.43	5.59
15	6.32	0.29	6.35	0.28	2.1	0.43	4.50
20	6.06	0.29	5.44	0.28	1.6	0.43	3.96
25	5.85	0.29	4.67	0.28	1.5	0.43	3.64

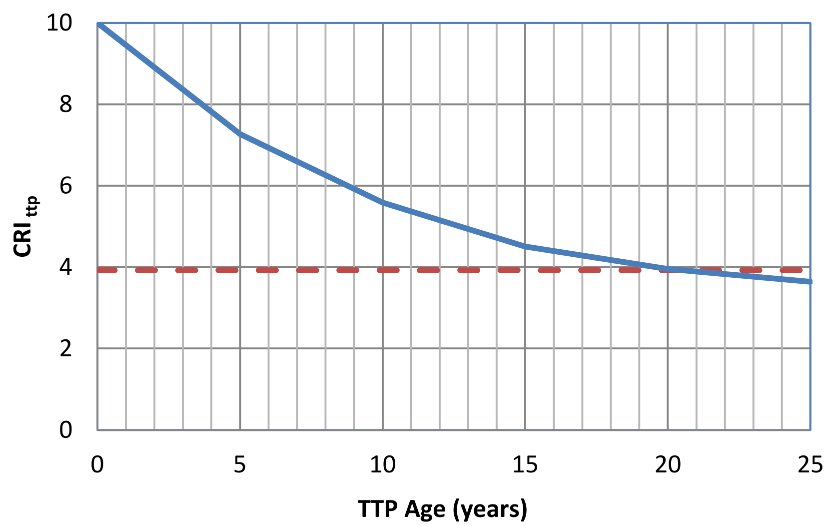


FIGURE E.18: TTP Deterioration Curve (Scenario 5)

The CRI_{TTP} calculations using the sixth scenario are shown in Table E.19. The deterioration curve for this phase, using the sixth scenario is shown in Figure E.19.

TBALE E.19.Tertiary Treatment Phase CR (CRI_{TTP}) for Scenario(6)

Tank Avg. Utility Value			Pipe Concrete		Pump Avg. Utility Value		
Age	CRI	w tanks	CRI	w pipe	CRI	w Pump	CRI_{PTP}
0	10.00	0.29	10.00	0.28	10	0.43	10.00
5	7.01	0.29	8.71	0.28	6.2	0.43	7.13
10	6.63	0.29	7.10	0.28	3.6	0.43	5.45
15	6.32	0.29	5.85	0.28	2.1	0.43	4.36
20	6.06	0.29	4.95	0.28	1.6	0.43	3.82
25	5.85	0.29	4.18	0.28	1.5	0.43	3.50

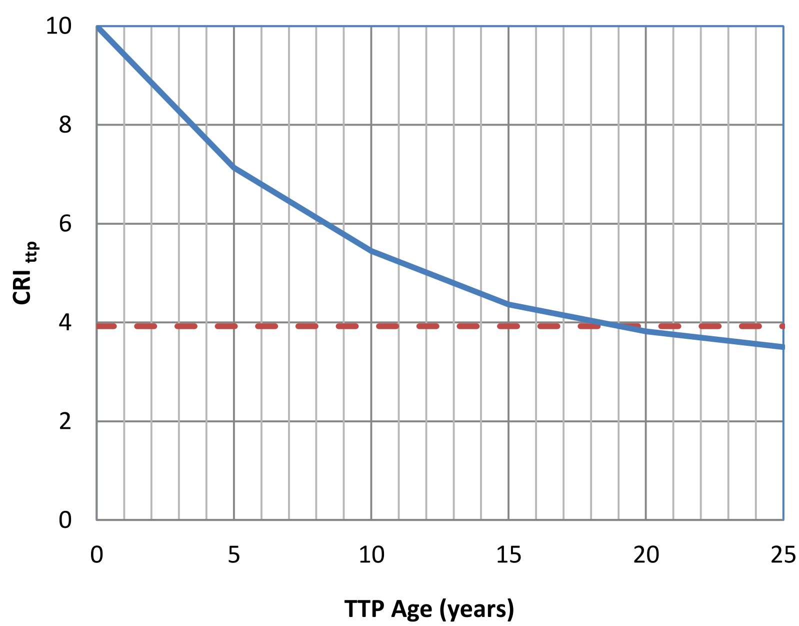


FIGURE E.19: TTP Deterioration Curve for Scenario 6

E.4 CRI for WWTP Infrastructures (CRIIP)

The CRIs of the three treatment phases within a WWTP give the condition rating index of the WWTP infrastructure performance (CRI_{IP}). Therefore, the infrastructure determines the performance of the three treatment phases of the WWTP. The CRI_{IP} is determined using the weighted sum of the condition rating index of the three treatment phases (primary, secondary and tertiary). The weights of each treatment phase are presented in Table 4.4. The relative weight of the primary treatment phase is (0.16) and the lowest among the treatment phases, while the secondary treatment phase has the highest relative weight at (0.6). Finally, the tertiary treatment phase has a relative weight of (0.24). The deterioration curves for WWTPs is developed using the weighted sum of the CRI of each treatment phase for different years along the estimated service life of the WWTP. The CRI_{IP} presented in this section is determined using the six scenarios previously discussed. The CRI_{IP} values using the first scenario are shown in table E.20. The WWTP deterioration curve using this scenario is shown in Figure E.20..

TABLE E.20: WWTP Infrastructure condition rating (CRI_{IP}) for Scenario (1)

Age	**Primary Treatment Phase**		**Secondary Treatment Phase**		**Tertiary Treatment Phase**		**CRI_{IP}**
	CRI	*wp*	CRI	*ws*	CRI	*wt*	
0	10.0	0.16	10.00	0.6	10.00	0.24	10.00
5	9.0	0.16	8.88	0.6	8.95	0.24	8.92
10	8.0	0.16	7.82	0.6	7.86	0.24	7.85
15	7.0	0.16	6.76	0.6	6.80	0.24	6.80
20	6.4	0.16	6.18	0.6	6.20	0.24	6.22
25	6.0	0.16	5.85	0.6	5.83	0.24	5.87

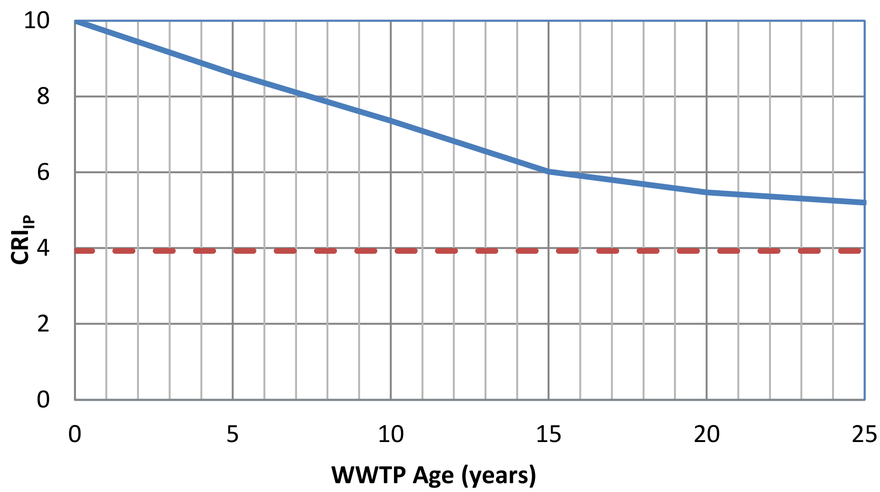


FIGURE E.20 WWTP Deterioration Curve (Scenario 1)

The CRI calculations for the whole WWTP using the second scenario are shown in table E.21 and the deterioration curve for the WWTP using the second scenario is shown in Figure E.21

TABLE E.21WWTP Infrastructure condition rating (CRI_{IP})for Scenario (2)

Age	**Primary Treatment Phase**		**Secondary Treatment Phase**		**Tertiary Treatment Phase**		**CRI_{IP}**
	CRI	*wp*	CRI	*ws*	CRI	*wt*	
0	10.0	0.16	10.00	0.6	10.00	0.24	10.00
5	9.0	0.16	8.85	0.6	8.91	0.24	8.88
10	7.9	0.16	7.79	0.6	7.81	0.24	7.82
15	6.9	0.16	6.72	0.6	6.76	0.24	6.76
20	6.3	0.16	6.15	0.6	6.16	0.24	6.18
25	5.9	0.16	5.82	0.6	5.79	0.24	5.83

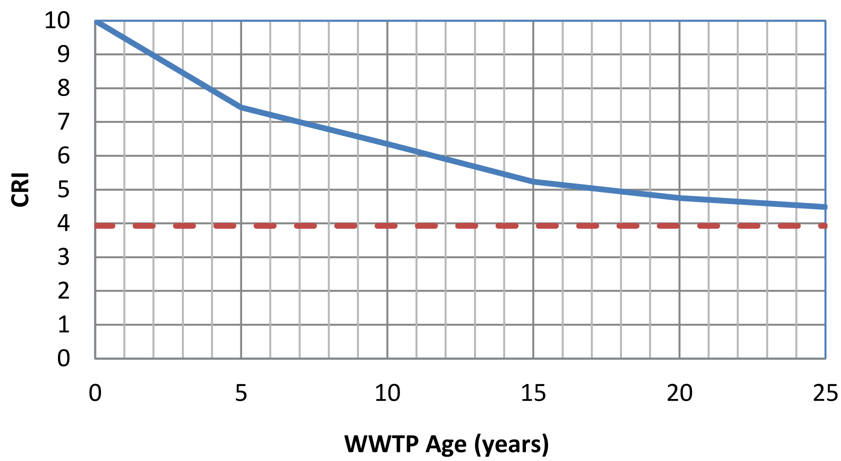


FIGURE E.21: WWTP Deterioration Curve (Scenario 2)

The CRI calculations for the whole WWTP using the third scenario are shown in Table E.22 and the deterioration curve for the WWTP using the third scenario is shown in Figure E.22.

TBALE E.22: WWTP Infrastructure condition rating (CRI_{IP})for Scenario (3)

Age	**Primary Treatment Phase**		**Secondary Treatment Phase**		**Tertiary Treatment Phase**		**CRI_{IP}**
	CRI	*wp*	CRI	*ws*	CRI	*wt*	
0	10.00	0.16	10.00	0.6	10.00	0.24	10.00
5	8.84	0.16	8.74	0.6	8.77	0.24	8.77
10	7.79	0.16	7.68	0.6	7.68	0.24	7.70
15	6.80	0.16	6.62	0.6	6.62	0.24	6.65
20	6.20	0.16	6.04	0.6	6.02	0.24	6.06
25	5.82	0.16	5.71	0.6	5.65	0.24	5.71

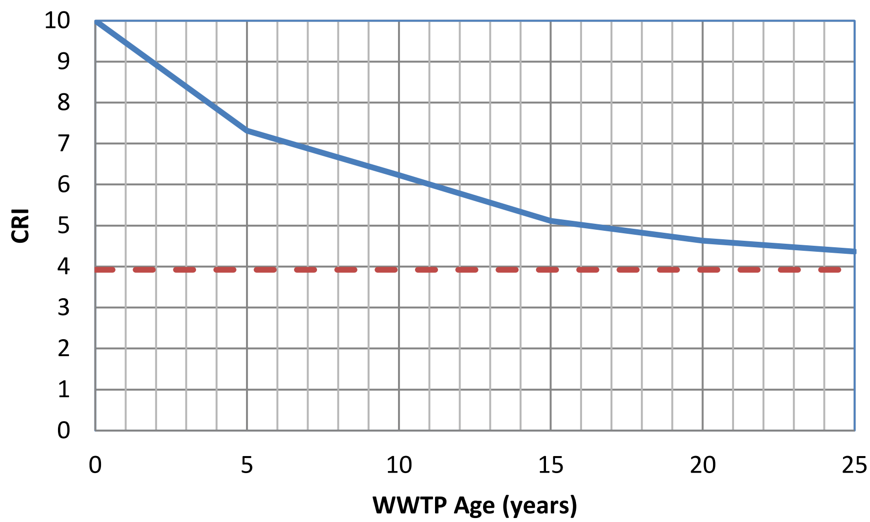


FIGURE E.22 WWTP Deterioration Curve (Scenario 3)

The CRI calculations for the whole WWTP using the fourth scenario are shown in Table 23 and the deterioration curve for the WWTP using the fourth scenario is shown in Figure E.23.

TABLE E.23: WWTP Infrastructure condition rating (CRI_{IP})for Scenario (4)

Age	**Primary Treatment Phase**		**Secondary Treatment Phase**		**Tertiary Treatment Phase**		**CRI_{IP}**
	CRI	*wp*	CRI	*ws*	CRI	*wt*	
0	10.00	0.16	10.00	0.6	10.00	0.24	10.00
5	7.44	0.16	8.32	0.6	7.43	0.24	7.97
10	6.21	0.16	6.99	0.6	6.06	0.24	6.64
15	5.38	0.16	5.97	0.6	5.15	0.24	5.68
20	4.89	0.16	5.41	0.6	4.64	0.24	5.14
25	4.55	0.16	5.07	0.6	4.30	0.24	4.80

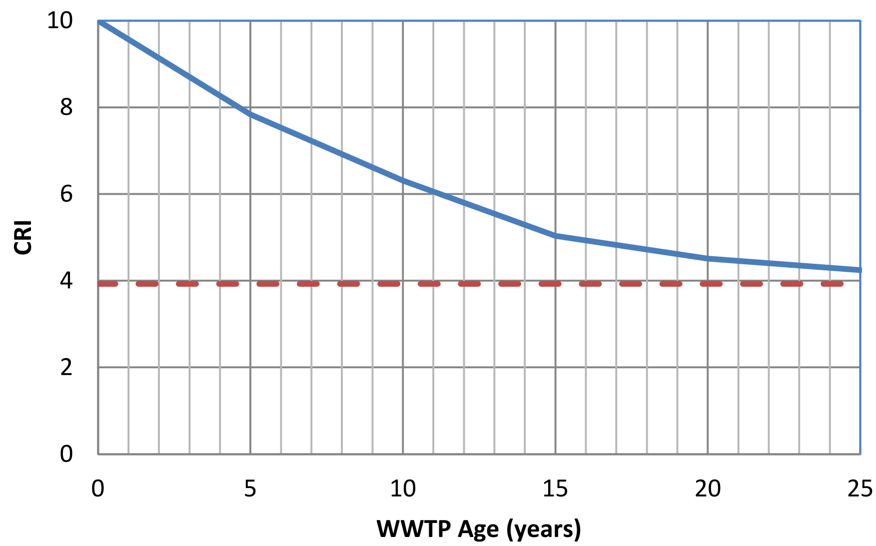


FIGURE E.23: WWTP Deterioration Curve (Scenario 4)

The CRI calculations for the whole WWTP using the fifth scenario are shown in Table E.24 and the deterioration curve for the WWTP using the fifth scenario is shown in Figure E.24

TABLE V.24 WWTP Infrastructure condition rating (CRI_{IP}) for Scenario (5)

Age	**Primary Treatment Phase**		**Secondary Treatment Phase**		**Tertiary Treatment Phase**		**CRI_{IP}**
	CRI	*wp*	CRI	*ws*	CRI	*wt*	
0	10.00	0.16	10.00	0.6	10.00	0.24	10.00
5	7.40	0.16	8.29	0.6	7.39	0.24	7.93
10	6.17	0.16	6.96	0.6	6.02	0.24	6.61
15	5.34	0.16	5.94	0.6	5.11	0.24	5.64
20	4.85	0.16	5.38	0.6	4.60	0.24	5.11
25	4.52	0.16	5.04	0.6	4.26	0.24	4.77

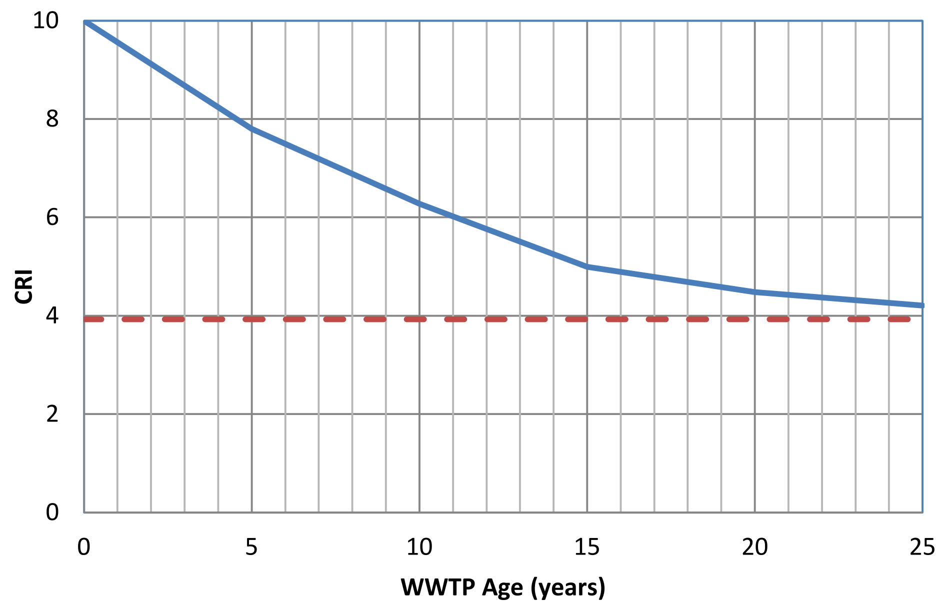


FIGURE E.24: WWTP Deterioration Curve (Scenario 5)

The CRI calculations for the whole WWTP using the sixth scenario are shown in Table E.25 and the deterioration curve for the WWTP using the sixth scenario is shown in Figure E. 25.

TABLE E.25. WWTP Infrastructure condition rating (CRI_{IP})for Scenario (6)

Age	**Primary Treatment Phase**		**Secondary Treatment Phase**		**Tertiary Treatment Phase**		**CRI_{IP}**
	CRI	*wp*	CRI	*ws*	CRI	*wt*	
0	10.00	0.16	10.00	0.6	10.00	0.24	10.00
5	7.27	0.16	8.18	0.6	7.25	0.24	7.81
10	6.04	0.16	6.85	0.6	5.88	0.24	6.49
15	5.21	0.16	5.83	0.6	4.97	0.24	5.52
20	4.72	0.16	5.27	0.6	4.46	0.24	4.99
25	4.38	0.16	4.93	0.6	4.13	0.24	4.65

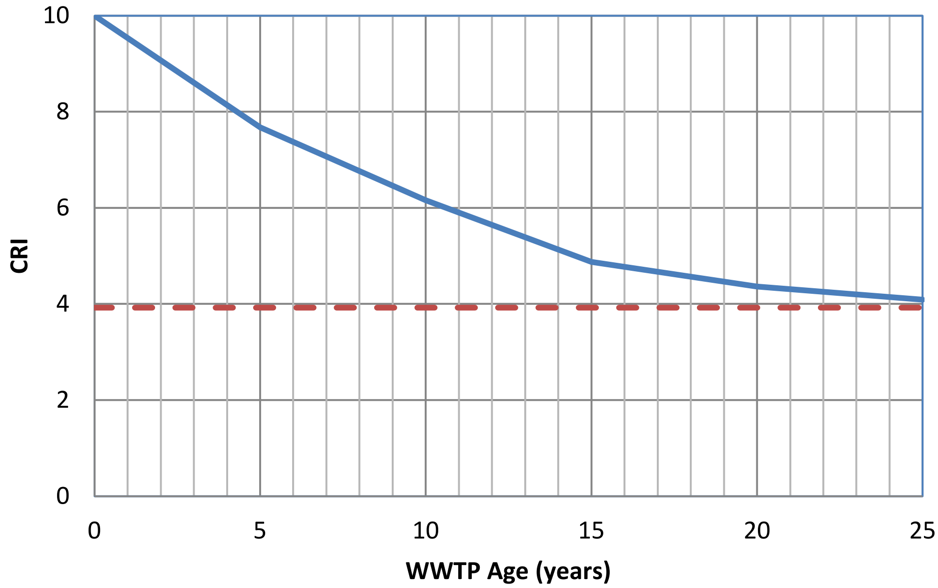


FIGURE E.25: WWTP Deterioration Curve (Scenario 6)

OPTIMIZATION

&

LINGO INPUTS & OUTPUT

F:1. Optimization Overview

The following section present the implementation of the optimization models developed in this study over P WWTP. Unfortunately, because S WWTP has no tertiary treatment phase applying the optimization model will always suggest to “Replace” all the tertiary treatment phase infrastructure units because their condition rating is “0”. The developed optimization models have the flexibility to accommodate all these variation by simply apply the optimization models over each treatment phase separately, however this needs to specify a certain budget for each treatment phase which will have its own assumptions and limitations.

F:2. Condition Rating Maximization

The following section shows the results of the optimization models, their lingo input codes and their lingo output results for different optimization alternatives. The first optimization alternative is to optimize the MR&R and rehabilitation decisions based on maximizing the overall condition ratings (CRI_{IP}) of P WWTP. This optimization is constraints by the MR&R for a 50000CAD budget and the minimum desired condition rating for each infrastructure units, which it set to a value of 6. The optimize decisions for this alternatives are presented in Table F:1. These decisions are highly affected by the rehabilitation budget. To show this effect the same optimization budget is raised from 5000CAD to 100000CAD while keeping the same constraints. The optimized MR&R decisions are shown in Table F:2. The effect of budget difference is shown over each treatment phase and its infrastructure units. Table F:3 shows the budget needed and rehabilitation decisions for P WWTP if the desired minimum condition rating for all infrastructure units is raised to 8. The MR&R for this option is significantly booted to a value of 3618700CAD.This optimization model provide WWTP operators to justify their budget request and can answer the question of "what is the level of improvements can be achieved within a certain budget.

Table F:1 P WWTP MR&R Decisions based on Max CR for a budget of 50000 and CR 6

Treatment Phase	Infrastructure unit	CRI_{IUt}	Min CRI	MR&R Selected	MR&R Cost	CRI_{IUt+1}
Primary Treatment Phase	Primary Sedimentation Tank	6.80	6	Nothing	0	6.732
	Primary phase Pipes	8.50	6	Maintain	2700	9.35
	Primary Phase Pump	7.60	6	Maintain	8000	8.74
	CRI_{PTP}	**7.65**	**6.00**			**8.44**
Secondary Treatment Phase	Secondary Sedimentation tank	6.80	6	Nothing	0	6.732
	A.S Reactor	7.00	6	Nothing	0	6.93
	Secondary Phase pipes	8.50	6	Maintain	2700	9.35
	Secondary Sedimentation Pump	8.60	6	Maintain	8000	9.89
	Secondary Phase Reactor Blower	8.60	6	Maintain	8000	9.89
	CRI_{STP}	**8.31**	**6.06**			**9.23**
Tertiary Treatment Phase	Chlorination Phase Tank	6.80	6	Nothing	0	6.7914
	Chlorination Phase Pipes	8.00	6	Maintain	2700	8.8
	Chlorination Phase Pump	7.70	6	Maintain	8000	8.855
	CRI_{TTP}	**7.52**	**6.00**		**40100**	**8.24**
	CRI_{IP}	**8.01**	**6.04**			**8.86**
Budget					**40100**	

Table F:2 P WWTP MR&R Decisions based on Max CR for a budget of 100000

Treatment Phase	Infrastructure unit	CRI_{IUt}	Min CRI	MR&R Selected	MR&R Cost	CRI_{IUt+1}
Primary Treatment Phase	Primary Sedimentation Tank	6.80	6	Nothing	0	6.732
	Primary phase Pipes	8.50	6	Maintain	2700	9.35
	Primary Phase Pump	7.60	6	Maintain	8000	8.74
	CRI_{PTP}	**7.65**	**6.00**			**8.44**
Secondary Treatment Phase	Secondary Sedimentation tank	6.80	6	Nothing	0	6.732
	A.S Reactor	7.00	6	Nothing	0	6.93
	Secondary Phase pipes	8.50	6	Maintain	2700	9.35
	Secondary Sedimentation Pump	8.60	6	Maintain	8000	9.89
	Secondary Phase Reactor Blower	8.60	6	Maintain	8000	9.89
	CRI_{STP}	**8.31**	**6.06**			**9.23**
Tertiary Treatment Phase	Chlorination Phase Tank	6.80	6	Nothing	0	6.7914
	Chlorination Phase Pipes	8.00	6	Maintain	2700	8.8
	Chlorination Phase Pump	7.70	6	Replace	40000	10
	CRI_{TTP}	**7.52**	**6.00**		**72100**	**8.73**
	CRI_{IP}	**8.01**	**6.04**			**9.0**
Budget					**72100**	

Table F:3 P WWTP MR&R Decisions based on Max CR for Min CR 8

Treatment Phase	Infrastructure unit	CRI_{IUt}	Min CRI	MR&R Selected	MR&R Cost	CRI_{IUt+1}
Primary Treatment Phase	Primary Sedimentation Tank	6.80	8	Replace	900000	10
	Primary phase Pipes	8.50	8	Nothing		8.33
	Primary Phase Pump	7.60	8	Maintain	8000	8.74
	CRI_{PTP}	**7.65**	**8.00**			**8.92**
Secondary Treatment Phase	Secondary Sedimentation tank	6.80	8	Replace	900000	10
	A.S Reactor	7.00	8	Replace	900000	10
	Secondary Phase pipes	8.50	8	Nothing	0	8.33
	Secondary Sedimentation Pump	8.60	8	Nothing	0	8.17
	Secondary Phase Reactor Blower	8.60	8	Nothing	0	8.17
	CRI_{STP}	**8.31**	**8.00**			**8.67**
Tertiary Treatment Phase	Chlorination Phase Tank	6.80	8	Replace	900000	10
	Chlorination Phase Pipes	8.00	8	Maintain	2700	8.8
	Chlorination Phase Pump	7.70	8	Maintain	8000	8.855
	CRI_{TTP}	**7.52**	**8.00**			**9.17**
	CRI_{IP}	**8.01**	**8.00**			**8.84**
Budget					**3618700**	

F:2.1 Lingo Input Code For Maximizing the Condition Rating for a Budget of 50000 and Minimum Condition rating of 6.

```
      Max=  CRIIP;
      CRIIP =((0.14 * PTPCR) + (0.6 * STPCR) + (0.26 * TTPCR));

      pmin_tank   = 0 * X1 + 90000 * X2 +  200000 * X3  + 900000 * X4;
      pmin_tank   = 0 * X1 + 90000 * X2 +  200000 * X3  + 900000 * X4;
      pmin_pipe   = 0 * X5 + 2700  * X6 +  25000  * X7  + 40000  * X8;
      pmin_pump   = 0 * X9 + 8000  * X10 + 25000  * X11 + 40000 * X12;

      smin_tank     = 0 * X13 + 90000 * X14 + 200000 * X15 + 900000 *
X16;
      smin_reactor  = 0 * X17 + 90000 * X18 + 200000 * X19 + 900000 *
X20;
      smin_pipe     = 0 * X21 + 2700  * X22 + 25000 * X23 + 40000  *
X24;
      smin_pump     = 0 * X25 + 8000  * X26 + 25000 * X27 + 40000 *
X28;
      smin_blower   = 0 * X29 + 8000  * X30 + 25000 * X31 + 40000 *
X32;

      tmin_tank = 0 * X33 + 90000 * X34 + 200000 * X35 + 900000 * X36;
      tmin_pipe = 0 * X37 + 2700 * X38 + 25000 * X39 + 40000 * X40;
      tmin_pump = 0 * X41 + 8000 * X42 + 25000 * X43 + 40000 * X44;

      p_TankCR= 6.8; p_PipeCR = 8.5; p_PumpCR =7.6;
      s_TankCR= 6.8; s_reactor=7; s_PipeCR = 8.5; s_PumpCR =8.6;
      s_blower =8.6;    t_TankCR= 6.86; t_PipeCR = 8; t_PumpCR =7.7;

budget =50000;

      pmin_tank + pmin_pump + pmin_pipe + smin_tank + smin_pipe +
      smin_pump + smin_blower+smin_reactor+ tmin_tank + tmin_pipe +
      tmin_pump < = budget;

      Up_TankCR =((p_TankCR * .99) * X1 )+ ((1.1 * p_TankCR)  * X2 ) +
      ((p_TankCR  * 1.6)* X3) + (10 * X4);
      Up_PipeCR =((p_PipeCR * .98) * X5 )+ ((1.1 * p_PipeCR) * X6  ) +
      ((p_PipeCR  * 1.4)* X7) + (10 * X8);
      Up_PumpCR =((p_PumpCR * .95) * X9 )+ ((1.15 * p_PumpCR) * X10 )
      + ((p_PumpCR  * 1.5)* X11) + (10 * X12);

PTPCR = ((0.23 * Up_TankCR) + ( 0.26 * Up_PipeCR) + (0.51 *
Up_PumpCR));

      Us_TankCR  = ((s_TankCR  * .99) * X13 )+ ((1.1 * s_TankCR )  *
      X14 ) + ((s_TankCR  * 1.6)* X15) + (10 * X16);
      Us_reactor = ((s_reactor * .99) * X17 )+ ((1.1 * s_reactor)  *
      X18 ) + ((s_reactor * 1.6)* X19) + (10 * X20);
      Us_PipeCR  = ((s_PipeCR  * .98) * X21 )+ ((1.1 * s_PipeCR )  *
      X22  ) + ((s_PipeCR * 1.4)* X23) + (10 * X24);
      Us_PumpCR  = ((s_PumpCR  * .95) * X25 )+ ((1.15 * s_PumpCR ) *
      X26 ) + ((s_PumpCR * 1.5)* X27) + (10 * X28);
      Us_blower  = ((s_blower  * .95) * X29 )+ ((1.15 * s_blower)  *
      X30 ) + ((s_blower * 1.5)* X31) + (10 * X32);
```

```
 STPCR = (0.08 * Us_TankCR )+ (0.13 * Us_reactor) + (0.22 * Us_PipeCR)
      + (0.21 * Us_PumpCR) + (0.37 * Us_blower);

      Ut_TankCR = ((t_TankCR * .99) * X33 )+ ((1.1  * t_TankCR ) * X34
      ) + ((t_TankCR * 1.6)* X35) + (10 * X36);
      Ut_PipeCR = ((t_PipeCR * .98) * X37 )+ ((1.1  * t_PipeCR ) * X38
      ) + ((t_PipeCR * 1.4)* X39) + (10 * X40);
      Ut_PumpCR =  ((t_PumpCR * .95) * X41 )+ ((1.15 * t_PumpCR ) *
      X42 ) + ((t_PumpCR * 1.5)* X43) + (10 * X44);

      TTPCR =(0.29 * Ut_TankCR) + (0.28 * Ut_PipeCR) + (0.43 *
Ut_PumpCR);

 CRIIP=((0.14 * PTPCR) + (0.6 * STPCR) + (0.26 * TTPCR));

      Up_TankCR > = 6;  Up_TankCR <=10;
      Up_PipeCR > = 6;  Up_PipeCR <=10;
      Up_PumpCR > = 6;  Up_PumpCR <=10;
      Us_TankCR > = 6;  Us_TankCR <=10;
      US_REACTOR > =6;  US_REACTOR <=10;
      Us_PipeCR > = 6;  Us_PipeCR  <=10;
      Us_PumpCR > = 6;  Us_PumpCR <=10;
      Us_blower > = 6;  Us_blower <=10;
      Ut_TankCR > = 6;  Ut_TankCR <=10;
      Ut_PipeCR > = 6;  Ut_PipeCR <=10;
      Ut_PumpCR > = 6;  Ut_PumpCR <=10;

costprimary= pmin_tank + pmin_pump + pmin_pipe;
      costsecondary= smin_tank + smin_reactor + smin_pipe + smin_pump
      + smin_blower;
costtertiary= tmin_tank + tmin_pipe + tmin_pump;
      tcost =costprimary+costsecondary+costtertiary;
      tcost<= budget;

      X1 + X2 + X3 + X4 = 1;
      X5 + X6 + X7 + X8 = 1;
      X9 + X10 + X11 + X12 = 1;
      X13 + X14 + X15 + X16 = 1;
      X17 + X18 + X19 + X20 = 1;
      X21 + X22 + X23 + X24 = 1;
      X25 + X26 + X27 + X28 = 1;
      X29 + X30 + X31 + X32 = 1;
      X33 + X34 + X35 + X36 = 1;
      X37 + X38 + X39 + X40 = 1;
      X41 + X42 + X43 + X44 = 1;

      @bin (x1); @bin( x2);  @bin (x3); @bin ( x4);
      @bin (x5); @bin( x6);  @bin (x7); @bin ( x8);
      @bin (x9); @bin( x10); @bin (x11); @bin ( x12);
      @bin (x13); @bin (x14);  @bin (x15); @bin ( x16);
      @bin (x17); @bin (x18);  @bin (x19); @bin ( x20);
      @bin (x21); @bin (x22);  @bin (x23); @bin ( x24);
      @bin (x25); @bin (x26);  @bin (x27); @bin ( x28);
      @bin (x29); @bin (x30);  @bin (x31); @bin ( x32);
      @bin (x33); @bin (x34);  @bin (x35); @bin ( x36);
      @bin (x37); @bin (x38);  @bin (x39); @bin ( x40);
      @bin (x41); @bin (x42);  @bin (x43); @bin ( x44);
```

F:2.1.1 Lingo Output Code For Maximizing the Condition Rating for a Budget of 50000 and Minimum Condition rating of 6.

```
Global optimal solution found.
Objective value:                              8.863443
Extended solver steps:                               0
Total solver iterations:                             8


                    Variable           Value        Reduced Cost
                       CRIIP        8.863443            0.000000
                       PTPCR        8.436760            0.000000
                       STPCR        9.232660            0.000000
                       TTPCR        8.241156            0.000000
                   PMIN_TANK        0.000000            0.000000
                          X1        1.000000          -0.2167704
                          X2        0.000000          -0.2408560
                          X3        0.000000          -0.3503360
                          X4        0.000000          -0.3220000
                   PMIN_PIPE        2700.000            0.000000
                          X5        0.000000          -0.3032120
                          X6        1.000000          -0.3403400
                          X7        0.000000          -0.4331600
                          X8        0.000000          -0.3640000
                   PMIN_PUMP        8000.000            0.000000
                          X9        0.000000          -0.5155080
                         X10        1.000000          -0.6240360
                         X11        0.000000          -0.8139600
                         X12        0.000000          -0.7140000
                   SMIN_TANK        0.000000            0.000000
                         X13        1.000000          -0.3231360
                         X14        0.000000          -0.3590400
                         X15        0.000000          -0.5222400
                         X16        0.000000          -0.4800000
                SMIN_REACTOR        0.000000            0.000000
                         X17        1.000000          -0.5405400
                         X18        0.000000          -0.6006000
                         X19        0.000000          -0.8736000
                         X20        0.000000          -0.7800000
                   SMIN_PIPE        2700.000            0.000000
                         X21        0.000000           -1.099560
                         X22        1.000000           -1.234200
                         X23        0.000000           -1.570800
                         X24        0.000000           -1.320000
                   SMIN_PUMP        8000.000            0.000000
                         X25        0.000000           -1.029420
                         X26        1.000000           -1.246140
                         X27        0.000000           -1.625400
                         X28        0.000000           -1.260000
                 SMIN_BLOWER        8000.000            0.000000
                         X29        0.000000           -1.813740
                         X30        1.000000           -2.195580
                         X31        0.000000           -2.863800
                         X32        0.000000           -2.220000
                   TMIN_TANK        0.000000            0.000000
                         X33        1.000000          -0.5120716
```

X34	0.000000	-0.5689684
X35	0.000000	-0.8275904
X36	0.000000	-0.7540000
TMIN_PIPE	2700.000	0.000000
X37	0.000000	-0.5707520
X38	1.000000	-0.6406400
X39	0.000000	-0.8153600
X40	0.000000	-0.7280000
TMIN_PUMP	8000.000	0.000000
X41	0.000000	-0.8178170
X42	1.000000	-0.9899890
X43	0.000000	-1.291290
X44	0.000000	-1.118000
P_TANKCR	6.800000	0.000000
P_PIPECR	8.500000	0.000000
P_PUMPCR	7.600000	0.000000
S_TANKCR	6.800000	0.000000
S_REACTOR	7.000000	0.000000
S_PIPECR	8.500000	0.000000
S_PUMPCR	8.600000	0.000000
S_BLOWER	8.600000	0.000000
T_TANKCR	6.860000	0.000000
T_PIPECR	8.000000	0.000000
T_PUMPCR	7.700000	0.000000
BUDGET	50000.00	0.000000
UP_TANKCR	6.732000	0.000000
UP_PIPECR	9.350000	0.000000
UP_PUMPCR	8.740000	0.000000
US_TANKCR	6.732000	0.000000
US_REACTOR	6.930000	0.000000
US_PIPECR	9.350000	0.000000
US_PUMPCR	9.890000	0.000000
US_BLOWER	9.890000	0.000000
UT_TANKCR	6.791400	0.000000
UT_PIPECR	8.800000	0.000000
UT_PUMPCR	8.855000	0.000000
COSTPRIMARY	10700.00	0.000000
COSTSECONDARY	18700.00	0.000000
COSTTERTIARY	10700.00	0.000000
TCOST	40100.00	0.000000

F:2.2 Lingo Input Code For Maximizing the Condition Rating for a Budget of 100000 and Minimum Condition rating of 6.

```
Max=  CRIIP;
      CRIIP =((0.14 * PTPCR) + (0.6 * STPCR) + (0.26 * TTPCR));
      pmin_tank   = 0 * X1 + 90000 * X2 +  200000 * X3  + 900000 * X4;
      pmin_tank   = 0 * X1 + 90000 * X2 +  200000 * X3  + 900000 * X4;
      pmin_pipe   = 0 * X5 + 2700  * X6 +  25000  * X7  + 40000  * X8;
      pmin_pump   = 0 * X9 + 8000  * X10 + 25000  * X11 + 40000 * X12;

smin_tank     = 0 * X13 + 90000 * X14 + 200000 * X15 + 900000 * X16;
smin_reactor  = 0 * X17 + 90000 * X18 + 200000 * X19 + 900000 * X20;
smin_pipe     = 0 * X21 + 2700  * X22 + 25000 * X23 + 40000  * X24;
smin_pump     = 0 * X25 + 8000  * X26 + 25000 * X27 + 40000 * X28;
smin_blower   = 0 * X29 + 8000  * X30 + 25000 * X31 + 40000 * X32;

tmin_tank = 0 * X33 + 90000 * X34 + 200000 * X35 + 900000 * X36;
tmin_pipe = 0 * X37 + 2700 * X38 + 25000 * X39 + 40000 * X40;
tmin_pump = 0 * X41 + 8000 * X42 + 25000 * X43 + 40000 * X44;

p_TankCR= 6.8; p_PipeCR = 8.5; p_PumpCR =7.6;
s_TankCR= 6.8; s_reactor=7; s_PipeCR = 8.5; s_PumpCR =8.6; s_blower
=8.6; t_TankCR= 6.86; t_PipeCR = 8; t_PumpCR =7.7;

budget =100000;

      pmin_tank + pmin_pump + pmin_pipe + smin_tank + smin_pipe +
      smin_pump + smin_blower+smin_reactor+ tmin_tank + tmin_pipe +
      tmin_pump < = budget;

Up_TankCR =((p_TankCR * .99) * X1 )+ ((1.1 * p_TankCR)  * X2 ) +
((p_TankCR  * 1.6)* X3) + (10 * X4);
Up_PipeCR =((p_PipeCR * .98) * X5 )+ ((1.1 * p_PipeCR) * X6  ) +
((p_PipeCR  * 1.4)* X7) + (10 * X8);
Up_PumpCR =((p_PumpCR * .95) * X9 )+ ((1.15 * p_PumpCR) * X10 ) +
((p_PumpCR  * 1.5)* X11) + (10 * X12);

PTPCR = ((0.23 * Up_TankCR) + ( 0.26 * Up_PipeCR) + (0.51 *
      Up_PumpCR));

Us_TankCR  = ((s_TankCR  * .99) * X13 )+ ((1.1 * s_TankCR )  * X14 ) +
((s_TankCR  * 1.6)* X15) + (10 * X16);
Us_reactor = ((s_reactor * .99) * X17 )+ ((1.1 * s_reactor)  * X18 ) +
((s_reactor * 1.6)* X19) + (10 * X20);
Us_PipeCR  = ((s_PipeCR  * .98) * X21 )+ ((1.1 * s_PipeCR )  * X22  )
+ ((s_PipeCR * 1.4)* X23) + (10 * X24);
Us_PumpCR  = ((s_PumpCR  * .95) * X25 )+ ((1.15 * s_PumpCR ) * X26 ) +
((s_PumpCR * 1.5)* X27) + (10 * X28);
Us_blower  = ((s_blower  * .95) * X29 )+ ((1.15 * s_blower)  * X30 ) +
((s_blower * 1.5)* X31) + (10 * X32);

STPCR = (0.08 * Us_TankCR )+ (0.13 * Us_reactor) + (0.22 * Us_PipeCR)
      + (0.21 * Us_PumpCR) + (0.37 * Us_blower);
      Ut_TankCR = ((t_TankCR * .99) * X33 )+ ((1.1  * t_TankCR ) * X34
      ) + ((t_TankCR * 1.6)* X35) + (10 * X36);
```

```
Ut_PipeCR = ((t_PipeCR * .98) * X37 )+ ((1.1  * t_PipeCR ) * X38 ) +
((t_PipeCR * 1.4)* X39) + (10 * X40);
Ut_PumpCR =  ((t_PumpCR * .95) * X41 )+ ((1.15 * t_PumpCR ) * X42 ) +
((t_PumpCR * 1.5)* X43) + (10 * X44);

TTPCR =(0.29 * Ut_TankCR) + (0.28 * Ut_PipeCR) + (0.43 * Ut_PumpCR);

CRIIP=((0.14 * PTPCR) + (0.6 * STPCR) + (0.26 * TTPCR));

      Up_TankCR > = 6;  Up_TankCR <=10;
      Up_PipeCR > = 6;  Up_PipeCR <=10;
      Up_PumpCR > = 6;  Up_PumpCR <=10;
      Us_TankCR > = 6;  Us_TankCR <=10;
      US_REACTOR > = 6; US_REACTOR <=10;
      Us_PipeCR > = 6;  Us_PipeCR  <=10;
      Us_PumpCR > = 6;  Us_PumpCR <=10;
      Us_blower > = 6;  Us_blower <=10;
      Ut_TankCR > = 6;  Ut_TankCR <=10;
      Ut_PipeCR > = 6;  Ut_PipeCR <=10;
      Ut_PumpCR > = 6;  Ut_PumpCR <=10;


costprimary= pmin_tank + pmin_pump + pmin_pipe;

costsecondary= smin_tank + smin_reactor + smin_pipe + smin_pump +
smin_blower;

costtertiary= tmin_tank + tmin_pipe + tmin_pump;

      tcost =costprimary+costsecondary+costtertiary;

      tcost<= budget;

      X1 + X2 + X3 + X4 = 1;
      X5 + X6 + X7 + X8 = 1;
      X9 + X10 + X11 + X12 = 1;
      X13 + X14 + X15 + X16 = 1;
      X17 + X18 + X19 + X20 = 1;
      X21 + X22 + X23 + X24 = 1;
      X25 + X26 + X27 + X28 = 1;
      X29 + X30 + X31 + X32 = 1;
      X33 + X34 + X35 + X36 = 1;
      X37 + X38 + X39 + X40 = 1;
      X41 + X42 + X43 + X44 = 1;

      @bin (x1); @bin( x2);  @bin (x3); @bin ( x4);
      @bin (x5); @bin( x6);  @bin (x7); @bin ( x8);
      @bin (x9); @bin( x10); @bin (x11); @bin ( x12);
      @bin (x13); @bin (x14);  @bin (x15); @bin ( x16);
      @bin (x17); @bin (x18);  @bin (x19); @bin ( x20);
      @bin (x21); @bin (x22);  @bin (x23); @bin ( x24);
      @bin (x25); @bin (x26);  @bin (x27); @bin ( x28);
      @bin (x29); @bin (x30);  @bin (x31); @bin ( x32);
      @bin (x33); @bin (x34);  @bin (x35); @bin ( x36);
      @bin (x37); @bin (x38);  @bin (x39); @bin ( x40);
      @bin (x41); @bin (x42);  @bin (x43); @bin ( x44);
```

F:2.2.1 Lingo output Code For Maximizing the Condition Rating for a Budget of 100000 and Minimum Condition rating of 6.

```
Global optimal solution found.
Objective value:                              8.991454
Extended solver steps:                               0
Total solver iterations:                            45
```

Variable	Value	Reduced Cost
CRIIP	8.991454	0.000000
PTPCR	8.436760	0.000000
STPCR	9.232660	0.000000
TTPCR	8.733506	0.000000
PMIN_TANK	0.000000	0.000000
X1	1.000000	-0.2167704
X2	0.000000	-0.2408560
X3	0.000000	-0.3503360
X4	0.000000	-0.3220000
PMIN_PIPE	2700.000	0.000000
X5	0.000000	-0.3032120
X6	1.000000	-0.3403400
X7	0.000000	-0.4331600
X8	0.000000	-0.3640000
PMIN_PUMP	8000.000	0.000000
X9	0.000000	-0.5155080
X10	1.000000	-0.6240360
X11	0.000000	-0.8139600
X12	0.000000	-0.7140000
SMIN_TANK	0.000000	0.000000
X13	1.000000	-0.3231360
X14	0.000000	-0.3590400
X15	0.000000	-0.5222400
X16	0.000000	-0.4800000
SMIN_REACTOR	0.000000	0.000000
X17	1.000000	-0.5405400
X18	0.000000	-0.6006000
X19	0.000000	-0.8736000
X20	0.000000	-0.7800000
SMIN_PIPE	2700.000	0.000000
X21	0.000000	-1.099560
X22	1.000000	-1.234200
X23	0.000000	-1.570800
X24	0.000000	-1.320000
SMIN_PUMP	8000.000	0.000000
X25	0.000000	-1.029420
X26	1.000000	-1.246140
X27	0.000000	-1.625400
X28	0.000000	-1.260000
SMIN_BLOWER	8000.000	0.000000
X29	0.000000	-1.813740
X30	1.000000	-2.195580
X31	0.000000	-2.863800
X32	0.000000	-2.220000
TMIN_TANK	0.000000	0.000000

X33	1.000000	-0.5120716
X34	0.000000	-0.5689684
X35	0.000000	-0.8275904
X36	0.000000	-0.7540000
TMIN_PIPE	2700.000	0.000000
X37	0.000000	-0.5707520
X38	1.000000	-0.6406400
X39	0.000000	-0.8153600
X40	0.000000	-0.7280000
TMIN_PUMP	40000.00	0.000000
X41	0.000000	-0.8178170
X42	0.000000	-0.9899890
X43	0.000000	-1.291290
X44	1.000000	-1.118000
P_TANKCR	6.800000	0.000000
P_PIPECR	8.500000	0.000000
P_PUMPCR	7.600000	0.000000
S_TANKCR	6.800000	0.000000
S_REACTOR	7.000000	0.000000
S_PIPECR	8.500000	0.000000
S_PUMPCR	8.600000	0.000000
S_BLOWER	8.600000	0.000000
T_TANKCR	6.860000	0.000000
T_PIPECR	8.000000	0.000000
T_PUMPCR	7.700000	0.000000
BUDGET	100000.0	0.000000
UP_TANKCR	6.732000	0.000000
UP_PIPECR	9.350000	0.000000
UP_PUMPCR	8.740000	0.000000
US_TANKCR	6.732000	0.000000
US_REACTOR	6.930000	0.000000
US_PIPECR	9.350000	0.000000
US_PUMPCR	9.890000	0.000000
US_BLOWER	9.890000	0.000000
UT_TANKCR	6.791400	0.000000
UT_PIPECR	8.800000	0.000000
UT_PUMPCR	10.00000	0.000000
COSTPRIMARY	10700.00	0.000000
COSTSECONDARY	18700.00	0.000000
COSTTERTIARY	42700.00	0.000000
TCOST	72100.00	0.000000

F:2.3 Lingo Input Code For Maximizing the Condition Rating for a Minimum Condition rating of 8.

```
Max=  CRIIP;
      CRIIP =((0.14 * PTPCR) + (0.6 * STPCR) + (0.26 * TTPCR));
pmin_tank   = 0 * X1 + 90000 * X2 +  200000 * X3  + 900000 * X4;
pmin_tank   = 0 * X1 + 90000 * X2 +  200000 * X3  + 900000 * X4;
pmin_pipe   = 0 * X5 + 2700  * X6 +  25000  * X7  + 40000  * X8;
pmin_pump   = 0 * X9 + 8000  * X10 + 25000  * X11 + 40000 * X12;

smin_tank     = 0 * X13 + 90000 * X14 + 200000 * X15 + 900000 * X16;
smin_reactor  = 0 * X17 + 90000 * X18 + 200000 * X19 + 900000 * X20;
smin_pipe     = 0 * X21 + 2700  * X22 + 25000 * X23 + 40000  * X24;
smin_pump     = 0 * X25 + 8000  * X26 + 25000 * X27 + 40000 * X28;
smin_blower   = 0 * X29 + 8000  * X30 + 25000 * X31 + 40000 * X32;

tmin_tank = 0 * X33 + 90000 * X34 + 200000 * X35 + 900000 * X36;
tmin_pipe = 0 * X37 + 2700 * X38 + 25000 * X39 + 40000 * X40;
tmin_pump = 0 * X41 + 8000 * X42 + 25000 * X43 + 40000 * X44;


p_TankCR= 6.8; p_PipeCR = 8.5; p_PumpCR =7.6;
s_TankCR= 6.8; s_reactor=7; s_PipeCR = 8.5; s_PumpCR =8.6; s_blower
=8.6; t_TankCR= 6.86; t_PipeCR = 8; t_PumpCR =7.7;

budget =3620000;

pmin_tank + pmin_pump + pmin_pipe + smin_tank + smin_pipe + smin_pump
+ smin_blower+smin_reactor+ tmin_tank + tmin_pipe + tmin_pump < =
budget;

Up_TankCR =((p_TankCR * .99) * X1 )+ ((1.1 * p_TankCR)  * X2 ) +
((p_TankCR  * 1.6)* X3) + (10 * X4);
Up_PipeCR =((p_PipeCR * .98) * X5 )+ ((1.1 * p_PipeCR) * X6  ) +
((p_PipeCR  * 1.4)* X7) + (10 * X8);
Up_PumpCR =((p_PumpCR * .95) * X9 )+ ((1.15 * p_PumpCR) * X10 ) +
((p_PumpCR  * 1.5)* X11) + (10 * X12);

PTPCR = ((0.23 * Up_TankCR) + ( 0.26 * Up_PipeCR) + (0.51 *
Up_PumpCR));

Us_TankCR  = ((s_TankCR  * .99) * X13 )+ ((1.1 * s_TankCR )  * X14 ) +
((s_TankCR  * 1.6)* X15) + (10 * X16);
Us_reactor = ((s_reactor * .99) * X17 )+ ((1.1 * s_reactor)  * X18 ) +
((s_reactor * 1.6)* X19) + (10 * X20);
Us_PipeCR  = ((s_PipeCR  * .98) * X21 )+ ((1.1 * s_PipeCR )  * X22  )
+ ((s_PipeCR * 1.4)* X23) + (10 * X24);
Us_PumpCR  = ((s_PumpCR  * .95) * X25 )+ ((1.15 * s_PumpCR ) * X26 ) +
((s_PumpCR * 1.5)* X27) + (10 * X28);
Us_blower  = ((s_blower  * .95) * X29 )+ ((1.15 * s_blower)  * X30 ) +
((s_blower * 1.5)* X31) + (10 * X32);

STPCR = (0.08 * Us_TankCR )+ (0.13 * Us_reactor) + (0.22 * Us_PipeCR)
      + (0.21 * Us_PumpCR) + (0.37 * Us_blower);
```

```
Ut_TankCR = ((t_TankCR * .99) * X33 )+ ((1.1  * t_TankCR ) * X34 ) +
((t_TankCR * 1.6)* X35) + (10 * X36);
Ut_PipeCR = ((t_PipeCR * .98) * X37 )+ ((1.1  * t_PipeCR ) * X38 ) +
((t_PipeCR * 1.4)* X39) + (10 * X40);
Ut_PumpCR =  ((t_PumpCR * .95) * X41 )+ ((1.15 * t_PumpCR ) * X42 ) +
((t_PumpCR * 1.5)* X43) + (10 * X44);

TTPCR =(0.29 * Ut_TankCR) + (0.28 * Ut_PipeCR) + (0.43 * Ut_PumpCR);
      CRIIP=((0.14 * PTPCR) + (0.6 * STPCR) + (0.26 * TTPCR));

      Up_TankCR > = 8;  Up_TankCR <=10;
      Up_PipeCR > = 8;  Up_PipeCR <=10;
      Up_PumpCR > = 8;  Up_PumpCR <=10;
      Us_TankCR > = 8;  Us_TankCR <=10;
      US_REACTOR > =8;  US_REACTOR <=10;
      Us_PipeCR > = 8;  Us_PipeCR  <=10;
      Us_PumpCR > = 8;  Us_PumpCR <=10;
      Us_blower > = 8;  Us_blower <=10;
      Ut_TankCR > = 8;  Ut_TankCR <=10;
      Ut_PipeCR > = 8;  Ut_PipeCR <=10;
      Ut_PumpCR > = 8;  Ut_PumpCR <=10;


costprimary= pmin_tank + pmin_pump + pmin_pipe;
      costsecondary= smin_tank + smin_reactor + smin_pipe + smin_pump
      + smin_blower;
costtertiary= tmin_tank + tmin_pipe + tmin_pump;
      tcost =costprimary+costsecondary+costtertiary;

tcost<= budget;

      X1 + X2 + X3 + X4 = 1;
      X5 + X6 + X7 + X8 = 1;
      X9 + X10 + X11 + X12 = 1;
      X13 + X14 + X15 + X16 = 1;
      X17 + X18 + X19 + X20 = 1;
      X21 + X22 + X23 + X24 = 1;
      X25 + X26 + X27 + X28 = 1;
      X29 + X30 + X31 + X32 = 1;
      X33 + X34 + X35 + X36 = 1;
      X37 + X38 + X39 + X40 = 1;
      X41 + X42 + X43 + X44 = 1;

      @bin (x1); @bin( x2);  @bin (x3); @bin ( x4);
      @bin (x5); @bin( x6);  @bin (x7); @bin ( x8);
      @bin (x9); @bin( x10); @bin (x11); @bin ( x12);
      @bin (x13); @bin (x14);  @bin (x15); @bin ( x16);
      @bin (x17); @bin (x18);  @bin (x19); @bin ( x20);
      @bin (x21); @bin (x22);  @bin (x23); @bin ( x24);
      @bin (x25); @bin (x26);  @bin (x27); @bin ( x28);
      @bin (x29); @bin (x30);  @bin (x31); @bin ( x32);
      @bin (x33); @bin (x34);  @bin (x35); @bin ( x36);
      @bin (x37); @bin (x38);  @bin (x39); @bin ( x40);
      @bin (x41); @bin (x42);  @bin (x43); @bin ( x44);
```

F:2.3.1 Lingo output Code For Maximizing the Condition Rating for a Minimum Condition rating of 8.

```
Global optimal solution found.
Objective value:                              8.836597
Extended solver steps:                               0
```

Variable	Value	Reduced Cost
CRIIP	8.836597	0.000000
PTPCR	8.923200	0.000000
STPCR	8.671200	0.000000
TTPCR	9.171650	0.000000
PMIN_TANK	900000.0	0.000000
X1	0.000000	-0.2167704
X2	0.000000	-0.2408560
X3	0.000000	-0.3503360
X4	1.000000	-0.3220000
PMIN_PIPE	0.000000	0.000000
X5	1.000000	-0.3032120
X6	0.000000	-0.3403400
X7	0.000000	-0.4331600
X8	0.000000	-0.3640000
PMIN_PUMP	8000.000	0.000000
X9	0.000000	-0.5155080
X10	1.000000	-0.6240360
X11	0.000000	-0.8139600
X12	0.000000	-0.7140000
SMIN_TANK	900000.0	0.000000
X13	0.000000	-0.3231360
X14	0.000000	-0.3590400
X15	0.000000	-0.5222400
X16	1.000000	-0.4800000
SMIN_REACTOR	900000.0	0.000000
X17	0.000000	-0.5405400
X18	0.000000	-0.6006000
X19	0.000000	-0.8736000
X20	1.000000	-0.7800000
SMIN_PIPE	0.000000	0.000000
X21	1.000000	-1.099560
X22	0.000000	-1.234200
X23	0.000000	-1.570800
X24	0.000000	-1.320000
SMIN_PUMP	0.000000	0.000000
X25	1.000000	-1.029420
X26	0.000000	-1.246140
X27	0.000000	-1.625400
X28	0.000000	-1.260000
SMIN_BLOWER	0.000000	0.000000
X29	1.000000	-1.813740
X30	0.000000	-2.195580
X31	0.000000	-2.863800
X32	0.000000	-2.220000
TMIN_TANK	900000.0	0.000000
X33	0.000000	-0.5120716

X34	0.000000	-0.5689684
X35	0.000000	-0.8275904
X36	1.000000	-0.7540000
TMIN_PIPE	2700.000	0.000000
X37	0.000000	-0.5707520
X38	1.000000	-0.6406400
X39	0.000000	-0.8153600
X40	0.000000	-0.7280000
TMIN_PUMP	8000.000	0.000000
X41	0.000000	-0.8178170
X42	1.000000	-0.9899890
X43	0.000000	-1.291290
X44	0.000000	-1.118000
P_TANKCR	6.800000	0.000000
P_PIPECR	8.500000	0.000000
P_PUMPCR	7.600000	0.000000
S_TANKCR	6.800000	0.000000
S_REACTOR	7.000000	0.000000
S_PIPECR	8.500000	0.000000
S_PUMPCR	8.600000	0.000000
S_BLOWER	8.600000	0.000000
T_TANKCR	6.860000	0.000000
T_PIPECR	8.000000	0.000000
T_PUMPCR	7.700000	0.000000
BUDGET	3620000.	0.000000
UP_TANKCR	10.00000	0.000000
UP_PIPECR	8.330000	0.000000
UP_PUMPCR	8.740000	0.000000
US_TANKCR	10.00000	0.000000
US_REACTOR	10.00000	0.000000
US_PIPECR	8.330000	0.000000
US_PUMPCR	8.170000	0.000000
US_BLOWER	8.170000	0.000000
UT_TANKCR	10.00000	0.000000
UT_PIPECR	8.800000	0.000000
UT_PUMPCR	8.855000	0.000000
COSTPRIMARY	908000.0	0.000000
COSTSECONDARY	1800000.	0.000000
COSTTERTIARY	910700.0	0.000000
TCOST	3618700.	0.000000

F:2.4 Minimizing the MR&R Cost

The other optimization alternative is to minimize the MR&R intervention cost. This options usually answer the question of “How much money is needed” for the rehabilitation of a certain WWTP while keeping the condition rating of all its infrastructure unit within a certain desired value. Applying this optimization model for P WWTP shows that if the minimum condition rating for all infrastructure units is allowed to go as low as six it will cost nothing. This means “do nothing” option is selected and the MR&R intervention for all infrastructure units. This option will allow these units to deteriorate. The results of this options is shown in Table F:4. This option will quantify the effect of not doing any maintenance over the P WWTP. This optimization alternative is also an important tool not only because it can provide decision makers the needed tool to figure out which treatment plants can withstand the consequences of maintenance deferrals it can also quantify these effects to be accommodated in future rehabilitation plans. However, if the minimum desired condition rating for P WWTP infrastructure units is 7, the minimum rehabilitation cost will jump to 360000CAD.The rehabilitation decisions for this optimization alternative are presented in Table F: 5.

Table F:4 “Do Nothing Option” Effect Over the CR of P WWTP Infrastructure Units

Treatment Phase	Infrastructure unit	CRI_{IUt}	Min CRI	MR&R Selected	MR&R Cost	CRI_{IUt+1}
Primary Treatment Phase	Primary Sedimentation Tank	6.80	6	Nothing	0	6.73
	Primary phase Pipes	8.50	6	Nothing	0	8.33
	Primary Phase Pump	7.60	6	Nothing	0	7.22
	CRI_{PTP}	**7.65**	**6**			**7.40**
Secondary Treatment Phase	Secondary Sedimentation tank	6.80	6	Nothing	0	6.73
	A.S Reactor	7.00	6	Nothing	0	6.93
	Secondary Phase pipes	8.50	6	Nothing	0	8.33
	Secondary Sedimentation Pump	8.60	6	Nothing	0	8.17
	Secondary Phase Reactor Blower	8.60	6	Nothing	0	8.17
	CRI_{STP}	**8.31**	**6.06**			**8.01**
Tertiary Treatment Phase	Chlorination Phase Tank	6.80	6	Nothing	0	6.79
	Chlorination Phase Pipes	8.00	6	Nothing	0	7.84
	Chlorination Phase Pump	7.70	6	Nothing	0	7.32
	CRI_{TTP}	**7.52**	**6**			**7.31**
	CRI_{IP}	**8.01**	**6**			**7.74**
Budget					**0**	

2.4.1 Lingo Input Code For Minimizing Rehabilitation Cost for a Minimum Condition rating of 6.

```
MIN = pmin_tank + pmin_pump + pmin_pipe + smin_tank + smin_pipe +
smin_pump + smin_blower+smin_reactor+ tmin_tank + tmin_pipe +
tmin_pump;

pmin_tank   = 0 * X1 + 90000 * X2 +  200000 * X3  + 900000 * X4;
pmin_pipe   = 0 * X5 + 2700  * X6 +  25000  * X7  + 40000  * X8;
pmin_pump   = 0 * X9 + 8000  * X10 + 25000  * X11 + 40000 * X12;

smin_tank     = 0 * X13 + 90000 * X14 + 200000 * X15 + 900000 * X16;
smin_reactor  = 0 * X17 + 90000 * X18 + 200000 * X19 + 900000 * X20;
smin_pipe     = 0 * X21 + 2700  * X22 + 25000 * X23 + 40000  * X24;
smin_pump     = 0 * X25 + 8000  * X26 + 25000 * X27 + 40000 * X28;
smin_blower   = 0 * X29 + 8000  * X30 + 25000 * X31 + 40000 * X32;

tmin_tank = 0 * X33 + 90000 * X34 + 200000 * X35 + 900000 * X36;
tmin_pipe = 0 * X37 + 2700 * X38 + 25000 * X39 + 40000 * X40;
tmin_pump = 0 * X41 + 8000 * X42 + 25000 * X43 + 40000 * X44;


!primary treament phase;

p_TankCR= 6.8; p_PipeCR = 8.5; p_PumpCR =7.6;
s_TankCR= 6.8; s_reactor=7; s_PipeCR = 8.5; s_PumpCR =8.6; s_blower
=8.6;
t_TankCR= 6.86; t_PipeCR = 8; t_PumpCR =7.7;

budget = 350000;

Up_TankCR =((p_TankCR * .99) * X1 )+ ((1.1 * p_TankCR)  * X2 ) +
((p_TankCR  * 1.6)* X3) + (10 * X4);
Up_PipeCR =((p_PipeCR * .98) * X5 )+ ((1.1 * p_PipeCR) * X6  ) +
((p_PipeCR  * 1.4)* X7) + (10 * X8);
Up_PumpCR =((p_PumpCR * .95) * X9 )+ ((1.15 * p_PumpCR) * X10 ) +
((p_PumpCR  * 1.5)* X11) + (10 * X12);

      PTPCR = ((0.23 * Up_TankCR) + ( 0.26 * Up_PipeCR) + (0.51 *
Up_PumpCR));
Us_TankCR  = ((s_TankCR  * .99) * X13 )+ ((1.1 * s_TankCR )  * X14 ) +
((s_TankCR  * 1.6)* X15) + (10 * X16);
Us_reactor = ((s_reactor * .99) * X17 )+ ((1.1 * s_reactor)  * X18 ) +
((s_reactor * 1.6)* X19) + (10 * X20);
Us_PipeCR  = ((s_PipeCR  * .98) * X21 )+ ((1.1 * s_PipeCR )  * X22  )
+ ((s_PipeCR * 1.4)* X23) + (10 * X24);
Us_PumpCR  = ((s_PumpCR  * .95) * X25 )+ ((1.15 * s_PumpCR ) * X26 ) +
((s_PumpCR * 1.5)* X27) + (10 * X28);
Us_blower  = ((s_blower  * .95) * X29 )+ ((1.15 * s_blower)  * X30 ) +
((s_blower * 1.5)* X31) + (10 * X32);

      STPCR = (0.08 * Us_TankCR )+ (0.13 * Us_reactor) + (0.22 *
Us_PipeCR) + (0.21 * Us_PumpCR) + (0.37 * Us_blower);
```

```
Ut_TankCR = ((t_TankCR * .99) * X33 )+ ((1.1  * t_TankCR ) * X34 ) +
((t_TankCR * 1.6)* X35) + (10 * X36);
Ut_PipeCR = ((t_PipeCR * .98) * X37 )+ ((1.1  * t_PipeCR ) * X38 ) +
((t_PipeCR * 1.4)* X39) + (10 * X40);
Ut_PumpCR =  ((t_PumpCR * .95) * X41 )+ ((1.15 * t_PumpCR ) * X42 ) +
((t_PumpCR * 1.5)* X43) + (10 * X44);

TTPCR =(0.29 * Ut_TankCR) + (0.28 * Ut_PipeCR) + (0.43 * Ut_PumpCR);

      CRIIP=((0.14 * PTPCR) + (0.6 * STPCR) + (0.26 * TTPCR));

      Up_TankCR > = 6;
      Up_PipeCR > = 6;
      Up_PumpCR > = 6;
      Us_TankCR > = 6;
      US_REACTOR > = 6;
      Us_PipeCR > = 6;
      Us_PumpCR > = 6;
      Us_blower > = 6;
      Ut_TankCR > = 6;
      Ut_PipeCR > = 6;
      Ut_PumpCR > = 6;


costprimary= pmin_tank + pmin_pump + pmin_pipe;
costsecondary= smin_tank +smin_reactor + smin_pipe + smin_pump +
smin_blower;
costtertiary= tmin_tank + tmin_pipe + tmin_pump;
tcost =costprimary+costsecondary+costtertiary;
tcost<= budget;

      X1 + X2 + X3 + X4 = 1;
      X5 + X6 + X7 + X8 = 1;
      X9 + X10 + X11 + X12 = 1;
      X13 + X14 + X15 + X16 = 1;
      X17 + X18 + X19 + X20 = 1;
      X21 + X22 + X23 + X24 = 1;
      X25 + X26 + X27 + X28 = 1;
      X29 + X30 + X31 + X32 = 1;
      X33 + X34 + X35 + X36 = 1;
      X37 + X38 + X39 + X40 = 1;
      X41 + X42 + X43 + X44 = 1;

      @bin (x1); @bin( x2);  @bin (x3); @bin ( x4);
      @bin (x5); @bin( x6);  @bin (x7); @bin ( x8);
      @bin (x9); @bin( x10); @bin (x11); @bin ( x12);
      @bin (x13); @bin (x14);  @bin (x15); @bin ( x16);
      @bin (x17); @bin (x18);  @bin (x19); @bin ( x20);
      @bin (x21); @bin (x22);  @bin (x23); @bin ( x24);
      @bin (x25); @bin (x26);  @bin (x27); @bin ( x28);
      @bin (x29); @bin (x30);  @bin (x31); @bin ( x32);
      @bin (x33); @bin (x34);  @bin (x35); @bin ( x36);
      @bin (x37); @bin (x38);  @bin (x39); @bin ( x40);
      @bin (x41); @bin (x42);  @bin (x43); @bin ( x44);
```

2.4.2 Lingo Output Code for Minimizing Rehabilitation Cost for a Minimum Condition rating of 6.

```
Global optimal solution found.
Objective value:                              0.000000
Extended solver steps:                               0
```

Variable	Value	Reduced Cost
PMIN_TANK	0.000000	0.000000
PMIN_PUMP	0.000000	0.000000
PMIN_PIPE	0.000000	0.000000
SMIN_TANK	0.000000	0.000000
SMIN_PIPE	0.000000	0.000000
SMIN_PUMP	0.000000	0.000000
SMIN_BLOWER	0.000000	0.000000
SMIN_REACTOR	0.000000	0.000000
TMIN_TANK	0.000000	0.000000
TMIN_PIPE	0.000000	0.000000
TMIN_PUMP	0.000000	0.000000
X1	1.000000	0.000000
X2	0.000000	90000.00
X3	0.000000	200000.0
X4	0.000000	900000.0
X5	1.000000	0.000000
X6	0.000000	2700.000
X7	0.000000	25000.00
X8	0.000000	40000.00
X9	1.000000	0.000000
X10	0.000000	8000.000
X11	0.000000	25000.00
X12	0.000000	40000.00
X13	1.000000	0.000000
X14	0.000000	90000.00
X15	0.000000	200000.0
X16	0.000000	900000.0
X17	1.000000	0.000000
X18	0.000000	90000.00
X19	0.000000	200000.0
X20	0.000000	900000.0
X21	1.000000	0.000000
X22	0.000000	2700.000
X23	0.000000	25000.00
X24	0.000000	40000.00
X25	1.000000	0.000000
X26	0.000000	8000.000
X27	0.000000	25000.00
X28	0.000000	40000.00
X29	1.000000	0.000000
X30	0.000000	8000.000
X31	0.000000	25000.00
X32	0.000000	40000.00
X33	1.000000	0.000000
X34	0.000000	90000.00
X35	0.000000	200000.0
X36	0.000000	900000.0

X37	1.000000	0.000000
X38	0.000000	2700.000
X39	0.000000	25000.00
X40	0.000000	40000.00
X41	1.000000	0.000000
X42	0.000000	8000.000
X43	0.000000	25000.00
X44	0.000000	40000.00
P_TANKCR	6.800000	0.000000
P_PIPECR	8.500000	0.000000
P_PUMPCR	7.600000	0.000000
S_TANKCR	6.800000	0.000000
S_REACTOR	7.000000	0.000000
S_PIPECR	8.500000	0.000000
S_PUMPCR	8.600000	0.000000
S_BLOWER	8.600000	0.000000
T_TANKCR	6.860000	0.000000
T_PIPECR	8.000000	0.000000
T_PUMPCR	7.700000	0.000000
BUDGET	350000.0	0.000000
UP_TANKCR	6.732000	0.000000
UP_PIPECR	8.330000	0.000000
UP_PUMPCR	7.220000	0.000000
PTPCR	7.396360	0.000000
US_TANKCR	6.732000	0.000000
US_REACTOR	6.930000	0.000000
US_PIPECR	8.330000	0.000000
US_PUMPCR	8.170000	0.000000
US_BLOWER	8.170000	0.000000
STPCR	8.010660	0.000000
UT_TANKCR	6.791400	0.000000
UT_PIPECR	7.840000	0.000000
UT_PUMPCR	7.315000	0.000000
TTPCR	7.310156	0.000000
CRIIP	7.742527	0.000000
COSTPRIMARY	0.000000	0.000000
COSTSECONDARY	0.000000	0.000000
COSTTERTIARY	0.000000	0.000000
TCOST	0.000000	0.000000

Table F:5 P WWTP MR&R Decisions for Min CR of 7

Treatment Phase	Infrastructure unit	CRI_{IUt}	Min CRI	MR&R Selected	MR&R Cost	CRI_{IUt+1}
Primary Treatment Phase	Primary Sedimentation Tank	6.80	7	Maintain	90000	7.48
	Primary phase Pipes	8.50	7	Nothing	0	8.33
	Primary Phase Pump	7.60	7	Nothing	0	7.22
	CRI_{PTP}	**7.65**	**7**			**7.57**
Secondary Treatment Phase	Secondary Sedimentation tank	6.80	7	Maintain	90000	7.48
	A.S Reactor	7.00	7	Maintain	90000	7.7
	Secondary Phase pipes	8.50	7	Nothing	0	8.33
	Secondary Sedimentation Pump	8.60	7	Nothing	0	8.17
	Secondary Phase Reactor Blower	8.60	7	Nothing	0	8.17
	CRI_{STP}	**8.31**	**7.07**			**8.17**
Tertiary Treatment Phase	Chlorination Phase Tank	6.80	7	Maintain	90000	7.546
	Chlorination Phase Pipes	8.00	7	Nothing	0	7.84
	Chlorination Phase Pump	7.70	7	Nothing	0	7.315
	CRI_{TTP}	**7.52**	**7**			**7.53**
	CRI_{IP}	**8.01**	**7**			**7.92**
Budget					**360000**	

2.5.1 Lingo Input Code for Minimizing Rehabilitation Cost for a Minimum Condition rating of 8.

```
MIN = pmin_tank + pmin_pump + pmin_pipe + smin_tank + smin_pipe +
smin_pump + smin_blower+smin_reactor+ tmin_tank + tmin_pipe +
tmin_pump;

pmin_tank   = 0 * X1 + 90000 * X2 +  200000 * X3  + 900000 * X4;
pmin_pipe   = 0 * X5 + 2700  * X6 +  25000  * X7  + 40000  * X8;
pmin_pump   = 0 * X9 + 8000  * X10 + 25000  * X11 + 40000 * X12;

smin_tank     = 0 * X13 + 90000 * X14 + 200000 * X15 + 900000 * X16;
smin_reactor  = 0 * X17 + 90000 * X18 + 200000 * X19 + 900000 * X20;
smin_pipe     = 0 * X21 + 2700  * X22 + 25000 * X23 + 40000  * X24;
smin_pump     = 0 * X25 + 8000  * X26 + 25000 * X27 + 40000 * X28;
smin_blower   = 0 * X29 + 8000  * X30 + 25000 * X31 + 40000 * X32;

tmin_tank = 0 * X33 + 90000 * X34 + 200000 * X35 + 900000 * X36;
tmin_pipe = 0 * X37 + 2700 * X38 + 25000 * X39 + 40000 * X40;
tmin_pump = 0 * X41 + 8000 * X42 + 25000 * X43 + 40000 * X44;


!primary treament phase;

p_TankCR= 6.8; p_PipeCR = 8.5; p_PumpCR =7.6;
      s_TankCR= 6.8; s_reactor=7; s_PipeCR = 8.5; s_PumpCR =8.6;
s_blower    =8.6; t_TankCR= 6.86; t_PipeCR = 8; t_PumpCR =7.7;

budget = 350000;

 Up_TankCR =((p_TankCR * .99) * X1 )+ ((1.1 * p_TankCR)  * X2 ) +
((p_TankCR  * 1.6)* X3) + (10 * X4);
 Up_PipeCR =((p_PipeCR * .98) * X5 )+ ((1.1 * p_PipeCR) * X6  ) +
 ((p_PipeCR  * 1.4)* X7) + (10 * X8);
 Up_PumpCR =((p_PumpCR * .95) * X9 )+ ((1.15 * p_PumpCR) * X10 ) +
((p_PumpCR  * 1.5)* X11) + (10 * X12);

PTPCR = ((0.23 * Up_TankCR) + ( 0.26 * Up_PipeCR) + (0.51 *
Up_PumpCR));

Us_TankCR  = ((s_TankCR  * .99) * X13 )+ ((1.1 * s_TankCR )  * X14 ) +
((s_TankCR  * 1.6)* X15) + (10 * X16);
Us_reactor = ((s_reactor * .99) * X17 )+ ((1.1 * s_reactor)  * X18 ) +
((s_reactor * 1.6)* X19) + (10 * X20);
Us_PipeCR  = ((s_PipeCR  * .98) * X21 )+ ((1.1 * s_PipeCR )  * X22  )
+ ((s_PipeCR * 1.4)* X23) + (10 * X24);
Us_PumpCR  = ((s_PumpCR  * .95) * X25 )+ ((1.15 * s_PumpCR ) * X26 ) +
((s_PumpCR * 1.5)* X27) + (10 * X28);
Us_blower  = ((s_blower  * .95) * X29 )+ ((1.15 * s_blower)  * X30 ) +
((s_blower * 1.5)* X31) + (10 * X32);

STPCR = (0.08 * Us_TankCR )+ (0.13 * Us_reactor) + (0.22 * Us_PipeCR)
      + (0.21  * Us_PumpCR) + (0.37 * Us_blower);
```

```
Ut_TankCR = ((t_TankCR * .99) * X33 )+ ((1.1  * t_TankCR ) * X34 ) +
((t_TankCR * 1.6)* X35) + (10 * X36);
Ut_PipeCR = ((t_PipeCR * .98) * X37 )+ ((1.1  * t_PipeCR ) * X38 ) +
((t_PipeCR * 1.4)* X39) + (10 * X40);
Ut_PumpCR =  ((t_PumpCR * .95) * X41 )+ ((1.15 * t_PumpCR ) * X42 ) +
((t_PumpCR * 1.5)* X43) + (10 * X44);

TTPCR =(0.29 * Ut_TankCR) + (0.28 * Ut_PipeCR) + (0.43 * Ut_PumpCR);
CRIIP=((0.14 * PTPCR) + (0.6 * STPCR) + (0.26 * TTPCR));

      Up_TankCR > = 7;
      Up_PipeCR > = 7;
      Up_PumpCR > = 7;
      Us_TankCR > = 7;
      US_REACTOR > = 7;
      Us_PipeCR > = 7;
      Us_PumpCR > = 7;
      Us_blower > = 7;
      Ut_TankCR > = 7;
      Ut_PipeCR > = 7;
      Ut_PumpCR > = 7;


costprimary= pmin_tank + pmin_pump + pmin_pipe;
costsecondary= smin_tank +smin_reactor + smin_pipe + smin_pump +
      smin_blower;
costtertiary= tmin_tank + tmin_pipe + tmin_pump;
      tcost =costprimary+costsecondary+costtertiary;
      tcost<= budget;

      X1 + X2 + X3 + X4 = 1;
      X5 + X6 + X7 + X8 = 1;
      X9 + X10 + X11 + X12 = 1;
      X13 + X14 + X15 + X16 = 1;
      X17 + X18 + X19 + X20 = 1;
      X21 + X22 + X23 + X24 = 1;
      X25 + X26 + X27 + X28 = 1;
      X29 + X30 + X31 + X32 = 1;
      X33 + X34 + X35 + X36 = 1;
      X37 + X38 + X39 + X40 = 1;
      X41 + X42 + X43 + X44 = 1;

      @bin (x1); @bin( x2);  @bin (x3); @bin ( x4);
      @bin (x5); @bin( x6);  @bin (x7); @bin ( x8);
      @bin (x9); @bin( x10); @bin (x11); @bin ( x12);
      @bin (x13); @bin (x14);  @bin (x15); @bin ( x16);
      @bin (x17); @bin (x18);  @bin (x19); @bin ( x20);
      @bin (x21); @bin (x22);  @bin (x23); @bin ( x24);
      @bin (x25); @bin (x26);  @bin (x27); @bin ( x28);
      @bin (x29); @bin (x30);  @bin (x31); @bin ( x32);
      @bin (x33); @bin (x34);  @bin (x35); @bin ( x36);
      @bin (x37); @bin (x38);  @bin (x39); @bin ( x40);
      @bin (x41); @bin (x42);  @bin (x43); @bin ( x44);
```

2.5.2 Lingo Output Code for Minimizing Rehabilitation Cost for a Minimum Condition rating of 8.

```
Global optimal solution found.
Objective value:                              360000.0
Extended solver steps:                               0


                      Variable           Value        Reduced Cost
                     PMIN_TANK        90000.00            0.000000
                     PMIN_PUMP        0.000000            0.000000
                     PMIN_PIPE        0.000000            0.000000
                     SMIN_TANK        90000.00            0.000000
                     SMIN_PIPE        0.000000            0.000000
                     SMIN_PUMP        0.000000            0.000000
                   SMIN_BLOWER        0.000000            0.000000
                  SMIN_REACTOR        90000.00            0.000000
                     TMIN_TANK        90000.00            0.000000
                     TMIN_PIPE        0.000000            0.000000
                     TMIN_PUMP        0.000000            0.000000
                            X1        0.000000            0.000000
                            X2        1.000000            90000.00
                            X3        0.000000            200000.0
                            X4        0.000000            900000.0
                            X5        1.000000            0.000000
                            X6        0.000000            2700.000
                            X7        0.000000            25000.00
                            X8        0.000000            40000.00
                            X9        1.000000            0.000000
                           X10        0.000000            8000.000
                           X11        0.000000            25000.00
                           X12        0.000000            40000.00
                           X13        0.000000            0.000000
                           X14        1.000000            90000.00
                           X15        0.000000            200000.0
                           X16        0.000000            900000.0
                           X17        0.000000            0.000000
                           X18        1.000000            90000.00
                           X19        0.000000            200000.0
                           X20        0.000000            900000.0
                           X21        1.000000            0.000000
                           X22        0.000000            2700.000
                           X23        0.000000            25000.00
                           X24        0.000000            40000.00
                           X25        1.000000            0.000000
                           X26        0.000000            8000.000
                           X27        0.000000            25000.00
                           X28        0.000000            40000.00
                           X29        1.000000            0.000000
                           X30        0.000000            8000.000
                           X31        0.000000            25000.00
                           X32        0.000000            40000.00
                           X33        0.000000            0.000000
                           X34        1.000000            90000.00
                           X35        0.000000            200000.0
                           X36        0.000000            900000.0
```

X37	1.000000	0.000000
X38	0.000000	2700.000
X39	0.000000	25000.00
X40	0.000000	40000.00
X41	1.000000	0.000000
X42	0.000000	8000.000
X43	0.000000	25000.00
X44	0.000000	40000.00
P_TANKCR	6.800000	0.000000
P_PIPECR	8.500000	0.000000
P_PUMPCR	7.600000	0.000000
S_TANKCR	6.800000	0.000000
S_REACTOR	7.000000	0.000000
S_PIPECR	8.500000	0.000000
S_PUMPCR	8.600000	0.000000
S_BLOWER	8.600000	0.000000
T_TANKCR	6.860000	0.000000
T_PIPECR	8.000000	0.000000
T_PUMPCR	7.700000	0.000000
BUDGET	360000.0	0.000000
UP_TANKCR	7.480000	0.000000
UP_PIPECR	8.330000	0.000000
UP_PUMPCR	7.220000	0.000000
PTPCR	7.568400	0.000000
US_TANKCR	7.480000	0.000000
US_REACTOR	7.700000	0.000000
US_PIPECR	8.330000	0.000000
US_PUMPCR	8.170000	0.000000
US_BLOWER	8.170000	0.000000
STPCR	8.170600	0.000000
UT_TANKCR	7.546000	0.000000
UT_PIPECR	7.840000	0.000000
UT_PUMPCR	7.315000	0.000000
TTPCR	7.528990	0.000000
CRIIP	7.919473	0.000000
COSTPRIMARY	90000.00	0.000000
COSTSECONDARY	180000.0	0.000000
COSTTERTIARY	90000.00	0.000000
TCOST	360000.0	0.000000