CONDITION ASSESSMENT TOOL FOR ELEMENTS OF DRINKING WATER TREATMENT PLANT

Sarker Md. Sajedur Rahman

A Thesis

In

The Department

Of

Building, Civil and Environmental Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science (Building Engineering) at
CONCORDIA UNIVERSITY
Montreal, Quebec, Canada

April 2007

Library and
Archives Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-34452-1
Our file Notre référence
ISBN: 978-0-494-34452-1

NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:
L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

ABSTRACT

CONDITION ASSESSMENT TOOL FOR SELECTED ELEMENTS OF DRINKING WATER TREATMENT PLANT

Sarker Md. Sajedur Rahman

Condition assessment of aging assets and infrastructure is a growing concern in North America. The Canadian Water and Wastewater Association (CWWA) estimated that a $ 28 billion investment is needed for municipal water systems in Canada from 1997 to 2012. The condition of 43% of water supply systems in Canada is unacceptable. A systematic condition assessment is a pre-requisite of an effective asset and infrastructure management practice. The present study focuses on analyzing the principal factors that affect infrastructure condition, data requirement, and how the condition of a targeted element can be assessed.

The main objectives of this research are to develop condition assessment models for selected existing elements of Drinking Water Treatment Plant (DWTP) and develop condition rating scales and a web-based tool. The condition of five DWTP elements are studied in this research: settling tank, filtration tank, chlorination tank, raw water pump and clean water pump. Condition rating (CR) models are designed using Analytical Hierarchy Process (AHP) and Multi Attribute Utility Theory (MAUT) approaches. Evaluation results show that the top ranked category for tanks is 'Physical (design and construction stage)' with a relative importance of 32% and for pumps is 'Operational' with an importance of 34%. The preference level of each parameter is being measured on a numerical scale of 0-10.

Twenty five practical case studies are used to validate the developed models, which show robust results. Condition rating scales are developed for tanks and pumps and verified by municipal experts. A web-based condition rating tool is developed and coded with AHP.NET.

AKNOWLEDGEMENT

I am grateful to al-mighty for giving me courage, inspiration and energy for completing this dissertation successfully.

It is my immense pleasure to express the deepest gratitude to my supervisor, Dr. Tarek Zayed, has been a mentor, teaching me ways to pursue research and contentiously supported, motivated and guided throughout the research tenure.

Thank you and gratitude to all experts from public and private sectors participated in survey and interview process. Special thanks to Mr. Maruf Mortula, NRC; Mr. Simon Martel, Dorval plant, Quebec; Mr. John Kehoe P. Eng., Manager of the Union Water System, Ontario and Ms. Jacqueline Weston, P. Eng.(Halton Region, Ontario), for sharing valuable information and guiding me about real local practices. I like to thank my fellow colleagues form graduate programs for helping in different level with constructive advices and criticisms.

I know my mom and dad would have been the most proud ones and I am grateful to my departed parents' for teaching me work with patience, sincerity and honesty. Sanjad, my beloved son being young very respectful to my work, I salute you and thankful too. My deepest appreciation to my wife (Shafina), sister and brothers for their sacrifice and encouragements, without their support it would not be possible for me to complete this endeavour.

TABLE OF CONTENTS

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

APPENDIX-A

APPENDIX-B

APPENDIX-C

APPENDIX-D

Appendix-E

Appendix-F

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE & ABBREVIATIONS

AHP	Analytical Hierarchy Process
AM	Arithmetic Means
ANN	Artificial Neural Networks
ANP	Analytic Network Process
ASCE	American Society of Civil Engineers
ASP	Active Server Page
AWWA	American water works association
AWWARF	American water works association research foundation
BPNN	Backpropagation neural networks
CAT	Condition Assessment Tool
CCTV	Closed Circuit Television
CFAP	Capital Facilities Assessment Program
CI	Condition Index
CLR	Common Language Runtime
CP	Compromise Programming
CR	Condition rating
CRI (I_{cri})	Condition rating index
CRS	Condition Rating Scale
CS	Case Study
CWP	Clean water pump
CWWA	Canada water works association
DEA	Data Envelopment Analysis
DRM	Direct Rating Method
DSS	Decision support system
DWTP	Drinking Water Treatment Plant
EM	Eigen value method
EPA	Environmental Protection Agency
EV	Eigen value
ELECTRE	Elimination et Choix Traduisant la Réalité

FHWA	Federal Highway Administration
FPPE	Filter Plant Performance Evaluation FCM
GAO	General accounting office
HP	High Pressure
HTML	Hyper Text Mark-up Language
IDSS	Integrated Decision Support Systems
IIS	Internet Information Server
LP	Low pressure
LPS	Least Preferred Scores
MAUA	Multi-attribute utility analysis
MAUT	Multi Attribute Utility Theory
MADA	Multi-attribute decision analysis
MCD	Multi-Criteria Decision
MCDM	Multi-Criteria Decision-Making
MCDT	Multicriteria Decision Technique
MCA	Multi-criteria analysis
MDP	Markove Decision Processes
MLE	Markov latent effects
MOE	Ministry of the Environment
MOMP	Multiple Objective Mathematical Programming
MOLP	Multiple Objective Linear Programming
MPS	Most Preferred Scores
NAMS	National Asset Management Steering Council
NSW	New South Wales
O&M	Operation and Maintenance
PBD	Probability Distribution
PDF	Probably Density Function
PMS	Preference Measure Scale
PROMETHEE	Preference Ranking Organization Method of Enrichment Evaluation
PS	Preference Scores
PWD	Philadelphia Water Department

RI	Random Index
RWP	Raw water pump
SAW	Simple Additive Weighting
SDK	Software Development Kit
SPW	Simple Product Weighting
SASW	Spectral Analysis of Surface Waves
SHM	The structural health monitoring
SMART	Simple Multiattribute Rating Technique
TOC	Total Organic Carbon
SPC	Statistical Process Control
ST	Settling Tank
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
WSA	Waterworks System Assessment
XML	Extensible Mark-up Language
$\mathrm{w}_{\mathrm{c,i}}$	Relative Weights
w_p	Relative Weight
$W_{d,ij}$	Decomposed Relative Weight
$w_{c,i}$	Category Weight
$\mathrm{u}_{\mathrm{i/j,r}}$	Preference Scores
$\mathrm{U_t}$ & $\mathrm{U_p}$	Varied Factors
C_t & C_p	Fixed Constants

CHAPTER 1

INTRODUCTION

1.1 Background

Potable water is undoubtedly one of the most important natural resources that has and will always play a major role in civilization. A potable water supply system is an integral part of municipal infrastructure and essential for survival and prosperity. According to a survey report, 43% of water supply systems, in Canada, are in unsatisfactory condition (Mirza and Hider, 2003). The average age of water supply systems is estimated to be 36 years. It is estimated that $3.1 billion is required to bring water supply systems to acceptable levels of performance at the national level (Mirza and Hider, 2003). The average age of Canada's municipal infrastructure is 42 years (Allouche and Freure, 2002). On the contrary, Canada's overall infrastructure ranked fifth out of 22 developed countries in the early 1990s (Infrastructure Canada, 2004). In the United States, the importance of improving water system infrastructure (treatment plants, distribution systems and storage facilities) started during early 1980's. A previous study estimated a need of $125 billion over a 20-year period for the 756 largest cities in US (Grigg, 1992). Water system is one of the six infrastructures identified as most critical. The Environmental Protection Agency (EPA) reported that the required capital for drinking water ranges from $154 to $446 billions with a point estimate of $274 billion over a 20-year period from 2000-2019. The American Society of Civil Engineers (ASCE) estimated a near failing grade of "D-" for the nation's drinking water infrastructure (AWWA, 2005). In the United States, 54,000 drinking water systems face annual shortfall of at least $11 billion for the replacement of aging facilities and adherence to water regulations. This amount does not consider any growth in demand over the next 20 years (ASCE, 2005). An investment of billions of dollars is needed for system inspection, repair, replacement and rehabilitation, which clearly indicates the importance of condition assessment for drinking water plant elements.

1.2 Problem Statement

A typical water system consists of intake, transmission, treatment and distribution. To avoid health hazards originating from potable water, water regulators impose very strict and stringent quality regulations. Water treatment plant operators are mostly responsible for proper implementation of the regulations dealing with water quality, and to keep the system functional. The physical, operational, and environmental conditions for water treatment plant must be analyzed. The uncertainty level and risk of time dependent factors increase with age thereby creating very challenging situations for managers to plan future short and long terms' operation and maintenance protocols.

To assess the condition of a plant as a whole, individual elements must be assessed in which it requires inventory of well-documented inspection reports, operation and maintenance records and finally a sophisticated assessment tool. The massive involvement of specialized personnel, reliable databases, substantial time, application of cutting-edge technology and equipment are required for an effective condition assessment, which will be too costly for most municipalities. Many factors will hinder this requirement, which can force the regulators to do nothing, especially in small systems. The cost-effective way of accomplishing this task is to perform a quick and effective condition assessment and then decide whether a more detailed condition assessment is required.

1.3 Objectives

The main objective of this research is to develop condition assessment models and tool for the major elements of drinking water treatment plants. The developed models and tool will feed information into a Decision Support System (DSS) in order to prioritize future actions. The present research objectives can be summarized as follows:

- Identify condition rating parameters and determine their relative weights.
- Develop condition rating models in order to calculate the Condition Index (CI)
- Develop Condition Rating Scale (CRS)
- Perform Sensitivity Analysis for parameter weights and utility scores
- Develop a web-based Condition Assessment model and a Scale.

1.4 Research Methodology

The aim of this study is to develop condition rating model for various elements of a drinking water treatment plant. To achieve the aforementioned research objectives, the following steps are accomplished:

1.4.1 Literature Review

A comprehensive literature review is performed focusing on the following primary areas: condition assessment, drinking water treatment plants, plant elements, conditions affecting parameters, assessment techniques, and assessment tools and protocols. Resources such as books, internet, research papers, and journals are utilized to carry out this literature review. More emphasis is given to analytical hierarchy process (AHP) and multi attribute utility theory (MAUT) because they are utilized in current research.

1.4.2 Data Collection

A questionnaire is prepared based on the research objectives and assessment techniques. It was sent to experts across Canada and the United States. Questionnaire responds are analyzed in order to rank the parameters and average the preference scores for the scenarios under each parameter. Case study information from twenty five cases are collected and used in model development.

1.4.3 Development of Condition Assessment Model (CAM) and Scale

The following are the steps involved in the development of the condition assessment model and Scale:

- Rank parameters by assigning weights using AHP
- Determine preference scores for scenarios under each parameter by applying MAUT
- Integrate AHP and MAUT for the development of CAM
- Design a Condition Rating (CR) scale
- Design a web-based prototype CAM, which is coded with AHP.NET

1.5 Thesis organization

The thesis comprises seven chapters and encompasses relevant discussion for data and results analysis of this study. The thesis begins with chapter 1, which briefly describes the background, objectives and scope and research of the study. Chapter 2 consists of literature review, which focuses on identifying the parameters that influence the condition of water treatment plant elements, existing assessment techniques and protocols. In addition, a brief description of existing CR scales is performed.

Chapter 3 describes the research methodology, which includes list of model's parameters, model hierarchy, and brief description of all major tasks.

Chapter 4 explains data collection initiatives and procedure, which focuses on preparation of questionnaire, selection of experts, mode of communication with experts, and preliminary analysis to test the consistency of the developed distributions.

Chapter 5 represents the integral part of this study. It introduces the development and applications of the model, research outcomes, implementations of uncertainties in the models, construction of preferences curves, a description of the proposed CR scale and sensitivity analysis. This is followed by the application and validation of the model using 25 real case studies.

Chapter 6 describes the web-based condition assessment tool. The operational processes are described step by step with a flow diagram of the model framework. Finally, the applications of the model are described using a practical example.

The final chapter includes conclusions, research contributions, limitations of the current study and recommendations for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

A comprehensive literature review has been carried out in order to provide a detailed description and better understanding of water treatment plants and other infrastructure. Based on this literature review, it is apparent that the majority of the research has focused on water distribution systems, water quality issues and treatment processes, rather than treatment plant infrastructure or more specifically plant elements. In the following sections, an introduction to drinking water treatment plants and its major elements will be conducted. In addition, asset management, condition assessment, condition affecting parameters, assessment techniques and assessment protocols or tools will be discussed. The two assessment techniques, AHP and MAUT will be discussed in detail, since these two techniques are applied in this study. Figure 2.1 is showing a summery diagram of current study literature review.

2.2 Drinking Water Treatment

Water treatment is a process that improves the chemical and biological quality of potable water. Five elements of a conventional DWTP are studied in this current study. 1) Settling Tank: is used to separate suspended solids. 2) Filtration Tank: provides support to filter media and aids in sludge disposal. 3) Chlorination Tank: is used for disinfection process before pumping to supply mains. 4) Raw Water Pump: require pumping raw or pre-treated water to settling tank and 5) Clean Water Pump: is used to pump treated water into distribution mains. For details on water treatment and DWTP elements, please refer to Appendix- A.

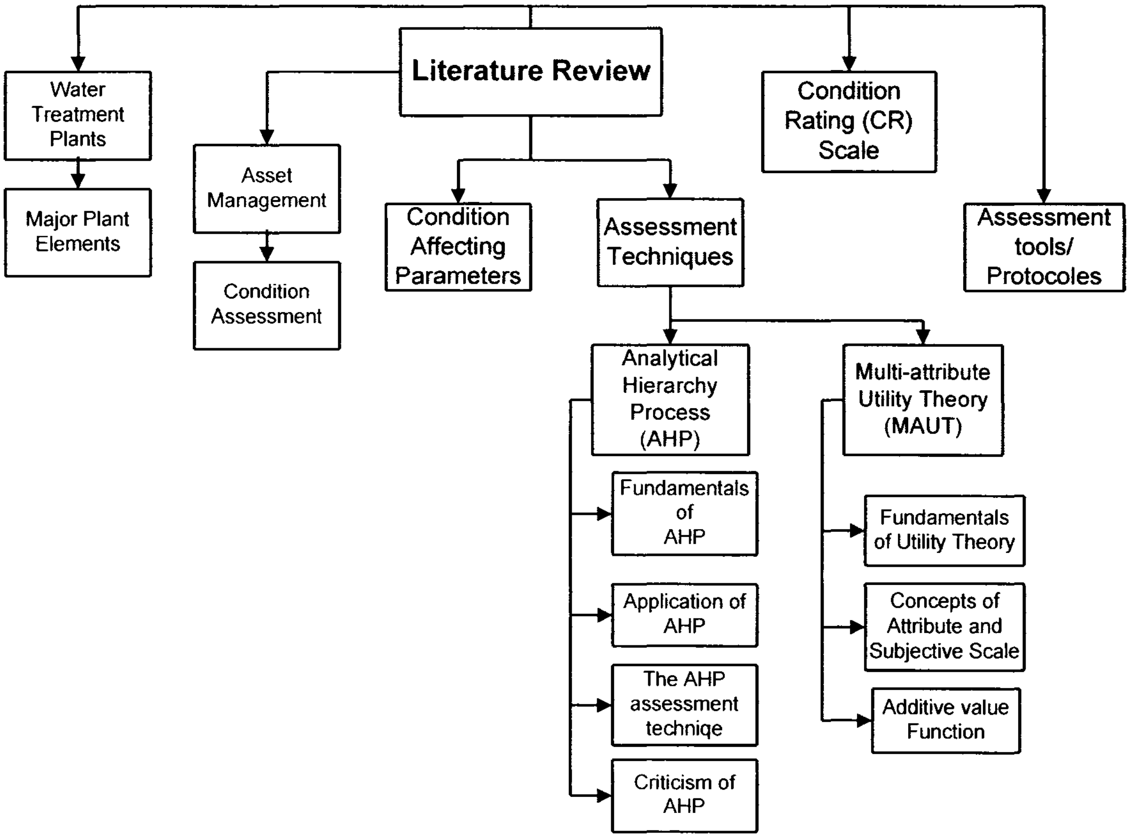


Figure2.1 Summery diagram of literature review

2.3 Asset Management

Proper management and strategic planning of aging water and wastewater infrastructure for macro level investment, requires complete data and funding. In order to accomplish a long-term sustainability of assets, the development of a standard asset management practice is paramount.

The United States Federal Highway Administration defines asset management as “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. The asset management approach incorporates the economic assessment of trade-offs among alternative investment options and uses this information to help make cost-effective investment decisions." (US FHWA, 2006)

In Australia, New Zealand and the United Kingdom, the successful application of asset management practices began more than a decade ago. These management practices aided water authorities to understand the interrelationship between all functions, to reduce the duplication of work, minimize risk and prioritize future actions. At present, North American systems are trying to adapt to this concept in a broader spectrum particularly in the utility sectors. In May 2005, the National Asset Management Steering Council (NAMS), with the assistance from the EPA and the National Science Foundation, conducted an international two-day session on asset management practices in the United States.

The experts identified the following top 10 consensus priorities:

1 Define best practices in asset management.

2 Define asset management by building business cases.

3 Develop a central depository of high-quality data available to researchers.

4 Develop an international training and resource clearinghouse.

5 Develop an asset management level of service business model.

6 Develop research tools for cost-effective physical conditions assessment

7 Design standards.

8 Develop common best practices for a risk management framework.

9 Evaluate whether asset management plans should be made a requirement for government funding.

10 Cultural changes. (Causey, 2005)

The secretary of NAMS mentioned that the key elements of any excellent asset management program are the following:

1 Integrate optimization techniques.

2 Delivery of service levels customers demand and desire.

3 Minimization of total life-cycle costs fully funded for all assets.

4 Conduction of operations oriented to acceptable risk.(Causey, 2005)

A formal asset management process accounts for proper condition assessment that will help meet the following challenges (Urquhart et al., 2005):

- Meet customer service expectations
- Determine the risk of failure
- Understand asset condition and remaining life, allowing for proactive budgeting for renewal/replacement of high-risk assets
- Quantification of the benefits of different management/operational strategies
- Determination of asset value and ensure compliance with accounting standards.

2.3.1 Condition Assessment

Infrastructure studies around the world showed that the state of existing water infrastructure is deteriorating with age and will require continuous and significant renewal or replacement work in order to keep the system's satisfactorily in service condition. Condition assessment is the best way to manage long-term maintenance, rehabilitation and replacement works and to assess the future needs in a reasonable range. "Condition assessment is a process of measuring the physical condition of system components using objective criteria. The process should include such parameters as safety and structural integrity, capacity, quality of service, role and age". (Grigg, 1997, O'Day and Neumann, 1984)

An effective and systematic condition assessment program of any drinking water treatment plant element, directly or indirectly, will bring benefits to the owners, users and managers by contributing to the following issues (Urquhart et al., 2005; GMAS, 2006):

- Identification of critical elements inside the system
- accurate capital planning and budgeting
- prioritise maintenance and rehabilitation works
- better risk management
- improved regulatory compliance
- provide valuable information to DSS
- strategic planning
- operations management
- Establish disposal planning.

A typical condition assessment program will include (BC Guidelines, 2005; GMAS, 2006)

- Selection of the appropriate condition assessment approach
- Inventory
- Review original drawings and all past records of inspection and major maintenance works.
- Inspection to assess condition of assets
- Determination of condition index
- Identify maintenance need and practise that need
- Estimation of time frame for actions and next assessment.

2.4 Parameters Contribute to Condition of Drinking Water Treatment Plant Elements

A modern complete drinking water treatment plant is an extremely complex system consisting of hundreds of elements. The current study covers only selected pumps and tanks/basins for condition assessment. It should be noted that all the factors that influence the parameters for every scenario have been considered in this research.

After reviewing previous studies conducted on condition assessment of drinking water treatment plant elements, it is apparent that minimal work has been done on plant elements. Most of the research focused on water mains or the water supply system as a whole. It can be considered that many condition parameters of water mains and water supply systems will be applicable to treatment plant elements as well. The factors affecting the deterioration of buried water infrastructure (i.e. water mains) can be classified in a few categories such as operational, environmental, and physical (Kleiner, 2001). There could be static factors (i.e. material size) and dynamic variables such as age and temperature (Rajani and Kleiner, 2002). In a study, researchers concluded that corrosion could be the most important factor contributing to structural failure of iron water mains. The potential for soil corrosivity can expedite that corrosion process.

(Najjaran *et al.* 2004 and Sadiq *et al.* 2004). Best Practices (2003) of The Canadian National Guide for water main deterioration and inspection, classified the major factors that contribute to deterioration. These factors are summarized in Table 2.1.

1. Physical factors
2. Environmental factors
3. Operational factors

Natural calamities such as Earthquakes could be one of the major factors to affect the condition of infrastructure including water treatment plants if the intensity exceeds the design limits. A technical report focusing on earthquake damage to water and oil pipelines, water supply, and water treatment following the 22 April 1991 Costa Rica Earthquake was conducted. According to the report, the earthquake damaged the water treatment plant. Cast iron, ductile iron and reinforced concrete water transmission lines were damaged by wave propagation and permanent ground deformation (O'Rourke and Ballantyne, 1992). In a study related to the development of a deterioration model for sewer systems, many variables were considered. Logistic regression models were used and age; diameter, material, and average depth of cover were modeled, using historical data. (Ariaratnam et al. 2001). One of the American water works association research foundation (AWWARF) report recommends that enhanced coagulation may cause potential pitfalls in plant elements. In a treatment plant, one of the most common means of improving Total Organic Carbon (TOC) is by reducing coagulation pH or using higher coagulant doses. There is a strong possibility that the lower coagulation pHs and higher coagulant doses will significantly accelerate degradation of treatment plant infrastructure. Lower pH levels can cause enhanced degradation within the plant from degassed chlorine in water. In a survey of enhanced coagulation and its impacts on infrastructure, among 275 water utilities, 24% have reportedly experienced some form of degradation. Metallic infrastructure such as pumps and pipes need more attention since the enhanced coagulation alters their corrosivity. (AWWARF Report, 2004; McNeill and Edwards, 2003). Table 2.2 shows possible degradation mechanisms of plant materials with various coagulants.

The search for condition parameters of drinking water treatment plant elements is further extended in many textbooks, national and provincial water supply assessment guidelines and protocols in practice across Canada and the Unites States. It is obvious, beyond the above-motioned factors; the following contribute to the overall condition of plant elements.

- Design considerations (uniformity, materials, joints etc.)
- quality of construction work,
- capacity of the plant element/ equipment,
- quality of intake water,
- treatment process and chemical doses,
- operation and maintenance practice,
- type of equipment,

Table2.1 Factors that Contribute to Water System Deterioration (Best Practices, 2003)

Factor		Explanation
Physical	Pipe material	Pipes made from different materials fail in different ways.
	Pipe wall thickness	Corrosion will penetrate thinner walled pipe more quickly.
	Pipe age	Effects of pipe degradation become more apparent over time.
	Pipe vintage	Pipes made at a particular time and place may be more vulnerable to failure.
	Pipe diameter	Small diameter pipes are more susceptible to beam failure.
	Type of joints	Some types of joints have experienced premature failure (e.g., leadite joints).
	Thrust restraint	Inadequate restraint can increase longitudinal stresses.
	Pipe lining and coating	Lined and coated pipes are less susceptible to corrosion.
	Dissimilar metals	Dissimilar metals are susceptible to galvanic corrosion
	Pipe installation	Poor installation practices can damage pipes, making them vulnerable to failure.
	Pipe manufacture	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure. This problem is most common in older pit cast pipes.
Environmental	Pipe bedding	Improper bedding may result in premature pipe failure.
	Trench backfill	Some backfill materials are corrosive or frost susceptible.
	Soil type	Some soils are corrosive; some soils experience significant volume changes in response to moisture changes, resulting in changes to pipe loading. Presence of hydrocarbons and solvents in soil may result in some pipe deterioration.
	Groundwater	Some groundwater is aggressive toward certain pipe materials.
	Climate	Climate influences frost penetration and soil moisture. Permafrost must be considered in the north.
	Pipe location	Migration of road salt into soil can increase the rate of corrosion.
	Disturbances	Underground disturbances in the immediate vicinity of an existing pipe can lead to actual damage or changes in the support and loading structure on the pipe.
	Stray electrical currents	Stray currents cause electrolytic corrosion.
	Seismic activity	Seismic activity can increase stresses on pipe and cause pressure surges.
Operational	Internal water pressure, transient pressure	Changes to internal water pressure will change stresses acting on the pipe.
	Leakage	Leakage erodes pipe bedding and increases soil moisture in the pipe zone.
	Water quality	Some water is aggressive, promoting corrosion
	Flow velocity	Rate of internal corrosion is greater in unlined dead-ended mains.
	Backflow potential	Cross connections with systems that do not contain potable water can contaminate water distribution system.
	O&M practices	Poor practices can compromise structural integrity and water quality.

Table2.2 Water Quality Changes from Coagulation and Possible Impacts on Materials Degradation (Adapted from McNeill and Edwards et al. 2003)

Water qult. change	**Reason for change**	**Potential consequence for**		
		Concrete	**Rebar**	**Metals**
Lower NOM	Removed by coagulation	Adverse	Unknown	Adverse
Lower pH	Higher coagulant doses and direct acid addition	Severe adverse	Adverse	Severe adverse
More chloride	Higher doses of ferric chloride, polyaluminum chloride, or HCl	Neutral; very high levels may prevent sulfate attack	Severe	Variable
More sulfate	Higher doses of alum, ferric sulfate, or sulfuric acid	Adverse for some types of concrete	None	No effect or detrimental
More $Al(OH)_3$ or $Fe(OH)_3$ solids	Typical consequence of higher coagulant doses	Benefit	Unknown	Unknown
More soluble Al^{+3}	Higher alum doses and lower pH may increase solubility of solids formed	Possible benefit	Unknown	Unknown
Higher CO_2	Acidification of waters containing bicarbonate	Severe adverse; DVGW recommends CO2 <0.7mM	Adverse	Adverse
More calcium	Addition of supplemental lime to maintain target coagulation pH and improve particle removal	Benefit; DVGW recommends Ca >0.2 mM	Unknown	Some benefits

Note:
NOM (Natural Organic Matter)
DVGW (German Technical and Scientific Association for Gas and Water)

- monitoring procedure
- training, adaptation of new technology and
- Inadequate funding
- competence and experience of staff,

2.5 Assessment Techniques Used for Water & Other Infrastructures

There are many techniques used to model deterioration, and assess the condition of in-service infrastructure components. The assessment techniques can be mechanical, mathematical, statistical or soft computing. Most research works conducted on drinking water infrastructure condition assessment have focused on water mains. As mentioned earlier, a drinking water treatment plant (DWTP) consists of hundreds of elements and equipment. The principal infrastructural components are steel and concrete structural elements, the connecting pipe system and pipe supporting members. Where financially and technically viable, the typical assessment methods that are used for materials and environment assessment can be applied to DWTP elements. In this current study, two techniques are used a) The Analytic Hierarchy Process (AHP) and b) Multi Attribute Utility Theory (MAUT). Both techniques are widely used in decision support systems. Some of the common assessment techniques found in literature are discussed briefly in the sections to follow.

2.5.1 Statistical Techniques

Partially Observable Markov Decision Processes (MDP): This approach was applied by Corotis et al. (2004) to problems for which the true states were known with probabilistic certainty. Using the same notation of Corotis et al. (2004), observations of the process (i.e. inspections) form a vector **Y(t)**, which partially attains the true state of the main process through a relationship matrix, P [Y|X], in which **X** is the condition state of the true process. The approach taken in this study was to develop an information vector, **q(t)**, which is known to the decision maker at any time. It consists of all prior information based on the history of inspection results for the **Y** process, and probability state changes due to all prior maintenance and repair works. Corotis stated that the information vector forms a Markov process; the decision process is solved using **q(t)** as an equivalent MDP problem. In the study, two major deterioration models were used: fatigue of steel girders and corrosion of steel reinforcement in concrete girders. These deterioration processes were then combined with a few inspection and maintenance strategies. The transition matrix of the structure at any stage consists of a combination of the change due to applied loads and environmental effects under both no-action and the maintenance action. To solve a finite horizon observable MDP, the current value effect of all decisions at a particular time phase were computed by projecting future state probabilities. By including initial design and operational considerations in the model, a lifetime optimal initial design can be selected only by iteration (Corotis et al., 2004)

Bayesian Inference: The study by Papadimitriou (2004) has presented Bayesian framework for structural model selection and damage detection by using a dynamic data level approach. In his two level approaches, the first level estimates the free parameters of a model class and at the second level, selects the best model class from a set of competing model classes. Each model class indicating the location of damage and its pattern accomplished structural damage detection. The study concluded that damage detection depends on the information contained in the data, the number of modes accounted for and the number of measured locations. The author also suggested that the optimization of the sensor configuration would improve the prediction of its location and damage severity (Papadimitriou, 2004).

Statistical ranking models: In this study, function-based condition indexing methodology was introduced using statistical ranking models. These models were employed to extract information from an historical database, based on the prioritization of maintenance and repair operations. This information aids in the development of a weight function that prioritises the importance of maintenance and repair operations. Weight functions are used to convert the condition index vector into a condition-indexing scalar. Besides physical parameters such as age and height, the authors suggested that other important parameters need to be considered in order to determine the weight functions for the final version of the condition indexing system (Chouinard et al., 1996).

2.5.2 Soft Computing Techniques

The most common soft computing techniques, namely artificial neural networks, fuzzy systems, genetic algorithms and hybrid systems are often used for infrastructure management decisions. These techniques may include condition assessment, performance assessment, need analysis and optimization.

Artificial Neural Networks (ANN): Artificial neural networks are structured on the functions of the human brain. This technique has the ability to predict patterns based on learning and recollection, similar to the human brain. An ANN can be an effective predictive tool and can be developed if it is trained by using an accurate number of examples. It also may give a valid answer from "noisy" data when provided with a reasonable number of examples to teach (Taylor, 1995). ANN techniques are useful for data-based hypothesis development, where causal relationships among variables are unknown (Sadiq *et al.* 2004). ANNs have highly intelligent behavior allowing for recognition without definition and enables these systems to make generalizations (Kosko,1992). Sawhney and Mund (2002) stated that ANN modeling techniques are more effective in such problems where solutions are not clearly articulated or the relationships among inputs and outputs are not clearly identified. The architecture of a neural network consists of a large number of simple neuron-like processing units that are randomly arranged and connected in different layers (input, hidden, and output). Neural networks act as a "black box," because the hidden layers are connected to input and output layers and they are not connected to the external world (Zayed and Halpin, 2005; Flintsch and Chen, 2004). In this technique it is not possible, to easily integrate prior (expert) knowledge or to extract the path followed to attain a solution and therefore represents a major weakness.

*Backpropagation neural networks (*BPNN)*:* Similar to all neural network concepts, BPNN learn by example and can generate patterns and predictions. Artificial neurons receive information from other neurons, filter it, and then send the information to the other neurons (Tsoukalas and Uhring, 1997). BPNN consists of at least three layers: an input layer, hidden layer and an output layer. Input neurons are fully connected to neurons in the hidden layer and hidden neurons are subsequently fully connected to neurons in the output layer. When one neuron receives inputs from other neurons, it shares its outputs to other neurons using an activation function (Chou and Pellinen, 2005; Moselhi and Shehab, 2000; Tsoukalas and Uhring, 1997). Backpropagation neural networks have been used to combine different pavement condition indicators into a condition index or pavement rating assignments (Flintsch and Chen, 2004).

Fuzzy set theory/Fuzzy Logic Systems: Zadeh (1965, 1973) stated that fuzzy logic systems are an extension of the traditional rule-based expert systems, which incorporate imprecise, qualitative data in the decision-making process by combining descriptive linguistic rules through fuzzy logic. To design a fuzzy system requires the definition of a set of membership functions and a set of fuzzy rules. Binary rules are applied to define conventional expert systems in this technique. This is unlike human behavior, where a smooth relation normally exists between action and consequence. Effective relationships can be achieved by using fuzzy rules that include descriptive expressions, such as poor, fair, or good, to categorize linguistic input and output variables. Fuzzy logic enables the variables to represent a particular set (up to a certain degree) and makes use of the generalizations of conventional boolean logic operators in data processing. A fuzzy approach is convenient to model expert opinions because they handle linguistic rules efficiently (Flintsch and Chen, 2004). In cases where there is a high degree of uncertainty in the available data, fuzzy set theory can be employed to convert linguistic descriptions into numerical format. By introducing composite programming techniques, a screening model can be developed to assess element (pipe) condition and rank them accordingly (Yan and Vairavamoorthy, 2003). The main limitation of fuzzy systems is that there are no formal algorithms to learn from existing data. The primary advantage of this technique is the possibility of introducing and using rules from experience, intuition, and heuristics. Functional transparency is also one fuzzy system characteristics (Flintsch and Chen, 2004).

Hybrid Systems: Numerous studies have shown that the development of a practical and efficient system may require integrating more than one technique into hybrid systems (Zadeh, 2001). A combined hybrid system makes it possible to "achieve tractability, robustness, low solution cost, and better rapport with reality" (Zadeh, 1997).

In hybrid soft computing architectures, one can combine several techniques that add to their capabilities and advantages. Fuzzy logic provides a solution for approximate reasoning and linguistic computing. Neural networks are efficient for learning and system identification; genetic algorithms are efficient in searching randomly and optimization heuristics. Therefore, it seems obvious that the combined tools may handle uncertain, subjective, incomplete, and/or ambiguous information, trained by learning from example and/or experts, and improve their performance when they are used appropriately (Flintsch and Chen, 2004).

2.6 Condition Assessment Techniques Used in Current Study

After reviewing previous studies on condition assessment for DWTP elements, it is apparent that there is no single systematic study prevails where conventional assessment techniques are applied. Initial data searching approaches have shown the non availability of reliable and required amounts of data that may required for assessment techniques such as artificial neural network (ANN); regression analysis etc. Subjective approaches are the best solution to overcome the scarcity of real world data and to continue the study. In order to cover the complexity of problems through expert input and achieve the study goal effectively, the following two techniques are applied:

1. Multi Attribute Utility Theory (MAUT)
2. The Analytic Hierarchy Process (AHP)

Why MAUT and AHP techniques used?

- These two approaches deals qualitative and qualitative effectively
- Deals with multi-attributes
- Hierarchy structure of these techniques give opportunity to handle multi-level criteria in the model
- Require expertise but not expensive approach.

2.6.1 Multi Attribute Utility Theory (MAUT)

2.6.1.1 Overview

Multi-criteria analysis (MCA) helps decision makers to establish objectives, measure criteria weights and scoring options for each performance criterion (DTLR Manual, 2006). It is well recognized that Keeney and Raiffa (1976) first established a complete description on multi-criteria decision theory. The authors systematically explained decision trees, the determination of objective(s), and the attribute selection process and expected utility rules.

2.6.1.2 Multi Attribute Utility Theory (MAUT) Application

Since Keeney and Raiffa (1976) established the MCDM approach, it has subsequently been applied in many real world decision-making processes. Elmisalami (2001) has used MAUT methodologies in his model for selecting information technologies in the construction industry. Park (2004), in his "multi-criteria decision models for seismic rehabilitation of structural systems", applied MAUT with uncertainty. Srdjevic et al., (2004) highlighted MAUT as one of the important and frequently used MCDM tools for agriculture and water management projects. Srdjevic et al., (2004) also mentioned common methods for solving MAUT problems are Analytic Hierarchy Process (AHP) (Saaty, 1980), Simple Multi-attribute Rating Technique (SMART), SMART with Swing weights, and Outranking methods (PROMETHEE and ELECTRE). Dias and Ioannou (1995) comprehensively used the concept of multi-attribute utility theory to establish 'a desirability model for the development of privately-promoted infrastructure projects.

2.6.1.3 Utility Theory

Utility is a value measuring theory that can handle risk and quantification of worth. Utility theory guides the decision maker in reflecting his value in the decision model through a quantified relative number. For detailed information related to utility theory, a few references are mentioned here (Ang and Tang, 1984; Keeney and Raiffa, 1993; Winterfeldt and Edwards, 1986; Winston, 1993; Hiller and Lieberman, 2001). The multi-attribute utility theory is derived from the work of Von Neumann and Morgenstern (1947), and followed by Savage (1954). Keeney and Raiffa (1976) developed a set of procedures that follows the previous normative-based works to evaluate multi-criteria options in practice (DTLR Manual, 2006).

With some assumptions, developing a multi-attribute function can be simplified (Park, 2004; Nguyen, 1995). The assumptions are as follows:

- Preferentially independent: trade-offs between any two attributes for a particular level will not be influenced by consequences of other attributes.
- Utility independent: utility of any attribute for a particular level can be estimated without considering the utility of other attributes.

Keeney and Raiffa (1993) proved if these assumptions hold for a set of attributes (x_1, x_2,.... x_n) under consideration, then the following statements are equivalent.

- $(x_1, x_2, \ldots x_n)$ are mutually independent with respect to utility
- x_1 is preferentially independent and (x_1, x_j) is preferentially independent for $j = 2, 3 \ldots\ldots\ldots n$ and $n \geq 3$

With this assumption, when $n \geq 3$, the following aggregation functional forms or *multi-attribute utility functions* are adapted (Keeney, 1974):

Additive utility function under uncertainty

$$u(x) = \sum_{i=1}^{n} k_i u_i(x_i) \tag{2.1}$$

The multi-attribute additive utility function is appropriate only if the attributes hold additive independence among them (Keeney and Raiffa, 1993).

Multiplicative utility function

$$ku(x) + 1 = \prod_{i=1}^{n} [kk_i u_i(x_i) + 1] \tag{2.2}$$

Where

u (x) utility functions and normalized to scale from 0 to 1

$u_i(x_i)$ are utility functions of attribute i, normalized to scale 0 to 1

k_i scaling factor to keep individual attribute assessment consistent with overall assessment u (x) and $0 < k_i < 1$

$k > -1$ is the non-zero scaling constant and is the solution to

$$1 + k = \prod_{i=1}^{n} (kk_i + 1) \tag{2.3}$$

The multiplicative utility function (2.2) reduces to the additive utility function (2.1) when

$\sum_{i=1}^{n} k_i = 1$ (k becomes 0).

2.6.1.4 Value Function

Many experts proposed a value function instead of a utility function to evaluate multi-attribute problems, even under uncertainty. According to De Neufville (1990), a value function determines the preference order of alternatives or ranked alternatives, when considering a single attribute. Gardiner (1974) asserted that when a choice involves no risk, this implies that the choices are not based on a lottery. Therefore, the outcome can be presented by a value function.

Under certainty conditions, if the attributes sustain the condition of mutually preferential independence for evaluation, then in the case of n $\geq$ 3 attributes, the additive value function will be as follows (Keeney and Raiffa, 1993):

$$v(x_1, x_2, \ldots\ldots\ldots, x_n) = \sum_{i=1}^{n} v_i(x_i) \tag{2.4}$$

v_i is value function for i th attribute

Winterfeldt and Edwards (1986) advocated that the use of a value function instead of a utility function is reasonable due to the following reasons:

1. Where lotteries are involved, there are no sure things, where all outcomes are without risk.
2. A value function built with sound strength-of-preference judgments may reflect the risks and attitudes as a utility function.

3. In case of repetitive choices someone can argue that all choices are repetitive (for more detail, please refer to Winterfeldt and Edwards, 1986).

Winterfeldt and Edwards (1986) presented an overall evaluation function *v(x)* of multi-attributes of an option/alternative (*x)* as a weighted addition function. This addition function is one of several aggregative functions. Using notation outlined by Schäfer (2006), the overall value function is as follows:

$$v(x) = \sum_{i=1}^{n} w_i v_i (x) \qquad (2.5)$$

Here, $v\ (x)_i$ is the value function of attribute i and w_i is the weight of attribute, n is the number of attributes (number of dimensions) $\sum_{i=1}^{n} w_i = 1$

2.6.1.5 Decomposition process in MAUT

The evaluation process in MAUT is broken down into different levels of objectives and the objectives are achieved by evaluating the attributes for each alternative. Overall evaluation of an option is accomplished by combining all single attributes into a single aggregative function (Elmisalami, 2001).

2.6.1.6 Hierarchical Structure in MAUT

All multi-criteria decision problems are involved in achieving objectives at different levels and with various scopes. The main objective(s) always represents the higher level objectives. These higher level objectives can be divided into lower level objectives. The answers to the questions regarding the importance and relevancy of low-level objectives with their higher level objectives will determine the effectiveness of the model (Pitz, 1984, Keeney and Raiffa, 1993, Elmisalami, 2001).

2.6.1.7 Construction of Subjective Attribute Scale

There are many objectives, for which no-objective indexes exist and to measure attributes under that objective, a subjective attribute scale is needed (Keeney and Raiffa, 1993). The basis of using a subjective scale should be to measure the attribute's ability of meeting the objectives.

2.6.1.8 Weighting of Attributes

In the multi-attribute evaluation process, the evaluator assigns weights to each attribute, which reflects the degree of importance and contribution of the attribute in the overall utility function. The importance attribute weight will reflect the range of variation in the attribute measuring scale, which can result in the elimination of the attribute (Elmisalami, 2001).

2.6.1.9 Uncertainty Issues

Considering time dependency, current evaluation for preference or performance may not be certain in the future. The reliability or validity of information may be in question when used for evaluation work (Cook and Campbell, 1979).

2.6.2 The Analytic Hierarchy Process (AHP)

2.6.2.1 Overview

Saaty developed the Analytic Hierarchy Process (AHP) method in 1977 and published his book 'Analytic Hierarchy Process' (1980). This is a decision analysis technique, which is characterised by the utilization of pair wise comparisons among decision parameters. Saaty (1991) stated AHP as a general theory of measurement. This technique helps to simplify a complex problem by decomposing multi-criteria complex problems into a hierarchal structure. By adapting AHP, decision makers can apply knowledge, experience, and rational judgements to determine the priorities among alternatives.

2.6.2.2 Applications of AHP in MCDA

The Analytic Hierarchy Process (AHP) has been applied intensively in many MCDA studies in a variety of fields such as planning and resource allocation, making resolutions for conflicts and for prediction purposes (Saaty, 2001). AHP or AHP in combination with other multi-criteria decision techniques (MCDT), have been successfully applied in the field of construction management such as contractor selection process, evaluating project delivery systems, and some of the studies that been referenced (Al-Harbi, 2001; Cheung, 2002; Al-Tabtabai and Thomas, 2004; Al Khalil, 2002). For developing a desirability model for 'privately-promoted infrastructure', Dias and Ioannou (1995) had utilized AHP for weighting the parameters. In the study of developing a model for assessing productivity of piling work, Zayed *et al.* (2004) applied AHP with fuzzy logic techniques, where the model considered ten qualitative productivity factors for evaluation

2.6.2.3 Basic Principles of the AHP Technique

Saaty (1980) proposed s few axioms for AHP. Referring to Nguyen (1995), these axioms are represented in *Appendix-C.*

2.6.2.4 The Assessment Activities in AHP

The major activities in the AHP assessment method are to determine the relative importance (weight) of the model parameters, measure the preference level of each alternative and obtain an overall ranking of alternatives (Nguyen, 1995). The reader is referred to Saaty (1982), Dias and Ioannou, (1995) and *Appendix-C* for a detailed procedure of assigning relative weights.

2.7 Drinking Water Treatment Plant Assessment Guidelines/Models/Tools

2.7.1 Overview

In general, all the assessment protocols introduced from different levels of governments have given primary emphasis on water quality. To ensure good quality water, the condition of all plant elements is needed to perform at a minimum expected level. The assessment guidelines deals condition assessment of plant elements up to a certain level and based on water quality. The condition assessment is a major concern when systematic asset management or need analysis programs take place.

2.7.2 Assessment Guidelines

The Ministry of the Environment (MOE) of Ontario has developed the *'Drinking Water Inspections Protocol'* (the Protocol) to guide its drinking water inspections for assessment purposes (in effect as of 2002). This comprehensive protocol includes the inspection of source, treatment and distribution of drinking water systems. It addresses the recommendations of the Walkerton Inquiry (the O'Connor Report), parts one and two. Some recommendations from part one of the reports is stated below:

- The development of a more comprehensive inspections protocol
- A continued commitment to annual inspections
- Adequate resources to inspect municipal water systems
- Systems with significant deficiencies be inspected at least once per year
- A combination of announced and unannounced inspections

- There will be a timelines for preparation and delivery of inspection reports and operator responses.

The report also stated that inspections should address the protection of drinking water from source through to distribution. In addition, the inspector should ensure the adoption of sound management practices and encourage the adoption of best practices.

According to Guidance for Safe Drinking Water in Canada: (2001) From Intake to Tap "the assessment of the drinking water supply forms the basis of all activities related to providing the cleanest, safest, most reliable drinking water to the public." Therefore, the comprehensive assessment process should identify the characteristics of the water source, potential hazards and risks caused by those hazards. In addition, the process should allow the determination of the best management practice to mitigate these risks. The guideline also dealt with third party evaluation and audits. Some of the suggested areas of focus for the audit are as follows:

- Construction audits
- Operational audits
- Treatment performance audits
- Design professional audits

British Columbia in its Comprehensive drinking Water Source to Tap Assessment Guidelines (2005) provides a systematic methodology for the complete assessment of works, through 8 modules, sequentially shown in Figure2. 2.

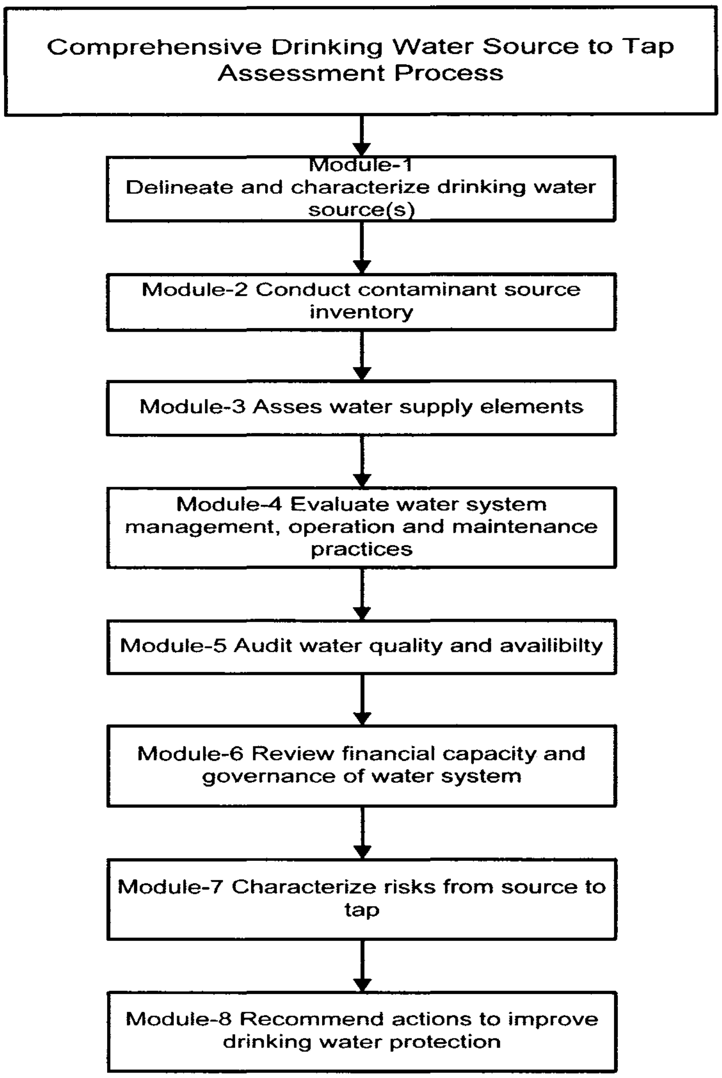


Figure2.2 Water source to tap assessment process (adapted from BC Guideline, 2005)

Activities under modules 3 and 4 cover the condition assessment steps including treatment plant elements. According to the guideline, Module 3 deals with the assessment of water supply elements, which includes inventory, condition evaluation, suitability and security. Module 4 focuses on the evaluation of management, operation and maintenance practices.

Saskatchewan developed the Waterworks System Assessment (WSA) Standards, with the intention of assessing all factors related to water infrastructure from source to end user. According to WSA standards, the following should be included:

- Treatment process
- Treatment components
- Equipment condition and sizing
- Design capacity
- Control and instrumentation
- Chemicals applied and their dosage
- Operation and maintenance practices etc.

The Pennsylvania Department of Environmental Protection has been conducting detailed evaluations of the state's surface water treatment plants. The on-going program, known as Filter Plant Performance Evaluation (FPPE), consists of a filter plant evaluator using several pieces of information in order to establish a final rating. These pieces of information include:

- Operational control of the plant, especially chemical pre-treatment and filter operation;
- Physical condition of the plant and its equipment;
- Water quality data, including the plant's long-term turbidity performance and turbidity and particle count profiles of one of the filters; and,
- Results of the Microscopic Particulate Analysis (MPA) (FPPE, 2005)

2.7.3 Assessment Models/Tools

The Philadelphia Water Department (PWD), under their Capital Facilities Assessment Program, (CFAP) developed a model to assess the current condition of the infrastructure of the water treatment plant. The elements considered for the models are key piping systems, major concrete and steel structures, concrete joints and pipe support systems. The main objectives of the model were: a) to identify the criticality of the concerned elements, b) to select alternatives for repair, rehabilitation or replacement work, c) to create a set of criteria and assign weights for evaluation processes and d) to select the most cost effective repair technique after performing proper screenings. The PWD hired a consultant to perform the aforementioned tasks and to give a structured form of the infrastructure model (Blair *et al.*, 2002).

- Conduct detail inspection
- Assess the current condition of concerned systems/elements
- Determine remaining service life
- Propose rehabilitation/replacement options for critical elements
- Prepare a preliminary design with cost estimation for selected options
- Create a design package for bidding

For the alternative evaluation phase, the following criteria were considered (Blair et al., 2002):

- Constructability
- Structural Integrity
- Corrosion Protection
- Water Quality impact
- Maintenance concerns
- Safety concerns and
- Construction cost

The infrastructure model adapted from PWD's CFAP study is as shown in Figure2.3

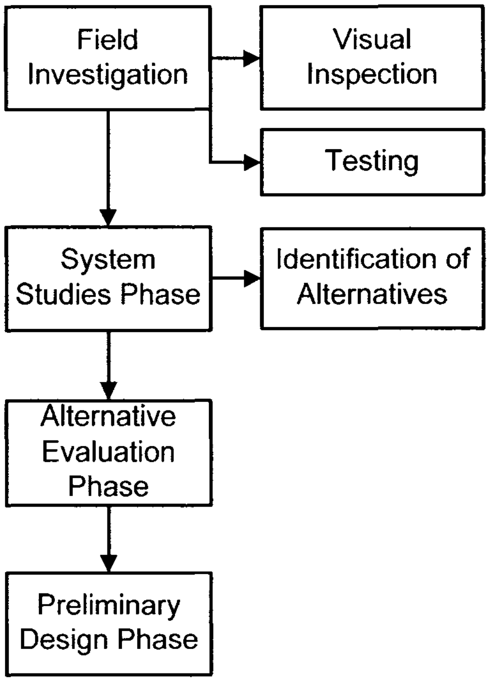


Figure2.3 Infrastructure model

The infrastructure model is plant specific and the environmental factors are not accounted for. *IRC Canada has developed a "Decision-support software tool' under its* Urban Infrastructure Rehabilitation program. This tool can be used for condition assessment of pipelines, to determine the remaining service life of pipes and conduct analysis of pipe failures. Historical inspection data including NDT test results can be fed in this tool. (Construction Innovation, 2004)

For assessing equipment conditions, ExpertALERT™ provides critical machinery health information instead of vibration data, by rapidly screening vibration measurements and by applying over 4,500 unique rules to identify individual faults in a wide variety of machine types (ExpertALERT™ , 2006)

Markov Latent Effects modeling: "Threat Assessment of Water Supply Systems Using Markov Latent Effects Modeling" explained how MLE modeling could be applied within the context of threat assessment in water distribution systems. Integral to the vulnerability evaluation of a system is the threat assessment. By adapting a vulnerability evaluation process, the credibility of a threat is quantified. There is insufficient experience and/or data to quantify the associated probabilities in full scale. For these reasons, investigators proposed a method predicated on Markov latent effects (MLE) modeling, which provides a framework (Figure2.4) for quantifying imprecise subjective metrics through probabilistic or fuzzy mathematics.

To account for all hidden factors without any negligence, the following steps were taken:

1. Recognize environmental constraints and threats.
2. Determine the management philosophy that is established within that environment.
3. Evaluate the working conditions.
4. Assess the risks inherent in actual operation.

This approach helps to identify risks, to determine reasons for problems might arise and to identify what can be done to improve overall integrity and correction measures (Tidwell et al., 2005). Lalonde and Prince (2003) introduced an innovative approach for condition assessment using hydraulic models: Integrated Decision Support Systems (IDSS) gives the opportunity to use information by combining multiple sources and specialized systems, such as hydraulic models. A condition assessment of water infrastructure is governed by structural integrity, performances (productivity, water quality) and hydraulic capacity. Lalonde and Prince (2003) mentioned following steps for conducting a complete condition assessment of a city water distribution system using hydraulic modeling.

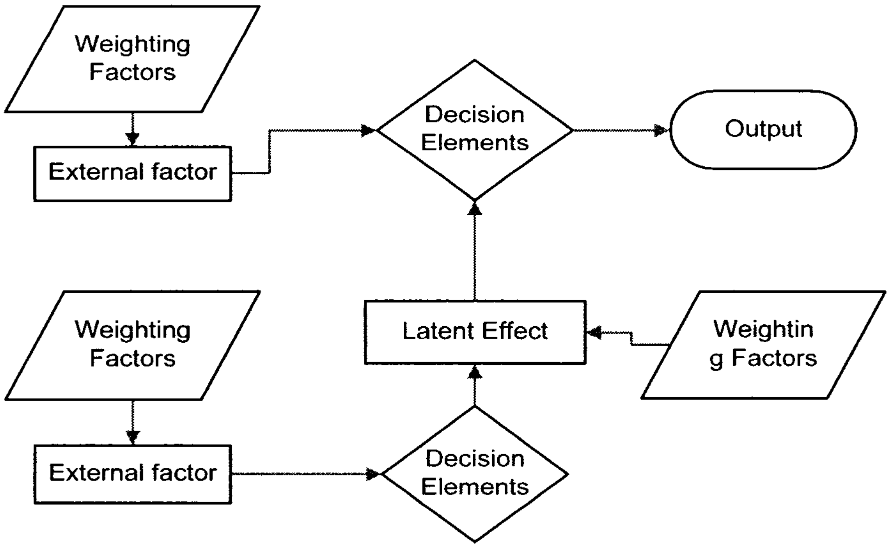


Figure2.4 Basic MLE Model structure (adapted from Tidwell, 2005)

- Data management (data sources identification, updated, avoid duplication, easy access)
- Validation of data (determination of level of precision and trimmed out database
- Actual condition analysis through index structure of Harfan condition assessment which covers structural and hydraulic factors.
- Access to condition assessment results through GIS
- Future condition rating using deterioration curves

Data source and attributes considered in the study are shown in Table2.3

Table2.3 List of sources of information related to condition assessment (Adapted from Lalonde and Prince, 2003)

Source	Attributes
AutoCAD drawings	Location, size, material etc.
Customer files Public works database	Water consumption Fire flow tests, pressure tests, Hydraulic inspection, water main break history
Engineering files Hydraulic Model	Past lining projects (cost) Model fire flows, Model Pressure, "C" Factors, Water main Age
Water treatment files	Water quality testing

The main features of index structure for the Harfan condition assessment are adapted from their model flow diagram as shown below (Figure2.5).

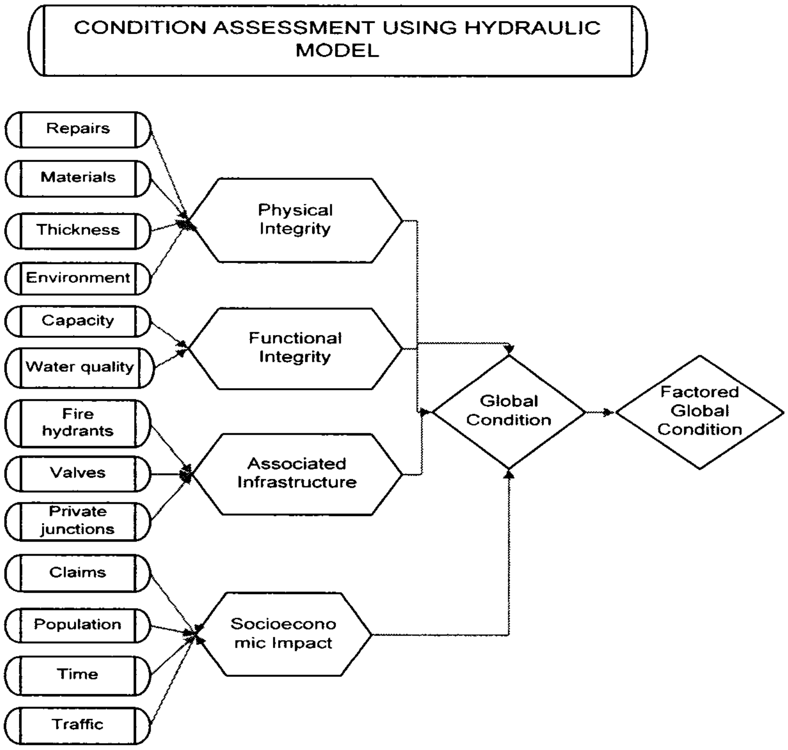


Figure2.5 Index structure of the Harfan condition assessment for water Infrastructure (Adapted from Lalonde and Prince, 2003)

2.8 Condition Rating Scale

2.8.1 Overview

A condition rating scale (CRS) will provide drinking water authorities with an effective aid for categorizing their assets and infrastructures after performing systematic condition assessment. This categorization is important to the prioritization and budget allocation in future drinking water projects. Literature reveals that across North America, standard condition rating practices for DWTP infrastructure elements are still not up to the mark. In the literature, there are some examples of using CRS for water main and sewer line assessment but most of the municipalities follow their own methodology for assessing elements of DWTP under their asset management policy. Within the drinking water sector, application of asset management practices in North America is still is a new concept. Australia, U.K. and New Zealand's have made substantial progress in asset management practices including drinking water sectors and they use standard condition ratings after systematic condition assessments (Causey, 2005; GMAS, 2006). The condition grading systems are scaled from 1 to 5; where, generally 1 indicates the best condition and 5 represents the worst condition. In the following sections, some examples of CRS are being discussed as references in the sections to follow.

2.8.2 Examples of CRS

The Australian Government Asset Management System suggested two types of condition ratings. The first one grades the assets according to strategic importance and based on the condition index (CI), shown in Table2.4. The second one graded assets based on the level of criticality instead of CI, shown in the Table2.5. These grading approaches are more effective when the task involves more than one facility. The measurement of CI and the level of criticality ranged from -4 to +4 and 1 to 5 respectively (where a CI of +4 represents the best condition and -4, the worst condition; criticality level 1 indicates that the condition is not critical and 5 indicates very critical).

Table2.4 Condition Index & Asset Strategic Importance (Adapted from GAMS-2006)

Condition Index	**Asset Strategic Importance**				
	1 Exceptional	**2 High**	**3 Average**	**4 Low**	**5 Very Low**
+2 to 4	Re-assess 1-2 years		Immediate Re-assessment of Suitability		
+1	Re-assess Condition in 1 - 2 years				Immediate Re-assessment of Suitability
0	No Action — Review in 1 Year				
-1	Urgent Action		Action Within 1 Year		
-2 to -4	Urgent Action				

In its Local Government's Manual, the State of New South Wales (NSW) of Australia, recommended a universal five-point scale of asset condition assessment with a specific asset condition rating (Walker et al., 1999). The scale accounts for only the physical condition and does not specify any point which can be considered as a satisfactory condition of an element. The subjective meaning of level 1 and 5 implies a near perfect and unserviceable asset respectively. Therefore, an increase in level indicates an increase in the deterioration of the asset. Some councils interpreted the concept of a ``satisfactory condition" as equivalent to the "desired condition" and defined as a recognized desire to upgrade existing facilities through various capital works programs (Yarrowlumla, NSW,

Table2.5 Criticality & Asset Strategic Importance (Adapted from GAMS, 2006)

Criticality	**Asset Strategic Importance**				
	1 Exceptional	**2 High**	**3 Average**	**4 Low**	**5 Very Low**
1	No Action Required — Review at next assessment				
2	Action within 5 Years		Monitor & Take Action as Required		
3	Rectify within 3 Years				
4			Rectify within 5 Years		
5	Rectify within 1 Year				

Council 1995-96 Annual Report, p. 26). Table2.6 summarizes the form of assessments on the physical condition of infrastructure reported by 176 councils of NSW in the year 1995-1996 or 1994-1995 annual reports. Eighty per cent of reported councils provided some information about the physical condition of public works and only eight (5 per cent) of these have used the rating systems recommended in the manual. Data shows some council has developed a more sophisticated asset rating system than the one suggested in the manual.

Since the early 90's, OFWAT in the UK introduced a five point grading system for water and sewerage companies to assess their non-infrastructure assets. These non-infrastructure assets consist mainly of surface assets such as water and sewage treatment works, sludge treatment facilities and company buildings. After receiving assessment reports, OFWAT examines overall trends in a range of indicators over several years, to make judgments on capital maintenance works. According to OFWAT (2000) report, their assessment is based on the concept of serviceability rather than physical condition. The suggested grading system is described briefly in Table2.7.

In Ireland's National Report (2000) on water, a scale of 1 to 5, has been established as a standard methodology, to assess water supply related assets. The report also suggests and assigns a data assessor and provides an estimate for the asset condition based on this CRS. The assets need to be assessed for overall condition and functionality and must be graded accordingly. The condition grading scale is shown in Table2.8 and has been adapted from volume 2 of the National Report on Water Supply, Ireland.

Table2.6 The form of assessments on the physical condition of infrastructure reported by 176 councils of NSW (Source: 1995-1996 annual reports for 170 councils and 1994-1995 reports for six others)

Rating System	Brief Description of Rating system	Asset Type		
		Bldg.	W.S.	Trn.
Recommendation in manual	General asset condition levels, level 1 (near perfect condition), through 3 (serious deterioration) to 5 (deterioration rendering the asset unserviceable	4	-	7
2 Point Scale	Unsatisfactory-satisfactory	33	14	25
3 Point Scale	Poor-fair-good; poor-adequate-good	6	7	5
4 Point Scale	Poor-fair-satisfactory-good	1	1	1
5 Point Scale	Poor-fair-average-good-excellent (10%, 30%, 50%, 70% and 90% life remains); unserviceable-poor-fair-good-very good (0%, 25%, 50%, 75% and 95% life remains); failed-poor-fair-good-new;	2	-	9
6 Point Scale	5-0 scale: poor ± index in excess of 3, fair-between 2 and 3, satisfactory ± 0, 1, 2, as new = 0; 5-0 scale: poor-satisfactory-fair good- as new	1	-	4
10 Point Scale	1-10 rating; 0-9 rating	-	-	4
11 Point Scale	0-10 rating, with 0 being the lowest and 10 the highest	1	-	2
Condition assessment scale unclear	Many councils disclose only some elements of the condition assessment scale used and do not provide full scale details	52	46	47
Descriptive statements of work Required only		15	16	29
Other forms of physical condition Description	Use of percentage of optimal or satisfactory condition	4	5	7
No information on physical condition		57	25	36
Total	Not every council controls water supply	176	114	176

Table 2.7 Water and Sewerage Non-Infra. Assets Condition Grades (OFWAT, 2000)

Condition grade	General Meaning
1	Sound modern structure, operable and well maintained.
2	As 1, but showing some minor signs of deterioration. Routine refurbishment and maintenance required.
3	Functionally sound, but appearance significantly affected by deterioration, structure is marginal in its capacity to prevent leakage, mechanical and electrical plant and components function adequately but with some reduced efficiency and minor failures.
4	Deterioration has a significant effect on performance of asset, due to leakage or other structural problems. Mechanical and electrical plant and components function but require significant maintenance to remain operational.
5	Serious structural problems having a detrimental effect on the performance of the asset. Will require major overhaul/replacement in short term.

Table 2. 8 Asset Condition Schedule (National Report, Ireland, 2000)

Condition Grade	Description	General Meaning
1	Good	Sound, well maintained modern facility. All aspects of asset fully operable. Generally refers to new or recently fully refurbished assets.
2	Fair	As per 1 but showing superficial wear and tear. No need for immediate work but will require re-inspection in the medium term.
3	Adequate	All asset components functioning acceptably but showing obvious wear and tear. Regular reports of minor failures. Requires regular maintenance but has not yet outlived its functional life. Not yet scheduled for replacement or major refurbishment.
4	Poor	Asset functioning with significant problems and frequent failures. Scheduled for replacement / refurbishment within the next 1 to 2 years. Functionality severely disrupted. Or design life exceeded but still functioning to some degree of adequacy but operating costs above the norm.
5	Decrepit	Out of commission due to poor structural integrity, safety concerns, contamination concerns, uneconomic and/or major components inoperable / unsafe. This asset has lost functionality and requires immediate replacement

2.9 Current Research Approach

After reviewing previous studies on the assessment of drinking water treatment plant elements, many initiatives were taken emphasizing various issues. Water works associations, city or municipal water departments and water regulatory agencies of upper level governments rather than individual initiatives to assess the DWTP, performed most of the studies. The DWTP assessment studies were concerned about water quality, vulnerability and compliance issues, with the exception the infrastructure model from PWD's CFAP study. In many cases, condition assessment was an integral part of standard asset management practice. Detailed guidelines for condition assessment have been adapted in the UK, New Zealand and Australia. Unlike those countries, asset management of drinking water sector is in its infancy in North America. At present, condition assessment has become a growing concern with the encouragement of establishing effective asset management practices in North America. There is not a single study that has been identified that only deals with condition assessment of DWTP elements and where all condition affecting parameters are accounted for. The current condition assessment study includes a selection of a few DWTP elements, identification of condition affecting parameters in a global perspective and parameter contributions to element conditions are measured, covering all possible scenarios in its life cycle (design stage to end of life). AHP and MAUT approaches introduced a deterministic condition assessment model and uncertainties were accounted for by applying Monte Carlo simulations. Finally, two prototype condition-rating scales (CRS) were proposed, based on study results. The scales also verified by the experts.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter will provide a chronological description of all actions that have been accomplished to complete the current study of condition assessment for selected DWTP elements (Fig 3.1). Study problem, objective and scope are briefly discussed in introduction. A comprehensive literature review is conducted for the study. This is followed by data collection, data analysis, and model development using AHP and MAUT techniques, condition rating scale development, sensitivity analysis and analyzed probability distribution. Finally, web version of the model is developed to introduce a web-based condition assessment tool for the practitioner involved with an assessment of DWTP elements. These tasks will be discussed in the following sections:

3.2 Literature Review

A very comprehensive literature review has been conducted to give a strong foundation of the current study. At the beginning of literature review, targeted elements of DWTP are introduced with brief descriptions. The reader is then introduced to the concept of condition assessment and asset management. One of the most important parts of this study is to identify condition parameters. Therefore, the literature review focuses on the factors considered in the previous assessment studies or guidelines for DWTP elements. A general condition assessment process requires inspections and a series of tests. At this stage, conventional testing and inspection methods are reviewed from previous studies or guidelines.

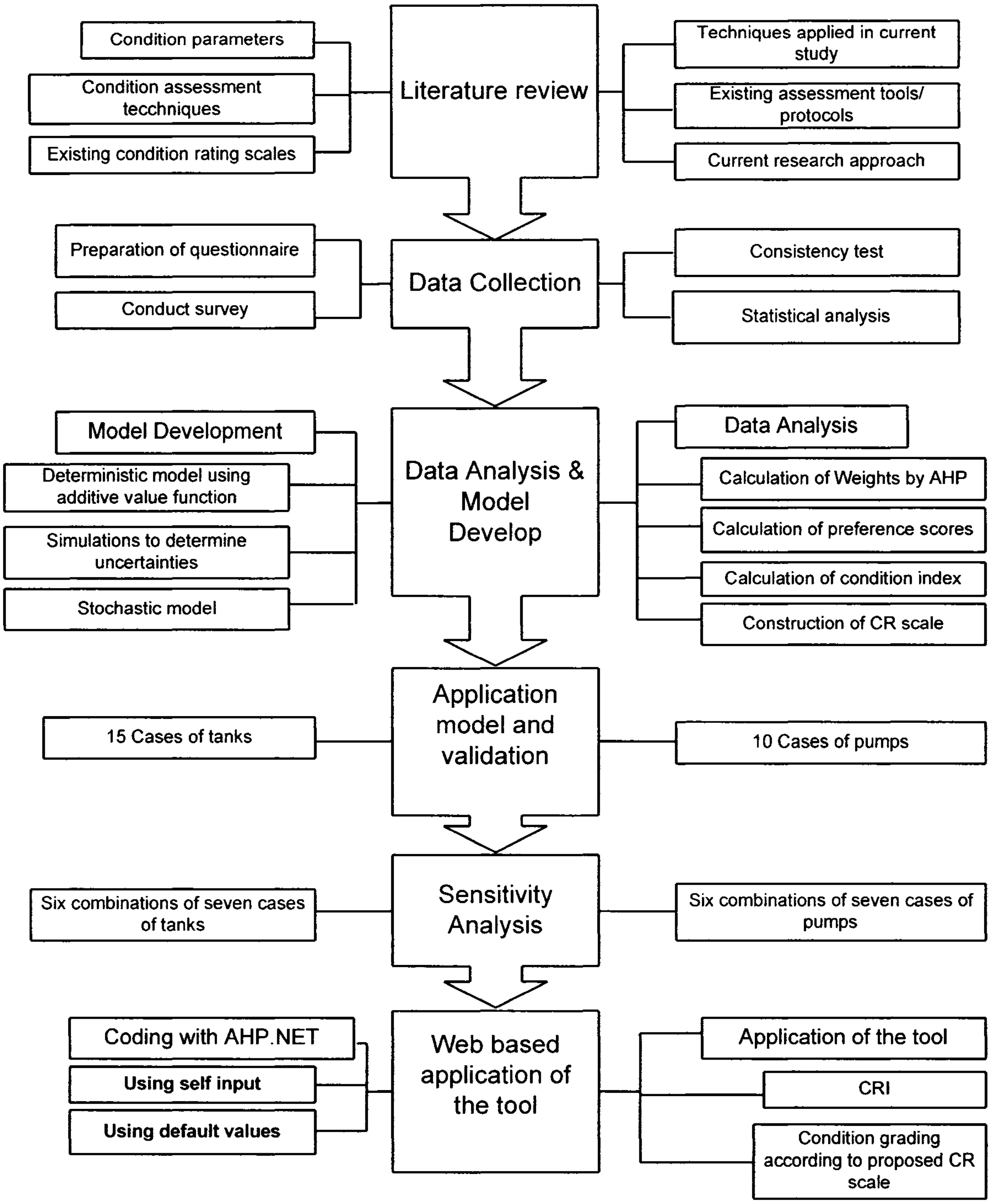


Figure3.1 Research Methodology Diagram

Following the inspection methods, various assessment techniques for condition assessment have been discussed. To develop the proposed condition assessment model, MAUT and AHP techniques are applied. The main features of these two assessment techniques have been covered including their applications in relevant studies. Existing condition rating scales are (CRS) reviewed to justify proposed CRS formation. Finally, briefly current research approach discussed and justified how it is a new initiative.

3.3 Data Collection

Once the model objective, subjects, parameters and assessment techniques finalized, the data requirements also configured. Depending on the requirements, a general data request letter was sent across Canada and responses were not satisfactory. In order to collect the required information, a detailed survey questionnaire was prepared. The target group included operation managers, designers, researchers and regulators. The questionnaire consists of two main parts: 1) contains comparison matrices to estimate weights from Eigen vector (EIV) method and 2) parameters with various condition scenarios to measure preferences in terms of their contribution to the overall condition of an element. Five selected experts tested the questionnaire before sending it to all potential experts. After sending the questionnaire, regular follow-ups were made to explain the concept and clarify further to expedite their response. Seventy questionnaires were sent to the experts and thirty-two (46 %) were completed.

3.4 Development of Condition Rating Model

Once the model objective and subject elements were finalized, the model parameter selection process was initiated. The five targeted elements consisted of three kinds of tanks or basins and two types of pumps.

***The Hierarchy Structure of the Model*:** To develop the multi-criteria condition assessment models, two separate sets of condition parameters were identified. Each set of model parameters consisted of 16 parameters. The parameters were divided into four categories (for more details, please refer to Table 3.1 and 3.2. The models were developed using a detailed hierarchal structure. The top of the hierarchy structure consists of the overall study goal (objective) condition assessment. The model output condition rating index is located at the bottom of the hierarchy. The categories of parameters are considered at level-1 of the hierarchy and the parameters are located under each category at level-2. A graphical presentation of the hierarchy structure of the model is shown in Figure 3.2. In the given hierarchy, categories and parameters for tanks/basins are considered and similarly it can be shown for pumps.

***AHP & MAUT Model Framework*:** After selecting the elements, the condition rating model parameters were defined based on MAUT and AHP principles. A comprehensive survey questionnaire was developed based on the target elements and assessment techniques. The experts provided inputs in comparison matrices to determine the relative importance of parameters. They assigned preference scores for the parameters on the basis of predefined scenarios and on a scale of 0-10 (Figure 3.4). To measure the preferences (utility or value) in terms of condition rating, each parameter was introduced with quantitative or qualitative measures (scenarios). Depending on field conditions scenarios for each parameter were matched with predefined ones. To attain the model output, Eigen-vector categories were used with relative importance weights. The parameters' decomposed weights were subsequently determined. The overall condition rating index (CRI) was obtained from a summation of all products between an individual parameter's composite relative weight and applicable preference scores. To aggregate the CRI for all model parameters, a multi-criteria additive value function was used.

Figure 3.3 shows a chronological flow diagram consisting of the condition rating (CR) model. Finally, the model was introduced with uncertainty by applying probability distributions for each preference score using Monte Carlo simulations.

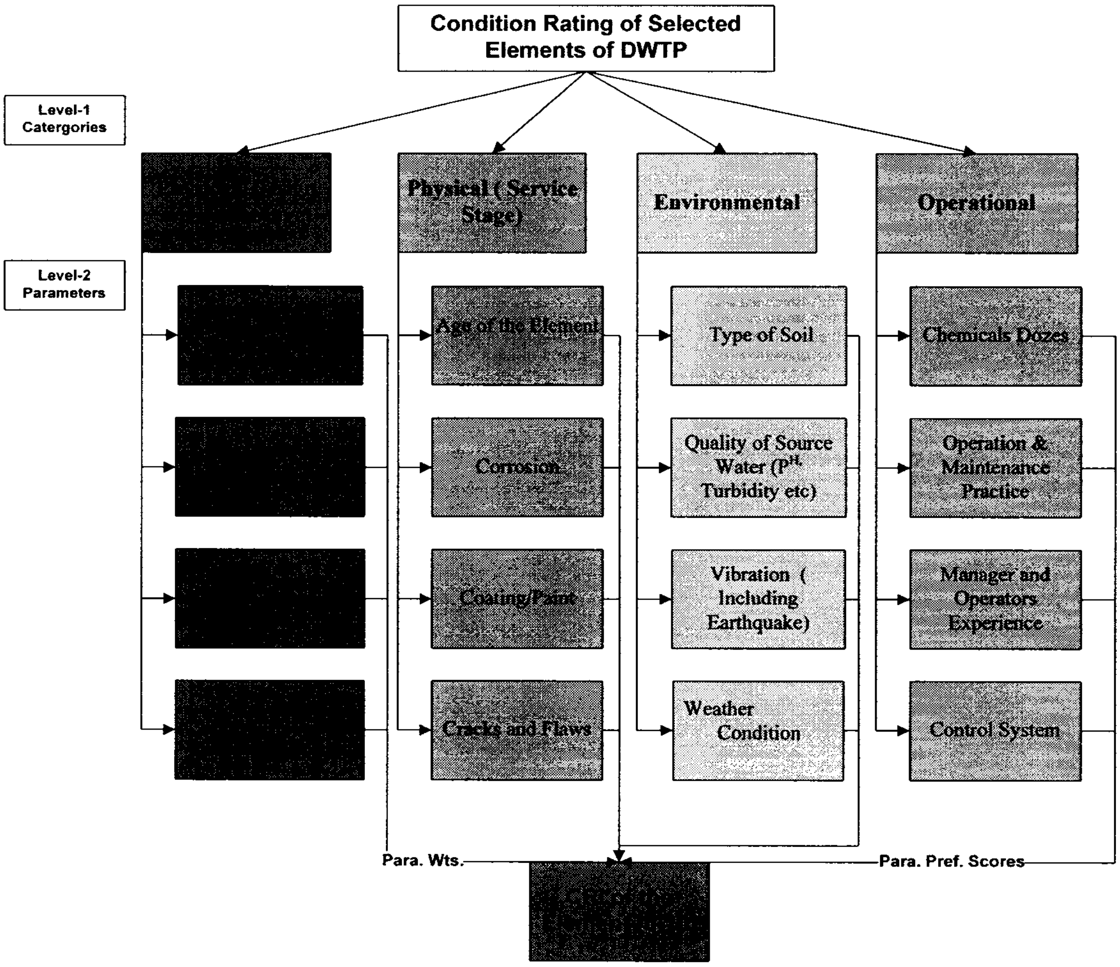


Figure3.2 Hierarchical Structure of the Developed Condition Rating Model

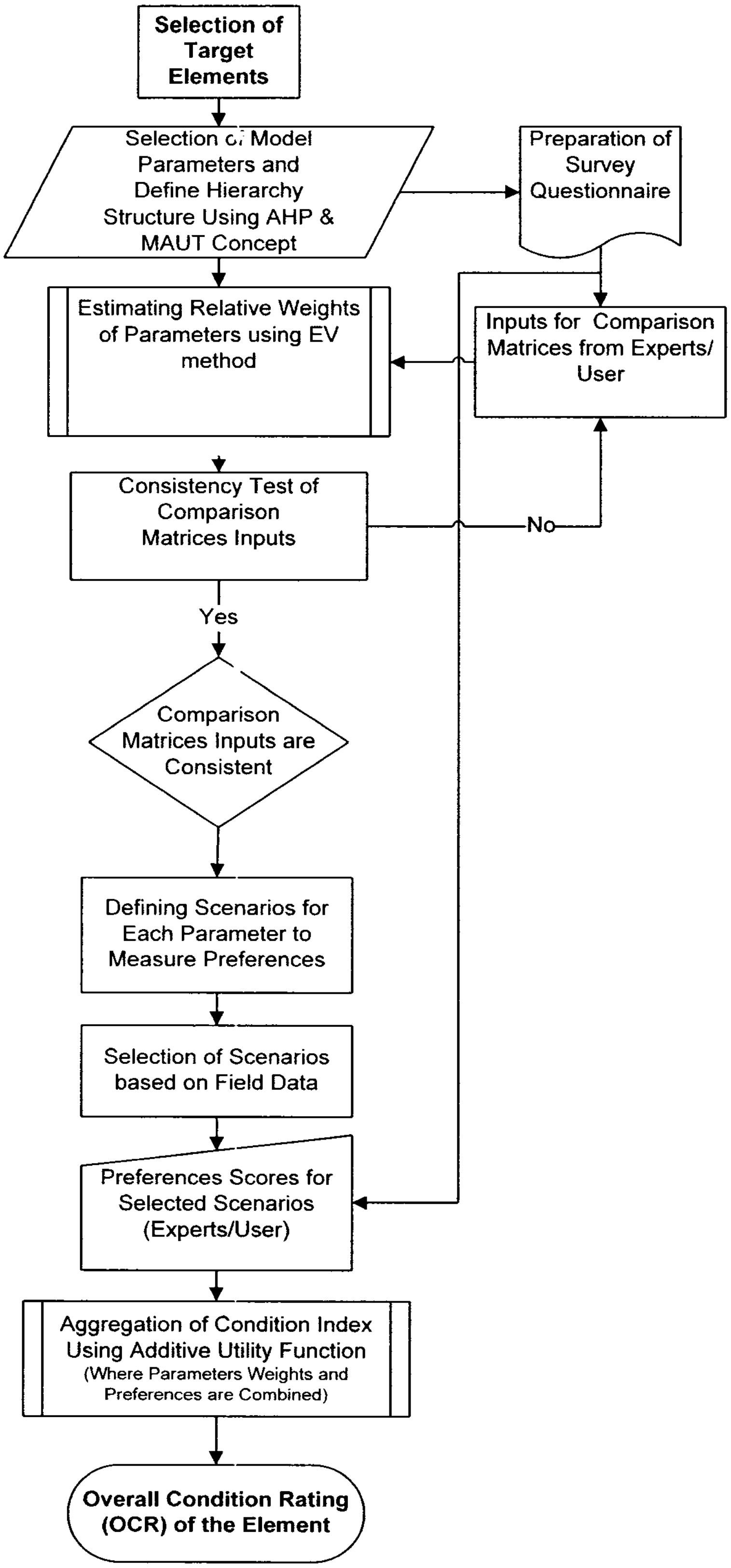


Figure3.3 AHP & MAUT Condition Rating Model Framework

Table3.1Condition Affecting Parameters of Water Production Plant Elements (Tanks/Basins):

Cat.	Parameters	Descriptions
a) Physical (design & cons. stage)	a.1) Design considerations (durability aspects, type of joints etc.)	Considerations of durability aspects, details of jointing and uniformities will have significant contribution to the condition in service life.
	a.2) Material type	Type and quality of materials and equipment used will affect the condition over time.
	a.3) Size & Capacity	Size and capacity may affect its condition.
	a.4) Quality control of cons. works	Levels of quality control during construction works will influence the future condition.
b) Physical (service stage)	b.1) Age of the element	The condition will deteriorate with time and actual age could be an important parameter.
	b.2) Corrosion	Presence of corrosion and its intensity is a significant indicator of current condition.
	b.3) Coating/paint	Quality of coating/paint will affect the condition of elements.
	b.4) Cracks and flaws	Presence of cracks and flaws (size and location) is an important indicator of current condition.
c) Environmental	c.1) Type of Soil	The type of soil will govern the choice of foundation type. Acidity, alkalinity, and presence of detrimental substances will also affect the elements in contact.
	c.2) Quality of source water (pH' Turbidity etc)	A better water quality source will need less treatment and will be less harmful to the infrastructure and equipment.
	c.3) Vibration (including earthquake)	Vibration originating from any source will have an impact on the condition of affected elements.
	c.4) Weather condition	Seasonal variation of temperatures may cause freeze-thaw effects and thermal expansions.
d) Operational	d.1) Chemicals dozes	The type of chemicals and their required doses will affect the condition of elements.
	d.2) Operation & Maintenance practice	Deviation from Standard Operation & Maintenance practice will expedite the deterioration process.
	d.3) Manager and Operators experience	Influences of many other parameters are depending on training and experience of the manager.
	d.4) Control system	A defective control system may cause sudden or long term damage of the elements.

Table3.2Condition Affecting Parameters of Water Production Plant Elements (Pumps):

Cat.	Parameters	Descriptions
a) Electro-Mechanical	a.1) Type of pump	Type of pumps may be one of the major considerations for condition assessment under service condition.
	a.2) Horse power	The power of the individual pump may be one parameter for condition assessment.
	a.3) Starting options	Generally soft-starting options are preferable over conventional starting method for pumps health condition
	a.4) Capacity of pumps	Pump's production capacity may be related to its condition.
b) Physical (service stage)	b.1) Age of the element	The condition of pumps deteriorates with time and the actual age at the time of condition assessment could be the most important parameter.
	b.2) Corrosion	Presence of corrosion and its intensity could be a significant indicator of the current condition of pumps.
	b.3) Coating/paint	The quality of coating/paint affects the condition of pumps.
	b.4) Cracks	Presence of cracks, their size and locations is an important indicator of the current condition of a pump.
c) Environmental	c.1) Quality of source water ($P^{H,}$ Turbidity etc)	If the quality of source water is reasonably bad that is especially harmful for raw water pumps (RWP).
	c.2) Vibration (including earthquake)	Unexpected vibration originating from any sources, including the pump itself, will have an impact on the condition of pumps
	c.3) Temperature	Seasonal variation of temperatures and temperature due to overheating may affect the pump condition.
d) Operational	d.1) Chemicals dozes	Application of chlorine for pre-treatment and for disinfection will have and impact on RWP & Clean water pump (CWP).
	d.2) Operation & Maintenance practice	Deviation from Standard Operation & Maintenance practice will expedite the deterioration process of pumps.
	d.3) Manager and Operators experience	Influences of many other parameters are dependent on training and experience of the managers.
	d.4) Daily pump running time	Like many other machinery, pumps are designed to run for certain running hours and average daily running time should have impact on condition of a in service pump.
	d.5) Control system	A defective control system may cause sudden or long term damage of elements. Manual control systems are prone to be more defective.

3.4.1 Estimation of relative Weights

The Eigen value (EV) method is applied to estimate relative weights. In the first part of the questionnaire, experts were requested to complete the comparison matrices, first for the comparison matrix of categories then for the parameters under each category. All comparison matrices hold the principles stated by Saaty (1980) in his AHP approach. Two sets of matrices were completed for two sets of parameters. Experts were to follow a 1/9 to 9 ratio scale to make their comparisons. After solving the comparison matrices using the Eigen value (EV) method, their consistencies were tested for matrix input. The eigenvectors of the corresponding matrix represents the relative weights of criteria considered in that matrix. Once the matrix satisfies the consistency requirement (C.R. $\leq$ 0.1) then the decomposition principles of the AHP have been applied. The overall relative weight (composite weight) of each parameter is then estimated. If any comparison matrix fails to fulfill the consistency requirements, the whole EIV calculation process must be repeated.

3.4.2 Measuring Preferences of Various Scenarios for Parameters

Each parameter is assigned different scenarios to measure the preferences of parameters in terms of condition rating for certain scenarios, based on a preference measure scale (PMS) of 0-10; (Figure:3.3). Scenarios are defined either quantitatively or qualitatively to measure preferences of a parameter for condition rating on a global perspective. The scenarios are also considered in such a way that they will cover all situations expected in a condition rating process of an element's service life. The scenarios under each parameter for both sets of parameters are shown in part two of the survey questionnaires (Appendix-B). Preference scores can be interpreted as the value or utility of a parameter for the condition under various scenarios. According to Gardiner (1974), the function expresses the decision maker's preferences for any outcome based on lotteries as "utility" When the choices are not based on lotteries is called a "value". De Neufville (1990) defines value as a function that ranks the preference among options for a single attribute without mentioning the intensity of the preferences. Winterfeldlt and Edwards (1986) advocated that making a distinction between value and utility is not logical due to the following reasons, presented as summarized by Dias and Ioannou (1995):

1. There is no such outcome and values that are to be presumed free of risk; in fact all outcomes are attached to uncertainties (gambles).
2. A person adverse to risk can be explained by marginally decreasing value functions.
3. Error and variation in methods of value and utility measurement procedures overshadow the distinction to a great extent.

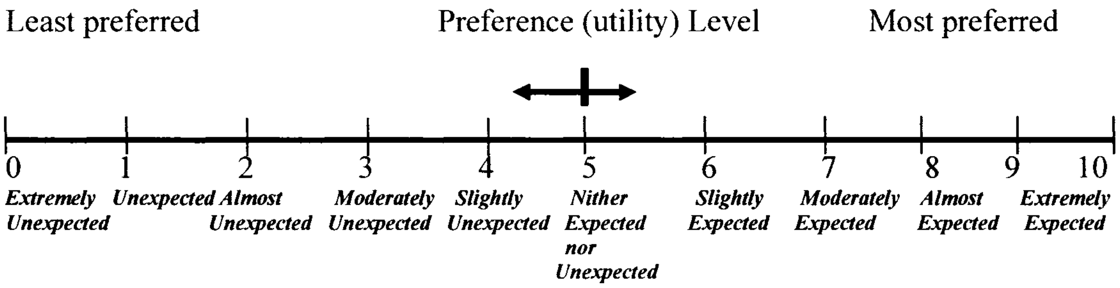


Figure3.4 Preference Measure Scale

In the second part of the survey questionnaire, experts were asked to provide their direct preference scores for all scenarios under each parameter. To judge preference scores, the respondent had to follow the given preference measure scale (PMS). Preference scores are assigned separately for each individual element. Preference scores of 10 and 0 indicate the best and worst scenario condition respectively. Here, preferences are measured according to the given PMS and is not based on lotteries for the following reasons:

1. The objective of the study is to perform a condition assessment of elements where the most likely decision makers will make riskless judgments for preferences based on their experience.
2. Sometimes, there are insufficient options (scenarios) to generate a utility curve.
3. Many respondents are not familiar with the concept of a utility function. Therefore, forcing them to consider uncertainty may mislead their judgments.
4. Considering Winterfeldlt and Edwards view regarding value and utility is acceptable.
5. Probability distribution of survey inputs (preference scores) can be a better presentation uncertainty level.

Each numeric value of the PMS was also qualitatively defined so that a respondent already knows how his/her preference scores will be interpreted qualitatively. A given PMS may reduce the freedom of a decision maker but when a group of experts is involved, a common PMS is required for consistency and uniformity of inputs.

3.4.3 Determination of Condition Rating Index (CRI)

Determining the CRI is the final step of the current model. Applying AHP approach, the relative composite weights of each parameter for both the set of parameters are estimated. Each parameter assigned preference scores by respondents for various scenarios according to a given PMS. For a specific element, scenarios under all parameters are to be defined based on historical data and inspection reports or inspection. Once the scenarios of all parameters are identified, applying an additive value function (equation 2.5), overall condition rating of that element can be determined.

3.4.4 Uncertainty Consideration in the Model

To deal with uncertainty issues, best-fit probability distributions of preference scores were constructed from 32 scores for each scenario using @Risk 4.5. Preference scores for the most preferred and the least preferred scenarios were identified for both set of parameters. The average of the most and the least preferred scenarios scores and the average scenario scores are also estimated for each of the parameters. Therefore, each parameter has three sets of scenario scores, in addition to the predefined scenarios. The best-fit probability distributions were also constructed for these three sets of scenarios (for each parameter). Initially, the CRI is determined from the spreadsheet model, using arithmetic mean (AM) of preference scores. Then instead of applying the arithmetic mean for the preference scores, the best-fit probability distributions of the applicable scenario scores are defined in @Risk in order to determine CRI values. After analyzing the mean CRI values obtained respectively from best-fit distribution and arithmetic means, an uncertainty factor is estimated for each class of elements. The values of the factors may vary with CRI values. The range of minimum and maximum CRI values also indicates a level of uncertainty. To account for this uncertainty, the range of maximum and minimum values in the model is compared to the mean values. Another factor, a constant, is also introduced in the model for each element type. Finally, the element is graded according to a proposed CRS, based on its CRI. The framework of the condition assessment model for elements of DWTP is shown Figure3.4.

3.5 Data Analysis and Application of the Model

Primary data analysis is being done by developing an Excel spreadsheet programming. The spreadsheet enables the use of the EV method to estimate the decomposed relative weights including the consistency test for matrix inputs given by an expert. Besides the relative weights of the parameters on the spreadsheet, the overall condition rating of individual elements can be determined according to that expert, if the scenarios and preference scores are assigned properly. After analyzing the experts' survey inputs, the arithmetic mean of each parameter's decomposed weights and preference scores for each scenario are calculated and applied in the model. Preference curves are constructed based on the average preference scores of scenarios.

The most important aspect of the model is how successfully it can be applied in solving real world problems. Five of the selected experts, directly involved with the operation of the DWTP were requested to match scenarios of each model parameter for the relevant five elements of their plants. Considering that the responses are reliable, the condition rating grades from the CRS are determined from the current model's overall CRI. To validate the model, the variation between the overall CRI and that from the model can be compared. For validation purposes, the experts involved with the case studies are kept aside while calculating the CRI from the model.

3.6 Condition Rating Scales (CRS)

After completing the condition assessment process, the subjective assets need to be classified into grades according to their overall condition-rating index (CRI). Future actions for replacement, rehabilitation or long-term maintenance works for the system can be prioritised based on that condition grading. The overall CRI in this study measured on a scale of 0 to 10. CRI score of 10 means new elements or that the overall condition is like new (most preferred). A CRI score of zero (0) means the overall condition is critical (least preferred) and must be replaced immediately. Based on the overall CRI obtained, the six grades for the proposed condition ratings scale (CRS) are A, B, C, D, E and F. The CRS had been reviewed, modified and verified by experts working within the field. To limit the CRI values for the highest and lowest rating in the scale, the average of all most preferred and least preferred CRI values assigned by the experts have been considered.

3.7 Sensitivity Analysis

Sensitivity analysis is conducted on all case studies, in order to identify how sensitive the preference scores are to the overall CRI of the elements. The sensitivity analysis considered the following different combinations: 1) changes in preference score for all parameters, 2) changes in preference scores for parameters under one or two categories and. Scores were varied up to ± 40%. The constraints that must be followed are that the weights of all parameters always total 1.0 and the preference scores must range from zero to 10. The sensitivity analysis considered two elements, namely the settling tank (ST) and the RWP. Sensitivity results obtained from the ST will be representative of filtration and chlorination tanks, as they all have the same set of parameters. Similarly, results from the RWP will be representative of a CWP.

3.8 Web-based Tool Design

A web-based program was designed using ASP.net and applied to the condition-rating model. The intended web-based condition assessment tool can be used as an aid to the decision support system concerning any future capital planning, rehabilitation and replacement related to the elements. The user will select whether his or her judgement will be used or whether the entire process will depend on a default database created from survey responses. The user will then select the element for which the condition rating is required. Once the element is selected from a default set of parameters, the categories will appear. The user, depending on his/her choice, will be required to make comparisons (based on instructions) starting from categories to parameters under each category, or to proceed directly to the selection of scenarios for each parameter. If the comparisons are user-defined, they must pass a consistency test for comparison matrices. After selecting the scenarios, the user can choose default preference scores or his or her scores according to a scale given in the instructions. The tool will automatically (by using an additive value function), combine the relative weights and preference scores to provide an overall CRI. The assessment tool will now classify the element in a grade according to the proposed CRS with a qualitative interpretation of the grade.

CHAPTER 4

DATA COLLECTION AND PRELIMINARY ANALYSIS

4.1 Introduction

Data collection is one of the most important considerations of this study. Initially, DWTP operators across Canada were contacted to provide real data related to condition assessment. Responses to this initial data request were not satisfactory. As a result, a systematic survey was conducted in order to obtain the required data. All measures have been taken to make the comprehensive survey process meaningful and effective.

4.2 Survey Questionnaires

A detailed questionnaire *(Appendix-B)* was prepared by considering research objectives, target elements, model parameters and assessment techniques. The study results are entirely based on inputs obtained from experts through survey questionnaires. Some of the initiatives for preparing questionnaires were as follows:

- Performing a study on DWTP elements
- Reviewing applications of assessment techniques from literature
- Reviewing previous survey questionnaires used in similar techniques
- Interviewing experts and visiting a few DWTPs in the Montreal area.
- Studying traditional and cutting edge technologies used in DWTP.
- Questionnaire was tested by five selected experts.

The questionnaire is divided into two main parts. In part-I, respondents are introduced to Saaty's 0-9 ratio scale and the construction of comparison matrix satisfying the axioms of AHP. This part contains two sets of sixteen parameters and each set of parameters are divided into four categories. Respondents are required to complete one comparison matrix for categories and four such matrices for the parameters. Therefore part-I consists of 10 comparison matrices to account for two sets of model parameters assigned for tanks and pumps respectively. The comparison matrices are being used to estimate relative weights of parameters using the EIV method.

In part-II, the respondents are introduced to a preference measuring scale (0-10). A preference score of 10 indicates the best scenario for a specific parameter in terms of its contribution to the condition of the elements. While a score of zero means the worst-case scenario. To measure parameter preferences, each parameter from both sets is assigned various scenarios ranging from the conceptual stage to end of life. The concept of MAUT forms the basis for measuring preferences and the given preference measure scale is constructed accordingly.

4.3 Survey Procedures

This survey was different from a traditional survey due to its complex nature. The respondents need to understand clearly the research goal, research approach and the basics of AHP and MAUT. Before sending the questionnaire to all potential respondents, it was tested on five selected experts and the final version was modified accordingly. The major suggestions were to ask respondents to complete only one row of the comparison matrices and to keep the preference score range from zero to 10 instead of 0 to 1 or 0 to 100. Operators, designers, consultants and regulators represent the target group of respondents. The survey questionnaire is designed in such a way that all professionals from the target group will have ample scope to share their view for achieving the study goal from different perspectives. To improve models acceptance level, views of diversified experts working with the DWTP are accounted. This entire group has direct or indirect understanding about condition phenomena of the plant elements.

In the Montréal region, most of the respondents were contacted in person and follow-ups were made by phone and e-mail. Generally, initial contact was made via e-mail across Canada and the USA. Some of the respondents asked for more clarifications and their questions answered accordingly for clarifications. Many respondents preferred to complete the questionnaire over the phone in order to expedite the process and to avoid unexpected mistakes. Survey responses were collected through email, fax and in person. The survey questionnaire was sent to seventy (70) potential respondents from a target group across Canada and the USA. Thirty- two (32) respondents sent back a completed questionnaire. The difficulties, as expressed by the respondents, for completing the questionnaire were as follows:

1. Inability to understand the application of Saaty's 1-9 ratio scale, especially where to use 1/2-1/9 as comparison inputs.
2. Inability to follow comparison rules (i.e. row item will be assigned an importance rating and this will be compared to each corresponding column item).
3. Completion of a comparison matrix with consistency was too time consuming
4. According to the utility theory, the most preferred and least preferred scenarios should have respectively maximum (10) and minimum (0) scores. In reality, respondents made varied judgments.
5. Sometimes, the respondents failed to make proper judgments that caused inconsistency or contradictory results. The process had to be redone using proper judgments.

4.4 Preliminary Analysis of Survey Inputs

4.4.1 Screening and Modification

After receiving a completed survey response, it was checked thoroughly for the following:

- Missing information
- Major problems with consistency
- Problems associated in understanding the question, thereby leading incorrect input.

If any survey response has missing information, the corresponding respondent is notified about it and a request is made to provide that information. Generally, the respondent preferred to solve the data-missing problem over the phone or resend correct information electronically. Some of the survey inputs are interpreted such that the respondents need more clarification on the survey questionnaire. The corresponding respondents were contacted over phone to clarify them then he/she is requested to make modifications.

4.4.2 Categorization of Survey Respondents

The survey respondents were selected in such a way that all the model parameters could have better judgment in the evaluation process. The model parameters cover the design stage, construction and operational phases. Accordingly, the 32 respondents include operators (17), consultants (5), designers (3), researchers (3) and water resources engineers (4). Figure4.1 displays the percentage of each respondent group, which is dominated by operators (53%).

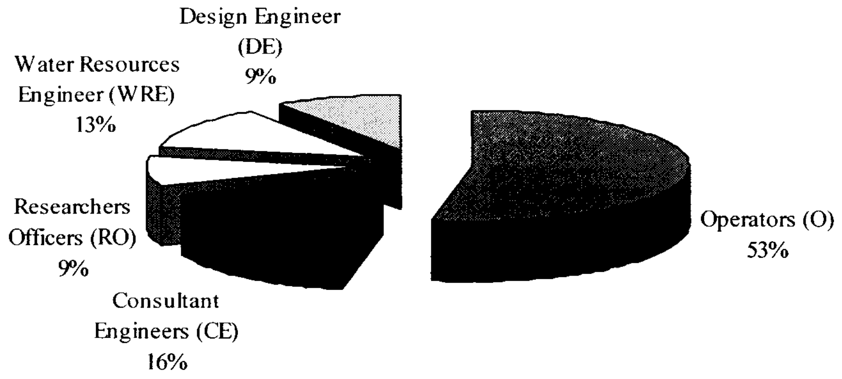


Figure4.1 Categorization of Survey respondents

4.4.3 Consistency Test

The consistency requirement of survey inputs for comparison matrices have been tested on an excel spreadsheet; according to the procedure prescribed by Saaty (1980) (C.R. is ≤ 10%). If any comparison matrix fails to meet the consistency requirement, the respective respondent was requested to make consistent judgments and modify his inputs accordingly. C.R. values calculated from all comparison matrices and completed by survey respondents are shown in Table4.1.

A counter measure of consistency was initiated in order to conclude whether the respondents' are consistent with their judgments after a time gap of at least two weeks. To make this time dependent consistency test, five out of the 32 respondents were selected to redo the comparison matrices after 30 to 60 days of their first response. After comparing the first and second evaluation results, there are found no significant variations in the parameters importance weights (see Table4.2). Variations of more than 20% were rare and most of them were within 15%. Therefore, it is expected that the same

Table4.1 CR (consistency ratio) values of all comparison matrixes completed by 32 respondents

RES.	TANKS					PUMPS				
	All Cat.	Cat_a	Cat_b	Cat_c	Cat_d	All Cat.	Cat_a	Cat_b	Cat_c	Cat_d
RES_1	0.001	0.054	0.002	0.002	0.036	0.000	0.005	0.000	0.000	0.001
RES_2	0.017	0.001	0.008	0.070	0.000	0.004	0.001	0.005	0.063	0.014
RES_3	0.000	0.012	0.026	0.008	0.018	0.000	0.085	0.004	0.000	0.011
RES_4	0.086	0.086	0.080	0.006	0.010	0.011	0.010	0.016	0.031	0.013
RES_5	0.008	0.010	0.005	0.002	0.018	0.008	0.010	0.002	0.009	0.013
RES_6	0.017	0.003	0.002	0.015	0.008	0.004	0.002	0.004	0.004	0.013
RES_7	0.003	0.023	0.023	0.009	0.003	0.029	0.021	0.059	0.009	0.005
RES_8	0.019	0.001	0.020	0.000	0.001	0.089	0.005	0.023	0.000	0.002
RES_9	0.077	0.026	0.042	0.078	0.081	0.025	0.081	0.068	0.052	0.075
RES_10	0.002	0.006	0.006	0.008	0.008	0.000	0.008	0.028	0.000	0.006
RES_11	0.002	0.000	0.006	0.041	0.003	0.002	0.005	0.005	0.000	0.007
RES_12	0.011	0.005	0.002	0.019	0.009	0.023	0.008	0.005	0.004	0.010
RES_13	0.004	0.000	0.000	0.000	0.000	0.018	0.000	0.006	0.000	0.000
RES_14	0.001	0.004	0.001	0.001	0.008	0.002	0.000	0.002	0.014	0.008
RES_15	0.005	0.012	0.002	0.004	0.017	0.030	0.021	0.004	0.005	0.020
RES_16	0.017	0.004	0.004	0.008	0.007	0.017	0.032	0.004	0.037	0.021
RES_17	0.015	0.006	0.006	0.036	0.007	0.017	0.036	0.008	0.018	0.008
RES_18	0.000	0.008	0.000	0.006	0.000	0.002	0.004	0.023	0.005	0.011
RES_19	0.003	0.009	0.002	0.008	0.002	0.006	0.002	0.006	0.004	0.017
RES_20	0.005	0.017	0.003	0.002	0.009	0.010	0.012	0.005	0.001	0.012
RES_21	0.002	0.000	0.002	0.015	0.001	0.000	0.006	0.002	0.018	0.016
RES_22	0.006	0.012	0.016	0.006	0.002	0.013	0.004	0.015	0.009	0.003
RES_23	0.006	0.002	0.000	0.015	0.012	0.000	0.001	0.023	0.000	0.013
RES_24	0.000	0.002	0.017	0.023	0.006	0.000	0.004	0.015	0.000	0.012
RES_25	0.009	0.002	0.006	0.002	0.005	0.011	0.000	0.005	0.014	0.013
RES_26	0.006	0.004	0.004	0.050	0.002	0.008	0.008	0.006	0.004	0.012
RES_27	0.016	0.005	0.004	0.002	0.002	0.002	0.004	0.013	0.004	0.001
RES_28	0.077	0.008	0.016	0.008	0.002	0.004	0.004	0.006	0.021	0.008
RES_29	0.000	0.000	0.008	0.004	0.005	0.000	0.000	0.004	0.009	0.004
RES_30	0.003	0.007	0.004	0.012	0.039	0.017	0.005	0.000	0.014	0.027
RES_31	0.002	0.038	0.015	0.003	0.012	0.016	0.004	0.015	0.003	0.019
RES_32	0.005	0.000	0.008	0.006	0.000	0.011	0.004	0.003	0.000	0.000

variation would result from other respondents and the survey response is truly consistent (not randomly assigned or time dependent).

Table4.2 Maximum and minimum % of variations of respondent's importance weights parameters after 30 to 60 days.

RESPONDANTS	TANK		PUMP	
	MAX	MIN	MAX	MIN
RES_01	22	0.7	12	0.04
RES_09	26	1.34	11	0.18
RES_14	14	0.88	17	0.54
RES_16	17	0.71	23	0.02
RES_29	24	0.45	28	1.36

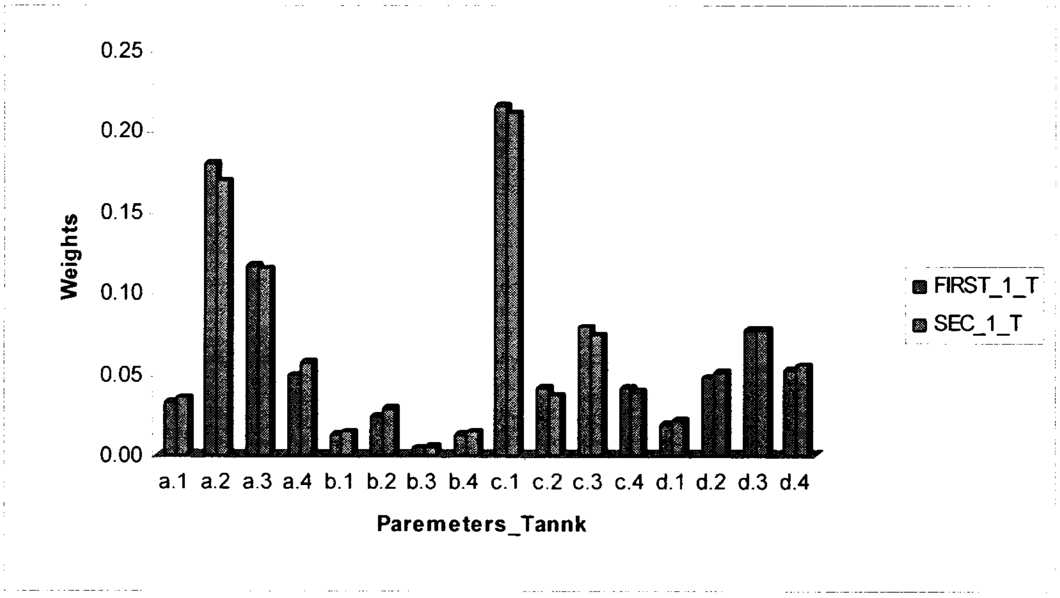


Figure4.2 Comparison of two responses of RES_1for the same set of parameters (tanks) with time gap of one month

As an example, one of the variations from the first and second responses is shown graphically in Figure4.2.

4.4. 2 Probability Distributions of Survey Inputs

The probability distributions (PBD) were developed with the survey inputs obtained for calculating the average preference scores of different scenarios, provided by the survey respondents. The primary reason for generating a PBD with preference scores was to observe statistical features of the survey inputs and results, such as the best-fit distribution, standard deviation, mean and confidence interval. The PBD for preference scores of various scenarios are applied in the simulations (using @Risk4.5) instead of the AM. Thereby uncertainties are introduced in the model for estimating CRI. To construct the PDB of any targeted data set, the data was fed to @Risk and the top ranked PDB fit was chosen from the best-fit list generated by @Risk. As an example a normal distribution of preference scores of scenario b.4.2 (minor) under parameter, b.4 (Crack and flows) for tanks is shown in Figure4.3. The basis for ranking the fits was the results of (1) Chi-squared (Chi-sq), (2) Anderson-Darling (A-D), and (3) Kolmogorov-Smirnov (K-S) tests. It was analyzed whether a data set is consistent with a normal distribution (null hypothesis (H_o)) or rejected and consistent with another type of distribution rather than normal (alternate hypothesis (H_a)). The most important fit results are extracted and presented in tabular form. As an example, one of many such tables (Table4.3) is presented here and some of the tables can be found in the *Appendix-D*, (Tables D.14 to D.19). The extracted results include the mean, standard deviation, the test statistics (TS) critical value (CV), P-value, the lower and upper limits of 95% confidence interval (C) in each of the three tests. After observing the best fit results of preference scores for scenario a.3.2 (Capacity 5000-10,000 m^3/day) under tank parameter a.3 (size and capacity) from Table 4.3, the ST values are as follows: TS-Chi-sq =13.00, TS-A-D =1.88, and TS-K-S = 0.22 and CVs at a 15% significance level are CV-Chi-sq = 8.12; CV-A-D = 0.55; and CV-K-S = 0.13. The lower CV values, when compare to the TS, will imply the non-acceptance of a null hypothesis (normal distribution) at a significance level of 15%. The P-value of any test is also a statistical parameter that shows the probability of rejecting H_o, although it may hold based on the rejection area of the sample. A P-value that tends to zero implies less confidence to the fitted distribution. A P-value tending to one indicates that the fitted distribution has a higher confidence level. In such cases where the significance is lower than the P-value, H_0 should not be rejected.

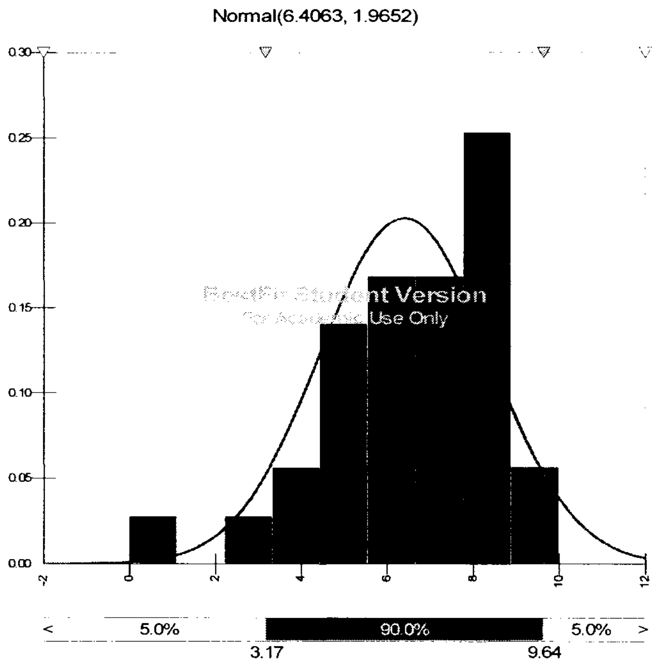


Figure4.3 Normal distribution of preference scores for scenario b.4.2 (minor) under parameter crack and flows.

Table4.3 Best Fit of Preference Scores of Parameters for Condition Assessment

Statistical Item	Statistical Analysis of Normal Distribution Fit								
	a.3.2_T	a.3.3_T	a.4.1_T	a.4.2_T	b.1.1_T	b.1.2_T	b.1.3_T	b.2.1_T	b.2.2_T
μ (min)	8.10	7.52	9.59	0.38	9.44	7.44	5.34	9.81	6.28
σ (min)	1.89	2.39	1.07	0.83	0.84	0.88	1.04	0.54	1.73
TS-Chi-sq	13.00	15.63	98.13	99.63	56.88	49.75	23.88	118.00	11.88
TS-A-D	1.88	1.64	7.64	7.95	4.24	3.95	1.54	9.30	1.14
TS-K-S	0.22	0.23	0.46	0.49	0.37	0.36	0.21	0.51	1.14
P Value-Chi-sq	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.04
P Value-A-D	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
P Value-K-S	< 0.01	< 0.01	< 0.01	< 0.005	< 0.01	< 0.01	< 0.01	< 0.01	0.025 <= p <= 0.05
Confid. @ 95%	0.65	0.83	0.37	0.29	0.29	0.30	0.36	0.19	0.60
μ - C (min)	7.45	6.69	9.22	0.09	9.15	7.13	4.99	9.63	5.68
μ + C (min)	8.76	8.35	9.97	0.66	9.73	7.74	5.70	10.00	6.88
CV-Chi-sq @ 15% =8.12				CV-A-D @ 15% =0.55		CV-K-S @ 15% =0.13			
Data Points =	32.00								

CHAPTER 5

MODEL IMPLEMENTATION AND ANALYSIS OF RESULTS

5.1 Introduction

Following the description concerning the development of the model for condition assessment of DWTP elements in section 3.4, this chapter focuses on the applications of the model and main findings of the study. This multi-attribute condition rating model introduces two techniques, namely AHP and MAUT. Thirty two expert opinions have been incorporated into the model in order to rank model parameters using comparison matrices. Experts also estimated preference scores for each parameter under predefined scenarios in terms of condition status and based on a given preference measuring scale. *Appendix-B* contains the survey questionnaire used for collecting expert opinions. Considering an individual scores for the most and least preferred scenarios respectively, the CRI for each element is determined by applying the model. To observe uncertainty levels in preference scores for each scenario, provided by experts, probability distributions are constructed by using @risk. Results also include the construction of the proposed CRS and validation with experts of the scale, coupled with a sensitivity analysis. Finally, twenty five practical examples are used to validate the developed model and apply it to solve real world problems.

5.2 Applications of the Model

5.2.1 Structure of the Model

Initially, two set of parameters respectively for basins/tanks and pumps, each under four categories were sent to experts for their suggestions regarding any further modification needed on those parameters and categorization for the effectiveness of the model. After considering valuable suggestions from the experts, both set of parameters were fixed at sixteen, under four categories. The details of each set of parameters are given in *Tables 3.1 and 3.2*. The four level hierarchal structure of the model is shown in *Figure 3.2*. Brief descriptions of each category are given below:

5.2.1.1 Categories and Parameters Considered for (Tanks/Basins)

a) Physical (design & construction stage): It is now well established that the current physical condition of any element may have a strong connection with the design considerations and quality of construction. Under this category, emphasis is given primarily on the detail of design parameters, durability aspects, design standard, quality control of construction work and workmanship. The parameters under this category are listed below:

- a.1) Design considerations (durability aspects, type of joints, etc.)
- a.2) Material type
- a.3) Size and Capacity
- a.4) Quality control of construction works

b) Physical (service stage): Condition assessment of an existing element is performed based on its physical condition and performance. Any physical manifestation of corrosion, cracks, flaws, distortions, shape irregularity and unexpected aesthetic view, will have a negative impact on the condition rating. The current age of the element compared to its design life will also have an impact on the physical condition. The parameters under this category are listed below:

b.1) Age of the element (at the time of condition assessment).

b.2) Corrosion

b.3) Coating/paint

b.4) Cracks/flaws

c) Environmental: Environmental factors have a direct impact on the condition of DWTP elements. Exposure to extreme weather conditions, ambient temperature, raw water conditions and soil characteristics will continuously influence the deterioration processes of the plant elements. The parameters under this category are listed below:

c.1) Soil type

c.2) Quality of water source (pH, Turbidity, etc.)

c.3) Seismic activity

c.4) Weather condition

d) Operational: Day to day operational and maintenance activities can be singled out as the most important category that influences the condition of DWTP elements. Experience and training of staffs and managers and the amount and type of chemical doses is also considered under operational activities. The parameters under this category are listed below:

d.1) Chemicals doses

d.2) Operation and Maintenance practice

d.3) Manager and Operators experience

d.4) Control system

5.2.1.2 Categories and Parameters Considered for Pumps

a) Electro-Mechanical: Electro-mechanical considerations on other machinery will have an impact on their condition in service life. Each type of pump is suitable for a specific operation. Capacity, power and starting options may directly or indirectly affect the condition of a pump under service condition. The parameters under this category listed below:

a.1) Type of pump

a.2) Horse power

a.3) Starting options

a.4) Capacity/ hourly production

b) Physical (service stage): Any physical damage, disintegration such as cracks, corrosion and general, wear and tear will determine the current condition of a pump. The quality of the paint and the actual age of the pump also affect the condition of an existing pump. The parameters under this category listed below:

b.1) Age of the pump (at the time of condition assessment).

b.2) Corrosion

b.3) Coating/paint

b.4) any type of Cracks/flaws

c) Environmental: Environmental issues such as temperature, vibration and the quality of water source will accelerate the deterioration of a pump. Temperature and vibration can originate from the pump itself or from external sources. The parameters under this category listed below:

- c.1) Quality of source water (pH, Turbidity, etc.).
- c.2) Vibration (any type)
- c.3) Temperature (including heat generated by pump)

d) Operational: For any pump designed to run for a certain number of hours, the daily running time will have impact on its condition. Any deviation from standard maintenance and operation procedures, as suggested by the manufacturer, may result in a poor condition earlier than expected. The operator's experience and control system may affect the condition of pumps in service. The parameters under this category listed below:

- d.1) Chemicals doses
- d.2) Operation and Maintenance practice
- d.3) Manager and Operators experience
- d.4) Daily running time
- d.5) Control system

5.2.2 Estimation of Relative Weights

5.2.2.1 Construction of Comparison Matrixes

In order to determine the relative weights of all categories and parameters under each category, survey respondents completed one comparison matrix for the categories and four matrices for the parameters. Therefore, to estimate relative weights, each set of parameters require five comparison matrixes. Respondents were instructed that comparison matrixes must satisfy AHP axioms. Comparisons are made on the basis of a subjective ratio scale proposed by Saaty (1980) and numerical inputs in these reciprocal matrixes range from 1/9 to 9. For any comparison element, if $a_{ij} = 9$, then $a_{ji} = 1/9$ and that implies parameter i is more important than parameter j. The diagonal components of the comparison inputs is 1 or '$a_{ii} = 1$'. Ten comparison matrices are presented in *Tables 5.1 to 5.10*, which were constructed by one of the respondents (No. 29), for both sets of model parameters.

Table5.1 Pair-wise comparison matrix for categories (Tanks/Basin)

Categories	Categories	a	b	c	d
a) Physical (D& C stage)	**a**	1	3	4	1
b) Physical (service)	**b**	1/3	1	2	1/2
c) Environmental	**c**	1/4	1/2	1	1/4
d) Operational	**d**	1	2	4	1

Table5.2 Pair-wise comparison matrix for parameters under category-a (Tanks/Basin)

a) Physical (D& C stage)	Parameters	a.1	a.2	a.3	a.4
a.1) Design considerations	**a.1**	1	1	5	1
a.2) Material type	**a.2**	1	1	3	2
a.3) Size & Capacity	**a.3**	1/5	1/3	1	1/3
a.4) Quality control	**a.4**	1	1/2	3	1

Table5.3 Pair-wise comparison matrix for parameters under category-b (Tanks/Basin)

b) Physical (service)	Parameters	b.1	b.2	b.3	b.4
b.1) Age of the element	**b.1**	1	1	1	1/3
b.2) Corrosion	**b.2**	1	1	2	1
b.3) Coating/paint	**b.3**	1	1/2	1	1/2
b.4) Cracks/flaws	**b.4**	3	1	2	1

Table5.4 Pair-wise comparison matrix for parameters under category-c (Tanks/Basin)

c) Environmental	Parameters	cl	c.2	c.3	c.4
c.1) Soil type	**c.1**	1	4	3	1
c.2) Quality of source water	**c.2**	1/4	1	1	1/4
c.3) Seismic activity	**c.3**	1/3	1	1	1/3
c.4) Weather condition	**c.4**	1	4	3	1

Table5.5 Pair-wise comparison matrix for parameters under category-d (Tanks/Basin)

d) Operational	Parameters	d.1	d.2	d.3	d.4
d.1) Chemicals dozes	**d.1**	1	1/5	1/3	1/2
d.2) O & M practice	**d.2**	5	1	2	3
d.3) Man. and Optrs. Exp.	**d.3**	3	1/2	1	2
d.4) Control system	**d.4**	2	1/3	1/2	1

Table5.6 Pair-wise comparison matrix for categories (Pumps)

Categories	Categories	a	b	c	d
a) Electro-Mechanical	a	1	1	1	1/2
b) Physical	b	1	1	1	1/2
c) Environmental	c	1	1	1	1/2
d) Operational	d	2	2	2	1

Table5.7 Pair-wise comparison matrix for parameters under category-a (Pumps)

a) Electro-Mechanical	Parameters	a.1	a.2	a.3	a.4
a.1) Type of pump	**a.1**	1	4	2	4
a.2) Horse power	**a.2**	1/4	1	1/2	1
a.3) Starting options	**a.3**	1/2	2	1	3
a.4) Capacity	**a.4**	1/4	1	1/3	1

Table5.8 Pair-wise comparison matrix for parameters under category-b (Pumps)

b) Physical	**Parameters**	**b.1**	**b.2**	**b.3**	**b.4**
b.1) Age of the pump	**b.1**	1	1/2	1	3
b.2) Corrosion	**b.2**	2	1	2	1/2
b.3) Coating/paint	**b.3**	1	1/2	1	1/3
b.4) Any type of Cracks/flaws	**b.4**	3	2	3	1

Table5.9 Pair-wise comparison matrix for parameters under category-c (Pumps)

c) Environmental	**Parameters**	**c.1**	**c.2**	**c.3**
c.1) Quality of source water	**c.1**	1	1/3	1/2
c.2) Vibration	**c.2**	3	1	2
c.3) Temperature	**c.3**	2	1/2	1

Table5.10 Pair-wise comparison matrix for parameters under category-d (Pumps)

d) Operational	**Parameters**	**d.1**	**d.2**	**d.3**	**d.4**	**d.5**
d.1) Chemicals dozes	**d.1**	1	1/2	1/2	1/2	1/2
d.2) O & M practice	**d.2**	2	1	1	1/2	1/2
d.3) Man. and Optrs. Exp.	**d.3**	2	1	1	1/2	1/2
d.4) Daily running time	**d.4**	2	2	2	1	1
d.5) Control system	**d.5**	2	2	2	2	1

According to the comparison matrix presented in Table5.1, the respondent comparison judgments for category- a (Physical (D& C stage)) is the most important, when dealing with the affect on the condition of the tanks in a DWTP. On the other hand, category-c (Environmental) has the lowest importance. When the respondent compared category-b with category-c, the assigned value was ‘2’, which means that category-b is twice as important as category-c for this specific objective.

5.2.2.2 Calculation relative weights at category level (Res. 29)

Using the eigenvalue method, relative weights ($w_{c,i}$) of all categories are estimated considering each of the comparison matrices constructed for the categories. Each response contains two comparison matrices for the categories for tanks and pumps respectively. Both matrix sizes are 4 x 4. After estimating relative weights, the categories can be ranked according to their contribution to the condition of the element. To satisfy the consistency requirements (C.R. $\leq$0.1) suggested by Saaty, the C. R. value is determined for each comparison matrix. It should be noted that only consistent comparison matrixes have been accounted for in the model. A prototype excel spreadsheet program is developed to solve the matrices, including a consistency test. After solving the comparison matrices (Table5.1 and 5.6) for weights and consistency, the results are summarized in *table 5.11& 5.12* respectively. Normalizing conditions apply to all cases, where: $\sum_{i=1}^{n} w_{c,i} = 1$

Table5.11 Weights and consistency results of comparison matrix for categories (tanks)

Categories	**Relative Weights (w_{ci})**	$\lambda_{\max}$	**Consistency Index (C.I.)**	**Consistency Ratio (C.R.)**
a) Physical (D& C stage)	0.394	4.001	0.00687	0.008
b) Physical (service)	0.164			
c) Environmental	0.089			
d) Operational	0.356			

$\lambda_{\max}$ = Maximum eigenvalue

Table5.12 Weights and consistency results of comparison matrix for categories (Pumps)

Categories	Relative Weights (w_c)	λ_{max}	Consistency Index (C.I.)	Consistency Ratio (C.R.)
a) Electro-Mechanical	0.2	4	0	0
b) Physical	0.2			
c) Environmental	0.2			
d) Operational	0.4			

The results show that this particular respondent deemed that physical (design and construction) and operational as the most important categories for tanks and pumps respectively. The environmental category received minimum weighting for tanks. And in case of pump electro-mechanical, physical and environmental all received equal importance.

5.2.2.3 Calculation of relative weights at parameters level (Res. 29)

Sixteen model parameters are sub-grouped under four categories and a comparison matrix is constructed for each group of parameters. Following the similar procedure as category level, all the comparison matrixes for the parameters (Tables5.2 to 5.10) are solved for estimating relative weights under a specific category ($w_{p,i/j}$). Moreover, consistency requirements also ensured. The results are shown in Table5.13 and 5.14 for tanks and pumps respectively.

Determination of Decomposed Composite Relative Weights of Parameters: The relative weight (w_p) of parameters at category level represents their importance among that sub-group of parameters. Decomposed relative weight ($W_{d,ij}$) of a parameter is calculated by multiplying category level parameter weight with the corresponding category weight ($w_{c,i}$).

Table5.13 Weights and consistency results of comparison matrix for parameters (tanks)

Parameters	**Relative Weights ($w_{p,i/j}$)**	λ_{max}	**Consistency Index (C.I.)**	**Consistency Ratio (C.R.)**
a) Physical (D& C stage)		4.093	0.03114	0.035
a.1) Design considerations	0.328			
a.2) Material type	0.344			
a.3) Size & Capacity	0.085			
a.4) Quality control	0.242			
b) Physical (Service Stage)		4.119	0.03952	0.044
b.1) Age of the element	0.184			
b.2) Corrosion	0.285			
b.3) Coating/paint	0.163			
b.4) Cracks/flaws	0.368			
c) Environmental		4.01	0.00346	0.004
c.1) Soil type	0.387			
c.2) Quality of source water	0.105			
c.3) Seismic activity	0.121			
c.4) Weather condition	0.387			
d) Operational		4.015	0.00485	0.005
d.1) Chemicals dozes	0.088			
d.2) O & M practice	0.482			
d.3) Man. and Optrs. Exp.	0.272			
d.4) Control system	0.158			

Mathematically, the equation used for determining the decomposed weights can be expressed as follows.

$$w_{d,i/j} = w_{p,i/j} * w_{c,i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.1$$

Where:

$w_{p,\,i/j}$ represents relative weight of *j th* parameter under *i th* category and $w_{d,i/j}$ represents decomposed relative weight of that *j th* parameter under *i th* category.

Applying equation 5.1, the decomposed relative weights are calculated for both sets of parameters of according to respondent-29 assessment. In the calculation process, Tables 5.11 to 5.14 have been used and the results are presented in Tables 5.15 and 5.16 for tanks and pumps respectively.

Table5.14 Weights and consistency results of comparison matrix for parameters (Pumps)

Parameters	Relative Weights ($w_{p,i/j}$)	$\lambda_{\max}$	Consistency Index (C.I.)	Consistency Ratio (C.R.)
a) Electro-Mechanical		4.021	0.00688	0.008
a.1) Type of pump	0.492			
a.2) Horse power	0.123			
a.3) Starting options	0.274			
a.4) Capacity	0.112			
b) Physical		4.01	0.00345	0.004
b.1) Age of the element	0.141			
b.2) Corrosion	0.263			
b.3) Coating/paint	0.141			
b.4) Cracks/flaws	0.455			
c) Environmental		3.009	0.0046	0.009
c.1) Quality of source water	0.164			
c.2) Seismic activity	0.539			
c.3) Weather condition	0.297			
d) Operational		5.078	0.01949	0.017
d.1) Chemicals dozes	0.110			
d.2) O & M practice	0.163			
d.3) Man. and Optrs. Exp.	0.163			
d.4) Daily running time	0.282			
d.5) Control system	0.282			

Table5.15 Decomposed relative weights of parameters (tanks)

Parameters	Relative Weights ($w_{p,i/j}$)	Relative weights of Category ($w_{c,i}$)	Decomposed relative weights ($W_{d,i/j}$)
a) Physical (D& C stage)		0.394	
a.1) Design considerations	0.328		0.129
a.2) Material type	0.344		0.136
a.3) Size & Capacity	0.085		0.034
a.4) Quality control	0.242		0.096
b) Physical (Service Stage)		0.164	
b.1) Age of the element	0.184		0.03
b.2) Corrosion	0.285		0.046
b.3) Coating/paint	0.163		0.026
b.4) Cracks/flaws	0.368		0.059
c) Environmental		0.089	
c.1) Soil type	0.387		0.034
c.2) Quality of source water	0.105		0.009
c.3) Seismic activity	0.121		0.011
c.4) Weather condition	0.387		0.034
d) Operational		0.356	
d.1) Chemicals dozes	0.088		0.031
d.2) O & M practice	0.482		0.172
d.3) Man. and Optrs. Exp.	0.272		0.097
d.4) Control system	0.158		0.056

5.2.3 Measuring Preferences Scores:

Any particular parameter has different preference levels based on the scenario it is representing. Scenarios are defined in order to measure the preferences of a parameter in terms of its contribution to the condition rating of the specific elements. Respondents were provided the PMS scale (Figure3.3) to estimate their preference scores ($u_{i/j,r}$). The most preferred score is given a maximum utility level 10 (equivalent to unit) and the least preferred score can be considered the lowest level of utility which is ‘0’. Preference scores were given for each element separately rather than for the entire class of elements.

The preference scores estimated by the respondents-29 for tanks and pumps respectivelyare attached in *appendix- D* (TableD.9 and D.10). For some parameters, the respondent assigned the same or similar preference scores for all scenarios such as tanks size and capacity; pump's horsepower, capacity and temperature. The same preference levels indicate that regardless of the scenarios, the parameter will have the same impact on the condition rating of the element.

Table5.16 Decomposed relative weights of parameters (Pumps)

Parameters	**Relative Weights** $(w_{p,i/j})$	**Relative weights of Category** $(w_{c,i})$	**Decomposed relative weights** $(W_{d,ij})$
a) Electro-Mechanical		0.2	
a.1) Type of pump	0.492		0.098
a.2) Horse power	0.123		0.025
a.3) Starting options	0.274		0.055
a.4) Capacity	0.112		0.022
b) Physical		0.2	
b.1) Age of the element	0.141		0.028
b.2) Corrosion	0.263		0.053
b.3) Coating/paint	0.141		0.028
b.4) Cracks/flaws	0.455		0.091
c) Environmental		0.2	
c.2) Quality of source water	0.164		0.033
c.3) Seismic activity	0.539		0.108
c.4) Weather condition	0.297		0.059
d) Operational		0.4	
d.1) Chemicals dozes	0.110		0.044
d.2) O & M practice	0.163		0.065
d.3) Man. and Optrs. Exp.	0.163		0.065
d.4) Daily running time	0.282		0.113
d.5) Control system	0.282		0.113

5.2.4 Determination of Condition Rating Index (CRI)

The main objective of this condition assessment model is to determine the CRI. It has been already discussed how the model estimates composite weights of model parameters and preference scores of parameters for different scenarios. By identifying or matching actual parameter scenarios of an element from reliable sources (inspection reports, drawings, records, visual inspection), the model need to be fed with that information. Once the parameter scenarios for the element are defined, using additive forms of the value function, the model provides CRI (I_{cri}) for the particular element. With the constraint, the sum of all parameters decomposed weights is one and the range of preference scores is 0-10. The CRI values also range between 0-10. The mathematical expression of the model will be as follows.

$$I_{cri} = \sum_{i=1}^{n}\sum_{j=1}^{m}[(w_{c,i} \times w_{p,i/j})(u_{i/j,r})] \text{..} (5.2)$$

Where,

I_{cri} is Condition Rating Index (CRI) of the element

$w_{c,i}$ is the relative weight of *i* th category

$w_{p,\,i/j}$ represents relative weight of *j th* parameter under *i th* category

n is number of categories

m is number of parameters under *i* th category

$u_{i/j,r}$ preference score of *j th* parameter under *i th* category for real scenario.

From equation 5.1, replacing $w_{c,i} \times w_{p,i/j}$ by parameters decomposed relative weight $w_{d,i/j}$, equation 5.2 can be expressed as follows:

$$I_{cri} = \sum_{i=1}^{n}\sum_{j=1}^{m}[(w_{d,i/j})(u_{i/j,r})] \text{...} (5.3)$$

Where, $w_{d,ij}$ represent decomposed relative weight of *j th* parameter under *i th* category. Considering the scores for the most preferred and the least preferred scenarios, CRI values were calculated from the model (Equation 5.3) for all five elements. These values were used in order to establish the average maximum and minimum expected CRIs. The CRIs calculated from respondent-29 are given in Table 5.17 and 5.18 respectively for the settling tank and the RWP, where CRI for settling tank are 9.74 and 2.23 for the most and least preferred scenarios respectively. The RWP values are 9.41 and 4.41 for the pumps and tanks respectively. Similarly, the CRI for a filtration tank, chlorination tank and clean water pump have been determined. The CRI calculation process is repeated for each respondent and the results can be seen in *Appendix-D* (Table D.13).

5.2.5 Uncertainty in the Model

Applying the arithmetic mean (AM) of the most preferred scores (MPS), the least preferred scores (LPS) and average preferred scenario scores, the CRI values (estimated from equation 5.3) for settling tanks (ST) and raw water pumps (RWP) are shown in Table 5.19. Using a probability distribution (PBD) of scores instead of AM in @Risk, the maximum, minimum and average CRI values obtained after Monte-Carlo simulations for ST and RWP also shown in Table 5.19. Each simulation was operated using 1000 iterations and 100 simulations to consider the results as acceptable. After analyzing, the variation between the CRI from AM and the mean CRI from simulation, two factors (U_t &U_p) were introduced in the model (Eq-5.3) for tanks and pumps respectively. The factors may vary with the magnitude of CRI value obtained from equation 5.3. Equation 5.3 can be re-written as follows:

$$I_{cri(t)} = U_t \sum_{i=1}^{n} \sum_{j=1}^{m} [(w_{d,i/j})(u_{i/j,r})] \qquad \text{..(5.4)}$$

$$I_{cri(p)} = U_p \sum_{i=1}^{n} \sum_{j=1}^{m} [(w_{d,i/j})(u_{i/j,r})] \qquad \text{.. (5.5)}$$

Where,

U_t= .95 when CRI $\geq$ 4; 4 and U_t= 1.15 when CRI < 4

U_p= .97 when CRI $\geq$ 4; 4 and U_t= .90 when CRI < 4

Table5.17 CRI of Settling Tank considering the most preferred and the least preferred scores assigned by respondent-29

Parameters	**Weights ($w_{d,i/j}$)**	**Most Pref. Score ($u_{i/j,r}$)**	**Least pref. Score ($u_{i/j,r}$)**	**CRI (Max.)**	**CRI (Min.)**
a)Physical (D & C stage)					
a.1) Design considerations	0.129	10	0	1.29311	0
a.2) Material type	0.136	10	0	1.35625	0
a.3) Size & Capacity	0.034	10	10	0.33528	0.33528
a.4) Quality control	0.096	10	0	0.95514	0
b) Physical (service stage)					
b.1) Age of the element	0.03	10	0	0.29768	0
b.2) Corrosion	0.046	10	0	0.4601	0
b.3) Coating/paint	0.026	10	0	0.26372	0
b.4) Cracks/flaws	0.059	10	0	0.59479	0
c) Environmental					
c.1) Soil type	0.034	8	5	0.27538	0.17211
c.2) Quality of source water	0.009	10	0	0.093	0
c.3) Seismic activity/vibration	0.011	10	6	0.10734	0.0644
c.4) Weather condition	0.034	9	5	0.3098	0.17211
d) Operational					
d.1) Chemicals dozes	0.031	10	8	0.31388	0.2511
d.2) O& M practice	0.172	10	1	1.71503	0.1715
d.3) Man. & Operator exp.	0.097	9	7	0.86965	0.6764
d.4) Control system	0.056	9	7	0.50397	0.39198
				9.74411	**2.23488**

Table5.18 RI of Raw Water Pump considering the most preferred and the least preferred scores assigned by respondent-29

	Weights ($w_{d,i/j}$)	Most Pref. Score ($u_{i/j,r}$)	Least pref. Score ($u_{i/j,r}$)	CRI (Max.)	CRI (Min.)
a)Physical (D & C stage)					
a.1) Type of pumps	0.098	10	9	0.98309	0.88478
a.2) Horse power	0.025	5	5	0.12289	0.12289
a.3) Starting options	0.055	10	5	0.5471	0.27355
a.4) Capacity	0.022	5	5	0.11202	0.11202
b) Physical (service stage)					
b.1) Age of the element	0.028	10	0	0.28228	0
b.2) Corrosion	0.053	10	3	0.5261	0.15783
b.3) Coating/paint	0.028	10	5	0.28228	0.14114
b.4) Cracks/flaws	0.091	10	0	0.90934	0
c) Environmental					
c.1) Quality of source water	0.033	10	0	0.32756	0
c.2) Vibration	0.108	10	0	1.07792	0
c.3) Weather condition	0.059	9	6	0.53506	0.35671
d) Operational					
d.1) Chemicals dozes	0.044	10	10	0.44054	0.44054
d.2) O& M practice	0.065	10	1	0.6525	0.06525
d.3) Man. & Operator exp.	0.065	9	6	0.58725	0.3915
d.4) Daily pump running time	0.113	8	7	0.90178	0.78906
d.5) Control system	0.113	10	6	1.12723	0.67634
				9.41495	**4.4116**

Table 5.19 CRI values obtained from different scenarios using the Best Fit PBD and AM

ELEMTS.	CRI FROM BEST FITS DIST									CRI FROM AM		
	Most pref.			*Least pref*			*Avg. Pref.*			*Most* Pref.	*Least* Pref.	*Avg.* Pref.
	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min			
SET. BASIN	9.21	8.78	8.19	3.39	2.32	1.35	6.17	5.53	4.88	9.43	1.95	5.80
R.W. PUMP	9.51	9.10	8.56	4.71	3.36	2.13	7.23	6.39	5.55	9.28	3.69	6.55

U_t= .95 when CRI $\geq$ 4; 4 and U_t= 1.15 when CRI < 4

U_p= .97 when CRI $\geq$ 4; 4 and U_p= .90 when CRI < 4

Application of the PBD in the model also provides a range of maximum and minimum CRI values. Comparing the maximum and minimum CRI values with the mean values of any element under the same scenario, constants (C_t & C_p) are determined for the model to estimate probable maximum and minimum CRIs. Equation 5.4 and 5.5 can be re-written for estimating the maximum and minimum CRI values of the element under the same scenario.

$$I_{cri(t)\max/\min} = U_t \sum_{i=1}^{n} \sum_{j=1}^{m} [(w_{d,i/j})(u_{i/j,r})] \pm C_t \qquad (5.6)$$

$$I_{cri(p)\max/\min} = U_p \sum_{i=1}^{n} \sum_{j=1}^{m} [(w_{d,i/j})(u_{i/j,r})] \pm C_p \qquad (5.7)$$

Where,

C_t = .90 and C_p = 1.0; considering + ve and – ve sign respectively maximum and minimum CRI can be estimated.

5.3 Study Results

In the survey process, the judgements provided by the 32 respondents were analysed to estimate the relative weights of the categories, the parameters under the categories and the decomposed relative weights, using AHP principles. The preferences scores for the parameters in various scenarios were analysed to determine the average of all preference scores obtained from the respondents. The CRI of the elements was then assessed with different combinations, including twenty-five real cases. Probability distributions were constructed using @Risk and were assigned for each scenario to observe the nature of the distribution and uncertainties. Preference curves were also constructed in Excel for each parameter from their average preference scores estimated for different scenarios.

5.3.1 Relative Weights

Relative weights of Categories: Relative weights of all categories for both classes of elements were estimated from each individual's comparisons. The resulting weights of categories from each individual's assessment are shown in *Appendix-D (Tables D.1 and D. 2)* tanks and pumps respectively. Figures 5.1 and 5.2 show a graphical representation of the relative weights of categories assessed from each individual's evaluation.

In the case of tanks, the average (arithmetic mean) values of the category weights are presented Figure 5.3. From the figure, it can be seen that the parameters under category a) physical (design & construction stage) have maximum importance (32%) and parameters under c) environmental category have minimum importance (18%). Parameters under operational and physical (service) category have 26% and 24% importance respectively.

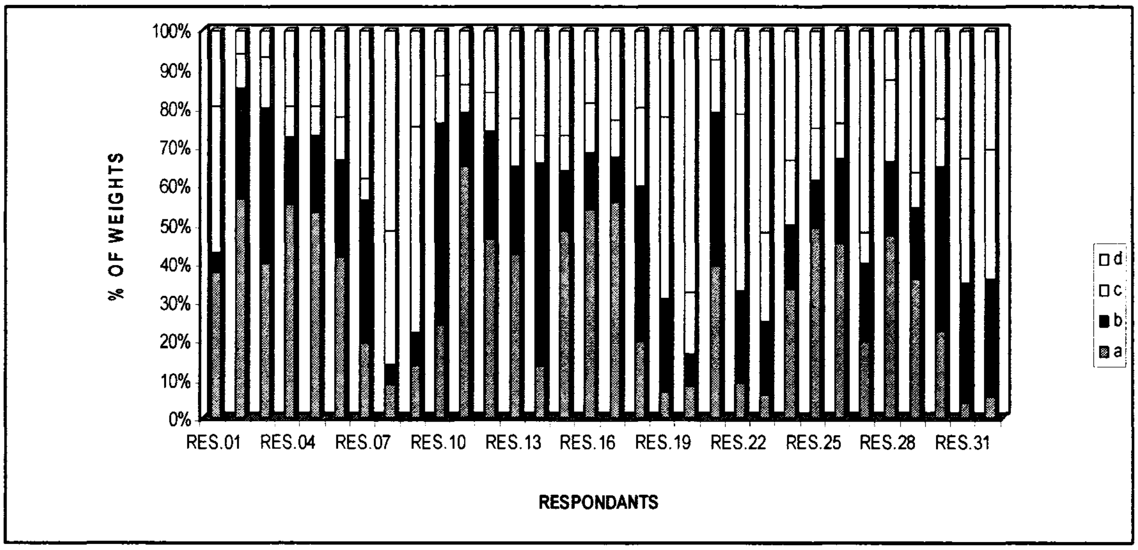


Figure5.1 Individual Respondent's Relative Weights of Categories for Tanks

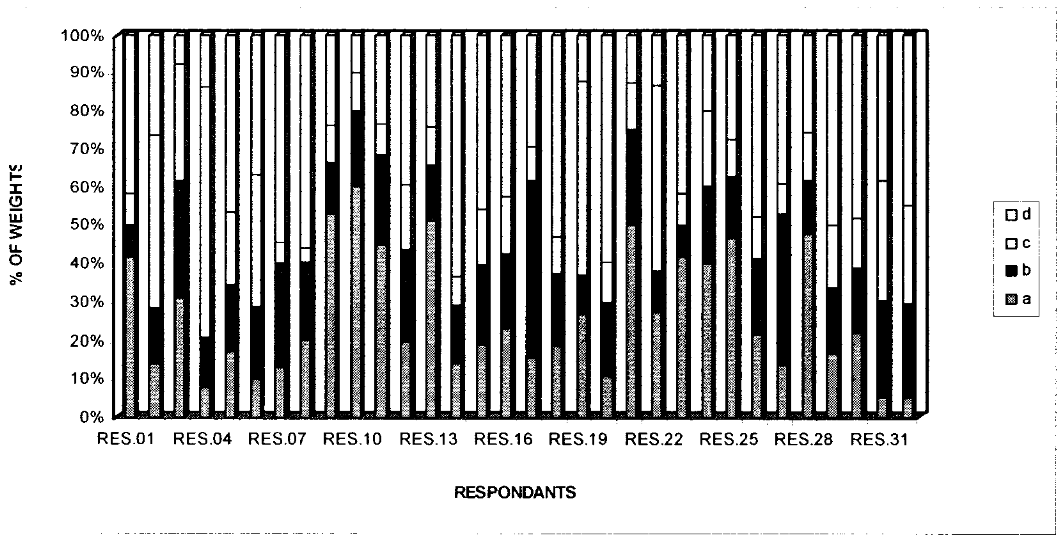


Figure5.2 Individual Respondent's Relative Weights of Categories for (Pumps)

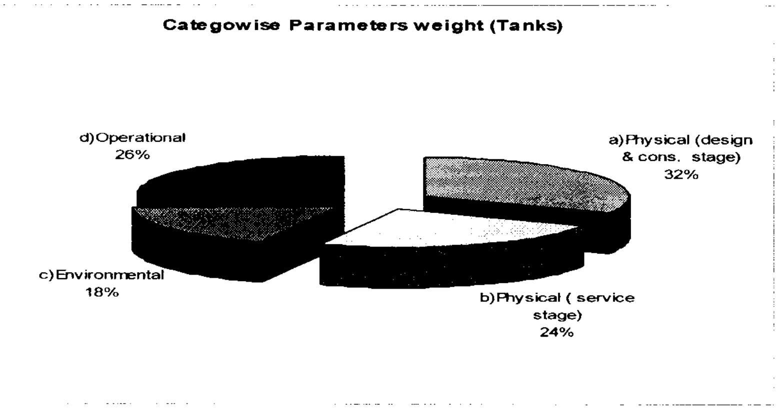


Figure5.3 Average Relative Weights of Categories (Tanks)

For pumps, the average (arithmetic mean) values of category weights and parameters under the operational category have maximum importance (34%). Similar to the tanks, the environmental category is assigned minimal importance (19%). Electro-mechanical and physical received 27% and 20% importance respectively. Figure 5.4 shows the relative weights for pumps for each category.

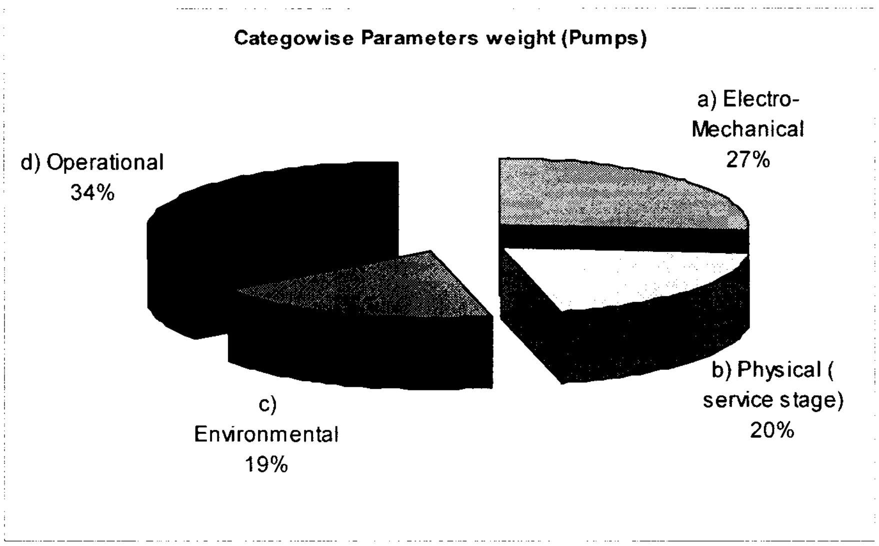


Figure5.4 Average Relative Weights of Categories (Pumps)

Relative Weights of Parameters: Relative weights for each set of parameters are estimated from a comparison of each respondent. The assessments of relative weights for the parameters within each category are shown for tanks and pumps in *Appendix-D, Table D.3 and D.4* respectively. The averages (arithmetic means) of the relative weights of each parameter within category, for both the set of parameters are given in Tables5.20 and 5.21 and graphically in Figures 5.5 and 5.6 respectively. The results show that in the case of tanks, parameters a.1 (Design considerations) and a.2 (Material type) under category 'a' have maximum importance (31%), parameter b.4 (Cracks/flaws) has maximum importance (33%) under category b and parameters c.1 (Soil type) and d.2 (Operation and Maintenance practice) have maximum importance (38% and 42%) under categories 'c' and 'd' respectively. Similarly, in the case of pumps, parameters a.3 (Starting options), b.4 (Cracks/flaws), c.2 (Vibration) and d.2 (Operation & Maintenance Practices) have been given maximum importance percentages of 35%, 36%, 45% and 31% respectively. At an individual level, the importance weights of parameters within each category do not show uniformity but many respondents have chosen two identical parameters to rank as top or second in each category group.

Decomposed Relative Weights: After estimating the relative weights of categories and parameters within each category, the decomposed weights of both sets of parameters has been calculated using equation 5.1. The estimated decomposed weights of all experts are given in *Appendix D,(Tables D.5 &D.6)* for both classes of elements respectively. The arithmetic means of the decomposed weights obtained from all respondents are shown in Tables 5.22 and 5.23 and graphically in Figures 5.7 and 5.8 tanks and pumps respectively. After taking the arithmetic mean of the decomposed weights estimated from all respondents, it was determined that the most important parameters are a.1 (Design considerations) and d.2 (Operation & Maintenance practices) for tanks and pumps respectively. The least important parameter is b.3 (Coating /paint) for both classes of elements. The second most important parameters identified are d.2 (Operation and Maintenance practices) and c.2 (Vibrations) for tanks and pumps respectively. There is no parameter from any set, which has been assigned more than 12% importance.

To observe how different targeted response groups have varied perceptions in assigning relative weights to parameters, the results were classified by group as shown in *Appendix-D, (Tables D.7 and D.8)* and graphically in Figures 5.9 and 5.10. After observing this group wise result, it is found that designers, consultants and operators share similar views regarding the relative importance of parameters, but researchers have a different view.

Table5.20 Average Relative Weights of Parameters within Category (Tank/Basins)

Parameters	a.1	a.2	a.3	a.4	b.1	b.2	b.3	b.4	c.1	c.2	c.3	c.4	d.1	d.2	d.3	d.4
Avg. Weights	0.31	0.31	0.14	0.24	0.29	0.25	0.14	0.33	0.38	0.18	0.17	0.26	0.18	0.42	0.23	0.18

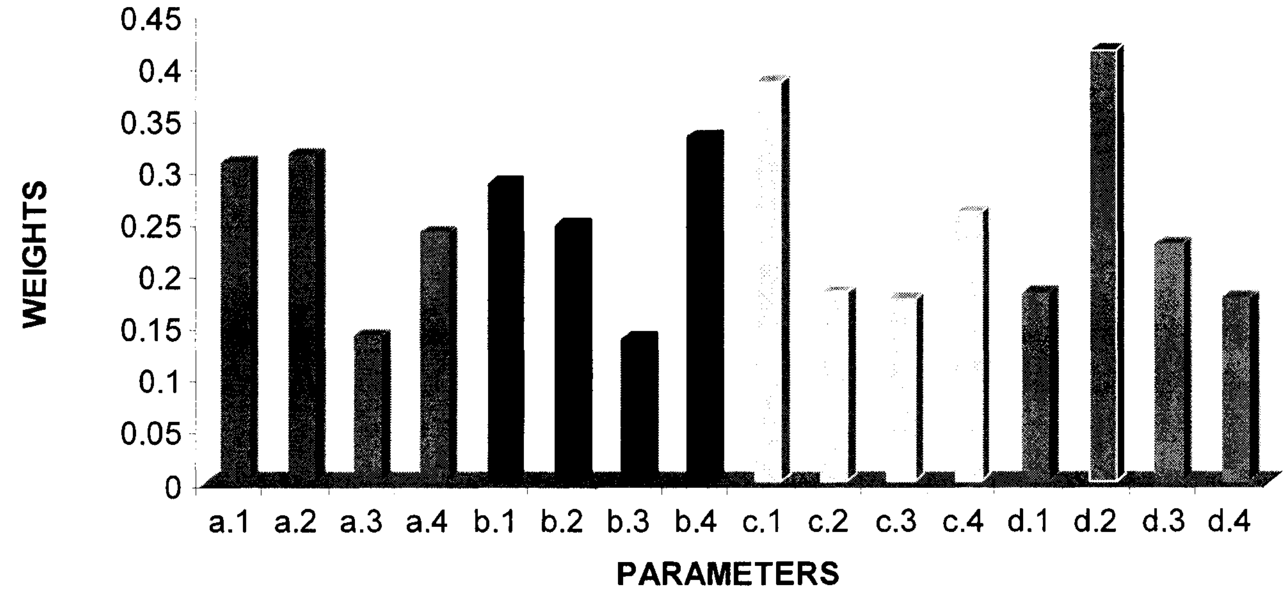


Figure5.5 Average Relative Weights of Parameters within Category (Tank/Basins)

Table5.21 Average Relative Weights of Parameters within Category (Pumps)

Parameters	a.1	a.2	a.3	a.4	b.1	b.2	b.3	b.4	c.1	c.2	c.3	d.1	d.2	d.3	d.4	d.5
Avg. Weights	0.31	0.14	0.35	0.20	0.30	0.22	0.12	0.36	0.32	0.45	0.22	0.10	0.31	0.19	0.23	0.18

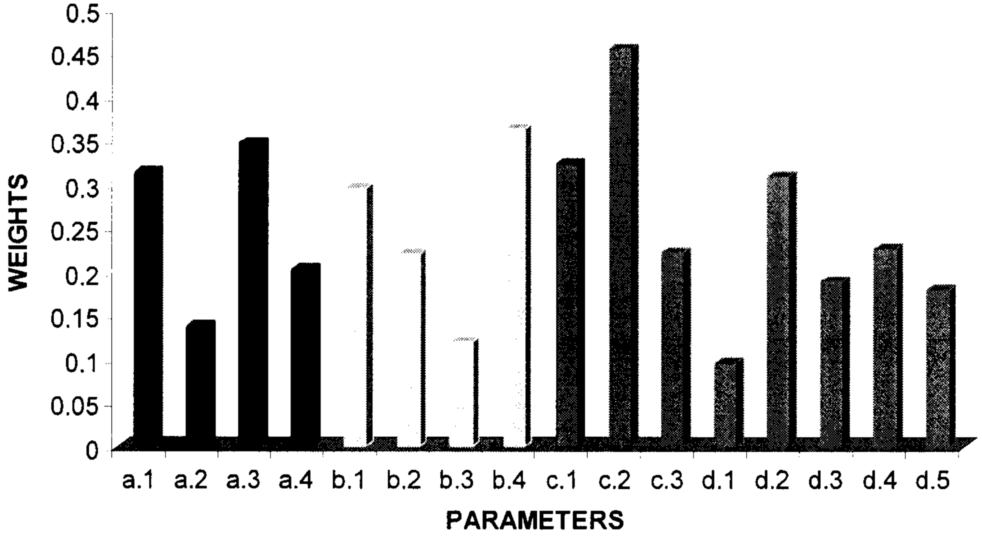


Figure5.6 Average Relative Weights of Parameters within Category (Pumps)

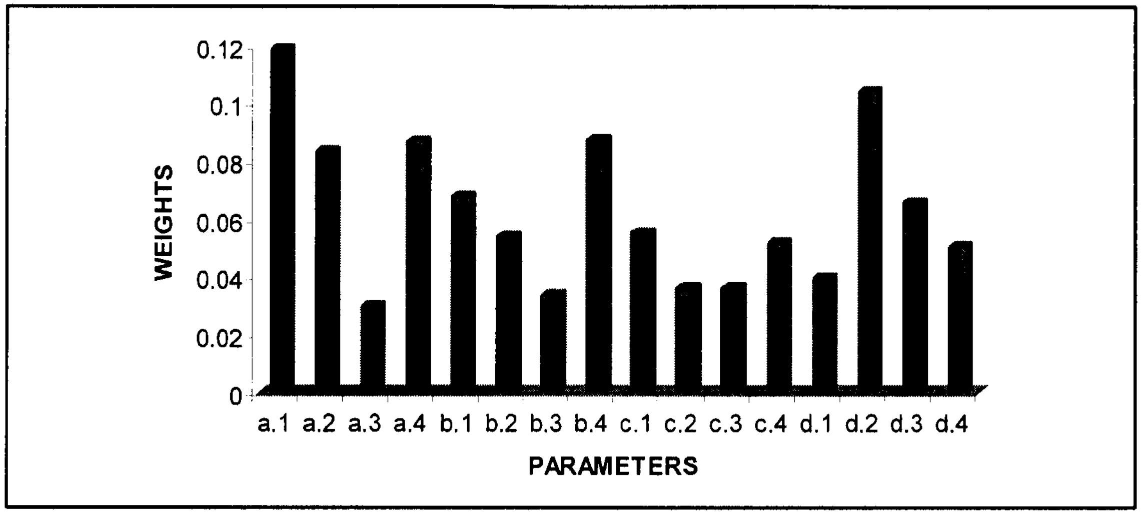


Figure5.7 Average Decomposed Weights of Parameters (Tanks/Basins)

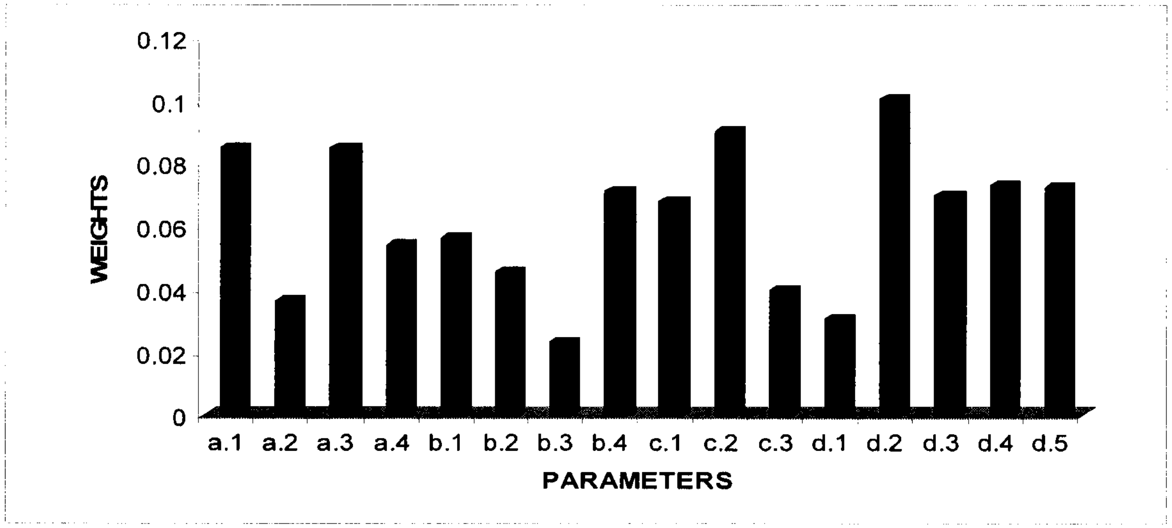


Figure5.8 Average Decomposed Weights of Parameters (Tanks/Basins)

Table5.22 Average Decomposed Weights of all Parameters (Tanks/Basins)

Parameters	a.1	a.2	a.3	a.4	b.1	b.2	b.3	b.4	c.1	c.2	c.3	c.4	d.1	d.2	d.3	d.4
Avg.Dcom. Wts.	0.12	0.09	0.04	0.08	0.07	0.06	0.03	0.08	0.06	0.04	0.03	0.05	0.04	0.11	0.07	0.05

Table5.23 Average Decomposed Weights of all Parameters (Pumps)

Parameters	a.1	a.2	a.3	a.4	b.1	b.2	b.3	b.4	c.1	c.2	c.3	d.1	d.2	d.3	d.4	d.5
Avg. Dcom. Wts.	0.08	0.04	0.08	0.07	0.06	0.05	0.02	0.07	0.06	0.09	0.04	0.03	0.11	0.07	0.07	0.07

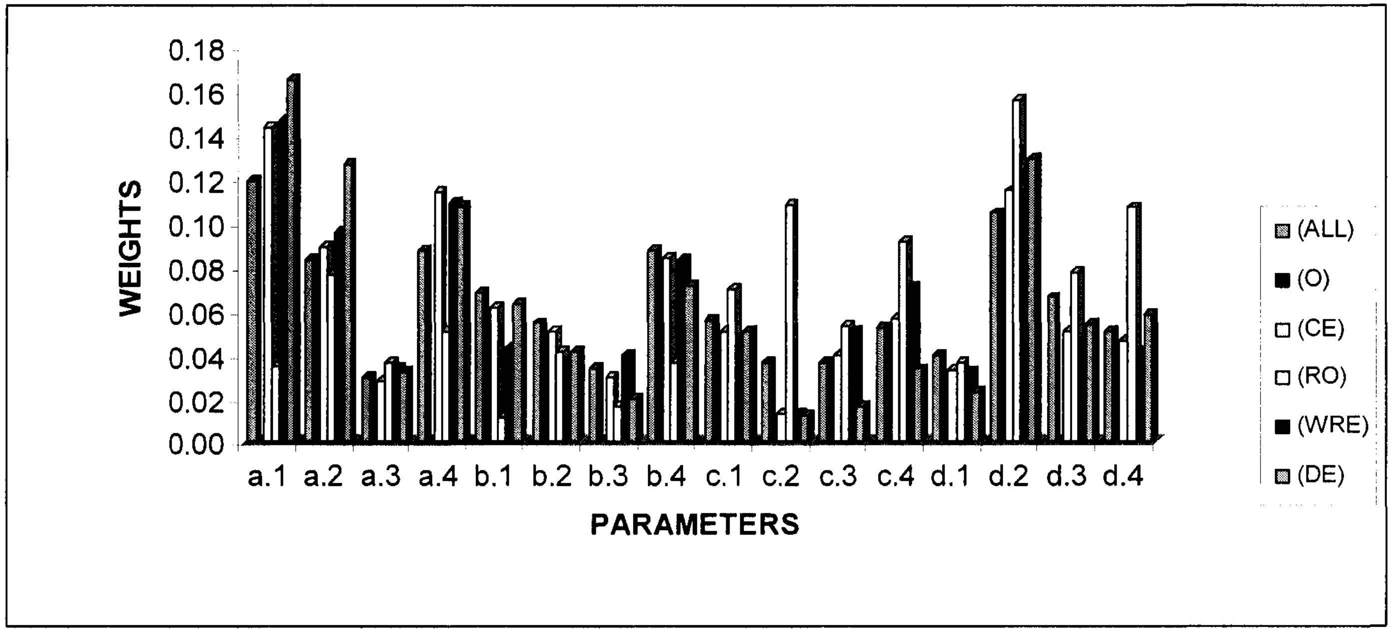


Figure5.9 Decomposed weights of parameters classified based on respondents group (Tanks)

N.B. All Respondents (ALL), Operators (O), Consultant Engineers (CE), Researchers Officers (RO), Water Resources Engineer (WRE), Design Engineer (DE)

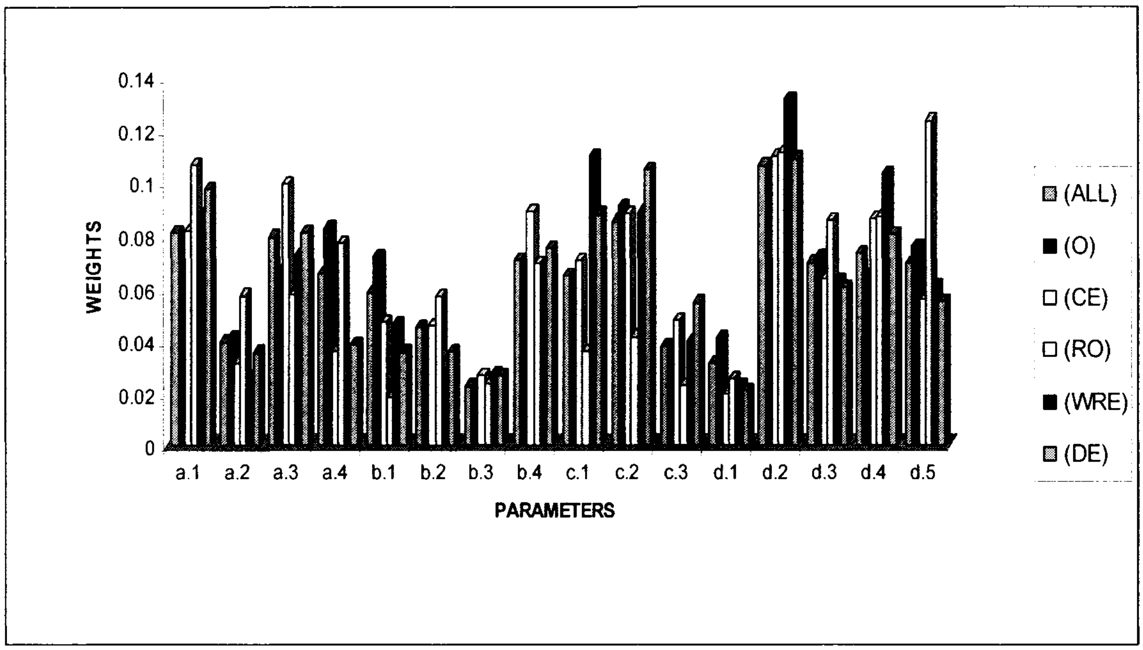


Figure5.10 Decomposed weights of parameters classified based on respondents group (Pumps)

N.B. All Respondents (ALL), Operators (O), Consultant Engineers (CE), Research Officers (RO), Water Resources Engineer (WRE), Design Engineer (DE)

5.3.2 Preference Scores

To measure preferences or utility in terms of assessing condition, each parameter is defined under possible scenarios of an in-service target element. The same scenarios are used for all elements of the class, which the parameter is representing. Even the scenarios are the same; respondents are to judge preferences scores for each element separately. Therefore, three elements under each tank class have one set of scenarios but three set of preference scores. Similarly, two types of pumps have one set of scenarios but two sets of preferences scores. Arithmetic means of the scenario preference scores provided by the respondents for each element are shown in A*ppendix D (Table D.11and D.12).*

In some cases, the average results of the preferences scores for a parameter did not vary with scenarios such as size and capacity of tanks, chemical doses used in the treatment process, type of pumps, pump horsepower and pump capacity. Closer preference scores for scenarios under a category imply that changing scenarios will have a negligible effect on the CRI. Especially, when the parameter is assigned a low relative weight.

5.3.2 Preference Curves

From the average preference scores for the scenarios, a preference curve has been constructed for each parameter. The shape of the curves varies with the number of scenarios defined for that parameter and the overall attitude of the decision makers in assigning the preference scores. The objective of this curve is to estimate any intermediate preference level between any two scenarios of a parameter. Probability is not accounted in the estimating preference scores or in the curves. The preference score for the most preferred scenario can be considered as the highest level of utility for the parameter (normally "1") and the score for the least preferred scenario as the lowest level of utility, (assigned "0") zero. For example, a few preference curves are shown in Figures 5.11 to 5.14 and some of them are shown in *Appendix-D (Figure D.1)*.

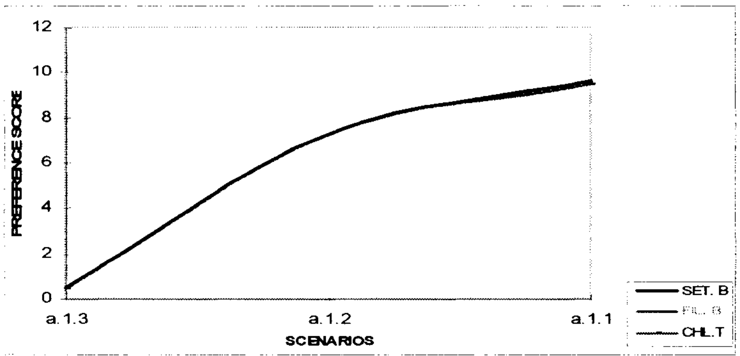


Figure5.11 Preference Curve for Parameter a.1 (Tanks/Basins)

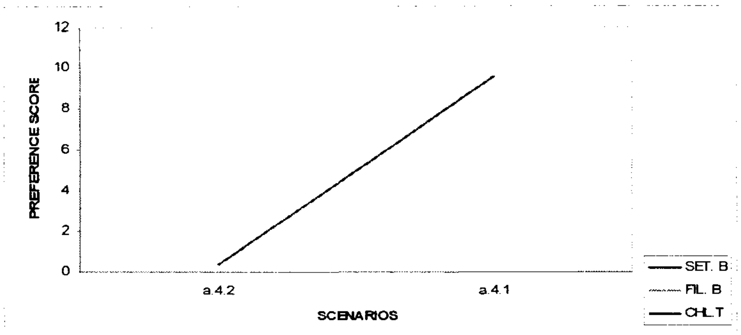


Figure5.12 Preference Curve for Parameter a.4 (Tanks/Basins)

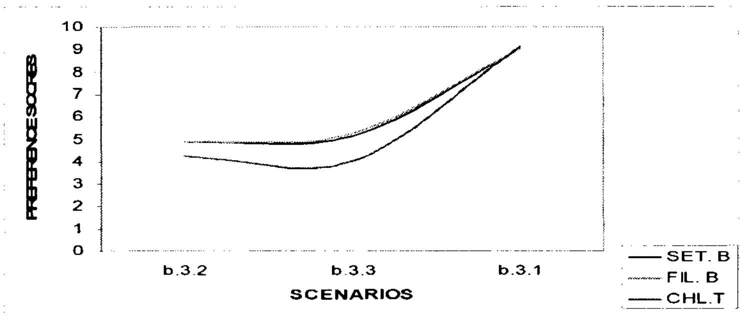


Figure5.13 Preference Curve for Parameter b.3 (Tanks/Basins)

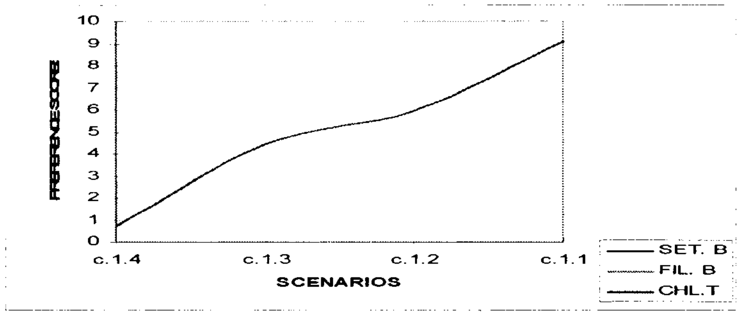


Figure5.14 Preference Curve for Parameter c.1 (Tanks/Basins)

5.3.3 Simulation Results

The selected best-fit distribution obtained from @Risk for the preference scores of various scenarios were applied to define the distribution functions for the preference scores of the model. In this study, @Risk4.5 version was used to perform the simulations. Simulations were done for the most preferred scenarios (MPS), least preffered scenarios (LPS) and average preferred scenarios (APS) to observed CRI values. In the simulation process, only the settling tank (ST) and raw water pump (RWP) are considered because filtration tanks and chlorination are almost identical to ST and clean water pumps (CWP) are mostly identical to RWP. As examples two of the simulation outputs (histogram) are shown in Figure 5.15 and 5.16, for the CRI values of ST and RWP at MPS respectively. Few important simulation graphs are shown in *Appendix-D (Figures D.5 and D.6).* The mean CRIs obtained from the simulation are compared to the corresponding CRI estimated by using the AM and are shown in Table 5.24.

Table5.24 CRIs considering different scenarios from simulations and AM

Elem. Type	**CRI From Best Fits Dist (Simulation)**									**CRI From AM**		
	Most pref.			*Least pref*			*Avg. Pref.*			Most pref.	Least pref.	Avg. pref.
	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min			
Set. Basin	9.21	8.78	8.19	3.39	2.32	1.35	6.17	5.53	4.88	9.43	1.95	5.80
R.W. Pump	9.51	9.10	8.56	4.71	3.36	2.13	7.23	6.39	5.55	9.28	3.69	6.55

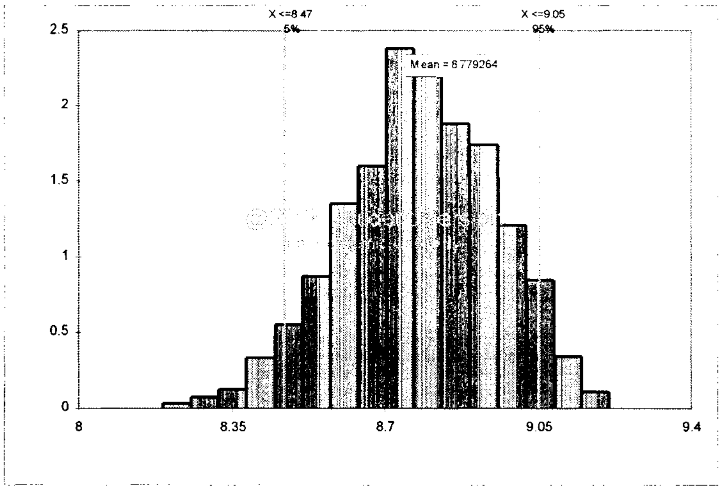


Figure5.15 1 CRI Histogram of Settling Tank at MPS

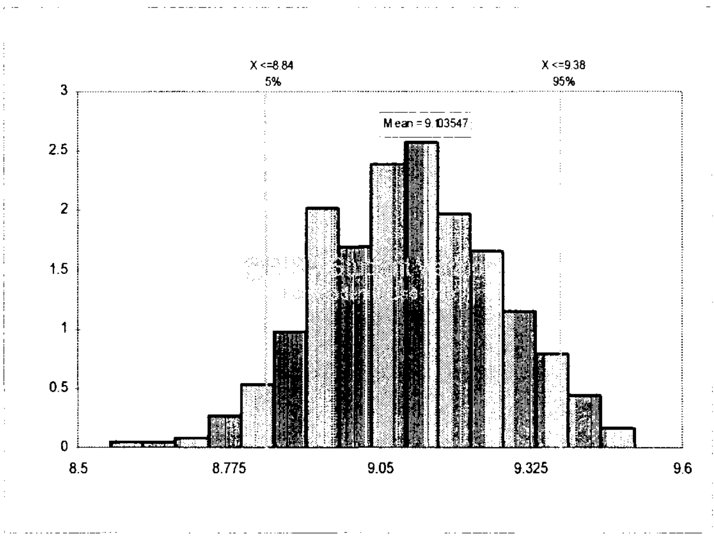


Figure5.16 CRI Histogram of Raw Water Pump at MPS

5.4 Proposed Condition Rating Scale (CRS)

To establish an effective CRS for DWTP elements, at first a generalized scale was prepared based on current study results. Other example of CRS in the literature and experts opinion on this also reviewed. The proposed scale suggested six condition grades depending on the condition index estimated for a specific element in the condition assessment program. The current study has maintained a condition index range of 0-10 (CI) for condition assessment. An incremental increase in the CI is an indication of better condition. In the proposed scale, an element with a CI of 9.1 to 10 falls under grade 'A' (excellent condition) and gradually the elements with a CI of 0 to 3 falls under a Grade 'F' (failure condition). Each grade was defined with a brief description and suggestions of the required actions have been made with a time frame for the elements under that group. Besides the CI, the current age of an element is taken into consideration as a primary criterion defining a grade, if there is no major repair or rehabilitation work involved. With all this detail, the prepared CRS was sent to 15 selected experts among the 32 surveyed respondents. Nine experts (60%) out of 15 returned the CRSs with their constructive comments. All experts liked the six point grading approach but most of them suggested to construct separate CRS for pumps and tanks. Some experts modified the definition and range of the CI for a specific grade. The suggestions also included considerations regarding the recommended action and time frame for those actions. After reviewing and comparing all comments on the proposed CRS and the recommended modifications, separate CRSs for each class of element have been prepared and are shown in Tables 5.25 and 5.26. The proposed CRSs will be able to provide guidance to operation managers for prioritizing future inspection, repair, rehabilitation and replacement work.

Table5.25 Condition Rating Scale Based on Condition Index (CI) Of DWTP's Tanks

CI Range	Cond. Grade	Explanations of Grades	Actions Required
9.1-10	**GRADE A**	**Excellent Condition** All of the considered condition parameters are at their highest expected utility level and current age of the element is < ¼ of its design life	Only routine maintenance required. Next assessment suggested after 10-15 years or at an age of 1/3 of design life, whichever is smaller.
8.1-9	**GRADE B**	**Very Good Condition** Most of the condition parameters are at their highest expected level and the remaining ones are in a moderately expected level. The current age of the element is < ½ of its actual design life.	Besides routine O&M, a few high ranking parameters may need to be rectified. Next assessment suggested after 5-10 years or at an age of 3/5 of design life, whichever is smaller
6.1-8	**GRADE-C**	**Good Condition** Most of the condition parameters are at their highest expected level and the remaining parameters are in moderate and low expected levels. The current age of the element is < ¾ of the actual design life.	Need to rectify the parameters that are at their lowest expected level under the O&M category. Next assessment is required after 5 years or at an age of 4/5 of design life, whichever is smaller
4.1-6	**GRADE-D**	**Moderate Condition** The major condition parameters have a better than expected utility level and the remaining parameters may vary from highest to lowest scenarios. The current age could be equal to the design life if it is well maintained.	Need to ensure standard O&M practices. Next assessment required after 3 years.
3.1-4	**GRADE-E**	**Poor Condition** Some of the highly ranked condition parameters are in their moderate and lowest expected level. Either very old (> design life) or poor operation and maintenance practice exist.	Major rehabilitation work and changes in O & M practice may be required.
0-3	**GRADE-F**	**Failure (Critical) Condition** Most of the parameters are at the lowest level. Very poor operation and maintenance practices. Element may have passed its design life and no longer suitable for service	Require immediate replacement and to ensure standard O&M practice.

Table5.26 Condition Rating Scale Based on Condition Index (CI) Of DWTP's Pumps

CI Range	Condition Grade	Explanations of Grades	Actions Required
9.1-10	**GRADE A**	**Excellent Condition** All of the considered condition parameters are at their highest expected utility level and current age of the element is < ¼ of its design life	Only routine maintenance required. Next assessment suggested after 3-5 years or at an age of 1/3 of design life, whichever is smaller.
8.1-9	**GRADE B**	**Very Good Condition** Most of the condition parameters are at their highest expected level and the remaining ones are in a moderately expected level. The current age of the element is < ½ of its actual design life.	Besides routine O&M, a few high-ranking parameters may need to be rectified. Next assessment suggested after 2-3 years or at an age of 3/5 of design life, whichever is smaller
6.1-8	**GRADE-C**	**Good Condition** Most of the condition parameters are at their highest expected level and the remaining parameters are in moderate and low expected levels. The current age of the element is < ¾ of the actual design life.	Need to rectify the parameters that are at the lowest expected level under the O&M category. Next assessment requires after 1-2 years or at an age of 4/5 of design life, whichever is smaller
5.1-6	**GRADE-D**	**Moderate Condition** The major condition parameters have a better than expected utility level and the remaining parameters may vary from highest to lowest scenarios. The current age could be equal to the design life if it is well maintained.	Need to ensure standard O&M practices. Assessment required once a year.
4.1-5	**GRADE-E**	**Poor Condition** Some of the highly ranked condition parameters are in their moderate and lowest expected level. Either very old (> design life) or poor operation and maintenance practice exist.	Major overhauling work and changes in O & M practice may be required.
0-4	**GRADE-F**	**Failure (Critical) Condition** Most of the parameters are at the lowest level. Very poor operation and maintenance practices. Element may have passed its design life and no longer suitable for service	Require Immediate replacement and to ensure standard O&M practice.

5.5 Case Studies and Model Validation

The developed condition-rating model has been successfully applied in 25 real cases. In the model application process, exact scenarios are to define for each parameter based on data available from inventory and inspection reports. To collect information for parameter scenarios of real cases, a special data request sheet *(Appendix-E)* was prepared based on the parameters and scenarios accounted for in the model. Requests were made to provide information on all five selected elements from tank and pump classes. Twenty data request sheets were sent to selected DWTP operators across Canada and only five (25%) of them sent back with complete information. It should be noted that among five plants, two plants were visually inspected by the plant representative and author jointly. The brief descriptions of all twenty-five case studies are given the Table 5.27.

To estimate the CRI for the elements, the AM for the preference scores for the defined scenarios and the AM of the relative weights are used in the model. Besides direct estimation, the CRI of the elements are also estimated by considering the relative weights and preference scores evaluated from survey inputs of the respondents representing that particular plant. The results and their variation, obtained from the former and latter considerations, are shown in Tables 5.28 to 5.31. Figures 5.17 and 5.18 are showing the CRIs estimated from each approach for settling tanks and RWPs respectively. Similar graphs for the other three elements are attached in *Appendix-D (Figures D.2 to D.4).*

Table5.27 List of the case studies model applied with

CS_#	Plant Location	Material	Capacity/day	Age
Settling Tanks				
1	Dorval, QC	Concrete	> 10000 M^3	> design life
2	Pointe-Claire, QC	Concrete	> 10000 M^3	> ¼ ≤ ½ of design life
3	Welland, ON	Concrete	<5000 M^3	> ½ ≤ design life
4	Brantford, ON	Concrete	> 10000 M^3	≤ ¼ of design life
5	Montréal, QC	Concrete	5000-10000 M^3	> ¼ ≤ ½ of design life
Filtration Tanks				
1	Dorval, QC	Concrete	> 10000 M^3	> design life
2	Pointe-Claire, QC	Concrete	> 10000 M^3	> ¼ ≤ ½ of design life
3	Welland, ON	Concrete	<5000 M^3	> ½ ≤ design life
4	Brantford, ON	Concrete	5000-10000 M^3	> design life
5	Montréal, QC	Concrete	> 10000 M^3	> ¼ ≤ ½ of design life
Chlorination Tank				
1	Dorval, QC	Concrete	> 10000 M^3	> design life
2	Pointe-Claire, QC	Concrete	> 10000 M^3	> ¼ ≤ ½ of design life
3	Welland, ON	Concrete	5000-10000 M^3	> ½ ≤ design life
4	Brantford, ON	Concrete	5000-10000 M^3	≤ ¼ of design life
5	Montréal, QC	Concrete	> 10000 M^3	> ¼ ≤ ½ of design life
		Type	**Capacity/Hour**	**Age**
Raw Water Pump				
1	Dorval, QC	Centrifugal	<1000 M^3/h	> ¼ ≤ ½ of design life
2	Pointe-Claire, QC	Centrifugal	>10000 M^3	> ½ ≤ design life
3	Welland, ON	Centrifugal	1000-10000 M^3	> ¼ ≤ ½ of design life
4	Brantford, ON	Centrifugal	1000-10000 M^3	≤ ¼ of design life
5	Montréal, QC	Centrifugal	> 10000 M^3	> ½ ≤ design life
Clean Water Pump				
1	Dorval, QC	Centrifugal	<1000 M^3/h	> ¼ ≤ ½ of design life
2	Pointe-Claire, QC	Centrifugal	>10000 M^3	> ½ ≤ design life
3	Welland, ON	Centrifugal	1000-10000 M^3	> ¼ ≤ ½ of design life
4	Brantford, ON	Centrifugal	1000-10000 M^3	> design life
5	Montréal, QC	Centrifugal	> 10000 M^3	> ½ ≤ design life

Table5.28 Over all CRI of Tanks (condition rating index)

	SET.TANK			FIL. TANK			CHL.TANK		
CASES	**Mod.**	**Self_M**	**Direct**	**Mod.**	**Self_M**	**Direct**	**Mod.**	**Self_M**	**Direct**
CS_01	6.71	8.09	8.00	6.89	9.26	8.00	6.07	7.70	6.00
CS_02	8.22	9.13	7.00	8.28	9.13	9.00	7.98	8.86	9.00
CS_03	7.91	7.30	7.00	7.80	7.47	9.00	7.45	6.80	7.00
CS_04	9.10	8.80	9.00	7.04	8.95	9.00	8.84	9.21	9.00
CS_05	8.43	8.09	8.00	8.80	8.10	7.00	9.08	8.28	8.00

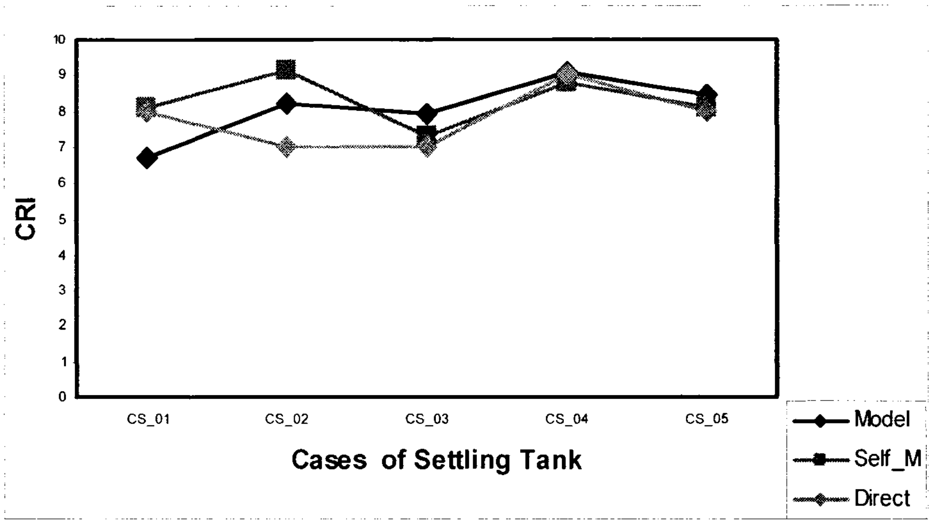


Figure5.17 CRIs from the model and individual expert

Table5.29 % of variation comparing Expert output with Model output

CASES	SET. TANK		FIL. TANK		CHL.TANK	
	Avg/Self	Avg/Direct	Avg/Self	Avg/Direct	Avg/Self	Avg/Direct
CS_01	20.58	16.11	34.31	13.85	26.88	-1.20
CS_02	11.01	-17.47	10.24	7.99	11.02	11.35
CS_03	-7.64	-12.96	-4.30	13.33	-8.64	-6.38
CS_04	-3.30	-1.14	27.21	21.79	4.19	1.76
CS_05	-4.05	-5.34	-7.98	-25.70	-8.86	-13.52

Table5.30 Over all CRI of Pumps (condition rating index)

CASES	RAW WATER PUMP			CLEAN _W_PUMP		
	Model	Self_M	Direct	Model	Self_M	Direct
CS_01	8.52	9.36	7.00	8.55	9.35	6.00
CS_02	7.76	9.19	8.00	7.60	9.13	7.00
CS_03	8.02	8.55	9.00	8.13	8.55	9.00
CS_04	7.86	9.74	10.00	8.23	9.47	9.00
CS_05	8.89	7.93	9.00	8.94	8.19	9.00

Table5.31 % of variation comparing Expert output with Model output

CASES	RAW WATER PUMP			CLEAN _W_PUMP	
	Avg/Self		Avg/Direct	Avg/Self	Avg/Direct
CS_01	9.93		-21.68	9.27	-42.55
CS_02	18.48		2.99	20.23	-8.53
CS_03	6.67		10.91	5.21	9.67
CS_04	23.89		21.37	15.02	8.56
CS_05	-10.79		1.25	-8.39	0.64

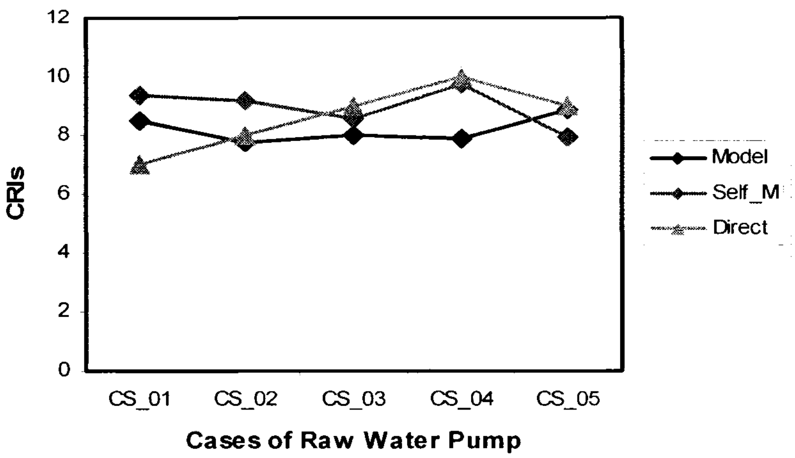


Figure5.18 CRIs from the model and individual expert

Analyzing the CRI variation for the same element obtained by using AM of all weights and preference scores and that from self (expert) assessment (direct and model), it is apparent that the most likely CRI in the latter case will be higher. For tanks, the CRI estimated from self (expert) assessments varies between 34% and -17%, when compared to that from the deterministic model. In the case of pumps, the corresponding variation ranged from 42% to -21%. The variations can be interpreted as a validation of the model, ranging from 99% to 66% for tanks and 99% to 58% for pumps.

The real examples are also used for simulations in order to observe CRIs with uncertainties. In simulations, scenario preference scores were defined with a best fit PBD of preference scores for that scenario instead of AM. After 100 simulations with 1000 iterations for all case studies, maximum, minimum and average CRIs for ST and RWP were found and are shown in Table5.32. The table also shows corresponding CRIs obtained using AM (Deterministic Model). A comparison of mean CRIs estimated from simulations with those obtained using AM shows slight variations (2% to 14%). For most of the cases, the mean CRIs from simulations slightly lower in comparison to those obtained from AM. For illustration purposes, two of the histograms of CRIs are generated as the output of simulations for ST and RWT of CS_1 respectively are shown in Figure5.19 and 5.20. One of the samples of quick summary reports, generated from simulations can be seen in *Appendix-F.*

Table5.32 CRIs of different elements of case studies from simulations and AM

Cases and Element Type	**BEST FITS DIST**			**DETERMIN. (AM)**	**VARIATION**	**% OF VARI. COMP. WITH B.F. MEAN TO AM**
	MAX	**MEAN**	**MIN**	**MEAN**		
	1	2	3	4	(4-2)	
Set. Basin_cs_1	7.81	6.54	5.39	6.71	0.17	2.60
Set. Basin_cs_2	8.75	7.76	6.69	7.22	-0.53	6.96
Set. Basin_cs_3	8.58	7.56	6.16	7.89	0.33	4.37
Set. Basin_cs_4	9.38	8.66	7.84	9.09	0.44	4.97
Set. Basin_cs_5	9.08	8.14	7.14	8.45	0.31	3.81
R.W. Pump_cs_1	9.13	8.18	7.12	8.52	0.34	4.16
R.W. Pump_cs_2	8.50	7.54	6.32	7.79	0.25	3.32
R.W. Pump_cs_3	8.76	7.84	6.67	8.05	0.21	2.68
R.W. Pump_cs_4	8.60	7.67	6.74	7.92	0.25	3.26
R.W. Pump_cs_5	8.65	7.81	6.77	8.87	1.05	13.57

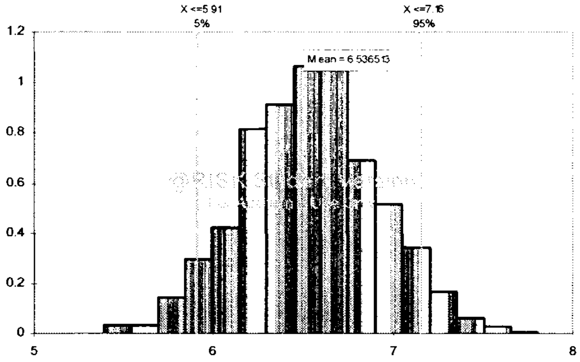


Figure5.19 CRI Histogram of Settling Tank (Case-1)

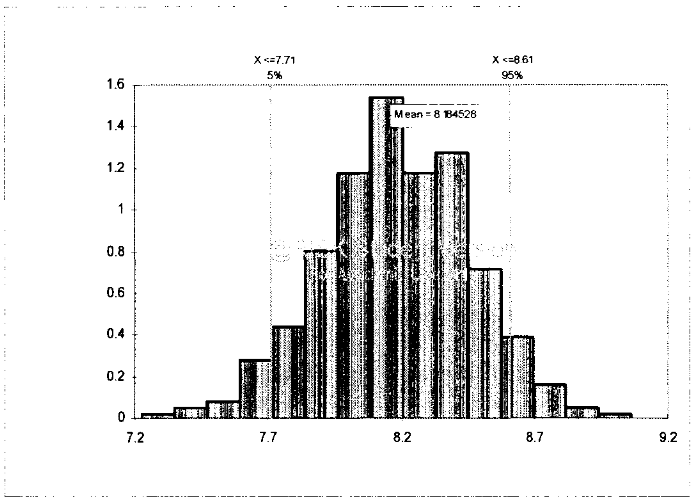


Figure5.20 CRI Histogram of R.W. Pump (Case-1)

5.5 Sensitivity Analysis

The developed condition-rating model has sixteen parameters and each parameter is defined with a few scenarios. With a constrain of $\sum w_i = 1$, for both tanks and pumps, changing the composite relative weights (±40%) of a particular parameter or even all parameters under a category, does not show any noticeable sensitivity in the model output (CRI). Based on the previous observations, the sensitivity of the model is tested only by varying the preference scores (±40%) of applicable scenarios. In the sensitivity analysis process, only ST and RWP are accounted from all real examples. There could be hundreds of combination of scenarios in real world problems. To observe the sensitivity in the case of all the most preferred (COM-1) scenarios besides the case studies, also considered. The result obtained from ST and RWP will be representative of the element class tanks and pumps respectively due to the use of same set of model parameters. In addition, the variation due to different preference scores observed for the same element group is also not significant.

5.5.1 Settling Tanks (ST)

To observe the sensitivity of preference scores (PS) on the CRI values, the PSs of all applicable scenarios were varied in the spreadsheet model with a 10% increase or -20% decrease up to ± 40% in all case studies and all the most preferred case (COM_01). In all cases, the preference scores are constrained such that they will range from zero to 10. Figure 5.21 shows the results after the above-mentioned sensitivity test is performed. A comparison of maximum and minimum CRIs in each case shows that variations are similar and range from 4.22 to 4.66. The variation of maximum and minimum CRIs in cases of the most preferred scenarios is 1.56. Therefore, the most preferred case does not have a maximum variation due to the influence of relative weights and the combination of scenarios. Case 2 and case 5 are most sensitive when the PSs of all parameters are varied.

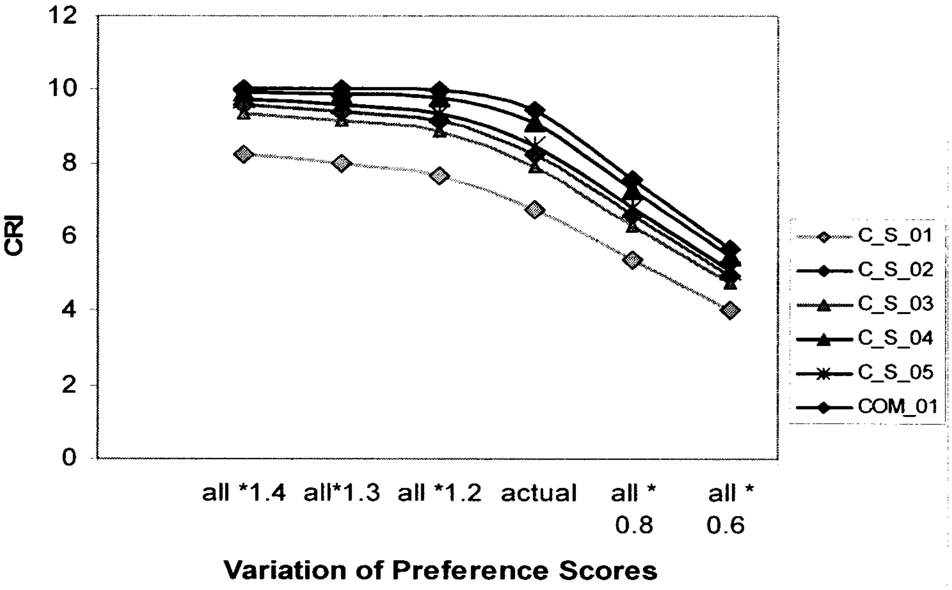


Figure5.21 Sensitivity on varying preference scores of all model parameters

Figure5.22 represents the CRI sensitivity results, when the PSs for the parameters under categories 'a' and 'b' are varied. The maximum and minimum CRI variation ranges between 2.40 to 2.73. The CRI of CS_2 is the most sensitive when the PSs of the parameters under category 'a' and 'b' are varied.

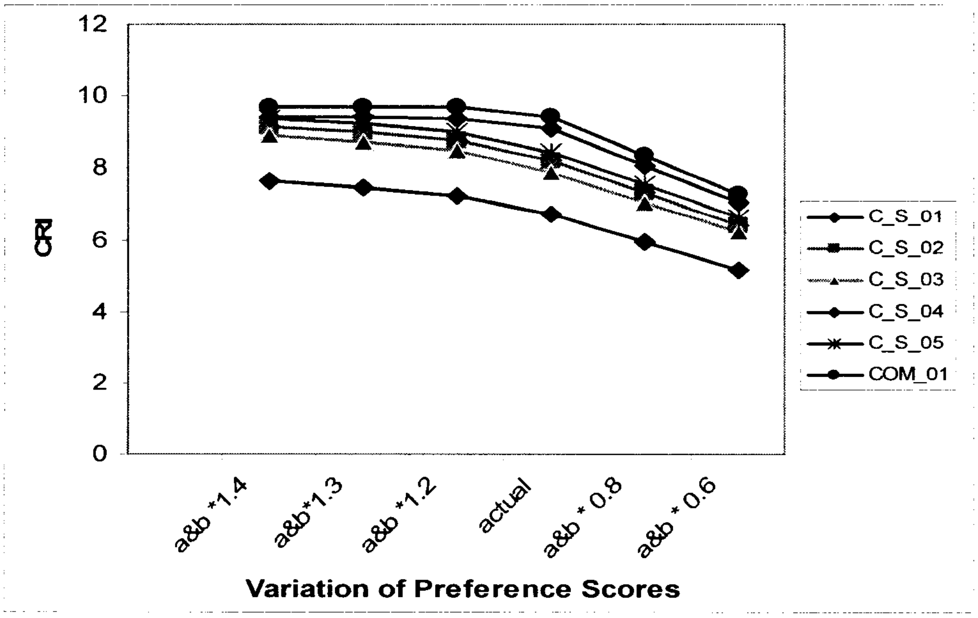


Figure5.22 Sensitivity on varying preference scores of model parameters under category a & b

To observe the sensitivity of the PSs for the parameters under category b and c on the CRIs, their scores were also varied in the model and the results are presented in Figure 5.23. Results show that with the exception of CS_2 the variation of maximum and minimum CRIs ranges from 1.74 to 1.94. The variation in case of CS_2 was 4.66, which clearly indicates that CS_2 is very sensitive to PSs of parameters under category 'c' and 'b'. The CRI sensitivity results are observed by varying the PSs for parameters under categories c and are presented in Figure5.24. The maximum and minimum CRIs variations range from 1.74 to 2.36. It can be concluded that the CRIs of CS_5 is the most sensitive.

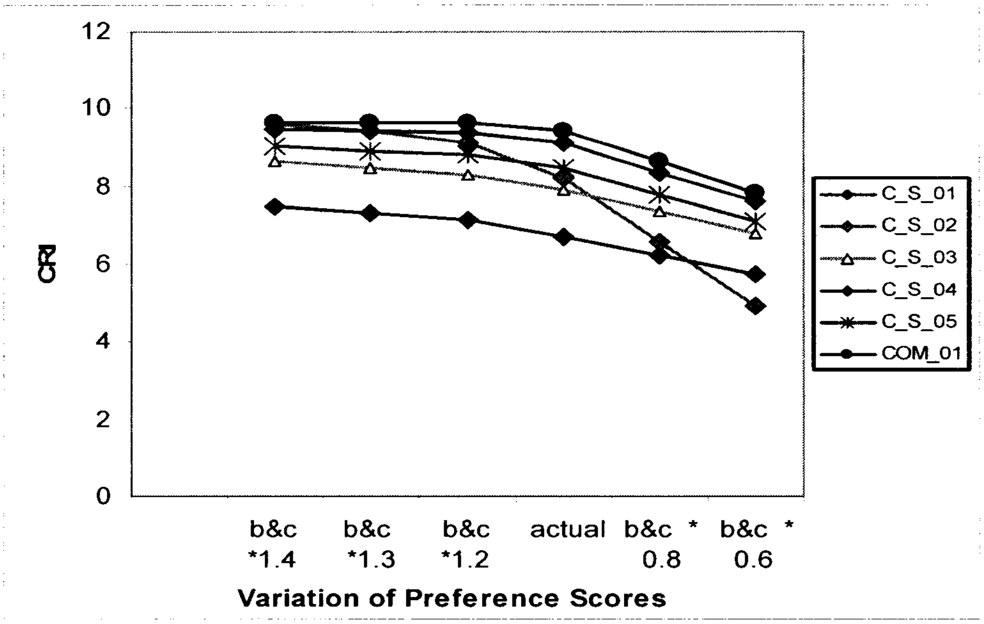


Figure5.23 Sensitivity on varying preference scores of model parameters under category b & c

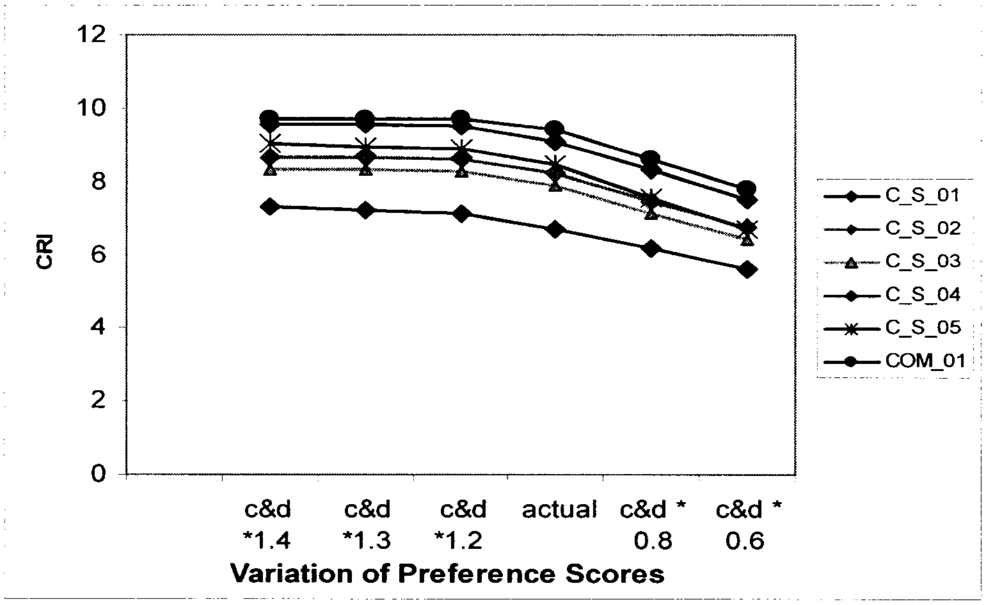


Figure5.24 Sensitivity on varying preference scores of model parameters under category c & d

The PSs for parameters under categories ‘a’ & ‘d’ were varied in the model in order to determine sensitivity of CRIs. The results are shown in Figure5.25 and they indicate that the variation of maximum and minimum CRIs range from 2.49 to 3.01.

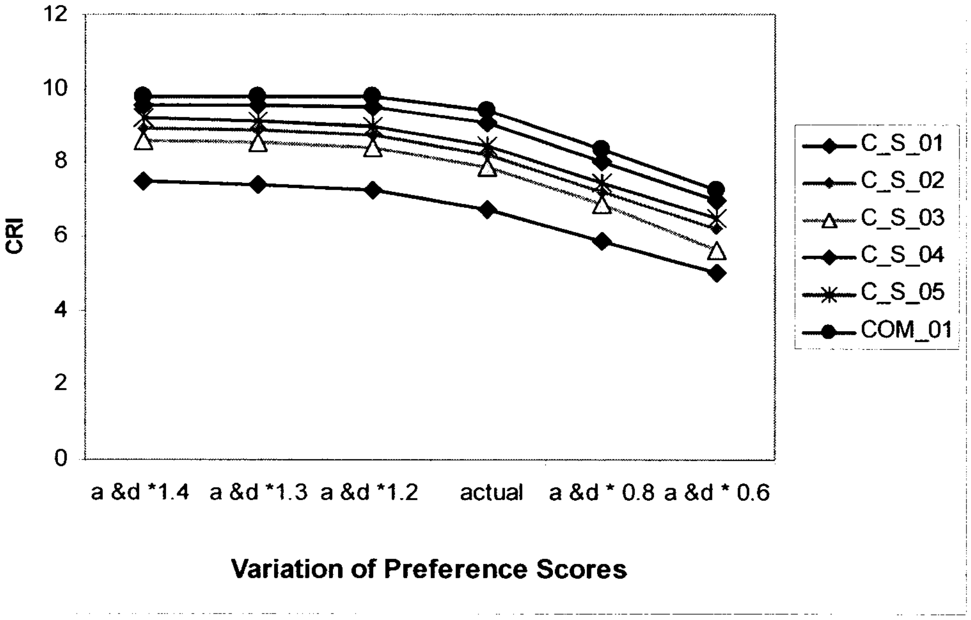


Figure5.25 Sensitivity on varying preference scores of model parameters under category a & d

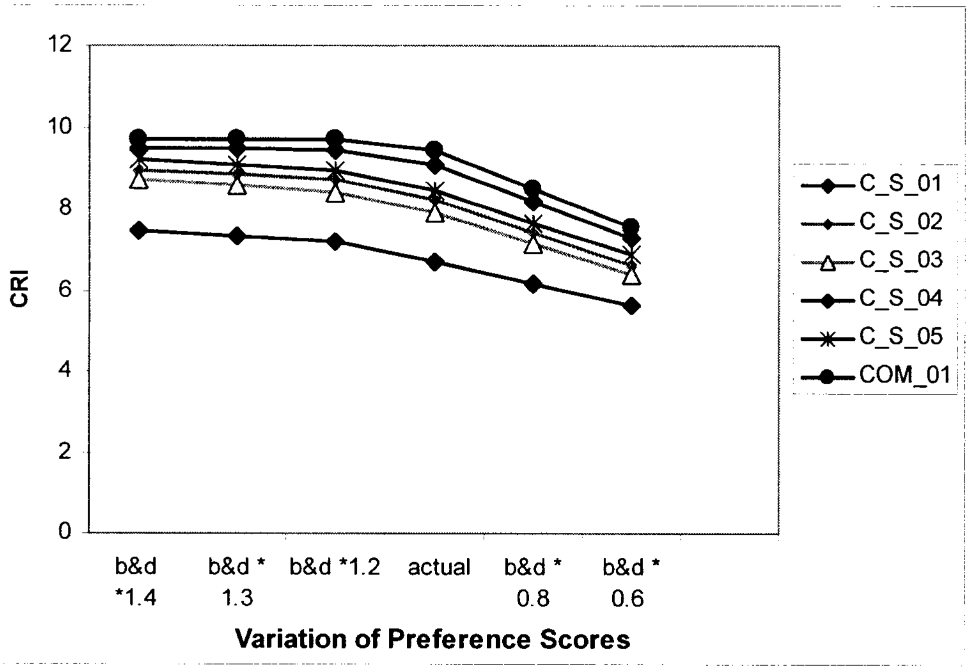


Figure5.26 Sensitivity on varying preference scores of model parameters under category b & d

Therefore, the PSs for the parameters under categories 'a' and'd' are most sensitive to CRI for CS_3. Finally, the PSs for the parameters under categories 'b' and'd' were also varied in the model to observe the sensitivity of CRIs. The results are shown in Figure 5.26. After comparing the variation of maximum and minimum CRIs, it is found that the values range from 1.83 to 2.35. The CRI of CS_3 appears to be the most sensitive to a variation of PSs of parameters.

5.5.2 Raw Water Pump (RWP)

In similar fashion to ST, a sensitivity analysis was also performed on CRIs for RWP by varying the PSs of the applicable parameter scenarios. Figure5.27 shows the sensitivity results obtained for pumps after varying the PSs of all parameters in the model. The differences between maximum and minimum CRIs for each case ranged from 4.10 to 4.76. Sensitivity outcomes of CRIs due to a variation of PSs of parameters under category 'a' and 'b' in the model are shown in Figure5.28. The PSs of parameters under categories 'a' and 'b' are more sensitive to the CRI of CS_3, in comparison to other cases. The PSs of parameters under categories b and c are varied in order to observe the level of sensitivity of CRIs due to those variations. The results presented in Figure 5.29 reveal that the differences between maximum and minimum CRIs ranged from 1.22 to 2.18. It can be concluded that category b and c is more sensitive to CS_2. Figure 5.30 represents the sensitivity results found after varying the PSs for the parameters under categories c and d. The variation of maximum and minimum CRIs ranged from 2.01 to 2.63, CS_1 appears to be the most sensitive to category c and d. The variation of PSs for the parameters under 'a' and'd' are made and the CRI results with respect to that variation are shown in Figure 5.31. Parameters under these categories are more sensitive to CS_2 in comparison to the others and the differences between maximum and minimum CRIs ranged from 2.39 to 2.95. Finally, the PSs of all parameters under categories b&d

were varied to observe the sensitivity of the CRIs resulting from those variations. Results are presented in Figure 5.32. The variation in maximum and minimum CRIs ranged from 2.41 to 2.61.

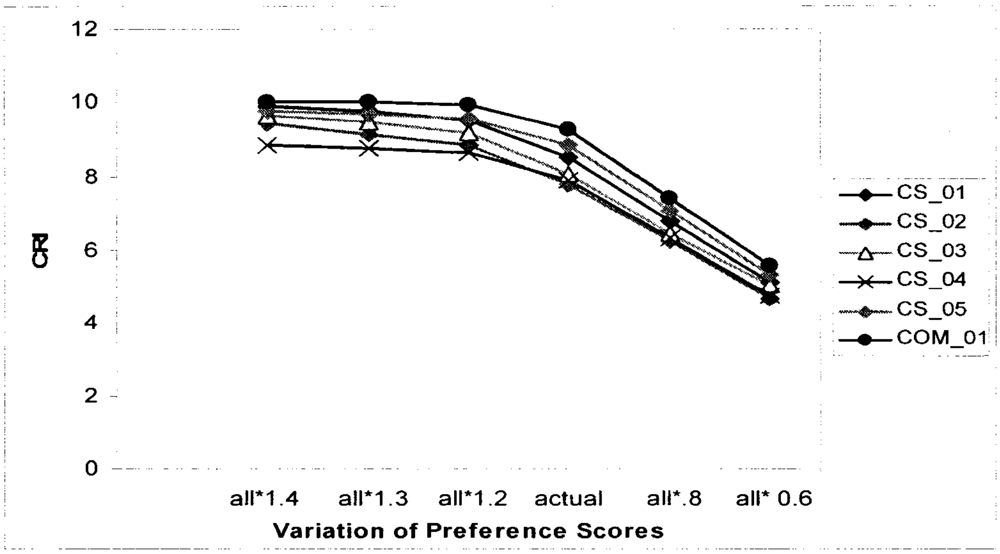


Figure5.27 Sensitivity of CRIs on varying preference scores of all model parameters

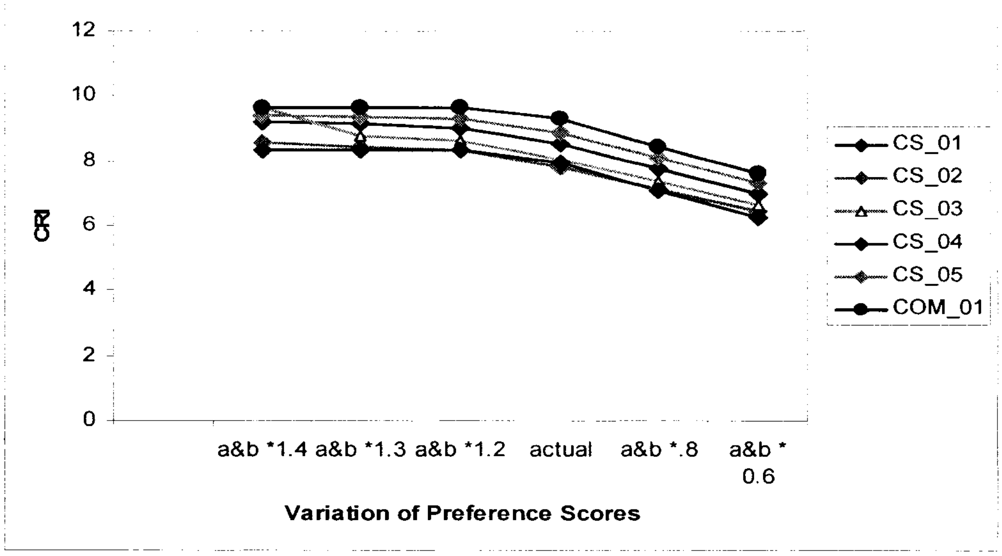


Figure5.28 Sensitivity on varying preference scores of model parameters under category a & b

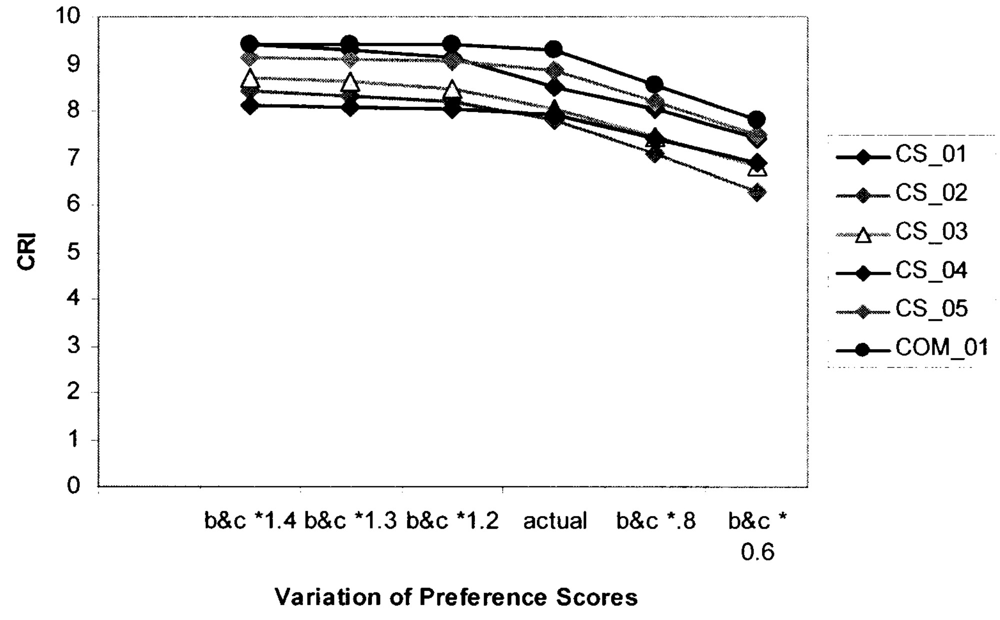


Figure5.29 Sensitivity on varying preference scores of model parameters under category b & c

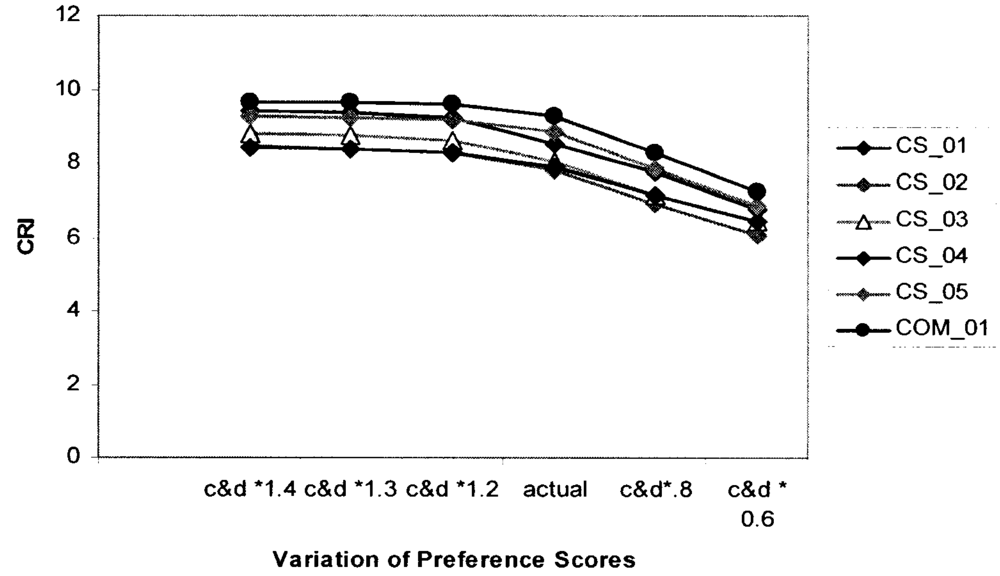


Figure5.30 Sensitivity on varying preference scores of model parameters under category c & d

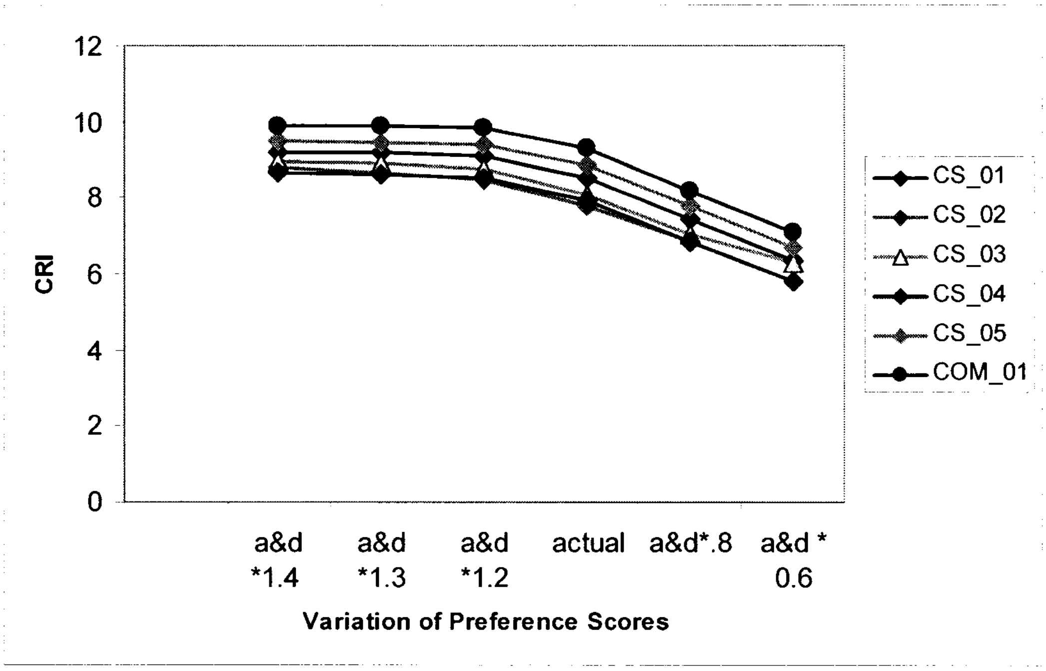


Figure5.31 Sensitivity on varying preference scores of model parameters under category a & d

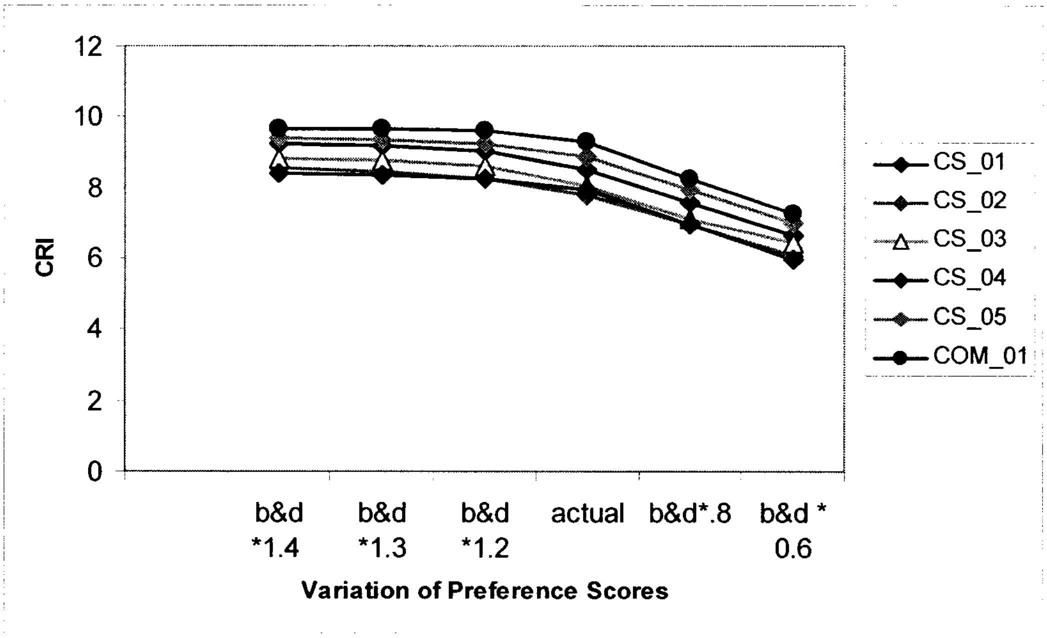


Figure 5. 32 Sensitivity on varying preference scores of model parameters under category b & d

CHAPTER 6

WEB –BASED CONDITION ASSESSMENT TOOL

6.1 Introduction

The use of the internet in recent years has expanded exponentially. Researchers use the internet as a primary tool to explore their professional needs. The internet is the most popular and convenient way to reach people and its access and use can be secured in a systematic way. The web version of the developed condition-rating model will provide an opportunity for global access. Many water authorities do not have their own tool for condition assessment of DWTP elements and may benefit from this web version model. After gaining experience with the model, many practitioners will give their feedback and the model can be updated accordingly.

6.2 The Framework of the Tool

The web version of the CR model is introduced as a prototype condition assessment tool for the selected elements of DWTP. The tool is based on an analytical hierarchy process (AHP) and an additive multi-attribute utility approach. A set of predefined model parameters are used in the condition assessment tool. These parameters require an estimation of relative weights and preference scores for a specific scenario. Each parameter is assigned a few scenarios to measure preferences for the current condition of a certain element. Using historical data and the best judgments, practitioners will be able to assess the condition of an element by applying this model. Initially, the output of the model will be the CRI (0-10) and then the element will be graded (A-F), where 0 and F implies worst condition and 10 and A indicates the best condition.

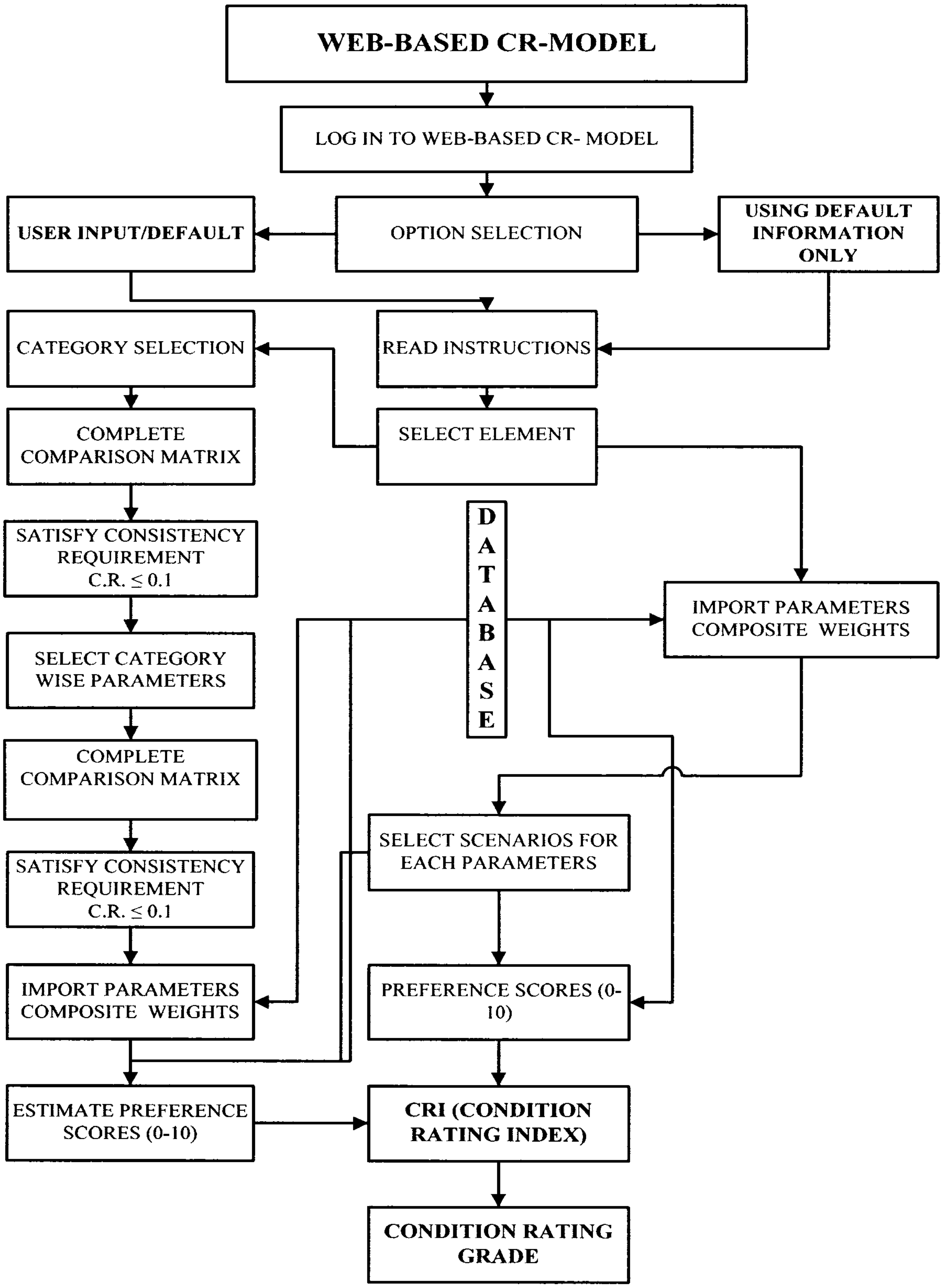


Figure6.1 Flow-diagram of web-based condition assessment tool

After completing the operation successfully, the user of the tool will be able to generate a report with all results. The flow diagram showing the framework of the tool is shown in Figure6.1.

6.3 The Program

The unified web development model ASP.NET is used to construct this condition assessment tool. The ASP (Active Server Page) is developed by Microsoft that allows creating a dynamic and interactive environment on the web with the user. ASP.NET is a part of the .NET framework, provided by Microsoft. The applications of ASP.NET can be coded in any language compatible with the common language runtime (CLR) such as Microsoft Visual Basic, C#, JScript .NET, and J# (Microsoft, 2006). Some of the most important features of ASP.NET are as follows:

- Completely object oriented
- Web pages can be requested from any browser and the same page can be used for multiple browsers.
- Controls written for one page are reusable
- An Extensible Markup Language (XML) web services framework can be established and it can work with Hyper Text Mark-up Language (HTML) elements
- Simple way to retrieve data from a database
- Can include specific files required for processing
- All the AHP.NET applications can be configured on an entire server or as individual pages (Microsoft, 2006)

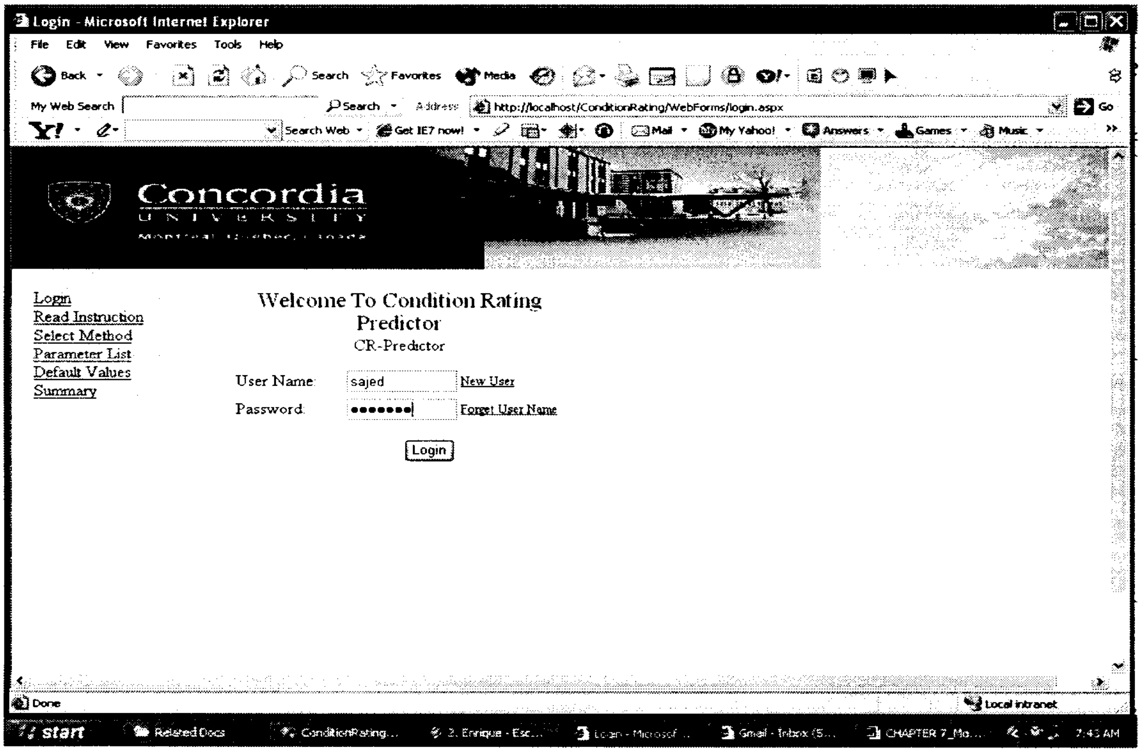
In the current tool, the program will create web pages and link them, allow the user to input data and or import data from a database perform calculations to provide results and finally generate reports. The primary requirements to run AHP.NET are a PC must have Internet Information Server (IIS) and .NET framework software development kit (SDK) locally installed.

6.4 Steps for Using the Tool

To use the tool, the user is required to sign in order to obtain access, which is shown in Figure 6.2. After sign in, the user has the option to choose whether he or she wants to proceed with only default information or with both default and user inputs simultaneously. Regardless of the choice of the project options, the user will be guided to read instruction sheets on providing comparison inputs, selection of scenarios and assigning preference scores for selected scenarios. The user then has the option to select the desired element. The tool will automatically import categories, set of model parameters and other information from a database based on the selection of the element. There are different levels in the hierarchy structure of the model as previously shown in chapter 3 (Figure 3.2.). At the top of hierarchy is the model goal condition rating. The category and parameters are located in level 1 and 2 respectively. The resulting CI is located at the bottom of the hierarchy.

6.4.1 User Input and Default Information Option

Under this option, after reading instructions and selecting the element, the user will be directed to select categories to construct the comparison matrix. Following the instructions, the user will complete the upper portion (upper triangle) of the reciprocating comparison matrix (as shown in Figure 6.3) based on his knowledge and experience. The model will estimate relative weights from the newly constructed matrix by solving a set of equations. To satisfy the consistency requirement of the comparison judgments of the user, the model will also verify that the consistency ratio (C.R.) of the matrix is ≤ 10% (0.1). If this criterion is not met, it must be redone until the consistency requirement is satisfied.



Welcome To Condition Rating Predictor

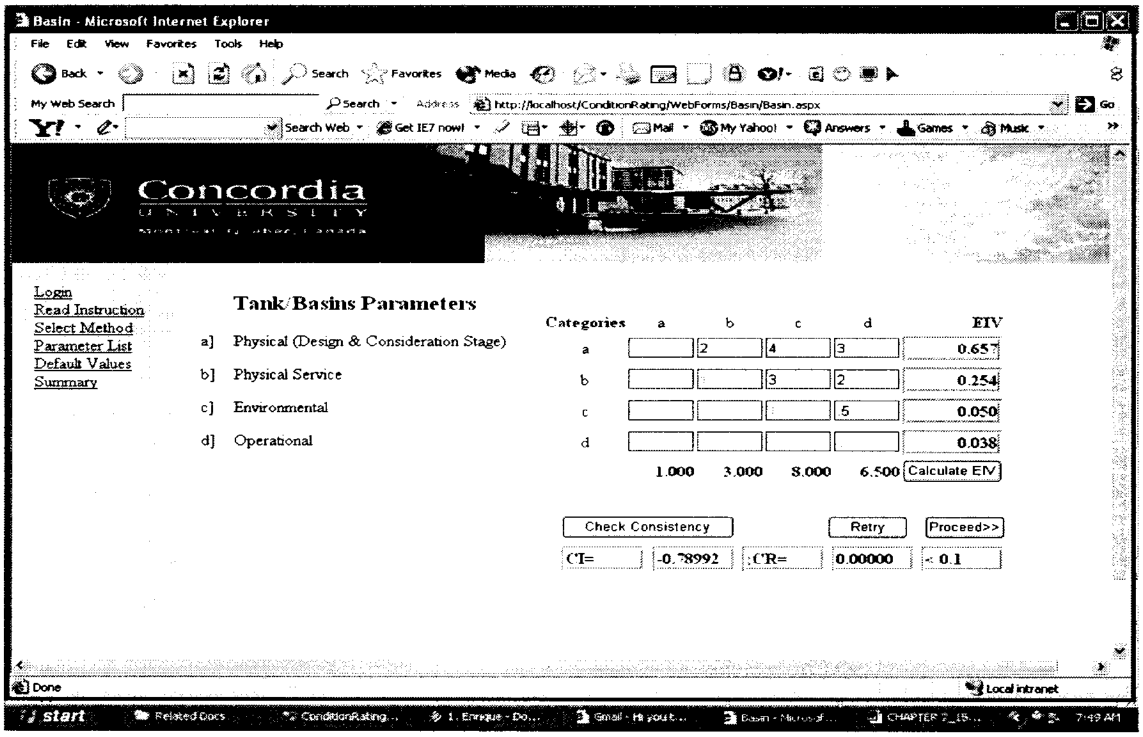
CR-Predictor

User Name: sajed

Password: •••••••

Figure6.2 Display is showing login process.

Secondly, the user will select a category to construct the comparison matrix for the parameters under that category. The entire process will be copied in the exact same fashion as previously done for the estimation of relative weights (EIV) and consistency requirements of categories. The process is continued until the parameters under all 4 categories have been considered. The model will decompose the relative weights of parameters according to equation 5.1 in order to provide composite or decomposed relative weights. If the user is not happy the outcome, the results may be disregarded and default decomposed relative weights may be imported. Figure 6.4 displays the decomposed relative weights of all 16 model parameters.



Tank/Basins Parameters

a] Physical (Design & Consideration Stage)
b] Physical Service
c] Environmental
d] Operational

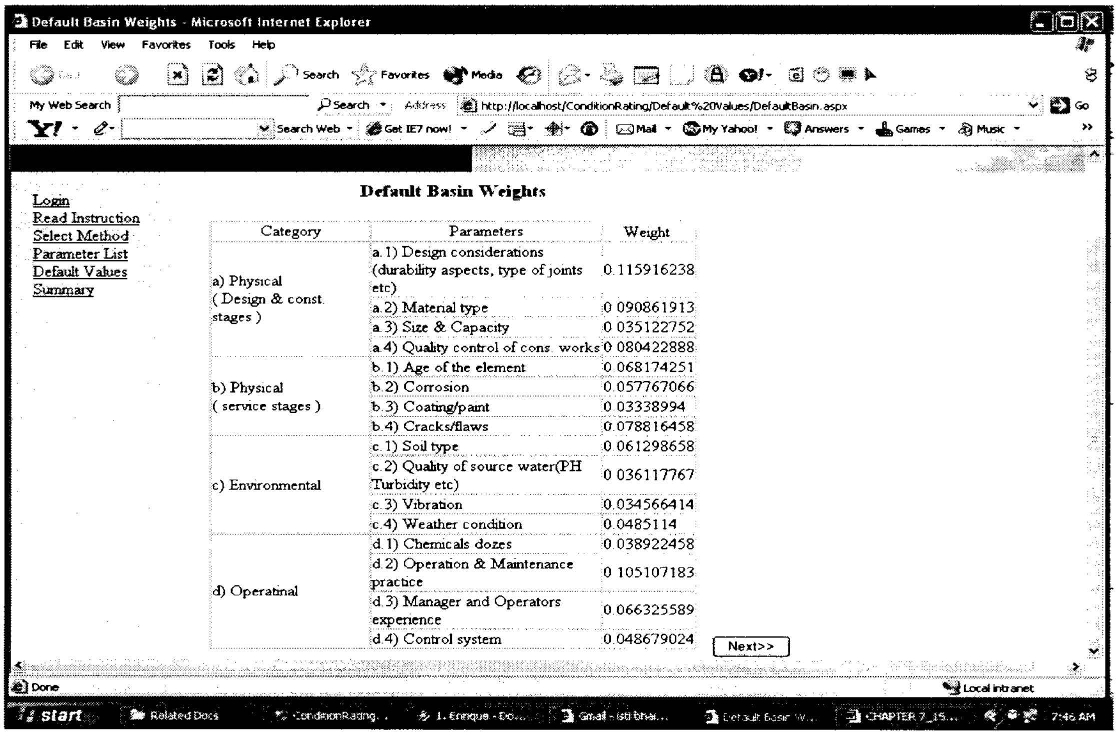
Categories	a	b	c	d	EIV
a		2	4	3	0.657
b			3	2	0.254
c				5	0.050
d					0.038
	1.000	3.000	8.000	6.500	

CI= -0.78992 ;CR= 0.00000 < 0.1

Figure6.3 Display showing process of completing comparison matrix with consistency test.

The user will now choose appropriate scenarios for each parameter from a given list. The selection of any scenario should not be random, rather the user will justify his choice based on historical data, engineering inspection reports or at least visual inspection. This part is critical to the ultimate outcome of the CR model and totally dependent on field conditions. Any mistake will mislead the resulting CR.

The user now estimates preference scores (PS) for the matched scenarios under each parameter. The instructions should be followed strictly in order to complete this part and the scores will range from 0-10. A PS of 0 implies the lowest level of utility, whereas a PS of 10 implies a maximum level of utility in contributing to the condition of the concerned element. Users can also choose default PSs instead of estimating their own. Figure6.5 shows the display screen of selected scenarios and assigned PSs for all 16 parameters.

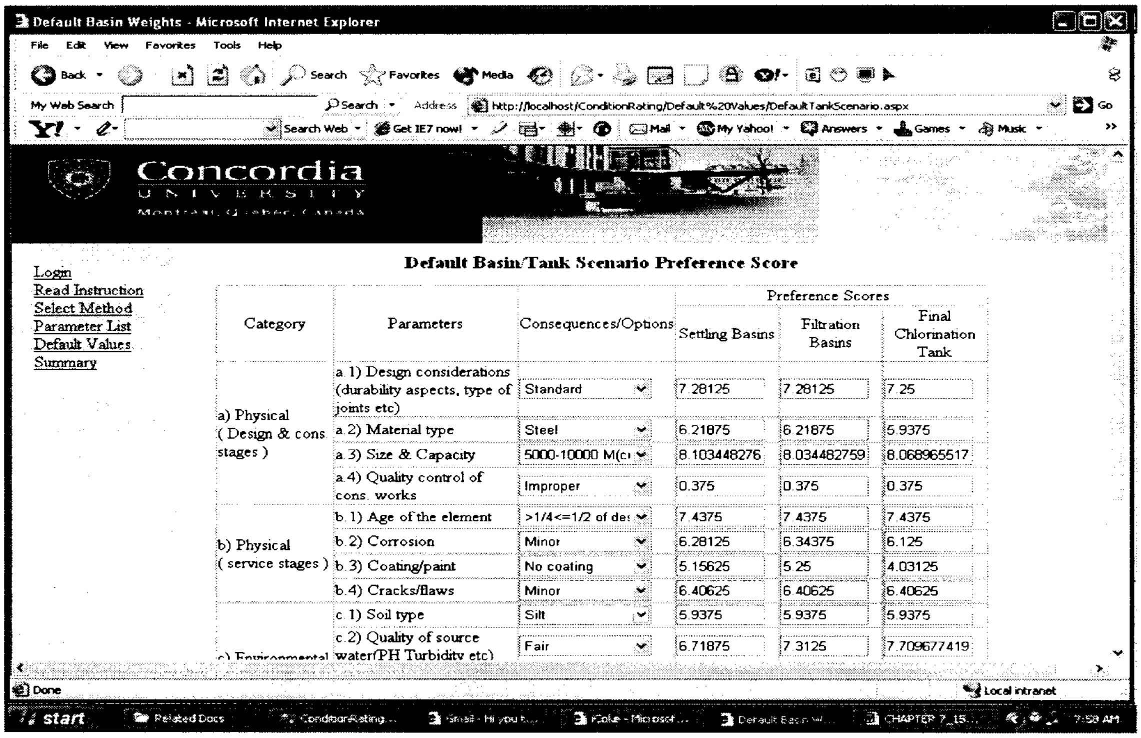


Default Basin Weights

Category	Parameters	Weight
a) Physical (Design & const. stages)	a.1) Design considerations (durability aspects, type of joints etc)	0.115916238
	a.2) Material type	0.090861913
	a.3) Size & Capacity	0.035122752
	a.4) Quality control of cons. works	0.080422888
b) Physical (service stages)	b.1) Age of the element	0.068174251
	b.2) Corrosion	0.057767066
	b.3) Coating/paint	0.03338994
	b.4) Cracks/flaws	0.078816458
c) Environmental	c.1) Soil type	0.061298658
	c.2) Quality of source water(PH Turbidity etc)	0.036117767
	c.3) Vibration	0.034566414
	c.4) Weather condition	0.0485114
d) Operatinal	d.1) Chemicals dozes	0.038922458
	d.2) Operation & Maintenance practice	0.105107183
	d.3) Manager and Operators experience	0.066325589
	d.4) Control system	0.048679024

Figure6.4 Display showing default composite weight of parameters (Tank/Basin)

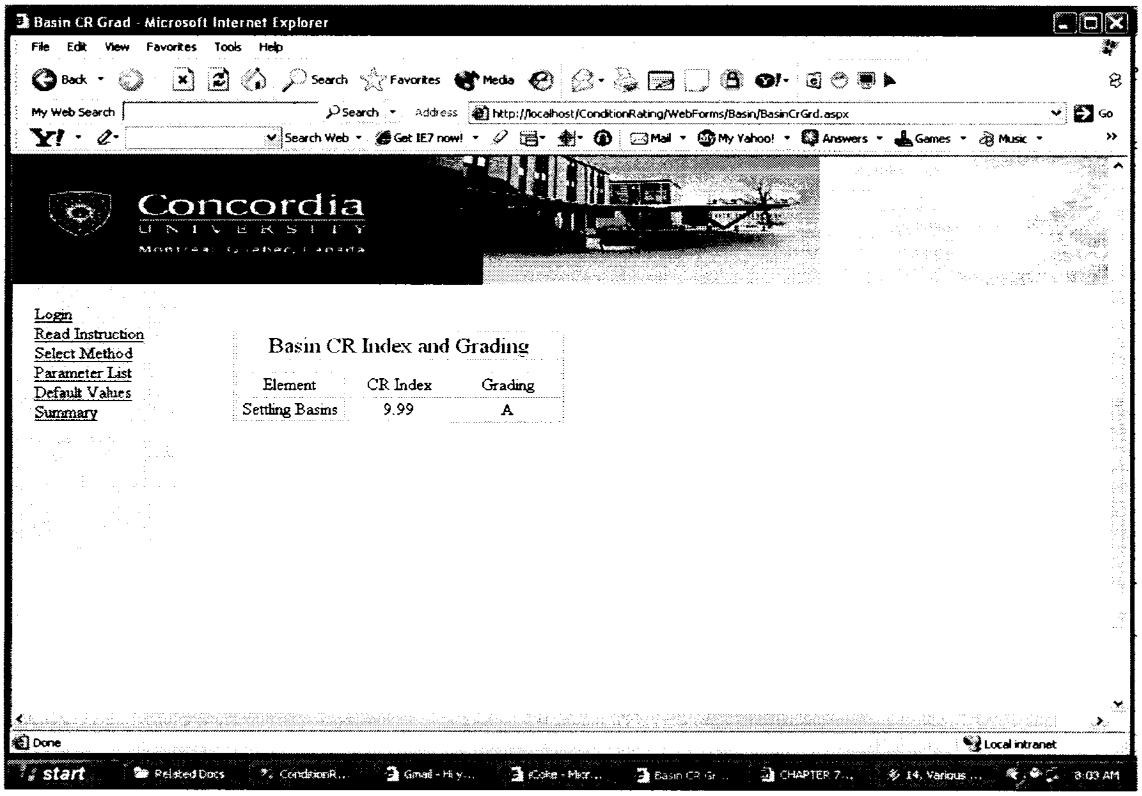
Finally, applying equation 5.3, the model will provide a CRI (0-10) of the element according to the inputs or imported data introduced in the tool. Depending on the CRI, the tool will make grade the element (A-F), as a grading criteria is predefined in the tool. The CRI and the grading of the element are shown in Figure 6.6. The tool will also generate a summary report with step by step intermediate outputs including final results.



Default Basin/Tank Scenario Preference Score

Category	Parameters	Consequences/Options	Preference Scores Settling Basins	 Filtration Basins	 Final Chlorination Tank
a) Physical (Design & cons stages)	a.1) Design considerations (durability aspects, type of joints etc)	Standard	7.28125	7.28125	7.25
	a.2) Material type	Steel	6.21875	6.21875	5.9375
	a.3) Size & Capacity	5000-10000 M(c	8.103448276	8.034482759	8.068965517
	a.4) Quality control of cons. works	Improper	0.375	0.375	0.375
b) Physical (service stages)	b.1) Age of the element	>1/4<=1/2 of de	7.4375	7.4375	7.4375
	b.2) Corrosion	Minor	6.28125	6.34375	6.125
	b.3) Coating/paint	No coating	5.15625	5.25	4.03125
	b.4) Cracks/flaws	Minor	6.40625	6.40625	6.40625
c) Environmental	c.1) Soil type	Silt	5.9375	5.9375	5.9375
	c.2) Quality of source water(PH Turbidity etc)	Fair	6.71875	7.3125	7.709677419

Figure6.5 Display shows scenario selection and default PS for tanks



Basin CR Index and Grading

Element	CR Index	Grading
Settling Basins	9.99	A

Figure6.6 Display is showing he CRI and grading of the element

6.4.2 Default Information Only Option

In this option, after reading instructions and selecting the desired element, the user can directly import decomposed relative weights for all parameters and jump to step 3 for selecting scenarios. The user needs to follow this procedure to accomplish this part as described for the other options above and displayed in Figure 6.5. Once the selections for scenarios are done, the system will import PSs for respective scenarios of each parameter accordingly. The tool will now provide a CRI and grading for the element as described above and shown in Figure 6.6.

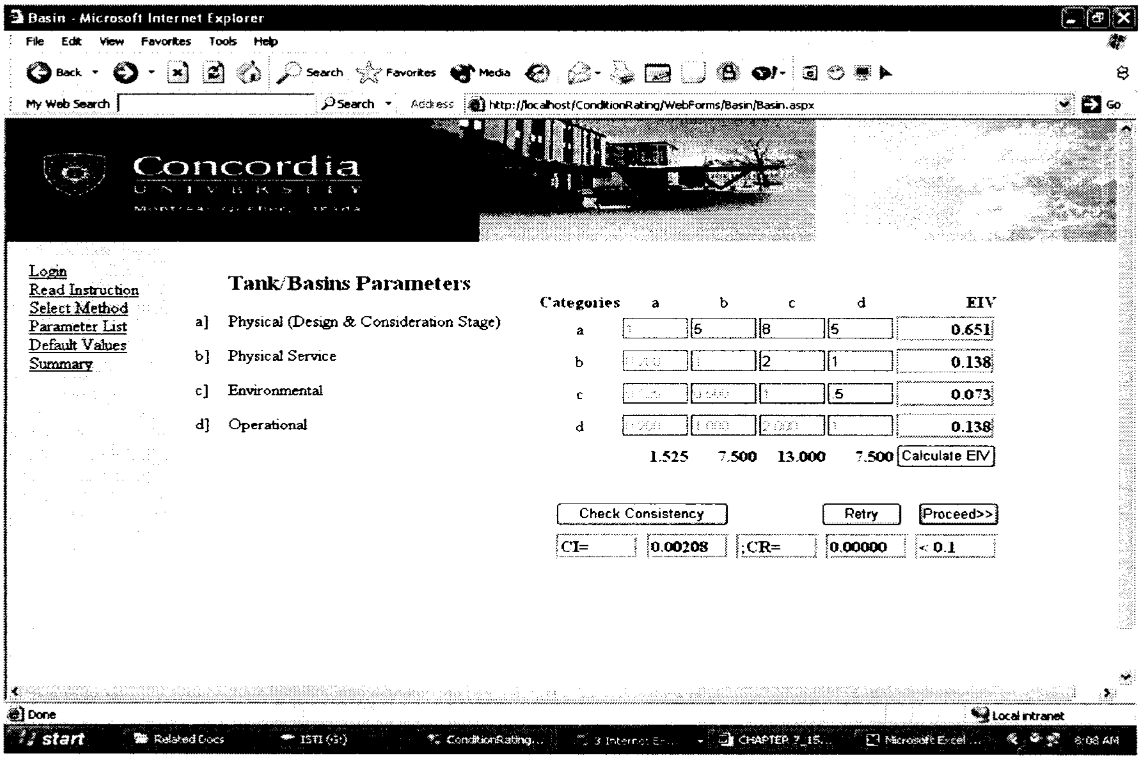
6.5 Application of Tool

To demonstrate the application of the developed condition assessment tool, a practical problem of a settling tank (ST_CS-2) is considered for using both options. The survey respondent (RES-11), who is responsible for the concerned element, is considered as the user and his survey responses and scenario data has been used.

6.5.1 Using User Inputs

After selecting the settling tank as a target element in the tool, the comparison matrix for 4 categories ((Physical Design & Construction stage), Physical (service), Environmental and Operational)) is constructed by providing information from survey responses of REP-11. After completing the calculations, the tool displaying the C.R. for the matrix is 0.002 (Figure 6.7), which is satisfactory. The category, Physical (D & C stage) is selected to construct the comparison matrix by using survey responses from REP-11, for the parameters (Design considerations, Material type, Size & Capacity and Quality control) under this category. After solving the matrix, the tool displayed a C.R. of $0 \leq 10\%$.

Similarly, the other three categories were selected to estimate the relative weights of parameters under those categories and the C.R. was found to be .006, .041 and -.05. The C.R. values obtained from the tool confirm the fulfillment of the consistency requirements of the user for all matrices. The display screen is shown in Figure6.8. The tool shows the decomposed weights of all the parameters according to user inputs.



Tank/Basins Parameters

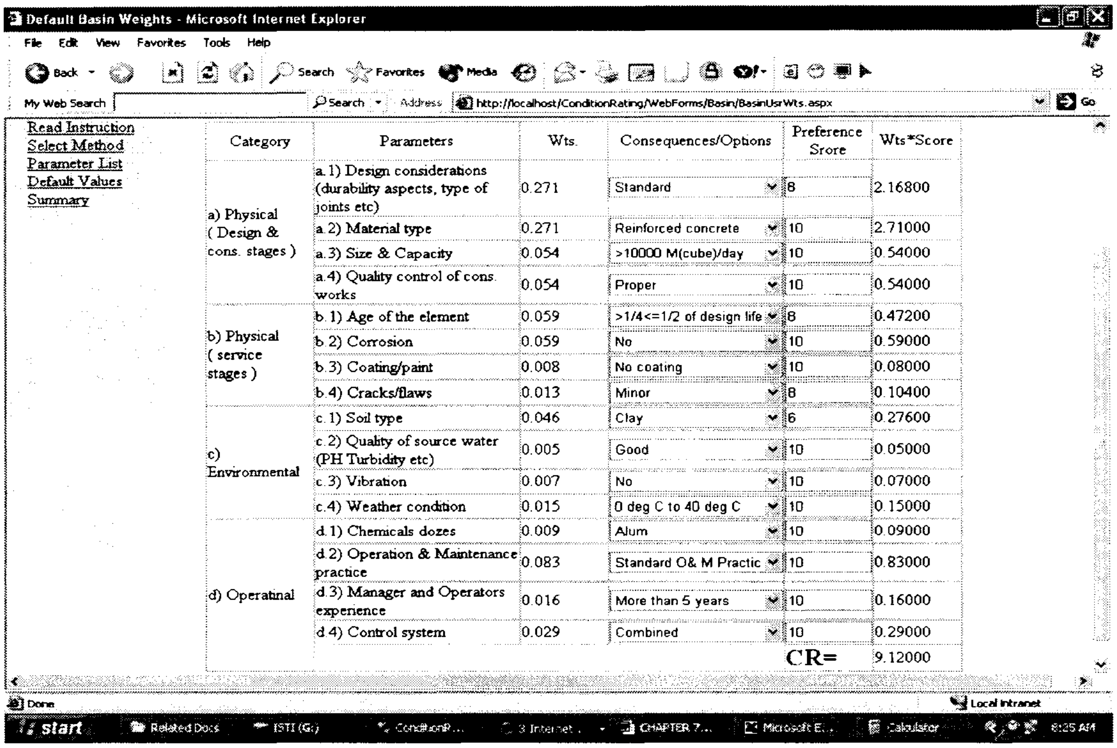
a] Physical (Design & Consideration Stage)
b] Physical Service
c] Environmental
d] Operational

Categories	a	b	c	d	EIV
a	1	5	8	5	0.651
b	0.200	1	2	1	0.138
c	0.125	0.500	1	.5	0.073
d	0.200	1.000	2.000	1	0.138
	1.525	7.500	13.000	7.500	

CI= 0.00208 ;CR= 0.00000 < 0.1

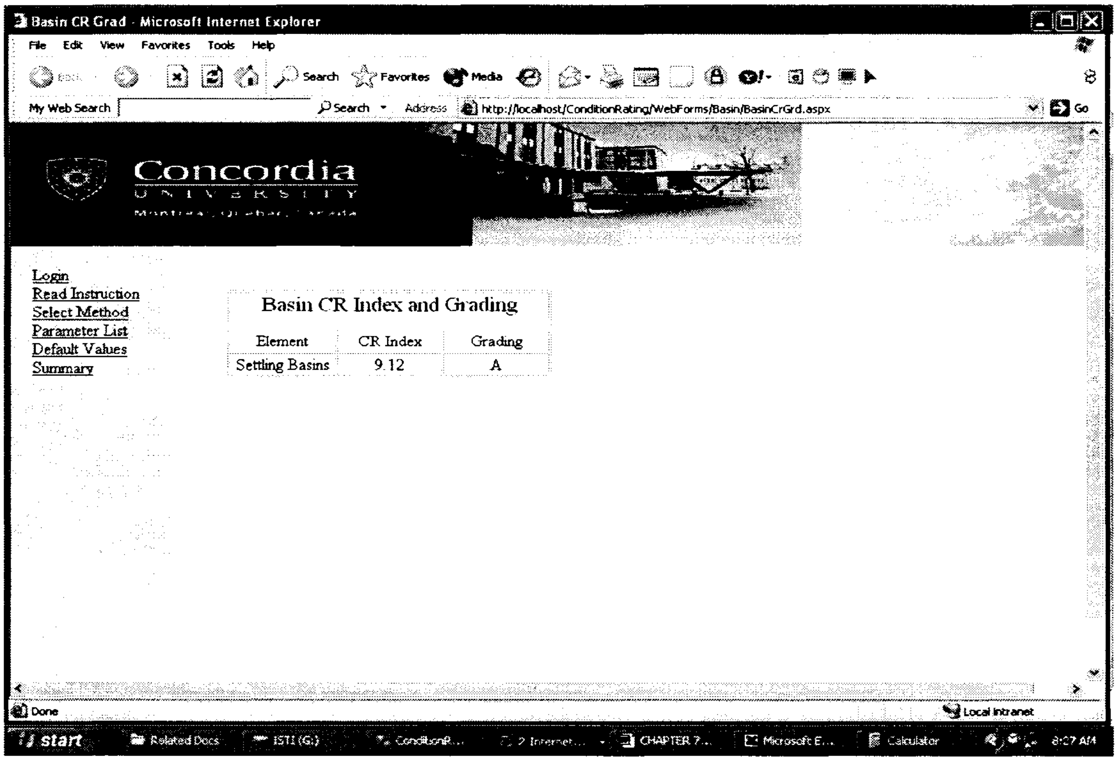
Figure6.7 Display showing matrix inputs, EIV and consistency results.

The scenarios under each parameter are selected according to user information and each scenario is assigned with a PS provided by the user. Finally, the tool calculates the CRI, for the particular ST (9.1287) and a condition grading (A), as shown in Figure6.8 and 6.9.



Category	Parameters	Wts.	Consequences/Options	Preference Srore	Wts*Score
a) Physical (Design & cons. stages)	a.1) Design considerations (durability aspects, type of joints etc)	0.271	Standard	8	2.16800
	a.2) Material type	0.271	Reinforced concrete	10	2.71000
	a.3) Size & Capacity	0.054	>10000 M(cube)/day	10	0.54000
	a.4) Quality control of cons. works	0.054	Proper	10	0.54000
b) Physical (service stages)	b.1) Age of the element	0.059	>1/4<=1/2 of design life	8	0.47200
	b.2) Corrosion	0.059	No	10	0.59000
	b.3) Coating/paint	0.008	No coating	10	0.08000
	b.4) Cracks/flaws	0.013	Minor	8	0.10400
c) Environmental	c.1) Soil type	0.046	Clay	6	0.27600
	c.2) Quality of source water (PH Turbidity etc)	0.005	Good	10	0.05000
	c.3) Vibration	0.007	No	10	0.07000
	c.4) Weather condition	0.015	0 deg C to 40 deg C	10	0.15000
d) Operatinal	d.1) Chemicals dozes	0.009	Alum	10	0.09000
	d.2) Operation & Maintenance practice	0.083	Standard O& M Practic	10	0.83000
	d.3) Manager and Operators experience	0.016	More than 5 years	10	0.16000
	d.4) Control system	0.029	Combined	10	0.29000
				CR=	9.12000

Figure6.8 Display showing decomposed weight of parameter



Basin CR Index and Grading

Element	CR Index	Grading
Settling Basins	9.12	A

Figure6.9 Display showing decomposed weight of parameter

6.5.2 Using Default Information

The same example of ST_CS_2 is used in the condition assessment tool. After selecting ST from the element list in the tool, the user needs to import relative weights (decomposed) from the database instead of employing the user's own judgments. Then the scenarios for each parameter are selected according to the data provided by RES-11. PSs are assigned by default according to the selected scenarios. The default relative weights and PSs are the arithmetic mean of all decomposed weights and PSs evaluated by the 32 survey respondents (experts). Finally, the tool calculates the CRI for the same ST (7.2236) and the corresponding condition grade (C).

Providing identical information, the results generated by the tool and that from the Excel spreadsheet model for this specific element is also identical. Therefore, it is proved that the web version of the model is working perfectly and is applicable to real world problems.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Current research work includes a thorough review of the condition parameters and existing assessment techniques, preparing questionnaires based on AHP and MAUT concepts, conducting surveys, developing prototype condition rating models, analyzing data, validating the model, performing sensitivity analysis, establishing a proposed condition grading scales and finally developing a web-based tool based on the developed model. Research contributions, limitations and suggested future work are also briefly discussed further.

- A set of sixteen model parameters under four categories for tanks and pumps have proven to be acceptable by all participants in the survey process with very little criticism. The total number of parameters was limited to sixteen in order to avoid any unnecessary complexity associated with comparison matrices.
- Survey participants were dominated by operational personnel. Among the 32 survey respondents, seventeen operators (53%), three designers (9%), five consultants (16%), three researchers (9%) and four water resources engineer (13%) were present.
- Variation of model outputs from deterministic model and probabilistic ones are not significant. With uncertainty, two types of element classes hold two different models unlike a single deterministic model. In general, the former model gives higher CRIs.

- Study results showed that none of the parameters appeared to be dominant. At an individual level and in most cases, one or a few parameters appear to be dominating. This implies that the experts were influenced by their experiences. The highest ranking category for tanks is 'Physical (design and construction stage)' with a relative importance of 32% and that for pumps is 'Operational' with an importance of 34%. Design Considerations assigned the highest (12%) average relative weight among all parameters for tanks. Similarly, in case of pump parameters, the most important parameter is O & M practices (11%). With all the most preferred scenarios, average CRI for settling tank and raw water pumps was 9.63 and 9.66 respectively while considering all the least preferred scenarios with average CRIs of 1.98 and 3.54 respectively. These CRI indicate, according to the assessment that these are the limiting CRIs.
- Most of the scenarios preferences scores follow normal distributions when they were fitted in @Risk.
- The developed model was applied with 25 elements to estimate CRIs and the results were compared with the respective estimations made by the experts. The individual expert's CRIs have been estimated directly and by using their survey inputs individually in the model. The variation of experts CRI in comparison to that from the model ranges from 34% to -17% and 42% to -21% for tanks and pumps respectively. In most cases, the variation is within 15% which implies adequate robustness of the model.
- The developed CR scale can be a useful tool for decision makers if used properly. The effectiveness of the scale is dependent on the efficiency of the scenario

selection during the condition assessment procedure. If any parameter falls under an unexpected preference level, it should be taken care of regardless of the CRI or CR rating of the element.

- The web-version of the model can be used by providing self judgments or solely based on default input resulting from all survey inputs.
- In the absence of any standard condition assessment tool for a DWTP element, a CR scale and web-version of the model will be very useful for practitioners and engineers dedicated to designing, assessing and operating DWTPs.
- Finally, proper utilization of the developed condition rating models, condition grading scales and web-based assessment tools will provide a quick gateway to obtain a simple and economic condition assessment of selected elements. The efficiency of the model will depend primarily on how accurately a user is able to select scenarios and evaluate the importance of model parameters.
- The assessment tool will help owners/operators to plan short term and long term O & M activities effectively, provide information to the designer and to give an emphasis on certain factors. Regulators and policy makers will have information to prioritise their actions.
- Most importantly, the assessment will help to allocate the budget effectively and take necessary action to keep the system smooth over its lifetime.

7.2 Research Contributions

The research contributes to the drinking water treatment (DWT) industry in the following manner:

- Identifies two sets of condition parameters for tanks and pumps.

- Provides an aid to the sustainable asset management program for DWTP.
- Develops a standard deterministic condition rating model and two probabilistic models
- Develops two condition rating scales (CRS) for tanks and pumps
- Develops a web-version of a condition assessment tool based on the developed deterministic model.
- Determines the sensitiveness of scenario preference scores on model outputs
- Develops a spreadsheet model to solve comparison matrices including a consistency test, determines relative composite weights and condition rating indexes (CRIs).

7.3 Research Limitations

A careful review of the current study warrants a discussion of the following major limitations:

- Some of the parameters have nearly the same preference level for all defined scenarios.
- There does not exist a scope to add or reduce any model parameter in the web version of the model
- The experts didn't consider probability in assigning their preference scores.
- The scenarios under each parameter are predefined and fixed
- The web-version of the model is deterministic only.

- One set of model parameters is considered for three types of tanks and two types of pumps. In reality, some parameters may have different importance levels depending on the element.
- Variation of quality in same material type is ignored.
- Variation of chemical doses is not considered.

7.4 Recommendations and Future Research Work

The limited time frame and scope confined the current research work in this form. From the experience of current research work and knowledge, some recommendations are made for areas of improvements and future research work.

Improvements:

- Dependencies or repetition of parameters may need to be revised (i.e. pump horse power may be related with pump capacity).
- Some of the parameters can be added and dropped. The capacity and size of the tanks and pumps and pump horse power can be dropped. The level of the water table, flow velocity for tanks and seasonal and daily low and peak demand (for both) can be added.
- Uncertainty can be added as a model parameter.
- The response from experts from relevant construction industries can be considered in the model
- Other aggregative methods such as multiplicative, multi-attribute functions can be used.
- Other method of estimating relative weights can be used.

- Statistical tests can be performed to show how significant the variations of model outputs from deterministic and probabilistic models.
- To show the co-relation between CRI and grades in the devepoled CRS it can be supported by a model.
- The web-based tool can be modified by incorporating uncertainty and sensitivity analysis options.

Extension of Current Work:

- A similar CR model can be developed considering the other elements of DWTP such as clarifiers, filters, piping systems etc.
- To reduce subjectivity in the model, new initiatives can be undertaken to obtain real data and apply other assessment techniques such as regression analysis, ANN or a combination of these methods with fuzzy theory.
- To create a complete assessment model, it should account for other factors such as treated water quality, performance, economic aspects, compliance results and political and social issues.
- Experts can be requested to provide probability values while estimating preference scores.
- The concept of multiplicative MAUT theory can be introduced in the model
- A modified web-based tool with options to add or remove new categories, parameters and scenarios can be developed.

REFERENCES

Al-Harbi, K. (2001). "Application of the AHP in Project Management". *International Journal of Project Management*, Vol. 19, pp. 19-27.

Al Khalil, M. (2002). "Selecting the Appropriate Project Delivery Method Using AHP". *International Journal of Project Management*, Vol. 20, pp. 469–474.

Alphonce, CB (1997). Application of the analytic hierarchy process in agriculture in developing countries, *Agricultural Systems*, Vol. 53, pp. 97-112.

Al-Tabtabai, H., and Thomas, V. (2004). "Negotiation and Resolution of Conflict Using AHP: An Application to Project Management". *Engineering, Construction and Architectural Management,* Vol. 11, No. 2, pp. 90–100.

Allouche, E.N., and Freure, P. (2002). Management and Maintenance Practices of Storm and Sanitary Sewers in Canadian Municipalities, *ICLR Research*, Paper Series No. 18.,http://www.iclr.org/pdf/Management%20and%20Maintenance%20Practices%20Allouche.pdf#search=%22Management%20and%20Maintenance%20Practices%20of%20Storm%20and%22 , surfed August 20, 2006)

Ang, A. H. and Tang, W. H. (1984). *Probability Concepts in Engineering Planning and Design – Vol. 2, Decision, Risk, and Reliability*, John Wiley & Sons, Inc.

Annual Council Report (1965-96)Yarrowlumla, NSW, , p. 26

Ariaratnam, S. T., El-Assaly, A. and Yang, Y. (2001). Assessment of infrastructure inspection needs using Logistic models, *Journal of Infrastructure Systems*, Vol. 7, No. 4, p 160-165.

Barqawi, H. A. A. (2006). *Condition Rating Models for Underground Infrastructure: Sustainable Water mains,* Master's Thesis, pp 7-62

BC Guideline-2005, '*Comprehensive drinking water source to tap assessment guidelines*', March-2005, http://www.bcwwa.org/source-to-tap/documents/mod-3-assess-water-system-components.pdf , surfed October 20, 2005.

Best Practices (2003). "*Deterioration and Inspection of Water Distribution Systems*" - Best Practice by the National Guide to Sustainable Municipal Infrastructure, Issue No. 1.1, April 2003.

Blair, A. D., Kuziw, J. and Nixon, R (2002). 'A Model for Evaluating Water Treatment Plant Infrastructure: The Philadelphia Story', Chap-7 of the Book '*Assessing the Future: Water Utility Infrastructure Management*', First Edition, AWWA, 2002.

Canadian Water and Wastewater Association (1997). "*Municipal Water and Wastewater Infrastructure*– Estimated Investment Needs 1997-2012".

Causey, P. H., Secretary (2005). *National Asset Management Steering Council Asset Management and Sustainable Infrastructure: Reaching Toward a Future Generation of Infrastructure Management*, http://www.uimonline.com/coverstory.htm, surfed December 21, 2005

Chou, S.; and Pellinen, T. (2005). "Assessment of Construction Smoothness Specification Pay Factor Limits Using Artificial Neural Network Modeling." *Journal of Transportation Engineering,* Vol. 131(7).

Chouinard, L.E.; Andersen, G.R.; Torrey, V.H. III (1996). Ranking models used for condition assessment of civil infrastructure systems, *Journal of Infrastructure Systems*, Vol. 2, No. 1, March 1996 pp-23-29

Cook, T. D. & Campbell, D. T. (1979). *Quasi Experimentation: Design and analysis issues for field settings.* Chicago: Rand McNally.

Corotis, R. B., Ellis , J. H. and Jiang, M. (2004). Modeling Of Risk-Based Inspection, Maintenance And Life-Cycle Cost With Partially Observable Markov Decision Processes, 9th *ASCE Joint Specialty Conference On Probabilistic Mechanics And Structural Reliability*, PMC2004, July 26-28.

De Neufville, R. (1990). *Applied System Analysis,* New York, NY: McGraw Hill.

Design of Sedimentation Basins (2006) http://ewr.cee.vt.edu/environmental/teach/wtprimer/sedimen/sedimen.html#water , surfed August-10, 2006.

Dias, A. Jr., and Ioannou, P. G. (1995). A desirability Model for the development of Privately-promoted infrastructure Projects, *Centre for Construction Engineering and Managemen*t, Michigan University, UMCEE report no. 95-09, pp. 85-108

DTLR, *multi-criteria analysis manual* (2006). www.communities.gov.uk/embedded_object.asp?id=1142252, surfed February 9, 2006)

Edwards, M., Scardina, P. and McNeill, L. S., (2004). *The AwwaRF report,* Enhanced Coagulation Impacts on Water Treatment Plant Infrastructure_ Impacts of Enhanced Coagulation on Corrosion of Water Treatment Plant Infrastructure [Project #2687] http://www.awwarf.org/research/topicsandprojects/execSum/2687.aspx, surfed August 17, 2006.

Edwards W. (1977). How to use Multi-Attribute Utility measurement for Social Decision Making. *IEEE transactions on Systems, Man and Cybernetics,* Vol. SMC-7 No.5, pp. 326-340

Elmisalami, T. E. (2001). 'Developing a Multi-attribute Utility Models (MAUM) for selecting information technologies in the construction industry',Ph. D. Thesis, Iowa state University pp. 10-29.

EPA (2000). The History of Drinking Water Treatment, United States Office of Water EPA-816-F-00-006, Environmental Protection Agency (4606) February 2000 http://www.epa.gov/safewater/sdwa25/sdwa.html, surfed May,2006.

ExpertALERT™ (2006) http://www.dliengineering.com/detail.asp?nID=68 (August 27, 2006)

Falconer, R. A., Ismail, A.I.B.M. (1997). "Numerical Modeling of Tracer Transport in a Contact Tank" *Environment International,* Vol. 23, No. 6, pp. 763-773.

Farrar,C. R., Doebling S. W. and Nix D. A. (2001)."Vibration-Based Structural Damange Identification", *Philosophical Transactions of the Royal Society: Mathematical, Physical & Engineering Sciences.*

Federation of Canadian Municipalities (FCM) (1996) and the Department of Civil Engineering and Applied Mechanics – McGill University, *"Report on the State of Municipal Infrastructure in Canada,"* January 1996.

Flintsch, G. W. and Chen, C. (2004). Soft Computing Applications in Infrastructure Management, *Journal of Infrastructure Systems*, Vol. 10, No. 4, pp 157-166

FPPE (Filter Plant Performance Evaluation) (2005). (www.dep.state.pa.us/dep/deputate/watermgt/WSM/WSM_DWM/Complian/default.htm , surfed September15, 2005.

GAMS (2006).Government Asset Management System Portal, Asset Management Policies, *Guidelines and Procedures, Links to Asset Management Resources.* www.gams.qld.gov.au/_documentation/ perform/physical/assconda.htm - 15k surfed June 12, 2006.

Gap Analysis (2002). The Clean Water and Drinking Water Infrastructure Gap Analysis- http://www.epa.gov/owm/gapreport.pdf , serfed May 20, 2006.

Gardner, P. (1974). "The Application of Design Technology and Monte Carlo Simulation to Multiple Objective Public Policy Decision Making: A Case Study in California Costal Management." *Doctoral Dissertation,* Los Angeles, CA: University Of Southern California.

Grigg,N. S. (1992). *Urban Water Infrastructure: Planning, Management, and Operations,* Krieger Publishing Company, Malabar, Florida, pp. 1-20

Guidance for Safe Drinking Water in Canada: (2001). From Intake to Tap Prepared by a working group of the Federal-Provincial-Territorial Subcommittee on Drinking Water of the Federal-Provincial-Territorial Committee on Environmental and Occupational Health.

Hiller, F. S., Lieberman, G. J. (2001), "*Introduction to Operations Research,*" McGraw-Hill.

Infracanada (2004).Research for Policy and Program Development http://www.infrastructure.gc.ca/research-recherche/rresul/rs/rs07_e.shtml#sec31, surfed January 20, 2006

Keck, J. C. (2000). "Public water supply Protection: A Evaluation of Water Treatment Plant and Watershed Management Approaches", *Thesis Dissertations*, pp. 1-22

Keeney, R. L. (1974). *Multiplicative Utility Functions*, Vol. 22 pp. 22-34.

Keeney, R. L., & Raiffa, H. (1976). *Decisions With Multiple Objectives: Preferences and Value Tradeoffs,* John Wiley, New York.

Keeney, R. L. and Raiffa, H. (1993), "Decisions with Multiple Objectives: Preferences and Value Tradeoffs," Cambridge University Press.

Kleiner, Y. (2001). "Optimal scheduling of rehabilitation and inspection/condition assessment in large buried pipes". *NRCC-44487, 4th International Conference on Water Pipeline Systems - Managing Pipeline Assets in an Evolving Market*, pp. 181-197

Kosko, B. (1992). *Neural networks and fuzzy systems: A dynamical systems approach to machine intelligence*, Prentice-Hall, Englewood Cliffs, N.J.

Laronde, E. and Prince, B. (2003). 'Innovative Approach to make a Condition Assessment using hydraulic Models, Pipelines 2003 pp 286-293.

McNeill, L. S. and Edwards,M. (2003). "Degradation of Drinking Water Treatment Plant Infrastructure from Enhanced Coagulation," *Journal of Infrastructure Systems*, Vol. 9, No. 4, p145-156.

Microsoft Corporation (2006), http://www.asp.net/learn/default.aspx?tabid=63, surfed August 18, 2006

Millar, G. A. (1956) "The Magical Number Seven Plus Or Minus Two: Some Limits On Our Capacity For Processing Information", *Psychological Review*, March Vol. 63 pp. 81-97.

Mirza, M. S., Haider,M. (2003). "*The State of Infrastructure in Canada: Implications for Infrastructure Planning and Policy*", Infra-Canada.

Moselhi, O. and Shehab-Eldeen, T. (2000). "Classification of Defects in Sewer Pipes Using Neural Networks." *Journal of Infrastructure System.* Vol.6, No. 3, pp. 97-104.

Najjaran, H., Sadiq, R. and Rajani, B. (2004). Modeling Pipe Deterioration using Soil Properties – An Application of Fuzzy Logic Expert System, *ACSE International Conference on Pipeline Engineering and Construction, Pipelines*, San Diego, CA., August 1-4, 2004, pp. 1-10

National Report, Volume 2 (2000), *National Water Study, Department of Environment & Local Government*, Ireland, WS Atkins Ireland, A Division of WS Atkins Consultants Ltd.

Nguyen, D. D. (1995). "*A Study of Group Decision Under Uncertainty Using the Multi-attribute Utility Theory and The Analytic Hierarchy Process,*" M.A.Sc. thesis, pp 6-18, 28-35

Novak, J. and Gates, K., Virginia (2006).Tech Pumps Page, http://ewr.cee.vt.edu/environmental/teach/wtprimer/pumps/pumps.html , surfed August 12, 2006.

O'Day D. K. and Neumann, L.A. (1984). ' Assessing Infrastructure Needs: The State of the Art', Hanson Royce, Ed., *Perspective on Urban Infrastructure*, National Academy of Sciences Press, Washington, D.C.

OFWAT (2000). Information Note No 35B[1] www.ofwat.gov.uk/aptrix/ofwat/publish.nsf/Content/serviceabilitywatertreatment-46k ,surfed June 15, 2006

Ontario Municipal Economic Infrastructure Financing Authority (2003). *Loan Eligibility Criteria and Definitions of Eligible Infrastructure Investments.*

O'Rourke, M. J. and Ballantyne, D. (1992). Observations on Water System and Pipeline Performance in the Limon Area of Costa Rica Due to the April 22, 1991 Earthquake. *Technical report, National Center for Earthquake Engineering Research*, National Science Foundation, Washington, DC.

Papadimitriou C. (2004). Bayesian inference applied to structural model updating and damage Detection, *9th ASCE Joint Specialty Conference on Probabilistic Mechanics and Structural Reliability*, PMC2004, July 26-28.

Park, J. (2004). "Development and Application of Probabilistic Decision Support Framework for Seismic Rehabilitation of Structural Systems, a thesis of Doctor of Philosophy

Pitz, F. Gordon, Mc killip Jack (1994). "Decesion analysis for program evaluations, usage publications," Beverly Hills.

Rajani, B.; Kleiner, Y. (2002). "Forecasting Variations and Trends in Water-main Breaks". NRCC-44677, *Journal of Infrastructure Systems*, Vol. 8 (4), pp. 122-131

Report Card (2005). http://www.asce.org/reportcard/index.cfm?reaction=factsheet&page=6 , (surfed March 27,2006)

Roth, R., Field, F. & Clark, J. (2006). Multi-Attribute Utility Analysis http://msl1.mit.edu/maua_paper.pdf#search=%22R.%20Roth%2C%20F.%20Field%2C%20%26%20J.%20Clark%22 , surfed March 20, 2006)

Saaty, T. L. (1977). A Scalling Method for Priorities in Hierarchical Structure. *Journal of Mathematical Psychology*, Vol. 15, pp. 234-281.

Saaty, T.L. (1980). *Analytic hierarchy process,* New York: McGraw-Hill.

Saaty, T. (1982). "*Decision Making for Leaders: The Analytic Hierarchy Process for Decision in a Complex World*". Lifetime Learning Publications, Belmont, California.

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

Saaty, T. L. (1994). Highlights and Critical Points in the Theory and Application of the Analytic Hierarchy Process. *European Journal of Operational Research*, Vol. 74, pp. 426-447.

Saaty, T. L. (2001). Decision Making With Dependence and Feedback, the Analytic Network Process, pp. 23-72

Sadiq, R., Rajani, B., and Kleiner, Y.(2004). "Fuzzy-Based Method to Evaluate Soil Corrosivity for Prediction of Water Main Deterioration," *Journal of Infrastructure Systems*, Vol. 10, No. 4, p 149-156, December, 2004.

Savage, L.J. (1954). *The Foundations of Statistics,* Wiley, New York, NY.

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

Schäfer, R. (2006). Rules for Using Multi-Attribute Utility Theory for Estimating a User's Interests, http://www.kbs.uni-hannover.de/~henze/ABIS_Workshop2001/final/Schaefer_final.pdf#search=%22Ru les%20for%20Using%20MultiAttribute%20Utility%20Theory%20for%22 , surfed March 22, 2006)

Shiono, K.(2000). 'Turbulent characteristics in a baffled contact tank', *Journal Of Hydraulic Research,* Vol. 38 No.4.

Shiono, K.; Teixeira, E.C.; Falconer, R.A. (1991). Turbulent measurements in chlorine contact tank. In: Proc. *first international conference on water pollution: Modelling, measuring and predicting.* Southampton, UK: Wessex Institution of Technology; 1991: pp. 519- 531.

Sohn, H., Czarnecki, J. A., and Farrar, C. R. (2000). Structural Health Monitoring Using Statistical Process control, *Journal of Structural Engineering*, Vol.126, No. 11, November, 2000, pp 1356-1363.

Srdjevic, B. (2002). Evaluation of storage reservoir purposes by means of multicriteria optimization models, Vodoprivreda, 195-200, 35-45.

Srdjevic, B., Srdjevic, Z., Zoranovic, T.and Potkonjak, S. (2004). 'Advanced Decision Support Tools In Agricultural And Water Management', *International Conference on Sustainable Agriculture and European Integration Processes* Novi Sad, Serbia and Montenegro • September 19th -24th.

Taylor, J. C. (1995). "Chapter 1: The promise of neural networks." *Neural Networks*, Alfred Waller, Henley on Thames, U.K.

Tidwell, V. C., Cooper, J. A., and Silva, C. J. (2005) : 'Threat Assessment of Water Supply Systems Using Markov Latent Effects Modeling' *Journal of Water Resources Planning and Management*, Vol. 131, No. 3, May 1, 2005.pp-218-227

Tsoukalas, L. H., and Uhrig, R. E. (1997). *Fuzzy and Neural Approaches in Engineering*, Wiley, New York.

Twort, A. C., Ratnayaka, D. D., Brandt, M. J.(2000). "Water Supply", Arnold & IWA publishing, fifth edition -2000)

United States Federal Highway Administration (US, FHWA), (2006). "Asset Management."http://www.fhwa.dot.gov/infrastructure/asstmgmt/assetman.htm. March 14, 2006)

Urquhart, T., Marlow, D. and Burn, S. (2005). Incorporating Condition Assessment into a Comprehensive Asset Management Program http://www.uimonline.com/featurestory.htm#top , surfed December 21-05)

Von Neumann, J, and Morgenstern, O. (1947). "*Theory of Games and Economic Behaviour*", second edition, Princeton University Press, Princeton.

Walker, R.G., Clarke, F.L. and Dean, G.W. (1999). Reporting on the state of infrastructure by local government Vol. 12 No. 4, 1999, pp. 441-458. # MCB University Press, 0951-3574

Winston, W. L. (1993), "Operations Research – Applications and Algorithms," Duxbury Press

Winterfeldt, D. V. and Edwards, W. (1986), "Decision Analysis and Behavioral Research," Cambridge University Press

Yan, J.M., Vairavamoorthy, K. (2003). Fuzzy Approach for Pipe Condition Assessment Proceedings of the ASCE International Conference on Pipeline Engineering and Construction: *New Pipeline Technologies, Security, and Safety,* v 1, 2003, p 466-476

Zadeh, L. A. (1965). "Fuzzy sets." *Inf. Control*, Vol.8, pp. 338–353.

Zadeh, L. A. (1973). "Outline of a new approach to the analysis of complex systems and decision processes." *IEEE Trans. Syst. Man Cybern.*, SMC 3, 28–44

Zadeh, L. A. (1997). "The role of fuzzy logic and soft computing in the conception, design, and deployment of intelligent systems." *Software agents and soft computing*, Springer, New York.

Zadeh, L. A. (2001). "Applied soft computing—Foreword." *Appl. Soft Comput.*, Vol. 1(1), pp. 1–2.

Zahedi, F. (1986) 'The analytic hierarchy process: a survey of the method and its applications', *Interfaces,* 16, pp.96- 108.

Zayed, T. and Halpin, D. (2005). "*Pile Construction Productivity Assessment.*" ASCEJournal of Construction Engineering and Management, Vol. 131 (6), June 1, pp.705–714.

APPENDICES

APPENDIX-A

(Drinking Water Treatment Overview)

Drinking Water Treatment

Historical Background of water treatment

Water treatment is a process that improves the quality of drinking water in such a way that it is chemically and bacteriologically safe for human consumption and aesthetically acceptable to its users. Efforts to improve the quality of water were recorded as early as 4000 B.C. during both Sanskrit and Greek civilizations. They used very simple methods such as filtering through charcoal, exposing to sunlight, boiling and straining. The history of water treatment in Egyptian civilization shows the first use of alum, as early as 1500 B.C. to settle suspended particles in water. During the 1700s, filtration was established as an effective means of removing particles from water. The design of most drinking water treatment systems built in the U.S. during the early 1900s was driven by the need to reduce turbidity and remove microbial contaminants that were causing fatal diseases such as typhoid, dysentery, and cholera. To reduce turbidity, some water systems began to use slow sand filtration and chlorine as a disinfectant. With the development of more advanced science and technology in the late 1960s, it was proven that the aesthetics, pathogens, and chemicals were not the only significant contaminants where drinking water quality was concerned. Pollution from industrial and agricultural sectors also had negative impacts on the environment and public health (EPA, 2000 and Keck, 2000). Historically it is proven that water quality is profoundly dominating concerns over infrastructural aspects.

Definition of Water Infrastructures

According to Environment Canada, "water infrastructure" includes water treatment plants, water mains, water towers and reservoirs, sewer pipes and sewage treatment plants. In the United States, according to general accounting office (GAO), water infrastructure is commonly divided into drinking water infrastructure and wastewater infrastructure (Infrastructure Canada, 2004).

Water supply elements

A typical water supply system will have physical and operational components which can be called supply elements. The following are the broad categories of supply elements

- Source of water
- Intake/well
- Treatment faculties
- Storage facilities
- Pumping facilities
- Distribution system
- Distribution system
- Power source

It also includes:

- Back-up systems
- Electronic equipment

(British Columbia Drinking water guideline, 2005)

Drinking Water Treatment Plants

Generally there are two types of drinking water treatment plant

- Surface water treatment plant
- Ground water treatment plant

As per infrastructure perspective drinking water treatment plant can be segregated following categories:

- Key piping system
- Major structural systems of steel and concrete
- Pipe support system (Blair-2002)

Major components of a drinking water treatment plants

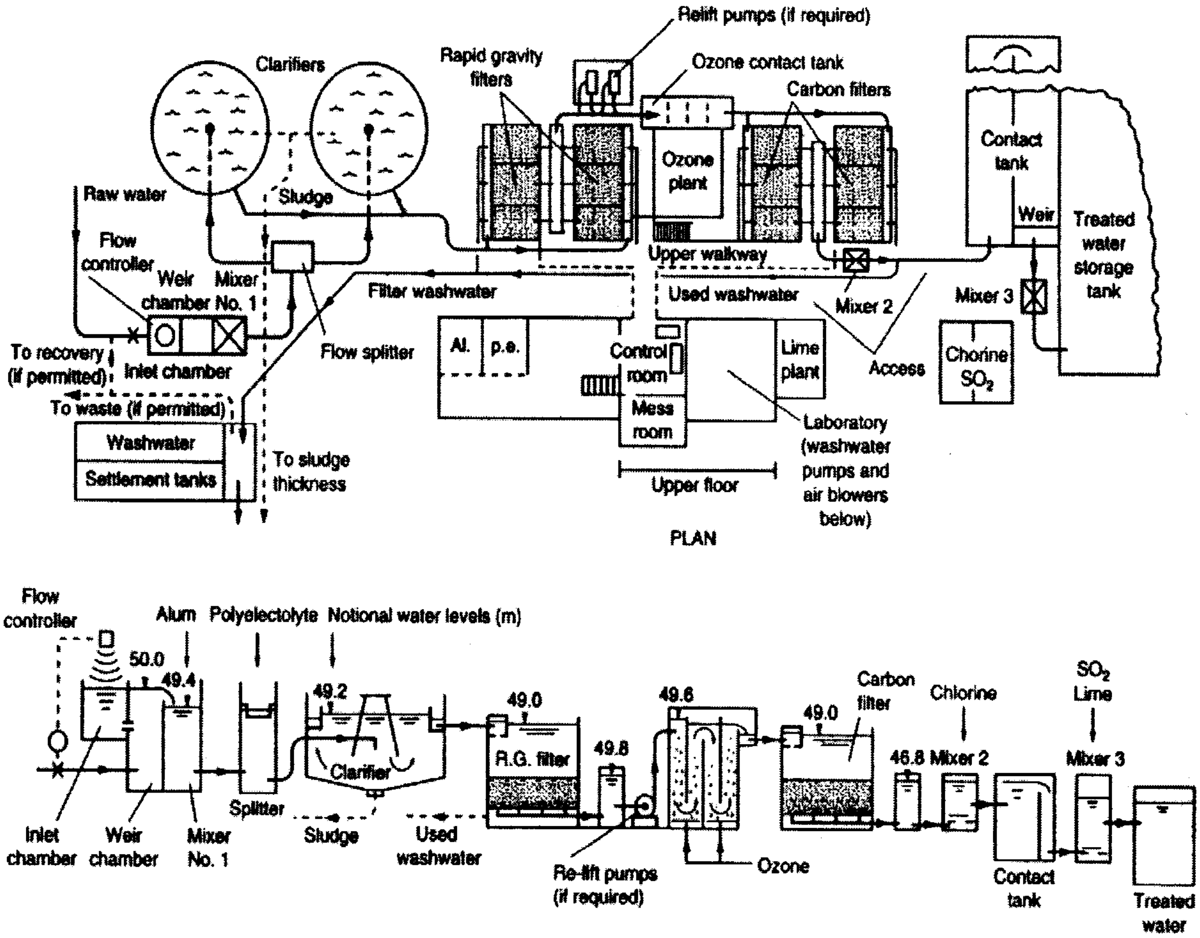
A modern drinking water treatment plant (Figure2.2) can be consisting of combinations of following elements:

1. Raw water storage tank
2. Screenings
3. Sedimentation and settling tanks
4. Clarifiers
5. Chemical dosing plant
6. Filtration and sludge disposal
7. Softening plant
8. Aerators
9. Chlorinator
10. Ozone plant
11. UV treatment chamber
12. Clear water well or Chlorination tank
13. Pumps (High pressure(HP) & Low pressure (LP))
14. Control and monitoring system

Brief descriptions of the selected plant elements

In this current study, the following five plant elements are selected for condition assessment

1. Settling basins/tanks
2. Filtration basins/tanks
3. Chlorination tanks
4. LP pumps used for pumping raw water
5. HP pumps used for pumping treated water to distribution system

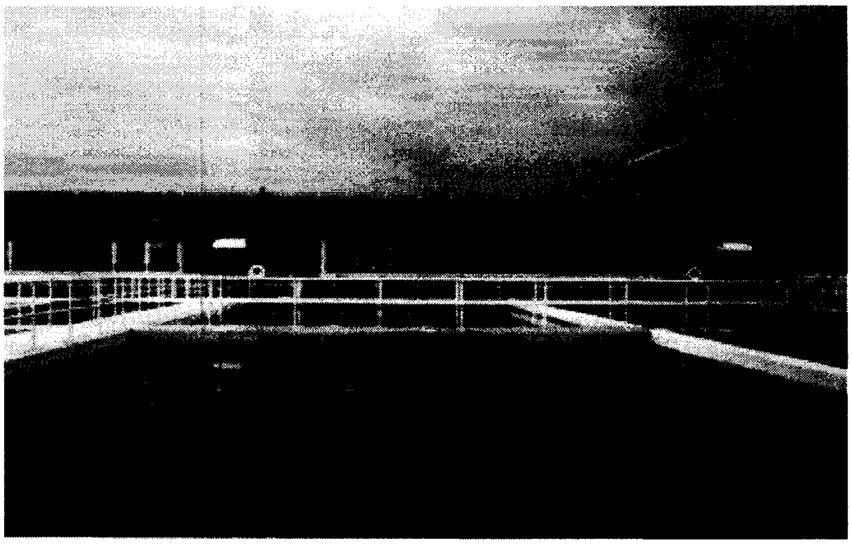


FigureA.1 Plan view and diagrammatic layout for a conventional water treatment plant incorporating ozonization and GAC filters (Twort, et al., 2000)

Sedimentation and Settling Tanks

Sedimentation tanks are required to separate suspended solids from water by utilizing gravity. Therefore, the tanks are designed to reduce the water velocity. Most of the settling tanks are rectangular or circular. The following are the main applications of settling tanks.

- Plain (settled by gravity alone) settling of solids
- Chemically assisted (coagulated and flocculated) sedimentation
- Settling of treated water in metal (iron etc.) removal plants



FigureA.2 The photographs of a sedimentation basin
Source:
http://ewr.cee.vt.edu/environmental/teach/wtprimer/sedimen/sedimen.html#water, 2006

The main factors influence the performances of a settling tank are:

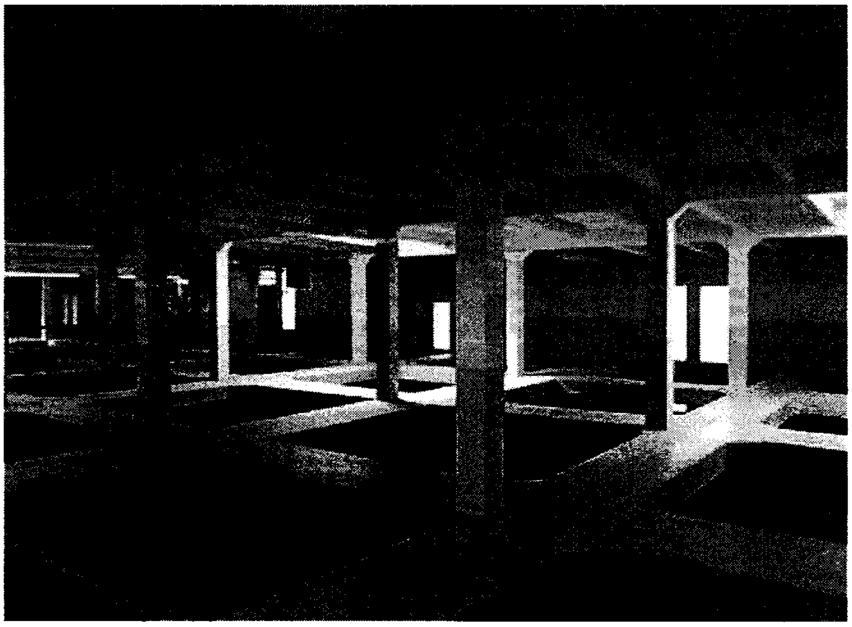
- The amount of suspended solids in water
- Relative density of solids
- Type of solids (discrete, flocculent, hindered, and compression)
- Shape of particles (Twort, et al., 2000)
- Extend of clarification required
- Ambient temperature
- Rate of the flow.

Filtration Tanks or Basins

Unlike settling basins various filter media is installed on a collector system in these filtration basins. These basins provide

- structural support to filter media and pipes
- help in sludge disposal and cleaning filters
- protection from contamination, as they are built with appropriate materials
- a stable floor surface that facilitates maintenance work

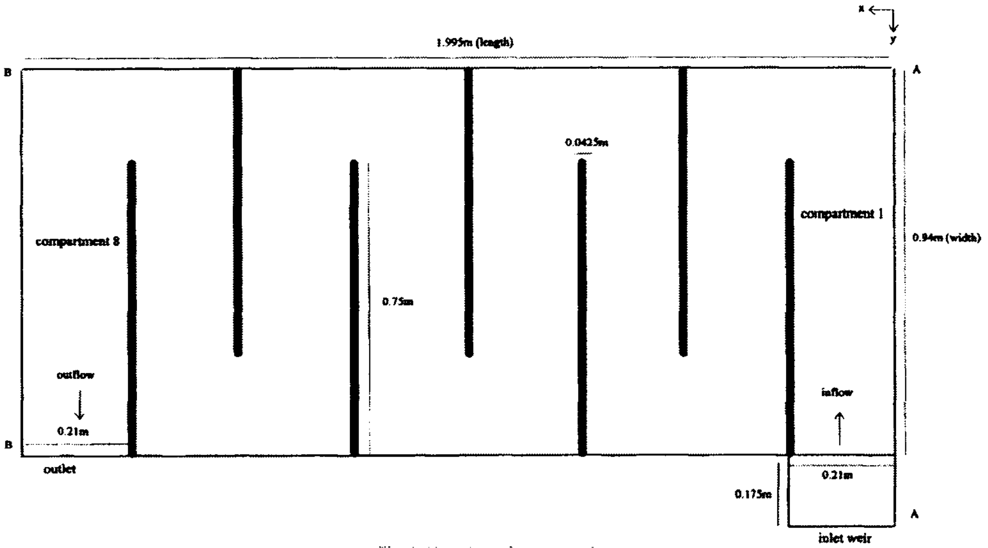
(Twort, et al., 2000)



FigureA.3 Columbia Heights Filtration Plant, Minneapolis, MN, USA
Source: www.water-technology.net/.../columbia1.html , 2006

Chlorination Tank/ Clear Water Well

In a drinking water treatment plant after filtration, water is temporarily stored in a chlorination tank or contact tanks for disinfection process before pumping to the distribution system. The design of chlorination tanks is typically based on the volume displacement criterion to ensure required contact time for disinfection. The arrangements of baffles in the tank and the tank inlet and outlet configuration may result in a complex flow pattern, which can result in turbulent intensive mixing, dead-space zones, and shortcircuiting (Shiono, 1991, Falconer & Ismail, 1997). Turbulence levels could be considerably high in the tank inlet, first and second compartments, which will expedite the decay process of the compartments.(Shiono *et al.* 2000).



FigureA.4 Plan view of a typical chlorination tank (Falconer & Ismail, 1997)

Pumps

Pumps are required in a water treatment plant to transfer raw water from the source to the plant, add proper chemical doses during treatment processes, to transfer and dispose sludge and finally to supply water in distribution mains.

Pumps can be classified in different ways according to their characteristics. Various types of pumps are installed in the same water treatment plant according to their needs. The choice of pump type and the installation location are driven by many factors. Some of the main factors are as follows:

- Capacity of pump (discharge flow and pressure)
- Functionality of a pump for specific need and environment
- Energy consumption

- Restrictions from regulatory guide lines
- Experience of plant managers regarding performance of pump
- Design life of and maintenance cost
- Cost and availability of space

Most commonly used pumps in water treatment plants are centrifugal pumps, positive displacement pumps, vertical turbine pumps and submersible pumps.

Centrifugal pumps:

A centrifugal pump is the most common type used in drinking water treatment plants. There are different kinds of centrifugal pumps including radial-flow, mixed-flow and axial flow. In a centrifugal pump, the motor rotates the shaft and the rotating impeller imparts a high velocity to the water. A casing surrounds the impeller, which is shaped like a spiral so that the water slows down, and the velocity head is converted to pressure head as it flows out of the casing. This partial conversion takes place in the pump casing and head losses due to conversion must be taken into consideration.(Bhardwaj, 2006; Novak and Gates, 2006).

Vertical turbine pumps:

Common vertical turbine pumps are used at raw water intakes and at booster stations to augment the pressure required in the mains and service lines. Common uses of positive-displacement pumps are to feed chemicals at various stages of the treatment process. These pumps are not suitable for pumping bulk volumes of water and are used primarily for high pressure and low flow service. There are two types of positive-displacement pumps: reciprocating pumps and rotary pumps.

APPENDIX-B

(Survey Questionnaire)

CONDITION GRADING OF DRINKING WATER TREATMENT PLANT ELEMENTS

PART-I

In this part, you are requested to do pairwise comparisons on the importance of categories and parameters with respect to the main objective of '**condition rating**' of drinking water treatment plant elements. While comparing the categories or parameters, the one that contribute more in terms of element's better condition will have more importance or preferences. In this study two types of elements have been considered, in type one all basins or tanks and the other type is pumps. Two sets of matrix need to be completed set-1 for basins/tanks, and set-2 for pumps. Each set contains 5 matrixes, one for four categories and others four for parameters under each category. The degree of importance or preference is measured on the following 9-point scale:

9 = Absolute importance of one over compared one
8 = Very strongly to absolutely; 7 = Very strongly; 6 = Strongly to very strongly
5 = Strongly; 4 = Moderately to strongly 3 = Moderately
2 = Equally to moderately; 1 = Equally important

(Adapted from, Saaty 1982)

Example for the demonstration of pair wise comparison matrix:
Suppose there are n parameters. We begin by writing down an n×n matrix (known as the pairwise comparison matrix) A. The entry in row i and column j of a (call it a_{ij}) indicates how much more important parameter i is then parameter j. "Importance" is to be measured on an integer- valued 1-9 scale as shown above. For all i it is necessary that $a_{ii} = 1$. If for example $a_{13} = 3$, parameter1 moderately more important then parameter 3. If $a_{ij} = k$ then for consistency, it is necessary that $a_{ji} = 1/k$. Thus if $a_{13} = 3$, then $a_{31} = 1/3$
Let us determine a pairwise comparison matrix of a three parameter model the parameters are A, B and C. Fist need to do pairwise comparison of the parameters; that is compare A with B and with C and B with C. Let say-

- A is moderately more important then B
- A has absolute importance then C
- So, B is moderately more important then C

Then the comparison matrix can be written as follows:

Parameters	A	B	C
A	1	3	9
B	1/3	1	3
C	1/9	1/3	1

[**N.B**. *To save time just top row of all the required matrixes can be completed, keeping consistency with values provided in top row rest of the matrix will be completed by author.*]

Name of the Organization:

Position of the Respondent: **Experience in years:**

Address:

SET-1: Tanks/Basin

Pairwise comparison matrixes for Categories and Parameters under those categories

Categories:

- **a) Physical (design & cons. stage)**
- **b) Physical (service stage)**
- **c) Environmental**
- **d) Operational**

Categories	a	b	c	d
a	1			
b		1		
c			1	
d				1

a) Physical (design & cons. stage)

- a.1) Design considerations (durability aspects, type of joints etc.)
- a.2) Material type
- a.3) Size & Capacity
- a.4) Quality control of construction works

Parameters under category-a	a.1	a.2	a.3	a.4
a.1	1			
a.2		1		
a.3			1	
a.4				1

b) Physical (service stage)

- b.1) Age of the element at the time of condition assessment.
- b.2) Corrosion
- b.3) Coating/paint
- b.4) Cracks/flaws

Parameters under category-b	b.1	b.2	b.3	b.4
b.1	1			
b.2		1		
b.3			1	
b.4				1

c) Environmental

- c.1) Soil type
- c.2) Quality of source water ($P^{H,}$ Turbidity etc)
- c.3) Seismic activity
- c.4) Weather condition

Parameters under category-c	c.1	c.2	c.3	c.4
c.1	1			
c.2		1		
c.3			1	
c.4				1

d) Operational

- d.1) Chemicals dozes
- d.2) Operation & Maintenance practice
- d.3) Manager and Operators experience
- d.4) Control system

Parameters under category-d	d.1	d.2	d.3	d.4
d.1	1			
d.2		1		
d.3			1	
d.4				1

SET-2: Pumps

Pairwise comparison matrixes for Categories and Parameters under those categories

Categories:
- **a) Electro-Mechanical**
- **b) Physical**
- **c) Environmental**
- **d) Operational**

Categories	a	b	c	d
a	1			
b		1		
c			1	
d				1

a) Electro-Mechanical
- a.1) Type of pump
- a.2) Horse power
- a.3) Starting options
- a.4) Capacity/ hourly production

Parameters under category-a	a.1	a.2	a.3	a.4
a.1	1			
a.2		1		
a.3			1	
a.4				1

b) Physical
- b.1) Age of the pump at the time of condition assessment.
- b.2) Corrosion
- b.3) Coating/paint
- b.4) Any type of Cracks/flaws

Parameters under category-b	b.1	b.2	b.3	b.4
b.1	1			
b.2		1		
b.3			1	
b.4				1

c) Environmental
- c.1) Quality of source water (P^{H,} Turbidity etc)
- c.2) Vibration (any kind)
- c.3) Temperature(including heat generated by pump)

Parameters under category-c	c.1	c.2	c.3
c.1	1		
c.2		1	
c.3			1

d) Operational
- d.1) Chemicals dozes
- d.2) Operation & Maintenance practice
- d.3) Manager and Operators experience
- d.4) Daily running time
- d.5) Control system

Parameters under category-d	d.1	d.2	d.3	d.4	d.5
d.1	1				
d.2		1			
d.3			1		
d.4				1	
d.5					1

PART-II

In this part while scoring, you are requested to consider all options (consequences) under each of the parameter separately to identify the most preferred and the least preferred options for the parameter, in terms of its contribution toward condition of the element under service life. The most preferred option will be given maximum score (up to 10) and the least preferred one will be given minimum score (0-10). For measuring preferences from subjective judgement, the given *preferences scoring scale can be used.*

For example, one of the parameter actual age of the element at the time of its condition assessment could have four Scenarios: *1.* ≤ ¼ of design life, *2.* > ¼ ≤ ½ of design life, *3.*> ½ ≤ design life and *4.*>design life. Considering main objective 'condition rating' of the element, most likely situation/option (1) will be the most preferred one and (4) will be the least preferred one. So, option 1 and 4 can be scored 10 and 0 respectively. Rest of the attributes 3 and 4 will be scored according to their importance and those will be <10<0.

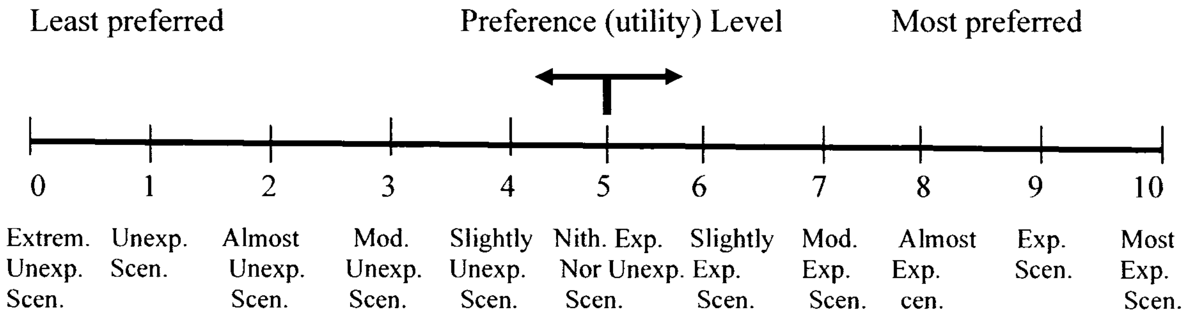


Figure B. 1 Preferences Scoring Scale (Subjective)

TableB.1 Tanks/Basins (In case of same score for all elements only one column can be completed and where the option is not applicable provide 'X')

Category	Parameters	Scenarios to Measure Parameters Preferences	Score according to preference level of the scenario towards better condition of the element (0-10)			Remarks
			Sett. Basins	Filt. Basins	Final Chl. Tank	
a) Physical (design & cons. stage)	a.1) Design considerations (durability aspects, type of joints etc.)	1. More detailed (special)				
		2. Standard				
		3. Sub-standard				
	a.2) Material type	1. Reinforced concrete				
		2. Steel				
		3. Wood				
		4. Other Fibre glass				
	a.3) Size & Capacity	1. <5000 M^3/day				
		2. 5000-10000 M^3/day				
		3. > 10000 M^3/daily				
	a.4) Quality control of cons. works	1. Proper				
		2. Improper				
b) Physical (service stage)	b.1) Age of the element (Actual age at the time of condition assessment)	1. ≤ ¼ of design life				
		2. > ¼ ≤ ½ of design life				
		3. > ½ ≤ design life				
		4. > design life				
	b.2) Corrosion	1. No				
		2. Minor				
		3. Major				
	b.3) Coating/paint	1. Best quality				
		2. Ordinary				
		3. No coating				
	b.4) Cracks/flaws	1. None				
		2. Minor				
		3. Significant				
c) Environm.	c.1) Soil type	1. Sand or Rock				
		2. Silt				
		3. Clay				
		4. Other organic				

	c.2) Quality of source water ($P^{H,}$ Turbidity etc)	1. Excellent				
		2. Good				
		3. Fair				
		4. Bad				
		5. Very Bad				
	c.3) Vibration (including earthquake)	1. No				
		2. Minor				
		3. Significant				
	c.4) Weather condition	1. 0° C to 40° C				
		2. -40° C to 40° C				
		3. -60° C to 25° C				
d) Operational	d.1) Chemicals dozes	1. None				
		2. Alum				
		3. Lime				
		4. Ozone				
		5. Chlorine				
		6. Silicate				
		7. Other chemicals (specify)				
	d.2) Operation & Maintenance practice	1. Standards O&M practice				
		2. Poor O&M practice				
	d.3) Manager and Operators experience	1. More then 5 years				
		2. >1 ≤5 years				
		3. 0-1 year				
	d.4) Control system	1. Automatic				
		2. Combined				
		3. Manual				

TableB.2 Pumps (In case of same score for all elements only one column can be completed and where the option is not applicable provide 'X')

Category	Parameters	Scenarios to Measure Parameters Preferences	Score according to preference level of the scenario towards better condition of the element (0-10)		Remarks
			For Raw Water Pumps	For Clean Water Pumps	
a) Electro-Mechanical	a.1) Type	1. Axial			
		2. Centrifugal			
		3. Reciprocating			
		4. Submersible			
		5. Vertical spindle			
		6. Other (specify)			
	a.2) Horse power	1. ≤ 100			
		2. >100≤200			
		3. >200			
	a.3) Starting options	1. Conventional			
		2. Soft starting			
	a.4) Capacity	1. 1000-10000 M^3/h			
		2. <1000 M^3/h			
		3. > 10000 M^3/h			
b) Physical	b.1) Age	7 ≤ ¼ of design life			
		8 > ¼ ≤ ½ of design life			
		9 > ½ ≤ design life			
		10 > design life			
	b.2) Corrosion	1. No			
		2. Minor			
		3. Major			
	b.3) Coating /paint	1. Best quality			
		2. Ordinary			
		3. No coating			
	b.4) Any type of crack	1. None			
		2. Minor			
		3. Major			
c) Environmental	c.1) Quality of source water ($P^{H,}$ Turbidity etc)	1. Excellent			
		2. Good			
		3. Fair			
		4. Bad			
		5. Very Bad			

	c.2) Vibration (including earthquake)	1. No			
		2. Minor			
		3. Significant			
	c.3) Temperature (including heat generated by pump)	1. 0° C to 40° C			
		2. -40° C to 40° C			
		3. -60° C to 25° C			
d) Operational	d.1) Chemicals dozes	1. None			
		2. Alum			
		3. Lime			
		4. Ozone			
		5. Chlorine			
		6. Silicate			
		7. Other chemicals (specify)			
	d.2) Operation & Maintenance practice	1. Standards O&M practice			
		2. Poor O&M practice			
	d.3) Manager and Operators experience	1. More then 5 years			
		2. >1 ≤5 years			
		3. 0-1 year			
	d.4) Daily pump running time	1. 24 hours			
		2. <24≥12 hours			
		3. < 12 hours			
		4. Emergency use only			
	d.5) Control	1. Automatic			
		2. Combined			
		3. Manual			

Comments:

THANK YOU FOR YOUR KIND COOPERATION

SARKER RAHMAN
M. A. Sc. Student
Building, Civil & Environmental Engineering Department
Concordia University, Montreal, Quebec, Canada
Mailing Address: 30-6320 Victoria Avenue, Montreal, QC, Canada H3W 2S4
Phone: 1-514-XXX 1819
E-mail: xxx@yahoo.ca; xx_ra@encs.concordia.ca or xxr@gmail.com
Fax: 1-514-848 xxxx (Attention Dr. T. Zayed)

APPENDIX-C

(Relative Weight Calculation Procedure in AHP)

Saaty (1986) proposed some axioms for AHP

Referring to Nguyen (1995), these axioms are represented below:

Given a set of alternatives X, the alternatives will be assessed (ranked) by the decision maker based on a set of criteria Y.

Axiom 1: For any two alternatives (or sub-criteria), i, j from the given set X, the decision maker will be able to make a pairwise comparison a_{ij} of these alternatives under any criteria of the given set Y, based on a ratio scale. The comparison must satisfy the following relation in the comparison matrix:

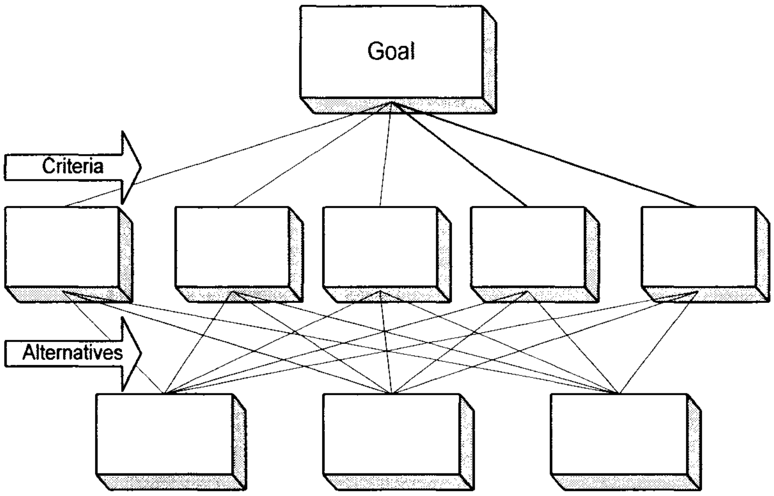
$a_{ij}=1/a_{ji}$ for all $i, j \in X$.

Axiom 2: A decision maker, when comparing any two alternatives i, j from the given set X under any criteria of the given set Y he/she cannot provide infinite importance to one alternative over the other. Therefore, the following relation should satisfy:

$a_{ij} \neq \infty$ for all $i, j \in X$.

Axiom 3: A multi-criteria decision problem in AHP must be structured in at least a 3-level hierarchy. The first level will represent the overall objective or goal and the second and third levels will represent the criteria (and sub-criteria) and the alternatives repectively, as shown in Figure 2.10.

Axiom 4: All parameters and alternatives relevant to the decision problem should be accounted in the hierarchy and ranked using the best judgement of the decision maker.



FigureC.1 Three level Hierarchy (Saaty, 2001)

Assigning relative weight

Saaty introduced the eigenvalue method (EM) in the AHP technique to calculate relative weights of parameters. To apply EM in a multi-criteria decision problem need to prepare a pairwise comparison matrix based on a qualitative scale. Saaty (1980) concluded that a qualitative scale with comparison intensities ranging 1-9 is the most suitable one. And the stated reasons behind this choice are presented by Dias and Ioannou (1995) as below:

- Differentiating by qualitative measures is meaningful in practice.
- Equal, weak, strong, very strong and absolute these five qualitative measures are well represented by human being. To make comparison between two adjacent measures will require another four measures, which means 1-9 range is appropriate.
- According to assumption of Miller (1956) that human brain can deal with 7±2 items simultaneously

In the original qualitative scale used by Saaty in AHP is presented in Table: 1

Construction of Comparison Matrix:

Pairwise comparison is one of the basic phenomena of AHP approach. In the multi-criteria decision problem when the pairwise comparisons among the considered criteria are done, the results are presented in a matrix form. Following are the procedures to construct such matrixes, which are used for the eigenvalue method to determine importance weights of parameters.

- If the number of criteria is n then the matrix dimension will be n×n.
- From the axiom, comparison of any two criteria i, j will satisfy the condition $a_{i,j}=1/a_{j,i}$, and all the diagonal elements will be one ($a_{ii}=1$); which means the matrix is to be reciprocal.

TableC.1The Fundamental Pairwise Comparison Scale (Saaty, 2001)

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the
2	Weak	Between Equal and Moderate
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	Between Moderate and Strong
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	Between Strong and Very strong
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	Between Very strong and Extreme
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation.

- Comparison will be done based on 1-9 qualitative importance scale so the comparison results will be in the range of 1/9 to 9.
- If the number of criteria in n, for complete judgement require n (n-1)/2 comparisons but to function the method at least (n-1) comparison required.

A example of 4x4 comparison matrix 'M' constructed as shown below: where a_1, a_2, a_3 and a_4 presenting 4 attributes.

$$\left|\begin{array}{ccccc} Criteria & a_1 & a_2 & a_3 & a_4 \\ a_1 & a_{1,1} & a_{1,2} & a_{1,3} & a_{1,4} \\ a_2 & a_{2,1} & a_{2,2} & a_{2,3} & a_{2,4} \\ a_3 & a_{3,1} & a_{3,2} & a_{3,3} & a_{3,4} \\ a_4 & a_{4,1} & a_{4,2} & a_{4,3} & a_{4,4} \end{array}\right| \textbf{ Can be written as } M = \left|\begin{array}{cccc} 1 & a_{1,2} & a_{1,3} & a_{1,4} \\ a_{2,1} & 1 & a_{23} & a_{2,4} \\ a_{3,1} & a_{32} & 1 & a_{3,4} \\ a_{4,1} & a_{4,2} & a_{4,3} & 1 \end{array}\right|$$

$$\text{Or } M = \left|\begin{array}{cccc} 1 & a_{1,2} & a_{1,3} & a_{1,4} \\ 1/a_{1,2} & 1 & a_{23} & a_{2,4} \\ 1/a_{1,3} & 1/a_{2,3} & 1 & a_{3,4} \\ 1/a_{1,4} & 1/a_{2,4} & 1/a_{3,4} & 1 \end{array}\right|$$

Each criteria has its relative weight that can be denoted by w_i ($i = 1, 2, \ldots n$). With normalizing condition for $\sum w_i = 1$, Solving a system of equations, eigenvectors $(w_1, w_2, w_3 \,\&\, w_4)$ of the above example can be estimated. Detail calculations are avoided here as the calculations of these equations are available in literature including texts by Saaty (1980, 1991).

In reality decision makers generally fails to give exact value of ${}^{w_i}\!/_{w_j}$ and the comparison matrix doesn't hold transitivity. If the decision makers make their estimate for the above matrix M in this manure and satisfy AHP axioms then the small errors in estimating $a_{i,j}$ will keep the maximum eigenvalue close to n (Saaty, 1980, 1991). And still a unique estimate of relative weights (w_i') is possible with the constraint $\sum_{i=1}^{n} w_i' = 1$. Let's denote the new comparison matrix M', and eigenvector w' so the following equation can be written

$$M'w' = \lambda_{\max} w' \text{ .... (C.1)}$$

Where $\lambda_{\max}$ the maximum eigenvalue of the matrix is is M'

The value of $\lambda_{\max}$ can be calculated following a procedure suggested by Saaty (1982).

Consistency Measure of Comparison Judgments

Saaty (1982) developed an index to quantify consistency of comparison judgments for a given comparison matrix (*n* x *n*) which is called consistency index (CI) and presented as follows:

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \text{ ....(C.2)}$$

So any variation of $\lambda_{\max}$ due to changes in comparisons ($a_{i,j}$) will give a measure of consistency of the matrix M'. Always $\lambda_{\max} \geq n$ as the matrix is consistent when $\lambda_{\max} = n$ and CI value closer to 0 indicates to be a more consistent comparison matrix (Saaty, 1980). Saaty (1980) also developed a random index (RI) by averaging resulting *CI* of randomly generated reciprocal matrix using 1-9 ratio scale so that $a_{i,j}$ elements can have values ranging 9 to 1/9. The table 2, given below showing RIs for matrices of different dimensions

TableC.2 Random Inconsistency of Different Size Matrix (Saaty, 2001)

n	1	2	3	4	5	6	7	8	9	10
R. I.	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

The consistency ratio (C.R.) compares CI obtained from a comparison matrix to the average consistency index (RI) obtained from a randomly generated comparison matrix of same dimension. Saaty (1980) suggested that C.R. should be $\leq$ 10% (or $\leq .1$) to consider as acceptable consistency of comparisons. C.R. can be expressed as the following equation

$$C.R. = \frac{(C.I.)}{(R.I)} \ldots\ldots\ldots\ldots\ldots\ldots (C.3)$$

Where,

C.I. = Consistency Index

R. I. = Random Consistency Index

Decomposition of Relative Weights (Composite Weight)

Many multi-criteria complex decision problems may have more then one level for criteria (criteria, sub-criteria) in the hierarchy. In that circumstance decomposition of relative weights is required. Same principles and procedure of AHP is applicable to estimate relative weights for both criteria and sub- criteria using comparison matrix. To estimate composite relative weights of sub-factors in a multi-level hierarchy problem Al Barqawi (2006) used the equation which presented below with same notations of the author:

Overall Sub-factor Decomposed Weight (SDWij) = Wi $*$ (Vij) ....(C.4)

Where:

Wi = Weight of factor *i*

Vij = Weight of sub-factor j within the factor i

Overall Ranking

When the estimation of relative weights for the decision attributes are completed, decision makers determine the preference levels of options/alternatives considering decision attributes (a single attribute at a time). The process of prioritizing options is the same as estimating relative weights from the comparison matrix. For example, if alternative j is being assessed for any criteria i and the priority weight of j is denoted as $w_{ij,}$ then the overall ranking for the alternative j in additive form can be expressed as follows:

$$R_{oj} = \sum_{i=1}^{n} w_i w_{ij} \text{..................} \quad (C.5)$$

Where

w_i is the relative weight of criteria i

R_{oj} is the overall ranking for the alternative j

APPENDIX-D

(Tables & Figures)

TableD.1 Weights at Category Level (Tanks/Basins)

REPONDANTS	**Categories**			
	a	**b**	**c**	**d**
RES.01	0.38	0.05	0.38	0.19
RES.02	0.57	0.29	0.09	0.06
RES.03	0.40	0.40	0.13	0.07
RES.04	0.55	0.17	0.08	0.20
RES.05	0.53	0.20	0.07	0.20
RES.06	0.42	0.25	0.11	0.22
RES.07	0.20	0.37	0.05	0.38
RES.08	0.09	0.05	0.34	0.51
RES.09	0.14	0.08	0.53	0.25
RES.10	0.24	0.52	0.12	0.12
RES.11	0.65	0.14	0.07	0.14
RES.12	0.47	0.28	0.10	0.16
RES.13	0.42	0.23	0.12	0.23
RES.14	0.14	0.52	0.07	0.27
RES.15	0.48	0.16	0.09	0.27
RES.16	0.54	0.15	0.12	0.19
RES.17	0.56	0.12	0.10	0.23
RES.18	0.20	0.40	0.20	0.20
RES.19	0.07	0.24	0.47	0.22
RES.20	0.09	0.08	0.16	0.67
RES.21	0.39	0.39	0.14	0.08
RES.22	0.09	0.24	0.45	0.22
RES.23	0.06	0.19	0.23	0.52
RES.24	0.33	0.17	0.17	0.33
RES.25	0.49	0.12	0.14	0.25
RES.26	0.45	0.22	0.09	0.24
RES.27	0.20	0.20	0.08	0.52
RES.28	0.47	0.19	0.21	0.13
RES.29	0.36	0.18	0.09	0.36
RES.30	0.23	0.42	0.12	0.23
RES.31	0.04	0.31	0.32	0.33
RES.32	0.06	0.31	0.33	0.31
AVERAGE	**0.32**	**0.24**	**0.18**	**0.26**

TableD.2 Weights at Category Level (Pumps)

REPONDANTS		Categories		
	a	b	c	d
RES.01	0.42	0.08	0.08	0.42
RES.02	0.14	0.14	0.45	0.26
RES.03	0.31	0.31	0.31	0.08
RES.04	0.08	0.13	0.65	0.14
RES.05	0.17	0.17	0.19	0.47
RES.06	0.10	0.19	0.35	0.37
RES.07	0.13	0.27	0.06	0.54
RES.08	0.20	0.20	0.04	0.56
RES.09	0.53	0.14	0.10	0.24
RES.10	0.60	0.20	0.10	0.10
RES.11	0.45	0.23	0.08	0.23
RES.12	0.20	0.24	0.17	0.39
RES.13	0.51	0.15	0.10	0.24
RES.14	0.14	0.15	0.07	0.63
RES.15	0.19	0.21	0.15	0.46
RES.16	0.23	0.19	0.15	0.43
RES.17	0.16	0.46	0.09	0.29
RES.18	0.19	0.19	0.10	0.53
RES.19	0.27	0.10	0.51	0.12
RES.20	0.11	0.19	0.11	0.60
RES.21	0.50	0.25	0.13	0.13
RES.22	0.27	0.11	0.49	0.13
RES.23	0.42	0.08	0.08	0.42
RES.24	0.40	0.20	0.20	0.20
RES.25	0.47	0.16	0.10	0.28
RES.26	0.22	0.20	0.11	0.48
RES.27	0.14	0.39	0.08	0.39
RES.28	0.48	0.14	0.13	0.26
RES.29	0.17	0.17	0.17	0.50
RES.30	0.22	0.17	0.13	0.48
RES.31	0.05	0.25	0.31	0.38
RES.32	0.05	0.24	0.26	0.45
AVERAGE	**0.27**	**0.20**	**0.19**	**0.35**

TableD.3 Relative Weights of Parameters within Category (Tank/Basins)

REPONDANTS	a.1	a.2	a.3	a.4	b.1	b.2	b.3	b.4	c.1	c.2	c.3	c.4	d.1	d.2	d.3	d.4
RES.01_O	0.09	0.48	0.31	0.13	0.23	0.45	0.08	0.23	0.57	0.11	0.21	0.11	0.10	0.24	0.39	0.27
RES.02_O	0.38	0.38	0.04	0.20	0.54	0.20	0.08	0.18	0.23	0.12	0.62	0.04	0.40	0.20	0.20	0.20
RES.03_O	0.43	0.43	0.04	0.10	0.34	0.48	0.11	0.06	0.56	0.09	0.17	0.18	0.58	0.17	0.14	0.11
RES.04_O	0.55	0.17	0.08	0.20	0.13	0.13	0.09	0.65	0.19	0.16	0.58	0.07	0.16	0.65	0.09	0.09
RES.05_WRE	0.41	0.07	0.12	0.41	0.09	0.27	0.16	0.48	0.57	0.11	0.11	0.21	0.07	0.37	0.31	0.25
RES.06_GT. CE	0.50	0.15	0.07	0.28	0.45	0.23	0.08	0.23	0.62	0.07	0.17	0.14	0.08	0.44	0.23	0.25
RES.07_CE	0.35	0.08	0.05	0.53	0.16	0.28	0.04	0.51	0.65	0.06	0.10	0.18	0.05	0.46	0.25	0.24
RES.08_RO	0.06	0.43	0.46	0.06	0.05	0.27	0.18	0.50	0.31	0.06	0.31	0.31	0.04	0.38	0.20	0.38
RES.09_RO	0.11	0.17	0.28	0.44	0.08	0.56	0.11	0.24	0.13	0.55	0.07	0.25	0.22	0.38	0.13	0.27
RES.10_O	0.08	0.21	0.61	0.10	0.06	0.51	0.23	0.20	0.20	0.48	0.11	0.22	0.55	0.11	0.09	0.25
RES.11_O	0.42	0.42	0.08	0.08	0.43	0.43	0.06	0.09	0.64	0.07	0.09	0.20	0.07	0.60	0.12	0.21
RES.12_CE	0.48	0.27	0.09	0.16	0.23	0.23	0.08	0.45	0.54	0.08	0.14	0.23	0.09	0.49	0.19	0.23
RES.13_O	0.23	0.46	0.08	0.23	0.20	0.20	0.20	0.40	0.36	0.18	0.09	0.36	0.20	0.40	0.20	0.20
RES.14_O	0.21	0.60	0.07	0.12	0.15	0.15	0.07	0.62	0.63	0.07	0.07	0.22	0.05	0.43	0.43	0.08
RES.15_WRE	0.48	0.17	0.07	0.28	0.20	0.10	0.11	0.59	0.48	0.13	0.14	0.26	0.10	0.43	0.18	0.29
RES.16_O	0.59	0.18	0.06	0.17	0.42	0.23	0.12	0.23	0.29	0.11	0.07	0.53	0.06	0.63	0.16	0.14
RES.17_CE	0.41	0.15	0.06	0.39	0.20	0.37	0.08	0.35	0.47	0.11	0.15	0.28	0.11	0.53	0.30	0.06
RES.18_O	0.09	0.14	0.38	0.38	0.25	0.25	0.25	0.25	0.54	0.11	0.09	0.26	0.13	0.38	0.38	0.13
RES.19_WRE	0.21	0.55	0.05	0.20	0.07	0.19	0.38	0.36	0.17	0.05	0.36	0.42	0.29	0.54	0.11	0.06
RES.20_O	0.14	0.12	0.64	0.09	0.58	0.16	0.08	0.17	0.14	0.63	0.07	0.15	0.14	0.49	0.25	0.12
RES.21_CE	0.40	0.13	0.07	0.40	0.59	0.11	0.10	0.20	0.18	0.14	0.11	0.56	0.22	0.63	0.08	0.08
RES.22_GT._CE	0.21	0.54	0.05	0.21	0.05	0.31	0.25	0.38	0.17	0.04	0.42	0.37	0.59	0.20	0.10	0.11
RES.23_O	0.08	0.68	0.08	0.15	0.73	0.09	0.09	0.09	0.68	0.13	0.08	0.10	0.08	0.13	0.72	0.07
RES.24_CE	0.37	0.19	0.07	0.37	0.17	0.25	0.11	0.47	0.45	0.14	0.19	0.22	0.10	0.53	0.11	0.26
RES.25_CE	0.32	0.32	0.07	0.30	0.61	0.09	0.08	0.21	0.42	0.09	0.10	0.39	0.06	0.46	0.24	0.25
RES.26_WRE	0.27	0.50	0.08	0.15	0.50	0.15	0.08	0.27	0.26	0.11	0.13	0.50	0.10	0.59	0.20	0.11
RES.27_O(REG.)	0.13	0.26	0.07	0.54	0.08	0.15	0.28	0.49	0.08	0.45	0.23	0.23	0.08	0.23	0.23	0.45
RES.28_O	0.45	0.09	0.05	0.41	0.08	0.13	0.20	0.59	0.09	0.66	0.07	0.18	0.08	0.69	0.15	0.08
RES.29_RO/CE	0.23	0.46	0.08	0.23	0.13	0.35	0.16	0.35	0.39	0.10	0.12	0.39	0.09	0.48	0.27	0.16
RES.30_O(REG.)	0.25	0.55	0.08	0.13	0.26	0.14	0.08	0.52	0.64	0.10	0.06	0.20	0.06	0.48	0.33	0.12
RES.31_O	0.17	0.63	0.05	0.14	0.56	0.18	0.14	0.11	0.05	0.37	0.20	0.38	0.10	0.43	0.43	0.04
RES.32_O	0.75	0.08	0.08	0.08	0.56	0.18	0.17	0.09	0.62	0.12	0.13	0.13	0.75	0.08	0.08	0.08
AVERAGE	**0.31**	**0.31**	**0.14**	**0.24**	**0.29**	**0.25**	**0.14**	**0.33**	**0.38**	**0.18**	**0.17**	**0.26**	**0.18**	**0.42**	**0.23**	**0.18**

TableD.4 Relative Weights of Parameters within Category (Pumps)

REPONDANTS	a.1	a.2	a.3	a.4	b.1	b.2	b.3	b.4	c.1	c.2	c.3	d.1	d.2	d.3	d.4	d.5
RES.01_O	0.09	0.27	0.16	0.48	0.13	0.13	0.13	0.63	0.09	0.73	0.18	0.04	0.20	0.20	0.37	0.20
RES.02_O	0.17	0.08	0.66	0.09	0.62	0.15	0.08	0.14	0.07	0.64	0.28	0.05	0.48	0.05	0.28	0.14
RES.03_O	0.43	0.27	0.14	0.16	0.41	0.41	0.11	0.06	0.43	0.43	0.14	0.50	0.10	0.12	0.17	0.10
RES.04_O	0.16	0.09	0.65	0.09	0.11	0.09	0.14	0.66	0.09	0.75	0.15	0.06	0.59	0.10	0.16	0.09
RES.05_WRE	0.16	0.09	0.65	0.09	0.19	0.19	0.10	0.53	0.42	0.46	0.13	0.05	0.23	0.13	0.38	0.22
RES.06_GT. CE	0.20	0.10	0.59	0.11	0.14	0.26	0.13	0.48	0.12	0.65	0.23	0.06	0.25	0.18	0.39	0.12
RES.07_CE	0.13	0.06	0.50	0.32	0.11	0.42	0.05	0.43	0.16	0.54	0.30	0.03	0.33	0.33	0.19	0.11
RES.08_RO	0.06	0.24	0.46	0.25	0.05	0.29	0.20	0.46	0.09	0.73	0.18	0.04	0.32	0.17	0.17	0.32
RES.09_RO	0.43	0.20	0.07	0.30	0.16	0.51	0.05	0.29	0.79	0.08	0.13	0.09	0.31	0.37	0.07	0.15
RES.10_O	0.20	0.20	0.18	0.43	0.10	0.65	0.08	0.17	0.11	0.78	0.11	0.08	0.14	0.08	0.54	0.16
RES.11_O	0.12	0.12	0.11	0.65	0.44	0.09	0.05	0.42	0.07	0.47	0.47	0.05	0.55	0.15	0.08	0.16
RES.12_CE	0.26	0.09	0.51	0.14	0.27	0.16	0.09	0.48	0.11	0.58	0.31	0.05	0.43	0.25	0.16	0.10
RES.13_O	0.14	0.14	0.14	0.57	0.24	0.22	0.09	0.45	0.08	0.46	0.46	0.05	0.19	0.19	0.38	0.19
RES.14_O	0.20	0.10	0.60	0.10	0.57	0.11	0.11	0.21	0.74	0.17	0.09	0.06	0.13	0.17	0.11	0.53
RES.15_WRE	0.32	0.07	0.48	0.12	0.26	0.14	0.13	0.48	0.13	0.59	0.28	0.05	0.39	0.13	0.27	0.15
RES.16_O	0.16	0.10	0.58	0.16	0.48	0.26	0.13	0.14	0.11	0.63	0.26	0.05	0.44	0.13	0.23	0.15
RES.17_CE	0.21	0.13	0.54	0.12	0.20	0.22	0.11	0.48	0.24	0.62	0.14	0.06	0.47	0.11	0.18	0.18
RES.18_O	0.26	0.14	0.45	0.14	0.49	0.16	0.14	0.20	0.13	0.59	0.28	0.08	0.37	0.15	0.25	0.15
RES.19_WRE	0.57	0.21	0.11	0.11	0.05	0.24	0.25	0.46	0.65	0.23	0.12	0.05	0.27	0.26	0.25	0.16
RES.20_O	0.26	0.12	0.09	0.53	0.08	0.16	0.09	0.67	0.68	0.08	0.24	0.13	0.46	0.23	0.08	0.10
RES.21_CE	0.21	0.10	0.60	0.08	0.57	0.11	0.11	0.21	0.14	0.24	0.62	0.06	0.20	0.12	0.54	0.08
RES.22_GT._CE	0.50	0.15	0.27	0.08	0.06	0.25	0.31	0.38	0.63	0.19	0.17	0.10	0.31	0.18	0.31	0.10
RES.23_O	0.72	0.09	0.09	0.10	0.72	0.08	0.08	0.13	0.78	0.11	0.11	0.07	0.08	0.66	0.11	0.07
RES.24_CE	0.42	0.12	0.23	0.23	0.10	0.25	0.16	0.49	0.14	0.57	0.29	0.09	0.47	0.11	0.18	0.15
RES.25_CE	0.20	0.20	0.40	0.20	0.16	0.27	0.09	0.48	0.08	0.59	0.33	0.06	0.28	0.23	0.19	0.24
RES.26_WRE	0.51	0.09	0.26	0.14	0.50	0.10	0.21	0.19	0.11	0.58	0.31	0.07	0.43	0.21	0.18	0.11
RES.27_O(REG.)	0.42	0.23	0.23	0.12	0.12	0.31	0.07	0.50	0.65	0.23	0.12	0.07	0.19	0.19	0.19	0.37
RES.28_O	0.45	0.14	0.26	0.14	0.16	0.19	0.07	0.58	0.13	0.79	0.08	0.05	0.48	0.08	0.17	0.21
RES.29_RO/CE	0.50	0.13	0.25	0.13	0.14	0.26	0.14	0.45	0.16	0.54	0.30	0.07	0.16	0.15	0.30	0.32
RES.30_O(REG.)	0.26	0.07	0.54	0.13	0.60	0.10	0.10	0.20	0.74	0.17	0.09	0.06	0.15	0.14	0.16	0.49
RES.31_O	0.57	0.18	0.17	0.09	0.56	0.18	0.14	0.11	0.76	0.12	0.12	0.11	0.40	0.41	0.04	0.04
RES.32_O	0.71	0.07	0.14	0.07	0.67	0.13	0.13	0.07	0.73	0.18	0.09	0.64	0.07	0.07	0.15	0.07
AVERAGE	**0.31**	**0.14**	**0.35**	**0.20**	**0.30**	**0.22**	**0.12**	**0.36**	**0.32**	**0.45**	**0.22**	**0.10**	**0.31**	**0.19**	**0.23**	**0.18**

TableD.5 Decomposed Weights of Parameters (Tanks/Basins)

REPONDANTS	a.1	a.2	a.3	a.4	b.1	b.2	b.3	b.4	c.1	c.2	c.3	c.4	d.1	d.2	d.3	d.4
RES.01	0.03	0.18	0.12	0.05	0.01	0.02	0.00	0.01	0.22	0.04	0.08	0.04	0.02	0.05	0.08	0.05
RES.02	0.22	0.22	0.02	0.11	0.15	0.06	0.02	0.05	0.02	0.01	0.06	0.00	0.02	0.01	0.01	0.01
RES.03	0.17	0.17	0.02	0.04	0.14	0.19	0.04	0.03	0.07	0.01	0.02	0.02	0.04	0.01	0.01	0.01
RES.04	0.30	0.10	0.04	0.11	0.02	0.02	0.02	0.11	0.02	0.01	0.05	0.01	0.03	0.13	0.02	0.02
RES.05	0.22	0.04	0.06	0.22	0.02	0.05	0.03	0.09	0.04	0.01	0.01	0.02	0.01	0.07	0.06	0.05
RES.06	0.21	0.06	0.03	0.12	0.11	0.06	0.02	0.06	0.07	0.01	0.02	0.02	0.02	0.10	0.05	0.06
RES.07	0.07	0.01	0.01	0.10	0.06	0.10	0.02	0.19	0.04	0.00	0.01	0.01	0.02	0.18	0.10	0.09
RES.08	0.01	0.04	0.04	0.01	0.00	0.01	0.01	0.02	0.11	0.02	0.11	0.11	0.02	0.20	0.10	0.20
RES.09	0.02	0.02	0.04	0.06	0.01	0.05	0.01	0.02	0.07	0.29	0.04	0.13	0.05	0.09	0.03	0.07
RES.10	0.02	0.05	0.15	0.02	0.03	0.26	0.12	0.10	0.02	0.06	0.01	0.03	0.06	0.01	0.01	0.03
RES.11	0.27	0.27	0.05	0.05	0.06	0.06	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.08	0.02	0.03
RES.12	0.22	0.13	0.04	0.07	0.07	0.07	0.02	0.12	0.05	0.01	0.01	0.02	0.01	0.08	0.03	0.04
RES.13	0.10	0.20	0.03	0.10	0.05	0.05	0.05	0.09	0.04	0.02	0.01	0.04	0.05	0.09	0.05	0.05
RES.14	0.03	0.08	0.01	0.02	0.08	0.08	0.04	0.33	0.04	0.01	0.01	0.02	0.01	0.12	0.12	0.02
RES.15	0.23	0.08	0.03	0.13	0.03	0.02	0.02	0.09	0.04	0.01	0.01	0.02	0.03	0.12	0.05	0.08
RES.16	0.32	0.10	0.03	0.09	0.06	0.03	0.02	0.03	0.04	0.01	0.01	0.07	0.01	0.12	0.03	0.03
RES.17	0.23	0.08	0.03	0.22	0.02	0.04	0.01	0.04	0.04	0.01	0.01	0.03	0.03	0.12	0.07	0.01
RES.18	0.02	0.03	0.08	0.08	0.10	0.10	0.10	0.10	0.11	0.02	0.02	0.05	0.03	0.08	0.08	0.03
RES.19	0.01	0.04	0.00	0.01	0.02	0.05	0.09	0.09	0.08	0.02	0.17	0.20	0.07	0.12	0.02	0.01
RES.20	0.01	0.01	0.06	0.01	0.05	0.01	0.01	0.01	0.02	0.10	0.01	0.02	0.09	0.33	0.17	0.08
RES.21	0.16	0.05	0.03	0.16	0.23	0.04	0.04	0.08	0.03	0.02	0.02	0.08	0.02	0.05	0.01	0.01
RES.22	0.02	0.05	0.00	0.02	0.01	0.07	0.06	0.09	0.08	0.02	0.19	0.17	0.13	0.04	0.02	0.02
RES.23	0.00	0.04	0.00	0.01	0.14	0.02	0.02	0.02	0.16	0.03	0.02	0.02	0.04	0.07	0.37	0.04
RES.24	0.12	0.06	0.02	0.12	0.03	0.04	0.02	0.08	0.07	0.02	0.03	0.04	0.03	0.18	0.04	0.09
RES.25	0.16	0.16	0.03	0.15	0.07	0.01	0.01	0.03	0.06	0.01	0.01	0.05	0.01	0.11	0.06	0.06
RES.26	0.12	0.22	0.04	0.07	0.11	0.03	0.02	0.06	0.02	0.01	0.01	0.05	0.02	0.14	0.05	0.03
RES.27	0.03	0.05	0.01	0.11	0.02	0.03	0.06	0.10	0.01	0.04	0.02	0.02	0.04	0.12	0.12	0.23
RES.28	0.21	0.04	0.02	0.20	0.02	0.02	0.04	0.11	0.02	0.14	0.02	0.04	0.01	0.09	0.02	0.01
RES.29	0.08	0.17	0.03	0.08	0.02	0.06	0.03	0.06	0.04	0.01	0.01	0.04	0.03	0.18	0.10	0.06
RES.30	0.06	0.12	0.02	0.03	0.11	0.06	0.03	0.22	0.08	0.01	0.01	0.02	0.01	0.11	0.08	0.03
RES.31	0.01	0.03	0.00	0.01	0.17	0.06	0.04	0.04	0.02	0.12	0.06	0.12	0.03	0.14	0.14	0.01
RES.32	0.04	0.00	0.00	0.00	0.17	0.06	0.05	0.03	0.21	0.04	0.04	0.04	0.23	0.03	0.03	0.03
AVERAGE	**0.12**	**0.09**	**0.04**	**0.08**	**0.07**	**0.06**	**0.03**	**0.08**	**0.06**	**0.04**	**0.03**	**0.05**	**0.04**	**0.11**	**0.07**	**0.05**

TableD.6 Decomposed Weights of Parameters (Pumps)

REPONDANTS	a.1	a.2	a.3	a.4	b.1	b.2	b.3	b.4	c.1	c.2	c.3	d.1	d.2	d.3	d.4	d.5
RES.01	0.04	0.11	0.07	0.20	0.01	0.01	0.01	0.05	0.01	0.06	0.02	0.02	0.08	0.08	0.16	0.08
RES.02	0.02	0.01	0.09	0.01	0.09	0.02	0.01	0.02	0.03	0.29	0.13	0.01	0.13	0.01	0.07	0.04
RES.03	0.13	0.08	0.04	0.05	0.13	0.13	0.03	0.02	0.13	0.13	0.04	0.04	0.01	0.01	0.01	0.01
RES.04	0.01	0.01	0.05	0.01	0.01	0.01	0.02	0.09	0.06	0.49	0.10	0.01	0.08	0.01	0.02	0.01
RES.05	0.03	0.02	0.11	0.02	0.03	0.03	0.02	0.09	0.08	0.09	0.02	0.03	0.11	0.06	0.17	0.10
RES.06	0.02	0.01	0.06	0.01	0.03	0.05	0.02	0.09	0.04	0.22	0.08	0.02	0.09	0.07	0.14	0.04
RES.07	0.02	0.01	0.06	0.04	0.03	0.11	0.01	0.11	0.01	0.03	0.02	0.02	0.18	0.18	0.10	0.06
RES.08	0.01	0.05	0.09	0.05	0.01	0.06	0.04	0.09	0.00	0.03	0.01	0.02	0.18	0.09	0.09	0.18
RES.09	0.23	0.10	0.04	0.16	0.02	0.07	0.01	0.04	0.08	0.01	0.01	0.02	0.07	0.09	0.02	0.03
RES.10	0.12	0.12	0.11	0.26	0.02	0.13	0.02	0.03	0.01	0.08	0.01	0.01	0.01	0.01	0.05	0.02
RES.11	0.05	0.05	0.05	0.29	0.10	0.02	0.01	0.10	0.01	0.04	0.04	0.01	0.13	0.04	0.02	0.04
RES.12	0.05	0.02	0.10	0.03	0.06	0.04	0.02	0.12	0.02	0.10	0.05	0.02	0.17	0.10	0.06	0.04
RES.13	0.07	0.07	0.07	0.29	0.03	0.03	0.01	0.07	0.01	0.05	0.05	0.01	0.05	0.05	0.09	0.05
RES.14	0.03	0.01	0.09	0.01	0.09	0.02	0.02	0.03	0.06	0.01	0.01	0.04	0.08	0.11	0.07	0.33
RES.15	0.06	0.01	0.09	0.02	0.05	0.03	0.03	0.10	0.02	0.09	0.04	0.02	0.18	0.06	0.12	0.07
RES.16	0.04	0.02	0.13	0.04	0.09	0.05	0.02	0.03	0.02	0.09	0.04	0.02	0.19	0.06	0.10	0.06
RES.17	0.03	0.02	0.08	0.02	0.09	0.10	0.05	0.22	0.02	0.06	0.01	0.02	0.14	0.03	0.05	0.05
RES.18	0.05	0.03	0.08	0.03	0.09	0.03	0.03	0.04	0.01	0.06	0.03	0.04	0.19	0.08	0.13	0.08
RES.19	0.15	0.06	0.03	0.03	0.01	0.02	0.03	0.05	0.33	0.12	0.06	0.01	0.03	0.03	0.03	0.02
RES.20	0.03	0.01	0.01	0.06	0.02	0.03	0.02	0.13	0.07	0.01	0.03	0.08	0.28	0.14	0.05	0.06
RES.21	0.11	0.05	0.30	0.04	0.14	0.03	0.03	0.05	0.02	0.03	0.08	0.01	0.03	0.01	0.07	0.01
RES.22	0.14	0.04	0.07	0.02	0.01	0.03	0.03	0.04	0.31	0.09	0.08	0.01	0.04	0.02	0.04	0.01
RES.23	0.30	0.04	0.04	0.04	0.06	0.01	0.01	0.01	0.06	0.01	0.01	0.03	0.03	0.28	0.05	0.03
RES.24	0.17	0.05	0.09	0.09	0.02	0.05	0.03	0.10	0.03	0.11	0.06	0.02	0.09	0.02	0.04	0.03
RES.25	0.09	0.09	0.19	0.09	0.03	0.04	0.01	0.08	0.01	0.06	0.03	0.02	0.08	0.06	0.05	0.07
RES.26	0.11	0.02	0.06	0.03	0.10	0.02	0.04	0.04	0.01	0.06	0.03	0.04	0.21	0.10	0.08	0.05
RES.27	0.06	0.03	0.03	0.02	0.05	0.12	0.03	0.20	0.05	0.02	0.01	0.03	0.07	0.07	0.07	0.14
RES.28	0.22	0.07	0.13	0.07	0.02	0.03	0.01	0.08	0.02	0.10	0.01	0.01	0.12	0.02	0.04	0.05
RES.29	0.08	0.02	0.04	0.02	0.02	0.04	0.02	0.08	0.03	0.09	0.05	0.03	0.08	0.08	0.15	0.16
RES.30	0.06	0.02	0.12	0.03	0.10	0.02	0.02	0.03	0.10	0.02	0.01	0.03	0.07	0.07	0.08	0.24
RES.31	0.03	0.01	0.01	0.00	0.14	0.05	0.04	0.03	0.24	0.04	0.04	0.04	0.15	0.16	0.02	0.02
RES.32	0.04	0.00	0.01	0.00	0.16	0.03	0.03	0.02	0.19	0.05	0.02	0.28	0.03	0.03	0.07	0.03
AVERAGE	**0.08**	**0.04**	**0.08**	**0.07**	**0.06**	**0.05**	**0.02**	**0.07**	**0.06**	**0.09**	**0.04**	**0.03**	**0.11**	**0.07**	**0.07**	**0.07**

TableD.7 Decomposed weights of parameters classified based on respondents group (Tanks)

Parameters	(ALL)	(O)	(CE)	(RO)	(WRE)	(DE)
a.1	0.12	0.11	0.14	0.03	0.15	0.16
a.2	0.09	0.10	0.09	0.08	0.10	0.13
a.3	0.04	0.04	0.03	0.04	0.03	0.03
a.4	0.08	0.06	0.11	0.05	0.11	0.11
b.1	0.07	0.08	0.06	0.01	0.04	0.06
b.2	0.06	0.07	0.05	0.04	0.04	0.04
b.3	0.03	0.04	0.03	0.02	0.04	0.02
b.4	0.08	0.08	0.08	0.04	0.08	0.07
c.1	0.06	0.07	0.05	0.07	0.05	0.05
c.2	0.04	0.04	0.01	0.11	0.01	0.01
c.3	0.03	0.03	0.04	0.05	0.05	0.02
c.4	0.05	0.03	0.06	0.09	0.07	0.03
d.1	0.04	0.04	0.03	0.04	0.03	0.02
d.2	0.11	0.09	0.11	0.16	0.11	0.13
d.3	0.07	0.08	0.05	0.08	0.05	0.05
d.4	0.05	0.04	0.05	0.11	0.04	0.06

TableD.8 Decomposed weights of parameters classified based on respondents group (Pumps)

Parameters	(ALL)	(O)	(CE)	(RO)	(WRE)	(DE)
a.1	0.08	0.08	0.08	0.11	0.09	0.10
a.2	0.04	0.04	0.03	0.06	0.03	0.04
a.3	0.08	0.07	0.10	0.06	0.07	0.08
a.4	0.07	0.08	0.04	0.08	0.02	0.04
b.1	0.06	0.07	0.05	0.02	0.05	0.04
b.2	0.05	0.04	0.05	0.06	0.03	0.04
b.3	0.02	0.02	0.03	0.02	0.03	0.03
b.4	0.07	0.06	0.09	0.07	0.07	0.08
c.1	0.06	0.06	0.07	0.04	0.11	0.09
c.2	0.09	0.09	0.09	0.04	0.09	0.10
c.3	0.04	0.03	0.05	0.02	0.04	0.05
d.1	0.03	0.04	0.02	0.03	0.02	0.02
d.2	0.11	0.10	0.11	0.11	0.13	0.11
d.3	0.07	0.07	0.06	0.09	0.06	0.06
d.4	0.07	0.06	0.09	0.09	0.10	0.08
d.5	0.07	0.08	0.06	0.12	0.06	0.06

TableD.9 Preference Scores for different scenarios in case of tank/basins (Rrespondent-29)

Category	Parameters	Scenarios	Preference scores for scenarios (0-10)		
			Settling Basins	Filtration Basins	Final Chlorination Tank
a) Physical (design & cons. stage)	a.1) Design consid. (dura. aspects, type of joints etc.)	1. More detailed (special)	10	10	10
		2. Standard	8	8	8
		3. Sub-standard	0	0	0
	a.2) Material type	1. Reinforced concrete	8	10	10
		2. Steel	5	5	5
		3. Wood	0	0	0
		4. Other (specify)	10	8	8
	a.3) Size & Capacity	1. <5000 M^3/day	10	10	10
		2. 5000-10000 M^3/day	10	10	10
		3. > 10000 M^3/daily	10	10	10
	a.4) Quality control of cons. works	1. Proper	10	10	10
		2. Improper	0	0	0
b) Physical (service stage)	b.1) Age of the element	1. ≤ ¼ of design life	10	10	10
		2. > ¼ ≤ ½ of design life	8	8	8
		3. > ½ ≤ design life	6	6	6
		4. > design life	0	0	0
	b.2) Corrosion	1. No	10	10	10
		2. Minor	6	6	6
		3. Major	0	0	0
	b.3) Coating/paint	1. Best quality	6	6	10
		2. Ordinary	0	0	0
		3. No coating	9	9	0
	b.4) Cracks/flaws	1. None	10	10	10
		2. Minor	6	6	6
		3. Significant	0	0	0
c) Environt.	c.1) Soil type	1. Sand or Rock	8	8	8
		2. Silt	5	5	5
		3. Clay	5	5	5
		4. Other (specify)	-	-	-

	c.2) Quality of source water ($P^{H,}$ Turbidity etc)	1. Excellent	10	10	10
		2. Good	8	8	8
		3. Fair	6	6	6
		4. Bad	4	4	4
		5. Very Bad	0	0	0
	c.3) Vibration	1. No	10	10	10
		2. Minor	9	9	9
		3. Significant	6	6	6
	c.4) Weather condition	1. 0° C to 40° C	9	9	9
		2. -40° C to 40° C	7	7	7
		3. -60° C to 25° C	5	5	5
d) Operational	d.1) Chemicals dozes	1. None	x	x	x
		2. Alum	10	10	10
		3. Lime	9	9	9
		4. Ozone	x	9	9
		5. Chlorine	8	8	8
		6. Silicate	9	9	9
		7. Other chemicals (specify)	9	9	x
	d.2) Operation & Maintenance practice	1. Standards O&M practice	10	10	10
		2. Poor O&M practice	1	1	1
	d.3) Manager and Operators experience	1. More then 5 years	9	9	9
		2. >1 ≤5 years	8	8	8
		3. 0-1 year	7	7	7
	d.4) Control system	1. Automatic	9	9	9
		2. Combined	8	8	8
		3. Manual	7	7	7

TableD.10 Preference Scores for different scenarios in case of pumps (Rrespondent-29)

Category	Parameters	Scenarios	Preference scores for scenarios (0-10)	
			For Raw Water Pumps	For Clean Water Pumps
a) Electro-Mechanical	a.1) Type of pumps	1. Axial	-	-
		2. Centrifugal	10	10
		3. Reciprocating	-	-
		4. Submersible	9	9
		5. Vertical spindle	-	-
		6. Other (specify)	-	-
	a.2) Horse power	1. ≤ 100	5	5
		2. >100≤200	5	5
		3. >200	5	5
	a.3) Starting options	1. Conventional	5	5
		2. Soft starting	10	10
	a.4) Capacity	1. 1000-10000 M^3/h	5	5
		2. <1000 M^3/h	5	5
		3. > 10000 M^3/h	5	5
b) Physical	b.1) Age	1. ≤ ¼ of design life	10	10
		2. > ¼ ≤ ½ of design life	8	8
		3. > ½ ≤ design life	5	5
		4. > design life	0	0
	b.2) Corrosion	1. No	10	10
		2. Minor	7	7
		3. Major	3	3
	b.3) Coating /paint	1. Best quality	10	10
		2. Ordinary	7	7
		3. No coating	5	5
	b.4) Any type of crack	1. None	10	10
		2. Minor	0	0
		3. Major	0	0
c) Environmental	c.1) Quality of source water ($P^{H,}$ Turbidity etc)	1. Excellent	10	10
		2. Good	8	9
		3. Fair	6	8
		4. Bad	2	7
		5. Very Bad	0	x
	c.2) Vibration	1. No	10	10
		2. Minor	5	5
		3. Significant	0	0
	c.3) Temperature	1. 0° C to 40° C	9	9
		2. -40° C to 40° C	7	9
		3. -60° C to 25° C	6	9

d) Operational	d.1) Chemicals dozes	1. None	x	10
		2. Alum	x	9
		3. Lime	x	9
		4. Ozone	x	9
		5. Chlorine	x	7
		6. Silicate	x	5
		7. Other chemicals (specify)	x	6
	d.2) Operation & Maintenance practice	1. Standards O&M practice	10	10
		2. Poor O&M practice	1	1
	d.3) Manager and Operators experience	1. More then 5 years	9	9
		2. >1 ≤5 years	8	8
		3. 0-1 year	6	6
	d.4) Daily pump running time	1. 24 hours	7	7
		2. 2. <24≥12 hours	8	8
		3. 3. < 12 hours	8	8
		4. 4. Emergency use only	8	8
	d.5) Control	1. Automatic	10	10
		2. Combined	8	8
		3. Manual	6	6

TableD.11 Average Preference Scores for All Scenarios (Tank/Basin), (Cont.)

OPTION/SCENARIOS	SET. B	FIL. B	CHL.T
a) Physical (design & cons. stage)			
a.1) Design considerations (durability aspects, type of joints etc.)			
a.1.1. More detailed (special)	9.63	9.59	9.47
a.1.2. Standard	7.28	7.28	7.25
a.1.3. Sub-standard	0.50	0.47	0.47
a.2) Material type			
a.2.1. Reinforced concrete	9.59	9.66	9.66
a.2.2. Steel	6.22	6.22	5.94
a.2.3. Wood	0.38	0.34	0.34
a.2.4. Other (Faber glass)	9.60	9.40	9.20
a.3) Size & Capacity			
a.3.1. <5000 M3/day	8.07	8.03	8.03
a.3.2. 5000-10000 M3/day	8.10	8.03	8.07
a.3.3. > 10000 M3/daily	7.52	7.72	7.52
a.4) Quality control of cons. works			
a.4.1. Proper	9.59	9.59	9.59
a.4.2. Improper	0.38	0.38	0.38
b) Physical (service stage)			
b.1) Age of the element			
b.1.1. ≤ ¼ of design life	9.44	9.44	9.44
b.1.2. > ¼ ≤ ½ of design life	7.44	7.44	7.44
b.1.3. > ½ ≤ design life	5.34	5.34	5.34
b.1.4. > design life	1.56	1.56	1.56
b.2) Corrosion			
b.2.1. No	9.81	9.81	9.81
b.2.2. Minor	6.28	6.34	6.13
b.2.3.Major	0.38	0.38	0.38
b.3) Coating/paint			
b.3.1. Best quality	9.06	9.06	9.13
b.3.2. Ordinary	4.88	4.88	4.25
b.3.3. No coating	5.16	5.25	4.03
b.4) Cracks and flaws			
b.4.1. None	9.81	9.78	9.81
b.4.2. Minor	6.41	6.41	6.41
b.4.3. Significant	0.41	0.41	0.41

Contd. TableD.11 Average Preference of Scores for All Scenarios (Tank/Basin)

OPTION/SCENARIOS	SET. B	FIL. B	CHL.T
c) Environmental			
c.1) Type of Soil			
c.1.1. Sand or Rock	9.13	9.13	9.13
c.1.2. Silt	5.94	5.94	5.94
c.1.3. Clay	4.44	4.44	4.44
c.1.4. Other (Organic)	0.71	0.71	0.71
c.2) Quality of source water ($P^{H,}$ *Turbidity etc)*			
c.2.1. Excellent	9.81	9.81	9.81
c.2.2. Good	8.78	9.00	9.00
c.2.3. Fair	6.72	7.31	7.71
c.2.4. Bad	3.94	5.06	5.61
c.2.5. Very bad	1.68	2.87	3.42
c.3) Vibration (including earthquake)			
c.3.1. No	9.53	9.56	9.56
c.3.2. Minor	7.00	7.09	7.06
c.3.3. Significant	1.50	1.69	1.72
c.4) Weather condition			
c.4.1. 0° C to 40° C	9.66	9.63	9.63
c.4.2. -40° C to 40° C	5.38	5.44	5.38
c.4.3. -60° C to 25° C	2.63	2.63	2.63
d) Operational			
d.1) Chemicals dozes			
d.1.1. None	9.29	9.28	9.23
d.1.2. Alum	7.81	7.77	7.96
d.1.3. Lime	6.71	6.79	6.65
d.1.4. Ozone	5.60	7.56	7.29
d.1.5. Chlorine	6.96	6.88	6.71
d.1.6. Silicate	8.95	9.11	8.81
d.1.7. Other	8.25	8.25	8.50
d.2) Operation & Maintenance practice			
d.2.1. Standards O&M practice	9.56	9.56	9.56
d.2.2. Poor O&M practice	2.03	2.00	1.91
d.3) Manager and Operators experience			
d.3.1. More then 5 years	9.03	9.03	9.06
d.3.2. >1 ≤5 years	6.59	6.59	6.63
d.3.3. 0-1 year	4.25	4.22	4.28
d.4) Control system			
d.4.1. Automatic	8.16	8.19	8.22
d.4.2. Combined	8.63	8.63	8.22
d.4.3. Manual	5.03	5.03	8.22

TableD.12 Average Preference Scores for All Scenarios (Pumps), (Cont.)

Parameter Scenarios	RWP	CWP
a) Electro-Mechanical		
a.1) Type of Pump		
a.1.1. Axial	6.59	6.59
a.1.2. Centrifugal	8.72	9.03
a.1.3. Reciprocating	7.36	7.79
a.1.4. Submersible	7.33	7.75
a.1.5. Vertical spindle	8.25	8.31
a.1.6. Other	10.00	10.00
a.2) Horse power		
a.2.1. ≤ 100	8.29	8.19
a.2.2. >100≤200	8.19	8.19
a.2.3. >200	7.97	8.13
a.3) Starting options		
a.3.1. Conventional	4.97	4.97
a.3.2. Soft starting	9.66	9.69
a.4) Capacity		
a.4.1. 1000-10000 M3/h	8.47	8.47
a.4.2. <1000 M3/h	8.17	8.30
a.4.3. > 10000 M3/h	8.47	8.63
b) Physical (service stage)		
b.1) Age of the element		
b.1.1. ≤ ¼ of design life	9.44	9.38
b.1.2. > ¼ ≤ ½ of design life	7.50	7.56
b.1.3. > ½ ≤ design life	5.38	5.41
b.1.4. > design life	5.38	2.03
b.2) Corrosion		
b.2.1. No	9.81	9.81
b.2.2. Minor	7.03	7.00
b.2.3.Major	1.34	1.31
b.3) Coating/paint		
b.3.1. Best quality	9.78	9.75
b.3.2. Ordinary	6.53	6.44
b.3.3. No coating	1.88	2.09
b.4) Cracks and flaws		
b.4.1. None	9.75	9.75
b.4.2. Minor	4.97	4.97
b.4.3. Significant	0.28	0.28

Contd. TableD.12 Average Preference Scores for All Scenarios (Pumps)

Parameter Scenarios	**RWP**	**CWP**
c) Environmental		
c.1) Quality of source water		
c.1.1. Excellent	9.66	9.90
c.1.2. Good	8.56	9.43
c.1.3. Fair	7.34	9.07
c.1.4. Bad	4.44	7.70
c.1.5. Very bad	2.03	6.48
c.2) Vibration		
c.2.1. No	9.75	9.78
c.2.2. Minor	6.34	6.31
c.2.3. Significant	0.13	0.13
c.3) Temperature		
c.3.1. 0° C to 40° C	9.66	9.63
c.3.2. -40° C to 40° C	6.28	6.28
c.3.3. -60° C to 25° C	4.22	4.50
d) Operational		
d.1) Chemicals dozes		
d.1.1. None	9.95	9.76
d.1.2. Alum	8.42	8.74
d.1.3. Lime	7.10	7.82
d.1.4. Ozone	8.40	8.00
d.1.5. Chlorine	7.53	7.13
d.1.6. Silicate	6.63	5.96
d.1.7. Other (Activated carbon)	-	8.00
d.2) Operation & Maintenance practice		
d.2.1. Standards O&M practice	9.78	9.78
d.2.2. Poor O&M practice	1.22	1.22
d.3) Manager and Operators experience		
d.3.1. More then 5 years	9.38	9.38
d.3.2. >1 ≤5 years	7.16	7.16
d.3.3. 0-1 year	4.00	4.00
d.4) Daily running time of pump operation.		
d.4.1. 24 hours	6.56	6.56
d.4.<24≥12 hours	7.78	7.81
d.4.< 12 hours	7.19	7.16
d.4.Emergency use only	6.13	6.27
d.5) Control System		
d.5.1. Automatic	8.97	8.97
d.5.2. Combined	8.06	8.06
d.5.3. Manual	4.59	4.56

TableD.13 Maximum and minimum CRIs calculated from individual survey respondents' inputs

	CRIs _MPS					CRIs_LPS				
RESP.	ST_T	FIL.T	CHL.T	RWP	CWP	ST. B	FIL. B	CHL.T	RWP	CWP
RES_1	10.00	10.00	10.00	10.00	10.00	2.51	2.51	2.93	4.71	4.79
RES_2	9.76	9.76	9.76	10.00	10.00	0.24	0.24	0.24	2.68	2.68
RES_3	8.71	8.78	8.94	8.62	8.88	0.70	0.67	0.84	3.40	4.57
RES_4	9.56	9.56	9.56	9.66	9.84	1.24	1.24	1.24	1.05	1.32
RES_5	9.74	9.74	9.74	9.87	9.87	1.45	1.57	1.43	3.19	3.58
RES_6	9.80	9.80	9.80	9.34	9.38	1.54	1.70	1.47	1.96	2.04
RES_7	10.00	10.00	10.00	10.00	10.00	0.88	0.95	0.88	1.82	1.92
RES_8	9.46	9.46	9.50	9.22	9.24	2.53	2.63	2.63	3.15	3.17
RES_9	7.85	7.74	8.07	8.56	8.45	3.56	3.43	3.62	5.40	5.88
RES_10	9.99	9.99	9.99	10.00	10.00	2.86	3.15	2.48	5.36	5.39
RES_11	10.00	10.00	10.00	10.00	10.00	2.28	2.25	2.25	5.09	5.09
RES_12	10.00	10.00	10.00	10.00	9.97	1.13	1.13	1.05	2.56	2.17
RES_13	9.86	9.86	9.86	10.00	10.00	1.18	1.18	1.27	5.03	5.00
RES_14	9.84	9.84	9.78	9.83	9.83	2.21	2.25	2.25	3.12	3.41
RES_15	9.05	9.10	9.15	9.10	9.31	2.23	1.94	1.49	3.12	3.30
RES_16	10.00	10.00	9.98	9.80	9.80	1.43	1.42	1.36	4.30	4.21
RES_17	9.95	9.95	9.95	9.82	9.75	1.27	1.29	1.32	3.07	3.19
RES_18	9.93	9.93	9.93	9.97	9.97	1.73	1.93	1.43	2.14	2.14
RES_19	8.26	8.26	8.20	8.91	8.89	2.78	2.69	2.62	2.01	2.97
RES_20	10.00	10.00	10.00	10.00	10.00	3.44	3.44	3.53	4.52	4.36
RES_21	9.97	9.97	9.97	9.76	9.76	1.36	1.36	1.36	3.74	3.82
RES_22	9.02	9.02	9.02	9.12	9.12	2.62	2.62	2.68	2.23	3.72
RES_23	9.78	9.78	9.78	9.93	9.93	1.87	1.87	2.03	3.20	3.02
RES_24	9.94	9.94	9.94	9.98	9.98	2.20	2.20	2.12	4.96	4.99
RES_25	9.45	9.45	9.45	9.17	9.16	1.79	1.83	1.85	2.96	2.95
RES_26	9.95	9.95	9.95	10.00	10.00	1.80	1.80	1.72	4.22	4.09
RES_27	9.98	9.98	9.98	9.95	9.95	3.72	3.76	3.51	3.17	3.46
RES_28	10.00	10.00	10.00	10.00	10.00	0.96	0.96	1.64	4.23	4.40
RES_29	9.74	9.74	9.74	9.36	9.36	2.22	2.22	2.22	4.59	4.76
RES_30	8.97	8.98	8.98	9.04	9.19	2.47	2.49	2.49	3.83	4.27
RES_31	9.92	9.80	9.80	10.00	10.00	2.33	2.38	3.17	1.51	1.54
RES_32	9.59	9.54	9.54	10.00	10.00	2.68	2.68	2.84	1.12	1.08
AVGE	**9.63**	**9.62**	**9.64**	**9.66**	**9.68**	**1.98**	**1.99**	**2.00**	**3.36**	**3.54**

TableD.14 Best Fit of Preference Scores of Parameters for Condition Assessment (tank/basin)

Statistical Item	**Statistical Analysis of Normal Distribution Fit**							
	a.2.1_T	**a.1.2_T**	**a.2.2_T**	**a.2.3_T**	**a.3.1_T**	**b.2.3_T**	**c.2.4_T**	**d.1.6_T**
μ (min)	9.59	7.28	6.22	0.38	8.07	0.38	3.94	8.95
σ (min)	0.91	1.46	1.85	0.83	2.56	0.83	2.21	1.77
TS-Chi-sq	89.87	14.88	17.50	89.88	27.25	83.50	4.38	32.13
TS-A-D	6.82	1.27	1.42	7.01	2.91	6.16	0.47	6.08
TS-K-S	0.45	0.22	0.23	0.46	0.24	0.42	0.47	0.44
P Value-Chi-sq	0.00	0.01	0.00	0.00	0.00	0.00	0.50	0.00
P Value-A-D	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.15 <= p <= 0.25	< 0.005
P Value-K-S	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.15 <= p <= 0.25	< 0.01
Confid. @ 95%	0.32	0.51	0.64	0.29	0.89	0.29	0.77	0.61
μ - C (min)	9.28	6.77	5.58	0.09	7.18	0.09	3.17	8.33
μ + C (min)	9.91	7.79	6.86	0.66	8.96	0.66	4.70	9.56

CV-Chi-sq @ 15% =8.12 CV-A-D @ 15% = 0.55 CV-K-S @ 15% = 0.13 Data Point =32

TableD.15 Best Fit of Preference Scores of Parameters for Condition Assessment (pump)

Statistical Item	Statistical Analysis of rather than Normal Distribution Fit									
	b.2.1_P	b.2.3_P	b.3.3_P	c.1.2_P	c.1.3_P	c.2.1_P	c.3.3_P	d.2.1_P	d.3.1_P	d.5.1_P
μ (min)	9.95	1.30	1.82	8.66	7.35	9.87	4.21	9.92	9.58	9.12
σ (min)	0.34	1.34	1.88	1.39	1.77	0.98	3.46	0.39	0.94	1.51
TS-Chi-sq	118.00	42.25	32.88	17.13	10.38	98.50	4.00	109.40	62.13	52.06
TS-A-D	9.62	16.11	11.60	1.28	1.01	7.12	0.70	8.78	4.49	3.17
TS-K-S	0.45	0.50	0.44	0.17	0.18	0.44	0.12	0.43	0.35	0.29
P Value-Chi-sq	0.00	0.00	0.00	0.00	0.07	0.00	0.55	0.00	0.00	0.00
P Value-A-D	< 0.005	< 0.01	< 0.01	< 0.005	< 0.01	< 0.01	0.05 <= p <= 0.1	< 0.005	< 0.005	< 0.005
P Value-K-S	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	> 0.1	< 0.01	< 0.01	< 0.01
Confid. @ 95%	0.12	0.47	0.65	0.48	0.61	0.34	1.20	0.14	0.33	0.52
μ - C (min)	9.83	0.84	1.17	8.18	6.74	9.53	3.01	9.78	9.25	8.59
μ + C (min)	10	1.77	2.47	9.15	7.97	10	5.41	10	9.91	9.64
CV-Chi-sq @ 15% =	8.12	8.12	8.12	8.12	8.12	8.12	8.12	8.12	8.12	8.12
CV-A-D @ 15% =	N/A	0.63	0.63	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CV-K-S @ 15% =	N/A	0.16	0.16	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Data Points =	32.00									

TableD.16 Best Fit of Preference Scores of Parameters for Condition Assessment (tank/basin)

Statistical Item	**Statistical Analysis of Normal Distribution Fit**								
	c.2.5_T	**c.3.1_T**	**c.3.2_T**	**c.3.3_T**	**c.4.1_T**	**c.4.2_T**	**d.1.3_T**	**d.1.4_T**	**d.1.5_T**
μ (min)	1.68	9.53	7.00	1.50	9.66	5.38	7.81	6.71	6.96
σ (min)	2.15	1.16	1.83	2.29	0.97	2.41	1.62	1.44	1.43
TS-Chi-sq	39.63	98.50	18.63	41.88	98.50	11.50	17.50	11.13	7.38
TS-A-D	3.17	7.71	18.63	4.12	7.56	2.51	1.72	1.40	1.87
TS-K-S	0.31	0.47	0.24	0.31	0.45	0.29	0.24	0.25	0.28
P Value-Chi-sq	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.05	0.19
P Value-A-D	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
P Value-K-S	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Confid. @ 95%	0.74	0.40	0.63	0.79	0.34	0.83	0.56	0.50	0.49
μ - C (min)	0.93	9.13	6.37	0.71	9.32	4.54	7.25	6.22	6.46
μ + C (min)	2.42	9.93	7.63	2.29	9.99	6.21	8.37	7.21	7.45
CV-Chi-sq @ 15% = 8.12		CV-A-D @ 15% = 0.55				CV-K-S @ 15% = 0.13			
Data Points =	32.00								

TableD.17 Best Fit of Preference Scores of Parameters for Condition Assessment (pump)

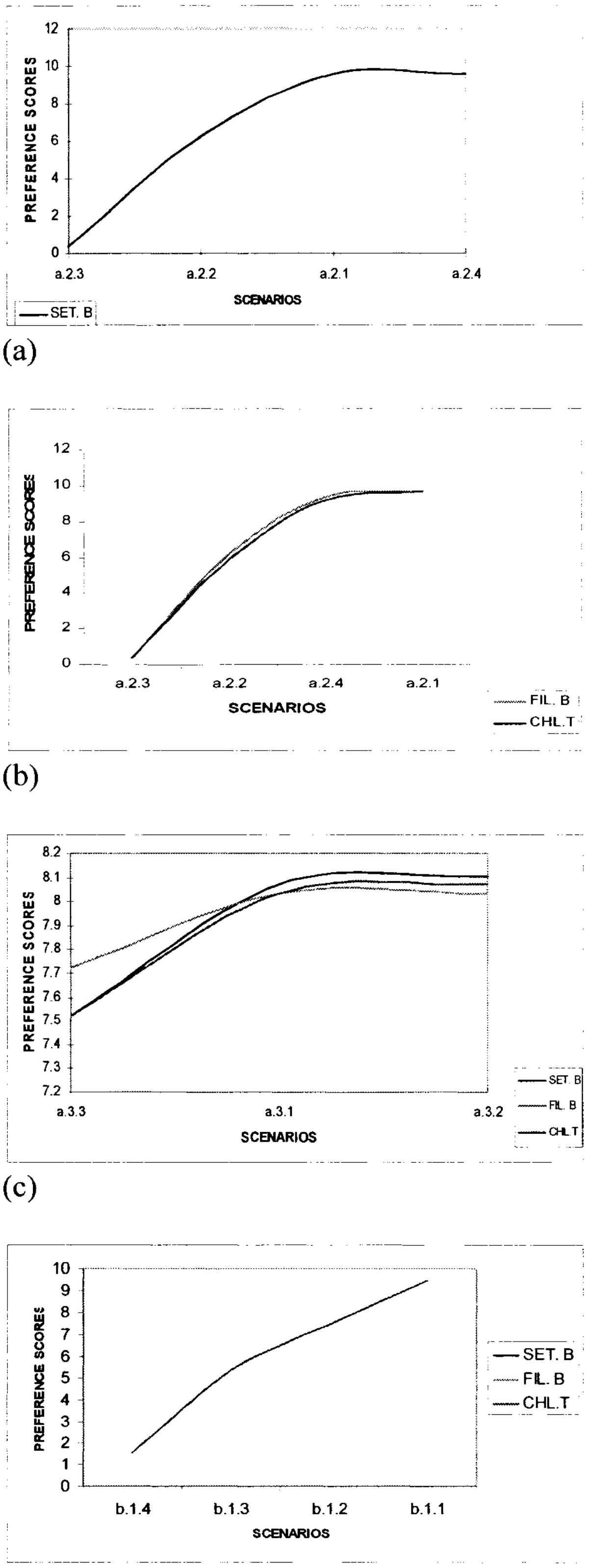
Statistical Item	Statistical Analysis of Normal Distribution Fit								
	a.1.1_P	**a.1.2_P**	**a.1.4_P**	**a.1.5_P**	**a.2.1_P**	**a.3.2_P**	**a.4.1_P**	**a.4.2_P**	**b.1.2_P**
μ (min)	6.59	8.72	7.33	8.25	8.30	9.66	8.47	8.17	7.50
σ (min)	1.27	2.20	1.77	1.31	2.62	0.70	1.91	2.38	1.08
TS-Chi-sq	28.00	41.13	10.00	52.38	40.38	83.50	29.13	30.63	30.25
TS-A-D	1.59	4.13	1.00	3.11	3.95	6.16	2.70	2.94	1.91
TS-K-S	0.25	0.28	0.16	0.30	0.31	0.44	0.29	0.28	0.24
P Value-Chi-sq	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00
P Value-A-D	< 0.005	< 0.005	0.01 <= p <= 0.025	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
P Value-K-S	< 0.01	< 0.01	0.025 <= p <= 0.05	< 0.01	< 0.01	< 0.01	< 0.005	< 0.01	< 0.01
Confid. @ 95%	0.44	0.76	0.61	0.45	0.91	0.24	0.66	0.83	0.37
μ - C (min)	6.15	7.96	6.72	7.80	7.39	9.41	7.80	7.34	7.13
μ + C (min)	7.03	9.49	7.95	8.70	9.21	9.90	9.13	8.99	7.87
CV-Chi-sq @ 15% =8.12		CV-A-D @ 15% =0.55				CV-K-S @ 15% =0.13			
Data Points =	32.00								

TableD.17 Best Fit of CRI Considering the Most Preferred and the Least Preferred Scenarios

Statistical Item	**Statistical Analysis of Normal Distribution Fit**					
	ST_MP	**ST_LP**	**FT_MP**	**FT_LP**	**Ch.T_MP**	**Ch.T_LP**
μ (min)	9.63	1.98	9.62	1.99	9.64	2.00
σ (min)	0.54	0.84	0.55	0.84	0.51	0.85
TS-Chi-sq	29.13	1.38	24.63	1.38	27.25	4.00
TS-A-D	3.31	0.23	3.20	0.17	3.08	0.38
TS-K-S	0.27	0.11	0.27	0.08	0.27	0.13
P Value-Chi-sq	0.00	0.93	0.00	0.93	0.00	0.55
P Value-A-D	< 0.005	> 0.25	< 0.005	> 0.25	< 0.005	> 0.25
P Value-K-S	< 0.01	> 0.15	< 0.01	> 0.15	< 0.01	> 0.15
Conf.@ 95%	0.19	0.29	0.19	0.29	0.18	0.30
μ - C (min)	9.44	1.68	9.43	1.70	9.46	1.70
μ + C (min)	9.82	2.27	9.81	2.28	9.81	2.29
CV-Chi-sq @ 15% =8.12		CV-A-D @ 15% =0.55 ;CV-K-S @ 15% =0.13				
Data Points	32.00					

TableD.18 Best Fit of CRI Considering the Most Preferred and the Least Preferred Scenarios

Statistical Item	**Statistical Analysis of Normal Distribution Fit**			
	RP_MP	RP_LP	CP_MP	CP_LP
μ (min)	9.66	3.36	9.68	3.54
σ (min)	0.45	1.25	0.43	1.25
TS-Chi-sq	37.75	4.75	37.75	3.25
TS-A-D	3.10	0.35	3.05	0.23
TS-K-S	0.25	0.11	0.25	0.08
P Value-Chi-sq	0.00	0.45	0.00	0.66
P Value-A-D	< 0.005	> 0.25	< 0.005	> 0.25
P Value-K-S	< 0.01	> 0.15	< 0.01	> 0.15
Confid. @ 95%	0.16	0.43	0.15	0.43
μ - C (min)	9.50	2.92	9.53	3.11
μ + C (min)	9.81	3.79	9.83	3.97
CV-Chi-sq @ 15% =8.12; CV-A-D @ 15% = 0.55 ;CV-K-S @ 15% =0.13				
Data Points =	32.00			



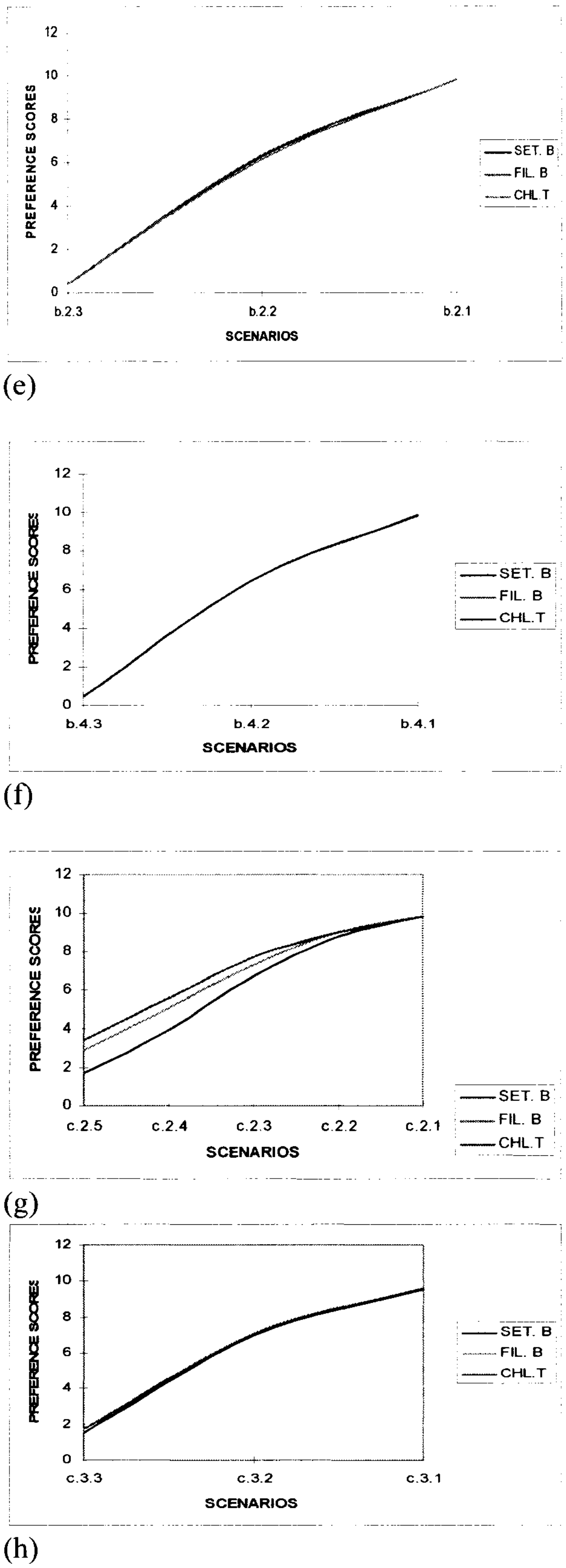
(a)

(b)

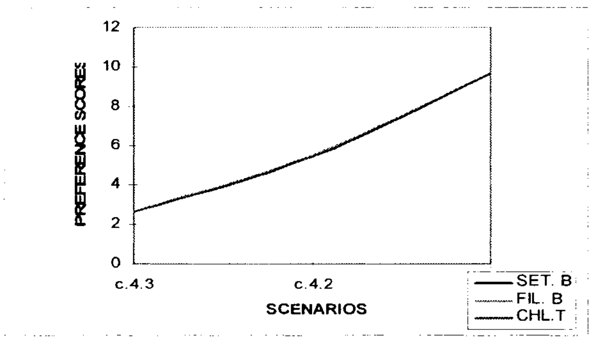
(c)

(d)

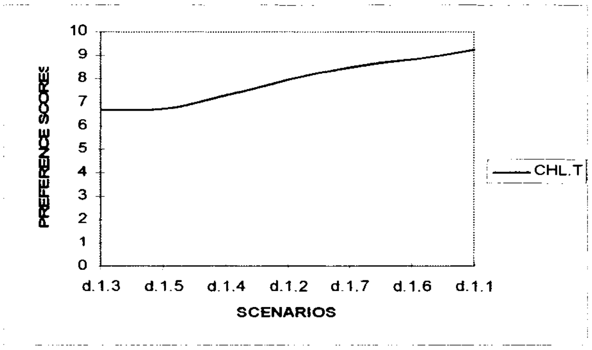
FigureD.1 Preference Curve for Various Parameters



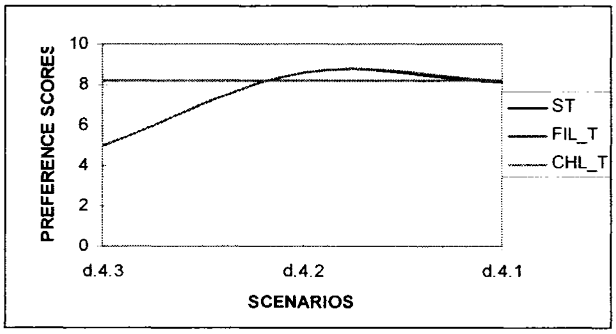
FigureD.2 Preference Curve for Various Parameters



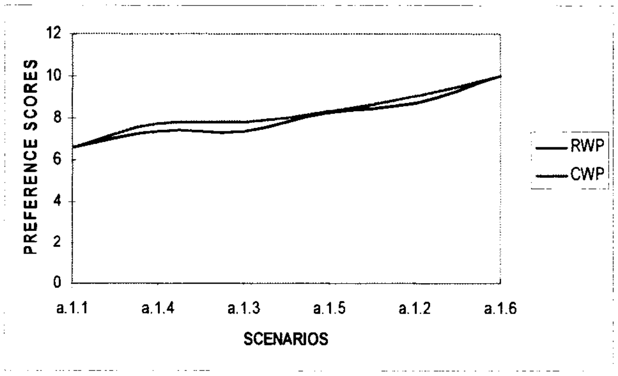
(i)



(j)

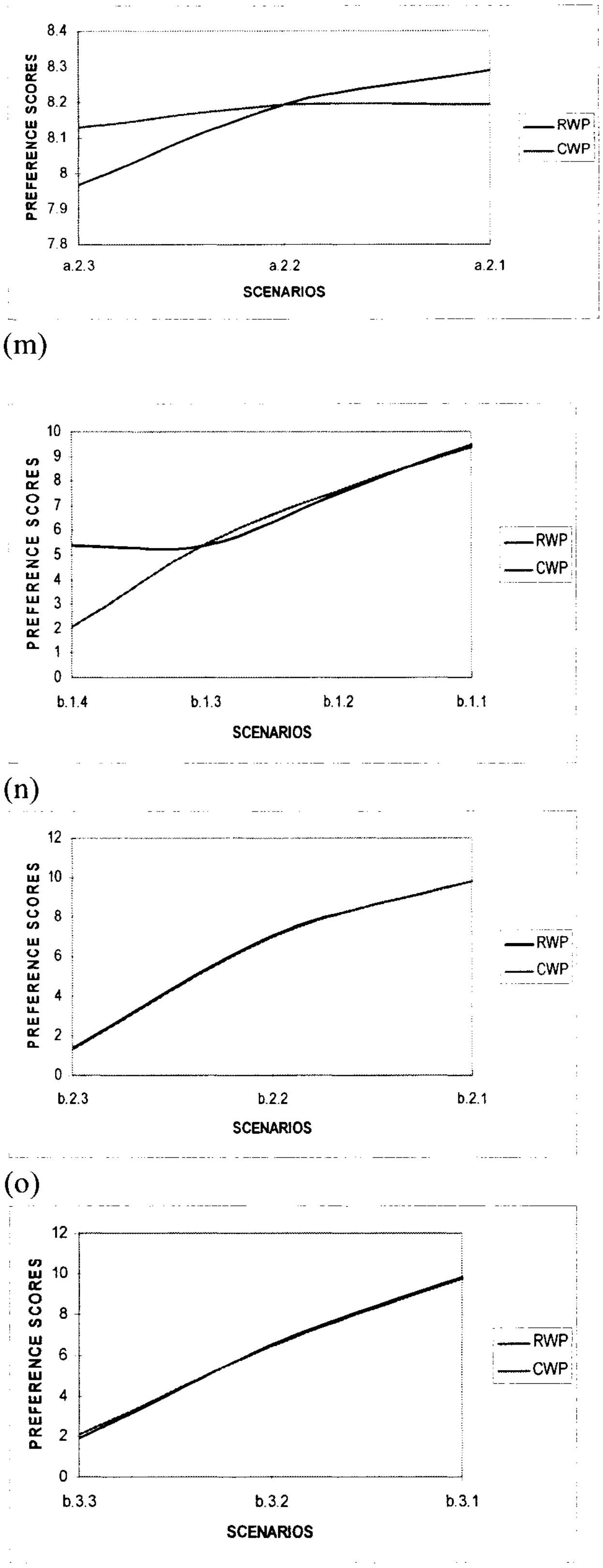


(k)



(l)

FigureD.3 Preference Curve for Various Parameters



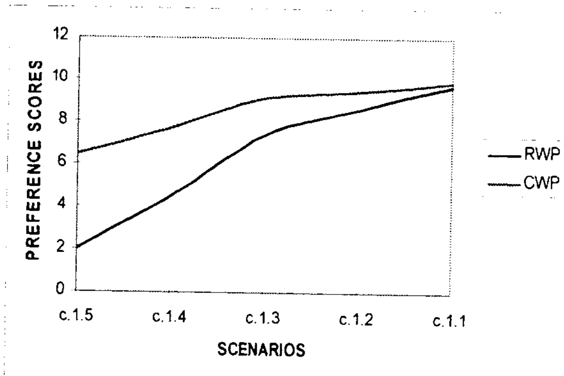
(m)

(n)

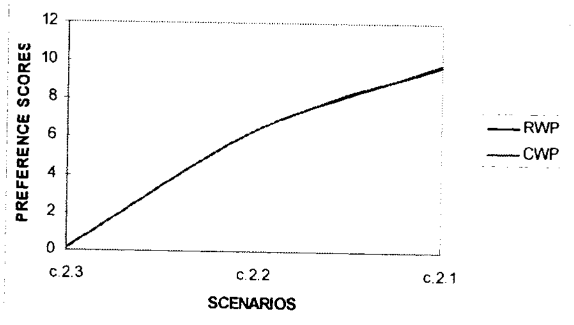
(o)

(p)

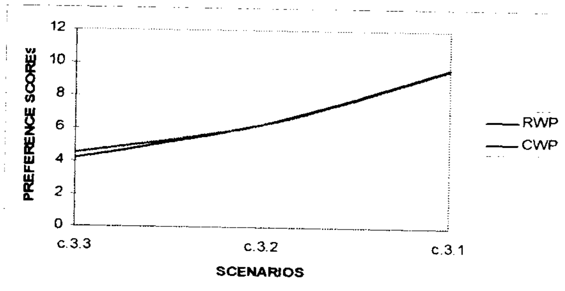
FigureD.4 Preference Curve for Various Parameters



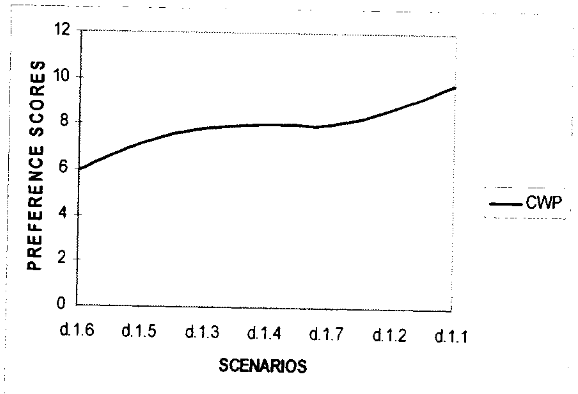
(q)



(r)

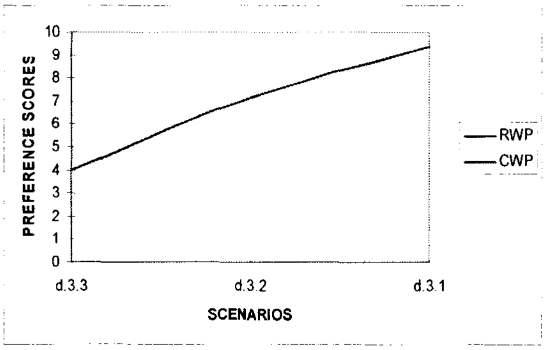


(s)

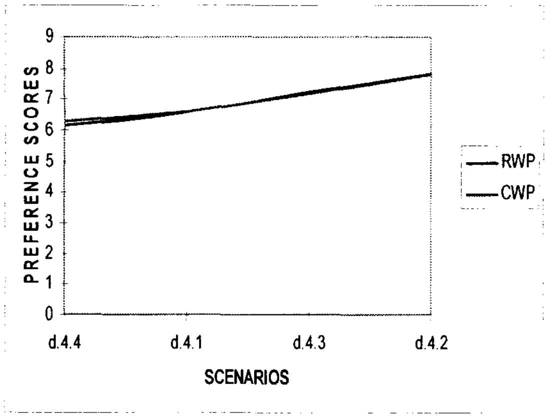


(x)

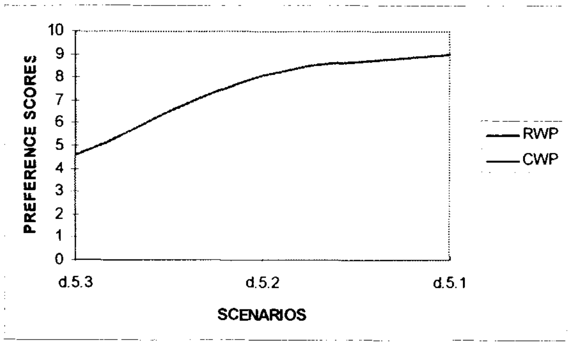
FigureD.5 Preference Curve for Various Parameters



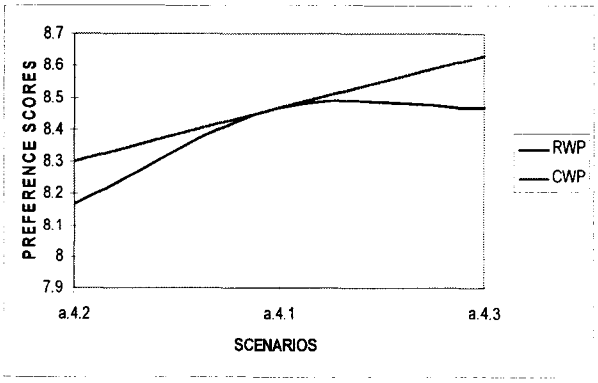
(w)



(y)

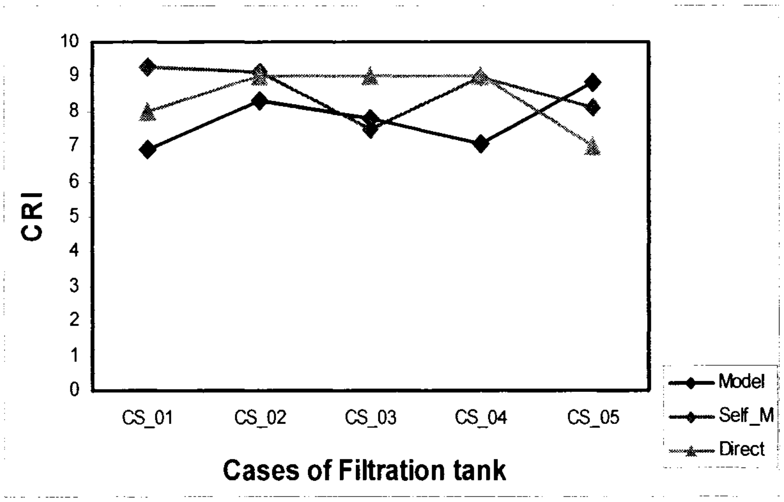


(z')

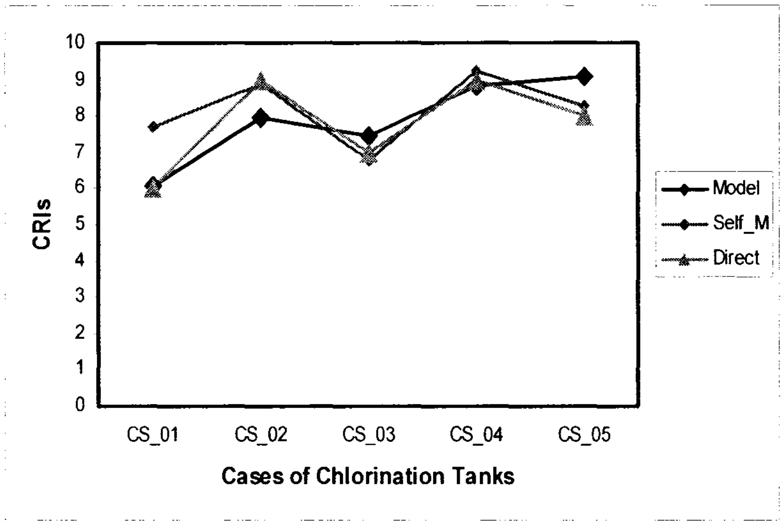


(a')

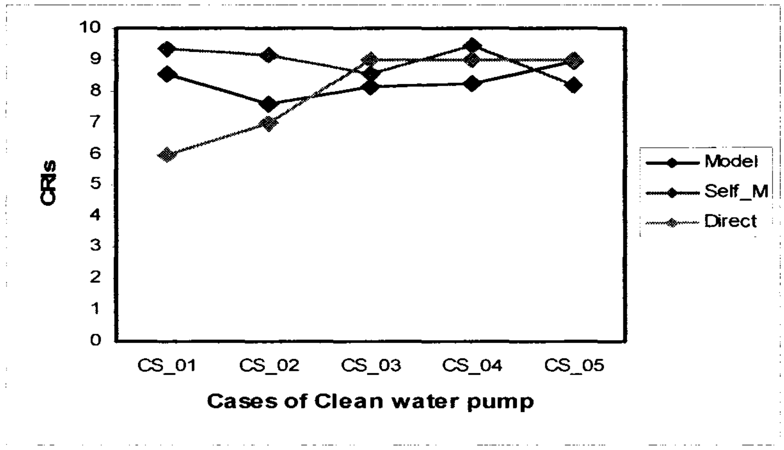
FigureD.6 Preference Curve for Various Parameters



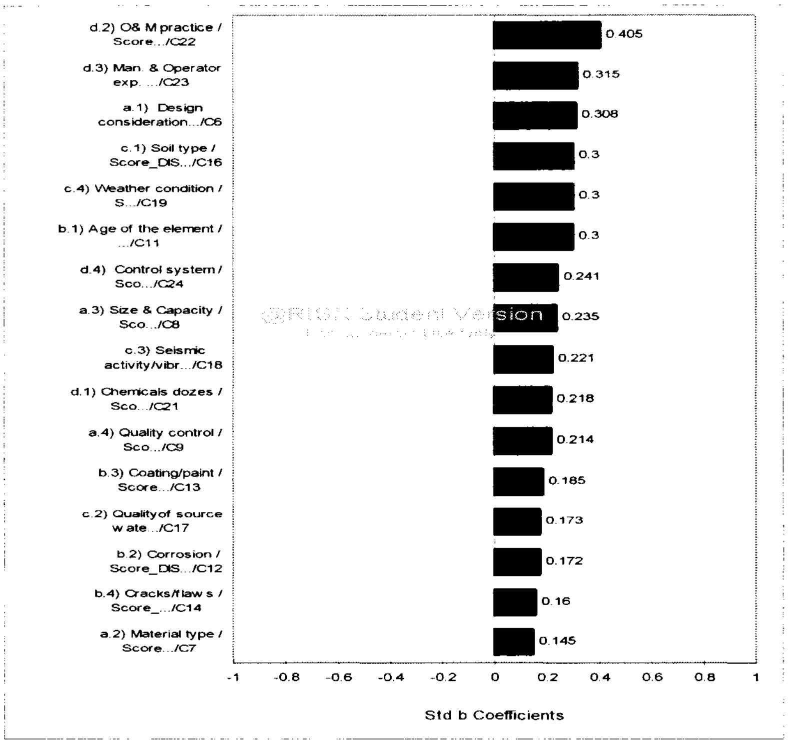
FigureD.7 CRIs from model and individual experts



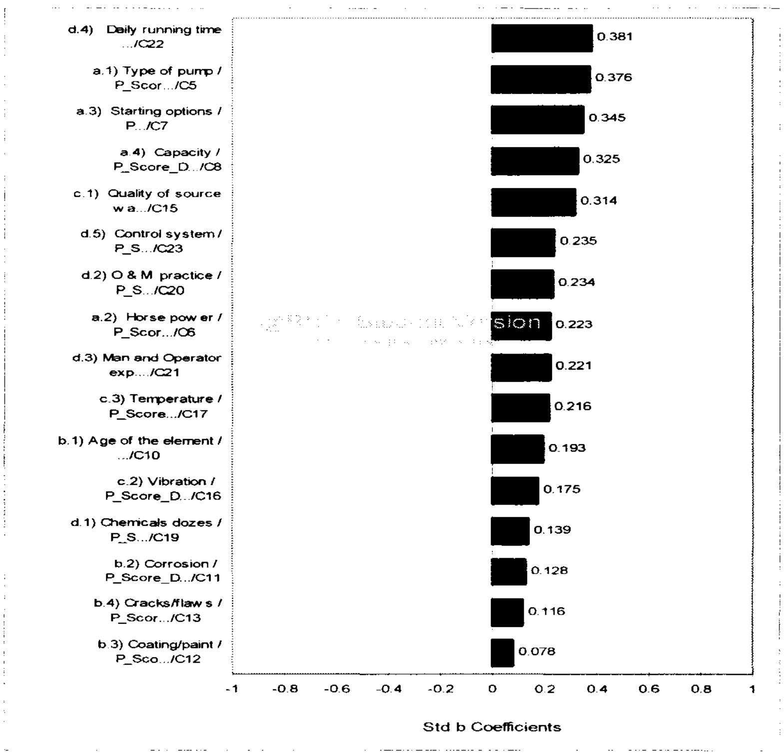
FigureD.8 CRIs from model and individual experts



FigureD.9 CRIs from model and individual experts



FigureD.10 Regression Sensitivity for CRI of Settling Tank at AVG_PS



FigureD. 11 Regression Sensitivity for CRI of RWP at AVG_PS

Appendix-E

(Scenarios Selection Form for Practical Examples)

CONDITION DATA OF FEW PLANT ELEMENTS

Name of the Plant: **Address:**

TableE.1 Tanks/Basins (In case of same answer for all elements only one column can be completed and where no options are applicable keep those blank)

Category	Parameters	Options	Mark 'Y' to options those apply to your plant		
			Settling Basins	Filtration Basins	Final Chlorination Tank
a) Physical (design & cons. stage)	a.1) Design considerations (durability aspects, type of joints etc.)	4. More detailed (special)			
		5. Standard			
		6. Sub-standard			
	a.2) Material type	5. Reinforced concrete			
		6. Steel			
		7. Wood			
		8. Other (specify)			
	a.3) Size & Capacity	4. <5000 M^3/day			
		5. 5000-10000 M^3/day			
		6. > 10000 M^3/daily			
	a.4) Quality control of cons. works	3. Proper			
		4. Improper			
b) Physical (service stage)	b.1) Age of the element	5. ≤ ¼ of design life			
		6. > ¼ ≤ ½ of design life			
		7. > ½ ≤ design life			
		8. > design life			
	b.2) Corrosion	4. No			
		5. Minor			
		6. Major			
	b.3) Coating/paint	4. Best quality			
		5. Ordinary			
		6. No coating			
	b.4) Cracks/flaws	4. None			
		5. Minor			
		6. Significant			
c) Environment	c.1) Soil type	5. Sand or Rock			
		6. Silt			
		7. Clay			
		8. Other (specify)			
	c.2) Quality of source water	6. Excellent			
		7. Good			

	($P^{H,}$ Turbidity etc)	8. Fair			
		9. Bad			
		10. Very Bad			
	c.3) Vibration	4. No			
		5. Minor			
		6. Significant			
	c.4) Weather condition	4. 0° C to 40° C			
		5. -40° C to 40° C			
		6. -60° C to 25° C			
d) Operational	d.1) Chemicals dozes	8. None			
		9. Alum			
		10. Lime			
		11. Ozone			
		12. Chlorine			
		13. Silicate			
		14. Other chemicals (specify)			
	d.2) Operation & Maintenance practice	3. Standards O&M practice			
		4. Poor O&M practice			
	d.3) Manager and Operators experience	4. More then 5 years			
		5. >1 ≤5 years			
		6. 0-1 year			
	d.4) Control system	4. Automatic			
		5. Combined			
		6. Manual			

TableE.2 Pumps (In case of same answer for both type of pumps only one column can be completed and where no options are applicable keep those blank)

Category	Parameters	Options	Mark 'Y' to options those apply to your plant	
			For Raw Water Pumps	For Clean Water Pumps
a) Electro-Mechanical	a.1) Type	7. Axial		
		8. Centrifugal		
		9. Reciprocating		
		10. Submersible		
		11. Vertical spindle		
		12. Other (specify)		
	a.2) Horse power	1. ≤ 100		
		2. $>100 \leq 200$		
		3. >200		
	a.3) Starting options	4. Conventional		
		5. Soft starting		
	a.4) Capacity	4. 1000-10000 M^3/h		
		5. <1000 M^3/h		
		6. > 10000 M^3/h		
b) Physical	b.1) Age	11 $\leq$ ¼ of design life		
		12 > ¼ $\leq$ ½ of design life		
		13 > ½ $\leq$ design life		
		14 > design life		
	b.2) Corrosion	4. No		
		5. Minor		
		6. Major		
	b.3) Coating /paint	1. Best quality		
		2. Ordinary		
		6. No coating		
	b.4) Any type of crack	4. None		
		5. Minor		
		6. Major		
c) Environmental	c.1) Quality of source water (P^{H}· Turbidity etc)	6. Excellent		
		7. Good		
		8. Fair		
		9. Bad		
		10. Very Bad		
	c.2) Vibration	4. No		
		5. Minor		

		6. Significant		
	c.3) Temperature	4. 0° C to 40° C		
		5. -40° C to 40° C		
		6. -60° C to 25° C		
d) Operational	d.1) Chemicals dozes	8. None		
		9. Alum		
		10. Lime		
		11. Ozone		
		12. Chlorine		
		13. Silicate		
		14. Other chemicals (specify)		
	d.2) Operation & Maintenance practice	3. Standards O&M practice		
		4. Poor O&M practice		
	d.3) Manager and Operators experience	4. More then 5 years		
		5. >1 ≤5 years		
		6. 0-1 year		
	d.4) Daily pump running time	2. 24 hours		
		2. <24≥12 hours		
		3. < 12 hours		
		4. Emergency use only		
	d.5) Control	4. Automatic		
		5. Combined		
		6. Manual		

Comments:

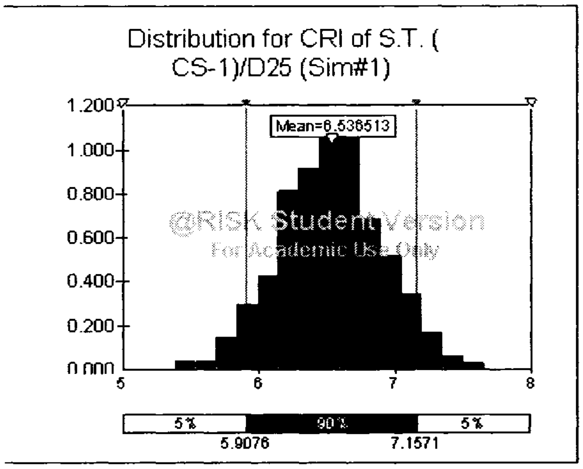
THANK YOU FOR YOUR KIND COOPERATION

SARKER RAHMAN
M. A. Sc. Student
Building, Civil & Environmental Engineering Department
Concordia University, Montreal, Quebec, Canada
Mailing Address: 30-6320 Victoria Avenue, Montreal, QC, Canada H3W 2S4
Phone: 1-514-731 1819
E-mail: smsajed@yahoo.ca; sarke_ra@encs.concordia.ca or smsajedr@gmail.com
Fax: 1-514-848 7965 (Attention Dr. T. Zayed)

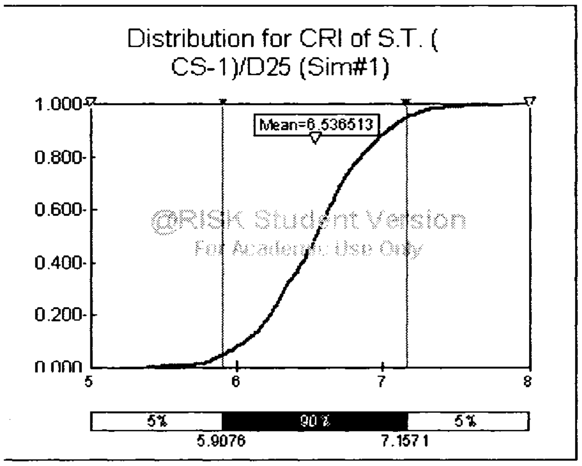
Appendix-F

(Sample Quick summery Reports from simulation for Case-Studies)

Simulation Results for
CRI of S.T. (CS-1) / D25 / Simulation 1

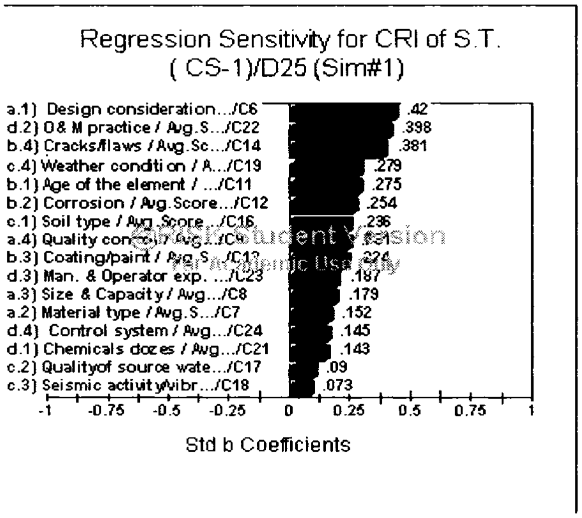


Summary Information	
Workbook Name	1_CS_1_ST_BESTFITS.
Number of Simulations	100
Number of Iterations	1000
Number of Inputs	16
Number of Outputs	1
Sampling Type	Latin Hypercube
Simulation Start Time	20/10/2006 16:02
Simulation Stop Time	20/10/2006 16:13
Simulation Duration	00:11:07
Random Seed	965231662



Summary Statistics

Statistic	Value	%tile	Value
Minimum	5.389340401	5%	5.907594204
Maximum	7.806763172	10%	6.055845737
Mean	6.536512763	15%	6.160239697
Std Dev	0.374122156	20%	6.225116253
Variance	0.139967388	25%	6.282723427
Skewness	0.028653278	30%	6.331815243
Kurtosis	3.004437802	35%	6.390455723
Median	6.541107655	40%	6.444336891
Mode	6.568807793	45%	6.491977692
Left X	5.907594204	50%	6.541107655
Left P	5%	55%	6.581521988
Right X	7.157086372	60%	6.623041153
Right P	95%	65%	6.672310352
Diff X	1.249492168	70%	6.716393948
Diff P	90%	75%	6.770186424
#Errors	0	80%	6.84794426
Filter Min		85%	6.931937218
Filter Max		90%	7.032482624
#Filtered	0	95%	7.157086372



Sensitivity

Rank	Name	Regr	Corr
#1	a.1) Design co	0.420	0.369
#2	d.2) O& M prac	0.398	0.436
#3	b.4) Cracks/fla	0.381	0.373
#4	c.4) Weather c	0.279	0.252
#5	b.1) Age of the	0.275	0.200
#6	b.2) Corrosion	0.254	0.263
#7	c.1) Soil type /	0.236	0.216
#8	a.4) Quality co	0.231	0.215
#9	b.3) Coating/pa	0.224	0.208
#10	d.3) Man. & Op	0.187	0.162
#11	a.3) Size & Ca	0.179	0.174
#12	a.2) Material ty	0.152	0.150
#13	d.4) Control sy	0.145	0.161
#14	d.1) Chemicals	0.143	0.141
#15	c.2) Qualityof s	0.090	0.081
#16	c.3) Seismic ac	0.073	0.096

FigureF.1 Sample Quick Summery Report of Simulation (CRI of ST_CS-1)