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Level of Service Based Methodology for Municipal Infrastructure Management

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Abstract**—**Development of levels of service in municipal context is a flexible vehicle to assist in performing quality-cost trade-off analysis for municipal services. This trade-off depends on the willingness of a community to pay as well as on the condition of the assets. Community perspective of the performance of an asset from service point of view may be quite different from the municipality perspective of the performance of the same asset from condition point of view. This paper presents a three phased level of service based methodology for water mains that consists of :1)development of an Analytical Hierarchy model of level of service 2) development of Fuzzy Weighted Sum model of water main condition index and 3) deriving a Fuzzy logic based function that maps level of service to asset condition index. This mapping will assist asset managers in quantifying condition improvement requirement to meet service goals and to make more informed decisions on interventions and relayed priorities.

Keywords**—**Asset Management, Level of Service, Condition Index, Analytical Hierarchy, Fuzzy Logic.

I. Introduction

THE Canadian "InfraGuide"[1] defines asset management as: "The combination of management, financial, economic, engineering, operational and other practices applied to physical assets with the objective of providing the required level of service in the most cost-effective manner". Best practices for municipal asset management require municipalities/communities to clearly define and state their respective goals that reflect their expectations (e.g. levels of service). Establishment of level of service is a fact-based, rational, transparent, reproducible and systematic process that not only assists in planning, but also in tracking and monitoring assets' performance against those initially set by the communities. Developing levels of service is essential to the rationalization of the asset management decision making process. In a way, levels of service define the terms of reference, set by the community either directly, through public consultation, or indirectly via elected officials, for the quality of services rendered by the municipality [2]. Levels of service are composite indicators, which may vary from one community to another, and account for the social, environmental and economic goals of the community as well as budget constraints. Establishment and achievement of levels of service are therefore important for sustainable development, which has been defined as "meeting the needs of the present generation without compromising the ability of future generations to meet their own needs"[3]. An asset management plan should therefore, identify a financial plan to sustain the assets. This plan must ensure that current users pay a fair share for the service so future users do not have to pay a higher cost for the same level of service. An efficient asset management plan should also minimize life cycle costs for infrastructure assets while maintaining an adequate level of service and an acceptable level of risk. Level of service can, therefore, be considered as an integral part of sustainable municipal asset management which has an upward link with sustainable asset management plan and a downward link with asset condition assessment.

Generally, the risk associated with assets is directly related to the condition and performance of the assets whereas the targets for asset condition and performance are related to the levels of service to be delivered to the public by the authority [4]. Depending on the age and condition the potential for infrastructure failure or reduction in level of service can increase. This risk will arise from the deterioration of assets. Knowing the representative condition and the historic deterioration rates of the various groups of assets is therefore, a prerequisite of asset management decision making. In order to accurately assess the condition of an asset, it needs to be inspected to acquire reliable data on its physical attributes and performance. There are several non-destructive inspection techniques available for water mains to assess their condition, yet none of these is able to exactly inspect the existing pipes, in order to identify and recognize all the distress indicators [5]. In addition, the output interpretation of these techniques has not been interpreted into pipe condition rating [5]. Keeping in view the above discussion, it can be implied that for sustainable asset management , asset managers are not only required to establish levels of service of various assets, expected by the community but are also required to relate that level of service to asset condition. A mapping of level of service to asset condition may assist asset managers in estimating the improvements required in asset condition to meet the expected service bench marks.

This paper presents a methodology to 1) to develop an asset performance based level of service model 2) to develop a distress based asset condition index and 3) to derive a function that maps the output of level of service model to asset condition model. This mapping function will interpret the improvements required in the asset condition necessary to meet the service goals. This map is also expected to assist in establishing priorities in repair/rehabilitation decisions and in the selection of techniques of rehabilitation.

II. Proposed Methodology

The analysis unit adopted in this study is the length between two intersections. This is considered to be adaptable with integrated approaches such as municipal corridor rehabilitation. The overall scope of the paper comprises of the following:

A. Analytical Hierarchy Model of Asset Level of Service

While dealing with level of service (LoS), asset managers should have clear and definite target values of performance measures that define the level of service. Normally these inputs are deterministic and quantitative in nature. Analytical hierarchy process was deemed appropriate to develop the intended LoS model.

B. Fuzzy Weighted Sum Model of Asset Condition

A review of water main condition rating models indicates that, most of the models do not determine pipe condition as a function of performance distress indicators. The model developed by Yan [6], which used fuzzy composite programming (FCP), is the closest to the concern mentioned above. Yet the hierarchy mostly comprised of physical attributes of pipes. To achieve the objective of developing a water main condition index model that is based on performance distresses and deals with the qualitative nature of inspection data (as referred earlier) the method developed by Schumker [7] was used. Using Schumker's relation a fuzzy weighted sum model of water mains condition index is formulated.

C. Mapping of Level of Service to Asset Condition

A fuzzy mapping function based on the algorithm proposed by Dong and Wong [8] is used to calculate the condition index of water mains from the fuzzy weighted sum model. The output calculated by this function is the condition of water main that corresponds to the performance based level of service established above. A hypothetical example is designed to illustrate the proposed methodology, an overview of which is presented in Fig. 1.

III. Data Requirements

Data requirement of the proposed methodology is not extensive. Data relating to asset identification and performance is essentially required. Ranges of values of performance measures corresponding to each level of service and the failure threshold values of each indicator are to be set. Similarly on the agency side, thresholds and the value of the distress indicators are to be set according to agency's approach and standards. The methodology is quite generic in nature as the thresholds and ranges of both the community oriented level of service and agency oriented asset condition may be modified according to the respective criteria.

Pertinent here is to briefly discuss the performance indicators and measures which form the basis of level of service. At its simplest, an indicator is a piece of information that provides insight into what you are trying to measure. In the case of municipal infrastructure, it is the typical data indicating a condition or state of something being measured. Indicators provide useful, relevant information to decision makers at all levels, from the operational to the tactical and up to the strategic level of decision making. The concept is to identify what is to be measured, and then define the necessary indicators. A few examples of performance indicators and the performance measures under them are given here. Operational Indicator: Number of breaks per kilometer of water pipeline, Average time it took to repair the break; Tactical Indicator: Total number of system outages, lost revenue; Strategic Indicator: Percentage of reinvestment compared to value of system, Needs versus budget. The performance measures used in the example problem, along with failure thresholds and ranges corresponding to different levels of service are presented in Table I. The existing and target values of these measures are given in Table II.

IV. AHP Based LoS Model of Water Distribution System

The AHP can assist decision makers in solving complex problems by organizing thoughts, experiences, knowledge, and judgments into a hierarchical framework, and guiding them through a sequence of pair wise comparison judgments [9]. The AHP has been widely used and applied in different fields, including planning and resource allocation, conflict resolutions, and status/ condition forecasting [10]. Others used the AHP to model risk and identify the factors that influence failure on specific portions of petroleum pipelines [11], to evaluate renewal priorities of irrigation assets grouped by types and location within the hydraulic system [12] and to rank the Regional Water Authorities' performance [13]. In this paper the AHP is used to develop the level of service model following the six steps described below:

Step 1: Setting up the Hierarchy

There are two levels of hierarchy: 1) performance indicators which comprise of structural, operational and water quality and 2) the corresponding performance measures defining these indicators (see Table I). The final outcome of this process is the level of service of water main expressed in terms of Service Percentile (scale of 0-100). Increasing number implies increasing level of service.

Step 2: Assigning Priorities and Establish Priority Vector

In this step, decision makers provide pair-wise comparison matrices for main factors as well as for their sub-factors. The AHP methodology is applied to these matrices in order to determine the weight of each measure. The pair-wise comparison matrix for the main indicators of the example problem is mentioned in Table III.

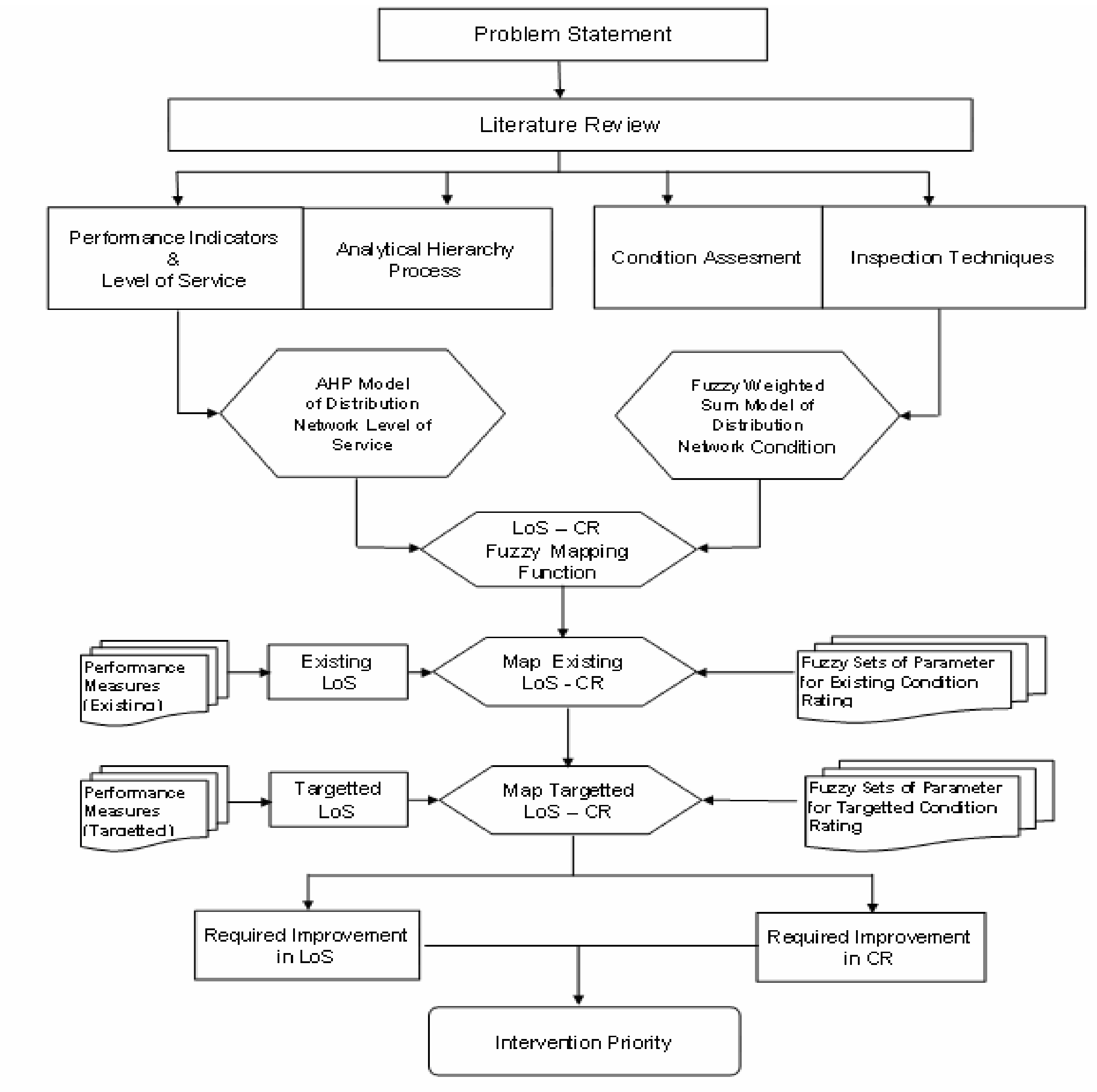

Fig. 1 Research Methodology

TABLE II
EXISTING AND TARGET VALUES OF PERFORMANCE MEASURES

Peformance Measure	Break rate (No./ km /Yr)	No of Leaks (No / km)	Leakage Volume (cum / hr)	Fire Flow (C-Factor)	Loss of Pressure (lbs/ sq.in)	Interruption Frequency (No. / Yr)	Lead (% of Threshold)	Iron (% of Threshold)	Seperation from Sewer (m)
Exising Value	1.5	1.25	0.25	120	10	7	50	55	1.5
Target Value	0	0.51	0.11	140	6	2	5	5	2

TABLE I
RANGES AND THRESHOLDS OF PERFORMANCE MEASURE VALUES FOR DIFFERENT LOS

Performance Indicator	Pefromance Measure	Range of Performance Measure for Different Levels of Service (LoS)					Service Thresholds
		LoS 1	LoS 2	LoS 3	LoS 4	LoS 5	
Structural	Annual Break Rate * (Breaks/km/Yr)	0 - 0 (1.0 - 1.0)	1 - 1 (0.75 - 0.75)	2 - 2 (0.5 - 0.5)	3 - 3 (0.25 - 0.25)	4 - 4 (0 - 0)	4 (0.0)
	Avergae Atribute Effect (AE_{ij})	100	75	50	25	0	
	No of Leaks (No/km) *	0.0 - 0.5 (1.0 - 0.75)	0.51 - 0.75 (0.74 - 0.63)	0.76 - 1.25 (0.625 - 0.38)	1.26 -1.75 (0.375 - 0.125)	1.76 - 2.0 (0.12 - 0.0)	2.0 (0.0)
	Avergae Atribute Effect (AE_{ij})	100	70	50	25	5	
	Leakage Volume (cum/hr) *	0.0 - 0.1 (1.0 - 0.80)	0.11 - 0.2 (0.79 - 0.60)	0.21 - 0.3 (0.59 - 0.40)	0.31 - 0.4 (0.39 - 0.20)	0.41 - 0.50 0.19 - 0.0)	0.5 (0.0)
	Avergae Atribute Effect (AE_{ij})	100	70	50	30	10	
Operational	Fire Flow (C-Factor)	150 - 101 (1.0 - 0.62)	100 - 81 (0.61 - 0.47)	80 - 61 (0.46 - 0.31)	60 - 41 (0.30 - 0.16)	40 - 21 (0.15 - 0.0)	21 (0.0)
	Avergae Atribute Effect (AE_{ij})	100	55	40	25	10	
	Loss in Internal Water Pressure at peak demand (psi) *	0-5 (1.0 - 0.8)	6-10 (0.79 - 0.60)	11-15 (0.59 - 0.4)	16-20 (0.39 - 0.2)	21-25 (0.19 - 0.0)	25 (0.0)
	Avergae Atribute Effect (AE_{ij})	100	70	50	30	10	
	Frequency of Interruption (No/Yr) *	0-3 (1.0 - 0.83)	4-6 (0.82 - 0.67)	7-10 (0.66 - 0.44)	11-14 (0.43 - 0.22)	15-18 (0.21 - 0.0)	18 (0.0)
	Avergae Atribute Effect (AE_{ij})	100	75	55	35	10	
Quality	Lead Concentration (% of threshold) *	0-10 (1.0 - 0.9)	11-25 (0.89 - 0.75)	26-45 (0.74- -0.55)	46-70 (0.54 - 0. 30)	71-100 (0.29 - 0.0)	100 (0.0)
	Avergae Atribute Effect (AE_{ij})	100	80	65	40	15	
	Iron Concentration (% of Threshold) *	0-10 (1.0 - 0.9)	11-25 (0.89 - 0.75)	26-45 (0.74- -0.55)	46-70 (0.54 - 0. 30)	71-100 (0.29 - 0.0)	100 (0.0)
	Avergae Atribute Effect (AE_{ij})	100	80	65	40	15	
	Sepaeration from Sewer (m)	2.25-2.01 (1.0 - 0.81)	2.00-1.76 (0.8 - 0.61)	1.75-1.51 (0.6 - 0.41)	1.5-1.26 (0.4 - 0.21)	1.25-1.0 (0.2 - 0.0)	1.0 (0.0)
	Avergae Atribute Effect (AE_{ij})	100	70	50	30	10	

* -- The normalized values are subtracted from 1 to change the order so that increase in normalized value results in increase in LoS

TABLE III
PAIR-WISE COMPARISON AND PRIORITY VECTORS FOR MAIN INDICATORS

	Structure	Operational	Water Quality	Normalized Vectors Structure	Normalized Vectors Operational	Normalized Vectors Water Quality	Weight Vectors
Structure	1	2	3	0.5454	0.5454	0.5454	$W_s = 0.5454$
Operational	1/2	1	3/2	0.2727	0.2727	0.2727	$W_{op} = 0.2727$
Water Quality	1/3	2/3	1	0.1818	0.1818	0.1818	$W_{wq} = 0.1818$
Column Sum	1.833	3.667	5.5				

Step 3: Consistency Analysis

This step verifies the consistency of pair-wise comparison matrix to check the rationality of the developed weights. If the matrix is consistent, the weights can be accepted. If not, the practitioner should re-review his/her evaluation. The CI and C.R. will be calculated as follows [9], [14] and [15]:

$$CI = \frac{\lambda max - m}{m - 1} \quad (1)$$

$$C.R. = CI / RI \quad (2)$$

where CI = matrix consistency index; m = matrix size; λmax = maximum eigenvalue; and RI = average random index which has a constant value depending on matrix size [14]. (See Table IV)

Step 4: Decomposed Priority Weights

After verifying the consistency of all matrices, priority weights 'Wi' are considered. Then the decomposed weight of each sub-factor will be calculated by multiplying the main factor weight by its sub-factor weight. This decomposed weight will represent the overall weight of that specific sub-factor. Accordingly, priority can be established based on the overall weight using (3) the results of which are shown in Table IV.

Overall sub-factor decomposed wt

$$(SDWij) = W_i * V_{ij} \quad (3)$$

where W_i = weight of factor i and V_{ij} = weight of sub-factor 'j' within the factor 'i'.

Step 5: Attributes Effect AEij.

The decomposed weights represent a generic weight for factors (indicators) and sub-factors (performance measure). However, each measure has range of values corresponding to different levels of services. Therefore, the effect of each performance measure on level of service of water main is considered through the attributes effect term AE_{ij}. Practitioners are required to assign the AE_{ij} for each measure using a scale from 0 to 100 where "0" represents the lowest attribute value and "100" represents the highest attribute value. See Table IV for AE_{ij} values used in this illustrative example

Step 6: Water Main Level of Service Model

The last step in the AHP model is to obtain the overall service percentile value on a scale of 0–100, using (4), which mathematically combines the weights and efficiency rating score for each criterion. A level of service model for water main is shown in (4):

Water main service percentile WMSP =

$$\sum_{i=1}^{n} \sum_{j=1}^{m} (SDWij) * (AEij) \quad (4)$$

Using the above developed WMSP model the existing and targeted service percentiles are determined to be 58.9 and 91.71 respectively.

V. Fuzzy Weighted Sum Water Main Condition Rating Model

The advantages of using linguistic grades for ratings (and weights) in a predominately qualitative engineering evaluation are well documented [16], [17], [18] and [19]. However, it demands an effective method for processing and combining the qualitative information obtained. One such method [7], is to process the information with the following equation:

$$R = \Sigma (R_i \times W_i) / \Sigma W_i \quad (5)$$

where R = the overall rating of the water main condition; R_i, = the rating of the water main condition according to a particular distress measure i; and W_i, = the weight of that distress measure i. Each term in the right-hand side of (5) is a linguistic grade or, simply, a letter grade—A, B, C, D, or E. A rational approach to evaluate (5) is to represent these letter grades with fuzzy sets [20]. Rather than using a single number to represent a letter grade, as is done in the conventional approach, a fuzzy set is used. A fuzzy set is a set of paired numbers that describe the degree of support to each level of distress. For example, in describing the iron concentration, a type of distress measure used in the study, a letter grade of D means that water has high percentage of iron contamination which implies that the water main is in an alarming state of internal corrosion. This letter grade "D" further means that this stress is likely to be in the range from 41% to 65% of the maximum allowable limit (See Table 5). Fuzzy sets can account for uncertainty associated with the quantification of linguistic or letter grade. In other words, these letter grades, when they are used along with the fuzzy sets in a qualitative evaluation, can form a comprehensive rating scale. For simplicity, a linear (triangular) membership function is assumed to illustrate the presented methodology. Although this assumption is deemed to be appropriate in this study and many others [17], [8], more accurate results may or may not be obtained using other membership functions; caution should be exercised when in doubt. When each term in the right-hand side of (5) is substituted by a fuzzy set, the evaluation of the equation involves operations such as fuzzy-set addition, fuzzy-set multiplication, and fuzzy-set division. Definitions of these fuzzy operations, as one might expect, are different from their counterparts in the conventional mathematics [7].

VI. Mapping Levels of Service to Condition Ratings

Classification of the values and weights of distress measures in case of condition rating may be different from the case of level of service. Here, it depends primarily on, how the concerned agency deals with a particular distress measure. Presented at Table V and Table VI, is the other part of the illustrative example in which the minimum and maximum performance values and weights of distress measure are same as the case of level of service but their range in each

TABLE IV
PROCESSING AND RESULTS OF AHP FOR LEVEL OF SERVICE

Factor	Consis-tency	Consis-tency	Main Factor	Sub-Factor	Sub-Factor Decompsed	Attribute Effect Value	Attribute Effect Value	AHP Model of LoS Existing	Target
Main Factors									
Structural			0.5454	-	-	-	-	-	-
Operational	0	0	0.2727	-	-	-	-	-	-
Water Quality			0.1818	-	-	-	-	-	-
Structural Factors									
Annual Break Rate				0.5839	0.3184	63	100	20.06	31.84
No of Leaks	0	0	0.5454	0.1638	0.0894	38	75	3.40	6.71
Leakage Volume				0.2971	0.1620	50	78	8.10	12.64
Operational factors									
Frequency of Interruption				0.5389	0.1469	77	92	11.31	13.51
Loss of Pressure at Peak	0	0	0.2727	0.2971	0.0810	60	76	4.86	6.16
Fire Flow				0.1638	0.0447	61	89	2.73	3.98
Water Quality Factors									
Lead Concentration				0.429	0.0780	50	95	3.90	7.41
Iron Concentration	0	0	0.1818	0.429	0.0780	45	95	3.51	7.41
Seperation from Sewer				0.142	0.0258	40	80	1.03	2.06
						Service Percentile		58.90	91.71

interval of condition index is different. This is due to the expected difference in technical approach of municipal engineer while dealing with condition assessment. Rather than directly implementing previously mentioned operations on fuzzy sets, the ά – cut algorithm developed by Dong and Wong [8] was used in this study. For a detailed explanation of the algorithm, readers may refer to Dong and Wong [8]. The fuzzy sets that represent the letter grades adopted in this study are characterized by their membership functions as shown in Table VII. The main idea is to "defuzzify" each fuzzy set into a group of real intervals before entering into (5), as shown in the Fig. 2. Once this is accomplished, the conventional mathematics takes over, which results in non-fuzzy outputs at these intervals.

The final fuzzy set is reconstructed from this group of non-fuzzy intervals. To achieve a water main condition assessment using the results of the distress observation and fuzzy set analysis, a Unified Water Main Distress Index (UWMDI) is defined. It is based on the final fuzzy set that represents the water main condition, and takes the following form:

$$UWMDI = \frac{A_{left} - A_{right} + 1}{2} \tag{6}$$

where A_{left} and A_{right} are respectively, the areas enclosed to the left and right of the membership function that depicts the final fuzzy set. The defined UWMDI value ranges from 0.0 to 1.0, with 0.0 indicating perfect condition and 1.0 indicating the worst distress condition of water main.

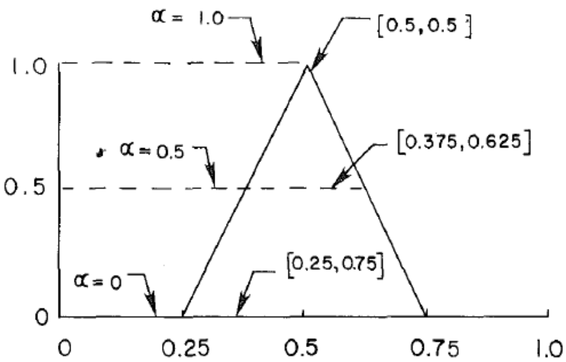

Fig. 2 ά-cut Concept

VII. MAPPING EXISTING & TARGETED LEVELS OF SERVICE TO CORRESPONDING CONDITION RATINGS

A brief explanation of the fuzzy computations of the existing situation at ά = 0 as defined in (5) and the UWMDI defined in (6) is presented. Ratings and weights for distress measures of a water main unit are given in Table VIII. The membership functions that define these input fuzzy sets are given in Table VII. The overall distress condition is first calculated in (5) using these input data. The computation process using the Dong and Wong [8] algorithm is described in the following step-by-step procedure:

TABLE V
THRESHOLDS AND RANGES OF DISTRESS MEASURES IN DIFFERENT CONDITION INDICES

Pefromance Measure	Fuzzy Grade	Normalized Values of Performance Measures in Fuzzy Sets for Condition Rating					Service Thresholds
		A	B	C	D	E	
Annual Break Rate	Description	None	Rare	Occassional	Intermittent	Frequent	
(Breaks/km/Yr)	Value	0	≤ 1	≤ 2	≤ 3	≤ 4	4
Range= (0 - 4)	Normalised Value	0	≤ 0.25	≤ 0.5	≤ .75	≤ 1	(1.0)
No of Leaks	Description	Rare	Very few	Occassional	Often	Frequent	
(No/km)	Value	≤ 0.5	≤ 0.75	≤ 1.0	≤ 1.5	≤ 2.0	2.0
Range= (0 - 2.0)	Normalised Value	≤ 0.25	≤ 0.375	≤ 0.5	≤ 0.75	≤ 1.0	(1.0)
Leakage Volume	Description	Very Slight	Slight	Moderate	Extensive	Severe	
(cum/hr)	Value	≤ 0.1	≤ 0.2	≤ 0.3	≤ 0.4	≤ 0.5	0.5
Range= (0 - 0.5)	Normalised Value	≤ 0.2	≤ 0.4	≤ 0.6	≤ 0.8	≤ 1.0	(1.0)
Fire Flow (C-Factor)	Description	Very High	High	Moderate	Low	Very Low	
Range= (150 - 21)	Value	≥ 121	≥ 96	≥ 71	≥ 46	≥ 21	21
	Normalised Value *	≤ 0.22	≤ 0.42	≤ 0.61	≤ 0.81	≤ 1.0	(1.0)
Loss in Internal Water	Description	Very Low	Low	Moderate	High	Very High	
Pressure at peak	Value	≤ 3	≤ 7	≤ 12	≤ 18	≤ 25	25
demand	Normalised Value	≤ 0.12	≤ 0.28	≤ 0.48	≤ 0.72	≤ 1.0	(1.0)
Frequency of	Description	Very Low	Low	Moderate	High	Very High	
Interruption (No/Yr)	Value	≤ 2	≤ 5	≤ 9	≤ 13	≤ 18	18
Range= (0 - 18)	Normalised Value	≤ 0.11	≤ 0.28	≤ 0.55	≤ 0.72	≤ 1.0	(1.0)
Lead Concentration	Description	Very Low	Low	Moderate	High	Very High	
(% of threshold)	Value	≤ 10	≤ 20	≤ 40	≤ 65	≤ 100	100
Range= (0 - 100)	Normalised Value	≤ 0.1	≤ 0.2	≤ 0.4	≤ 0.65	≤ 1.0	(1.0)
Iron Concentration (%	Description	Very Low	Low	Moderate	High	Very High	
of Threshold)	Value	≤ 10	≤ 20	≤ 40	≤ 65	≤ 100	100
Range= (0 - 100)	Normalised Value	≤ 0.1	≤ 0.2	≤ 0.4	≤ 0.65	≤ 1.0	(1.0)
Seperation from	Description	Vey Large	Large	Adequate	Small	Very Small	
Sewer (m)	Value	≥1.95	≥ 1.7	≥ 1.45	≥ 1.20	≥ 1.0	1.0
Range= (2.25 - 1.0)	Normalised Value *	≤ 0.24	≤ 0.44	≤ 0.64	≤ 0.84	≤ 1.0	1.0

(*-- A value of 1.0 is subtracted from the normalized value to change the order so that decrease in normalized value result in lower number of Condition Rating)

1. Select a group of ά-values needed for defuzzifying a fuzzy set. In most cases, use of 11 ά -values from 0.0 to 1.0 with an increment of 0.1 to defuzzify a fuzzy set is accurate enough. In this example, for simplicity, only three a values (0.0, 0.5, and 1.0) are used.

2. For ά = 0.0, obtain the ά-cut interval for each of the input fuzzy sets. According to the membership functions defined in Table (7), the following ά-cut intervals can be obtained for the given input fuzzy sets (see Fig. 2, for ά-cut concept):
I_{R1}, I_{R3}, I_{R5}, I_{R6} and I_{R9} = Fuzzy Grade/Set "C" = (0.3,0.7); I_{R2}, I_{R7}, and I_{R8} = Fuzzy Grade/Set "D" = (0.5,0.9); I_{R4} = Fuzzy Grade/Set "B" = (0.1,0.5).
Similarly for weights: I_{W1}, = Fuzzy Grade/Set "A" = (0.0,0.2); I_{W2} = Fuzzy Grade/Set "E" = (0.8,1.0); I_{W3}, I_{W6} and I_{W7} = Fuzzy Grade/Set "B" = (0.1,0.5); I_{W4}, I_{W5} and I_{W8} = Fuzzy Grade/Set "C" = (0.3,0.7) and I_{W9} = Fuzzy Grade/Set "D" = (0.5,0.9).

3. Calculate 'R' using (5), with ά -cut intervals (for ά = 0.0, 0.5 and 1.0) This step is essentially to perform an interval computation [8]. Illustration calculation for ά-cut = 0 is given as an example.

(0.30, 0.70) x (0.00, 0.20) + (0.50, 0.90) x (0.80, 1.00)+
(0.30, 0.70) x (0.10, 0.50) + (0.10, 0.50) x (0.30, 0.70)+
(0.30, 0.70) x (0.30, 0.70) + (0.30, 0.70) x (0.10, 0.50)+
(0.50, 0.90) x (0.10, 0.50) + (0.50, 0.90) x (0.30, 0.70)+
(0.30, 0.70) x (0.50 0.90)

(0.00, 0.20) + (0.80, 1.00) + (0.10, 0.50) + (0.30, 0.70)+
(0.30, 0.70) + (0.10, 0.50) + (0.10, 0.50) + (0.30, 0.70)+ (0.50 0.90)

R (ά = 0) = (0.376, 0.753)

4. Repeat steps 2 and 3 for a ά = 0.0, = 0.50 and 1.0. This step results in R(ά = 0.5) = (0.46, 0.67) and R(ά =1.0) = (0.56, 0.56).

5. The selected values and the calculated intervals as a whole represent the resulting fuzzy set as shown in Fig. 3.

TABLE VI
LINGUISTIC GRADES FOR WEIGHTS

Grade	Description	Performance Measure
A	Extremely Important	Break Rate
B	Very Important	Leakage Volume Frequency of Interruption Lead Concentration
C	Important	Fire Flow Loss of Pressure Iron Concentration
D	Moderately Important	Seperation from Sewer
E	Relatively Unimportant	No of Leaks

TABLE VII
FUZZY SETS OF LINGUISTIC GRADES

Fuzzy Grade	Membership Function	
A	f (y) = 5(y)	0 ≤ y ≤ 0.2
B	f (y) = 5 (y - 0.1)	0.1 ≤ y ≤ 0.3
	f (y) = 5 (0.5 - y)	0.3 ≤ y ≤ 0.5
C	f (y) = 5(y - 0.3)	0.3 ≤ y ≤ 0.5
	f (y) = 5 (0.7 - y)	0.5 ≤ y ≤ 0.7
D	f (y) = 5(y - 0.5)	0.5 ≤ y ≤ 0.7
	f (y) = 5 (0.9 - y)	0.7 ≤ y ≤ 0.9
E	f (y) = 5(y - 0.8)	0.8 ≤ y ≤ 1.0

The UWMDI value calculated using (6), is 0.56. Similarly the UWMDI corresponding to performance measure values of the target service percentile of 91.71, (in this illustrative example), is calculated to be 0.842.

In order to develop the relation between the level of service and corresponding condition index, a set of condition index values corresponding to level of service are calculated, using the developed AHP and Fuzzy Logic models, as discussed earlier. Depending upon the particular set of community set of community preferences towards service goals and agency interpretation of performance distress to asset condition, assumed in this example, the function as shown in Fig. 4 has the following form:

$$y = 0.861x + .5286 \tag{7}$$

where; y = Condition index on a scale of 0-10, x = Service percentile on a scale of 0-100

TABLE VIII
DISTRESS MEASURE VALUES, WEIGHTS & FUZZY SETS FOR EXISTING & TARGET CONDITION

Performance Measure		Existing Scenario			Targetted Scenario		
		Actual	Normalised	Fuzzy Grade	Actual	Normalised	Fuzzy Grade
Break Rate	Value	1.5	0.38	C	0	1	A
	Weight	-	-	A	-	-	A
No of Leaks	Value	1.25	0.63	D	0.51	0.26	B
	Weight	-	-	E	-	-	E
Leakage Volume	Value	0.25	0.5	C	0.11	0.22	B
	Weight	-	-	B	-	-	B
Fire Flow	Value	120	0.23	B	140	0.08	A
	Weight	-	-	C	-	-	C
Lossof Pressure at Peak	Value	10	0.4	C	6	0.24	B
	Weight	-	-	C	-	-	C
Frequency of Interruption	Value	7	0.39	C	2	0.11	A
	Weight	-	-	B	-	-	B
Lead Concentration	Value	50	0.5	D	5	0.05	A
	Weight	-	-	B	-	-	B
Iron Concentration	Value	55	0.55	D	5	0.05	A
	Weight	-	-	C	-	-	C
Seperation from Sewer	Value	1.5	0.6	C	2	0.2	A
	Weight	-	-	D	-	-	D

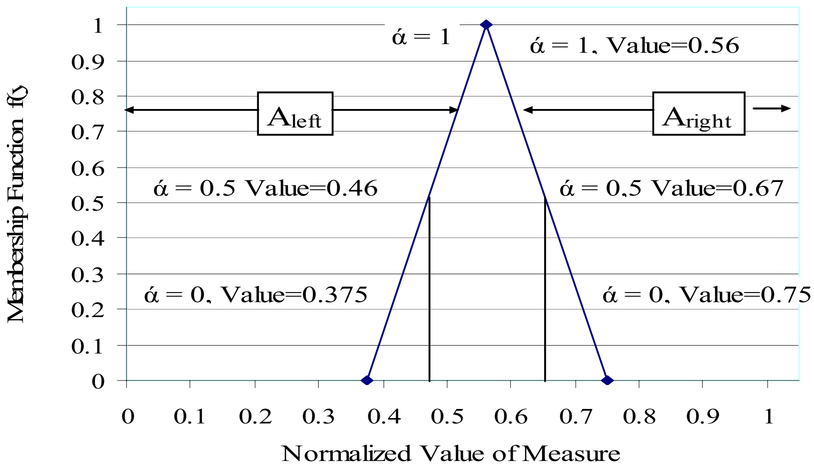

Fig. 3 Calculation of Unified Water Main Distress Index

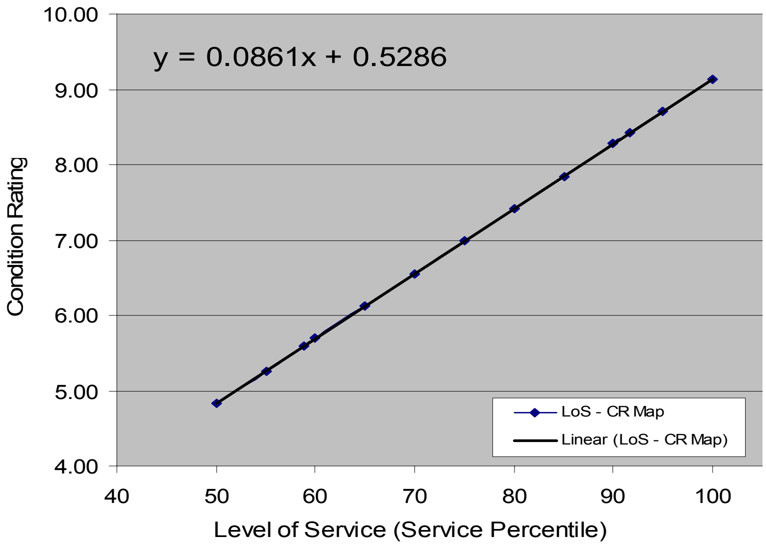

Fig. 4 Level of Service to Condition Index Mapping Function for Water Mains

VIII. Summary and Conclusion

Level of service is an integral part of sustainable municipal asset management which has an upward link with sustainable asset management plan and a downward link with asset condition assessment. In this perspective, a three-phase methodology is proposed to relate level of service targets to asset condition ratings. Operational level performance indicators relating to water distribution mains are identified and based on those indicators, an illustrative example is designed to explain the proposed methodology. A performance measure based, AHP model of level of service of water mains is developed. The output of this model is the level of service, expressed in service percentile. A performance distress based, Fuzzy Weighted Sum model of water main condition index is developed. Further, a mathematical relation is derived, using Fuzzy ά-cut algorithm, which relates the outputs of the two models. It should be noted that such a relationship is not fixed. It is community and agency specific and may change from one asset to another. As such, the proposed methodology is quite generic and can be easily modified to suit a wide range of preference levels.

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