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Asset Management of Stormwater System using Fuzzy Logic

A. Kannapiran[1], J. Jeyakumaran[1], A. Chanan[2], J. Kandasamy[1], G. Singh[2], P. Tambosis[2] and A. Al-Jumaily[1]
[1]Faculty of Engineering, University of Technology Sydney, Australia
[2]Assets and Services, Kogarah Council, Sydney, Australia

Abstract—**Management of urban water cycle in an integrated manner is an essential task to protect, restore and enhance in a sustainable manner. Strategic asset management planning is being developed as local government authorities face many challenges associated with managing the urban water cycle system. Statistical or conventional mathematical modelling approach is not practical for the assessment of deteriorating infrastructures. Alternatively, the application of fuzzy logic-based models was found to be more suitable as it is able to exploit the availability of engineering judgement, experience and scarce field data of deteriorating assets. In this study, a network of buried stormwater system's data was analysed and a pipe condition index was derived by linking the field data and reasoning using the fuzzy approach. The pipe condition indices of a representative network were compared with the asset condition derived from a CCTV inspection. The trends of the result are found to be very useful in guiding asset management decisions.**

Keywords- asset management; condition assessment; fuzzy based modelling; infrastrucutre assets; linguistic information.

I. INTRODUCTION

Public infrastructure assets like roads, drainage and underground structures, parks and other essential services in Australia are predominantly maintained by local government councils. Stormwater assets comprise many components that collectively form an urban drainage collection and disposal system. The basic design requirement of a stormwater network is to disposal of the stormwater as quickly as possible. While current Council environmental and drainage regulations now require a more sustainable approach to stormwater, most of stormwater assets and services remain unimproved. The other challenges of managing this infrastructure are, increasing demand in services, shrinking financial resources, and increasing deterioration. Inevitably natural deterioration of stormwater assets occurs due to usage, environmental and climatic conditions. In particular the factors contributing to the deterioration in performance include operational conditions, design parameters, external traffic loads, internal loads from operating pressures, temperature changes, loss of bedding support, pipe properties and pipe conditions.

A well planned, operated and maintained stormwater system should drain stormwater runoff effectively during normal periods and during floods. However in rapidly expanding cities, unanticipated issues arising from changes in land usage, system over-loading, pollution and other environment related problems contribute to the failure of stormwater assets. These issues are more prominent in larger and older cities where replacement cost is very high. Significant part of Council's stormwater assets was constructed back in 1930's and it anticipates many challenges as it manages the urban water cycle system in an integrated manner to protect, restore and enhance the assets.

The Council's vast drainage data is available through an extensive Geographic Information System (GIS). Though some of the data are available in numerical form, most of the vital data still exists in subjective and unrelated form. Information in subjective form is not favourable for a systematic engineering assessment. The uncertainty and ambiguity in the data have been addressed through optimization methods such as statistical programming, probability bound analysis and soft computing methods. These approaches assimilate the data in to a meaningful form otherwise available in disparate form.

There are number of real world asset management applications associated with sewer, and water distribution networks are available, however only a very few information is available for stormwater related applications [1, 2]. The fuzzy based approach is one of the soft computing methods was used to assess stormwater systems. This method is based on describing imprecise information and interpreting concepts defined by linguistic expressions, into a mathematical model [3]. This methodology is proven to be more powerful when used in conjunction with engineering judgement and experience [4, 5]. This paper explains the asset management principles, introduces a rule based fuzzy approach, and applies this technique to a representative stormwater network. The findings show that the application of fuzzy based modelling technique provides a more pragmatic tool for the Council's asset management process. The current approach on the asset management of the Council's stormwater infrastructure can equally be applicable to other similar assets.

II. ASSET MANAGEMENT AND ITS RELEVANCE

The main streams in asset management are the identification of the components of the asset, and the service of the asset including ongoing operation and maintenance. In addition, asset management incorporates elements for facilitating the delivery of community benefits such as comfort, mobility, economic development and social justice. The following sections discuss the current issues of Kogarah Council's stormwater assets and the applicability of a fuzzy logic-based modelling approach. A case study of a representative stormwater network is also presented.

Current issues with the Kogarah Council

The Kogarah Council was established in 1885 and is bound by a railway line, highways and the Georges River. The current population of about 50,000 lives in an area of about 20 square km. Kogarah Council owns a significant part of infrastructure assets and the majority of assets are old and nearing the end of its projected life. The Council's stormwater network in Sydney includes pipes, pits, retention basins and open channels. The 100 km stormwater network has about 2400 stormwater pits mostly constructed of concrete and the others are made of clay, PVC and terracotta. Stormwater ultimately drains into bays, creeks and rivers comprising the 18 kilometers of river foreshore, adding to the pollution that river already carry. The average age of the Kogarah's stormwater system is over 60 years and it is anticipating higher costs for maintaining the assets. The traditional approach of "replacing a pipe with a pipe" is no longer necessarily a feasible management option.

The Council is recognized as one of the leaders in local government with asset management process. One of Council's principle aims is to help in planning the replacement of this old infrastructure to meet future service demands. The Council's asset management team has identified four key strategies to assist in managing their assets: Research customer expectations, development of asset decision support, development of new asset management techniques and investigation of multi-agency approach. The Council is exploring new assessment methods and best management strategies for redeveloping its aging stormwater network. In particular, the Council has taken following major steps to achieve the objectives:

- A better understanding of the community needs, and the ability to correlate the stakeholders' aspirations with a quality of sustained service.
- Development of predictive tools for cost effective maintenance standards.
- Development of deterioration models for changes in land usage, traffic load and environment.
- Development of tools that predict the remaining service life of major components.

III. RULE BASED FUZZY MODEL

The original concept of linguistic fuzzy models imitating the human way of thinking was elaborated by Zadeh [6] in his pioneering works. Based on this concept, Mamdani and Sugeno [7] developed a fuzzy model utilizing human expert knowledge. Fuzzy logic is a methodology for computing with linguistic expressions rather than numbers and effectively employs modes of reasoning that are approximate rather than exact. The centre stage of most fuzzy logic is the if-then rules or fuzzy rules which act as a mechanism for dealing with fuzzy inputs or antecedents and fuzzy consequents [8-10].

The advantages of using fuzzy logic are that they are simple, flexible, and tolerant of imprecise data. It can be built on top of the experience of engineering experts, blended with conventional control techniques and modelling complex nonlinear functions. The structure of fuzzy logic system employed is shown in Fig. 1. Details of the fuzzy based model developed for Kogarah stormwater system is provided in Kannapiran et al. [11].

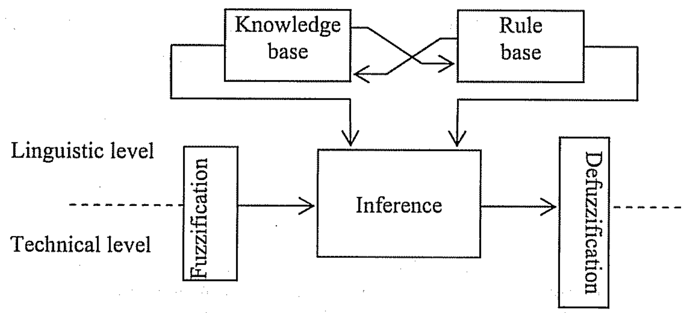

Figure 1. Structure of fuzzy system

A case-study

Fig. 2 shows the Kogarah Council's buried stormwater network and inter-connected pipes which traverses the city's residential area, business and park areas, roadways and other facilities. The configuration of the networks is complex, widespread in areal reach and yet interconnected in a cluster of segments.

In this study, data available from the entire stormwater network was incorporated when establishing a fuzzy based model for assessing conditional status. The initial investigation focused on a representative stormwater network shown in Fig. 3. Pipe inspections and condition assessment of this network were carried out by the Council. These pipe deterioration data were compared with the pipe indices derived from the fuzzy based model.

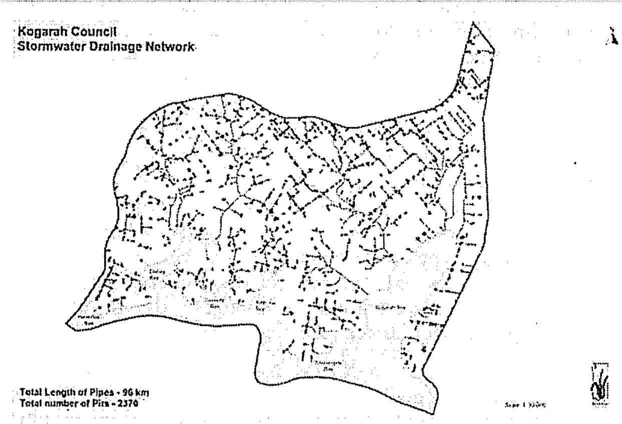

Figure 2. Network of the entire Council

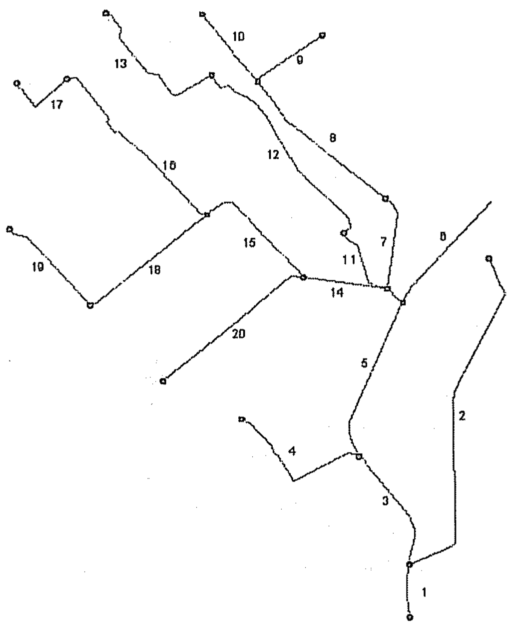

Figure 3. Representative stormwater network

Variables for the fuzzy model

There are large number of physical and environmental factors that directly and indirectly effect the performance of a stormwater pipes. The factors contributing to the deterioration in performance include operational conditions, design parameters, traffic loads, internal loads from operating and surge pressures, temperature changes, loss of bedding support, pipe properties and pipe condition [12]. In general, it is very difficult to ascertain the exact cause of failure of stormwater pipe as they are not regularly inspected for condition assessment. However, information of asset parameters such as age, material, grade, depth, hydraulic capacity, and location are available through electronic database systems and are very useful for pipe condition assessment.

In our investigation, the principal parameters used to influence the deterioration are pipe age, pipe diameter, traffic conditions, maintenance level and the land usage. The pipe length and pipe material are not considered since these were assumed to be influenced indirectly by the pipe diameter and environmental factors. The majority of the pipe diameters vary between 300 and 475 mm while the maximum pipe diameter is 2400 mm. the age of the pipes vary between 50 and 70 years. As the first step, for the each numbered pipe of the representative network in Fig. 3, the parameters are expressed in linguistic form as shown in Table 1. The linguistic indicators in each variable are decoded into fuzzy numbers. The decoded fuzzy numbers and the degree of memberships are derived from engineering judgement and experience of Council's staff and maintenance personnel.

TABLE 1. VARIABLES AND ITS LINGUISTIC INDICATORS

No	Variable	Linguistic indicators
1	Pipe age	Brand new, new, young, medium, old, very old, too old
2	Pipe diameter	Very small, small, medium, large
3	Traffic load	Low, moderate, high
4	Maintenance	Low, medium, high
5	Land usage	Low, medium, high

This is a better way of representing subjective factors as it has the ability to handle the uncertainty involved in expert's assessments. The condition assessment of infrastructure distress by different experts is subjective and there is an element of uncertainty concerning the true value of the severity levels [13]. This difference of opinion is incorporated in fuzzy based model where each distress variable is presented as widely as possible in the membership function instead of a discrete value. The degree of membership is represented subjectively by a continuous function between 0 and 1. Small values represent a low degree and high values represent a high degree of membership.

Logical operations and fuzzy rules

Evaluation of sensitive information requires the knowledge of the operational behaviour of the network. The simplest way to extract knowledge is from queries formed out of rules. The uncertainty connected to rules of fuzzy system is processed by fuzzy inference tool. In modelling the fuzzy system, the knowledge base consists of fuzzy sets and the definition of rules that define relationships between variables.

The system behaviour is defined by the rules that form the basis to obtain fuzzy output. The rule based system uses linguistic variables as its antecedents and consequents given by IF the antecedent, THEN the consequent. The relationships between variables in the if-then rules assume the following general form:

If an *antecedent* proposition **then** a *consequent* proposition (1)

In a system having two inputs (x_1 and x_2) and one output (y), the general rule of a linguistic of Mamdani fuzzy model is given by:

If (x_1 is *small*) **AND** (x_2 is *medium*) **THEN** (y is *large*) (2)

where, *small* and *medium* are fuzzy sets. The logical connectives determine the qualitative relationship between the input and output states by joining fragments of a rule to get a final inference. The logical connectives used are AND, OR and NOT operations. To process information in a real system, any number of well-defined methods can fill in for the logical connectives. The accuracy of a fuzzy model depends on the number, shape and parameters of membership function and the logical connectives used [14]. In order to preserve the results of logical connectives, appropriate operators are to be identified and also it must be extendable to all real numbers between 0 and 1. The AND, OR and NOT operators are used in the majority of fuzzy logic applications:

$$\left.\begin{array}{ll} \text{AND} & : \mu_{a \wedge b} = \min\{\mu_a, \mu_b\} \\ \text{OR} & : \mu_{a \vee b} = \max\{\mu_a, \mu_b\} \\ \text{NOT} & : \mu_{\neg a} = 1 - \mu_a \end{array}\right\} \quad (3)$$

where μ_a and μ_b are membership functions of variables a and b respectively.

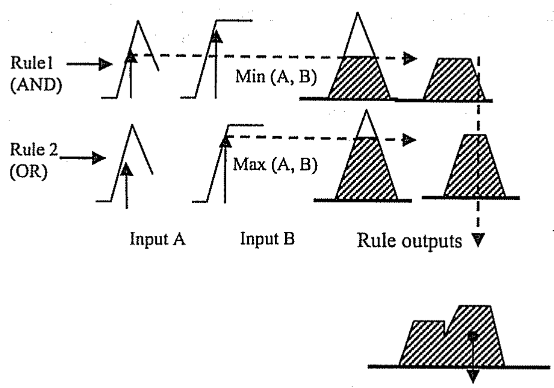

Figure 4. Fuzzy inference mod

The fuzzy operation is applied for a given rule to obtain one number that represents the result of the antecedent for that rule. This number is then applied to the output function. Fig. 4 illustrate the fuzzy logic operations of AND and OR respectively. The input for this implication process is a single number and the output is a fuzzy set. The implication process is implemented for each rule. Fig. 4 demonstrates for a two rule, two input variables with one output variable for each rule. Results from each output are aggregated to evaluate the degree of sensitivity of the whole problem.

The fuzzy model developed for the representative stormwater network of Kogarah was built out of 24 rules. The rules are framed by taking no more than two input parameters for any one rule because of lack of in-depth knowledge between system parameters.

Table 2 shows the combination of variables that have been combined for the rules. Appropriate indicators were chosen for representing each parameters (e.g., *very small, small, medium* and *large* were chosen for pipe diameter). No special node-by-node analysis of inference was attempted, however all the relevant data, expert knowledge and engineering judgement were included in the model. The rules are applied in a holistic manner collectively to the representative network. The applied rules are presented in Table 3 with nomenclature. As may be noticed, each rule contains no more than two parameters. The rule 1 for example can be read as

If (Age is *Brand New*) **AND** (Diameter is *very small*)
THEN (condition index is *Excellent*) (4)

TABLE 2. COMBINATIONS OF STRATEGIC VARIABLES

Combination	Pipe Age	Pipe Diameter	Traffic	Maintenance	Land use
1	√	√	-	-	-
2	√	-	-	√	-
3	-	√	√	-	-
4	-	√	-	-	√
5	-	-	√	-	√

TABLE 3. COMBINATION OF PARAMETERS IN THE RULE

Rule no.	Age	Dia-meter	Mainte-nance	Land use	Traffic	Condition index
1	BN	VS	-	-	-	E
2	M	M	-	-	-	G
3	O	L	-	-	-	VB
4	BN	L	-	-	-	E
5	O	VS	-	-	-	B
6	BN	-	L	-	-	VG
7	M	-	M	-	-	G
8	O	-	L	-	-	B
9	O	-	H	-	-	B
10	-	VS	-	H	-	VB
11	-	S	-	L	-	B
12	-	M	-	M	-	B
13	-	L	-	H	-	VB
14	-	-	-	L	L	VG
15	-	-	-	L	M	G
16	-	-	-	L	H	G
17	-	-	-	M	L	G
18	-	-	-	H	H	VB
19	-	-	-	M	H	B
20	-	VS	-	-	H	B
21	-	M	-	-	H	B
22	-	L	-	-	H	VB
23	-	L	-	-	L	G
24	-	VS	-	-	L	VG

BN- Brand new; M- Medium: O- Old; VS= Very small; L= Large/ Low; H= High; VB= Very bad; B= Bad; G= Good; VG= Very good; E= Excellent

Evaluation of condition index

The objective of the condition evaluation is to identify the condition index for the pipe system using the components of the fuzzy model shown in Fig. 5. The condition index is expressed through an index scale of 1-100, the lowest value corresponds to worst condition and the highest value refers to an ideal or excellent condition. An example of the definition of fuzzy sets for condition index is shown in Fig. 6. The output indicators *very bad, bad, good, very good* and *excellent* are assigned subjectively. This is a yardstick parameter to assess the condition status of the entire representative network.

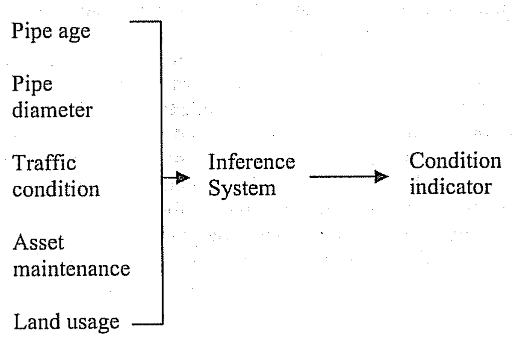

Figure 5. Components of the fuzzy system

The fuzzy logic operation gives the degree of support for each rule, and this is assigned to shape the output in the implication process. The shape of the output function is mostly a complicated profile as the calculations are accomplished by rule base, inference mechanics and membership function. This output process gives one fuzzy set for each output variable. The final decisions are made based on applying of all the rules in the fuzzy inference engine. The resulting list of changed output functions are combined into a single aggregated fuzzy set. This is pre-processing operation that is required before defuzzifying the aggregated result.

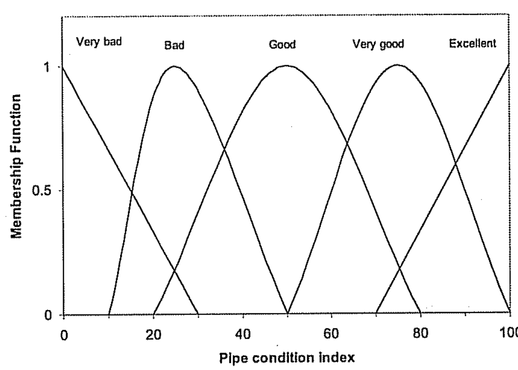

Figure 6. Fuzzy sets of the output for condition index values

The defuzzification converts the model output to a standard crisp signal, which is the condition index for the current asset condition. There are numerous types of defuzzifications such as centre of gravity, centre-of-sums, first-of-maxima, middle-of maxima and mean-of-maxima [7, 15] with each one of which has advantages and disadvantages. The criteria that should be considered in choosing a defuzzification scheme are plausibility, computational simplicity and continuity [16]. The plausibility scheme represents the crisp value in the centre or that lies in a high degree of membership of the fuzzy set. In this study, the centre of gravity method, a method which has been widely adopted, is used. This has the advantage of producing smoothly varying output.

IV. CONDITION ASSESSMENT RESULTS

Results of pipe condition indices derived from the fuzzy logic analysis are shown in Fig. 7. The results presented here are for the age of the pipe, when the diameter, traffic, maintenance and land use parameters are at its mid values. The prediction of the age index shows the expected trend, however the actual interpretation of the values must be used with caution. Referring to Fig. 7, the pipe condition is clearly declining with age, initially very slowly from the current year of 50 years and then rapidly after 20 years. The index value for the current year is about 53. The current condition of the infrastructure is usually known, and hence the index value of future years gives an indication of the asset condition in the future. The relative variation with pipe age may be used for comparison purpose only and should not to be used as an absolute indicator. Similar results and trends for other parameters such as pipe diameter, levels of maintenance, traffic condition and land usage can be derived.

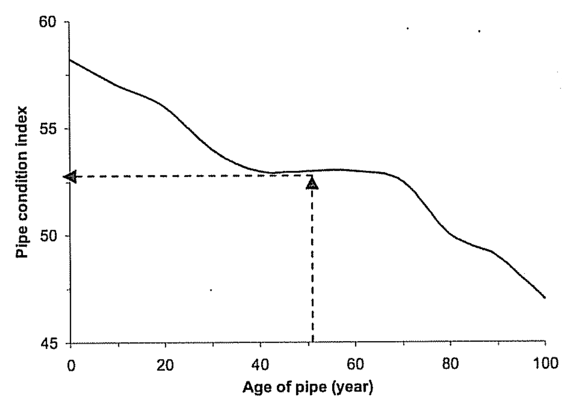

Figure 7. Pipe index for age

Comparison of fuzzy data with visual inspection

Complex problems of this nature modelled through fuzzy rule-based system are actually not easily validated in the traditional sense [1]. The pipe condition index derived upon composite variables like age, diameter and other variables are not amenable to a characteristic property that can be measured and compared. However, the relative comparison of poor and good asset condition can be observed in the result presented. For example, a poor asset condition is observed with poor maintenance and intense land use while a good asset condition results from a pipe that has had good maintenance and light land usage. In this regard an attempt was made to compare the fuzzy prediction with the visually assessed data.

A CCTV (Closed Circuit Television) inspection was carried out for 45 pipes in a portion of a catchment in Kogarah including the representative network shown in Fig. 3. Based on the CCTV inspection, the pipes were rated as *very bad, bad, good, very good* and *excellent* corresponding to pipe indices of 20, 40, 60, 80 and 100. The predicted values from the fuzzy model were compared with the CCTV ratings. The results are given in Fig. 8 with an error band of one standard deviation on either side of average predicted values. It is noted that none of the CCTV inspected pipes are rated as failure (20) or excellent (100).

The results show a reasonable correlation to the fuzzy model. It is important to note that the CCTV ratings are assessed at discrete points whereas the fuzzy based model provides a condition assessment that is continuous with pipe indices between 0 and 100. In particular, the CCTV ratings are assessed at points 20 indices apart. This implies that the difference between the results of the fuzzy-based model and the CCTV ratings can, in part, be explained by the discontinuous nature of the ratings in comparison with that provided by the fuzzy based model. However if there is perfect agreement between the CCTV ratings and fuzzy based model indices then the average value of the latter should all lie on the dotted line in Fig. 8. The degree of departure of the average values from this line is indicative of the degree to which there is lack of agreement.

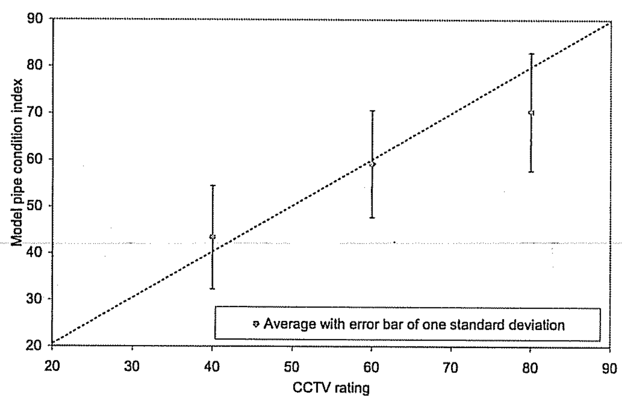

Figure 8. Correlation between model pipe index and CCTV pipe rating

The correlation could be improved by modelling a more detailed description of the asset condition by incorporating other physical, environmental and land usage parameters to the fuzzy model. In addition, combining various interacting variables in the rule making process will improve the accuracy of the fuzzy model. It is important to incorporate within these rules as much relevant knowledge, evidences, engineering judgement and experience. These are areas of further investigation.

V. SUMMARY AND CONCLUSION

Application of sound management principles to infrastructure assets management is essential. The problems of objective assessment are that infrastructure has complex inter-related physical dependencies, inevitable deterioration over time, and absence of reliable data that allows for a statistical or conventional mathematical modelling. To overcome this fuzzy logic was applied. With this approach various factors that affect the performance are identified and assessed to yield current and emerging future situations. The fundamental principles involved with the rule based fuzzy logic technique are presented with the focus on its application to stormwater pipe systems. The existing database of the Council provided favourable linguistic descriptions of the assets and they are converted into appropriate numerical form. Through a case study, the characteristics of the most influential physical parameters of a network are considered and the over all condition of the network was assessed. The pipe condition indices of a representative network of 45 pipe elements were compared with the asset condition derived from a CCTV inspection. The trends of the result are found to be very useful in guiding asset management decisions. The modelling procedure, although applied to a stormwater system, has the potential to be applied to other similar infrastructures.

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REFERENCES

[1] Cobiac, L. and K. Jansons, *A fuzzy method of assessing sustainablilty in stormwater planning*. Water intellingence online, 2005. 4(May).

[2] Kleiner, Y., R. Sadiq, and B. Rajani, *Modelling the deterioration of buried infrastructure as a fuzzy Markov process*. Journal of Water Supply Research and Technology-Aqua, 2006. **55**(2): p. 67-80.

[3] Revelli, R. and L. Ridolfi, *Fuzzy Approach for Analysis of Pipe Networks*. Journal of Hydraulic Engineering, 2002. **128**(1): p. 93-101.

[4] Homayoun, N., S. Rehan, and R. Balvant. *Modeling pipe deterioration using soil properties - An application of fuzzy logic expert system*. 2004: ASCE.

[5] Kleiner, Y., B.B. Rajani, and R. Sadiq. *Management of failure risk in large-diameter buried pipes using fuzzy-based techniques*. in *4th International Conference on Decision Making in Urban and Civil Engineering*. 2004. Porto, Portugal.

[6] Zadeh, L.A., *Fuzzy logic, neural networks, and soft computing*. Communications of the ACM, 1994. **37**(3): p. 77-84.

[7] Abonyi, J., *Fuzzy model identification for control*. 2002, Birkhauser: Boston.

[8] Adriaenssens, V., et al., *Fuzzy rule-based models for decision support in ecosystem management*. Science of the Total Environment, 2004. **319**(1-3): p. 1-12.

[9] Tesfamariam, S. and B. Rajani, *Impact of uncertainties on the translation of remaining pipe wall thickness to structural capacity*, in *INFRA 2004 Urban Infrastructure: Managing the Assets, Mastering the Technology*. 2004, National research council, Canada: Montreal, Quebec. p. 1-16.

[10] Yan, J.M., K. Vairavamoorthy, and S.D. Gorantiwar, *Contaminant Transport Model for Unsaturated Soil Using Fuzzy Approach*. Journal of Environmental Engineering, 2006. **132**(11): p. 1489-1497.

[11] Kannapiran, A., et al., *An innovative model for sustainable cost effective management of stormwater drainage assets*. Water Asset Management International, 2007. 3(2): p. 4-11.

[12] Davies, J.P., et al., *Factors influencing the structural deterioration and collapse of rigid sewer pipes.* Urban Water, 2001. 3(1-2): p. 73-89.

[13] Fwa, T.F. and R. Shanmugam. *Fuzzy logic technique for pavement condition rating and maintenance-needs assessment.* in *Proceedings 4th Int.Conf.on Managing Pavements.* 1998. Durban, South Africa.

[14] Piegat, A., *Fuzzy modeling and control / Andrzej Piegat.* 2001, Heidelberg ; New York :: Physica-Verlag.

[15] Bandara, N. and M. Gunaratne, *Current and future pavement maintenance prioritization based on rapid visual condition evaluation.* Journal of Transportation Engineering, 2001. **127**(2): p. 116-123.

[16] Wang, L.-X., *A course in fuzzy systems and control.* 1997, Prentice Hall: Upper Saddle River, N.J.