Development of a Performance Index for Stormwater Pipe Infrastructure using Fuzzy Inference Method

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ABSTRACT

Stormwater pipe infrastructure collects and conveys surface runoff resulting from rainfall or snowmelt to nearby streams. Traditionally, stormwater pipe systems were integrated with wastewater infrastructure through a combined sewer system. Many of these systems are being separated due to the impact of environmental laws and regulations; and the same factors have led to the creation of stormwater utilities. However, in the current ASCE Infrastructure Report Card, stormwater infrastructure is considered a sub-category of wastewater infrastructure. Stormwater infrastructure has always lacked attention compared to water and wastewater infrastructure. However, this notion has begun to shift, as aging stormwater pipes coupled with changes in climatic patterns and urban landscapes makes stormwater infrastructure more complex to manage. These changes and lack of needed maintenance has resulted in increased rates of deterioration and capacity. Stormwater utility managers have limited resources and funds to manage their pipe system. To effectively make decisions on allocating limited resources and funds, a utility should be able to understand and assess the performance of its pipe system. There is no standard rating system or comprehensive list of performance parameters for stormwater pipe infrastructure. Previous research has identified performance parameters affecting stormwater pipes and developed a performance index using a weighted factor method. However, the weighted performance index model does not capture interdependencies between performance parameters. This research developed a comprehensive list of parameters affecting stormwater pipe performance. This research also developed a performance index using fuzzy inference method to capture interdependencies among parameters. The performance index was evaluated and validated with the pipe ratings provided by one stormwater utility to document its effectiveness in real world conditions.

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GENERAL AUDIENCE ABSTRACT

Stormwater pipe infrastructure collects and conveys the surface water resulting from rainfall or snowmelt to nearby streams. Traditionally, stormwater pipe system was integrated with wastewater infrastructure by combined sewer system. Environmental regulations forced creation of stormwater utilities and separate stormwater system, however, according to ASCE infrastructure report, stormwater infrastructure has been considered a sub-category of wastewater infrastructure. Stormwater infrastructure has always lacked attention compared to water and wastewater infrastructure. However, this notion has to shift, as aging stormwater pipes coupled with changes in climatic patterns and urban landscapes makes stormwater infrastructure complex to manage resulting in increased rate of deterioration and design capacity. Stormwater utility managers have limited resources and funds to manage their pipe system. To effectively make decisions on allocating limited resources and funds, a utility should be able to understand and assess the performance of its pipe system. There is no standard rating system for assessing the condition of stormwater pipe infrastructure. This research developed an index using fuzzy inference method to capture the interdependencies. Fuzzy inference method basically captures the interdependencies between parameters using if-then rule statements. Parameters are individual elements affecting the performance of stormwater pipes. The performance index was evaluated and validated with the pipe ratings provided by one stormwater utility to document its effectiveness in real world conditions.

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Abbreviations

ASCE - American Society of Civil Engineers
ASTM - American Society for Testing and Materials
CCTV - Closed-circuit television
CIP - Capital Improvement Plan
CMP - Corrugated Metal Pipes
Fps - Feet per second
GIS - Geographic Information System
HDPE - High-density polyethylene
NASSCO - National Association of Sewer Service Companies
NNM - Neural Network Model
O&M - Operation & Maintenance
PACP - Pipeline Assessment and Certification Program
PVC - Polyvinyl chloride
RCP - Reinforced Concrete Pipe
SVM - Support Vector Machines
USEPA - U.S. Environmental Protection Agency
USGS - U.S. Geological Survey
UV - Ultra-violet
WRC - Water Resource Commission

Chapter 1

Introduction

Infrastructure investments have a major influence over a nation's economy and quality of life (US General Accounting Office 2000). According to the 2017 ASCE infrastructure report card, investment required to upgrade and build the water, wastewater and stormwater infrastructure system of the U.S. falls short by $105 billion (ASCE 2017). Traditional or gray stormwater infrastructure consists of engineered structures that are designed to collect and convey stormwater (Lampe et al. 2005). These engineered systems consist of pipes, inlets, outlets, open channels and chambers, but predominantly consist of pipes. Similar to other infrastructure systems, the deterioration of stormwater pipes can be gradual or abrupt depending on the physical, operational and environmental parameters influencing it. Stormwater infrastructure in the U.S. is aging as evident by several pipe failures and sinkhole creation reported by national news media (Allison Sundel 2017); (Burgess 2016); (CBS8 2010); (Cripe 2016); (Blom 2016). As a result, stormwater utilities across the country are facing challenges on allocating the necessary funding to maintain and upgrade their pipe network. The emergence of the green infrastructure concept, using land as a natural drainage system, has been well received. Though the adoption and implementation of green infrastructure concepts will not solely solve stormwater pipe infrastructure issues, it will reduce the burden on the existing gray infrastructure. The performance of these assets and their interdependencies will influence the performance of the system as a whole.

Traditionally, stormwater pipe systems were integrated with wastewater infrastructure using a combined sewer system. Environmental regulations forced creation of stormwater utilities and separate stormwater systems, however, according to the ASCE Infrastructure Report Card, stormwater infrastructure is currently considered a sub-category of wastewater infrastructure (ASCE 2017). While stormwater utilities have adopted the asset management practices and approaches followed by wastewater utilities, there remains no standardized system to manage the stormwater pipe assets in the U.S. (Betz 2013).

Assessing the performance of the existing stormwater infrastructure will provide utilities with a better understanding of their network and will aid them in prioritizing their funding based on asset criticality. Existing condition rating systems like NASSCO's PACP and WRC were initially developed for wastewater systems. Bhimanadhuni and Sinha (2015) performed a substantial research work on identifying the performance parameters affecting stormwater pipes and developed a performance index specifically for stormwater pipes. Bhimanadhuni and Sinha (2015) used a weighted factor method to develop the index; however, it lacked interdependencies between parameters. The objective of this research is to update and enhance the list of stormwater pipe performance parameters identified by previous research and develop a new performance index capturing interdependencies between parameters.

Chapter 2

Stormwater Pipe Infrastructure – Components, Pipe Materials and Failure Characteristics

2.1 Components of Stormwater Pipe Infrastructure

Similar to other water and wastewater pipeline infrastructure systems, stormwater pipe infrastructure system is comprised of linear engineered structures (i.e. stormwater pipes) and appurtenant structures (i.e. inlets, outlets and manholes). These linear and appurtenant structures collectively form a stormwater pipe infrastructure system. This section will list and address various components of a stormwater pipe infrastructure system.

2.1.1 Stormwater Pipe

Stormwater pipes serve as a backbone of a stormwater system. Stormwater pipes convey the runoff from the source to outfall. These are linear engineered structures designed based on design storm intensity and duration. Frequent inspection and cleaning of debris will help resolve structural integrity and maintenance issues. Minimum flow velocity of 3 fps should be maintained to reduce sediment accumulation (Drainage Manual 2000)

2.1.2 Manholes

Manholes provide access to the stormwater pipes, to perform maintenance and inspection activities. They are placed at locations were two or more stormwater pipes join or where a change in alignment or where a change in pipe size is observed (Drainage Manual 2000). Precast Manholes, cast-in-situ, and masonry manholes are the most commonly available types.

2.1.3 Inlet

Stormwater Inlets are designed to capture runoff and act as an entry to the stormwater conveyance system. Stormwater inlets can prevent debris, trash, and sediments from entering the stormwater system (Morgan et al. 2005). There are three major inlet types available to collect runoff:

- Grate Inlets: Grates are attached to the inlets to remove debris.
- Curb-Opening Inlets: Vertical openings allowing runoff and debris to pass through.
- Combination Inlets: Provision of grate and curb openings.

2.1.4 Outlets

Outlets are designed to discharge stormwater into a natural water body or a detention pond. Stormwater pipe outlets are typically protected with pavement, riprap, and headwalls to reduce erosion or scour at the discharge point.

2.2 Stormwater Pipe Materials & Failure Characteristics

Knowledge of available stormwater pipe materials and understanding their failure mechanisms assists in understanding the deterioration process. Stormwater pipes are available in varying sizes and materials generally consist of concrete, corrugated metal and plastic pipes. Other pipe materials include brick and vitrified clay; however, utilities have stopped adopting them in practice because of cost and poor performance (Betz 2013). Therefore, this section will only discuss concrete, corrugated metal and plastic pipes.

2.2.1 Concrete Pipes

Concrete pipes are suitable for stormwater application and available in varying sizes, shapes, strengths and pressure classes. These pipes are less susceptible to corrosion compared with metal pipes, but discrepancies in concrete mix design can cause severe deterioration due to external loading and environmental factors. Concrete pipes can be classified into non-reinforced and reinforced concrete pipes. According to American Concrete Pipe Association (ACPA) and (Beieler et al. 2013), the design life of concrete pipes is estimated to be 100 years.

2.2.1.1 Failure Factors

Concrete pipes deteriorate due to chemical attacks, frost penetration, carbonation, overloading, abrasion and ground settlements. Concrete pipes are subjected to constant freezing and thawing cycles over their lifetime causing initiation of micro cracks and leading to serviceability issues and structural damage (Li et al. 2005). Corrosion in reinforcement steel results in rust, which occupies more space than the reinforcement steel causing spalling, cracks and delamination (Portland Cement Association 2002). Dynamic traffic loading and static earth loads can lead to fatigue causing cracks and collapses (Meis et al. 2003). The invert of the entire concrete pipe is vulnerable to abrasion, as stormwater carries debris and solid particles that erode the pipe (Skipworth et al. 1999). Settlement or ground movement can cause vertical misalignment in a concrete pipe leading to faulting and sagging, the presence of stagnant water makes the pipe susceptible to corrosion. Finally, groundwater pressure and soil expansion may result in invert heaving (Indiana DOT 2014).

2.2.2 Corrugated Metal Pipes

Corrugated metal pipes are available in steel and aluminium. For several decades, stormwater utilities have used corrugated metal pipes. Corrugated metal pipes are manufactured using steel or aluminium plates with a continuous seam (Zhao et al. 1998). The structural stability of these pipes is dependent on the soil/pipe interaction. Well compacted structural fill around these pipes can increase its buckling resistance up to 7 times (Tenbusch 2009). Corrugated steel pipes are galvanized, aluminized or bituminous coated to resist corrosion. The design service life of corrugated metal pipes is expected to exceed 75 years (Ault 2003).

2.2.2.1 Failure Factors

Corrugated metal pipes (CMP) are prone to corrosion based on factors such as soil pH, soil resistivity, acidic runoff, non-homogenous backfill and de-icing of road salts (Wenzlick and Albarran-Garcia 2008). Delamination of polymer coated corrugated metal pipes can be caused by UV rays. Defection at joints and seams result due to overload and poor backfill (Tenbusch 2009). Joint separation can cause exfiltration of stormwater or infiltration of soil leading to undermining of the surrounding soil. Abrasion of CMPs via solid particles washed by surface water is also an issue. Flow velocity and the size of the particles are some factors which influence the degree of abrasion.

2.2.3 Plastic Pipes

Plastic pipes possess better abrasion resistance compared to metal pipes. Unlike reinforced concrete pipes and corrugated metal pipes, corrosion does not take place in plastic pipes. Polyvinyl Chloride (PVC) and High-Density Polyethylene (HDPE) are two major plastic pipes adopted for stormwater applications. PVC pipes are manufactured with the PVC resin conforming to the ASTM standards. HDPE pipes are made by polymerization of ethylene and can vary in properties based on the method of polymerization. The design service life of plastic pipes is expected to exceed 100 years (Plastic Pipe Institute).

2.2.3.1 Failure Factors

Plastic pipes placed under poor backfill and heavy loading are susceptible to deflection causing cracks and crushing. The common mode of failure of a polyethylene pipe is a slow propagation of a brittle crack through pipe wall (McGarry et al. 1985). Mechanical and chemical stresses acting together can cause failure in plastic pipes, this process is called environmental stress cracking (Ezrin 1996). An impact of excavation equipment during adjacent utility construction may lead to rapid stress propagation resulting in an accidental pipe damage (O'Connor 2011). Shallow ground cover may lead to holes and broken sections due to excessive load on the pipe (Sinha et al. 2008).

Chapter 3

Literature Review

Assessing and comprehending the present condition of stormwater pipe assets will enhance the ability of stormwater utility managers to make informed decisions on capital investments. Stormwater pipe materials deteriorate due to several factors and at different rates. Understanding these factors and measuring them will be crucial in determining the performance of a pipe. Data collection from pipe inventories, records, observations, and inspections are essential for evaluating the state of stormwater pipe assets. Currently, no standardized methods exists for assessing the condition of stormwater pipes in the U.S. (Betz 2013). Pipe rating systems are classified into condition and performance based rating systems. The pipe rating systems applicable for stormwater pipe infrastructure system are listed in Figure 3-1.

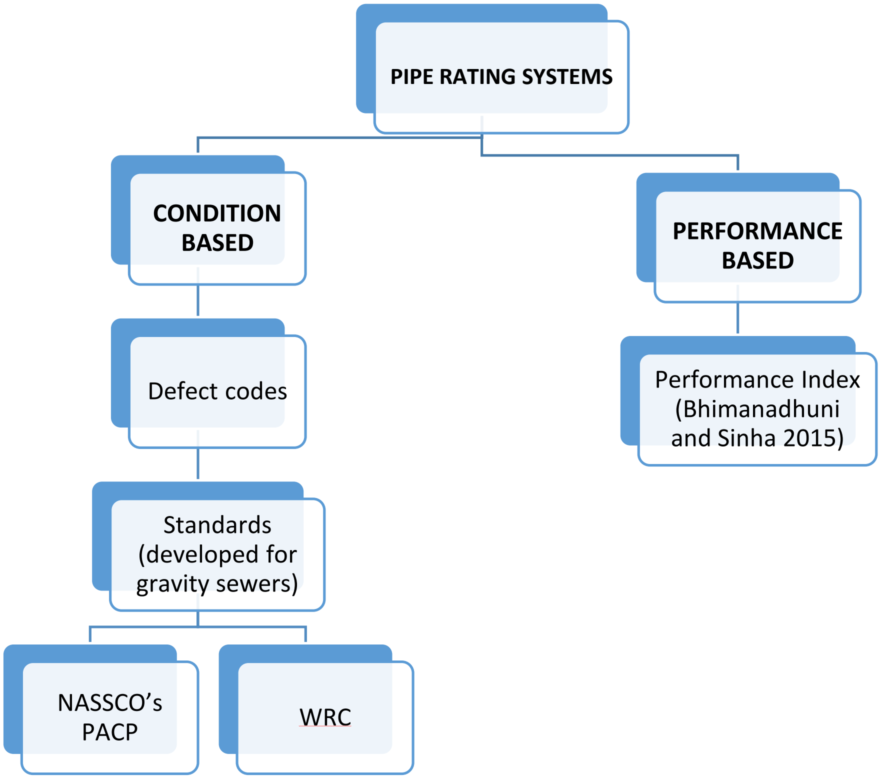


Figure 3-1: Pipe Rating Systems

3.1 Condition Assessment Methodologies

The structural integrity of buried pipelines depends on many factors including the overall geometry of the pipe, the material properties of the pipe, the material properties of the soil-pipe structure interface, and the magnitude and distribution of the earth loads transmitted to the pipe structure (Moore et al. 1985).

Based on the literature, the process to assess the condition of a stormwater water pipes can be summarized in the following steps.

1. Determine the failure factors and parameters influencing stormwater pipes.
2. Inspection of stormwater pipes to assess their condition.
3. Rate the defects observed based on its severity.
4. Determine the overall condition of each stormwater pipe.

3.1.1 NASSCO's PACP Rating

The National Association of Sewer Service Companies' (NASSCO) Pipeline Assessment and Certification Program (PACP) is a standardized system developed to evaluate the condition of wastewater gravity collection systems using CCTV inspection data (Koo and Ariaratnam 2006). This rating system was developed based on the U.K.'s Water Resource Commission (WRC) rating system (Gemora 2003). PACP is a defect rating system; pipes scores are based on the severity and frequency of visual defects (Whittle et al. 2011). PACP rating system relies on the internal condition of a pipe, external factors such as soil conditions, loading conditions, pipe depth and material are not considered for developing the pipe scores (Islam et al. 2009). Many stormwater utilities follow NASSCO's PACP to assess the condition of their stormwater collection system (Betz 2013). The defect coding system is classified into five groups based on the defects and features; continuous defects, structural defects, operational and maintenance, construction features, and miscellaneous features (Strauch and Wetzel 2006).

Continuous Defect Coding: Continuous defect coding is classified into two categories; "truly" and "repeated." A truly continuous defect runs along the pipe without any interruption for more than a meter (For example, longitudinal fractures and cracks observed along the length of a pipe). Repeated continuous defect occurs at a regular interval along the pipe (For instance, root intrusion observed at sequential joints) (NASSCO 2001).

Structural Defect Coding: Structural defect coding is classified into several categories based on the structural integrity of the pipes. Table 3-1 lists the various pipe defects classified under the structural defect category (NASSCO 2001).

Table 3-1: Structural Defects – NASSCO PACP

Defects	Symbol	Description
Cracks	C	Visible break line on the surface of the pipe, pipe still intact
fractures	F	Advanced stage of a crack, portions of the pipe are noticeably open
Broken	B	Displacement of a portion of pipe from its original position
Hole	H	Missing pipe portions, exposing soil envelope
Deformed	D	Up to 40% Distortion of pipe wall cross section of rigid pipes
Collapse	X	More than 40% Distortion of pipe wall cross sectional area
Joint	J	Anomalies or displacement at pipe joint (Defects: Offset, Angular and Separated)
Surface Damage	S	Degradation of pipe interior wall due to erosion, chemical attack and abrasion
Buckling	K	Deformation in flexible pipes without loss of visible structural integrity
Lining Failure	LF	Defects observed on a lined pipe (buckling, blistering, overcut etc.)
Weld Failure	WF	Defects observed at the welded joints
Point Repair	RP	Observed point repairs
Brickwork	BW	Defects observed in brickwork

Operational and Maintenance Defect Coding: Defects that pose a threat to operation and maintenance of pipes are categorized into O&M Codes. Table 3-2 lists the various pipe defects classified under the O&M defect category (NASSCO 2001).

Table 3-2: O&M Defects – NASSCO PACP

Defects	Symbol	Description
Deposits	DS/DA/DN	Deposits leads to blockages and causes reduction in pipe capacity
Roots	R	Root intrusions causing hindrance to hydraulic flow (Fine, Tap, Medium and Ball)
Infiltration	I	Infiltration of groundwater into the pipe
Obstacles	OB	Obstructions such as construction debris, pipe material debris and others
Vermin	V	Presence of vermin or other animals
Grout	G	Recording grouting and sealing operations.

Construction Features Coding: Codes indicating construction features are observed in or around a pipe, such as intruding seal material (IS) and tap (T). Table 3-3 lists the various pipe defects classified under the construction features category (NASSCO 2001).

Table 3-3: Construction Features – NASSCO PACP

Defects	Symbol	Description
Tap	T	Records the condition of service connection to the mainline
Intruding Sealing	IS	Presence of intrusions caused by the sealing material (hanging, burst and loose)
Line	L	Variation in sewer line direction
Access Points	A	Access and exit points of the CCTV cameras

Miscellaneous Features Coding: This category represents the defect subtypes to define the nature of a defect type further. (NASSCO 2001).

PACP condition grading system uses a 1-5 scale to determine the severity of the pipe defects based on the defect classification (Whittle et al. 2011). First, defect codes are assigned based on the type and criticality. Following that, separate condition grade scores are assigned to the structural and O&M defects based on the number of occurrences. This results in an individual segment score for structural and O&M respectively. The pipe score is then calculated by aggregating all the defects occurring in a pipe segment (Bhimanadhuni 2015). Table 3-4 shows the PACP grading scale and its description.

Table 3-4: Condition Grading Scale – NASSCO PACP

(Sinha, S., and Angkasuwansiri, T. (2010). "Phase 2: Development of a robust wastewater pipe performance index." Development of protocols and methods for predicting the remaining economic life of wastewater pipe infrastructure assets. Report No. 06-SAM-1 CO, Water Environment Research Foundation, Alexandria, VA. Used with permission of Carrie W. Capuco, JD, Water Environment Research Foundation.)

Grade	Grade Description	Grade Definition
1	Excellent	Minor defects
2	Good	Defects that have not begun to deteriorate
3	Fair	Moderate defects that will continue to deteriorate
4	Poor	Severe defects that will become Grade 5 in the foreseeable future
5	Immediate Attention	Defects requiring immediate attention

NASSCO's PACP "Quick Score" rate the pipes based on defect severity and frequency of highest and second highest defect, the resultant score is a 4-digit alphanumeric (Opila 2011). For instance, if the resultant quick score is 4A3B, the first and third digit represent the highest and second highest defect score, the second and fourth digit represents the frequency of occurrence of the highest and second highest defect. This quick summary enables utility to prioritize renewal decisions.

3.1.2 Water Research Center (WRC) Sewer Rehabilitation Manual

The WRC manual has been in the industry since 1978 and has undergone several revisions until the recent version in 2004. Though this condition rating scheme was developed for wastewater gravity lines, it can be modified to cater stormwater pipes. This manual consists of two volumes;

- Volume 1 - discusses the failure mechanisms of sewers, surveying techniques, and maintenance planning.
- Volume 2 – addresses sewers renovation and design methods for renovations.

Additionally, the 2001 version addresses new practices in automatic rating systems, environmental factors, operations and maintenance. These practices are aligned with the European defect rating systems.

Data from visual inspection technologies (i.e. CCTV) are utilized as an input for gauging the condition of pipes. The scale of 1 to 165 is adopted by the WRC condition rating system to rate the pipes based on the structural and operational defects. Following that, condition grades will be assigned on a scale of 1 to 5, it is recommended to use maximum defect value to determine the condition grade.

3.1.3 Comparison of NASSCO's PACP and WRC

- Compared to the WRC rating system, NASSCO's PACP captures detailed information on classification, descriptors and modifiers for each defect (Khazraeializadeh 2012).
- Table 3-5 compares the structural deduct values used for NASSCO's PACP and WRC. Both rating systems assign maximum value to a collapsed pipe and minimum value to a newly installed pipe.

Table 3-5: Structural Deduct Values – NASSCO PACP vs WRC

Rating System	NASSCO PACP	WRC
Deduct values	1-5	1-165

- WRC rating system uses the peak score of all deduct values to assign the overall condition grade of a pipe. In contrast, NASSCO's PACP, uses a weighted average method based on the frequency of occurrence of defect scores in a pipe (Khazraeializadeh et al. 2014).

3.1.4 Performance Index for Stormwater Pipeline Infrastructure

Bhimanadhuni and Sinha (2015) developed a performance index model specifically for stormwater pipes. Parameters influencing the deterioration of stormwater pipes were identified and categorized into five modules; capacity, blockage, load, surface wear and structural; as shown in Figure 3-2. The categorization was based on survey replies from 10 stormwater utility experts across the nation. This index uses a weighted factor method to assign a rating to a performance parameter.

Each parameter is rated on a scale of one to five, where one implies "Excellent" and five implies "Very poor" (Bhimanadhuni and Sinha 2015). These parameter scores are combined into an overall performance index. Though this index is one of its kind, it has some limitations. The weighted factor method utilized to develop this index considers each parameter and module as independent and lacks the capability to capture the interdependencies between the parameters and modules. Capturing the interdependencies between the performance parameters and modules is necessary to model actual scenarios. Certain critical parameters accelerate deterioration significantly, when coupled with each other. The model was piloted on a stormwater utility data, it performed well and the utility manager validated the results and expressed that they matched his heuristic expectations (Bhimanadhuni and Sinha 2015).

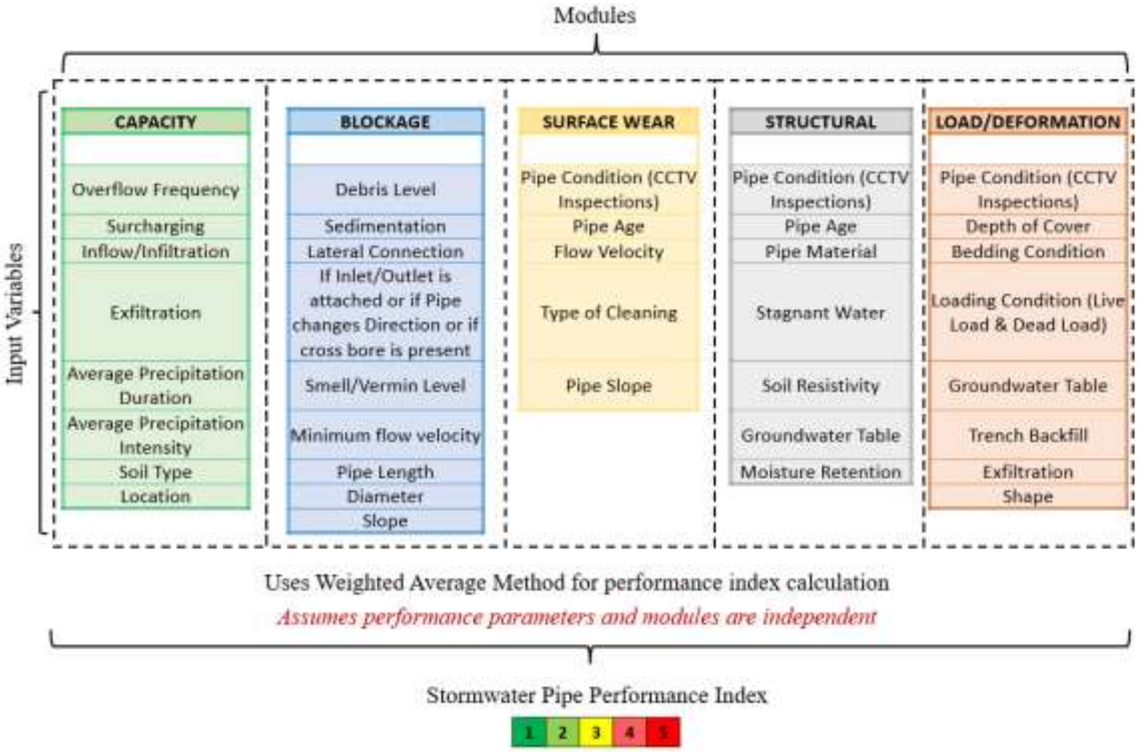


Figure 3-2: Stormwater Performance Parameters and Modules (Bhimanadhuni and Sinha 2015)

3.2 Literature Review Summary

The condition of a pipe can be categorized based on the severity of damage. Rating systems are based on two criteria; condition and performance. Most ratings are condition based, and they evaluate the pipe condition based on the defects observed during the visual inspection. Standard condition rating systems identified through literature were NASSCO's PACP and WRC. A numerical value is assigned according to the severity of the damage, and a cumulative rating score is developed. NASSCO's PACP rates the assets on a scale of (1-5), and WRC utilizes a structural scoring scale of 1 -165. Performance-based rating systems were also identified for stormwater pipes, which evaluates physical, operational, environmental and financial parameters to develop an individual performance index for each module: pipe integrity, internal and external environment. Further, these individual indices can be combined to produce an overall performance index. Performance-based indices are robust and complement the prediction modeling processes.

Chapter 4

Practice Review

This research identified stormwater utilities practicing the condition rating systems introduced in the literature review. Stormwater utilities across the U.S. were contacted to collect data on the condition rating system each adopted. Collected information on utility practices is compiled in this section.

4.1 NASSCO's PACP

The City of Chesapeake, the City of Austin and the City of Virginia Beach adopted NASSCO's PACP. However, each utility differs on the extent to which the PACP rating system is implemented. The City of Chesapeake uses only the NASSCO's PACP "Quick score" to rate its stormwater pipe system. The City of Austin applies both NASSCO's PACP "Quick score" and Overall Rating to assess the condition of its stormwater pipes. Finally, the City of Virginia Beach modified the NASSCO's PACP to incorporate utility specific criteria.

4.1.1. City of Chesapeake, Virginia - NASSCO's PACP "Quick Score"

The City of Chesapeake, VA stormwater division had to oblige USEPA's mandate to protect the Chesapeake Bay from stormwater pollutants like nitrogen, phosphorous and sediment.

The city's stormwater pipe systems have a length of 1200 miles, 30% of their stormwater system is tidally influenced. The city performs condition assessment using CCTV inspection and grades its pipes based on NASSCO's PACP Quick Score. NASSCO's PACP "Quick Score" scores the pipes based on defect severity and frequency of highest and second highest defect, the resultant score is a 4-digit alphanumeric. For instance, if the resultant quick score is 4A3B, the first and third digit represent the highest and second highest defect score, the second and fourth digit represents the frequency of occurrence of the highest and second highest defect. Table 4-1 shows the scoring scale for each resultant quick score.

Table 4-1: NASSCO's PACP Quick Score

Score	1ST Digit	2nd Digit	3rd Digit	4th Digit
Scoring Scale	1-5	A,B,C, etc. (frequency ranges)	1-5	A,B,C, etc. (frequency ranges)

The city inspects and assesses the condition of storm pipes to prioritize and determine resource needs. It also supports to match "renewal" need with available funding. It helps in coordinating with the City's CIP and implementation schedule.

4.1.2 City of Austin, Texas – NASSCO's PACP

The City of Austin, Texas inspects their stormwater assets using CCTV. The City follows the industry standard; NASSCO's PACP to rate the condition of its stormwater pipes. As discussed in the previous chapter, NASSCO's PACP rating system rates the pipes based on their structural, operational and overall condition. Each pipe gets individual scores for the structural and O&M conditions as well as an overall defect score. These scores are assigned based on the severity of the defect identified during the inspection process.

The City utilizes both the "Quick Score" and "Overall Rating" to assess each pipe segment. The generated rating is incorporated in the utility's GIS database, to make renewal decisions and plan for capital investments.

4.1.3 Virginia Beach, Virginia – Modified NASSCO's PACP

The City of Virginia Beach, Stormwater Division looks to prevent cave-ins and increase asset life of its stormwater infrastructure. Therefore, the city utilized NASSCO's PACP rating system to assess the condition of their pipelines based on the defects identified. Since NASSCO's PACP was initially developed for wastewater pipe condition assessment, the city sought a modified PACP approach by including stormwater specific criteria to achieve its goal: preventing cave-ins and increasing asset life.

As discussed earlier, since NASSCO's PACP was developed for wastewater infrastructure, failure factors specific to stormwater infrastructure were absent. Therefore, before modifying the NASSCO's PACP and developing a new methodology, the City identified failure factors specific to stormwater infrastructure. These included: infiltration of soil/water at the joint, deflected and gasket-less joints, lifting holes, pipe-structure connection, and tidal influence.

The City developed supplemental above ground defect coding to improve the PACP approach, where the field inspector categorizes the deformities observed above the ground. Modifiers are then applied based on the observed above ground settlements, cracks and holes affecting pavements. These above ground defects indicate the soil envelope around the pipe surrounding is yielding, leading to a potential cave-in. In addition to the supplemental defect coding, reclassification of some defects from O&M defects to structural defect category were also performed. The city also intended to prioritize their assets to make pipe rehabilitation and replacement decisions. Risk assessment was performed for each pipe based on traffic loading, geographical location, pipe size, and material, to assess the consequence of failure. The overall condition of a pipe is determined by combining the PACP defect scores, supplemental scores (modified defects and above ground defects) and the risk scores.

4.2 Water Resource Commission (WRC) Condition Rating System

The Water Resource Commission (WRC) condition rating system was developed for assessing the state of wastewater pipes. The City of San Diego modified this rating according to their pipe criteria. Section 4.2.1 will describe the modified WRC rating system tailored for stormwater pipes.

4.2.1 City of San Diego – Modified WRC Rating System

The City of San Diego follows a modified WRC Rating System. They categorize the observations as general codes, pipe codes, joint codes and service codes. These observations were then rated on their severity based on the structural and maintenance points. Cameras are used to assess the interior pipe wall. An inspection engineer reviews the video files and codes the defects based on its severity. At the end of the assessment, the pipe will have a structural score and a maintenance score. Pipes are also given one of the following recommendations: Replace, Rehab, Maintain, or No Action.

- General Codes – This category comprises of observations related to pipe inspection details, camera submerge level, navigation and initial exploration of the pipe.
- Pipe Codes - This category list the pipe observations related to structural and operational defects (cracks, deformation, corrosion, collapsed pipe, debris, infiltration, and root intrusion).
- Joint Codes – Observations on joint defects are captured in this category.
- Service Connections – Defects hindering service are captured in this category (Intrusion of lateral, broken pipe connections, and root intrusion).

Remaining life analysis is performed based on expected life of the material used for the pipe. Corrugated metal, reinforced concrete and plastic pipes make up the majority of the City's storm drain system. For the most part, the City replaces the deteriorated pipe with a new pipe. They rarely line a pipe as a rehab option to extend the life of an existing pipe.

4.4 In-House Developed Condition Rating Systems

Some stormwater utilities developed their own condition rating system. These systems are usually simple and capture utility specific factors only. This section presents two condition rating system developed by City of Shawnee, Kansas and King County, Washington.

4.4.1 City of Shawnee, Kansas – Condition Rating System

The City of Shawnee, Kansas uses an in-house developed rating. The City categorizes the condition of stormwater pipes into "excellent", "Fair", "Repair" and "Replace", and it uses the physical condition of a pipe to gauge its rating. Table 4-2 shows the physical condition rating system used by the city.

Table 4-2: City of Shawnee – Physical Condition Rating System

Condition Rating	Condition Description
Excellent	No cracks, no defects, no corrosion
Fair	Minor defects/cracking, joint damage, deterioration
Repair	Pipe patching needed soon, monitor pipe for further deterioration
Replace	Pipe deformation/ major cracks/ major corrosion

The functional condition of a stormwater pipe is evaluated based on its capability to meet its service requirements, ability to indicate loss of capacity, potential for blockage and water tightness. Table 4-3 shows the functional condition rating system used by the city.

Table 4-3: City of Shawnee – Functional Condition Rating System

Condition Rating	Condition Description
No Obstructions (1)	Pipe is clear from any debris/ flow is uninterrupted
Minor Obstructions (2)	Small amount, minor effect on flow of water
Major obstruction or debris (3)	Large amount, major effect on flow of water

The construction condition of a stormwater pipe is evaluated based on the features relating to the construction of the stormwater pipe; pipe connections & bedding. Table 4-4 shows the construction condition rating system used by the city.

Table 4-4: City of Shawnee – Construction Condition Rating System

Condition Rating	Condition Description
Excellent Condition (1)	Pipe connections are strong/joints secure
Fair (2)	Connection to structure is cracked/crumbling
Poor (3)	Connection to structure is very weak/ blocked/deformed

4.4.2 King County, Washington – Condition Rating System

King county uses a condition rating system with a scale of 1-5; similar to NASSCO's PACP. This condition rating system is used to rate the structural condition of their storm drainage system. Assets are rated on structural integrity and ability to perform their functions. Maintenance needs are not considered when evaluating structural conditions.

Each pipe is rated based on the condition indicators mentioned below:

Condition Indicators:

- Pitting/Rusting – Small pits are visible on the surface of the pipe; if metal, has rust but still solid.
- Spalling/Flaking – Flat chips of concrete are lost from feature's surface; if metal there are flakes of rust.
- Cracks – Visible crack.

  - Longitudinal: A crack running in the direction of the weld axis. May be found in the weld or base metal.
  - Circumferential: A crack running around the diameter of the pipe.
- Hole – Hole goes completely through the asset’s material or missing mortar.
- Joints Separated – Joints between two pipe sections are separated (lengthwise), may allow soil to filter through.
- Max Joint Separation – Estimate or measure the largest separation between pipe sections (interior of pipe).
- Separated Apron – Identify if pipe has a separated apron.
- Misalignment – the pipe sections’ alignment is offset, causing a zigzag appearance.
- Deformation – Pipe shape is distorted, flattened, or squashed.
- Infiltration – Evidence that soil or water is seeping into pipe.
- Piping – Water flowing along the outside of pipe (causes loss of soil in roadbed).
- Deter. Ties (Deteriorated Ties) – Pipe ties are in poor shape, may not hold joints together.

This condition rating system is categorized based on the pipe material type; concrete, metal, and plastic pipes.

4.5 Practice Review Summary

Stormwater utilities adopt standard rating systems like NASSCO’s PACP and WRC or in-house developed rating systems. These numerical ratings are calculated based on the defects observed in individual stormwater pipe segments and aid in determining the extent of damage/deterioration. A numerical value is assigned to each defect seen in a segment, and it is categorized based on the type of defect and extent of damage. These defect values are combined to produce a cumulative defect score for that pipe segment. Some utilities have also modified the standard defect coding to their requirements. For example, The City of Virginia Beach, VA, modified the NASSCO’s PACP by adding modifiers which incorporate factors causing cave-ins due to failure of stormwater pipes. Similarly, The City of San Diego uses a modified WRC coding system tailored to their requirements. However, in-house developed rating systems are also common amongst the stormwater utilities. These rating systems are also condition based and categorized material-wise. Condition ratings implemented by the stormwater utilities in the practice review is a significant step forward to proactive asset management. However, condition rating systems are based on the existing conditions of the pipe and defects identified. Various external factors influence the deterioration of the stormwater pipes. Therefore, as a next step, stormwater utilities should implement performance-based rating systems and prediction models.

4.6 Research Gaps

Literature and practice review clearly indicates that there is a lack of standardized pipe rating system for assessment of stormwater pipes. Standard ratings such as NASSCO PACP, WRC, and other utility developed rating systems do not capture factors specific to stormwater pipes. Bhimanadhuni (2015) identified a list of parameters affecting stormwater pipes and developed a performance index specifically for them which was the first of its kind. However, the list of parameters identified by previous research needs to be expanded. Adding to that, the performance index developed by Bhimanadhuni (2015) uses a weighted factor method and assumes the performance parameters are independent. However, in real-world conditions, performance parameters are interdependent (Angkasuwansiri and Sinha 2014). It is essential to capture these interdependencies. For instance, soil resistivity and moisture retention capacity, when coupled together can accelerate corrosion on metal pipes at greater rates compared to their independent influence on a pipe alone. Given the gaps in research, there is a need to develop a performance index for stormwater pipe infrastructure capturing the interdependencies between parameters.

Chapter 5

Research Goals, Objectives & Methodology

5.1 Research Goal & Objectives

The goal of this research is to develop a stormwater pipe performance index capturing the interdependencies between performance parameters. The research objectives are visualized in Figure 5-1 and include:

1. Develop a comprehensive list of performance parameters affecting stormwater pipes.
2. Develop a performance index specifically for stormwater pipes which captures the interdependencies between parameters and individual modules and pilot it with one stormwater utility to validate results.
3. Develop performance prediction models for stormwater pipes.

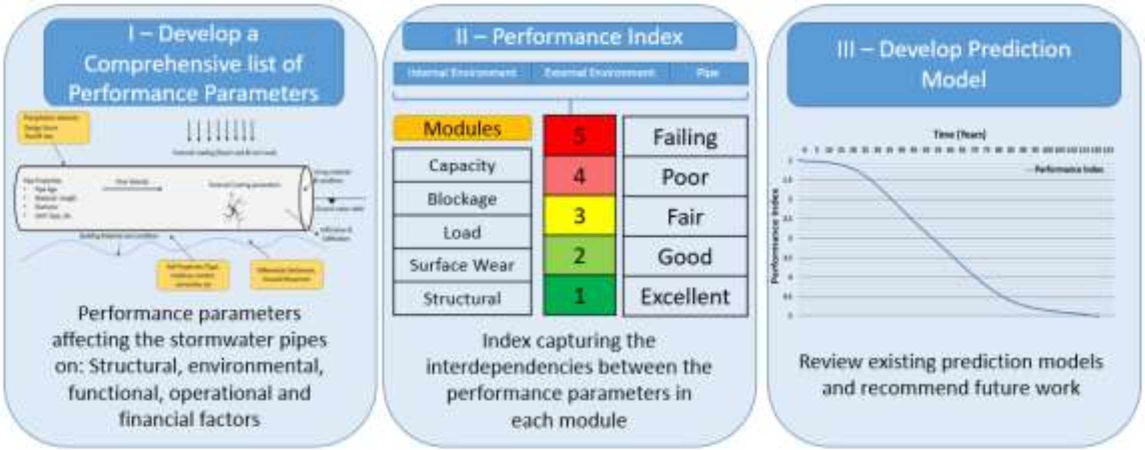


Figure 5-1: Research Objectives

5.2 Research Methodology

Before developing the performance index, performance parameters identified by existing research was reviewed and necessary additions were made based on literature, utility interactions and previous work on gravity sewers pipes (Angkasuwansiri and Sinha 2013). Similar to Bhimanadhuni (2015), performance parameters were categorized into capacity, blockage, load/deformation, surface wear and structural modules.

This study reviewed existing literature on condition and performance models adopted for gravity wastewater and stormwater pipes, to identify a suitable mathematical model that is capable of capturing interdependencies. Unlike Gravity wastewater sewers, stormwater pipes are buried in shallow depths and include shorter pipe sections. Since condition/performance models for stormwater pipes were very limited, gravity wastewater condition/performance models were reviewed and this information is summarized in Table 5-1.

Table 5-1: Condition/performance models – Sewers and stormsewer

Reference	Mathematical Technique
(Rowe et al. 2011)	Intermediate aggregation approach - NASSCO
(Rahman and Vanier 2004)	Peak score (WRc)
(Rahman and Vanier 2004)	Mean score, Total score, Peak score
(Najafi and Kulandaivel 2005)	Neural networks
(Koo and Ariaratnam 2006)	Logistic regression
(Chughtai and Zayed 2007)	Multiple regression
(Bai et al. 2008)	Hierarchical evidential reasoning model
(Tagherouit et al. 2011)	Fuzzy inference system
(Ennaouri and Fuamba 2011)	Analytic Hierarchy Process (AHP), Weighted summation
(Angkasuwansiri and Sinha 2014)	Weighted summation, Fuzzy logic
(Bhimanadhuni and Sinha 2015)	Weighted summation
(Khan et al. 2010)	back propagation and probabilistic neural network
(Yan and Vairavamoorthy 2003)	Multi criteria decision making
(Opila and Attoh-Okine 2011)	Mean Time to Failure (MTF)
(Zhou et al. 2009)	PROMETHEE method

Upon review of the literature, the Fuzzy Inference System (FIS) was selected to develop the performance index. Main reasons that led to the selection of FIS were;

1. The FIS can capture the interdependencies between performance parameters.
2. The scarcity of stormwater data, ambiguity, imprecision and vagueness in data can be justified using the FIS (Angkasuwansiri and Sinha 2014).
3. The simple user interface of MATLAB® Fuzzy Logic Toolbox™ will facilitate modification of input variables, rule statements, and output variables.

To develop the index, membership functions and their ranges were defined; if-then rule statements were created to capture the behavior of performance parameters and their interdependencies. To evaluate the model, band testing was performed using artificial data to observe the sensitivity of the model. To pilot the model, stormwater pipe data, inspection data and external data from one stormwater utility were utilized. The resultant model output (i.e. performance index) was validated with the PACP condition rating adopted by that utility.

Chapter 6

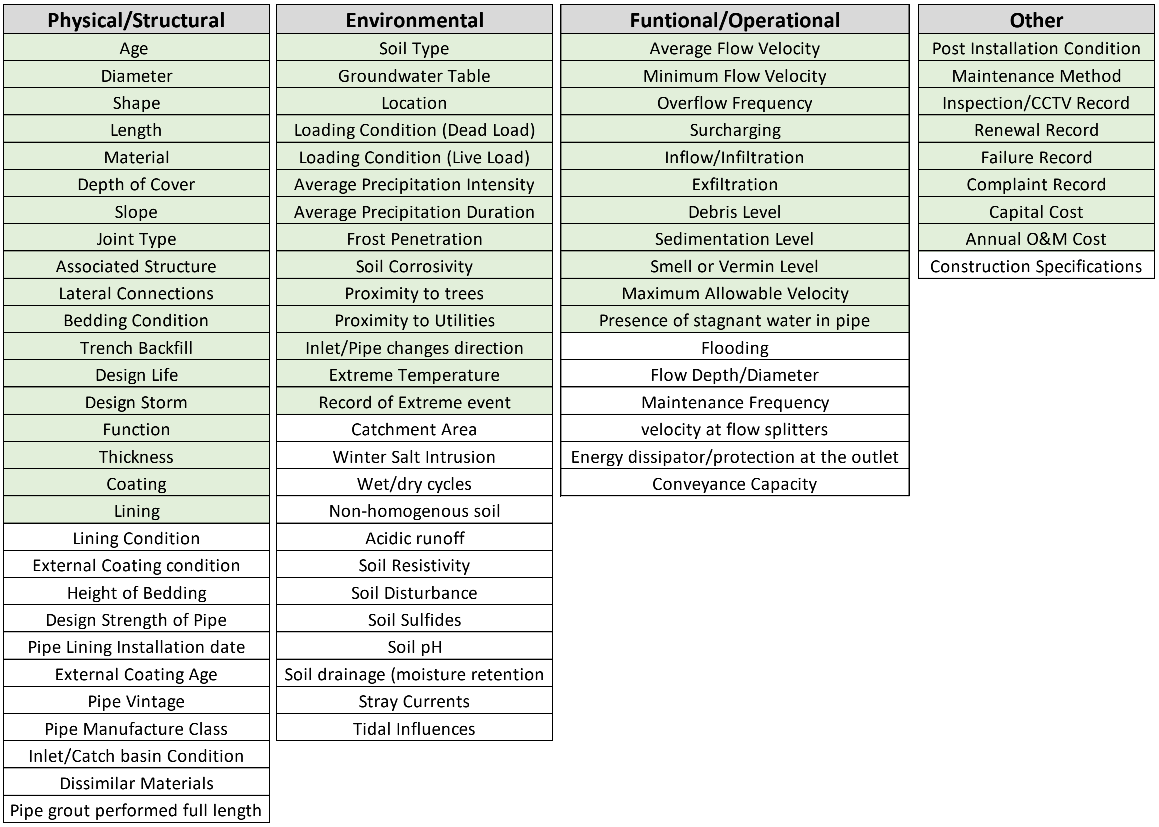
Development of a Comprehensive List of Stormwater Pipe Performance Parameters

Stormwater pipes are influenced by similar internal and external factors affecting performance as water and wastewater buried pipelines. The performance of a stormwater pipe is determined by its ability to meet a targeted level of service while complying with environmental regulations and maintaining structural and hydraulic integrity (Bhimanadhuni 2015).

Stormwater utilities lack a standard pipe data structure to collect and record pipe related parameters. Though some utilities follow a protocol with very minimal parameters, there is need for a standard data structure with uniformity in units. Utilities generally follow their own data formats and units in data collection. Before feeding this data into a model, significant effort to convert it to a standard format is needed. This research developed a comprehensive data structure specifically for stormwater pipes to address this issue. Utilities can utilize this data structure to modify their existing data collection process.

6.1 Stormwater Pipe Performance Date Structure

A list of performance parameters identified in previous research was compiled by Bhimanadhuni (2015) . Additional parameters were added based upon the work of Angkasuwansiri and Sinha (2013); Dasari (2016); Najjaran et al. (2004); Wenzlick and Albarran-Garcia (2008), design manuals (Urban Drainage Design Manual 2001), guidelines (Urban Drainage Design Manual 2001), utility plans (Arlington County Watershed Management Plan 2001) and utility interaction. General pipe and soil related parameters relevant to stormwater pipes were included from wastewater gravity and force mains research (Angkasuwansiri and Sinha 2013 ; Dasari 2016). The identified performance parameters were categorized into Physical/Structural, Operational, Environmental and Other. Units and detailed descriptions of the performance parameters identified by Bhimanadhuni (2015) are compiled in Appendix A. Figure 6-1 shows the list of parameters identified by earlier research in green and parameters defined in this research in white.



Physical/Structural	Environmental	Funtional/Operational	Other
Age	Soil Type	Average Flow Velocity	Post Installation Condition
Diameter	Groundwater Table	Minimum Flow Velocity	Maintenance Method
Shape	Location	Overflow Frequency	Inspection/CCTV Record
Length	Loading Condition (Dead Load)	Surcharging	Renewal Record
Material	Loading Condition (Live Load)	Inflow/Infiltration	Failure Record
Depth of Cover	Average Precipitation Intensity	Exfiltration	Complaint Record
Slope	Average Precipitation Duration	Debris Level	Capital Cost
Joint Type	Frost Penetration	Sedimentation Level	Annual O&M Cost
Associated Structure	Soil Corrosivity	Smell or Vermin Level	Construction Specifications
Lateral Connections	Proximity to trees	Maximum Allowable Velocity	
Bedding Condition	Proximity to Utilities	Presence of stagnant water in pipe	
Trench Backfill	Inlet/Pipe changes direction	Flooding	
Design Life	Extreme Temperature	Flow Depth/Diameter	
Design Storm	Record of Extreme event	Maintenance Frequency	
Function	Catchment Area	velocity at flow splitters	
Thickness	Winter Salt Intrusion	Energy dissipator/protection at the outlet	
Coating	Wet/dry cycles	Conveyance Capacity	
Lining	Non-homogenous soil		
Lining Condition	Acidic runoff		
External Coating condition	Soil Resistivity		
Height of Bedding	Soil Disturbance		
Design Strength of Pipe	Soil Sulfides		
Pipe Lining Installation date	Soil pH		
External Coating Age	Soil drainage (moisture retention		
Pipe Vintage	Stray Currents		
Pipe Manufacture Class	Tidal Influences		
Inlet/Catch basin Condition			
Dissimilar Materials			
Pipe grout performed full length			

Figure 6-1: Stormwater Pipe Performance Parameters.

6.1.1 Physical/Structural Parameters

This category captures basic pipe characteristics like material, age, size, slope, shape, vintage and manufacturing class. Other parameters related to bedding, lining, external coating, grouting and associated structures that can be associated with the structural integrity of a pipe are also represented in this category. Overall, this category represents parameters related to pipe characteristics and structural integrity. Definitions and units of each newly added parameter in this category are explained in Table 6-1.

Table 6-1: List of Newly Added Physical/Structural Parameters

Parameter	Units	Explanation	Source
Lining Condition	Level	Condition of the lining will have significant influence on pipe performance.	Authors discretion
External Coating condition	Level	Condition of external coating will have significant influence on pipe performance	Authors discretion
Height of Bedding	Inches	Height of bedding is an important factor in deterioration. Insufficient bedding leads to joint separation	(Dasari 2016)
Design Strength of Pipe	Psi	Original design strength of each pipe	(Dasari 2016)
Pipe Lining Installation date	Year	Year liner installed. Similar to pipes, the lining material also deteriorates with time.	(Dasari 2016)
External Coating Age	Year	Year external coating was applied. Similar to pipes, the external coating material also deteriorates with time.	Authors discretion
Pipe Vintage	Year	The pipe vintage can determine the metallurgy, uniformity, thickness, pressure class and available diameters of the various pipe materials	(Angkasuwansiri and Sinha 2013)
Pipe Manufacture Class	Class	Manufacturing class determine the rate of deterioration for pipes	(Angkasuwansiri and Sinha 2013)
Inlet/Catch basin Condition	Level	Condition of the associated structure will have an influence over pipe performance	Utility Interaction
Dissimilar Materials	Yes/No	When dissimilar metals are connected and exposed to an electrolyte, galvanic corrosion will occur since the metals have different properties.	(Angkasuwansiri and Sinha 2013)
Pipe grout performed full length	Yes/No	Additional bearing strength will be achieved when grouting is performed full length between pipe liner and host pipe.	(Filice 2001)

6.1.2 Environmental Parameters

This category captures parameters affecting the stormwater pipes from the external environment. Major parameters in this category are soil characteristics, groundwater table, loading condition, climate and extreme events. The external environment has a significant impact on stormwater pipes, as stormwater pipes are buried in different soils, climates and loading conditions. Overall, this category represents parameters related to pipe external environment. Definitions and units of each newly added parameter in this category are explained in Table 6-2.

Table 6-2: List of Newly Added Environmental Parameters

Parameter	Units	Explanation	Source
Catchment Area	Sq.m	Catchment area is an important factor to determine the precipitation received.	Utility Interaction
Winter Salt Intrusion	Yes/No	If pipe is exposed to the salt applied for frost mitigation of roads.	(Wenzlick and Albarran-Garcia 2008)
Wet/dry cycles	Yes/No	The wet/dry cycles as a result to climate can lead to expansion and/or contraction of the soil	(Angkasuwansiri and Sinha 2013)
Non-homogenous soil	Yes/No	It is an important factor that accelerates corrosion	(Wenzlick and Albarran-Garcia 2008)
Acidic runoff	Yes/No	Results in chemical attack on stormwater pipelines and results in deterioration	(Wenzlick and Albarran-Garcia 2008)
Soil Resistivity	Level	Soil resistivity is a measure of the soil to serve as an electrolyte. The lower the resistivity value, more prone to corrosion	(Angkasuwansiri and Sinha 2013)
Soil Disturbance	Yes/No	Disturbances in the pipe bedding or alignment can lead to beam failure if the pipe is not adequately supported and/or the pipe depth is not sufficient	(Angkasuwansiri and Sinha 2013)
Soil Sulfides	%	Soils containing sulfide indicate that there is a problem caused by sulfate-reducing bacteria. Soils with positive sulfide content are more prone to pipeline corrosion	(Angkasuwansiri and Sinha 2013)
Soil pH	Level	Soil pH is a measure of the soil acidity or alkalinity. A low pH represents an acidic soil promoting corrosion and is also a soil that serves well as an electrolyte	(Angkasuwansiri and Sinha 2013)
Soil drainage (moisture retention)	%	Soil moisture content accelerates the rate of corrosion	(Najjaran et al. 2004)
Stray Currents	Yes/No	Stray currents are caused by a local direct current (DC) flowing through the earth. These stray currents can be present if the pipe is near a transportation system such as a railway, or if other utilities are close to the pipe.	(Angkasuwansiri and Sinha 2013)
Tidal Influences	Yes/No	Tidal influences within coastal areas can influence the soil groundwater table	(Angkasuwansiri and Sinha 2013)

6.1.3 Functional/Operational Parameters

This category captures parameters affecting the operational performance of stormwater pipes. The parameters in this category generally create capacity and blockage issues in stormwater pipes. Major parameters affecting the internal environment of stormwater pipes are velocity, debris & sediment accumulation, overflow & surcharging, infiltration & exfiltration and maintenance frequency. Overall, this category represents parameters related to pipe internal environment. Definitions and units of each newly added parameter in this category are explained in Table 6-3.

Table 6-3: List of Newly Added Functional/Operational Parameters

Parameter	Units	Explanation	Source
Flooding	Level	Flooding can impact the pipe and soil equilibrium causing the pipe to collapse or float out of alignment.	(Angkasuwansiri and Sinha 2013)
Flow Depth/Diameter	Ratio	Pipes with different flow depth over diameter ratios deteriorate differently	(Dasari 2016)
Maintenance Frequency	Occurrence Level	Frequency of maintenance reduces the risk of blockage in stormwater pipes	Utility Interaction
Velocity at flow splitters	Fps	Hydraulic disturbances within flow splitters often result in regions of flow velocity reduction.	(Urban Drainage Design Manual 2001)
Energy dissipater/protection at the outlet	Yes/No	Reduces scouring at the outlet, keeping the soil intact	(Urban Drainage Design Manual 2001)
Conveyance Capacity	Level	Determines the conveyance capacity of a pipes, (i.e. surcharging, insufficient free board or flooded)	(Arlington County Watershed Management Plan 2001)

6.1.4 Other Parameters

Parameters that do not fall into physical, environmental and operational categories are classified as other parameters. Parameters associated with cost, complaint records, construction specifications, failure, renewal and inspection records are categorized in this group.

Chapter 7

Development of Stormwater Pipe Performance Index

Decision making is a part of everyday actions. Every person must make decisions every day, whether it is for everyday actions or domain specific decisions. Stormwater utility managers are no exception. They are expected to routinely make decisions on capital improvement, maintenance actions, renewal strategies, funding, utility rates and other departmental issues. Assessing the performance of stormwater pipes helps them in making better decisions with respect to stormwater pipes. As stated in the research objective, this research aims to capture the interdependencies between performance parameters. Since, stormwater utility pipe data generally have some missing fields, a FIS was selected to address vagueness, imprecision, and ambiguity issues in the data. A FIS is also capable of capturing the interdependencies using *if-then* rule statements. This chapter explains the development of stormwater pipe performance index using a fuzzy inference system.

7.1 Fuzzy Inference System

The concept of fuzzy sets having a partial degree of membership was established by Zadeh (1965). Unlike the classical set which involves either inclusion or exclusion of value i.e. 0 or 1. Fuzzy set classifies a value with a varying degree of membership between 0 and 1 (Flintsch and Chen 2004). Fuzzy inference is a method to process the input functions and map it to the output using fuzzy logic. Mamdani and Assilian (1999) proposed this method in 1975. There are two types of fuzzy inference systems; Mamdani and Sugeno (Flintsch and Chen 2004). The major difference between these two systems lies in the output functions. In the Mamdani system, the output is generated as a fuzzy set. In the Sugeno system, a weighted average is used to produce a linear or constant output (Hamam and Georganas 2008). In this research, the Mamdani system was adopted since the output function can address data vagueness, imprecision, and ambiguity.

The initial step in creating a FIS involves defining the input-output variables and ranges using membership functions. The second step involves creating IF-THEN rules which comprise of the inputs and outputs applying logical operations and weights. The final step involves aggregation of the consequences and defuzzification of the output into a single value. An example of a Mamdani FIS is shown in Figure 7-1.

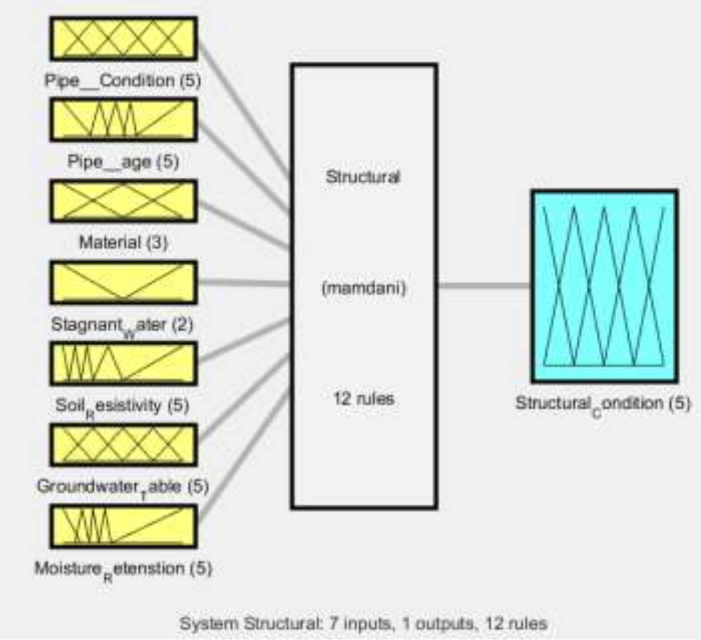


Figure 7-1: Fuzzy Inference System

7.1.1 Membership functions

Membership functions are represented by a line or a curve indicating the degree of membership for each input and output variable. There are 11 different membership functions developed based on basic functions such as; Linear, Gaussian, Sigmoidal, Quadratic and Cubic Polynomial. Triangular and Trapezoidal membership functions are widely used for their simplicity. For this research, Triangular membership function was selected since using other membership functions would require defining the degree of curvature. With the existing knowledge of the input parameter's role in obtaining a resulting output, using the curve functions introduces a complexity that cannot be justified. Following the creation of membership functions, a range of input variables is interpreted or fuzzified into linguistic terms by a process called fuzzification. For example, a range of loading condition can be classified into linguistic terms; heavy, medium and low.

7.1.2 Rule Statements

Fuzzified input variables are subjected to IF-THEN rule statements. These rule statements represent expert opinion and engineering judgments. The interdependencies between the input variables are captured using Boolean logic operators AND, OR and NOT. For example, the relationship between two input variables with an output is:

"IF input 1 is A and input 2 is B, THEN output 1 is C."

Each rule statement is assigned a weight to prioritize its influence on the output.

7.1.3 Defuzzification

The aggregate output obtained is fuzzified. Defuzzification is a process that converts the output to a single number. Several defuzzification methods exist including: centroid, middle of maximum, largest of maximum, smallest of maximum and bisection. Centroid defuzzification methods return the center of an area under the curve. The middle of maximum (MOM) defuzzification methods return the mean maximum value. This research utilizes the MOM method, as it returns output at the highest or lowest possible rating.

7.2 Model Development

Stormwater pipes are subjected to several internal and external conditions over their lifespan. The behaviour of a stormwater pipe varies based on the condition in which it is placed. In addition to the condition of a pipe, internal and external performance parameters should be considered when assessing its performance. As mentioned earlier, this research aims to capture the interdependencies between performance parameters. The initial step of the model development involved categorizing the performance parameters into individual modules, determining the layout of the index, developing membership function ranges, and creating rule statements. This section explains the steps involved in developing the stormwater performance index model.

7.2.2 Layout of the Index

The performance parameters were categorized into five modules: capacity, blockage, surface wear, structural and load/deformation. The categorization of parameters was adapted from Bhimanadhuni and Sinha (2015). However, inclusion of new parameters was made to each module to improve the index. In the capacity module, conveyance capacity was included. In blockage and surface wear module, maintenance/cleaning frequency and type of cleaning were included. Similarly, in the structural module, the presence of stagnant water, soil resistivity and moisture retention were added.

These modifications were based on literature review and practice review with stormwater utilities. The modified layout of the performance modules is shown in Figure 7-2. This research expanded the existing list of parameters to make it comprehensive.

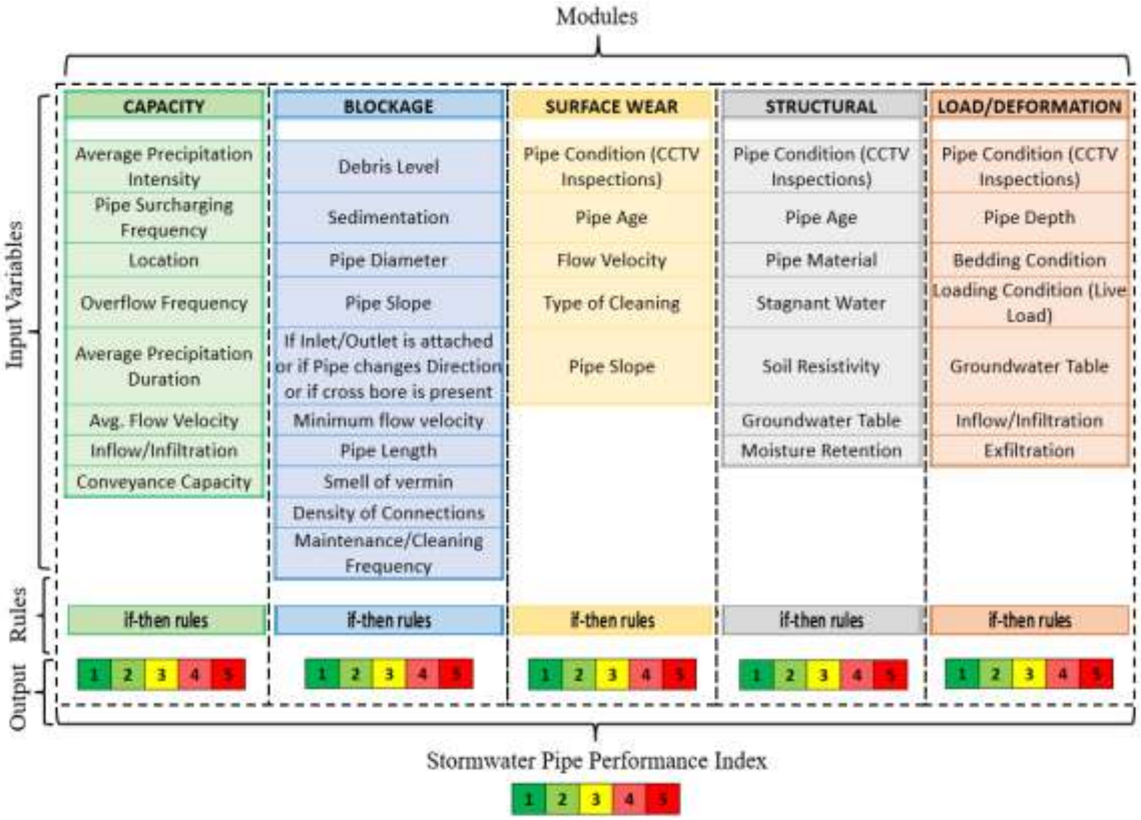


Figure 7-2: Layout of the Stormwater Pipe Performance Index

The scale adapted for the performance index is similar to NASSCO's PACP and Bhimanadhuni and Sinha (2015), i.e.; 1 – 5 scale. Where one represents 'excellent condition' and five represents 'Very Poor.' The pipe scores and corresponding performance scales are shown in Table 7-1.

Table 7-1: Performance Scale - Adapted from (Bhimanadhuni and Sinha 2015)

Pipe Score	Performance Scale	Description
1.0-1.5	1	Excellent
1.5-2.5	2	Good
2.5-3.5	3	Fair
3.5-4.5	4	Poor
4.5-5.0	5	Very Poor

7.2.3 Development of Membership Functions & Ranges

The performance parameters were categorized into five different modules based on their influence on a stormwater pipe include:

- Capacity
- Blockage
- Surface Wear
- Structural
- Load/Deformation

Each module was created in MATLAB® with input and output parameters with their ranges defined. MATLAB® Fuzzy Logic Toolbox™ was used for the development of modules (Fuzzy Logic Toolbox™ MATLAB® 2016). Triangular membership functions were used in developing the membership functions. Following that, the input and output parameters ranges was fuzzified into suitable linguistic terms (Appendix B). The membership ranges for capacity, blockage, surface wear, structural and load/deformation modules are shown in Tables 7-2, 7-3, 7-4, 7-5 and 7-6 respectively.

Table 7-2: Performance Parameters and Membership Ranges – Capacity Module

S. No	Input Variables	Units	Ranges	Linguistic Terms	Membership Ranges
1	Average Precipitation Intensity	Level	Greater than Design Storm Intensity	High	[3 5 5]
			Equal to Design Storm Intensity	Medium	[2 3 4]
			Less than Design Storm Intensity	Low	[1 1 3]
2	Pipe Surcharging Frequency	level	Frequent (weekly, monthly) & high magnitude	Very High	[4 5 5]
			Frequent & low magnitude	High	[3 4 5]
			Occasional (1- 12 times per year) & high magnitude	Moderate	[2 3 4]
			Occasional - low magnitude	Low	[1 2 3]
			no	Very Low	[1 1 2]
3	Location	Type	Pavements, City Business Areas, Dense Residential (6-15 units/acre)	Very Poor	[4 5 5]
			Normal Residential (3-6 units/acre), Industrial area, apartment areas	Poor	[3 4 5]
			Light residential (< 3 units/acre), cultivated lands	Fair	[2 3 4]
			Parks, playgrounds	Good	[1 2 3]
			Unimproved lands	Excellent	[1 1 2]
4	Overflow Frequency	Level	Frequent (weekly, monthly) & large volume	Very High	[4 5 5]
			Frequent & small volume	High	[3 4 5]
			Occasional (1-12 times per year) & large volume	Moderate	[2 3 4]
			Occasional & small volume	Low	[1 2 3]
			No	Very Low	[1 1 2]
5	Average Precipitation Duration	Level	Greater than Design Storm Duration	High	[3 5 5]
			Equal to Design Storm Duration	Medium	[2 3 4]
			Less than Design Storm Duration	Low	[1 1 3]
6	Avg. Flow Velocity	fps	Less than minimum design flow velocity (2 - 3 fps)	High	[3 5 5]
			Greater than maximum design flow velocity	Medium	[2 3 4]
			Between min. and max. design flow velocity	Low	[1 1 3]
7	Inflow/Infiltration	Type	Gusher	Very High	[4 5 5]
			Runner (continuous flow of water)	High	[3 4 5]
			Dripper (water dripping)	Moderate	[2 3 4]
			Weeper (slow ingress of water)	Low	[1 2 3]
			No	Very Low	[1 1 2]
8	Conveyance Capacity	Type	If the HGL rose above the ground surface	Flooded	[4 5 5]
			If the HGL rose to within 1 foot of the ground surface	Insufficient Freeboard	[2.5 3.5 4.5]
			If the HGL rose above the crown of the pipe but below the insufficient freeboard mark	Surcharged	[1.5 2.5 3.5]
			If the HGL below the crown of the pipe	Partial	[0.5 1.5 2.5]
			No Surcharge	No Surcharge	[0 0 1]

Table 7-3: Performance Parameters and Membership Ranges – Blockage Module

S. no	Input Variables	Units	Ranges	Linguistic Terms	Membership Ranges
1	Debris Level	Level	Occupy more than 75 % of pipe	Very High	[0.75 1 1]
			Occupy 50% -75% of the pipe	High	[0.5 0.75 1]
			Occupy 25% - 50% of the pipe	Moderate	[0.25 0.5 0.75]
			Occupy 1% - 25% of the pipe	Low	[0 0.25 0.5]
			No	Very Low	[0 0 0.25]
2	Sedimentation	Level	Occupy more than 75 % of pipe	Very High	[0.75 1 1]
			Occupy 50% -75% of the pipe	High	[0.5 0.75 1]
			Occupy 25% - 50% of the pipe	Moderate	[0.25 0.5 0.75]
			Occupy 1% - 25% of the pipe	Low	[0 0.25 0.5]
			No	Very Low	[0 0 0.25]
3	Pipe Diameter	Inch	6' - 12'	Very Small	[1 1 12]
			12'-18'	Small	[1 12 18]
			18-24'	Medium	[12 18 24]
			24-36'	Large	[18 24 36]
			Greater than 36'	Very Large	[36 70 70]
4	Pipe Slope	%	Less than 0.5%	Very Low	[0 0 0.5]
			Greater than 5%	Very High	[5 10 10]
			0.5% - 1%	Low	[0 0.5 1]
			1% - 2%	Moderate	[0.5 1 1.5]
			2% - 5%	Good	[1 3 5]
5	If Inlet/Outlet is attached or if pipe changes direction or if cross bore is present	Yes/No	Yes	Undesirable	[3 5 5]
			No	Desirable	[1 1 3]
6	Minimum flow velocity	fps	Less than minimum design flow velocity (2 fps - 3 fps)	Highly Likely	[3 5 5]
			Equal to minimum design flow velocity	Likely	[2 3 4]
			Greater than min. design flow velocity	Less Likely	[1 1 3]
7	Pipe Length	Ft	Greater than 500ft	Very Long	[400 1000 1000]
			400ft - 500ft	Long	[300 400 500]
			300ft - 400ft	Average	[200 300 400]
			200ft - 300ft	Short	[1 200 300]
			Less than 200ft	Very Short	[1 1 200]
8	Smell or vermin	Type	Significant	Significant	[4 5 5]
			Very High	Very High	[3 4 5]
			Moderate	Moderate	[2 3 4]
			Minimal	Minimal	[1 2 3]
			No	No	[1 1 2]
9		Level	Very Dense (>5 per 100ft)	Very Dense	[5 10 10]

S. no	Input Variables	Units	Ranges	Linguistic Terms	Membership Ranges
	Density of Connections		Dense (4-5 per 100ft)	Dense	[2 3 5]
			Medium (2-3 per 100ft)	Medium	[1 2 3]
			Light (1-2 per 100ft)	Light	[0 1 2]
			Very Light (<1 per 100ft)	Very Light	[0 0 1]
10	Maintenance/Cleaning Frequency	Type	Annual Maintenance	Frequent	[0 0 1]
			2-3 Year Maintenance	Regular	[1 2 3]
			3-5 year	Rarely	[3 5 5]

Table 7-4: Performance Parameters and Membership Ranges – Surface Wear Module

S. no	Input Variables	Units	Ranges	Linguistic Terms	Membership Ranges
1	Pipe Condition (CCTV Inspections)	Type	Emergency repairs/replacement required	Failing	[4 5 5]
			Poor Condition	Poor	[3 4 5]
			Fair Condition	Fair	[2 3 4]
			Good Condition	Good	[1 2 3]
			No deficiencies	Excellent	[1 1 2]
2	Pipe Age	Year	If age = 0-30	Very Young	[0 0 30]
			If age = 30-45	Young	[28 38 48]
			If age = 45-60	Middle aged	[45 55 65]
			If age = 60-75	Old	[63 70 77]
			If age = >75	Very old	[75 125 125]
3	Flow Velocity (to calculate time of concentration)	fps	Greater than maximum design flow velocity	High	[3 5 5]
			Between minimum and maximum design flow velocity	Medium	[2 3 4]
			Less than minimum design flow velocity (2 fps - 3 fps)	Low	[1 1 3]
4	Type of Cleaning	Type	Jetting	Best	[1 1 3]
			Rodding	Average	[2 3 4]
			Bucketing	Worst	[3 5 5]
5	Pipe Slope	%	0% - 2%	Low	[0 0 2]
			2% - 4%	Moderate	[1 2.5 4]
			4% - 5%	High	[3.5 5 5]

Table 7-5: Performance Parameters and Membership Ranges – Structural Module

S. no	Input Variables	Units	Ranges	Linguistic Terms	Membership Ranges
1	Pipe Condition (CCTV Inspections)	Type	Emergency repairs/replacement required	Failing	[4 5 5]
			Poor Condition	Poor	[3 4 5]
			Fair Condition	Fair	[2 3 4]
			Good Condition	Good	[1 2 3]
			No deficiencies	Excellent	[1 1 2]
2	Pipe Age	Year	If age = 0-30	Very Young	[0 0 30]
			If age = 30-45	Young	[28 38 48]
			If age = 45-60	Middle aged	[45 55 65]
			If age = 60-75	Old	[63 70 77]
			If age = >75	Very old	[75 125 125]
3	Pipe Material	Type	Thermoplastic	Desirable	[1 1 3]
			Reinforced Concrete	Preferable	[1 3 5]
			Metal	Mediocre	[3 5 5]
4	Stagnant Water	Yes/No	Yes	Undesirable	[3 5 5]
			No	Desirable	[1 1 3]
5	Soil Resistivity	Ohm-cm (Level)	0-1000	extremely corrosive	[0 0 1000]
			1000-3000	very corrosive	[1000 2000 3000]
			3000-5000	Likely	[3000 4000 5000]
			5000-10000	Moderately corrosive	[5000 7500 10000]
			>= 10000	mildly corrosive	[10000 20000 20000]
6	Groundwater Table	Level	In the regular backfill	V High	[4 5 5]
			In the trench backfill - above pipe crown	High	[3 4 5]
			In the trench backfill - close to pipe	Moderate	[2 3 4]
			In the bedding	Low	[1 2 3]
			Below bedding	V Low	[1 1 2]
7	Moisture Retention (% clay (soil particles < 0.002 mm) fines by weight)	%	gravel (15%)	V Low	[0 0 0.15]
			coarse sand (22%)	Low	[0.1 0.16 0.22]
			fine sand and silt (25% - 30%)	Medium	[0.22 0.25 0.3]
			Silty Clay (35%)	High	[0.3 0.35 0.4]
			Clay (>40%)	V High	[0.4 1 1]

Table 7-6: Performance Parameters and Membership Ranges – Load/Deformation Module

S. no	Input Variables	Units	Ranges	Linguistic Terms	Membership Ranges
1	Pipe Condition (CCTV Inspections)	Type	Emergency repairs/replacement required	Failing	[4 5 5]
			Poor Condition	Poor	[3 4 5]
			Fair Condition	Fair	[2 3 4]
			Good Condition	Good	[1 2 3]
			No deficiencies	Excellent	[1 1 2]
2	Pipe Depth	Feet	0ft - 5ft	Very Shallow	[1 1 5]
			5ft - 10ft	Shallow	[5 7.5 10]
			10ft - 20ft	Average	[10 15 20]
			20ft – 30ft	Deep	[20 25 30]
			Greater than 30 ft.	Very Deep	[30 40 40]
3	Bedding Condition	Type	Good (class B)	Good	[1 1 3]
			Fair (class C)	Fair	[2 3 4]
			Poor (class D)	Poor	[3 5 5]
4	Loading Condition (Live Load)	Level	>50ft from road or railway	Light	[50 100 100]
			50ft from road or railway	Moderate	[20 35 50]
			20ft from major road or railway	Heavy	[0 0 20]
5	Groundwater Table	Level	In the regular backfill	V High	[4 5 5]
			In the trench backfill - above pipe crown	High	[3 4 5]
			In the trench backfill - close to pipe	Moderate	[2 3 4]
			In the bedding	Low	[1 2 3]
			Below bedding	V Low	[1 1 2]
6	Inflow/Infiltration	Type	Gusher	Very High	[4 5 5]
			Runner (continuous flow of water)	High	[3 4 5]
			Dripper (water dripping)	Moderate	[2 3 4]
			Weeper (slow ingress of water)	Low	[1 2 3]
			No	Very Low	[1 1 2]
7	Exfiltration	Level	Significant erosion of soil around pipe	Very High	[4 5 5]
			Very High erosion of soil	High	[3 4 5]
			Moderate erosion of soil	Moderate	[2 3 4]
			Minimal erosion of soil	Low	[1 2 3]
			No erosion of soil	Very Low	[1 1 2]

7.2.3 Development of if-then Rule Statements

The rule statements reflect expert knowledge on the interrelationships between parameters and their influence on the resultant output. The rule statements were created based on the previous research work on wastewater pipes (Angkasuwansiri and Sinha 2014) and interactions with stormwater utility experts. Rule statements were created for each of the five modules. Appendix C lists the if-then rule statements for each of the five performance modules.

7.3 Model Evaluation

The developed model was subjected to band testing evaluation. Band testing was performed by varying all the parameter input ranges to check the sensitivity of the model. For band testing, three basic scenarios and several other scenarios were tested. For example, when unfavorable parameter ranges were fed as an input, the output demonstrated "Very Poor" pipe condition. Similarly, favorable and fair parameter ranges were fed as an input to test the model sensitivity.

7.3.1 Model Evaluation – Observations

While testing the sensitivity of the model, the following observations between the performance parameters were recorded.

- The developed performance index model was subjected to three band testing and performed well. When favorable, mediocre and unfavorable parameter ranges were entered, the resultant output was in excellent, fair and very poor condition ranges respectively.
- The interdependencies between the parameters were tested by substituting in different parameter ranges to test the parameters that influence the output. It was observed that CCTV inspection data had the highest weight on the output. However, if the CCTV inspection data had "excellent" condition score, and when other parameters had unfavorable ranges, the resultant output demonstrated "fair" conditions.
- In the Capacity module, parameters such as pipe overflow frequency, surcharging frequency and conveyance capacity had a major influence on the output.

- In the Blockage module, the pipe O&M score (CCTV data) coupled with parameters such as density of connections and cleaning frequency had a major influence on the output.
- The individual modules performed well, and their outputs behaved based on the modelled fuzzy logic rules. The outputs were impacted based only on the related input variables of individual module.
- If no input variable was present in a given module, then the calculated output showed “fair” condition.
- In the Structural module, if the CCTV inspection data shows “excellent” condition and the pipe lies in a corrosive soil or heavy loading condition, then the output was observed to have “moderate” values. This reconfirms that, the rate of deterioration accelerates when the pipe lies in unfavorable internal or external environment, even if the present pipe condition is excellent.
- The Structural module was observed to have a significant impact on the overall performance index.
- Overall, the model performed well, and the outputs were observed to follow the modelled fuzzy rules.

7.4 Percentage Reliability

As observed during the literature and practice review, lack of data has been a dominant issue with asset management systems serving stormwater utilities. Some of the performance parameters; soil characteristics and distance to major roads was extracted from external sources such as USGS Web Soil Survey (USDA NRCS 2017) and transportation data respectively. Parameters such as cleaning frequency and type of cleaning was arrived based on the discussion with the concerned utility personnel. The total number of input variable entered vs. the total number of input variable that the model can support impacts the reliability of the output. Each parameter was also classified based on the method of collection; direct record, indirect and educated guess (St Clair 2013). The confidence scale relies on the method of data collection as shown in Table 7-7.

Table 7-7: Performance Parameters Confidence Scale Based on Method of Data Collection

Parameter Source	Confidence Scale (CS)
Direct Record	5
Derived Indirectly	4
Educated Guess (High Confidence)	3
Educated Guess (Medium Confidence)	2
Educated Guess (Low Confidence)	1

(Sinha, S., and Angkasuwansiri, T. (2010). "Phase 2: Development of a robust wastewater pipe performance index." Development of protocols and methods for predicting the remaining economic life of wastewater pipe infrastructure assets. Report No. 06-SAM-1 CO, Water Environment Research Foundation, Alexandria, VA. Used with permission of Carrie W. Capuco, JD, Water Environment Research Foundation.)

$$Reliability\ Percentage = \frac{Collected\ Parameters\ (n)}{Required\ Parameters\ (38)} = \frac{\sum_{i=1}^{n} CS_i}{5\ \times n} \times 100$$

$$Reliability\ Percentage = \frac{\sum_{i=1}^{n} CS_i}{5\ \times 38} \times 100$$

$$Percentage\ Reliability = \frac{\sum_{i=1}^{n} CS_i}{1.9}\ \%$$

Equation 1: Percentage Reliability based on Confidence Scale

7.5 Piloting – Utility A

The stormwater performance index model that was developed as part of this research was piloted with Utility A. The city's watershed protection department manages the stormwater infrastructure. Initially, Utility A provided their stormwater pipe geodatabase to pilot the model. Following that, they provided the pipe inspection tables. Utility A uses NASSCO's PACP condition rating system for assessing the condition of their stormwater pipes based on CCTV inspection data. The percentage reliability of the data received from Utility A to calculate the performance index is between 16 to 46 percent.

7.5.1 Utility A - Pipe Data

The city's watershed protection department maintains 89,256 stormwater pipes; 33,390 curb inlets; 226 combination inlets; 1,265 grate inlets; 8,473 manholes and 12,660 open channels. The stormwater geodatabase provided by the utility had details on pipe material, pipe diameter, installation date, pipe shape, pipe slope and pipe length. Other parameters were derived using spatial overlays. The density of connections was arrived by intersecting the drainage pipe layer over the manhole, curbs and inlets layer. The method and frequency of cleaning were determined after a discussion with utility personnel. The city uses mechanical cleaning method and follows an annual maintenance schedule. The stormwater geodatabase had missing data for some of the pipes.

7.5.2 Utility A – CCTV Inspection Data

Utility A uses NASSCO's PACP rating system to capture the pipe index based on CCTV inspections. Pipe inspection tables provided by the utility consisted pipe "Operation & Maintenance" and "Structural" Score. The rating scale adopted was on a scale of 1-5, where one relates to "excellent" condition and five related to "very poor" condition. The inspection table was joined with the drainage layer in ArcGIS desktop using the Drainage ID field. Out of 89,256 pipes, only 4,547 pipes were inspected and had pipe ratings.

7.5.3 Utility A – External Data

In addition to the GIS data provided by Utility-A's GIS, soil characteristics of the region were determined based on USGS Soil Survey Geographic (SSURGO) database (USDA NRCS 2017). The GIS shapefiles were downloaded from USGS SSURGO database, and it was spatially joined with the drainage pipe layer provided by the utility. Loading condition was determined based on the proximity to major roads, railroads and highways. Major roads, railroads and highways layer, was downloaded from the city's GIS database. The Near tool in ArcGIS desktop was utilized to arrive at the proximity of major roads, highways and railroads.

7.5.4 Utility A – Analysis using Weighted Factor Method

The data obtained from the utility was analyzed using the weighted factor method adopted by previous research (Bhimanadhuni 2015). Each parameter in the utility data and external data was assigned a weight based on previous work as shown in Table 7-8.

Table 7-8: Weights for Performance Parameters

Parameter	Weights
Pipe Condition	0.1060
Age	0.0895
Inlet/Pipe changes direction/Cross bore present)	0.0277
Material	0.1080
Shape	0.0214
Diameter	0.0796
Length	0.0238
Slope	0.0266
Soil Type	0.0169
Live Load	0.0116
Density of Connections	0.023
Average Precipitation Intensity	0.025
Average Precipitation Duration	0.022

The weighted factor method assigns a weight to each parameter based on the survey results from previous study. The model used for this analysis is represented using Equation 2;

$$Performane\ Index = \sum_{i=1}^{n} w_i \times p_i$$

Equation 2: Equation of weighted factor method

7.5.5 Results – Weighted Factor Method

The utility data set was utilized to run the weighted factor method in an MS EXCEL^{TM} spreadsheet. The results from the weighted factor model were classified into a 1-5 pipe performance index, where "one" implies excellent condition and "five" represents very poor condition. On observing the results, it is evident that most of the pipes present in the utility network are rated 2 and 3 (i.e. good and fair condition). Overall, 628 pipes were rated excellent, 36,869 pipes were rated good, 44,659 pipes were rated fair, 7,074 pipes were rated poor and 26 pipes were rated very poor (Table 7-9).

Table 7-9: Results – Weighted Factor Method

Pipe Rating	Condition	No. of Pipes
1	Excellent	628
2	Good	36,869
3	Fair	44,659
4	Poor	7,074
5	Very Poor	26

7.5.6 Utility A – Analysis using Fuzzy Inference Method

The extracted utility and external data was checked for data quality. Anomalies in each pipe parameter were noted, i.e., if a slope value was entered as 9999, then slope for that pipe was considered null. After the data quality check, the performance parameters were categorized based on structural, capacity, blockage, surface wear and load/deformation modules. Each module was run on MATLAB's Fuzzy Toolbox using the categorized input variables. The output of each module was considered as input variables for the performance index module. The resultant output (i.e. performance index) was exported as an MS EXCEL^{TM} spreadsheet.

7.5.7 Results – Fuzzy Inference Method

The utility data set was utilized to run the fuzzy inference method on MATLAB's Fuzzy Toolbox. The results from the fuzzy inference method were classified into a 1-5 pipe performance index, where "one" implies excellent condition and "five" represents very poor condition. On observing the results, there is spread across all pipe ratings, however, the predominant number of pipes present in the utility network were rated 2, 3 and 4 (i.e. good, fair and poor condition). Overall, 96 pipes were rated excellent, 1,252 pipes were rated good, 85,690 pipes were rated fair, 1,882 pipes were rated poor and 341 pipes were rated very poor (Table 7-10).

Table 7-10: Results – Fuzzy Inference Method

Pipe Rating	Condition	No. of Pipes
1	Excellent	96
2	Good	1,252
3	Fair	85,690
4	Poor	1,882
5	Very Poor	341

7.6 Validation – Case Study (Utility A)

To validate the model, the model output (i.e. performance index) for the stormwater pipes inspected by CCTV was selected. These pipes comprised 20% of Utility A's stormwater pipes. (i.e. 4,547 pipes out of 89,256 pipes). The fuzzy performance index was compared with the PACP rating and the weighted performance index.

7.6.1 Comparison between PACP Ratings and Fuzzy Performance Index

PACP ratings are based on visual inspection, and do not consider environmental and operational factors impacting the deterioration of stormwater pipes. A comparison of PACP vs. Fuzzy Performance Index is shown in Table 7-11. If a pipe is rated as "excellent" in PACP and lies in unfavorable conditions, then the rate of deterioration is considered to be significant, which is something the PACP rating fails to capture. On the other hand, the stormwater pipe performance index developed using fuzzy inference method considered external and internal factors acting on a pipe, and coded the pipe to a subsequent rating even if the PACP showed "excellent" conditions. This is evident in Table 7-11, where, 135 pipes were rated "excellent" by PACP, but, only 95 pipes were rated "excellent" by the Fuzzy Performance Index. This pattern was observed in other pipe conditions as well.

Table 7-11: Comparison of PACP Vs. Fuzzy Performance Index

Pipe Rating	Condition	PACP Index		Performance Index - Fuzzy	
		No. of Pipes	% within	No. of Pipes	% within
1	Excellent	135	3%	95	2%
2	Good	2120	47%	1250	27%
3	Fair	1615	36%	2023	44%
4	Poor	585	13%	839	18%
5	Very Poor	92	2%	340	7%
Total		4547	100%	4547	100%

7.6.2 Comparison between Weighted and Fuzzy Performance Index

The weighted performance index was determined using the weights developed by Bhimanadhuni (2015). The weighted model output for the CCTV inspected pipes was selected to compare with the fuzzy performance index. It is evident from Table 7-12 that the model output of the weighted performance index shows clusters of pipes in "good" and "fair conditions, and does not reflect actual conditions. Though weighted performance index captured weights for each parameter based on severity, however, the weighted performance index was less sensitive because the weights assigned to each parameter were firm. In contrast, the fuzzy performance index provided sensitive results by capturing interdependencies between parameters, thereby, reflecting ground truth.

Table 7-12: Comparison of Weighted Average Vs. Fuzzy Performance Index

Pipe Rating	Condition	Weighted Index		Performance Index - Fuzzy	
		No. of Pipes	% within	No. of Pipes	% within
1	Excellent	3	0.1%	95	2%
2	Good	3148	69%	1250	27%
3	Fair	1394	31%	2023	44%
4	Poor	2	0%	839	18%
5	Very Poor	0	0%	340	7%
Total		4547	100%	4547	100%

7.6.3 Index Comparison

Utility A provided CCTV inspection reports for further analysis. These reports consisted of pipe details, PACP inspection ratings and inspection snapshots of major defects. Two sample pipes were selected to analyze and compare their fuzzy performance index with PACP and weighted performance index. The selected pipe samples lied in a highly corrosive soil and was subjected to heavy live loads due to adjacent major highways. Drainage ID 527083 comprised of 24” diameter Corrugated Metal Pipe (CMP) and Drainage ID 527314 comprised of 24” diameter Reinforced Concrete Pipe (RCP).

PACP Rating Index

The PACP ratings for both the pipe samples were “4” i.e. poor condition. By observing Figure 7-3 and 7-4, it is evident that the corrugated metal pipe that lied in a highly corrosive soil deteriorated due to corrosion. On the other hand, the reinforced concrete pipe subjected to heavy live loading resulted in a broken pipe section.

Weighted Performance Index

The weighted performance index for these pipe samples were “3” i.e. fair condition. It implies that these pipes have a low likelihood of failure.

Fuzzy Performance Index

The fuzzy performance index for these pipe samples were “5” i.e. very poor condition. It implies that these pipes have a high likelihood of failure.

Figure 7-3: Sediments and Corroded Pipe

Figure 7-4: Broken Pipe Due to External Loading

The fuzzy performance index reflected the ground truth and provided sensitive results by capturing interdependencies between parameters. In contrast, the weighted performance index produced less sensitive results as the weights assigned to each parameter were fixed. This is also evident from Figure 7-5, where, the weighted performance index is clustered towards the good and fair conditions, which do not represent actual conditions.

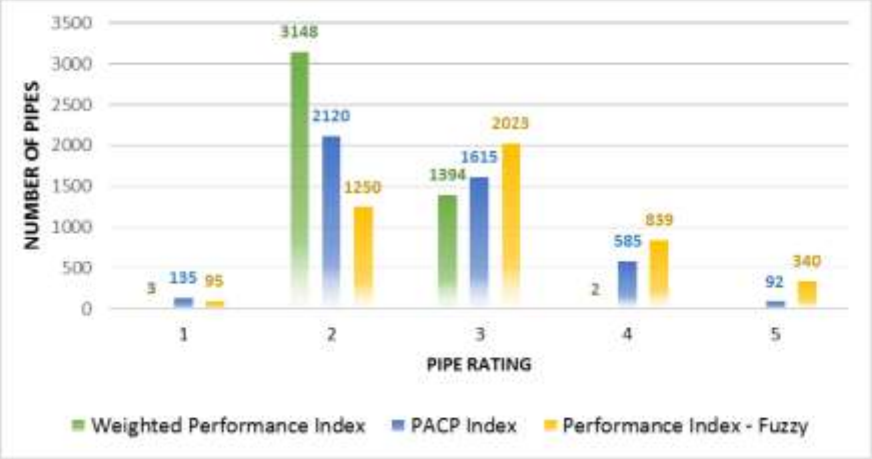


Figure 7-5: Comparison between Weighted Performance Index Vs PACP Vs Fuzzy Performance Index

Chapter 8

Development of a Stormwater Pipe Prediction Model

Like other engineering structures, stormwater pipes wear out or deteriorate with time which reduces their structural integrity and hydraulic capacity. The effects of pipe deterioration can cause pipes to collapse with consequences such as traffic disruption, flooding, and environmental pollution. Therefore, managing and maintaining the performance of buried stormwater pipes is a significant task to asset managers. This task requires information on the current and future condition of stormwater pipes. Accurate prediction of stormwater pipe structural deterioration plays an essential role in asset management and capital improvement planning. The prediction of an asset's durability is difficult because of the number of variables in the natural environment that affect the asset's service life.

8.1 Overview

Performance prediction models forecast the deterioration behavior of an asset over time based on its present performance and the surrounding environment. Understanding of asset performance changes over time plus a comprehensive understanding of current performance is pivotal to accomplish effective infrastructure asset management frameworks. Figure 8-1 shows a generic pipe performance prediction curve based on performance index plotted over time.

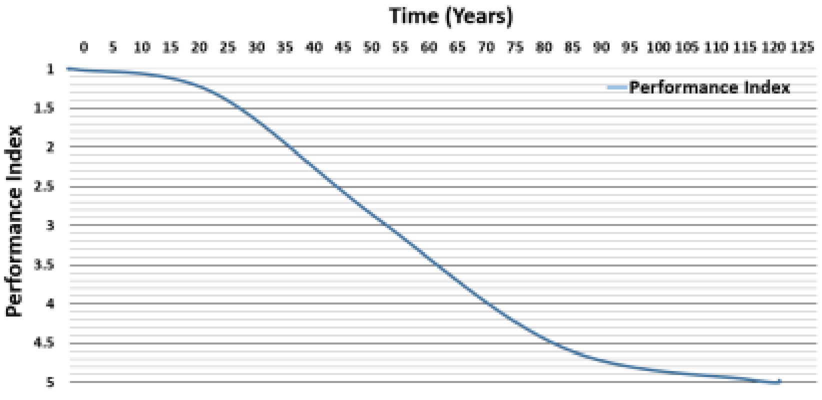


Figure 8-1: Pipe Performance Prediction Curve

Performance prediction models will aid utility managers to proactively plan renewal projects to rehabilitate or replace pipes before they fail. Prediction models aid proactive renewal planning to avoid emergency failure costs such as emergency contractor fees, labor overtime, and other unplanned costs. It can help decision makers to plan and execute renewal projects in conjunction with pavement projects for a specific pipe location. Existing prediction models for stormwater pipes do not capture all performance parameters affecting stormwater pipe deterioration. Sections 8.2 and 8.3 discusses existing prediction models and Section 8.4 discusses future work on stormwater pipe prediction models.

8.2 Markov Model – Stormwater Pipes

The Markov model is based on the assumption that the future condition of a stormwater pipe relies on its current condition and it does not take the historical states into account (Ross 2014). Markov models can be used to predict the remaining life of stormwater pipes (Tran et al. 2008). Markov models are based on Markov chain theory (Ross 2014). For instance, the deterioration process of a stormwater pipe is in condition state i at time t, the probability that the deterioration process moves to condition state j at time $t+1$ is P_{ij}.

In a Markov model, the sample of pipes required to estimate a transition matrix is assumed to depict a uniform population and the transition matrix for a network of pipe can be estimated. This concludes that all the pipes in that network are assumed to have same transition matrix and represents the performance of pipes considering the change in condition states over time. The transition probabilities can be determined using the structural condition of the sample pipe population as explained in (Tran et al. 2008).

Micevski et al. (2002) utilized Markov models to predict the deterioration process for a network of pipes. Though this model performed well on the network level, it lacked prediction of deterioration process for individual pipes.

8.3 Neural Network Model (NNM) and Support Vector Machines (SVM)

Tran et al. (2007) developed neural network models to predict the remaining life of stormwater pipes in Dandenong, Australia. CCTV pipe inspection data was collected, representing 2.2 % of the total length of stormwater pipes in that location. Although neural networks performed well for predicting the structural condition of a pipe, several limitations existed related to model development (Harvey and McBean 2014).

Tran and Ng (2010) developed a support vector machine model to predict the remaining life of stormwater pipes using the CCTV data from Dandenong, Australia. This model was tested and compared with the back propagation neural network model. It has been observed that the SVM model outperforms the NNM on a network level and for individual pipes. The parameters used to develop the model includes: pipe size, age, slope, depth, tree-count, hydraulic condition, pipe location, soil type and moisture. However, available prediction models lack transparency and do not capture the interdependencies between the input parameters.

8.4 Future Work on Prediction Models

Prediction models are very crucial in determining the remaining life of stormwater pipes. However, since available prediction models act as black boxes they capture only limited parameters and fail to represent real world conditions. Existing prediction models use CCTV data and limited parameters to determine the remaining life. Unlike, existing models, future research should utilize the performance index framework in this study to develop prediction models, since the fuzzy performance index captures;

- A comprehensive list of performance parameters impacting stormwater pipe deterioration.
- Better representation of real world conditions by analysing the interdependencies between parameters.

Performance prediction models are merely performance index moving in time. Therefore, the reliability of a robust prediction model lies on how well the actual performance is captured; where traditional condition ratings fail. As a next step, state dependent prediction models can be developed; determines the probability of a pipe segment remaining in its current state at a given time. Markov-based state dependent prediction models are widely used to predict deterioration of infrastructure systems. This research recommends future work on stormwater pipe prediction models to utilize existing prediction model frameworks developed by (Micevski et al. 2002); (Tran et al. 2008); Tran et al. (2007); Tran and Ng (2010) and incorporate fuzzy performance index into the above mentioned models to take them a step further.

8.4.1 Development of cohorts to collect time dependent data

Developing performance prediction models with only the present condition is irrational and unreliable. Pipe internal and external environment changes over time. The reliability of a performance prediction model relies on the richness of time dependent data used. Developing time dependent performance prediction models for stormwater pipes is complicated; as they require historical data, which is currently not available. Collecting historical data with minimal funds is unreasonable and overburdens stormwater utilities. However, stormwater utilities should put efforts to collect historical data for a target location or a cohort within its boundary to support future research on prediction modeling.

Chapter 9

Conclusion & Recommendation

9.1 Conclusions

Stormwater pipe asset management is a relatively new concept, inviting several potential research opportunities. This research aims to assist stormwater utilities, to better understand their system and to assess the performance of their stormwater pipes. This research made an effort to compile and expand the list of parameters affecting stormwater pipes to make it comprehensive. Stormwater utilities can utilize the parameters and units proposed in this research for effective and efficient data collection. Adopting this data structure enables the utilities to collect relevant data, and considerably improves the confidence of the model and reliability of the index.

A performance index for stormwater pipes was developed utilizing performance parameters affecting stormwater pipes. The developed performance index serves as a comprehensive index capturing the parameters and their interdependencies. It aids stormwater utilities to gauge the performance of its pipes, thereby, assisting them in making decisions on maintenance and prioritizing renewal projects. The model was validated with the inspection pipe ratings provided by one stormwater utility to verify its effectiveness.

Unlike, traditional pipe rating system, this model does not solely depend on inspection data, it further makes improvements to capture other physical, operational and environmental parameters, making it a comprehensive tool. The fuzzy inference model performed well and compensated for inaccuracies, vagueness and incomplete information. Unlike the weighted factor method adopted by the previous study (Bhimanadhuni 2015), the FIS adopted by this research capture interdependencies between performance parameters and modules. Overall, this study has developed a comprehensive list of stormwater pipe performance parameters and made noticeable improvements to the existing performance index.

9.2 Recommendations for future study

This research discusses the scope of research in stormwater pipe prediction modeling and recommends improvements. The following are the recommendations proposed by this study;

- This study identified 80 parameters affecting stormwater pipes. However, due to limited availability of data, only 38 critical parameters were considered for developing the model. Future research should review the critical parameters and incorporate additional parameters in the model.
- Enhance the performance index from the current scale to higher scale (i.e.) from 1-5 scale to a higher scale for better stratification of the performance of stormwater pipes. The enhanced scale could assist decision makers to understand the system better and aids them in making informed decisions.
- The developed model was evaluated and validated. Future research should utilize standard verification and validation techniques to document the accuracy of the model. Further, the developed index needs to be validated by comparing it with the pipe samples from participating utilities.
- The rules statements and parameter ranges were drawn up by reviewing previous work, interaction with utilities and engineering judgment. Future research should aim to conduct a nation-wide survey to verify the parameter ranges and rule statements.
- Existing knowledge on the failure mechanisms and factors influencing the deterioration of stormwater pipes are minimal. Future studies should aim to capture these mechanisms and factors by surveying subject matter experts, consultants, and utility managers.
- Future research should focus on incorporating the factors influencing the deterioration of appurtenant structures such as inlets, junctions, and outlets. Moreover, their impact on the performance of stormwater pipes should be studied.
- The developed performance index should be integrated with PIPE*i*D – Living National Database. Participating utilities should have access to upload their data, run the model, and visualize the results in an online GIS environment created as a part of PIPE*i*D.

- Estimating the remaining life of stormwater pipe is very crucial for predicting the end life of pipes and planning for future capital investment decisions, however, this is beyond the scope of this research. Future work should utilize the performance index in this study with state or time-dependent models to develop prediction models that gauge the remaining life of stormwater pipes.
- Stormwater utilities should start collecting time dependent data by creating cohorts or target locations within the utility network to support future research on performance prediction models.

REFERENCES

Allison Sundel, K. (2017). "Massive Lynden sinkhole could take months to fix." *North West News for Washington, Oregon and Idaho*.

Angkasuwansiri, T., and Sinha, S. K. (2013). "Comprehensive list of Parameters Affecting Wastewater Pipe Performance." *Technology Interface International Journal*, 13(2), 68-79.

Angkasuwansiri, T., and Sinha, S. K. (2014). "Development of wastewater pipe performance index and performance prediction model." *International Journal of Sustainable Materials and Structural Systems*, 1(3), 244-264.

Arlington County Watershed Management Plan (2001). "Watershed Management Plan."

ASCE (2017). "ASCE's 2017 Infrastructure Report Card."

Ault, J. P. (2003). "Service Life Evaluation of Corrugated Steel Pipe " *TRB*.

Bai, H., Sadiq, R., Najjaran, H., and Rajani, B. (2008). "Condition assessment of buried pipes using hierarchical evidential reasoning model." *Journal of Computing in Civil Engineering*, 22(2), 114-122.

Beieler, R. W., Environmental, Water Resources Institute . Task Committee on Pipelines for Water, C., and Drainage (2013). *Pipelines for water conveyance and drainage*, American Society of Civil Engineers, Reston, Virginia.

Betz, J. W. (2013). "Fundamentals of Stormsewer Pipe Asset Management." *Masters in Civil Engineering, Virginia Polytechnic Institute and State University*.

Bhimanadhuni, S. (2015). "Development of a Performance Index for Stormwater Pipeline Infrastructure." Virginia Tech.

Bhimanadhuni, S., and Sinha, S. K. (2015). "Development of Performance Index for Stormwater Pipeline Infrastructure." *Pipelines 2015*, 1005-1016.

Blom, D. (2016). "Aging metal stormwater pipes and lots of rain create sinkholes; Mission facing several repairs after pipes fail."

Burgess, J. (2016). "Old pipes, big problems: More than 20 sinkholes in Asheville." *Citizen Times - Part of the USA Today Network.*

CBS8 (2010). "Crews to begin repairing sinkhole near gas line in El Cajon." *CBS*.

Chughtai, F., and Zayed, T. (2007). "Sewer pipeline operational condition prediction using multiple regression." *Pipelines 2007: Advances and Experiences with Trenchless Pipeline Projects*, 1-11.

Cripe, A. (2016). "Sinkhole exposes storm drain problem." *Corvallis Gazette-Times*.

Dasari, V. M. B. (2016). "Web-Based Platform for Force Main Infrastructure Asset Management." Virginia Tech.

Drainage Manual (2000). "Minnesota Department of Transportation, Minnesota, Chapter 8.".

Ennaouri, I., and Fuamba, M. (2011). "New integrated condition-assessment model for combined storm-sewer systems." *Journal of Water Resources Planning and Management*, 139(1), 53-64.

Ezrin, M. (1996). *Plastics Failure Guide: Cause and Prevention*, Hanser Pub.

Filice, J. (2001). "Best Practices Guidelines for Culvert Liner Selection."

Flintsch, G. W., and Chen, C. (2004). "Soft Computing Applications in Infrastructure Management." *Journal of Infrastructure Systems*, 10(4), 157-166.

Fuzzy Logic Toolbox^{TM} MATLAB® (2016). *Math Works Inc*.

Gemora, I. (2003). "Pipeline Assessment and Certification Program." *New Pipeline Technologies, Security, and Safety*.

Hamam, A., and Georganas, N. D. "A comparison of Mamdani and Sugeno fuzzy inference systems for evaluating the quality of experience of Hapto-Audio-Visual applications." *Proc., Haptic Audio visual Environments and Games, 2008. HAVE 2008. IEEE International Workshop on*, IEEE, 87-92.

Harvey, R., and McBean, E. (2014). "Understanding Stormwater Pipe Deterioration Through Data Mining." *Journal of Water Management Modeling*.

Indiana DOT (2014). "Inspection Manual for Precast Concrete Pipe and Structures."

Islam, M. M., Ali, A., and Purtell, J. (2009). "Enhanced Condition Assessment Methodologies of Buried Infrastructure." *Pipelines 2009*.

Khan, Z., Zayed, T., and Moselhi, O. (2010). "Structural Condition Assessment of Sewer Pipelines." *Journal of Performance of Constructed Facilities*, 24(2), 170-179.

Khazraeializadeh, S. (2012). "A Comparative Analysis on Sewer Structural Condition Grading Systems Using Four Sewer Condition Assessment Protocols." University of Alberta.

Khazraeializadeh, S., Gay, L. F., and Bayat, A. (2014). "Comparative analysis of sewer physical condition grading protocols for the City of Edmonton." *Canadian Journal of Civil Engineering*, 41(9), 811-818.

Koo, D.-H., and Ariaratnam, S. T. (2006). "Innovative method for assessment of underground sewer pipe condition." *Automation in Construction*, 15(4), 479-488.

Lampe, L., Barrett, M., Woods-Ballard, B., Kellagher, R., Martin, P., Jeffries, C., and Hollon, M. (2005). "Performance and Whole Life Costs of Best Management Practices and Sustainable Urban Drainage Systems: Final Report 2005, WERF Project 01-CTS-21T." *Water Environment Research Foundation: Alexandria, Virginia*.

Li, Z., Chau, C. K., and Zhou, X. (2005). "Accelerated Assessment and Fuzzy Evaluation of Concrete Durability." *Journal of Materials in Civil Engineering*, 17(3), 257-263.

Mamdani, E. H., and Assilian, S. (1999). "An Experiment in Linguistic Synthesis with a Fuzzy Logic Controller." *International Journal of Human-Computer Studies*, 51(2), 135-147.

McGarry, F. J., Mandell, J. F., and Hsueh-Lee, L. "Brittle fracture in PVC pipe material." *Proc., Journal of Polymer Science: Polymer Symposia*, Wiley Online Library, 83-110.

Meis, R. D., Maragakis, E. M., and Siddharthan, R. (2003). "Behavior of underground piping joints due to static and dynamic loading."

Micevski, T., Kuczera, G., and Coombes, P. (2002). "Markov model for storm water pipe deterioration." *Journal of infrastructure systems*, 8(2), 49-56.

Morgan, R. A., Edwards, F. G., Brye, K. R., and Burian, S. J. (2005). "An evaluation of the urban stormwater pollutant removal efficiency of catch basin inserts." *Water environment research*, 77(5), 500-510.

Najafi, M., and Kulandaivel, G. (2005). "Pipeline condition prediction using neural network models." *Pipelines 2005: Optimizing Pipeline Design, Operations, and Maintenance in Today's Economy*, 767-781.

Najjaran, H., Sadiq, R., and Rajani, B. (2004). "Modeling pipe deterioration using soil properties-an application of fuzzy logic expert system." *Pipeline Engineering and Construction: What's on the Horizon?*, 1-10.

NASSCO (2001). "Pipeline Assessment Certification Program (PACP) Manual." Reference Manual, NASSCO.

O'Connor, C. (2011). "The nature of polyethylene pipe failure." *Modern Plastics Worldwide*, 88(2), 20-22.

Opila, M. C. (2011). *Structural condition scoring of buried sewer pipes for risk-based decision making*, University of Delaware.

Opila, M. C., and Attoh-Okine, N. (2011). "Novel Approach in Pipe Condition Scoring." *Journal of Pipeline Systems Engineering and Practice*, 2(3), 82-90.

Portland Cement Association (2002). "Types and Causes of Concrete Deterioration."

Rahman, S., and Vanier, D. J. (2004). "An Evaluation of Condition Assessment Protocols for Sewer Management." *Client Report. NRC Institute for Research in Construction*.

Ross, S. M. (2014). *Introduction to probability models*, Academic press.

Rowe, R., Kathula, V., Bergin, J., and Kennedy, C. C. (2011). "Asset Management Likelihood of Failure Scoring Improved by Condition Assessment Scoring Integration Techniques." *Pipelines 2011*.

Sinha, S., Angkasuwansiri, T., and Thomasson, R. (2008). "Phase-1: Development of standard data structure to support wastewater pipe condition and performance prediction." *Development of protocols and methods for predicting the remaining economic life of wastewater pipe infrastructure assets, Water Environment Research Foundation, Alexandria, VA.*

Skipworth, P. J., Tait, S. J., and Saul, A. J. (1999). "Erosion of sediment beds in sewers: Model development." *J. Environ. Eng.-ASCE*, 125(6), 566-573.

St Clair, A. M. (2013). "Development of a Novel Performance Index and a Performance Prediction Model for Metallic Drinking Water Pipelines."

Strauch, J. A., and Wetzel, D. M. (2006). "Collection System Asset Management — Benchmarking Performance through Annual Reporting." *Pipelines 2006*.

Tagherouit, W. B., Bennis, S., and Bengassem, J. (2011). "A fuzzy expert system for prioritizing rehabilitation of sewer networks." *Computer-Aided Civil and Infrastructure Engineering*, 26(2), 146-152.

Tenbusch, A., Dorwart, B., & Tenbusch, A. F (2009). "Failing Culverts-The Geotechnical Perspective." <http://www.tenbusch.com/underground_equipment/files/FailingCulvertsGeotechnicalPerspective.pdf>.

Tennessee Erosion Control Handbook (2002). "Tennessee Erosion Control Handbook."

Tran, D., Ng, A. W. M., Mcmanus, K., and Burn, S. (2008). "Prediction models for serviceability deterioration of stormwater pipes." *Structure and Infrastructure Engineering*, 4(4), 287-295.

Tran, D. H., Ng, A. W. M., and Perera, B. J. C. (2007). "Neural networks deterioration models for serviceability condition of buried stormwater pipes." *Engineering Applications of Artificial Intelligence*, 20(8), 1144-1151.

Tran, H. D., and Ng, A. (2010). "Classifying structural condition of deteriorating stormwater pipes using support vector machine." *Pipelines 2010: Climbing New Peaks to Infrastructure Reliability: Renew, Rehab, and Reinvest*, 857-866.

Urban Drainage Design Manual (2001). "Hydraulic Engineering Circular No. 22." *US Department of Transportation*.

US General Accounting Office (2000). *U.S. Infrastructure: Funding Trends and Opportunities to Improve Investment Decisions : Report to the Congress*, The Office.

USDA NRCS (2017). "Web Soil Survey." <http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>. (Apr. 1, 2017).

Wenzlick, J. D., and Albarran-Garcia, J. (2008). "Effectiveness of Metal and Concrete Pipe Currently Installed in Missouri (Phase 2)."

Whittle, L. G., Steiner, K., and Sinha, S. (2011). "The Need for National Data Standards for Condition Assessment." *Pipelines 2011*.

Yan, J. M., and Vairavamoorthy, K. (2003). "Fuzzy Approach for Pipe Condition Assessment." *New Pipeline Technologies, Security, and Safety*.

Zadeh, L. A. (1965). "Fuzzy sets." *Information and control*, 8(3), 338-353.

Zhao, J. Q., Kuraoka, S., Baker, T. H. W., Gu, P., Masson, J. F., Boudreau, S., and Brousseau, R. J. (1998). "Durability and Performance of Gravity Pipes: A State-of-the-Art Literature Review." 60.

Zhou, Y., Vairavamoorthy, K., and Grimshaw, F. (2009). "Development of a Fuzzy Based Pipe Condition Assessment Model Using PROMETHEE." *World Environmental and Water Resources Congress 2009*.

Appendix A. Stormwater Pipe Performance Parameters

This appendix contains a list of stormwater pipe performance parameters identified by previous research work.

Sl.No	**Parameter**	**Unit**	**Brief Explanation**
1	Age	Year	Age is the length of time since pipe was installed. It may or may not be a strong indicator of pipe deterioration. Typically, it is assumed that effects of pipe deterioration become more apparent with time.
2	Diameter	Inch	Diameter is typically classified by nominal or outside diameter rather than inside diameter. The failure pattern and rate of failure vary with a pipe diameter. Smaller diameter pipes are more susceptible to failure than larger diameter pipes as they can be easily blocked and their depth of cover requirements are underestimated by designers.
3	Shape	Type	The pressure on a pipe due to similar load varies with the shape of the pipe. Moreover, the cross-section area in contact with water differs with pipe shape, for the same volume of water.
4	Length	Feet	Length of pipe refers to the distance between manholes or nodes. Short length pipes have an increased number of joints leading to more possible point of failure.
5	Thickness	Inch	Thickness can dictate the time corrosion takes to result in pipe failure. The loading stress on a pipe is a function of depth of cover and thickness of pipe.
6	Material	Type	Different material types are designed for different service needs and dictate the resistance to corrosion and resilience to strength.
7	Depth of Cover	Feet	The depth of pipe has a role in the stress being transferred from the live and dead load on surface and protection from frost. Shallow pipes fail faster than deeper pipes. Stormwater pipes typically are said to be at shallower depths in comparison to wastewater pipelines.
8	Slope	Gradient	Slope effects the rate of gravity flow. Steep slopes lead to faster flow rates, thereby having a higher deterioration rates when compared to flatter slopes. If the slope of the stormwater pipe is not adequate it may result in blockage or sedimentation.
9	Joint Type	Type	Different choices of joint types are available for each pipe material. It is crucial to understand the features of the pipe material and required performance of the joint (leak resistant, soil tight, withstand bending, pull-apart scenarios etc.) to design the joining system. A wrong choice or deteriorated joint affects the performance of the storm sewer by aggravating infiltration and exfiltration or creating stress.
10	Coating	Yes/No Type	External coating increases the service life of stormwater pipes by preventing against corrosion and abrasion. It is important for metal pipes. .
11	Lining	Yes/No Type	Internal surface of a pipe can be coated to halt material deterioration, provide structural strength, and prevent infiltration and exfiltration. The lining materials can alter the water quality. Popular materials include cement mortar, epoxy, polyurethane and polyurea.
12	Associated Structures	Type	Different types of drainage structures are associated with a stormwater pipe. Stormwater is typically collected by catch basins, grated inlets, hooded grate inlets, etc. Headwalls, flared end sections and end of pipe structures can either collect or discharge stormwater runoff. Junction boxes and manholes are used to accommodate change in pipe direction, diameter or depth. The structure condition and sediment, debris or water levels in the structure are crucial to the performance (esp. blockage levels) of the attached stormwater pipes.
13	Lateral connections	No./ length	The required capacity of the stormwater pipe is depended on the service connections. If the size of the pipe is inadequate it leads to frequent overflows.

Sl.No	Parameter	Unit	Brief Explanation
14	Bedding Condition	Yes/No Condition	A pipe must be supported through even bedding that is properly tamped. Loss of bedding can lead to beam stress on pipe.
15	Trench Backfill	Type Condition	Trench backfill provides surrounding support for pipe stability and reduces displacements. Poor backfill can create shearing or friction forces on the side of the pipe.
16	Design Life	Year	The period of time the pipe was expected to function operationally when installed.
17	Design Storm	Intensity-Inch/hour, Duration-Hour, Frequency-Years	Design storm is a mathematical representation of precipitation in a given area for design of infrastructure. It is classified by intensity (how much inches of precipitation occurred in a given time), duration (how long the storm lasted) and recurrence interval (2 year or 5 year or 10 year). A storm of given intensity and duration and can occur only one time every 'x' years. A 2 year storm is less severe than 5 year storm and so on.
18	Function	Type	Different uses of the pipe (gravity main, lateral, pressurized main) affect the deterioration rate of the pipe. The unit is *type.*
19	Soil Type	Type	The pipe trench (with or without bedding and backfill) is sitting in a soil type. Certain soil types have high corrosion potential, are more prone to expansion and contraction when wet and have varying unit weights that determine the dead load from the soil.
20	Soil Corrosivity	Level	Soil corrosivity cannot be directly measure and hence needs to be documented. It is function of several soil properties like soil redox potential, soil pH, soil resistivity, soil sulfides, moisture content etc.
21	Groundwater Table	Feet or Level	Elevation of, or depth to the groundwater table is important to analyze its impact on infiltration, exfiltration causing groundwater contamination.
22	Location	Type	Location of the pipe aids in determining the type of land cover used for run off calculations.
23	Loading Condition (Dead Load)	Level	The magnitude of increase in the load on the pipe due to modernization or development leads to compressive forces on the pipe wall. If the pipe material and thickness do not match the load upon the pipe, it might lead to deformation in pipes.
24	Loading Condition (Live Load)	Level	Live loading from traffic can also lead to compressive forces on the pipe wall. Excessive bending and excessive crushing forces can lead to longitudinal and circumferential cracking online. It is also a measure for consequence of failure.
25	Proximity to Trees	Feet	A pipe that is in close proximity to trees has a higher probability of being subject to root intrusion.
26	Proximity to Utilities	Type Feet	One of the major reasons for damage of stormwater pipes is when the existing utilities damage them during their respective installation or repair activities.
27	Average Precipitation Intensity	Inch/hour	This factor enables to gauge if the stormwater pipe capacity is adequate.
28	Average Precipitation Duration	Hour	This factor enables to gauge if the stormwater pipe capacity is adequate.
29	Frost Penetration	Feet	It is an important design parameter for stormwater pipes. Installing stormwater pipes below the frost line protects them from excessive frost loading and prevents water from freezing in pipes.
30	Extreme Temperature	F	An obvious measure of climate is temperature. Extreme cold can cause rapid freezing which can cause pipes to burst. Extreme cold can reduce the infiltration capacity of the soil resulting in larger runoff volumes.

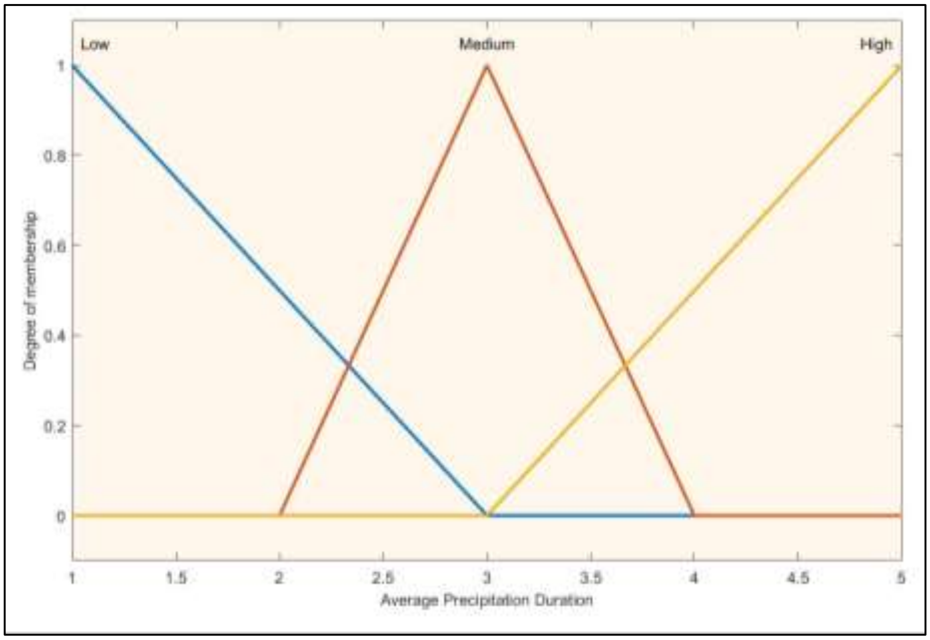
Sl.No	Parameter	Unit	Brief Explanation
31	Record of Extreme Event	Text	Any extreme event like third party disturbance or natural calamity that affected the stormwater pipe shall be documented here. This will help in improving the knowledge of the utilities about their assets.
32	Average Flow Velocity	Fps	The flow velocity in a stormwater pipe should be a minimum of 2 fps - 3 fps (as per the utility standard) to ensure self-cleaning. Also, velocities above the maximum allowable limit lead to surface wear.
33	Minimum Flow Velocity	Fps	The minimum flow velocity should be above the standard to ensure self-cleaning of pipe.
34	Maximum Allowable Velocity	Fps	The maximum allowable flow velocity for a pipe material to avoid mechanical surface wear.
35	Overflow Frequency	Level	Hydraulic deterioration is a process that reduces the discharge capacity of the pipe. The frequency and volume of overflows are an indication of hydraulic failure of the stormwater pipe.
36	Surcharging	Level	Surcharging is the condition where pipe flows full and under pressure. It is a consequence of hydraulic deterioration of the pipe or high groundwater tables.
37	Inflow and Infiltration	Level	Groundwater or stormwater entering into the system through cracks, holes or defects in joints. It increases the inflow volume and leads to entry of surrounding soil into pipe.
38	Exfiltration	Level	Exfiltration refers to water exiting the system through cracks, holes or defects in joints. It can give a false impression about the capacity of the storm sewer. It can contaminate the surrounding environment and groundwater.
39	Presence of stagnant water in pipe	Yes/No	Presence of stagnant water can lead to increased rate of corrosion in metal pipes. It is also an indication of a poor gravity flow design. The unit is *yes/no*.
40	Debris Level	Level	It is the amount of leaf matter, wooden matter, trash or other material observed in the pipe that affect its ability function to full capacity.
41	Sedimentation Level	Level	It is the amount of sediment observed in the pipe. It affects the hydraulic capacity of the pipe.
42	Smell or Vermin Level	Level	Smell is an indication of maintenance requirement of the pipe.
43	Post Installation Condition	Text	This parameter indicates the condition of the pipe post construction. It is typically assumed that all storm sewers have been laid as per the construction specifications. However, it is well acknowledged that poor installations can cause damage to pipe or poor bedding support.
44	Maintenance Method	Type Frequency	Inappropriate maintenance methods used to clean stormwater pipe can lead to accelerated deterioration for example jetting involves high water pressure resulting in surface wear.
45	Inspection/ CCTV Record	Text	Records help in understanding the stormwater pipe deterioration process. They provide an idea of the frequent problems associated with a pipe.
46	Renewal Record	Text	Records help in understanding the stormwater pipe deterioration process. They provide an idea of the frequent problems associated with a pipe.
47	Failure Record	Text	Records help in understanding the stormwater pipe deterioration process. They provide an idea of the frequent problems associated with a pipe.
48	Complaint Record	Text	Records help in understanding the stormwater pipe deterioration process. They provide an idea of the frequent problems associated with a pipe.
49	Capital Cost	Dollars	Records help in understanding the cost of replacing a stormwater pipe.
50	Annual Operation and Maintenance Cost	Dollars	Records help in understanding the annual amount spent on the maintenance and functioning of the pipe. If this amount is higher than the capital cost then the utility can consider the replacement of the pipe in the next capital improvement plans.

Appendix B. Fuzzy Membership Functions

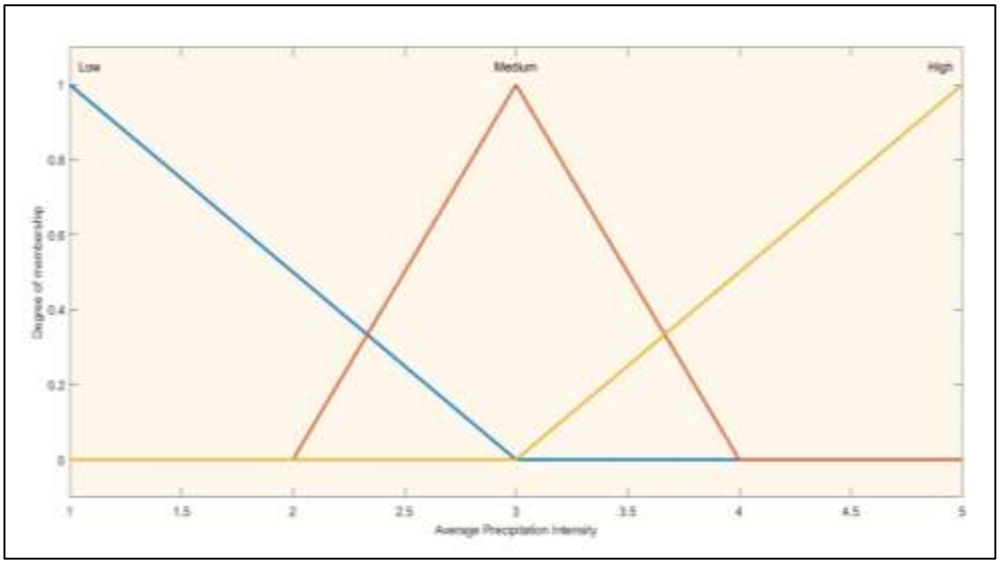
This appendix contains a list of fuzzy membership functions and their ranges for input and output variables for each module.

Capacity Module

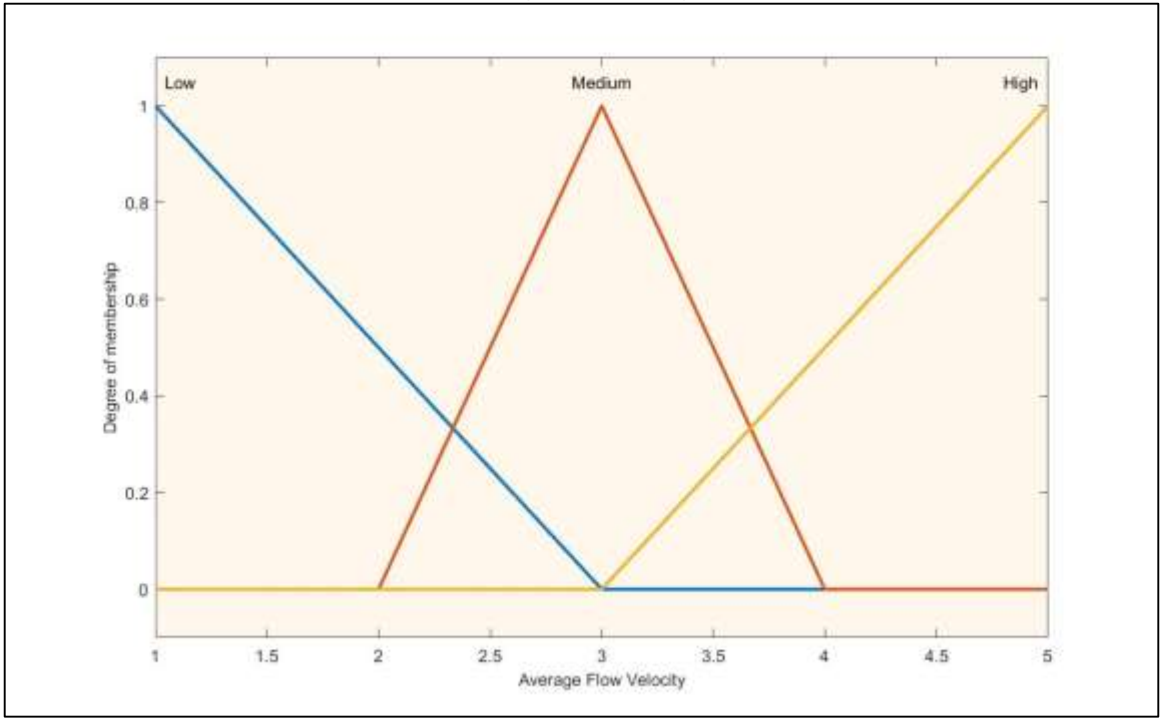
Average Precipitation Duration



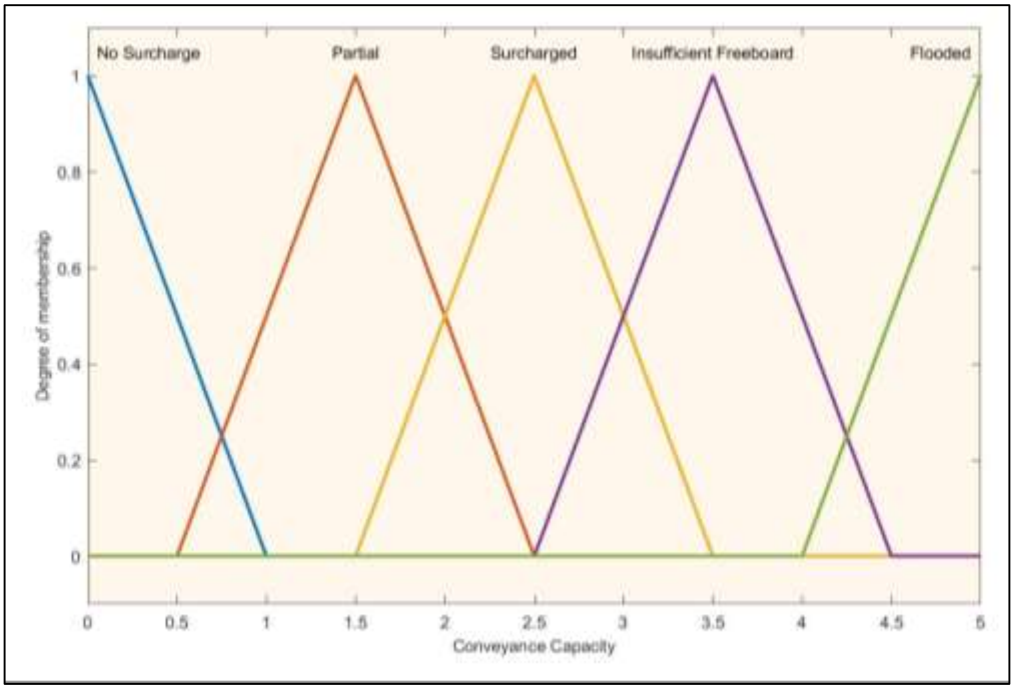
Average Precipitation Intensity



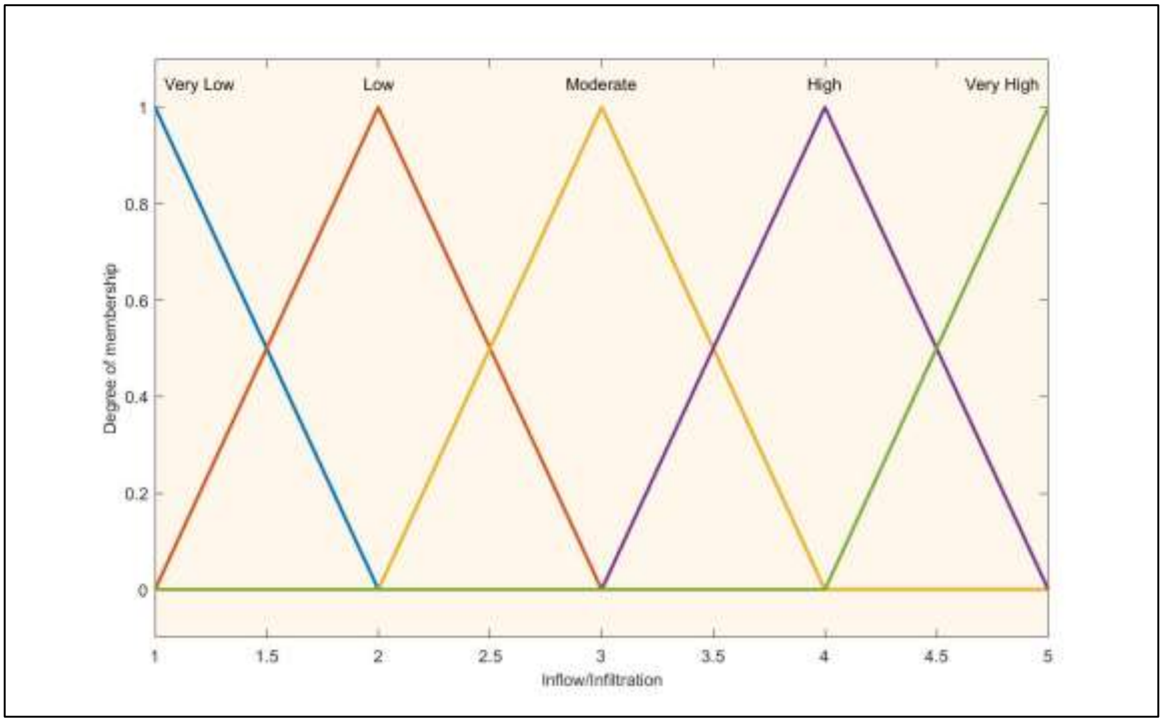
Average Flow Velocity



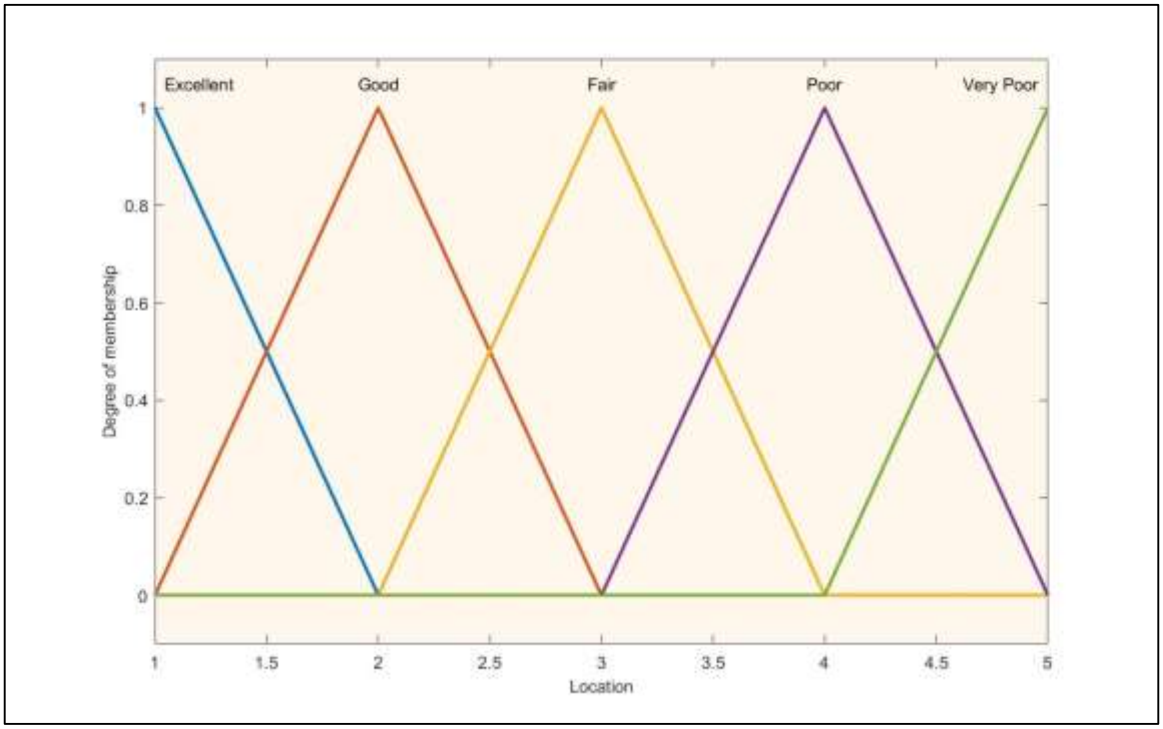
Conveyance Capacity



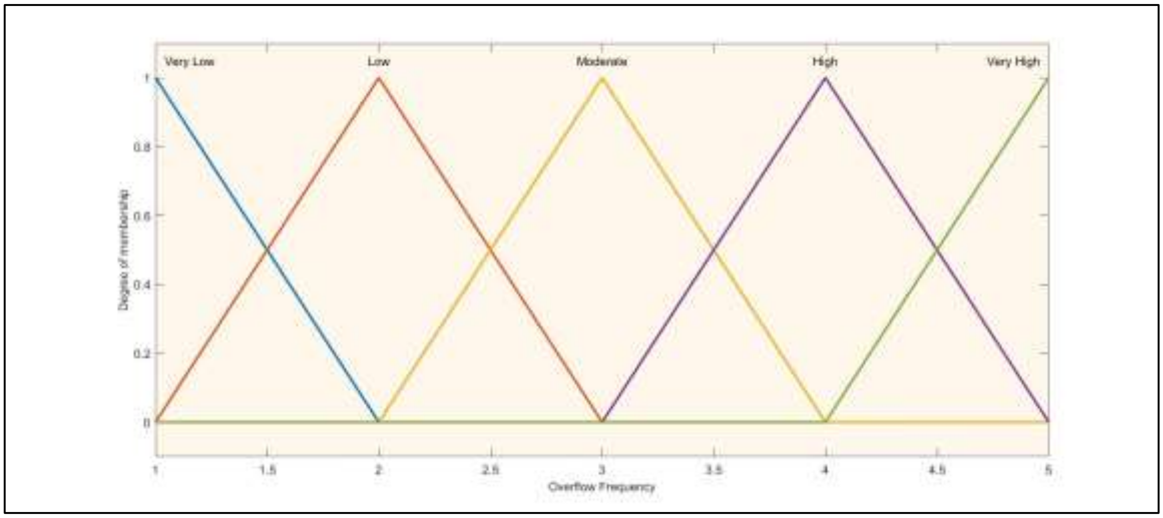
Inflow/ Infiltration



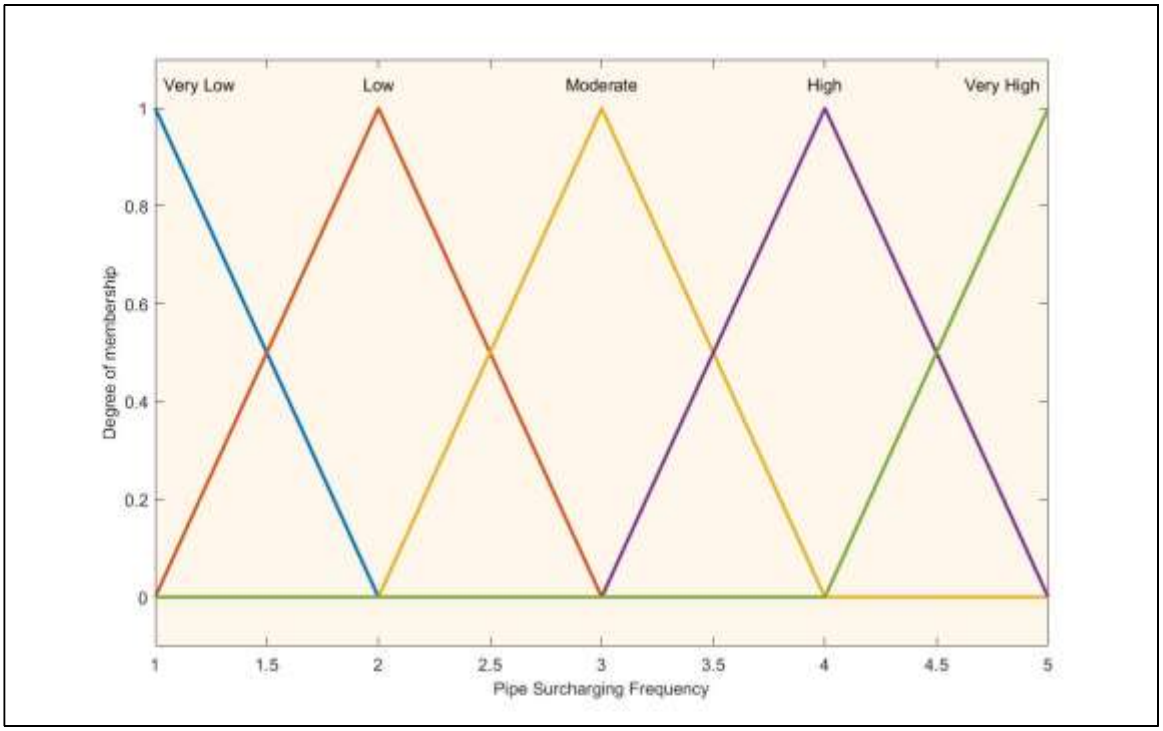
Location



Overflow Frequency

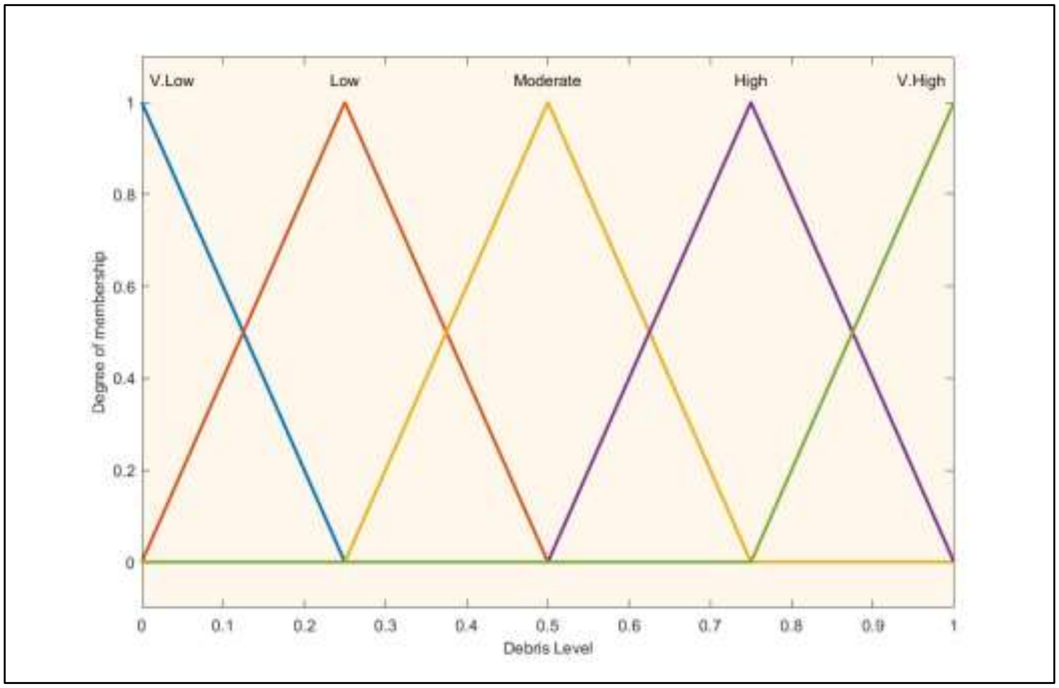


Pipe Surcharging Frequency

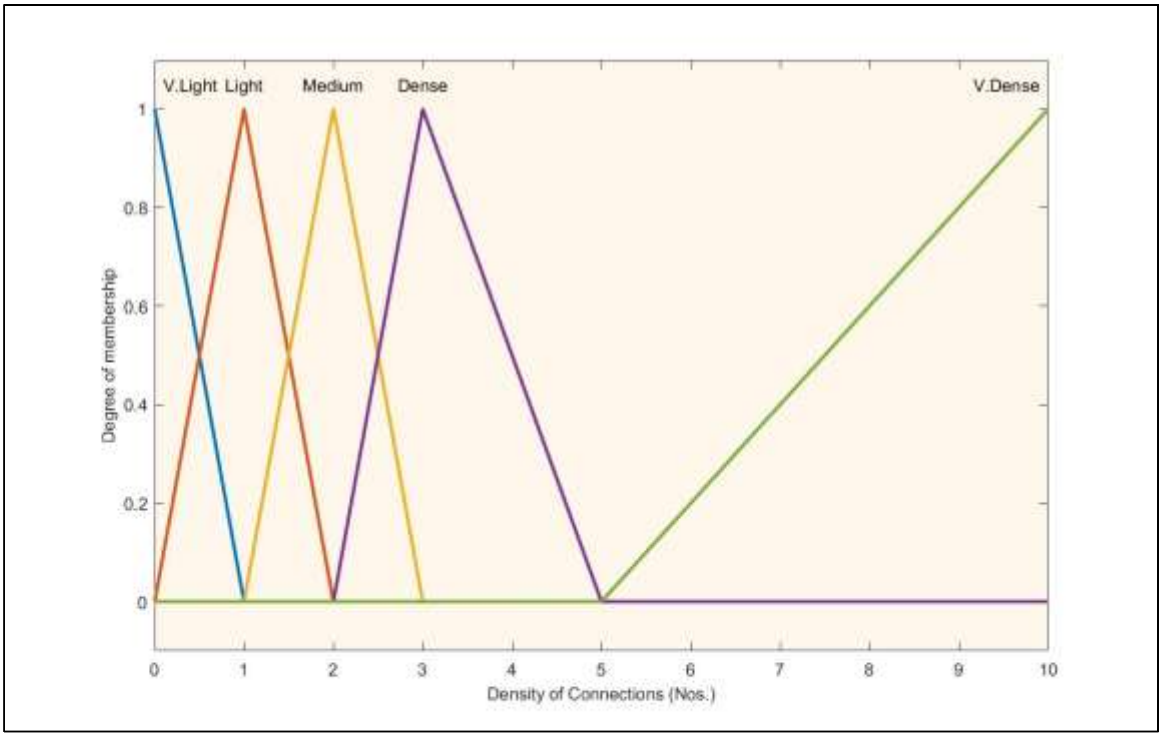


Blockage Module

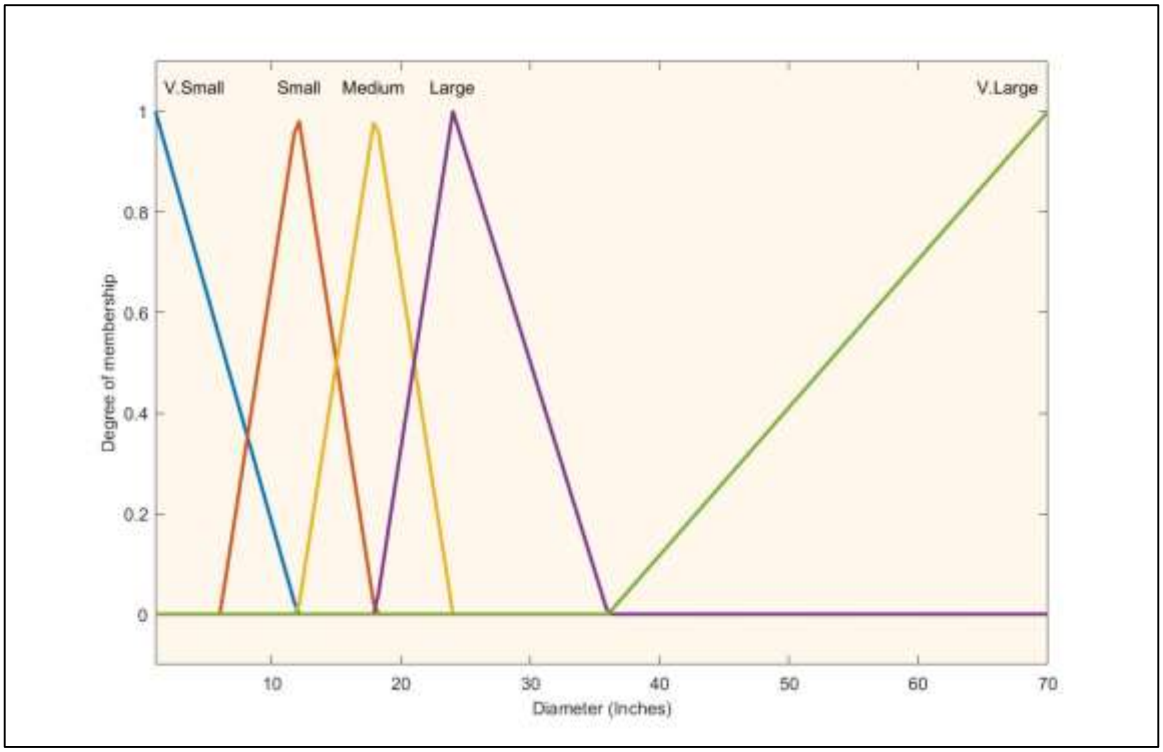
Debris Level



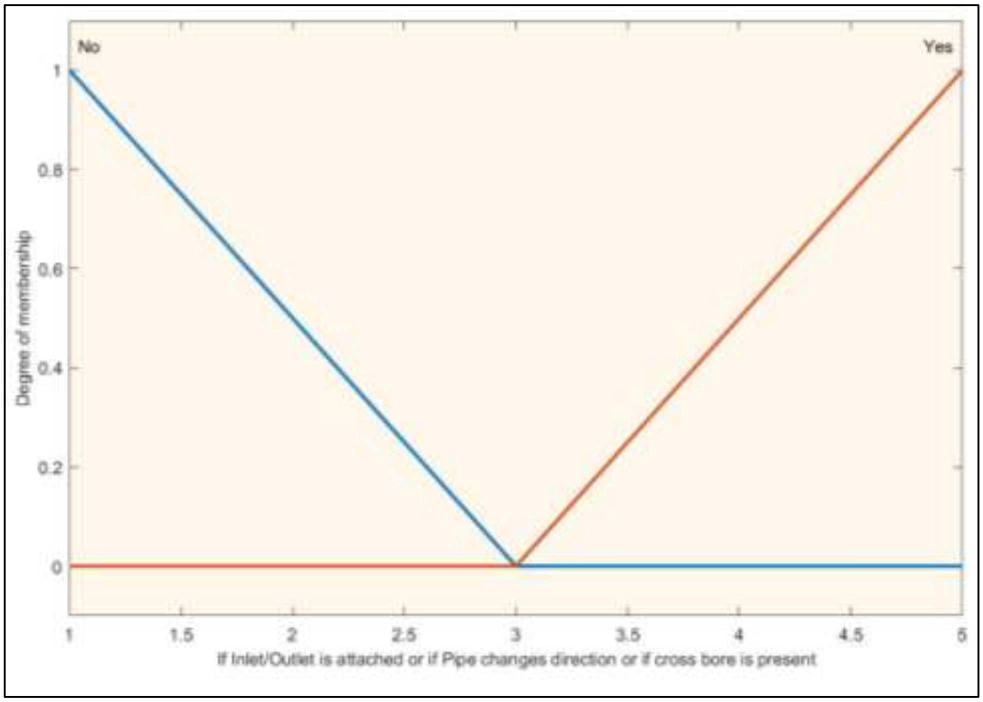
Density of Connections



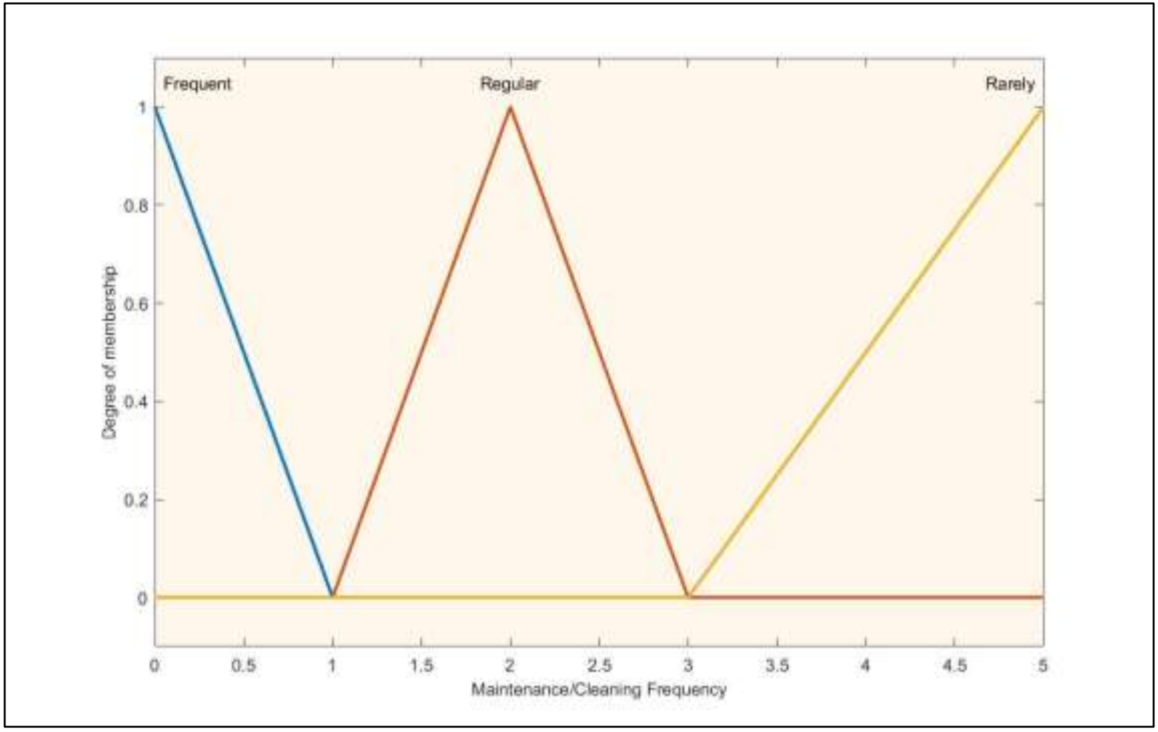
Diameter



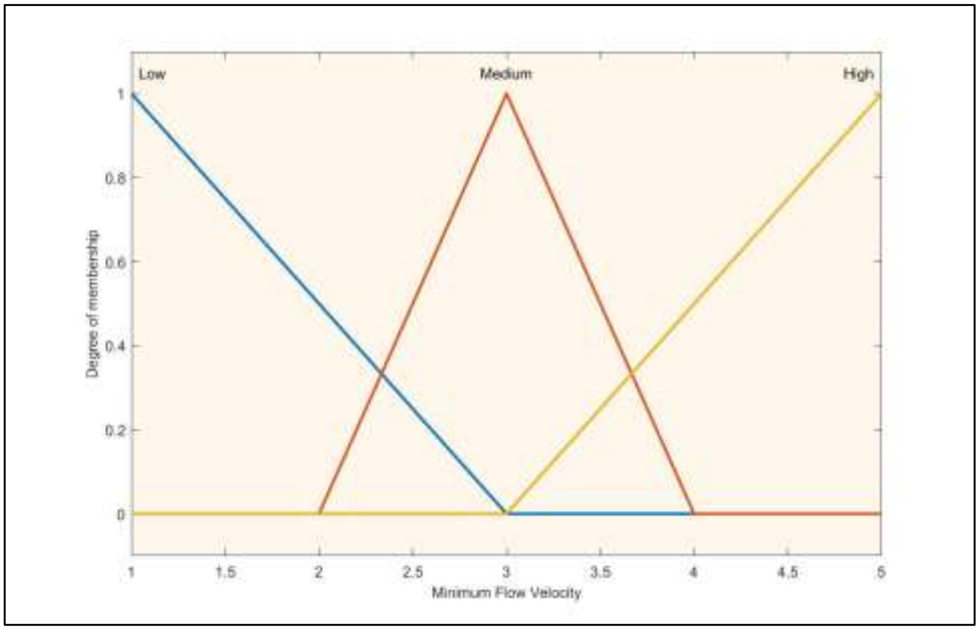
If Inlet/Outlet attached/pipe changes direction/cross bore is present



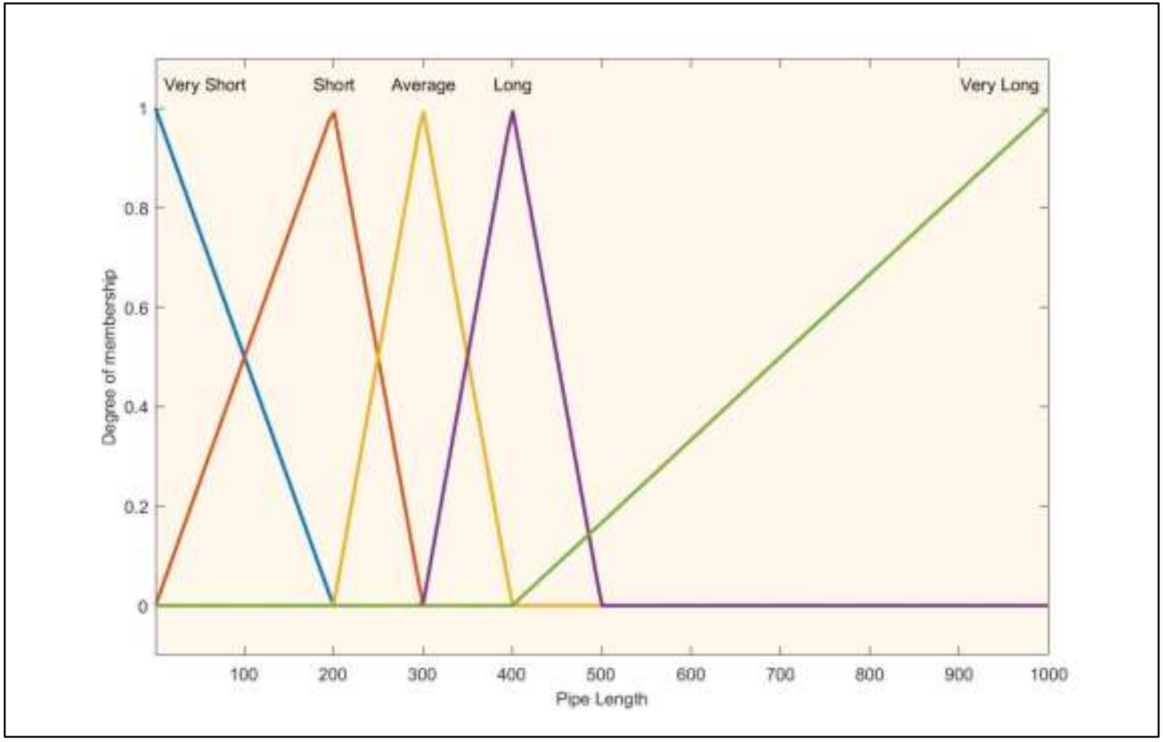
Maintenance/ Cleaning Frequency



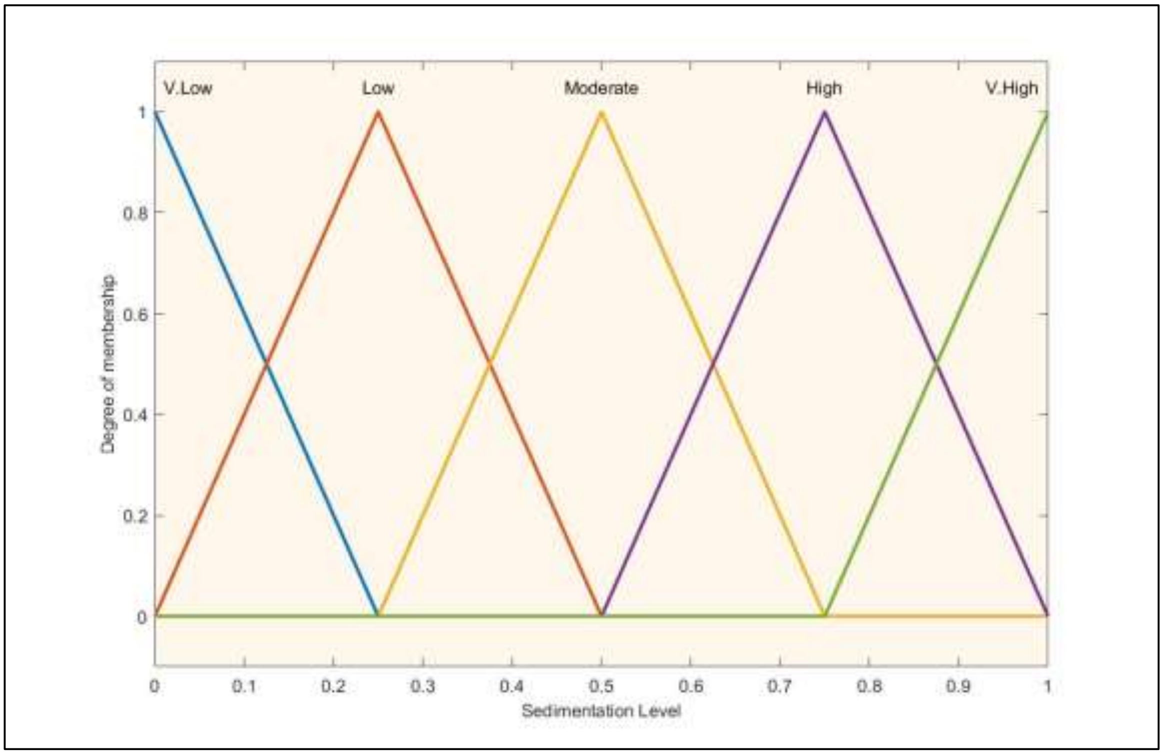
Minimum Flow Velocity



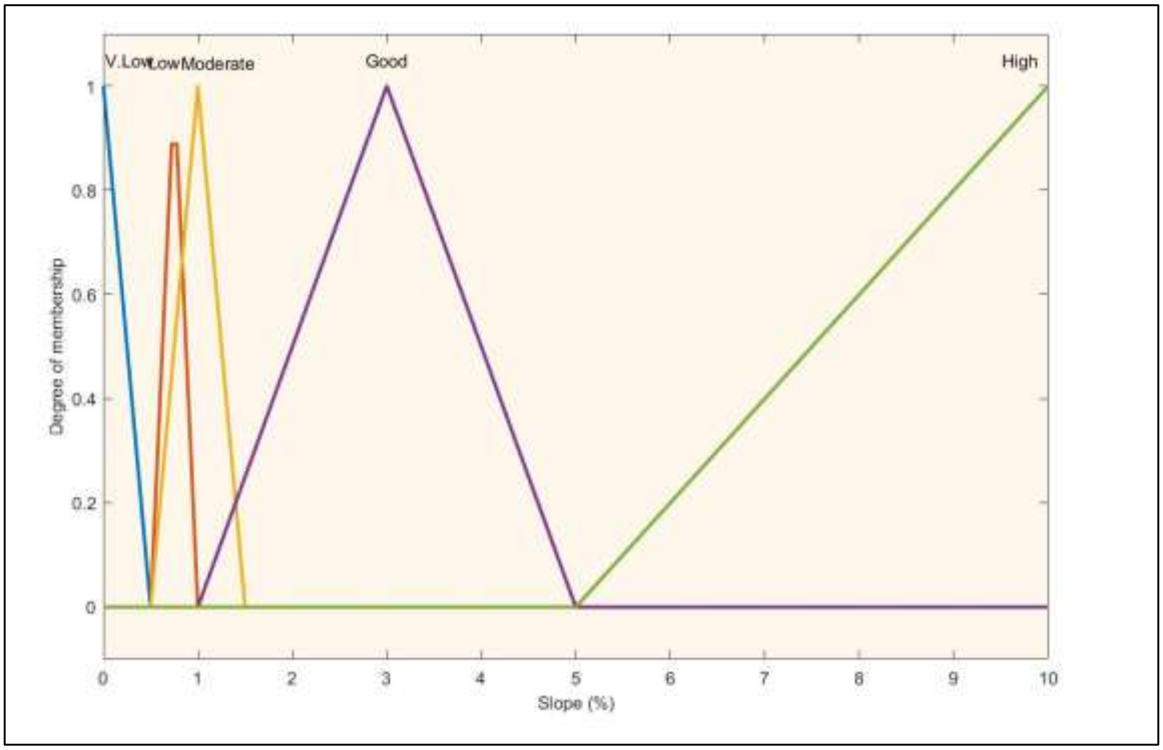
Pipe Length



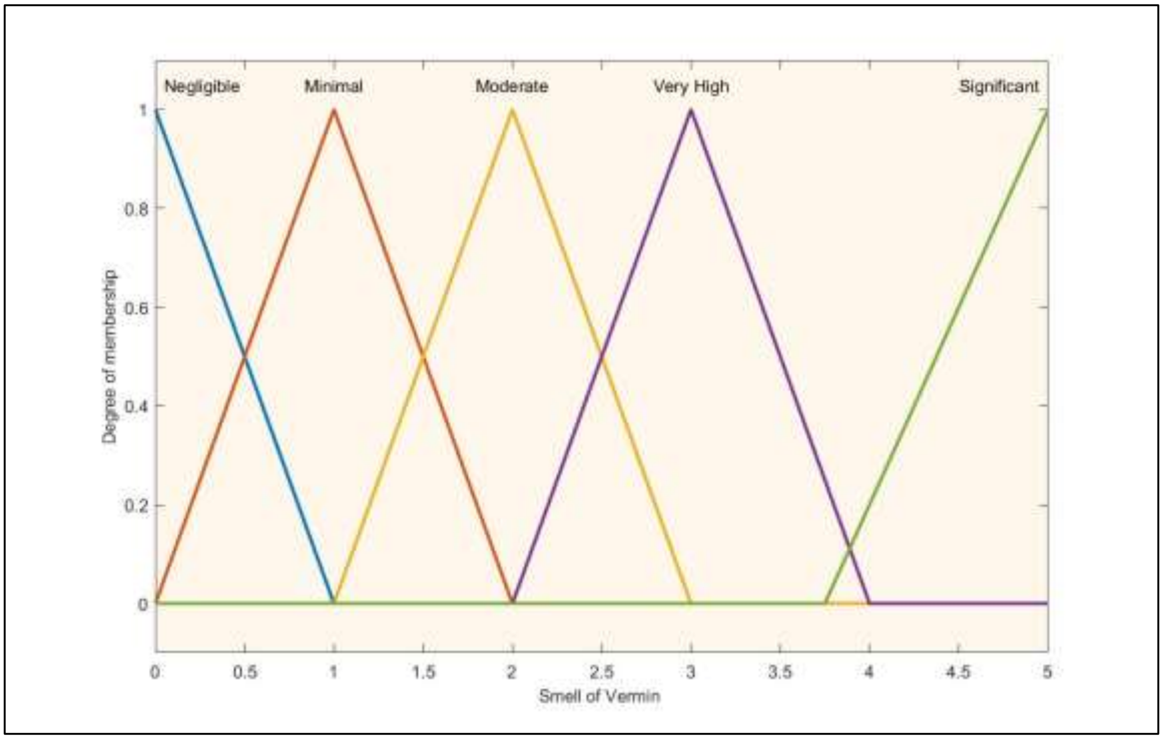
Sedimentation Level



Slope

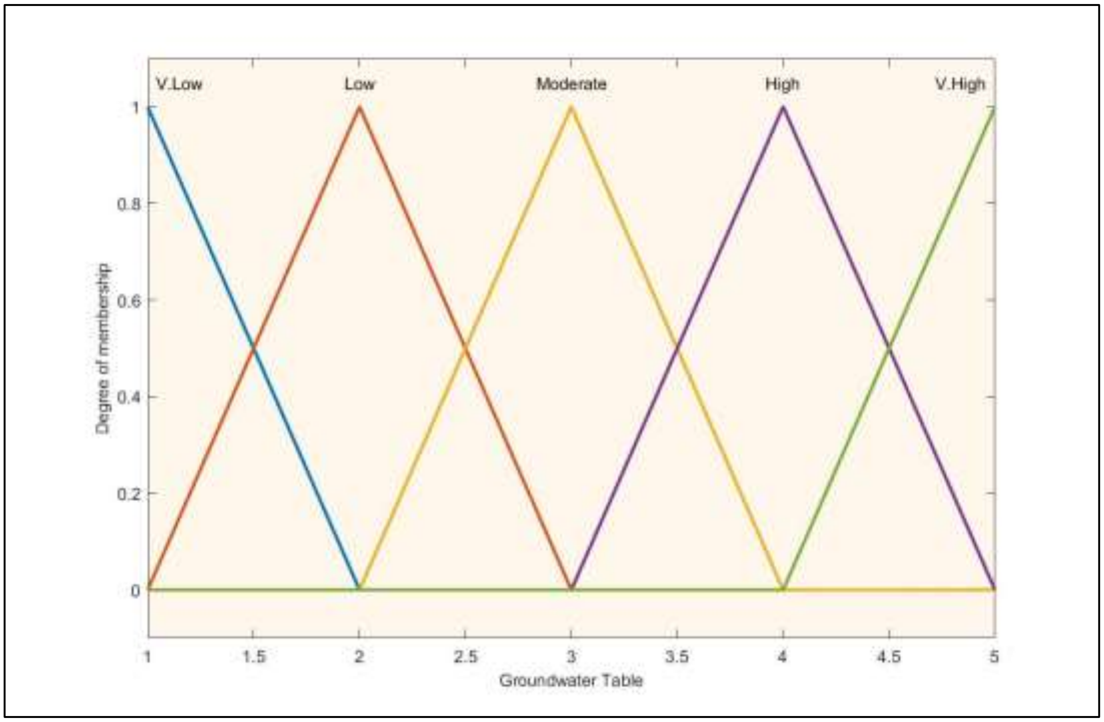


Smell or Vermin Level

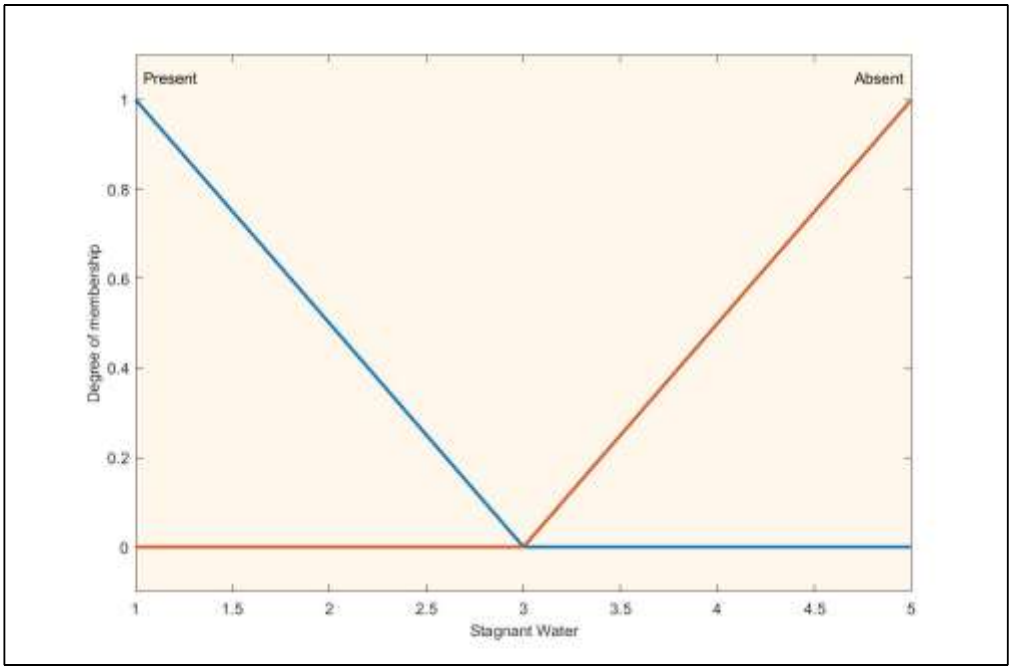


Structural Module

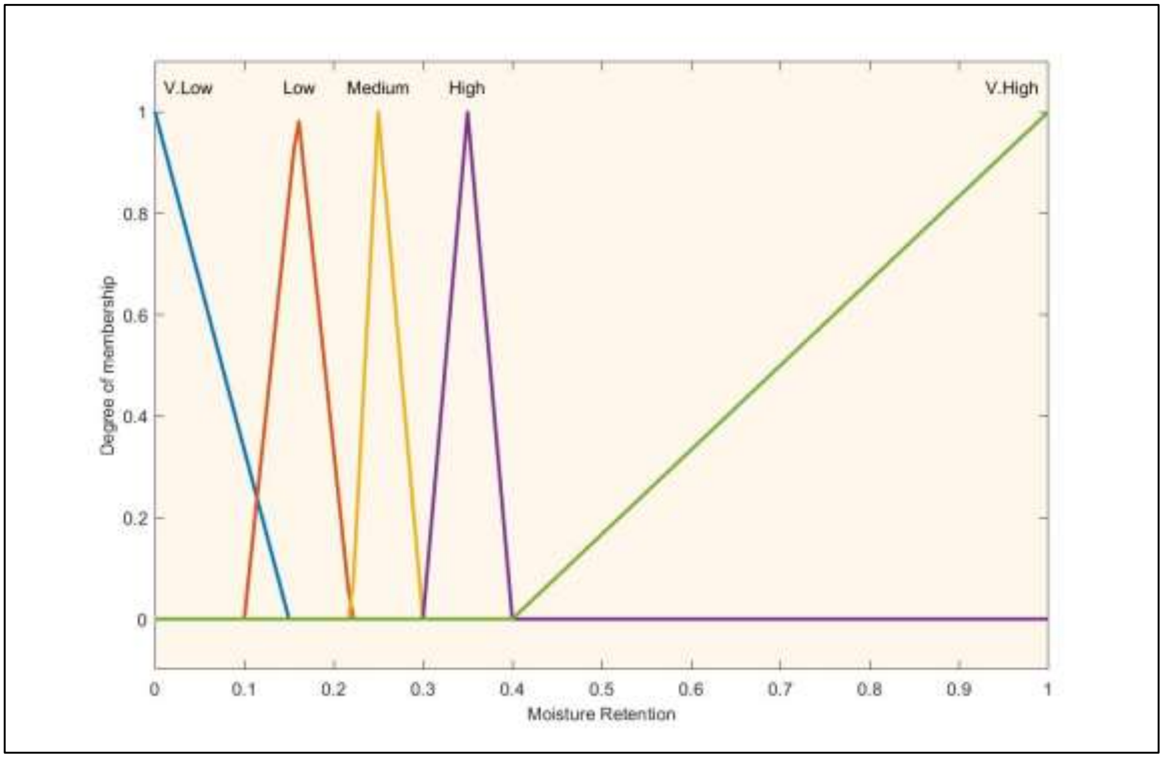
Groundwater Table



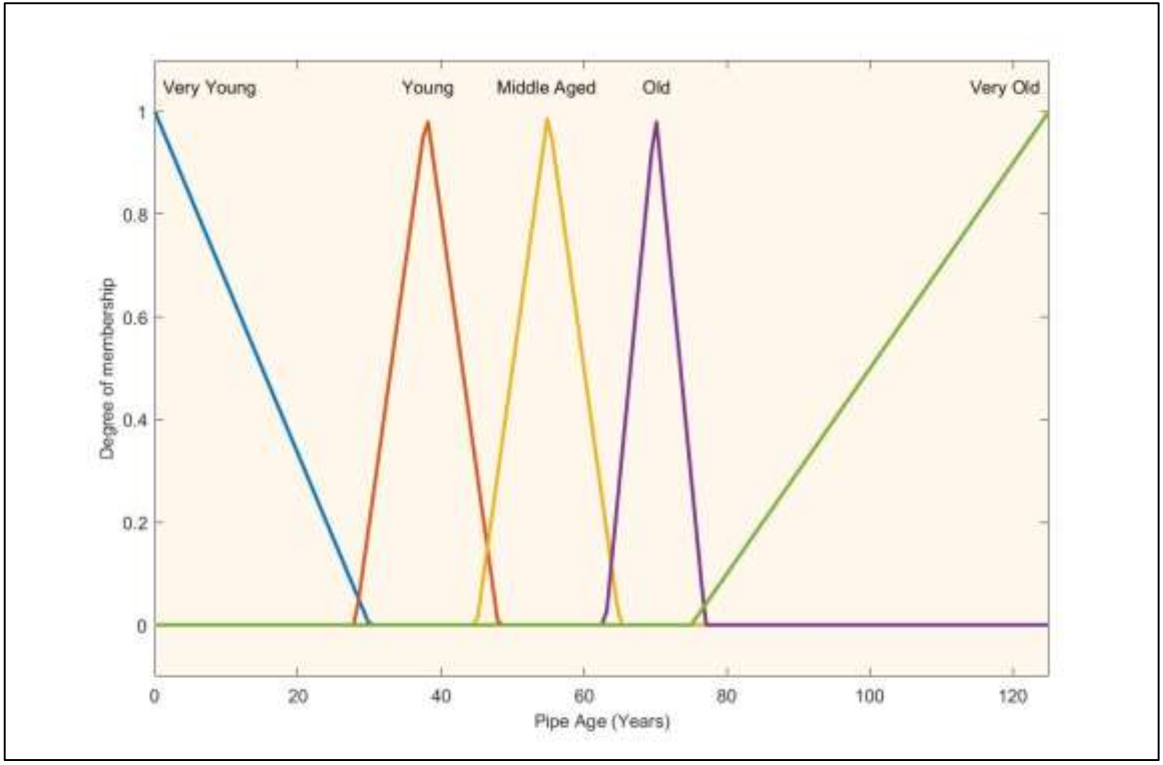
Stagnant Water



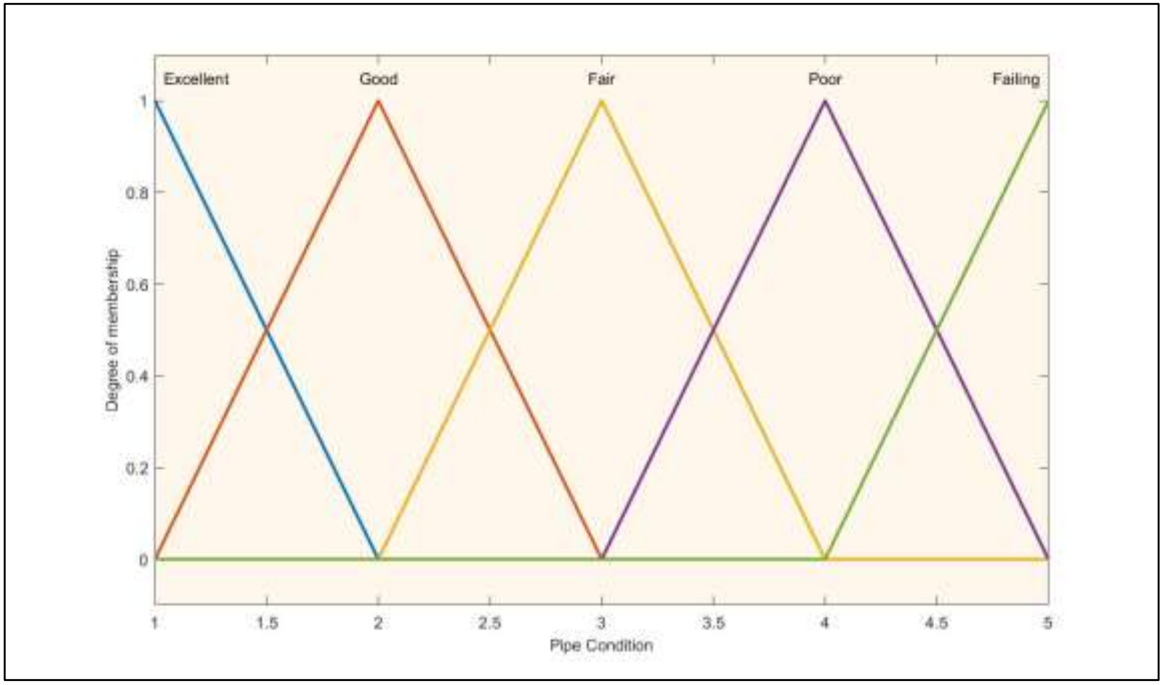
Moisture Retention



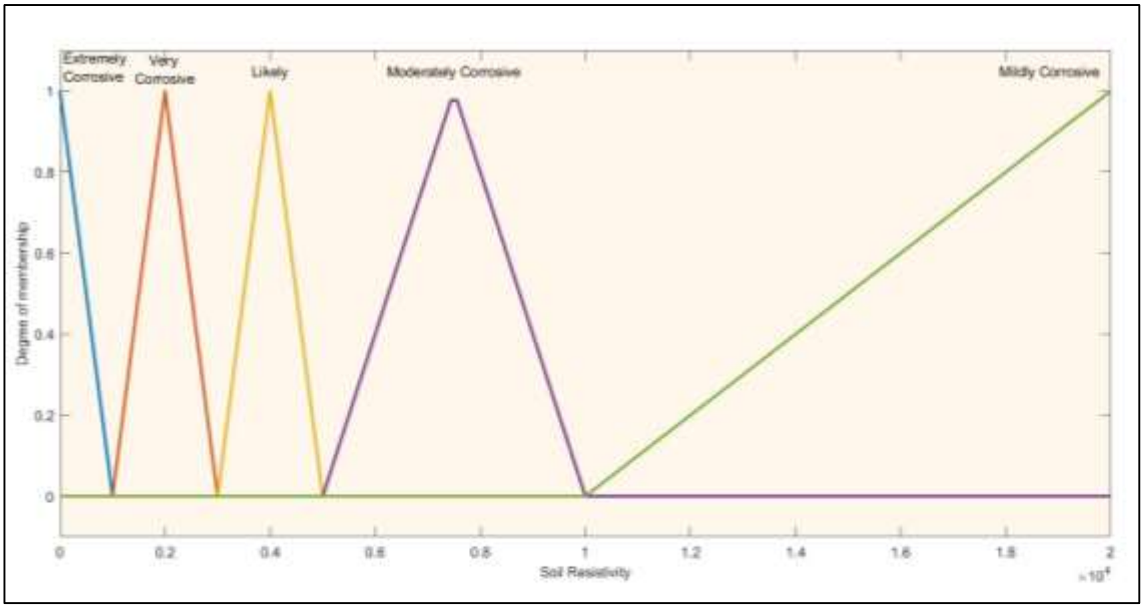
Pipe Age



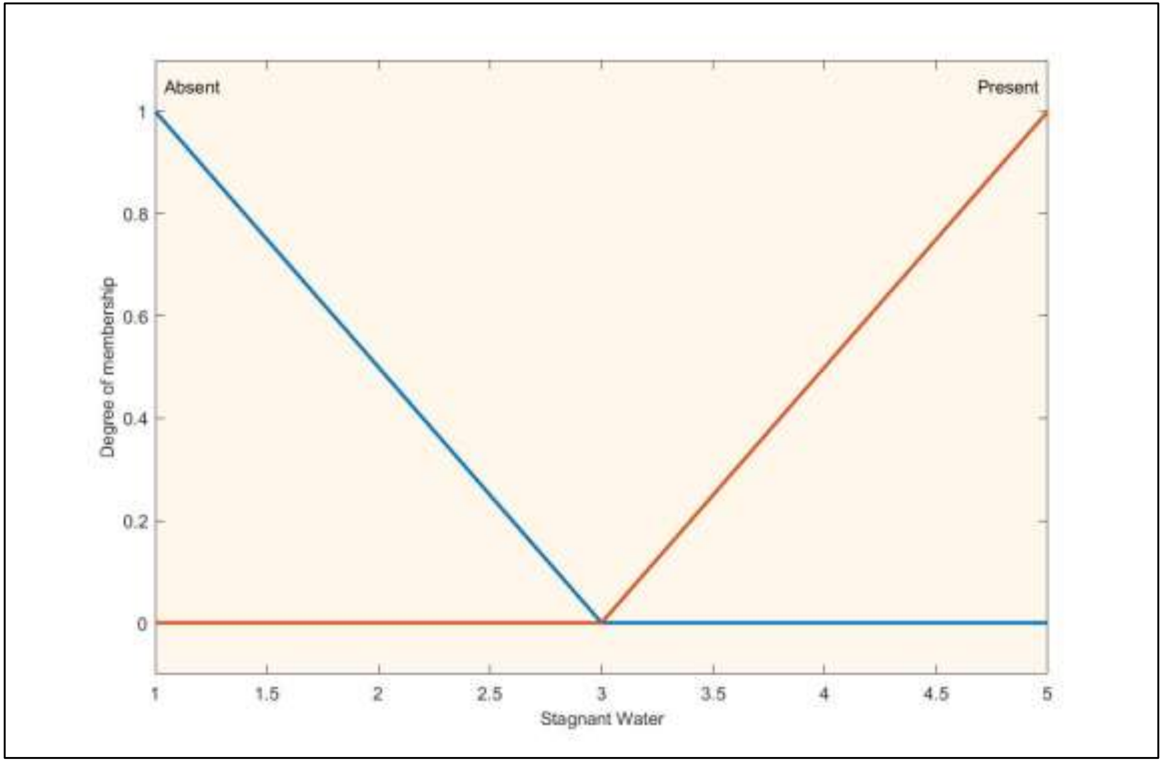
Pipe Condition



Soil Resistivity

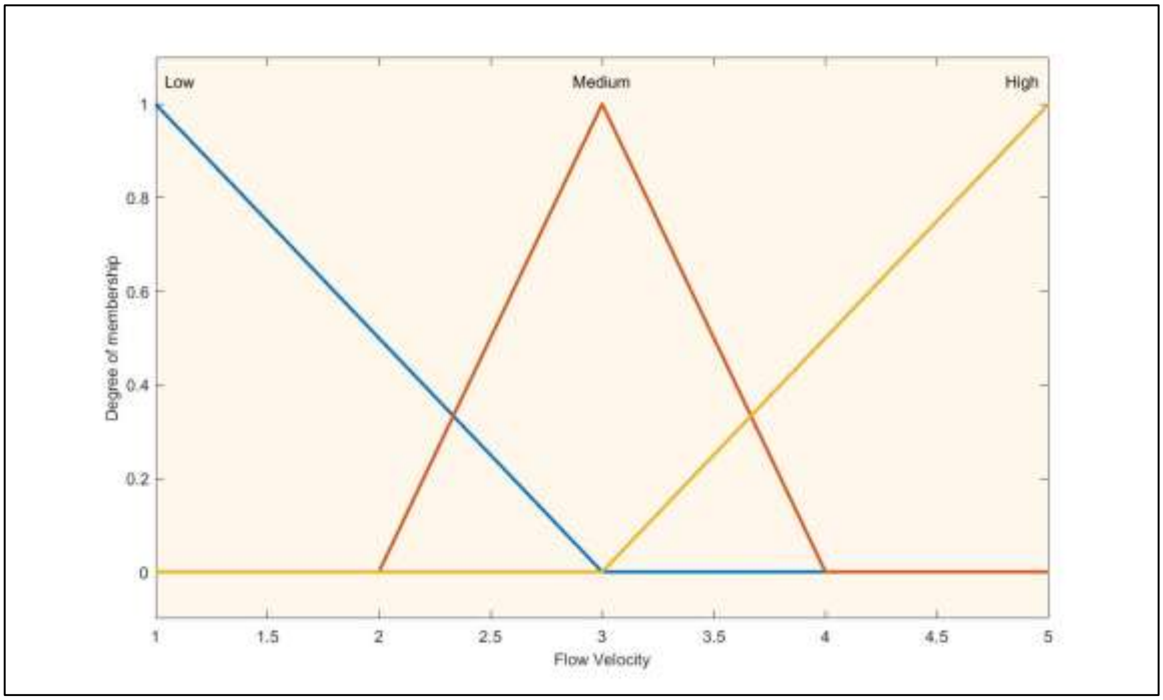


Stagnant Water

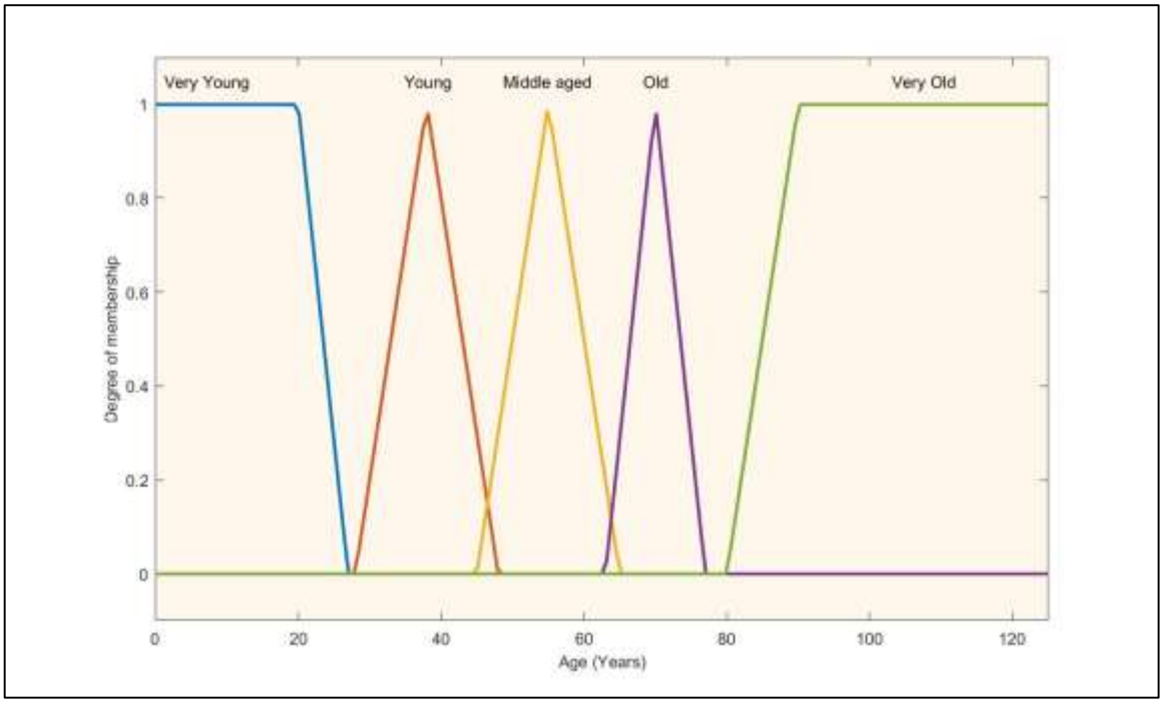


Surface Wear

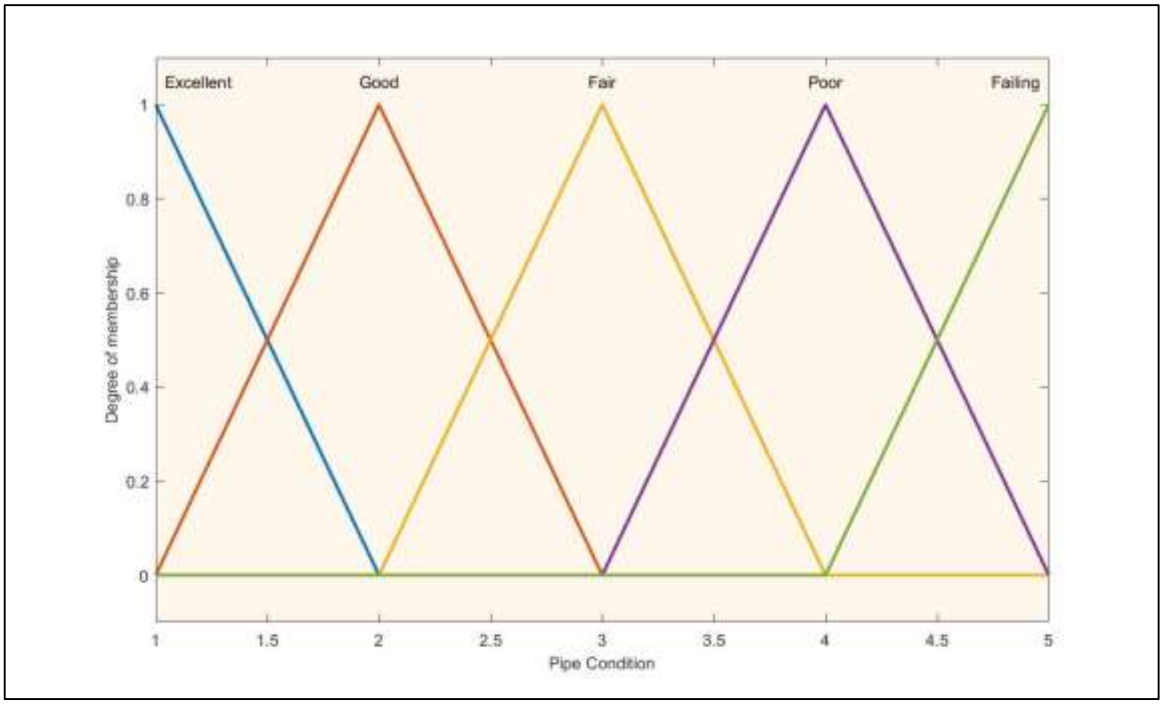
Flow Velocity



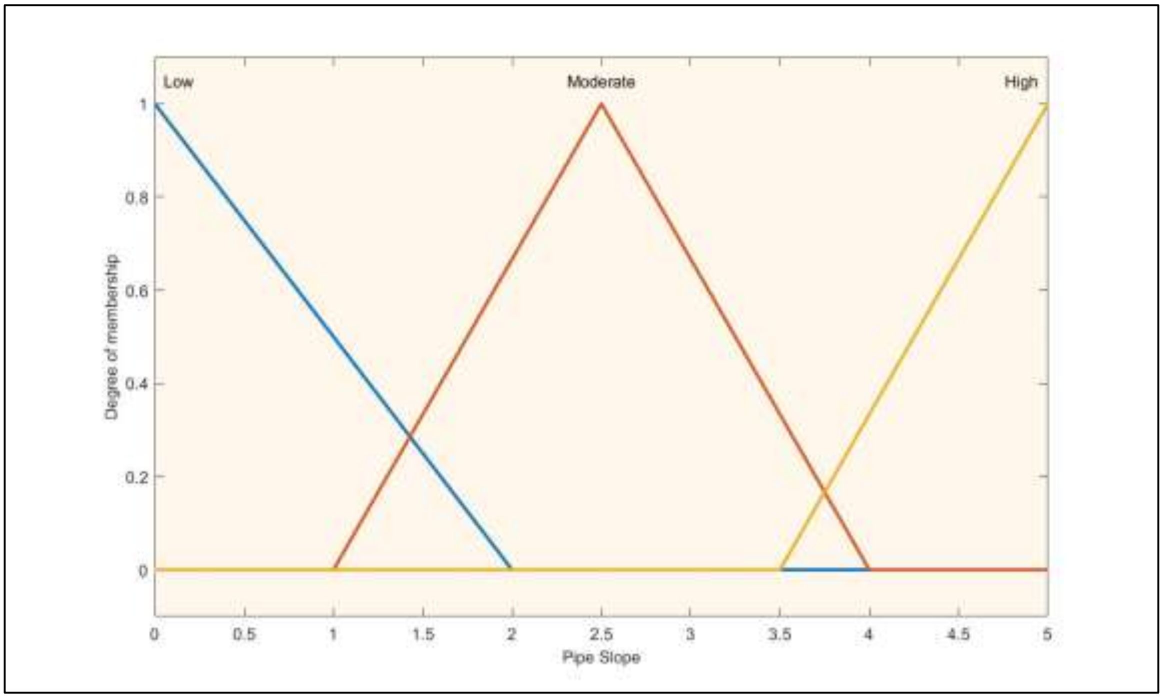
Pipe Age



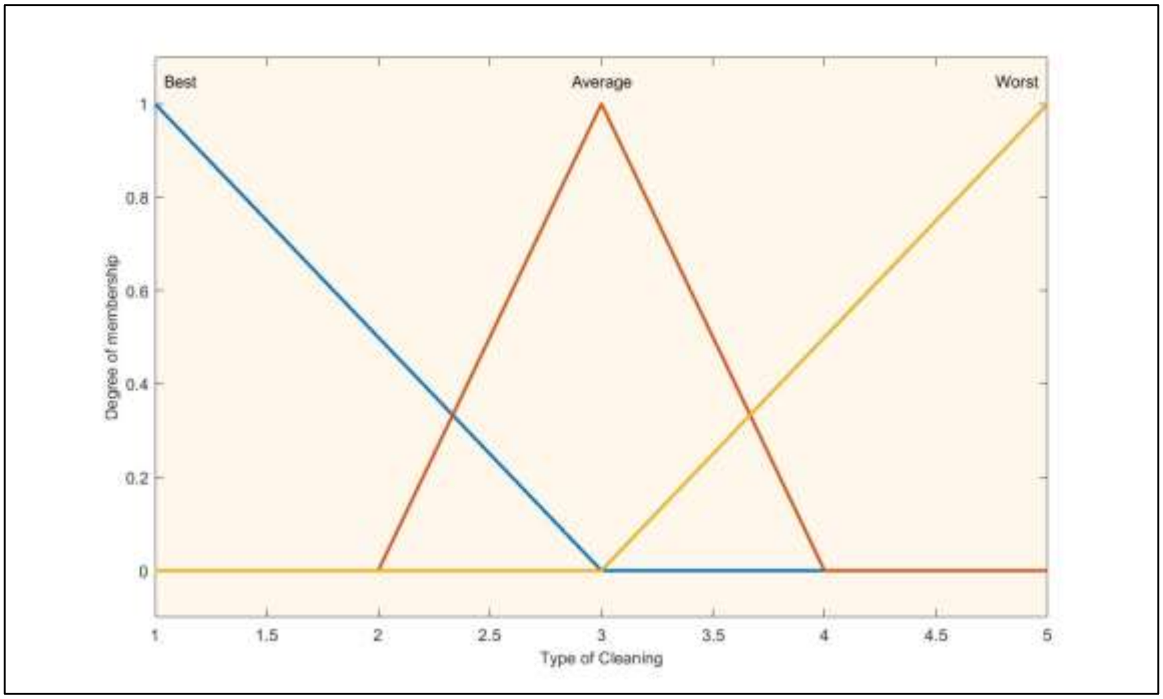
Pipe Condition



Pipe Slope

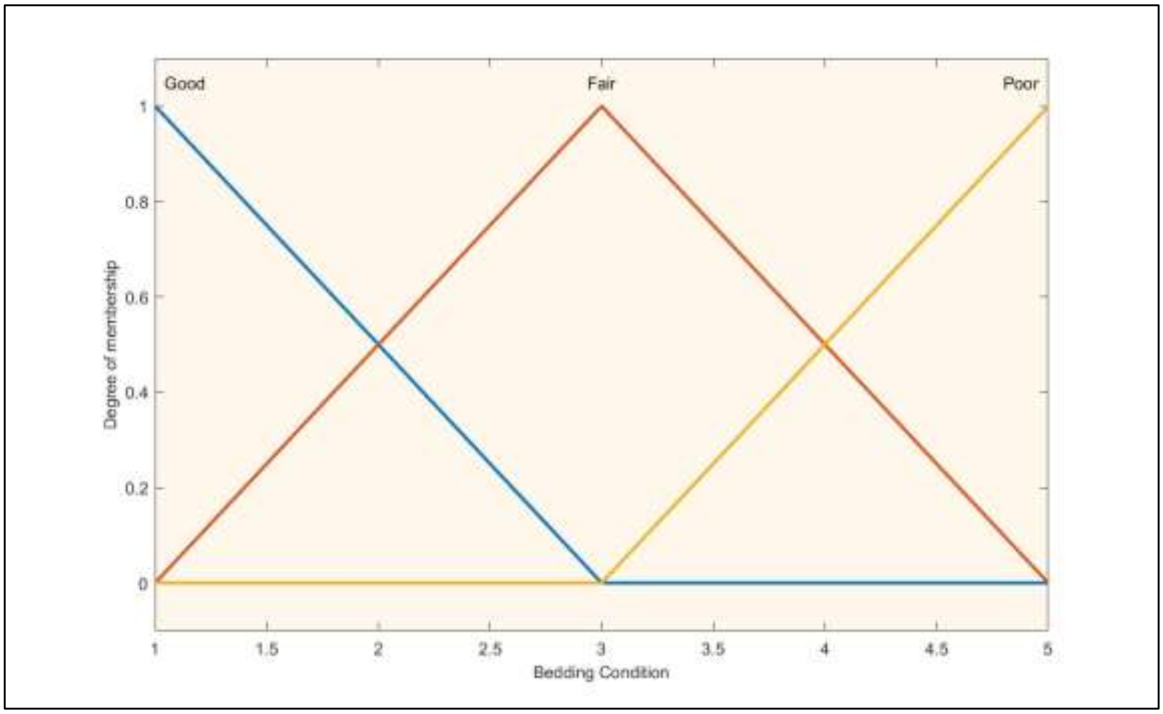


Type of Cleaning

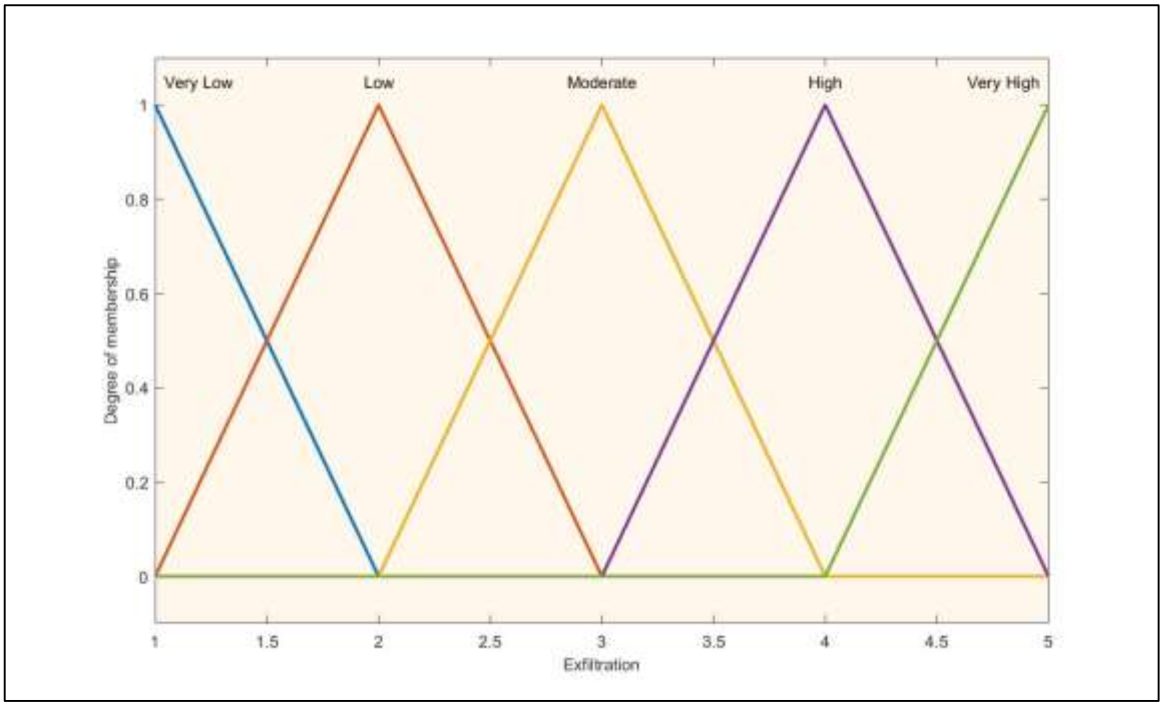


Load/Deformation Module

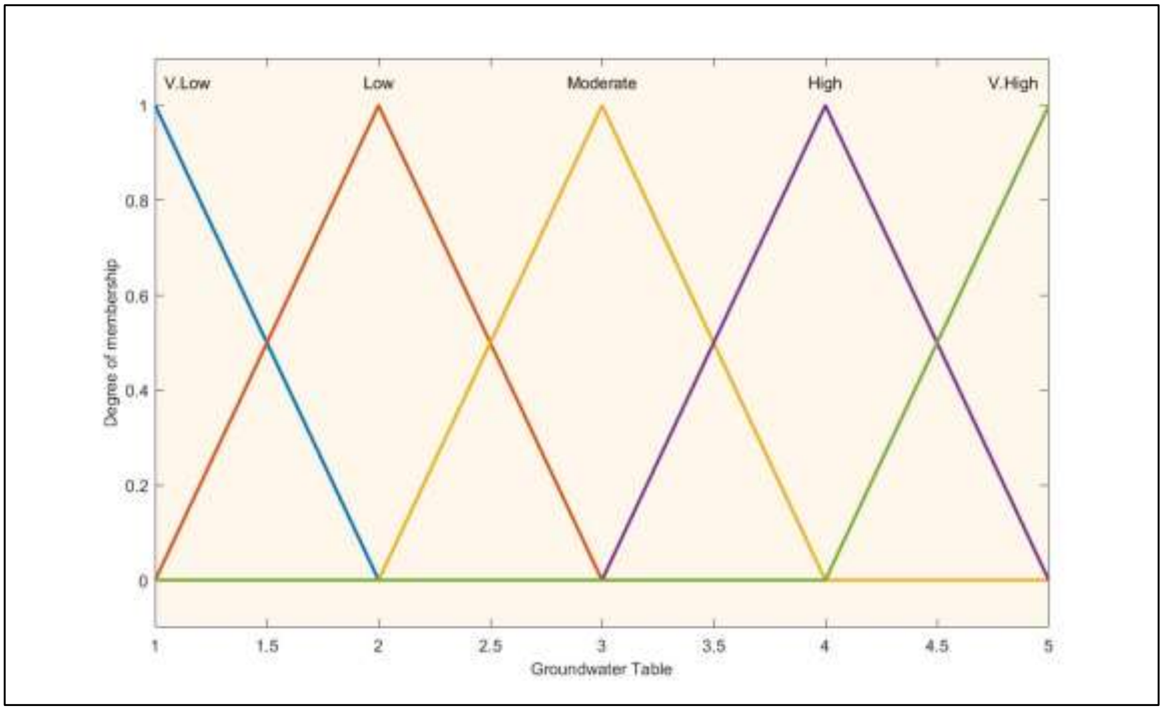
Bedding Condition



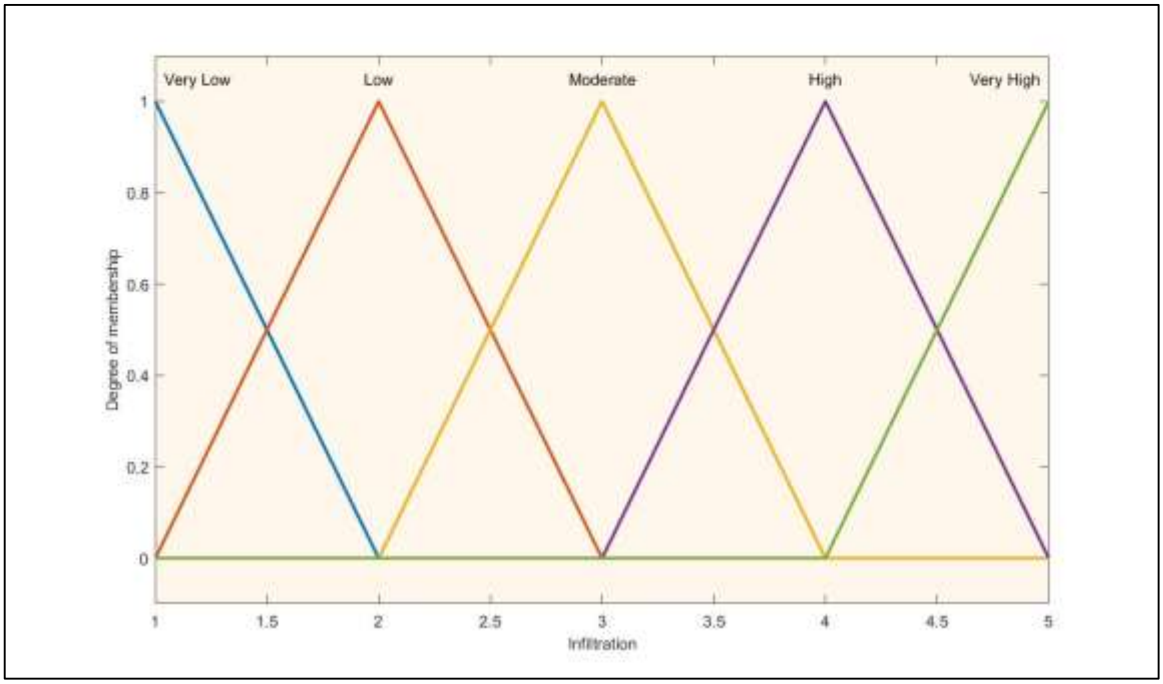
Exfiltration



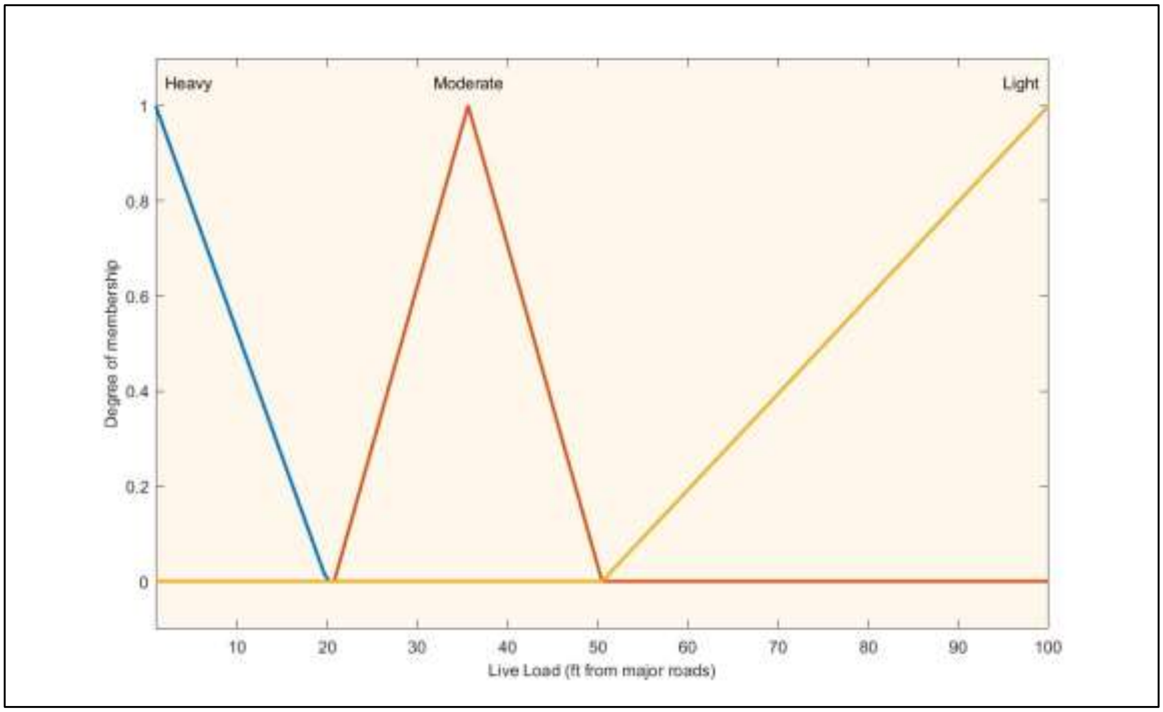
Ground Water Table



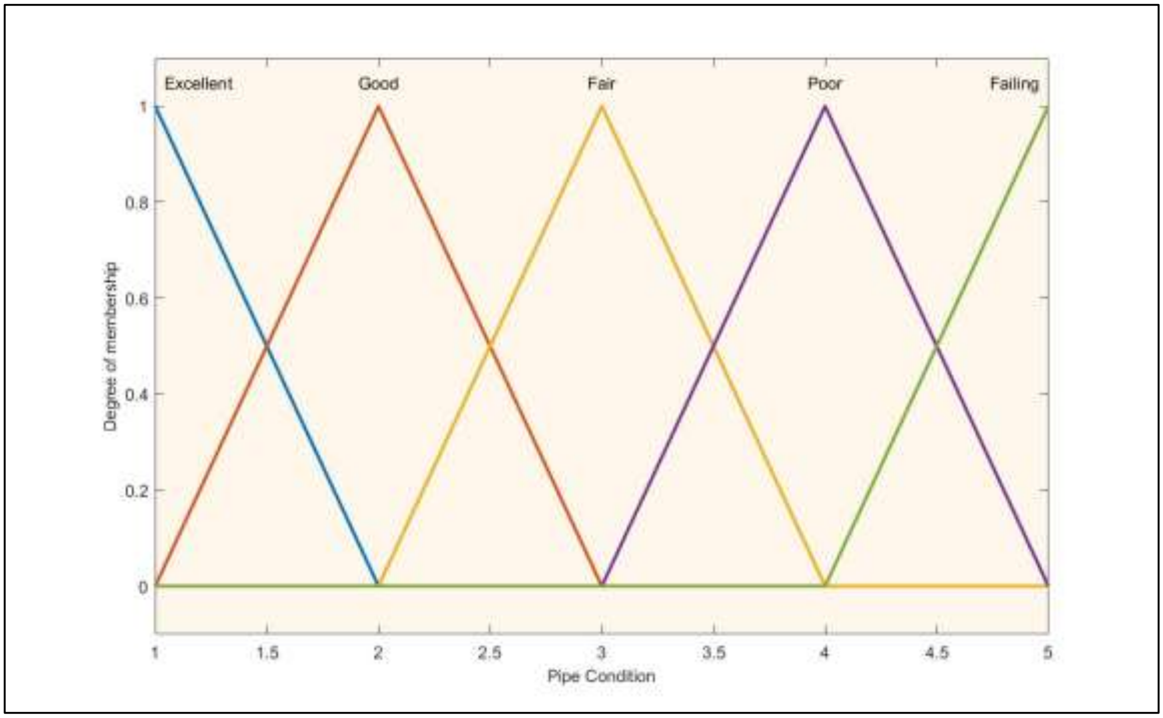
Infiltration



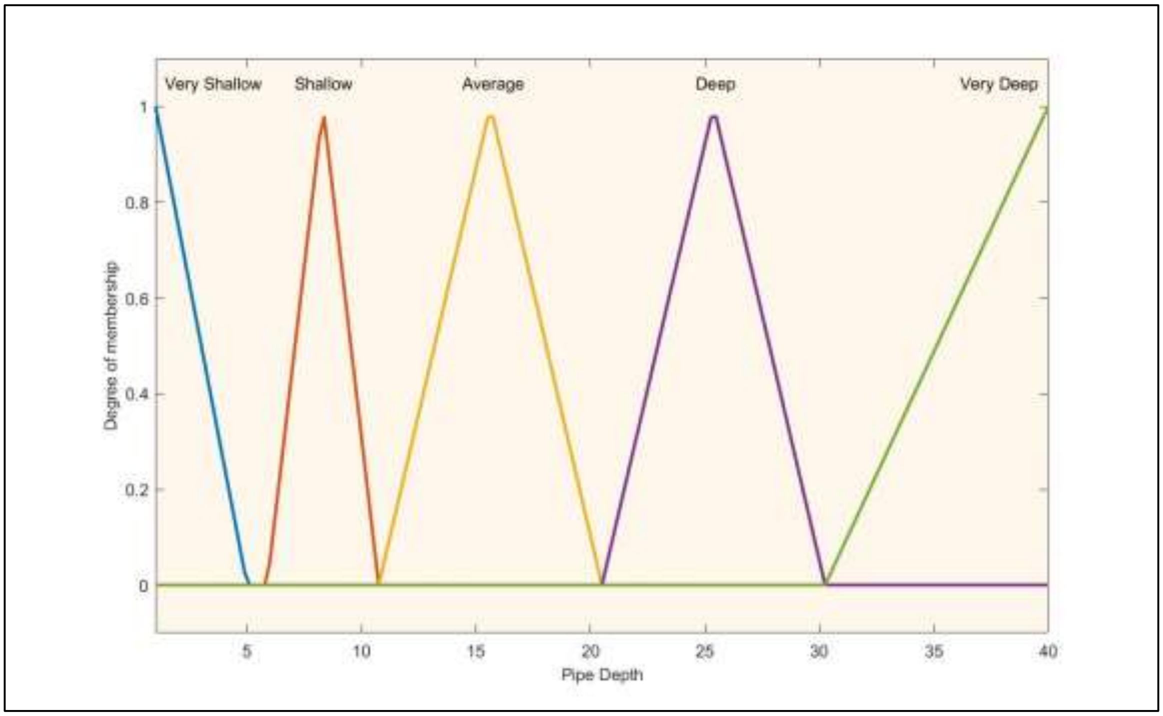
Live Load



Pipe Condition



Pipe Depth


Very Shallow
Shallow
Average
Deep
Very Deep
Degree of membership
0
0.2
0.4
0.6
0.8
1
5
10
15
20
25
30
35
40
Pipe Depth

Appendix C. Fuzzy Rule Statements

This appendix contains a list of fuzzy membership functions and their ranges for input and output variables for each module.

Surface Wear Module

1. If (Pipe Condition is Excellent) then (Structural Condition is Excellent) (1)
2. If (Pipe Condition is Fair) then (Structural Condition is Fair) (1)
3. If (Pipe Condition is Failing) then (Structural Condition is Failing) (1)
4. If (Material is Mediocre (Metal)) and (Soil Resistivity is extremely corrosive) and (Moisture Retention is V High) then (Structural Condition is Failing) (0.3)
5. If (Stagnant Water is Undesirable) then (Structural Condition is Failing) (0.2)
6. If (Stagnant Water is Desirable) and (Soil Resistivity is mildly corrosive) and (Moisture Retention is V Low) then (Structural Condition is Excellent) (0.2)
7. If (Soil Resistivity is extremely corrosive) and (Moisture Retention is V High) then (Structural Condition is Failing) (0.2)
8. If (Pipe age is Very Old) and (Stagnant Water is Undesirable) and (Moisture Retention is V High) then (Structural Condition is Failing) (0.2)
9. If (Soil Resistivity is extremely corrosive) then (Structural Condition is Failing) (0.4)

Structural Module

1. If (Pipe Condition is Excellent) then (Structural Condition is Excellent) (1)
2. If (Pipe Condition is Fair) then (Structural Condition is Fair) (1)
3. If (Pipe Condition is Failing) then (Structural Condition is Failing) (1)
4. If (Material is Mediocre (Metal)) and (Soil Resistivity is extremely corrosive) and (Moisture Retention is V High) then (Structural Condition is Failing) (0.3)
5. If (Stagnant Water is Undesirable) then (Structural Condition is Failing) (0.2)
6. If (Stagnant Water is Desirable) and (Soil Resistivity is mildly corrosive) and (Moisture Retention is V Low) then (Structural Condition is Excellent) (0.2)
7. If (Soil Resistivity is extremely corrosive) and (Moisture Retention is V High) then (Structural Condition is Failing) (0.2)
8. If (Pipe age is Very Old) and (Stagnant Water is Undesirable) and (Moisture Retention is V High) then (Structural Condition is Failing) (0.2)
9. If (Soil Resistivity is extremely corrosive) then (Structural Condition is Failing) (0.4)

Load/Deformation Module

1. If (Pipe Condition is Excellent) then (Load/Deformation is Very Low) (1)
2. If (Pipe Condition is Fair) then (Load/Deformation is Medium) (1)
3. If (Pipe Condition is Failing) then (Load/Deformation is Very High) (1)
4. If (Pipe Depth is V Shallow) and (Bedding Condition is Poor) and (Live Load is Heavy) then (Load/Deformation is Very High) (0.3)
5. If (Pipe Depth is Very Deep) and (Bedding Condition is Good) and (Live Load is Light) then (Load/Deformation is Very Low) (0.3)
6. If (Infiltration is Very High) and (Exfiltration is Very High) then (Load/Deformation is Very High) (0.2)
7. If (Infiltration is Very Low) and (Exfiltration is Very Low) then (Load/Deformation is Very Low) (0.2)

Capacity Module

1. If (Avg. Precipitation Intensity is Low) and (Location is Excellent) and (Average Precipitation Duration is Low) and (Conveyance Capacity is No Surcharge) then (Capacity is Excellent) (0.5)
2. If (Pipe Surcharging Frequency is Very High) and (Overflow Frequency is Very High) and (Inflow/Infiltration is Very High) and (Conveyance Capacity is Flooded) then (Capacity is Very Poor) (0.5)
3. If (Conveyance Capacity is Insufficient Freeboard) then (Capacity is Poor) (0.3)
4. If (Pipe Surcharging Frequency is Very High) or (Overflow Frequency is Very High) or (Conveyance Capacity is Flooded) then (Capacity is Very Poor) (0.3)
5. If (Pipe Surcharging Frequency is Very High) then (Capacity is Very Poor) (0.2)
6. If (Conveyance Capacity is No Surcharge) then (Capacity is Excellent) (0.2)

Blockage Module

1. If (Debris is Very High) and (Sedimentation is Very High) and (Maintenance/Cleaning Frequency is Frequent) then (Blockage is V Low) (1)
2. If (Debris is V Low) and (Sedimentation is Very Low) and (Maintenance/Cleaning Frequency is Frequent) then (Blockage is V Low) (1)
3. If (Debris is Moderate) and (Sedimentation is Moderate) and (Maintenance/Cleaning Frequency is Regular) then (Blockage is Moderate) (1)
4. If (Debris is Very High) and (Sedimentation is Very High) and (Maintenance/Cleaning Frequency is Rarely) then (Blockage is V High) (1)
5. If (If Inlet/Outlet is attached or if Pipe Changes Direction or if cross bore is present is Desirable) or (Density of Connections is V Light) then (Blockage is V Low) (0.3)
6. If (If Inlet/Outlet is attached or if Pipe Changes Direction or if cross bore is present is Undesirable) and (Density of Connections is Very Dense) then (Blockage is V High) (0.3)
7. If (Vermin is Significant) then (Blockage is V High) (0.2)
8. If (Vermin is Negligible) then (Blockage is V Low) (0.2)
9. If (Maintenance/Cleaning Frequency is Frequent) then (Blockage is V Low) (0.2)
10. If (Maintenance/Cleaning Frequency is Rarely) then (Blockage is V High) (0.2)
11. If (Slope is V Low) and (Min Flow Velocity is Low) and (Pipe Length is Very Long) then (Blockage is V High) (0.2)
12. If (Slope is Good) and (Min Flow Velocity is High) and (Pipe Length is Very Short) then (Blockage is V Low) (0.2)
13. If (Diameter is Very Large) then (Blockage is V Low) (0.1)