

Research Article

A Qualitative Approach to Determine the Areas of Highest Inflow and Infiltration in Underground Infrastructure for Urban Area

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Inflow and infiltration (I&I) is an unavoidable problem which affects underground infrastructures such as water mains, sewer lines, and storm water systems. The additional water and intruded debris, due to I&I, can hinder the flow capacity of the pipe network. However, with proper management, such problems can be minimized or controlled. By using a qualitative approach to determine the areas susceptible to I&I, application of geographic information system (GIS) can minimize cost and time. The results found can highlight the most I&I vulnerable areas, which can be used for underground infrastructure management. In this study, maps of Youngstown's sewer lines and surrounding areas were generated and used. Pipe age, an empirical operating coefficient, sewer classifications, and soil hydraulics were the parameters used to identify each pipe segments. The results of this study show that majority of pipelines from downtown and south side of the city were determined to be in very poor conditions. The method used in this study reduces the scale of work, by generating a map, indicating areas with highest susceptibility.

1. Background

In the United States, most municipal sewer systems are aged at least 60 years and that for communities are older than 100 years [1–3]. Sewer conveyance systems are designed to carry expected flow called designed flow/capacity of the pipe network. However, excessive inflow and infiltration (I&I) lessens the capacity and efficiency of waste water transport [4–6]. In general, due to material and joint degradation/deterioration, poorly designed or constructed systems allow for I&I to occur [7, 8]. Furthermore, I&I can increase the cost associated with collection system and treatment facility by adding extra run time for pumps and pumping station, maintenance, and repairs [9, 10].

There are two types of approaches to assess possible location of I&I: (i) quantitative and (ii) qualitative. Quantitative method such as flow rate measurement, stable isotope method, and pollutant time-series method is used to assess the amount of the I&I in pipe network, while smoke

testing, dye testing, distributed temperature sensing (DTS) method, and closed circuit television (CCTV) method are listed as the qualitative method and are used to locate/detect the I&I problems in the underground pipe network [11–13]. This research is a qualitative approach to help find susceptible I&I areas. Maps are generated considering some important but not all influencing factors, contributing to I&I. The major influential factors used in this research were pipe age, soil types (hydrologic soil groups) encompassing the pipes, sewer classifications (main and lateral), and empirical operating coefficient.

The quantification of I&I is difficult and costly due to the large network of sanitary pipes and expenses related to water monitoring [14, 15]. The quantitative methods, sometimes, hinder regular traffic flow and cause a loss of regular business hours, leading to socioeconomic loss. The qualitative approach can reduce the amount of work load by giving a rough estimate of susceptible areas. Once the high susceptible areas are located, field testing or inspection can

be carried out, which are exemplified in the model. Therefore, using a qualitative approach as a pilot study for the quantitative research is considered to be more effective and economical methods. As a result of this research, one can prioritize piping segments in need of future inspection.

2. Methodology

Youngstown, Ohio, USA, was a target area of this study. The analysis was performed using commercial Geographic Information System (GIS) software. The GIS data for the study included the sewer systems and the hydrologic soil classifications of the city of the Youngstown area. In general, soils can be classified by their hydraulic nature, which is a function of grain size distribution, runoff potential, and infiltration capacity. Groups A through D are the four main soils classification used in this model. For example, soils with gravel and coarse sand (group A) have high infiltration capacity (0.3 to 0.45 in/hr) with low runoff potential. The soil group B has moderate coarse texture with slow infiltration rate (0.15 to 0.30 in/hr), and group C has moderately fine to fine texture with slow infiltration rate (0.05 to 0.15 in/hr). Similarly, the soil group D is composed of clays and has low infiltration capacity (0 to 0.05 in/hr) with high runoff potential. The groups A, B, C, and D has high (0.30 to 0.45 in/hr), moderate (0.15 to 0.30 in/hr.), slow (0.05 to 0.15 in/hr.), and a very slow (0 to 0.05 in/hr) rate of water transmission, respectively [16]. The detailed descriptions of soil classifications are given in the soil classifications section.

Various mapping models were generated to identify the I&I prone areas, considering the influential factors contributing to the I&I problem. There were four parameters/factors in the model: pipe age, empirical operating coefficients, soil classifications, and sewer classifications. The first three factors were more likely to be responsible for the I&I in the sewer segments, while the sewer classifications emphasized the overall effects of I&I. In the model, pipes age for each segment was calculated by subtracting their date of construction or rehabilitation from the current year, 2017. Empirical operating coefficients for each pipe segment were calculated following the procedure discussed in the next section. The sewer classifications were divided into two categories: lateral (6 inches to 18 inches) and main (more than 18 inches) lines.

The different types of models were created by combining the effect of each parameter in equal or by differing the weightage basis. For example, a model was created giving each parameter an equal weightage (25% each). Similarly, other maps were generated, giving different weightage values for each parameter, which indicated areas susceptible to I&I problems. Then, maps were generated based upon these weightage values. More details about each model are discussed in Results below.

3. Model Parameters

As discussed above, pipe age, the empirical operating coefficient, and soil classifications are used in the model to investigate the amount of I&I in the sewer lines. The others,

TABLE 1: Pipe age statistics.

Number of sections	1768
Youngest age	67
Oldest age	132
Average age	112
Standard deviation	12.3

sewer classification, emphasize the effect of I&I in the sewer lines. Each parameter is discussed in more detail in the following sections.

3.1. Pipe Age. The type of materials and manufacturing techniques used affects the life expectancy of a pipeline. The average useful life span of cast iron pipes installed around the late 1800's is approximately 120 years on average. Pipes installed in the 1920s have an average life of about 100 years, and pipes which were laid post World War II have an expectancy of about 75 years [1, 17, 18]. As pipes age, they deteriorate and form cracks or weaken structural integrity of the pipe, allowing extraneous water to enter these pipe network [19].

Kerr Wood Leidal Assoc. [20] developed an empirical relationship between age and I&I rate in the pipe network. The study was conducted in 54 independent sewer catchments with corresponding 100-year I&I rate during the peak hour. The correlation coefficient value (R^2) from the study was evaluated to be 0.9 which indicates that the relationship between the pipe age and the I&I rate is highly correlated. The derived equation (1) from the experimental study resembles that there is an exponential relationship between I&I rate and the sewer age for the vitrified clay pipe:

$$IR = 123.55 e^{(0.0325 * y)}, \quad (1)$$

where y is the pipe age in years and IR is the I&I rate in liter/hectare/day.

In this study, pipe age was given to each pipe segment manually because files collected from City of Youngstown were in a Tag Image File Format (.tif) and the pipe age was not available in the GIS shape file. The given .tif file consists of information such as name of the street, date of construction, name of the contractor, and the name of the person involved in the installation of pipelines. In addition, the file also has the invert elevation and elevation of street. The date of construction was manually input in the GIS file for each pipe segment using attribute table properties. The current age of the pipe was simply evaluated by subtracting their date of construction or rehabilitation from the current year, 2017.

The statistical results are shown in Table 1 and are displayed in Figure 1. As shown in Figure 1, the pipe age ranges from 70 years to 130 years, and most of the pipe segments are determined to be aged between 110 to 120 years. In general, the pipes are older near the downtown area and south side of Youngstown.

3.2. Empirical Operating Coefficient. A study conducted by Chughtai and Zayed [21] proposed an empirical regression

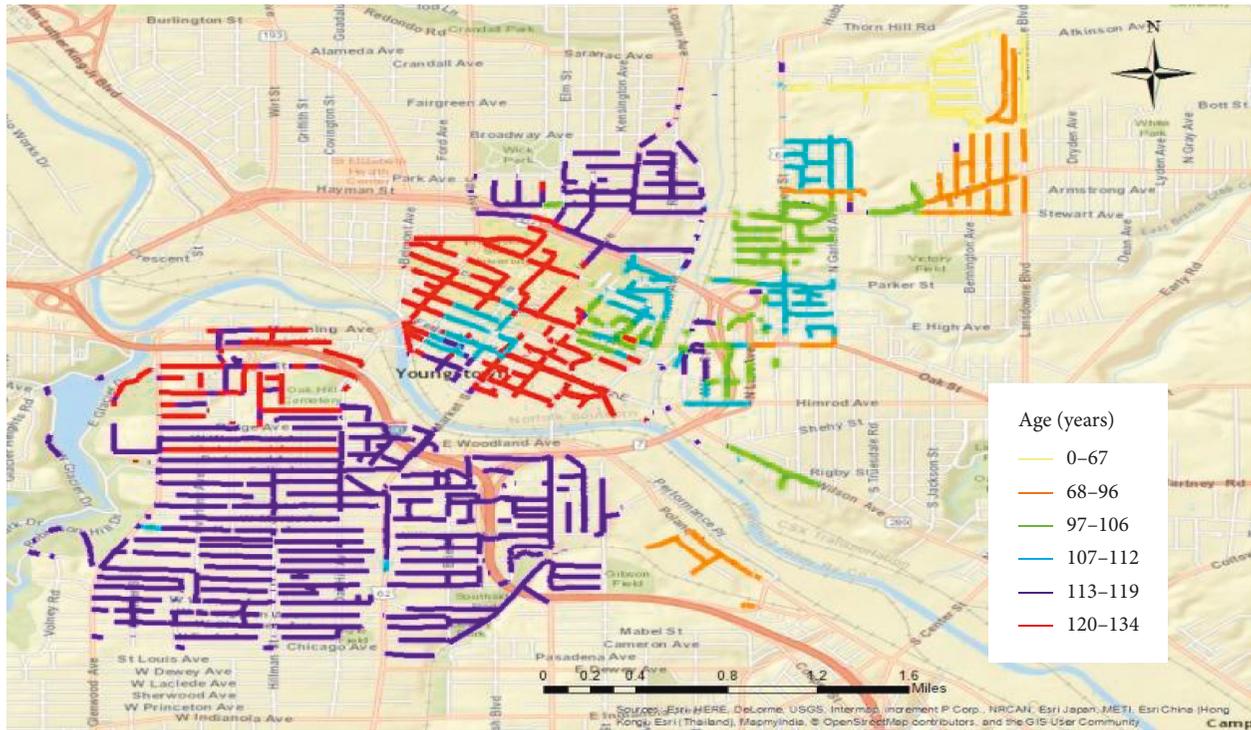


FIGURE 1: Age of sewer lines overlade in ArcGIS 10.5 base map.

model to quantify the operational performance of sanitary sewers. They used various pipe properties such as pipe age, diameter, length, and slope to evaluate the operational performance of the pipe sections. The developed model was used in operation performance analysis of Montreal’s collection system in Canada. By using these parameters, they created an equation that took these factors in account as follows:

$$(OP)^{0.63} = 0.308 + \frac{0.507 \cdot (y/D^n)L^S}{y^{0.63}}, \quad (2)$$

where OP is the operational performance, n is Manning’s roughness coefficient, L is the length of the pipe section (m), D is the pipe diameter (mm), and y is the pipe age (years), and S is the slope (grade) of pipe segment (%).

Variables for the Youngstown’s sewers were entered into equation (2), to obtain operational values of the Youngstown and surrounding areas. Age for each pipe segment was taken using the method discussed in the previous subsection. The pipe lengths, diameter, and slope were taken from the Youngstown sewer shape file.

According to Ries and Leighton [22], vitrified clay was the major choice for the sewers by the 1800–1900s. Since the majority of pipes in Youngstown were laid between 1800 and 1900s, it can be speculated that the sewer lines in Youngstown are also made of vitrified clay. Manning’s roughness coefficient for vitrified clay, closed conduit, ranges from 0.011 to 0.017 [23]. In the model, Manning’s roughness coefficient (n) was assumed to be 0.011.

The calculated operating performance values, ranges from 2 to 48, are summarized in Figure 2. The higher the performance value, the better the condition of the pipe, and

vice versa. The majority of the performance values range between 6 and 8.

3.3. Soil Classification. The soil classification used in the model is a depiction of composition and primary soil characteristics. Soil texture such as percentage of sand, silt, and clay are the major inherent factors affecting infiltration rates [24]. The Part 630 Hydrology, National Engineering Handbook [16], categorized soil into four groups—A, B, C, and D. This classification is related to the infiltration capacity of the soils. Soils categorized in group A have a high infiltration capacity, whereas soils classified in group D have the lowest capacity. In this study, hydrologic soil group data for the Youngstown area was retrieved from the NRCS soil database (<https://websoilsurvey.sc.egov.usda.gov>, assessed in May, 2017). The soil is labeled with the hydrologic soil group letter (A, B, C, or D). A map with varying soils types encompassing different pipe segments can be seen in Figure 3. A majority of the soils in the downtown area were determined as category A. As shown in Figure 3, loamy soils were observed on the both banks of the Mahoning River. Types C and D are the major soil classification comprising the south side of downtown of Youngstown. Soils classified in groups C and D may decrease the likelihood of infiltration, but this claim cannot be made by the soil type alone. Other factors, such as the sewer type, pipe age, and empirical operation coefficient need to be considered, as well.

3.4. Sewer Classification. Sewer type was classified into two groups, by size. Overall, the size of sewer lines used in the study ranges from 0 inches to 68 inches, and the majority of pipes are between 6 to 18 inches. Zero inches indicate missing

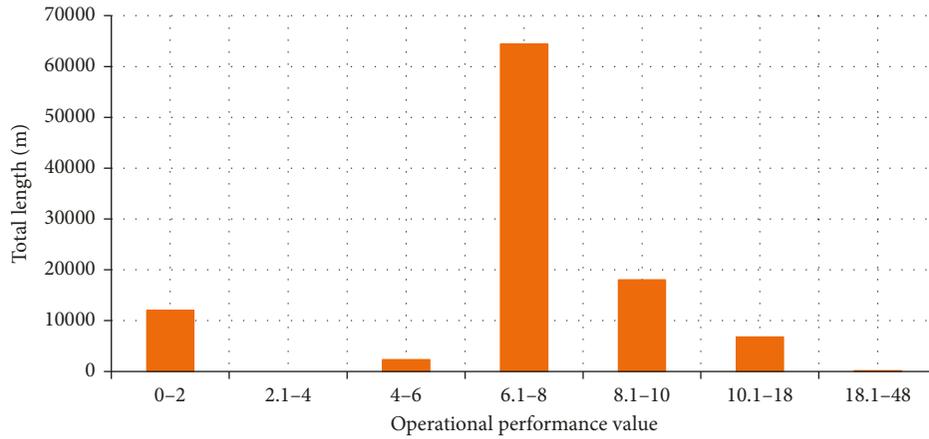


FIGURE 2: Range of operating performance values.

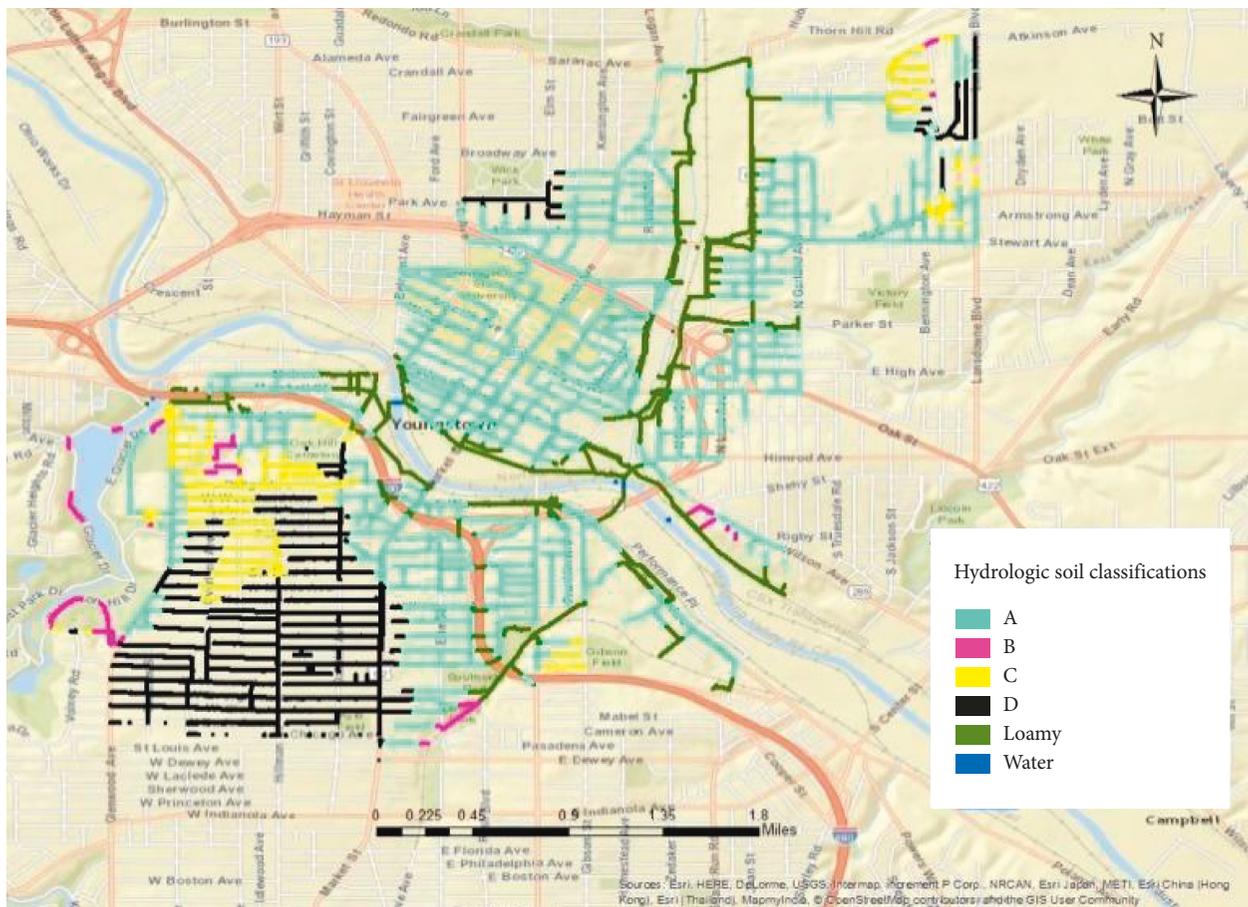


FIGURE 3: Hydrologic soil classification for the Youngstown area (base map by ArcGIS 10.5).

information in the sewer sizing. In the model, laterals range from 6 inches to 18 inches and main consist of pipes greater than 18 inches. Laterals are always connected to the main line.

4. Model Interface

This section includes detailed description of how various parameters merged are used in the model. The central

feature of this study is to create a simplistic model that combines the parameters and makes it user-friendly. The model allows the users to control the input weightage parameters. The weighted value assigned for different parameters and its range are the major functional variations which will alter the results. Regardless of the weightage given to each parameter, as long as they are similar in nature, the results for the model will be similar.

TABLE 2: Weighted value matrix for the model.

Emphasis	Varying weightage values for model comparison			
	Pipe age	Empirical value	Soil type	Equally weighted
Pipe age	0.6	0.2	0.2	0.25
Empirical value	0.1	0.6	0.1	0.25
Sewer type	0.1	0.1	0.1	0.25
Soil type	0.2	0.1	0.6	0.25
Summation	1	1	1	1

TABLE 3: Sample value parameter for age, sewer system, and soil type.

FID	Pipe size (mm)	Pipe grade (%)	Age factor		Sewer system factor		Operational performance values	Soil type factors	
			Age (years)	Value parameter	Sewer system	Assigned value parameter		Soil classification	Assigned value parameter
0	457.2	3.12	110	8	Lateral	8	8.00	D	10
1	609.6	3.33	112	8	Main	10	8.40	A	4
2	0	0	112	8	NA	10	7.77	A	4
3	381	0.89	117	9	Lateral	8	7.00	D	10
4	0	0	112	8	NA	10	7.37	A	4

FID: field identification.

TABLE 4: Assigned value for pipe age.

Pipe age (years)	67	<67 ≤ 96	<96 ≤ 106	<106 ≤ 112	<112 ≤ 119	<119 ≤ 134
Assigned values	5	6	7	8	9	10

The model consists of two steps. First step includes identifying the parameter with the highest influence on the model. Table 2 is an example of the weightage value used in this model. As shown in Table 2, the highest weight is assigned to the most important parameter and remaining percentages are distributed to the other parameters. The sum of total weightage distribution should be equal to one in each case.

Table 3 describes the second step. In this step, depending on the functional value evaluated for each parameter, the user assigns a certain number ranging from 1 (being excellent condition) to 10 (being very poor condition) for each parameter. The functional value for each parameter is defined as the values or categories, which directly affect I&I. For example, age of the pipe was found to be ranging from 67 years to 134 years. Since the older pipes have more chances of the I&I problem in comparison with newer pipes, a value of 5 was given to 67-year-old pipe while 10 was given to the oldest pipe, as shown in Table 4.

A value was assigned for the type of sewer and was also expressed in a similar way. A parametric value of 10 was assigned to mains. The concept behind this assignment was that the main pipes should carry more discharge in comparison to lateral pipes. In addition, laterals are always connected to main. Therefore, a higher chance of I&I may occur in mains than the lateral lines. Lateral lines were given 8 as the value parameter. The assignment value totally depends on user’s choice; however, the evaluated final value (importance/effect) after using the weighted parameter

TABLE 5: Assigned value for empirical performance value.

Operational performance values	0 ≤ 8	8.1 ≤ 12	12.1 ≤ 18	18.1 ≤ 48
Assigned values	10	8	7	4

should resemble the same result due to the distribution of weighted values among all the parameters in a similar way.

Similarly, soil types A, B, C, and D were given 10, 8, 6, and 4, respectively, as a value parameter. Since, soil type A has more infiltration capacity in comparison to D, a higher value is given to A. In the other words, soil type A has more contribution to the I&I problem compared to type D. Weighted parameters ranging from 4 to 10 for the calculated empirical coefficients are shown in Table 5. As discussed above, high empirical performance value indicates good condition of pipe [21].

Finally, the model creates a total weighted value summing of each 4 parameters. The final results produce a number ranging from 1 to 10. Low number represents pipe segments with the minimum susceptibility to I&I, while high numbers show pipe segment with the maximum susceptibility to the I&I problem, i.e., very poor condition. Table 6 gives an example of the four weighted parameters for the pipe segment named as FID 0. The sum of the value showed that the total sum of the final weighted value is 8.4. Since the sum of the total value is 8.4, the pipe FID 0 has a relatively high chance of I&I. After analyzing all pipe segments, the final calculated values are uploaded back to GIS in an attribute table of the

TABLE 6: Sample calculation for FID 0.

Parameter	Value parameter	Weightage	Weighted value
Pipe age	8	0.6	4.8
Empirical value	8	0.1	0.8
Sewer system	8	0.1	0.8
Soil type	10	0.2	2
Sum			8.4

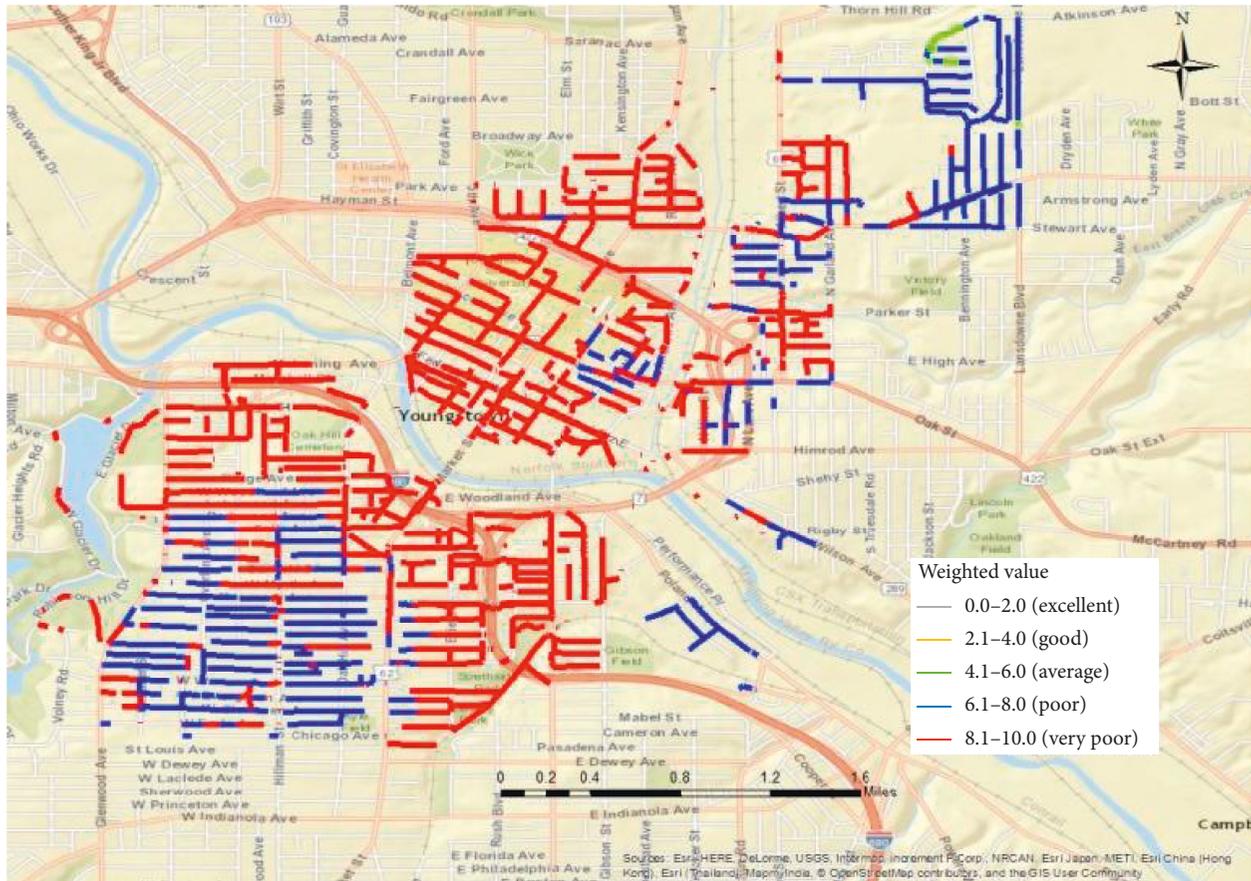


FIGURE 4: Map with age emphasis (base map by ArcGIS 10.5).

sewer lines. A final map was then generated based upon the assigned values made during the calculation process. The results are discussed in the following section.

5. Results

Following the process discussed above, the resulting weighted values are used in ArcGIS [25] to generate the maps for various scenarios. The pipe segments were defined in certain given ranges and then coded with different colors. As explained in the previous sections, a lower number indicates good condition, while higher number indicates areas with possible inflow and infiltration. The pipe segments which fall in the higher range may be prioritized for the future I&I field investigation. Since the results shown in this section are an estimate, the field verification process is needed to validate and refine the model. The research team is

currently working on a proposal to perform the field I&I testing. The results discussed in this study will be used as a preliminary study, and the scope of this study is limited to a qualitative approach for I&I analysis.

5.1. Age Emphasis. Pipe age is very important factor for its condition, more specifically, cracks, and its structural integrity. Aged pipes have more cracks, resulting in a higher level of infiltration [19, 26–28]. Chughtai and Zayed [21] also expressed that pipe age is the main factor which affects the structural performance of the sewer pipelines. Considering the pipe age as a main factor contributing to I&I problems, the weightage value for pipe age was assigned as 60%. The remaining 40% weightage was distributed to other factors: empirical value (10%), sewer type (10%), and soil type (20%). One could give different weights for each parameter (e.g., 70%, 10%, 10%, and 10% for age, empirical value, sewer

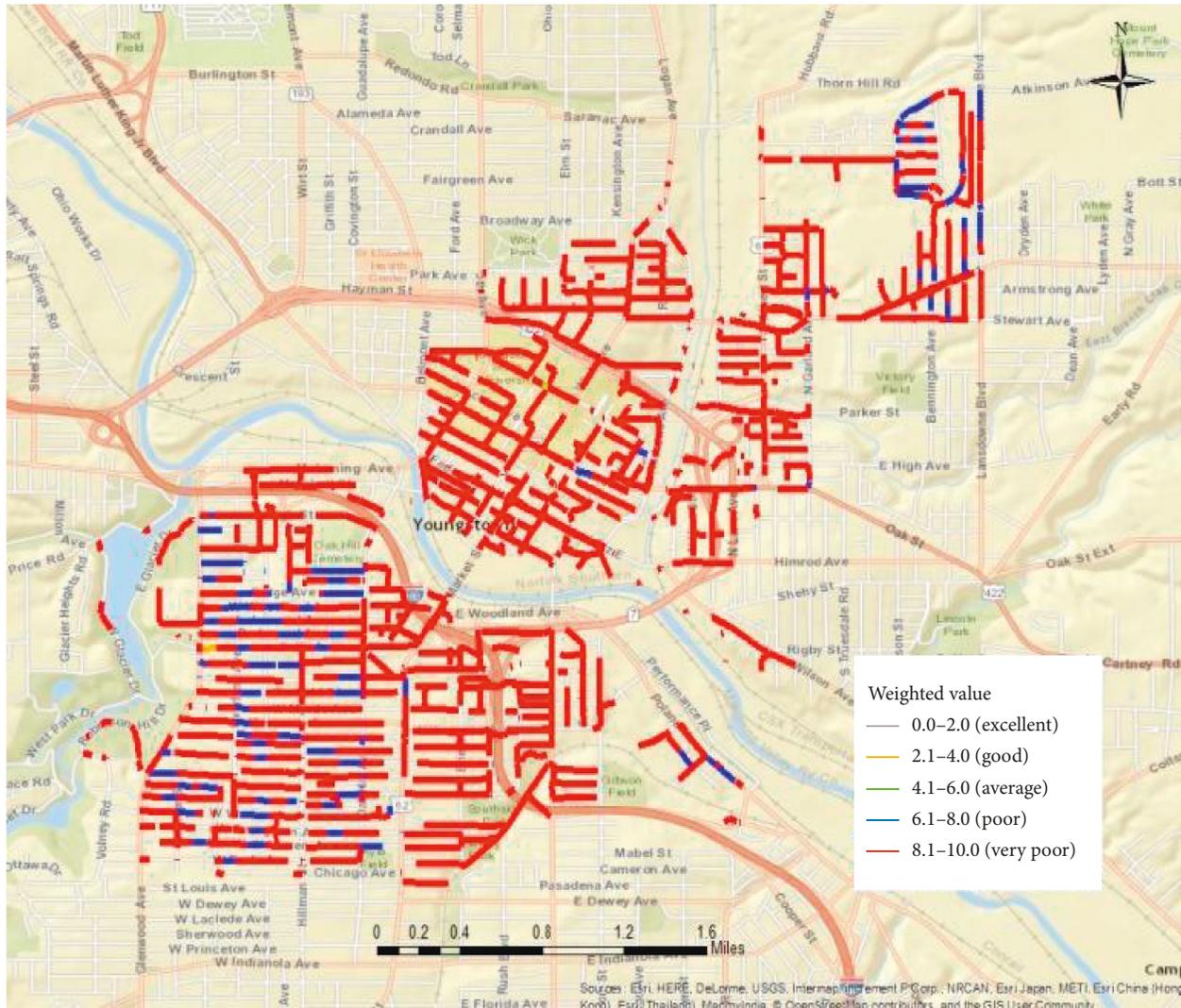


FIGURE 5: Map with empirical value emphasis (base map by ArcGIS 10.5).

type, and soil type, respectively), but as long as the age has the biggest portion of the weight and the rest of the weights are distributed among other three, the nature of the results would be the same. In other words, the results of the pipes indicating its condition (very poor to very good) would still be in the same ratio as it was in the 60% age weight. Therefore, this weight is considered as one of the constraints in the model that the user can have control over the input.

Figure 4 illustrates the results of age emphasis with red-, blue-, green-, orange-, and grey-labeled pipe. These colors represent conditions of the pipe as very poor, poor, average, good, and excellent condition, respectively. The majority of pipes surrounding the downtown area are determined to be in very poor conditions due to its age. More specifically, approximately 72% of sewer lines are determined to be in very poor condition when the age factor is considered to be the main parameter influencing I&I. Similarly, 27% of sewer lines are noticed to be in poor condition. Based upon the analysis, the pipe with excellent and good conditions was not observed. A minute amount (417 m) of the pipelines was observed to be in average condition with the value 4.1 to 6.

5.2. Empirical Value Emphasis. In this model, the empirical performance value, pipe age, sewer type, and soil type was given weightage of 60%, 20%, 10%, and 10%, respectively. This model considered pipe age, diameter, length, and slope associated with equation (2). The results illustrated in Figure 5 are an indication that the majority of the pipelines in downtown and south side of Mahoning River (approximately 96,190 m in total length) are in poor (6.1–8.0) to very poor (8.1–10) conditions. The results showed that none of the pipelines were described with an empirical factor less than 4. As discussed by Chughtai and Zayed [21], since the age is the major contributing factor in calculation of empirical coefficient, the results also agreed with the fact that most of the pipelines are older than 100 years, resulting in a higher empirical factor.

5.3. Soil Type Emphasis. In this model, 60% weightage was given to the soil type as shown in Table 2. Similarly, 20% for pipe age, 10% for empirical value, and 10% for sewer type were assigned as the weightage value to generate the model. As explained in the soil classification section, soils around

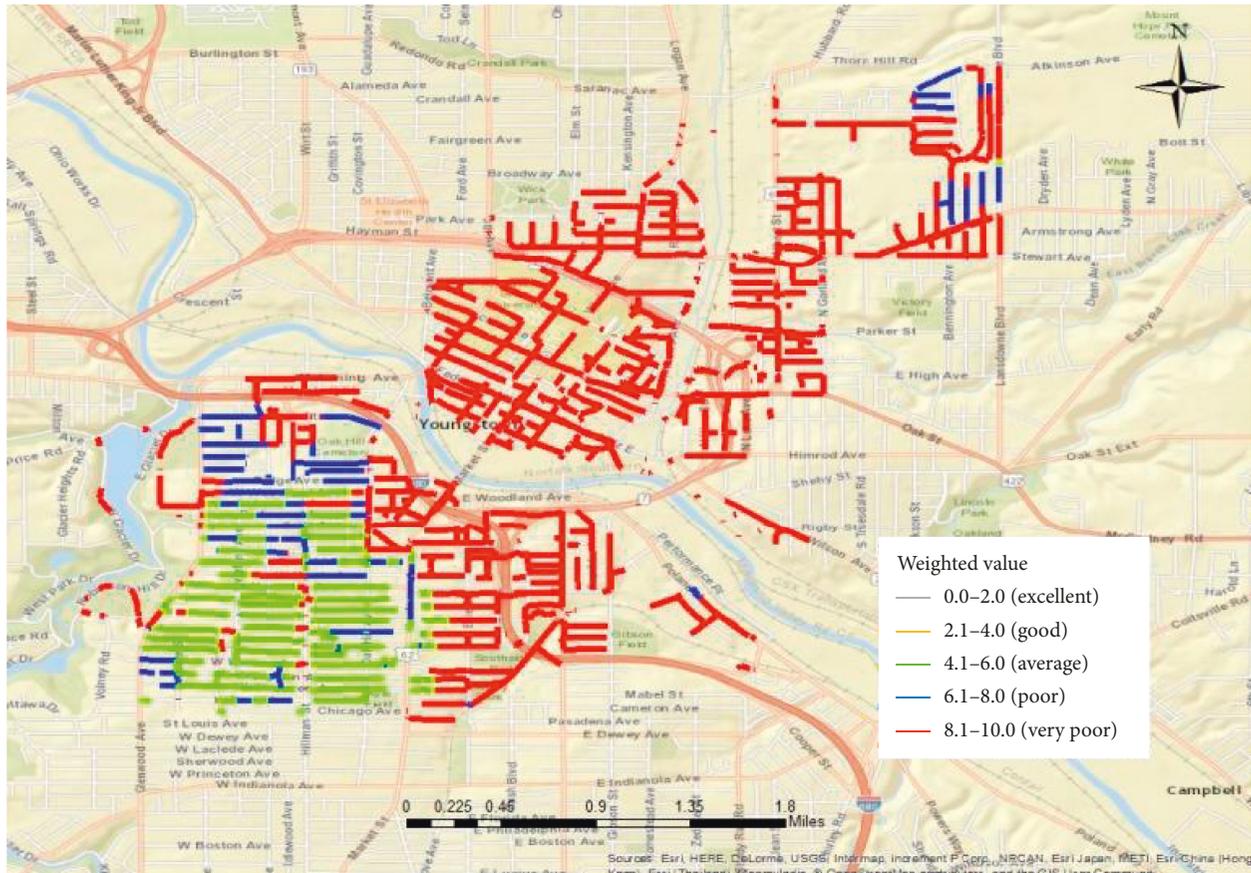


FIGURE 6: Map with soil type emphasis (base map by ArcGIS 10.5).

the sewer lines are one of the important factors for the I&I problem. Infiltration rate is the measure of how fast the water moves into ground and is the function of soil texture (percentage of sand, silt, and clay), and clay mineralogy [29]. The results from the model are shown in Figure 6. The sewer lines of Overland Avenue which runs in the North–South direction, Garfield Street, W Myrtle Avenue, and Kenmore Avenue running East–West direction were found to be in average condition with the value 4.1–6.0. However, the majority of the sewer lines are in very poor conditions. Approximately 81,500 m out of 103,600 m of total length was determined to be in very poor condition. Out of the total length, only 12.1% was determined to be in average condition when the soil type was emphasized with 60% weightage value.

5.4. Emphasis on Equal Weight of All Parameters. In this model, pipe age, empirical value, sewer type, and soil type were given equal weightage and the result for this model is shown in Figure 7. Most of the pipelines are determined to be in very poor conditions. As summarized in Figure 8, 86,000 m of pipe are determined to be in very poor condition, which equals to a value greater than 80%. Similarly, 16% of the piping was found to be in poor condition and piping, ranging from excellent to average was not noticed. Figure 8 summarized all the results from the models used in this study.

6. Conclusions

From this study, sewer conveyance system with different weighted values indicated the susceptible areas prone to the I&I problem. Downtown and the surrounding areas of Youngstown were identified as having high I&I susceptibility. These results are useful to prioritize the segments which need I&I field investigation. The pipelines located in the downtown area and encompassing the Mahoning River are encased in soils with high infiltration capacity. These areas were found to be areas of high concern when describing susceptibility to the I&I problem. Field testing is recommended and should be prioritized in those areas where I&I problems are of major concern. By testing the integrity of these pipes, utility can decrease the cost associated with I&I problems. The initial cost is relatively low when compared to the overall cost. It can be observed the age of pipes can correlate directly to I&I problems and consequently public health. The sewage plant, in question, can be over burdened by these excess inflows and thus causing the excess sewage water that cannot be handled to be discharged in water channels surrounding the Youngstown area.

7. Limitations

Date of construction was not available in the shape file, and the map provided by City of Youngstown did not have date

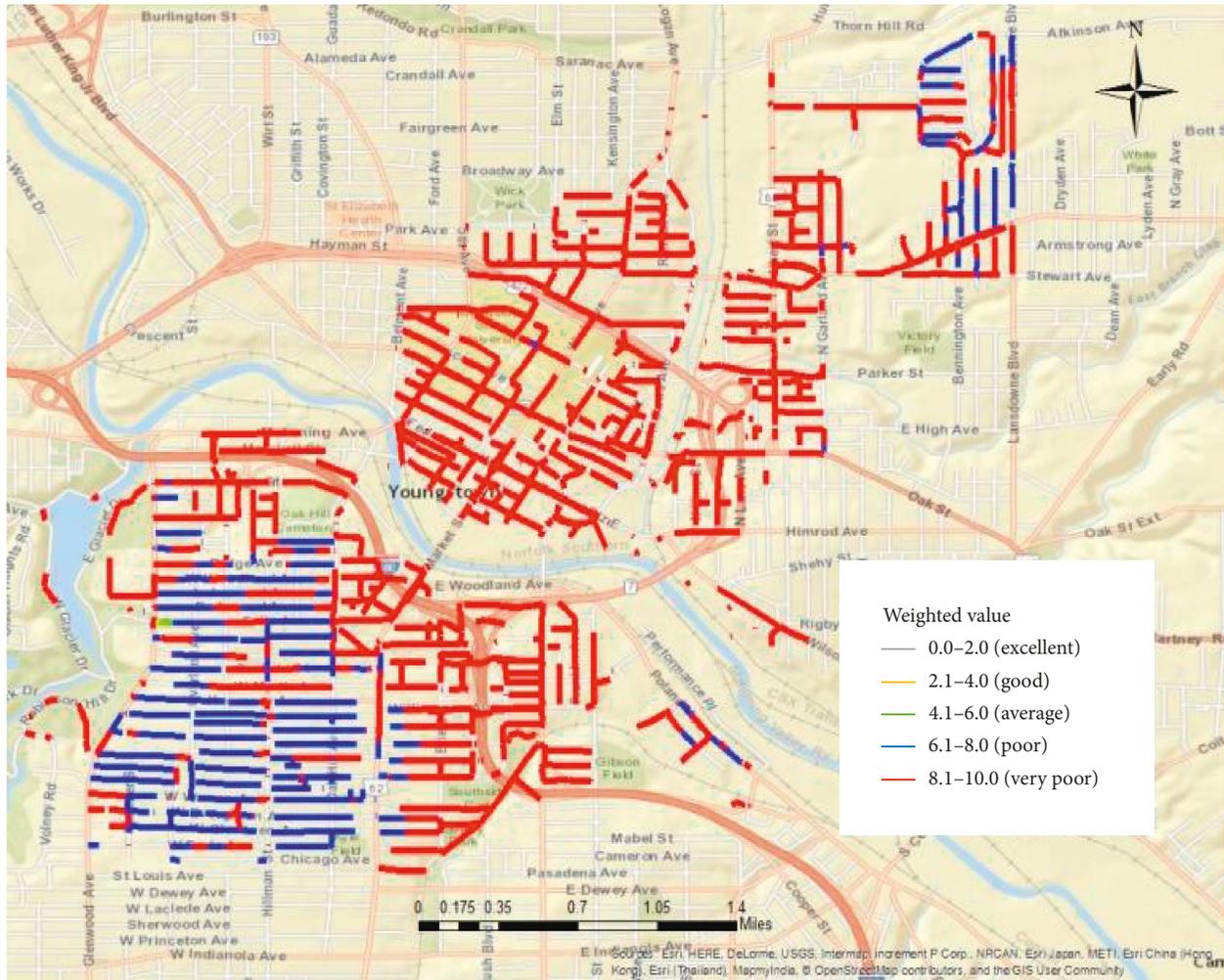


FIGURE 7: Map with emphasis on equal weight of all parameters (base map by ArcGIS 10.5).

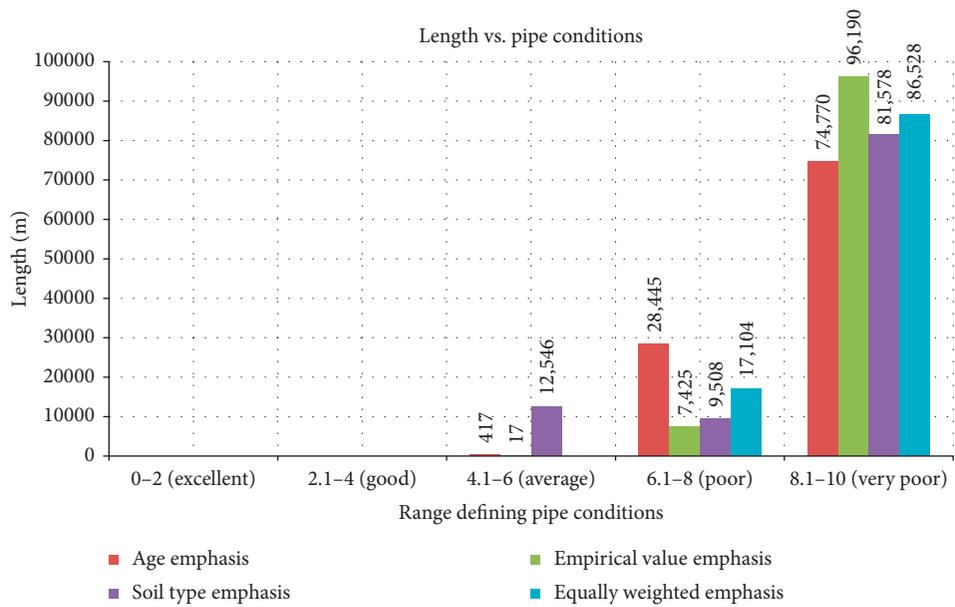


FIGURE 8: Summary of all the results from the different emphasis model.

of construction on file for some of pipe segments. Manual input of the data and assumption of the date of construction and rehabilitation probably incurred a slight error in the model. This is a qualitative approach and provides a preliminary estimate for areas of I&I susceptibility. I&I is a complex phenomenon and can be affected by various factors such as ground water table, quality of the pipe material, quality of construction, proximity of the underground structure, properties of the soil, type of sewer, and structural condition (empirical coefficient). However, only some of the important factors were considered in this model. Other factors such as the sewer subsystem, type of waste, depth of pipe, frost conditions, and proximity to other underground utilities were not considered.

Manning's roughness coefficient (n) was assumed to be 0.011, assuming vitrified clay for the pipe material. Since Manning's roughness coefficient is different depending on the pipe material, the used value in this study may have differed than the actual value of the pipelines in Youngstown.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the URC.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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