CLASSIFICATION OF ASSET LEVELS OF SERVICE WITHIN THE WATER DISTRIBUTION SYSTEM OF SMITHS FALLS VIA MULTI-CRITERIA EVALUATIONS (MCE)

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Abstract

Municipalities manage public infrastructure to provide services to their citizens. The province of Ontario requires under O. Reg 588/17 that all municipalities document current levels of service within their public infrastructure and assets to better inform asset management and resource allocation. These services include maintenance of road networks, sewer lines, and specific to this research, drinking water distribution. A series of multi-criteria evaluation (MCE) models were created to best estimate the current levels of service within the drinking water distribution of Smiths Falls, Ontario. These estimates integrate vulnerability of pipes to internal and environmental factors as well as consequences of pipe failure into overall Asset Levels of Service (ALOS) scores throughout the network. It was found that vulnerability scores carried more importance in determining ALOS scores than consequence scores, likely due to the high spatial variance of consequence-related factors. Our models estimate that 90.67% of the pipes in the drinking water network of Smiths Falls were classified with ALOS ranks of "Very Good, "Good", or "Fair", while only one pipe was found to have an ALOS score of 100 giving it a rank of "Very Poor". Our research suggests that the Smiths Falls drinking water distribution network is providing an adequate level of service to citizens. This research allows for streamlined assessment of public assets while accounting for numerous spatial variables with implications for the use of MCE models in municipal asset management.

Keywords: asset management, multi-criteria evaluation, drinking water distribution, infrastructure vulnerability, levels of service

Introduction

Disruptions to drinking water networks can be caused through fracturing, leaks, or complete pipe blowouts (collectively termed “pipe failure”) and can result in costly maintenance or repair (Barton et al., 2019). The quality and sustainability of underground drinking water networks is subject to many environmental factors (Aschilean et al., 2018; Moerman et al., 2016; Barton et al., 2019), as well as wear that is inherent with physical properties (Barton et al., 2019; Farrow et al., 2017; Hanusch et al., 2013; Yan and Vairavamoorthy, 2003). The combination of these environmental and physical factors contributes to Asset Levels of Service (ALOS). ALOS measures the adequacy of assets to provide customer services (*Association of Municipalities Ontario*, 2020) and are classified in the context of this research as a combination of vulnerability of pipes to failure and consequence of failure the latter being a proxy for social, financial, and environmental costs associated with pipe failure. Determining ALOS is essential for effective asset management and is required to address part of recently updated provincial mandates under Ontario Regulation 588/17 (2017). Compliance with O. Reg. 588/17 ensures than municipalities remain well positioned for grant eligibility and that investment priorities can be rationalized with an educated understanding of existing conditions (*O. Reg. 588/17*, 2017).

Multiple criteria may be used to classify the condition of water distribution piping, with the more significant pipe-intrinsic criteria being age, diameter, and material (Barton et al., 2019). Additionally, spatial environmental criteria impact the likelihood of pipe failure and the financial, environmental, and social consequences associated with pipe failure (Aşchilean et al., 2018; Garmabaki et al., 2020). Spatial factors such as land use and zoning (Adeoson, 2014), as well as proximity to waterbodies, environmentally significant areas (T. Dunlop, personal communication, March 23, 2021), and existing infrastructure (Aşchilean et al., 2018; Moerman et al., 2016) influence the consequences of pipe failure. These criteria require geospatial analysis to understand the ALOS in a network, as they vary spatially (Fischer, 2003). Smaller municipalities often lack resources to allocate towards identifying these levels of services across all branches of public infrastructure. Utilizing geospatial analysis allows for pipes with high vulnerability to and high consequence of failure to be identified through ALOS determination to properly inform planning, aiding in the provision of effective and efficient services (Fischer, 2003).

There are a variety of approaches possible to geospatially analyze water distribution systems. Hazard Vulnerability Assessment is a technique for determining levels of vulnerability within an area, but is often applied to natural disaster vulnerability making it inapplicable to drinking water networks (*Hazard Vulnerability Assessment*, n.d.; Krishnamurthy & Krishnamurthy, 2012). Network Analysis is another approach for addressing conditions of a drinking water distribution network, but is most optimally used for route efficiency and pathfinding, not vulnerability analyses (GITTA, 2013). Suitability analysis allows for the assessment of geospatial factors and is often used in the determination of suitable sites based on multiple criteria. Suitability analysis allows for a suitability score (or vulnerability score) to be calculated across a network of vector or raster features (Malczewski, 2006; Jankowski et al., 1997).

There are three types of suitability models: simple (binary), fuzzy, and weighted (GITTA, 2013). Weighted Suitability Analysis in the form of Multi-Criteria Evaluation (MCE) was deemed to be most appropriate in assessing ALOS with a combination of intrinsic and geospatial factors. This form of MCE analysis allows for unequal importance to be assigned to variables, reflecting real world decision-making (GITTA, 2013). MCE analysis for the evaluation of a drinking water network was utilized by Yan and Vairavamoorthy (2003), but besides this study, limited research has been found demonstrating this method for the analysis of infrastructure networks besides those determining site locations.

Statement of Research Purpose

The purpose of this research is to create models of vulnerability and consequence of pipe failure for the drinking water distribution network in the Town of Smiths Falls, Ontario to determine ALOS scores and subsequent municipally standardized rankings. The secondary purpose of this research is to provide a model for municipalities to utilize MCE in addressing the requirements put forth by O. Reg. 588/17. These research purposes will be addressed by meeting the following research objectives:

Objectives

Objective I: Identify variables and criteria for use in the vulnerability and cost and consequence MCEs. The identified criteria will then be preprocessed for integration into the MCE and assigned weights.

Objective II: Create a model for the vulnerability MCE using respective weighted factors. This will determine vulnerable areas for failure within the drinking water network of Smiths Falls.

Objective III: Create a model for the consequence MCE using respective weighted factors. This will determine the consequences associated with pipe failure throughout the Smiths Falls drinking water network based on environmental and pipe-intrinsic criteria.

Objective IV: Combine scores from both vulnerability and cost and consequence MCEs to create a final ALOS evaluation score. Create ALOS rankings aligned with the standard municipal ranking system based on ALOS scores.

Objective V: Assess and discuss the strengths, limitations, and applications of our research findings.

Study Area

The Town of Smiths Falls (Figure 1), is a community of approximately 9,000 residents in Eastern Ontario, Canada (*Statistics Canada*, 2016). The town lies between the cities of Kingston and Ottawa on Ontario Highway 15. Smiths Falls was identified as a suitable study area to integrate geospatial analyses in the determination of current ALOS for the town's drinking water distribution network for several reasons. Due to its reasonably small geographic size the town provides a suitable scale for the application of this research. The town utilizes pipes of varying ages and materials within their existing distribution system, allowing for a broad range of criteria to be evaluated through the MCEs. While the town plans to hire a GIS and Asset Management Coordinator in 2021, they have previously lacked resources to undertake this project independently, making the results of this research directly applicable to the town's asset management planning. The town provides drinking water under standard best practices for treatment and distribution, as outlined under the Clean Water and Safe Drinking Water Acts. These practices reflect standards within the province of Ontario (*O. Reg. 169/03*, 2003).

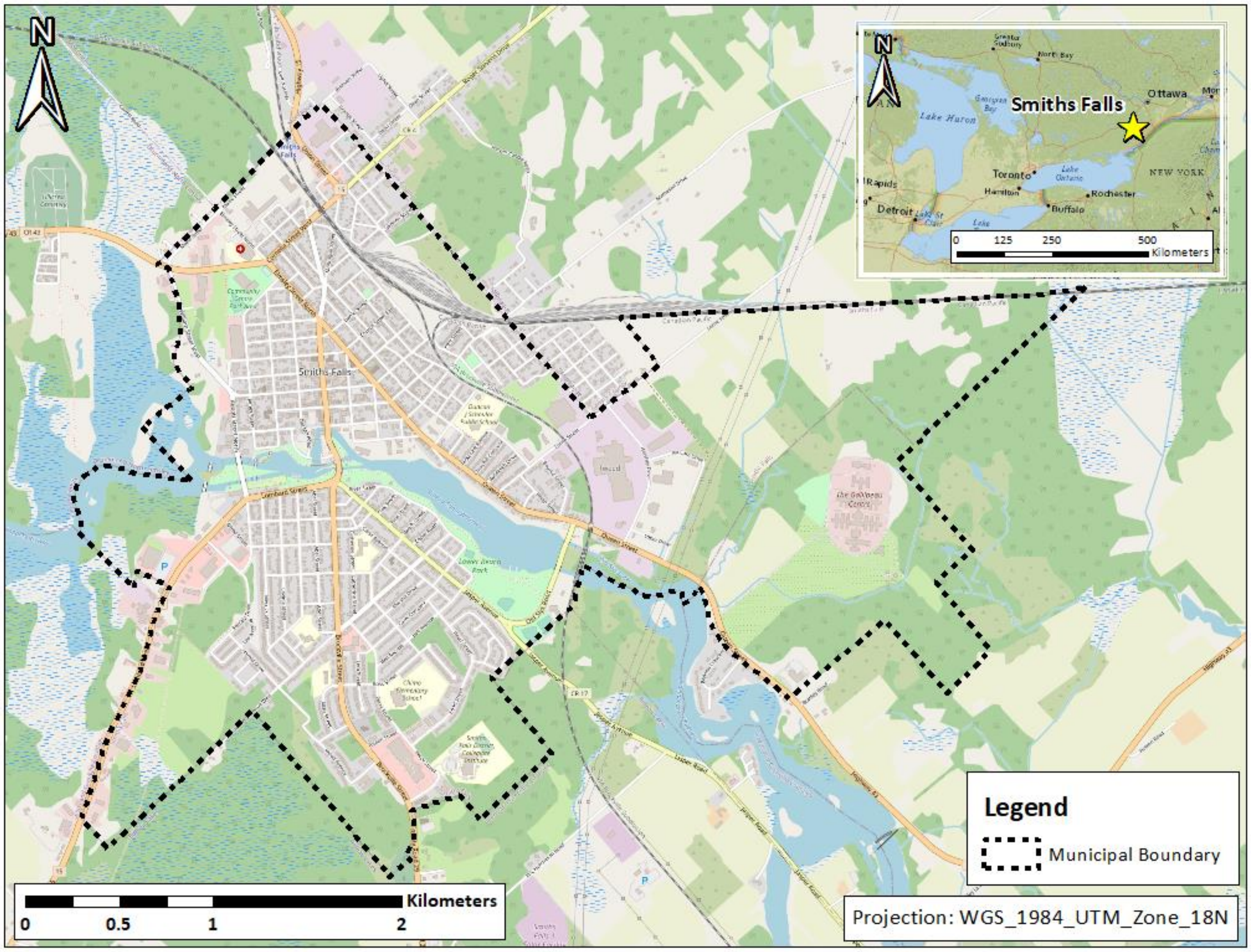


Figure 1. Boundary map of the Town of Smiths Falls, including inset map for provincial context.

Research Approach

1. Select Criteria and Prepare Data for Model Input

1.1 Selection of Criteria – Objective I

The first step in the standard procedure for MCE outlined by GITTA (2013) is the selection of criteria. Criteria selection involves the determination of spatial and intrinsic pipe characteristics contributing to vulnerability to and consequence of pipe failure. This was done using academic literature and consultation with our community contact for the town's Public Works and Utilities Department.

Selected criteria had factors applied to allow for specifications within the model. These include minimum and maximum values, appropriate buffers, and rankings of pipe characteristics. Criteria and associated factors as described in Table 1. 20m buffers were applied to line features to provide a two-dimensional area for which the watermain network may intersect and to reflect the width of the roads within the town. The hospital was given a 20m buffer to include pipes in proximity that would feed into the hospital. ESAs were given a buffer of 120-metres to comply with provincial standards outlined by the Ministry of Natural Resources (MNR) and Rideau Valley Conservation Authority (RVCA) set in 2015.

Table 1. Description of individual criterion with brief explanation of implication within the model, factors, buffers where applicable, literature source, and data source. Criteria will be used in the creation of vulnerability and consequence MCEs.

Criterion	Implication	Factors	Buffer	Source	Data Source
Road Network	Road type decides traffic capacity, which influences vulnerability to pipe failure.	Collector, Arterial, Local	20m	Aschilean et al., 2018; Moerman et al., 2016	Producer: CGIS Date published: 2021-02-09 Source: Town of Smiths Falls Public Works Department – Troy Dunlop
Water Features	Larger financial and social consequence associated with work intersecting water feature.	Rideau River, Minor Tributaries	20m	T. Dunlop, personal communication 04/23/2021	Producer: RVCA Date published: 2013-06-29 Permalink: https://gis.rvca.ca/arcgis/rest/servicesCGIS
Landuse Zoning	Social and financial costs associated with land use will define weightings for specific landuse designations.	Major Institutional, Hospital, Industrial, Corridor Commercial, Neighbourhood Commercial, Residential, Open Space, Downtown Core (DT Core)	N/A	Adeoson, 2014; T. Dunlop, personal communication, 04/23/2021	Producer: CGIS Date published: 2021-02-09 Source: Town of Smiths Falls Public Works Department – Troy Dunlop

Criterion	Implication	Factors	Buffer	Source	Data Source
Pipe-Intrinsic Factors	Influence on vulnerability of pipe, with some factors such as diameter influencing consequence of failure.	Pipe Age, Material, Diameter (mm)	N/A	T. Dunlop, personal communication, 04/23/2021; Barton et al., 2019; Farrow et al., 2017; Hanusch et al., 2013; Yan and Vairavamoorthy, 2003	Producer: Public Works – Town of Smiths Falls Works Date published: 2021-02-09 Source: Town of Smiths Falls Public Works Department – Troy Dunlop
Water Main Network Smiths Falls	Baseline vector for water main networks.	Pipe Age, Material, Diameter (mm)	N/A	Town of Smiths Falls, 2016	Producer: CGIS Date published: 2021-02-09 Source: Town of Smiths Falls Public Works Department – Troy Dunlop
Environmentally Significant Areas	Increased financial costs and additional resources due to permit requirements, contributing to consequence of failure.	PSW, ANSI, Provincially significant ecological and forested areas	120m	T. Dunlop, personal communication 04/23/2021; RVCA, 2018	Producer: MNR, RVCA, ECCC Date published: 2015-04-30 Permalink: https://data.ontario.ca/dataset/wetlands
Railway	Intersection with railway features increases vulnerability due to weight loading and vibrations. Social and financial costs increase consequence score.	Railway Network	20 m	Garmabaki et al., 2020, T. Dunlop, personal communication, 04/23/2021	Producer: CGIS Date published: 2021-02-09 Source: Town of Smiths Falls Public Works Department – Troy Dunlop
Trails	Social and financial cost associated with intersection of popular public trails increases consequence score.	Cataraqui Trail, TransCanada Trail	20 m	T. Dunlop, personal communication 04/23/2021	Producer: CGIS Date published: 2021-02-09 Source: Town of Smiths Falls Public Works Department – Troy Dunlop

1.2 Data Pre-Processing and Standardization

Data layers were reprojected to WGS 1984 UTM 18N and clipped to the study area, allowing for synthesis between layers in the steps to follow.

Data layers for environmental factors as well as pipe-intrinsic attributes were rescaled between 0 and 100 by their associated indicator values to prepare data layers for uniform comparison during evaluation (Vafaei et al., 2016). Equation 1 was used, applying linear stretches in the prewritten scripts for both vulnerability and consequence MCEs.

$$X_i = {(x_i - X_{min})}\Big/{(X_{max} - X_{min})} \tag{1}$$

In which X_i represents the criterion score of factor i, x_i represents the original value of factor i, X_{max} represents the maximum factor of X, and X_{min} represents the minimum factor of feature X (GITTA, 2013).

1.3 Determination of Weights

Saaty's Pairwise Comparison technique was used to determine weightings of vulnerability and consequence criteria. This technique creates weights based on all relative relationships between variables with the aim of reducing subjectivity inherent in weighting systems (ESRI, n.d.). Ranks given to variables during pairwise comparisons were educated by our community contact and supported by academic literature (Table 1). Pairwise Matrices are appended (Appendix A).

2. Creation of Multi-Criteria Evaluation Models – Objectives II and III

Steps 2 and 3 (and associated sub-steps) describe the workflow as visualized in Figures 3, 4 and 5.

2.1 Merging and Dissolving Data Layers

Features with the same weighting were merged, then dissolved to form a single continuous feature. Roads were ranked as arterial, collector, or local depending on daily traffic load. To manage the overlap at intersections, these rankings were clipped according to the highest traffic load, and then clipped to reflect that road-type.

2.2 Calculate MCE Scores at Segmented Pipe Level

Using the watermain network and the features relevant to each MCE, the intersect tool was used to identify which features each pipe crosses through. As shown in Figure 2, at regions where a single pipe crossed several features (Figure 2.1), the pipe would be segmented based on the boundaries of those features (Figure 2.2). An MCE score was then generated at the segmented level based on the vulnerability and consequence factors each segment intersected with using MCE Score (2) (Figure 2.3).

$$MCE\ Score = \sum w_i X_i \prod C_j \tag{2}$$

Where w_i is representative of the weight assigned to factor i, X_i represents the criterion score of factor i, and C_j is representative of constraint j.

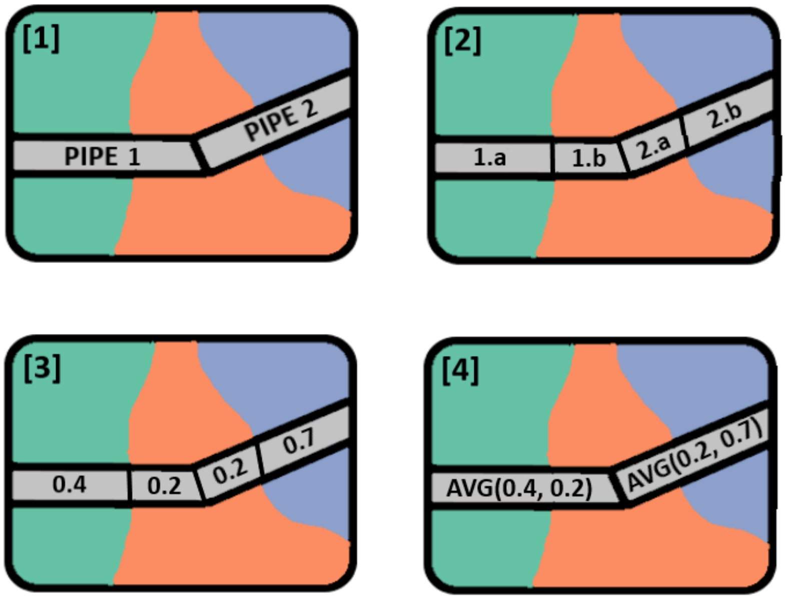


Figure 2. [2.1] Existing watermain network throughout the town shown by full pipes with pipe IDs.
[2.2] Spatial features are intersected with the watermain network, producing segmented pipes with segmented pipe IDs still associated with their respective original pipe IDs.
[2.3] The MCE script is run, and the resulting scores are applied to each segment based on the weightings for criteria that the segments intersect with.
[2.4] The segments are dissolved back to the original extent in [2.1] while taking the average score of the segmented components.

2.3 Calculate MCE Scores at Full Pipe Level

The segmented watermain network with associated scores was dissolved back to the original extent of the pipe using the associated full pipe ID for each segment. While dissolving the network, the mean score for the individual segments was taken as the value for the entire pipe. This is a simplified method to assign scores at the full pipe level and does not consider the length of each segment when aggregating back to the full pipe. The resulting score from this method is the final value for both the vulnerability and consequence maps.

3. Combining Consequence and Vulnerability MCE to create final ALOS Output - Objective IV

3.1 Creating ALOS Score

The aggregated vulnerability and consequence MCE scores were then summed and rescaled to 0-100 using Linear Stretch (Eq. 1) to form each pipe's final combined ALOS score. This method was utilized to ensure that the differences between scores were not exaggerated.

3.2 Municipal Rankings

These scores were categorized into municipal ALOS rankings of “Very Poor”, “Poor”, “Fair”, “Good”, and “Very Good”. This ranking system matches existing standard for municipal asset management planning and helps with public communication of the results (personal communication, T. Dunlop, 8/04/2021). The ranks were determined using the equal interval method.

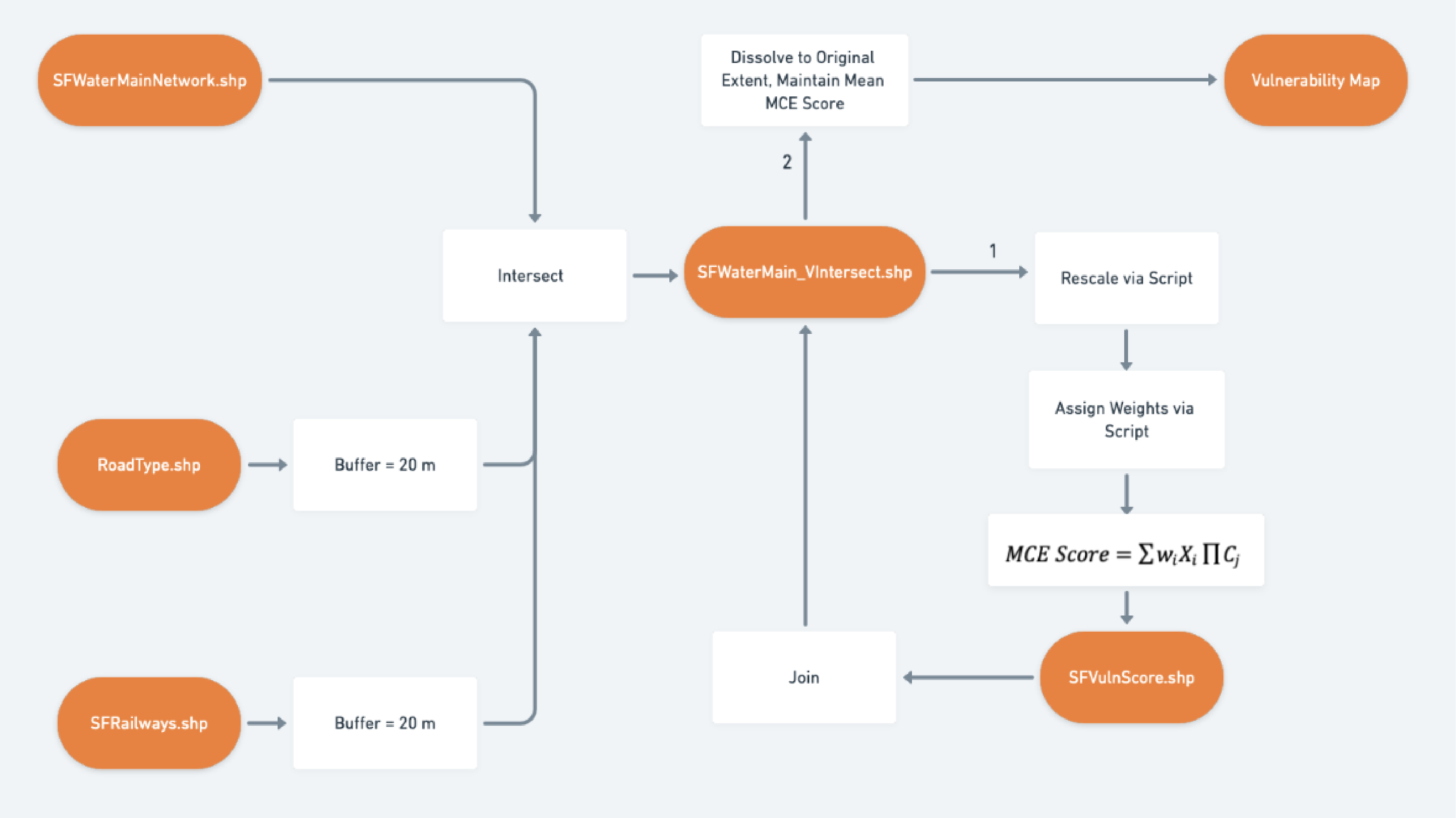


Figure 3. Procedure to spatially align the watermain inventory and pre-process the pipe network, road network, and railways. The section labelled with a 1. denotes the first steps done to SFWaterMain_VIntersect.shp before the steps following path 2. Weightings calculated using Saaty's Pairwise Comparison technique and applied to the network to produce vulnerability scores by pipe segment.

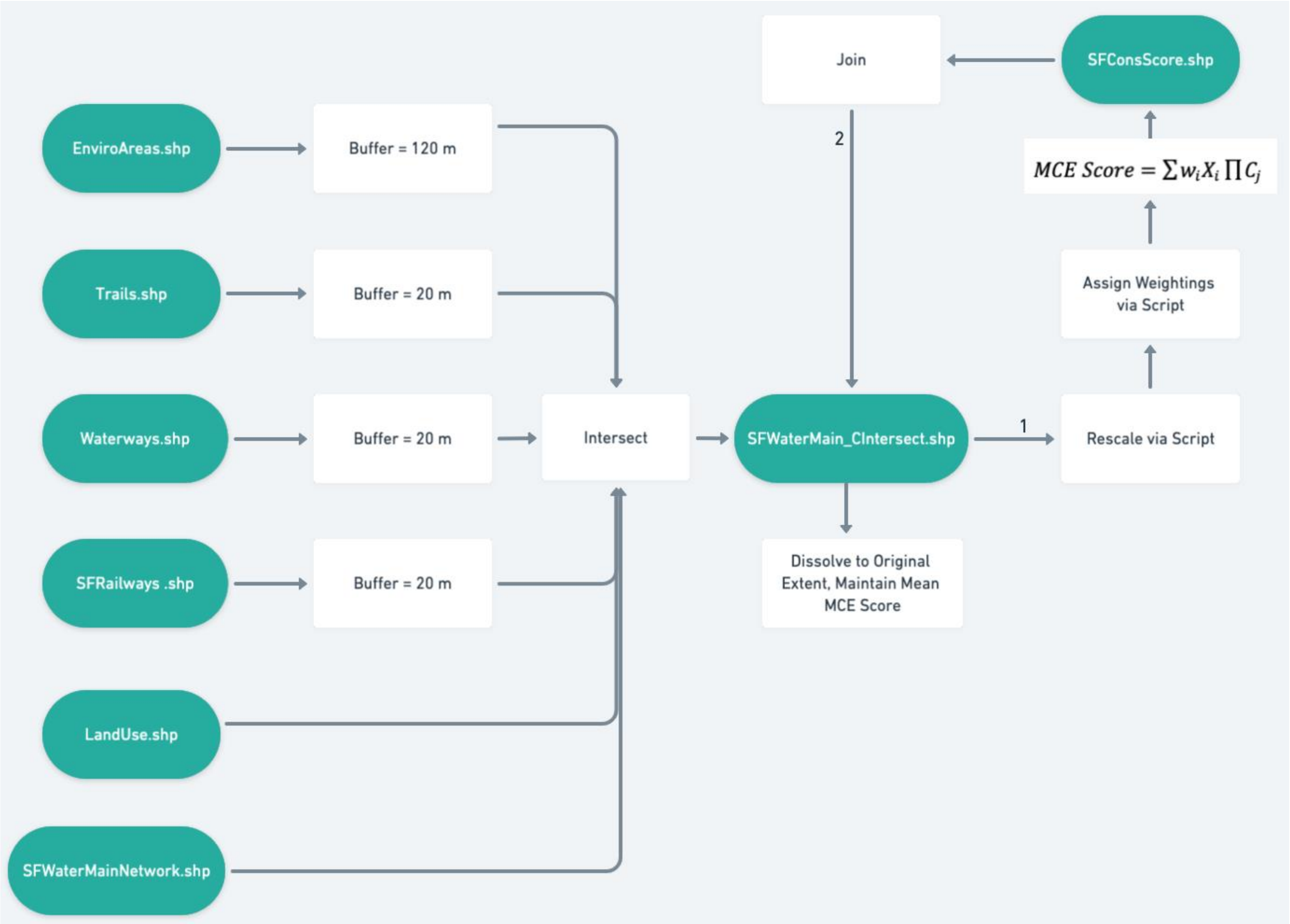


Figure 4. Procedure to pre-process the waterways, railways, environmentally significant regions, and urban land use features. The section labelled with a 1. denotes the first steps done to SFWaterMain_VIntersect.shp before the steps following path 2. Weightings calculated using the Saaty's Pairwise Comparison technique and applied to the network to produce consequence of failure scores by pipe segment.

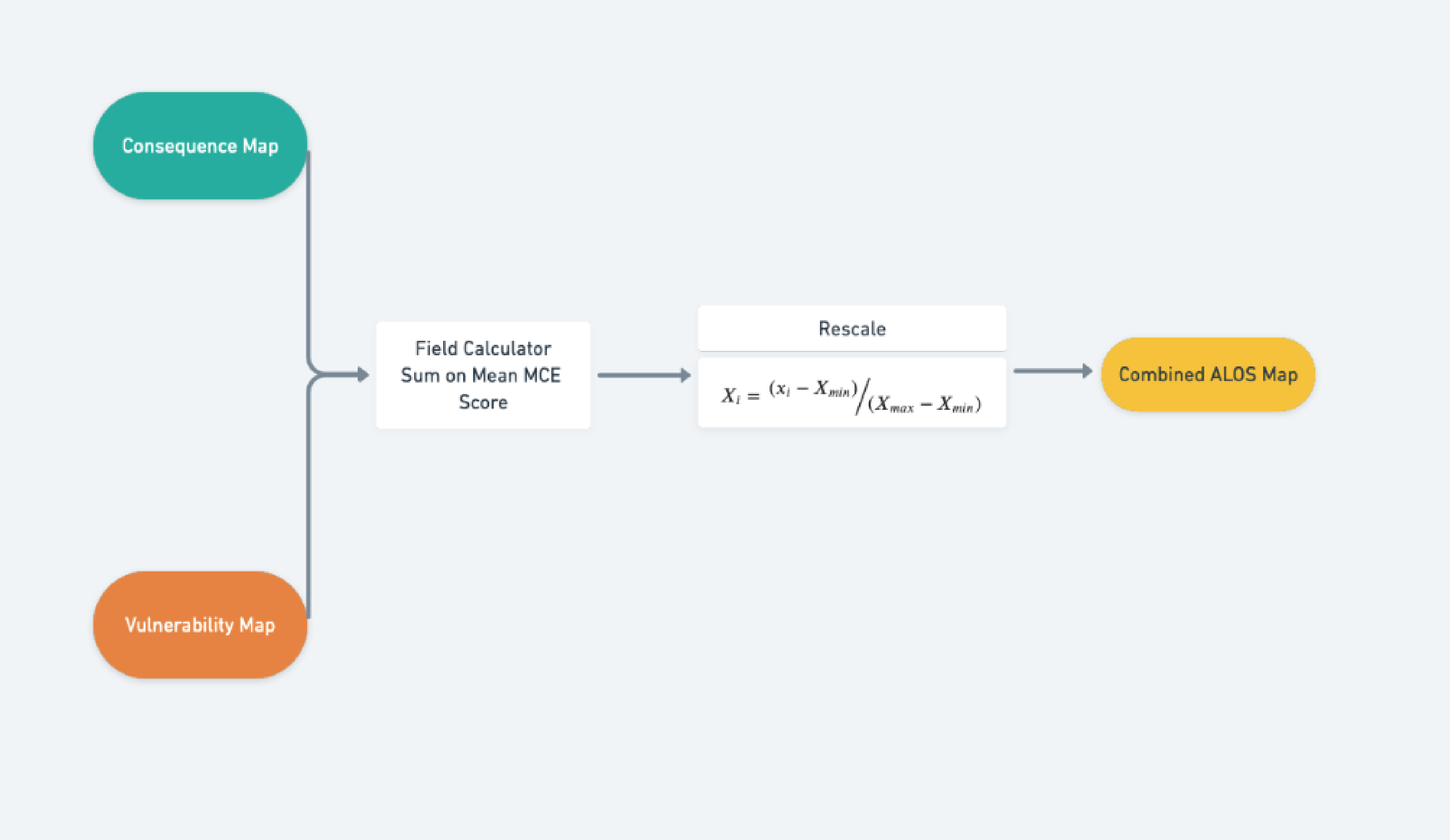


Figure 5. Consequence and vulnerability outputs (MCE scores at full pipe level) were summed through the field calculator tool. They were then rescaled using Eq. 1 to create the final combined ALOS Score which was then classified using equal intervals of 20 to produce the ALOS ranks in the ALOS map.

Results

Vulnerability MCE Output

Vulnerability MCE scores are shown across the network at the full pipe extent in Figure 6. As seen in Table 2 below, only 561.30 m of pipe in the drinking water network for Smiths Falls has a vulnerability score between 80 to 100, representing only 0.94% of the total network length as shown in Table 2. Table 2 further shows that ~70% of the total network length has a vulnerability score below 60 out of 100. This trend can be seen in Figure 6, where there is a low concentration of pipes in the highest vulnerability score range, with the highest being 88.76.

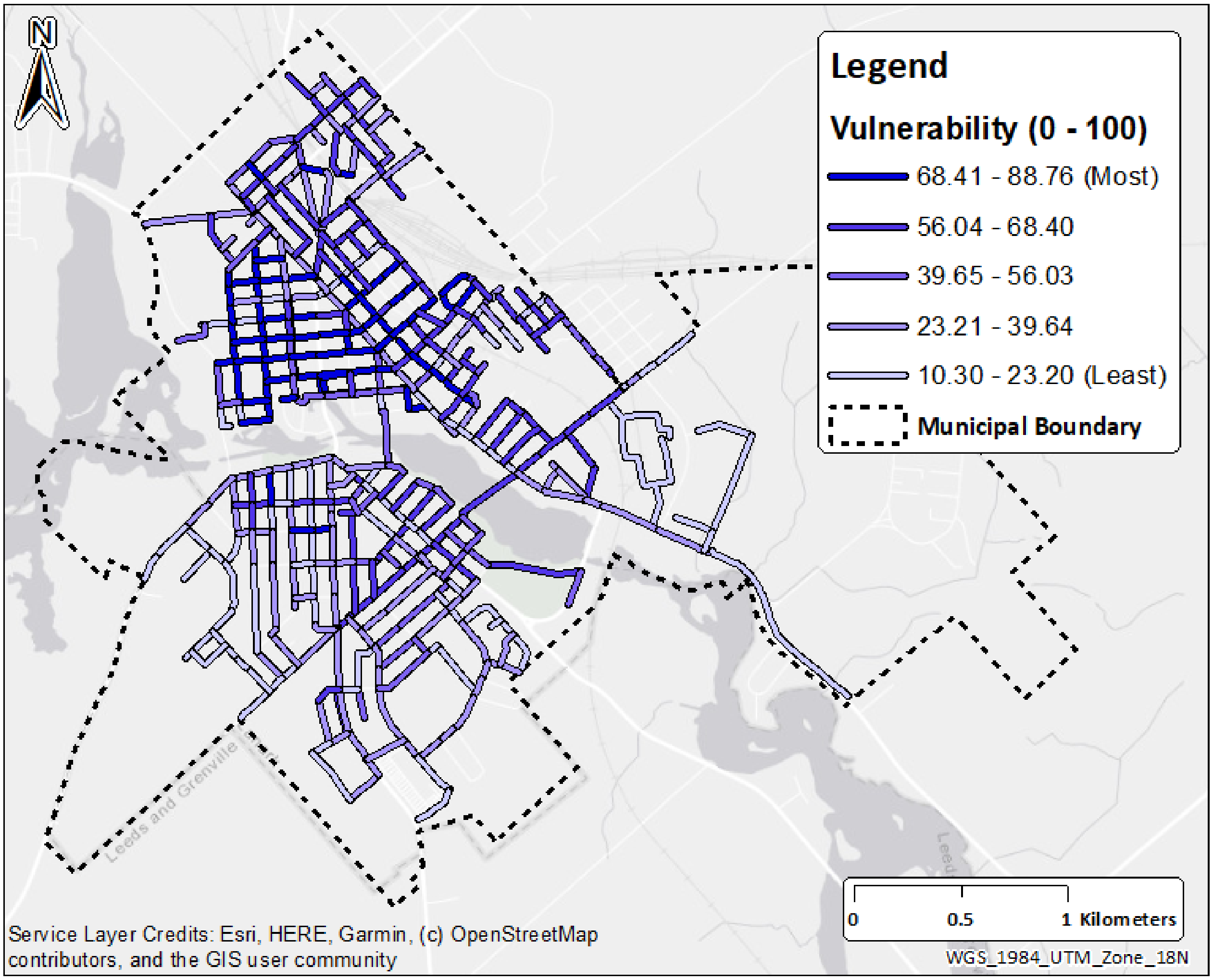


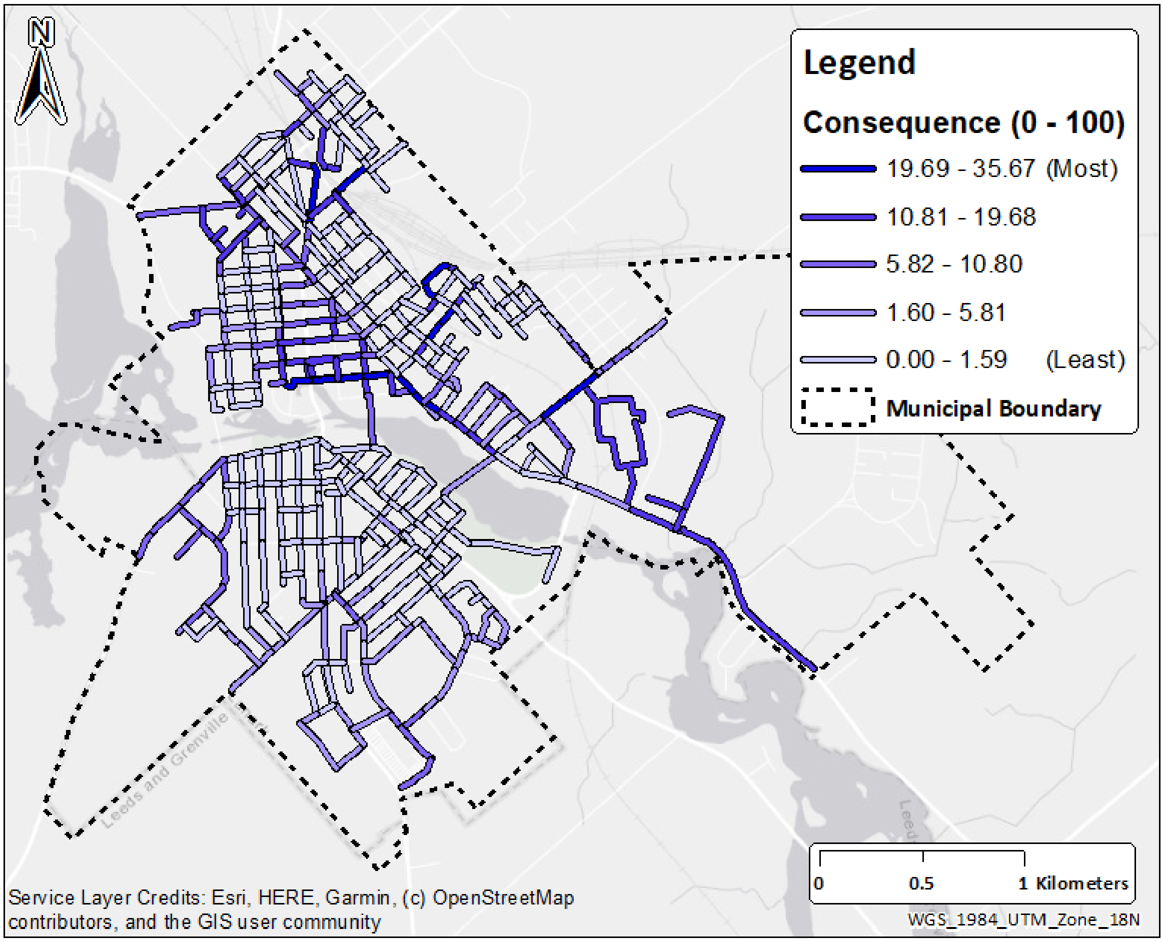
Figure 6. Vulnerability scores are shown across the study area of Smiths Falls, Ontario. Ranges resolved via natural breaks using Jenks' method.

Table 2. Vulnerability MCE scores are broken down based on natural patterns in the data. Total pipe length and percent of the network are shown for each category of scores.

Vulnerability Score	Total Pipe Length (m)	Percent of Network (%)
80-100	561.30	0.94
60-79.99	17585.04	29.59
40-59.99	12064.22	20.30
20-39.99	19330.19	32.53
0-19.99	9887.57	16.64

Consequence MCE Output

The consequence MCE output as shown in Figure 7 shows relatively low scores compared to the vulnerability MCE output (Fig. 6), with just over half of the network (50.59%) scored at 0. Table 3 highlights that 100% of the network has a consequence score of 24 out of 100. In addition, 50.59% of the network has a consequence score of 0, as shown in Table 3. 2.53% of the network received a score over 24 out of 100, suggesting low consequences to potential failures across the network.



Service Layer Credits: Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 7. Consequence of failure scores are shown across the study area of Smiths Falls, Ontario. Ranges resolved via natural breaks using Jenks' method.

Table 3. Consequence scores are broken down based on natural patterns in the data. Total pipe length and percent of the network are shown for each category of scores.

Consequence Score	Total Pipe Length (m)	Percent of Network (%)
24+	1505.73	2.53
16-24	6395.41	10.76
8-16	6899.82	11.61
0-8	14563.50	24.51
0	30063.87	50.59

ALOS Output

The output of the combined MCE ALOS scores and their associated ranks is displayed in Figure 8 and shows that much of Smiths Falls' drinking water network has a score below 60 out of a possible 100. This is further shown in Table 4 where approximately 96% of the total network length has an ALOS score below 0. Only 0.24% of the network has a score in the "Very Poor" range of 80-100, which consists of a single pipe with an ALOS score of 100, contributing only 144.39m to the total network length out of 59428.32m. The breakdown of the network's ALOS rankings in Table 4 highlights the majority (90.67%) of the network is classified as being "Very Good", "Good", or "Fair".

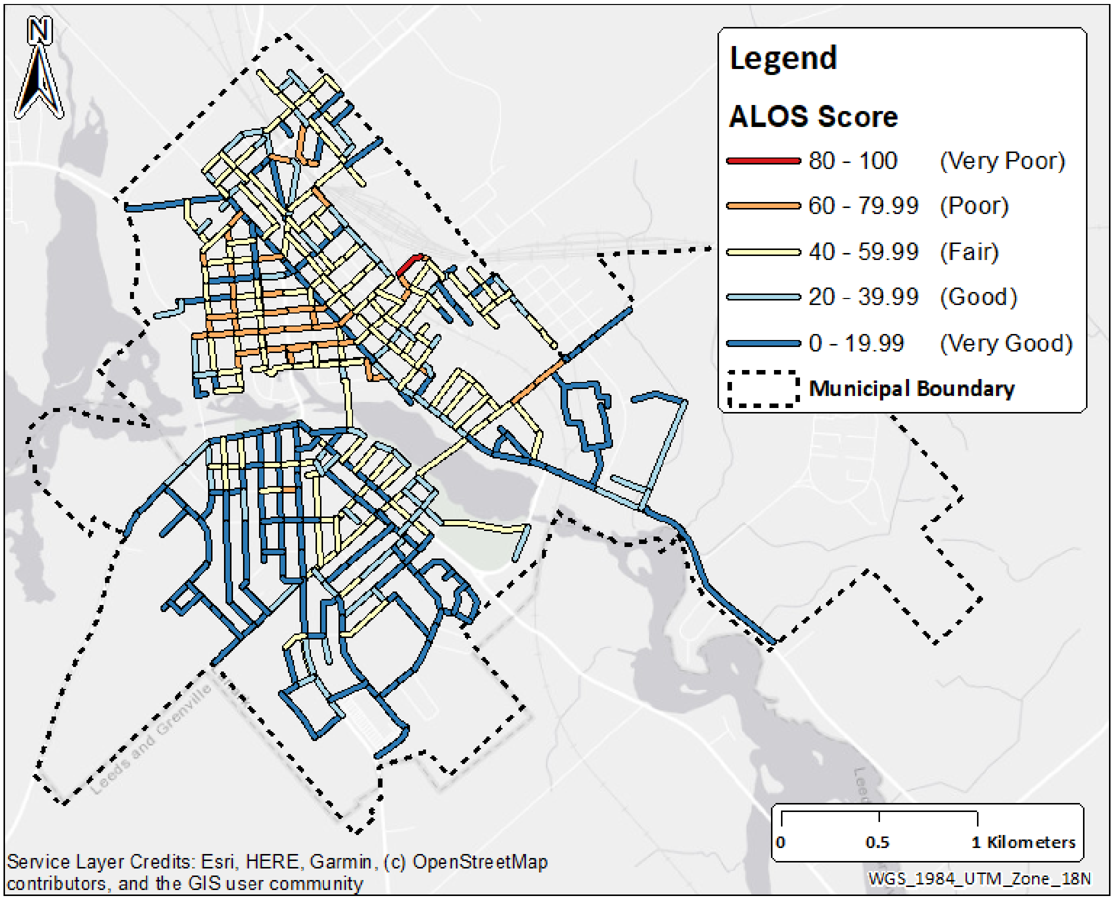


Figure 8. Combined Associated Level of Service (ALOS) scores are shown across the study area of Smiths Falls, Ontario.

Table 4. Combined Associated Level of Service (ALOS) scores are ranked based on 5 equal intervals. Total pipe length and percent of the network are shown for each category of scores.

ALOS Score	ALOS Rank	Total Pipe Length (m)	Percent of Network (%)
80-100	Very Poor	144.39	0.24
60-80	Poor	5397.84	9.08
40-60	Fair	20252.32	34.08
20-40	Good	9647.10	16.23
0-20	Very Good	23986.68	40.36

Discussion

It can be seen from the consequence MCE output that the scores are relatively low compared to those of the vulnerability MCE. This is likely because the factors contributing to consequence scores vary spatially. For example, a pipe which runs under a waterbody is unlikely to also run under a railway, cross a provincially significant environmental area, and be within 20m of the Hospital in Smiths Falls in the same segment. This explains the pattern seen in the northern end of Smiths Falls, where the scores in the consequence output (Fig. 7) range from 0 to 5.81, but in the vulnerability output (Fig. 6), this area has scores ranging from 68.41 to 88.76, the highest classification of vulnerability scores in the network. This is likely due to the age of cast iron pipes in this older part of town, as age contributes significantly to vulnerability but does not impact the consequence of pipe failure. In general, the network is more impacted by factors contributing to vulnerability to pipe failure than it is to those contributing to the consequences of pipe failure.

In addition, as approximately half of the network length received a consequence score of 0, half of the network in the ALOS output is based solely on the associated vulnerability score per pipe. As this pattern in our results is caused by unique spatial factors considered for consequence to pipe failure, it likely will differ if the model is applied to other municipalities.

The combined ALOS scores as seen across the network in Figure 8 show several patterns. Only the singular pipe achieving the ALOS score of 100 was impacted by nearly all the least favourable traits for both vulnerability and consequence factors. This was the only pipe to be categorized with an ALOS score of 100 and a rank of “Very Poor”, which represents only 0.24% of the total network. The combined ALOS scores led to the ranking of 90.67% of the network as being in “Very Good”, “Good”, or “Fair” condition. This is significant for the asset management of the town’s drinking water network, as few pipes need the most immediate attention based on our results.

The results of the ALOS output for the town allows for determination of areas of concern within existing assets and efficient asset management, partially satisfying the requirements for Smiths Falls outlined in O. Reg. 588/17. This approach streamlines the assessment of ALOS within public infrastructure, aiding smaller municipalities in making well educated decisions on asset management and optimizing their use of resources. While certain data is spatially unique such as land use zoning, ESAs, and waterbodies, the general framework and research approach utilized in the creation of the vulnerability and consequence MCEs leading to the ALOS determination can be customized to fit other municipal infrastructure networks. Our methods involved calculating scores at a segmented level then aggregating back to the full pipe extent, which is a technique applicable to other line networks, such as sewage networks, road networks, and more.

This research focuses on drinking water distribution, but the methods applied can be adjusted to create ALOS outputs for other infrastructure networks within the same municipality to meet the full requirements for O. Reg. 588/17. Scripts created to run the workflow of this research are publicly available through Github.com (Appendix B). Methods for rescaling and creating MCE scores will remain consistent, and the framework for defining weights is well suited for customizations based on spatial differences between municipalities. Limitations to the expansion of this method of ALOS are dependent on the availability of spatial data and funding for data collection and interpretation.

Subjectivity is inherent in the MCE process, even though Saaty's Pairwise Comparison reduced subjectivity in scores compared to other weighting schemes (GITTA, 2013). Potential means of reducing subjectivity in the process could involve utilizing input from additional stakeholders in the weighting process. For example, data layers for environmental factors such as ESAs or waterbodies could include input from stakeholders such as Natural Heritage Committees, and conservation authorities respectively. In addition, community input could be incorporated in the weighting process, especially for the consequence MCE to reflect valued community components that may not be reflected from scientific literature and input from the Public Works Department of Smiths Falls.

Furthermore, certain aspects of asset management could not be integrated into the MCEs due to limited access to properly scaled data and time limitations. Criteria left out of the models discussed in the literature as important to pipe failure vulnerability include water pressure and soil characteristics. Some data was not applicable to the study area due to scale, while other data was simply unavailable. Thus, the vulnerability MCE model is missing some environmental and pipe-intrinsic factors that would likely impact the results and conclusions. In addition, our methods do not consider the relative impact of segment length when aggregating MCE scores to the full pipe extent.

Reference data was unavailable to perform quality control on the outputs of the MCE models, so sensitivity of the models was not measured. We recommended municipalities include quality control with reference data when replicating this research for their respective ALOS rankings. Reference data for this application may be in the form of historical break records that can be spatially analysed to determine if patterns historically match the patterns shown in the MCE outputs.

Conclusion

The quality and sustainability of underground drinking water networks is subject to many environmental factors such as proximity to railways, waterbodies, and ESAs as well as wear that is inherent with physical properties including pipe age, material, and diameter. The combination of these environmental and physical factors contributes to ALOS which is classified in the context of this research as a combination of vulnerability of pipes to failure and consequence of failure. The aim of this research was to apply geospatial analysis to the drinking water network of Smiths Falls to further understand the spatial impacts on service level determination required for all Ontario Municipalities by O.Reg. 588/17 (2017). Two MCEs were created, studying criteria contributing to vulnerability and consequence of pipe failure in the Town of Smiths Falls, Ontario. The MCEs were created using a weighted model to account for relative importance of factors contributing to vulnerability and consequence.

Our results include 3 outputs: a vulnerability MCE, a consequence MCE, and a combined output that reflects the overall ALOS scores and subsequent municipally standardized rankings. Several patterns were seen in the outputs, including general low consequence scores - likely due to the high spatial variance across the network regarding consequence factors - which led to the final ALOS output being largely influenced by vulnerability scores. The majority (90.67%) of the drinking water network of Smiths Falls is classified as being in “Very Good”, “Good”, or “Fair” condition.

There are many applications of this research, including the expansion of the MCE model use for determining service levels for other municipal infrastructure required for O.Reg. 588/17 beyond just drinking water networks. Our methods involved calculating scores at a segmented level then aggregating back to the full pipe extent which is a technique applicable to other line networks, such as sewage networks, road networks, and more. Additionally, this research sets a precedent for other Ontario municipalities to use in their determination of ALOS.

Future research could involve the recreation of our study using additional significant variables such as pipe pressure and soil characteristics that were left out of this research due to unavailability of data. In addition, subsequent research could utilize a weighted average based on pipe segment length when creating MCE scores at the full pipe level, thus accounting for relative impact of segment length in the final MCE scores.

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Close

Appendix A: Saaty's Pairwise Comparison Matrices

Vulnerability Pairwise Comparison Matrix

	Pairwise Ranks					Individual Weights					TOTAL WEIGHTS
	Pipe Diameter	Pipe Material	Pipe age	Traffic	Railways	Pipe Diameter	Pipe Material	Pipe age	Traffic	Railways	
Pipe Diameter	1.0000	0.2000	0.2000	3.0000	3.0000	0.0857	0.0435	0.0265	0.2903	0.2903	**0.1473**
Pipe Material	5.0000	1.0000	0.3333	5.0000	5.0000	0.4286	0.2174	0.0442	0.4839	0.4839	**0.3316**
Pipe age	5.0000	3.0000	1.0000	0.3333	0.3333	0.4286	0.6522	0.1327	0.0323	0.0323	**0.2556**
Traffic	0.3333	0.2000	3.0000	1.0000	1.0000	0.0286	0.0435	0.3982	0.0968	0.0968	**0.1328**
Railways	0.3333	0.2000	3.0000	1.0000	1.0000	0.0286	0.0435	0.3982	0.0968	0.0968	**0.1328**
SUM	**11.6666**	**4.6000**	**7.5333**	**10.3333**	**10.3333**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**

Consequence Pairwise Comparison Matrix

	Pairwise Ranks					Individual Weightings					TOTAL WEIGHTS
	ESAs	Trails	Land Use	Waterways	Railways	ESAs	Trails	Land Use	Waterways	Railways	
ESAs	1.0000	3.0000	0.2000	0.1111	0.1429	0.0448	0.1304	0.0175	0.0251	0.0761	**0.0588**
Trails	0.3333	1.0000	0.2000	0.1111	0.2000	0.0149	0.0435	0.0175	0.0251	0.1066	**0.0415**
Land Use	5.0000	5.0000	1.0000	0.2000	0.2000	0.2239	0.2174	0.0877	0.0452	0.1066	**0.1362**
Waterways	9.0000	9.0000	5.0000	1.0000	0.3333	0.4030	0.3913	0.4386	0.2261	0.1777	**0.3273**
Railways	7.0000	5.0000	5.0000	3.0000	1.0000	0.3134	0.2174	0.4386	0.6784	0.5330	**0.4362**
SUM	**22.3333**	**23.0000**	**11.4000**	**4.4222**	**1.8762**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**

Appendix B: Publicly available scripts

Consequence MCE Script:
https://github.com/caryselle/DrinkingWaterNetworkMCE/blob/0795d0bf828e87332551d57b362c775a3b39d849/Consequence_Modified.py

Vulnerability MCE Script:
https://github.com/caryselle/DrinkingWaterNetworkMCE/blob/0795d0bf828e87332551d57b362c775a3b39d849/VulnerabilityMCE_NV_modified.py

Appendix C: Intermediate Maps

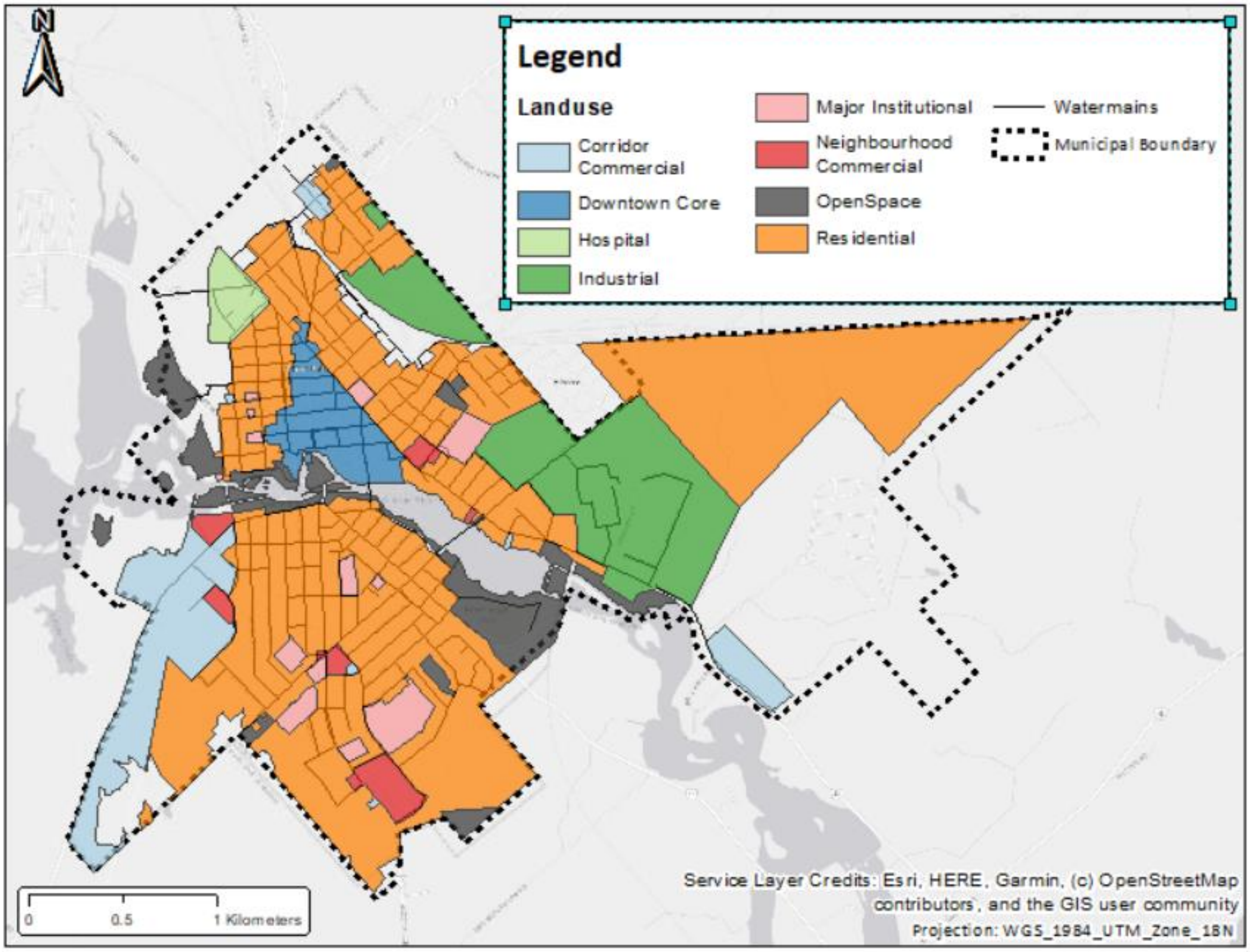

Figure C1. Landuse features overlayed upon the watermain network within Smiths Falls. These features were used in the MCE creation for the consequence map.

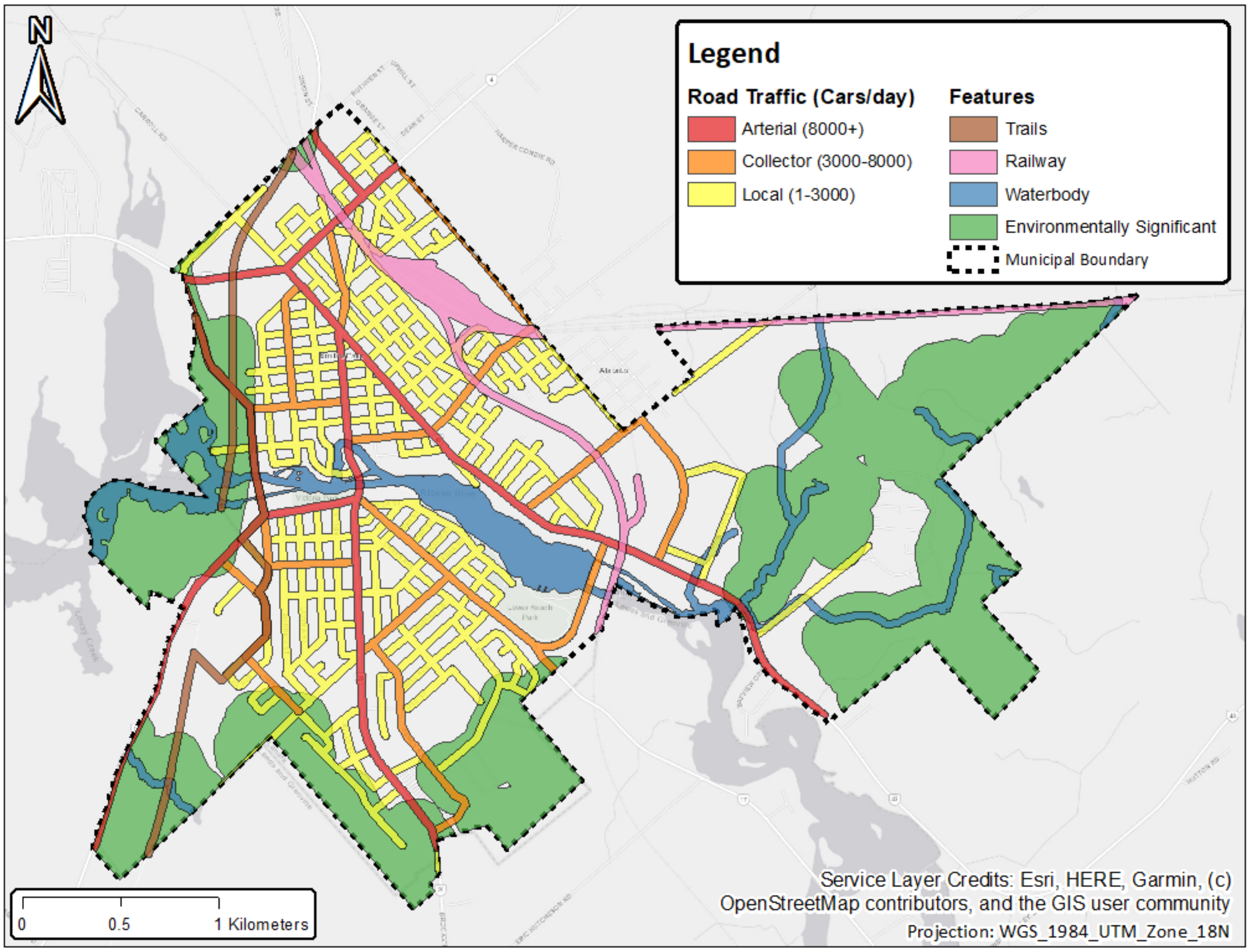

Figure C2. Road features with respective traffic flow, as well as trails, railways, waterbodies, and areas of environmental significance within the town of Smiths Falls. These features were used in the creation of both the vulnerability and consequence map MCEs.