Identifying Critical Locations in an Urban Environment Using ArcGIS

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ABSTRACT: With aging infrastructures and budgetary constraints, utilities and municipalities are turning to risk models to define where they need to spend limited inspection and rehabilitation dollars. The majority of this work has been done on individual asset networks, but the reality of an urban environment is that surface and subsurface assets have spatial relationships that should be considered in rehabilitation decisions. Road, water, sanitary, and storm networks are evaluated individually using a consequence evaluation process and then across assets to define critical locations. This process leads to the development of priorities for inspection and rehabilitation programs.

INTRODUCTION

Many cities have horror stories about the day an asset failed, leading to millions of dollars in repairs and in settling damage claims. Once the asphalt is restored, the road opened, and the television cameras have stopped recording, staff will be asked, “What happened?” In investigating and reporting on the incident, staff will likely find that multiple assets have failed. It is also possible that an everyday failure of a minor asset has caused the failure of critical assets. Inevitably the investigation and reports will lead to more questions about the operation and maintenance of assets within the various networks.

With assets running parallel to and across each other, the proximity and interaction between assets needs to be evaluated when considering the consequences of failure and then the possibility of failure. Rather than waiting for the failure of a crucial asset, managers need to look at their individual networks and then consider all assets within an urban right-of-way. Consequence and spatial analysis will identify vital assets in each network. The location of the critical assets and locations where there is the potential for multiple failures are considered in defining consequences that are unacceptable to the community. The analysis will prompt utility managers to develop proactive plans to mitigate unacceptable outcomes of multiple failure scenarios. This analysis and an understanding of the community’s tolerance to outcomes of an asset failure will help decision-makers in setting a strategic direction to ensure timely inspection, maintenance, repair, and rehabilitation of assets in these sensitive locations.

It is up to the owners of the assets within a right-of-way to work together to identify critical locations and to develop proactive plans that are based on technical and service considerations and an understanding of the consequence of catastrophic failures. It is the responsibility of utility managers to quantify the consequences and potential for failure and report this to their board or council. Ultimately, it is up to decision-makers to define the community's tolerance to failure through their strategic direction and to be prepared to support and fund proactive programs to maintain assets at a level that is acceptable to the community.

ArcGIS is used along with consequence and risk models in an analysis framework. Assets within individual networks are first categorized in terms of consequences. They are then considered spatially in identifying critical locations and locations of concern where there is a potential for individual and multiple asset failures that would have detrimental outcomes for the community. This leads to asset action plans that focus on minimizing the risk of these failures.

BACKGROUND

Located on the Canadian Prairies, the City of Saskatoon serves a population of 215,000. The City maintains the road network and provides water and sewer services through municipally owned utilities. These networks include 1,126 kilometres of roads, 1,003 kilometres of water mains, 858 kilometres of sewer main and 535 kilometres of storm sewers. The City has the advantage of not having any combined sewer systems.

Saskatoon has been working towards a fully implemented geographic information system (GIS) since 1996. Council's support of the development of spatial inventories has led to the creation of databases for assets within the road right-of-way. In 2000, ArcGIS was selected as an analytical tool to look at maintenance, condition, capacity, and inventory information in defining asset management strategies.

DEFINING THE COMMUNITY'S RISK TOLERANCE

Tolerance to the risk of failure, or more appropriately risk aversion, is a personal issue. When looking at assets and critical locations, decision-makers must first consider what the community is willing to accept as assets deteriorate and eventually fail. From this perspective, there is no universal definition of risk or an accepted level of risk beyond legislative requirements imposed on a community by senior government.

Decision-makers face challenges in defining their risk tolerance. Asset managers do not define risk in terms that decision-makers can understand and use in developing the agency's strategic direction. Unfortunately, in the absence of a clear understanding of potential outcomes, decision-makers' risk aversion only becomes an issue after a failure leads to outcomes that impact on the well-being of the community.

Defining critical locations in an urban environment requires an understanding of the community's acceptance of risk, their willingness to pay to ensure service, and their desire to reduce the risk of unacceptable outcomes. Risk is the probability of failure multiplied by the consequence. The probability of failure can be difficult to estimate, particularly where historical inspection and maintenance information was not collected with a goal to developing asset performance models. Without condition data, determining the probability of failure is unlikely. For some assets that are crucial to the network, the goal is to be proactive in ensuring that failures are unlikely to occur. The alternative is to consider the consequences and the possibility of failure of an asset.

Consequences are considered in terms of finances, social considerations, and environmental impacts, defined as a “triple bottom line.” In financial terms, consequences have either direct or indirect costs. Direct costs are paid by the utility or municipality to repair assets, to resolve damages to other assets and private property, and to fund litigation and fines associated with failing to comply with legislation. Indirect costs are borne by users of the right-of-way in detouring around a repair site and the loss of revenue to businesses dependent upon vehicle access or utility service for their business. Social implications include the impacts that the community would find unacceptable. These may include impacts to citizens who are least able to deal with these consequences. This could also be damage to a civic structure or park that defines the municipality or it could be the loss of community’s reputation that will impact the city’s ability to attract new business or tourism.

A key financial and social consideration is public safety. Failure of underground utilities poses a risk not only to other assets within the road right-of-way, but can also impact on private property and public safety. Customers are normally oblivious to the potential outcomes of asset failure. They rely on operations managers to ensure their safety and the safety of their property. Customers are not concerned with what happened when an asset fails. They are concerned when their personal safety is jeopardized, their property is damaged, their service is lost, or the cost of their services increases.

For water and sewer utilities there are environmental considerations that have moral implications and financial consequences for non-compliance with regulatory requirements. The damage to the reputation of the municipality and lost consumer confidence will have social and financial implications.

The analysis framework provides an assessment of the consequence of the failure of different assets. By understanding the possible consequence of failure, decision-makers can begin to define the agency’s direction, understanding not only the cost of maintaining or replacing an asset, but also the risk of not undertaking timely inspection and rehabilitation activities.

ANALYIS FRAMEWORK

The analysis framework begins with a consequence model. This model focuses on the impact of the failure of assets within individual networks by considering the impacts independent of the probability that the failure may occur. The second phase of the analysis considers the spatial relationships and interactions between assets and private property in defining critical locations. The consequences of multiple asset failures at these locations are evaluated and the outcomes reported to boards and councils for their consideration in defining the community’s values with respect to the outcomes of a failure.

Identification of critical locations will also establish assets that should be assessed. Where inspections have not been undertaken, inspection plans can be developed and costs estimated. Where data is available, the analysis of critical locations will provide direction in setting rehabilitation and replacement programs that will reduce the probability of unacceptable consequences of failure. With good alignment with the community's tolerance, the inspection and rehabilitation plans can be presented to decision-makers for their consideration in defining the strategic direction for the agency.

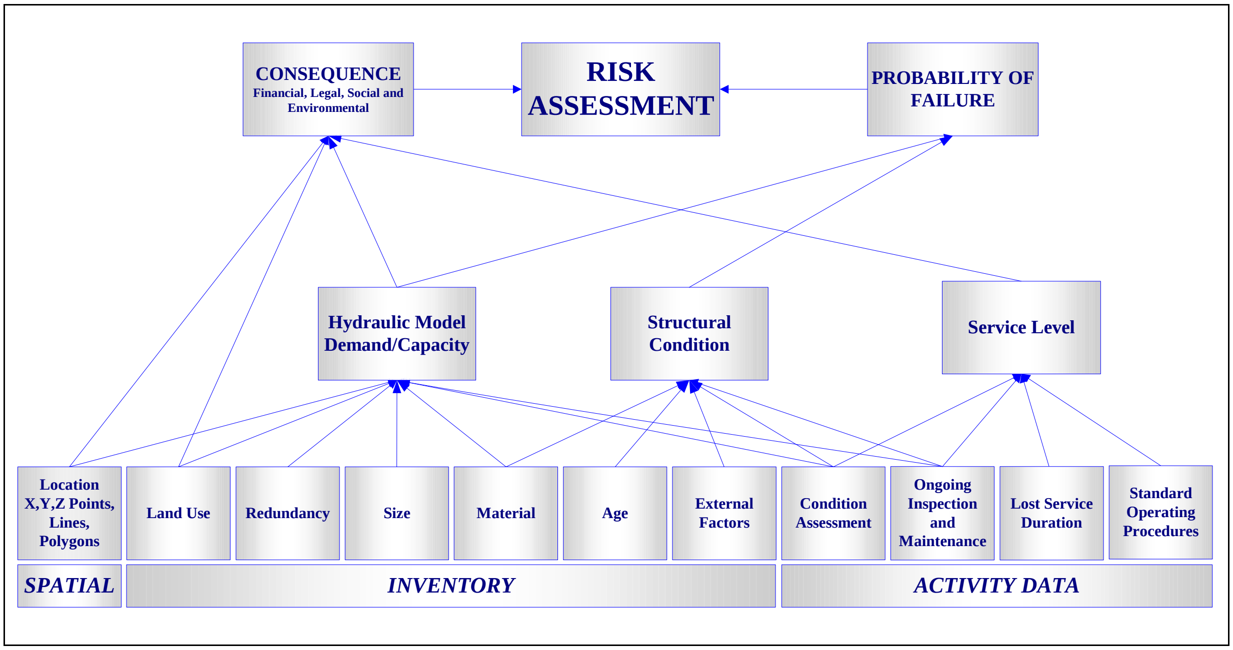

Figure 1: Geographical Information System Data Model

This framework relies heavily on the knowledge of staff and on spatial, inventory, and activity data. Figure 1 illustrates the spatial, inventory, and activity data that is stored in a GIS and is illustrated in the development of a risk assessment.

Demand and capacity are considered in defining the consequence of failure. Networks are traditionally designed by considering the surrounding land use to define the demand on each of the systems and then sizing the asset with a factor of safety to meet the capacity. Depending on the asset, the design will consider other factors such as material and redundancy. Spatial attributes such as slope and elevation are utilized in defining capacity. An understanding of the design criteria and, more importantly, the safety factors are necessary to develop a consequence and risk assessment model. In addition to the demand and capacity assessment, an analysis of the consequences of failure needs to include land use and spatial location of assets. Redundancy, or rather the lack of redundancy, is a factor in how the network functions and, more importantly, how it functions when one or more of the assets fail. For the road and water network and to a lesser extent storm networks, there is normally a high degree of redundancy. At the other extreme are sanitary sewer systems that have limited redundancy.

By considering these factors, it is possible to define the cost and consequences of failure of an individual asset for decision-makers. One way of analyzing and quantifying this exposure is the Consequence Cube illustrated in Figure 2. The cube quantifies the potential costs and outcome of a failure. This analysis leads to a response level that is consistent with the strategic direction. Each asset failure can be categorized as either meeting the strategic direction in terms of the consequence or failing to meet the agency's strategic direction. Beyond the defined level of service, there are financial and social consequences may be or are unacceptable to the community. A failure may lead to litigation for not being proactive in ensuring the protection of private property or the environment. Within this scale, failures that affect public safety are the ultimate failure.

The Consequence Cube provides a framework to quantify the community's tolerance to a specific outcome. By providing well thought out scenarios for the failure of assets, decision-makers will be in a position to quantify their tolerance to the outcomes and provide strategic feedback on what are unacceptable outcomes.

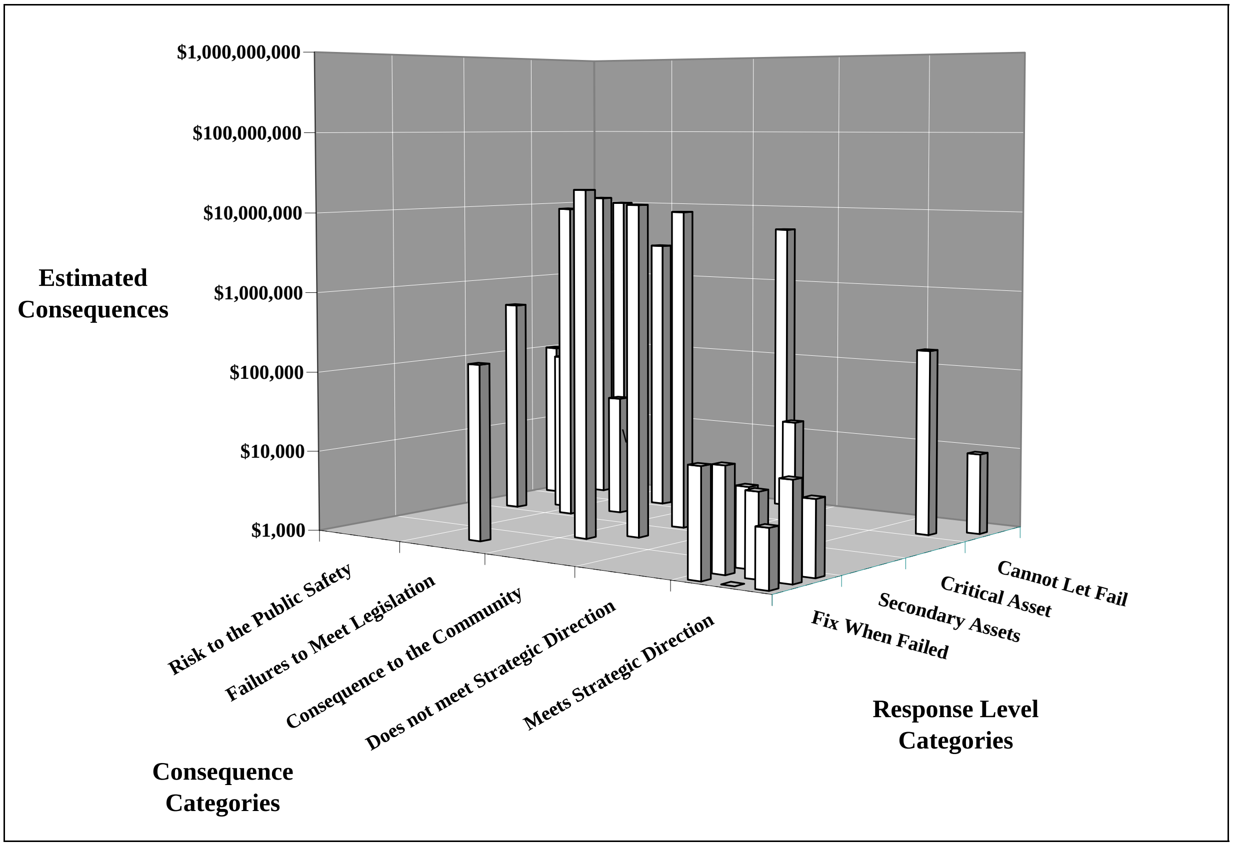

Figure 2: Consequence Cube

It is possible to provide decision-makers with an understanding of the agency's exposure to different types of failures by defining the consequences and potential costs of each type of asset failure. A questionnaire can be used that will allow boards and council to indicate their tolerance to the consequences of an asset failure. Using a number of failure scenarios, they can be polled on their tolerance to a single failure. By doing so, their financial tolerance and their tolerance to outcomes that are socially and environmentally unacceptable can be established.

Within an urban environment, there are asset failures that the community would see as unacceptable. Obvious examples are the failure of a bridge, the loss of the water treatment plant, or failure within a storm or sanitary network resulting in widespread flooding of homes with either runoff or sewage. These assets fall within a "Cannot Let It Fail" (CLIF) response level where the consequences exceed the tolerance of boards and councils. This threshold can be quantified in dollars, in terms of social and environmental consequences or defined as unacceptable risks to public safety. For these unacceptable outcomes, the utility or municipality will be willing to pay to avoid failures.

There are also critical assets for which the community would be willing to accept a small risk of failure. A strategic direction for these assets would include taking reasonable steps to react when evidence of deterioration indicates the probability of failure, and therefore the risk of failure, would be unacceptable. Strategies could include an inspection plan to define the level of deterioration. The plan could require inspections of critical locations at regular intervals to define the deterioration rate. At some point, observed deterioration would result in a general inspection of the entire asset. An inspection strategy may also include the decision to inspect different portions of the network at regular intervals with the expectation of completing the network over a period of time. In all cases, the strategy should consider location criticality in defining priorities. For critical assets, the utility or municipality should be in a financial position to overcome the outcomes of a single failure. The probability of such failures should be unlikely. The probability of two such failures within a short period should be extremely unlikely.

For secondary assets there is a tolerance to the consequences of failure. Although a single failure is tolerable, repeated failures or large number of failures within a network may be unacceptable. Rehabilitation decisions for these assets are driven by economics and service levels for repair, rehabilitation, or replacement. The number of failures or deterioration may allow the probability of failure to be modeled by undertaking performance and predictive models. These models can be used in economic modeling to define repair, rehabilitation, and treatment strategies.

There are assets where the response strategy will be to fix it when it fails (FIWIF). For these assets there will be a high community tolerance to the consequences of failure. The decision to replace the asset may be determined either during normal operations or during inspections.

NETWORK CONSEQUENCE ASSESSMENT

The analysis of individual networks leads to an initial response category for each asset. The GIS inventory and a number of queries are used to consider the inventory in each of the networks based on business rules, available data, an expectation of community risk tolerance, and knowledge of individual networks. This is by no means a complete analysis, but does provide a starting point for consideration of the consequences of failure in developing a response level for each asset. Each of the four networks is evaluated using the initial business rules and information available in the GIS.

Sanitary Sewer Collection System

Sanitary sewer systems have minimal redundancy outside of lift stations. Collapse or failure of a sewer will inevitably require temporary pumping or will lead to either sewage backing up into customers’ basements or to the discharge of sewage into a watercourse. Neither outcome is acceptable. The agency's ability to respond to a point failure sets the threshold between secondary assets and critical assets. Where the outcome is unacceptable to the community, there is a need to be proactive to minimize the risk of these failures[1].

As with many sewer utilities across North America, the City of Saskatoon has a major sewer main that carries the sewage from the city to the sewage treatment plant. The sewer crosses the city from south to north and generally follows the west bank of the South Saskatchewan River. This location takes advantage of the grade, but its proximity to a major river increases the possibility of sewage escaping into the river. The interceptor and other CLIF assets are shown in red in Figure 3 (upper right) and critical assets in yellow.

Lift stations and force mains are also crucial assets in a sanitary sewer network. Depending on the capacity of these assets, the failure of one of these mains can have consequences when considering that the sewer main is under pressure.

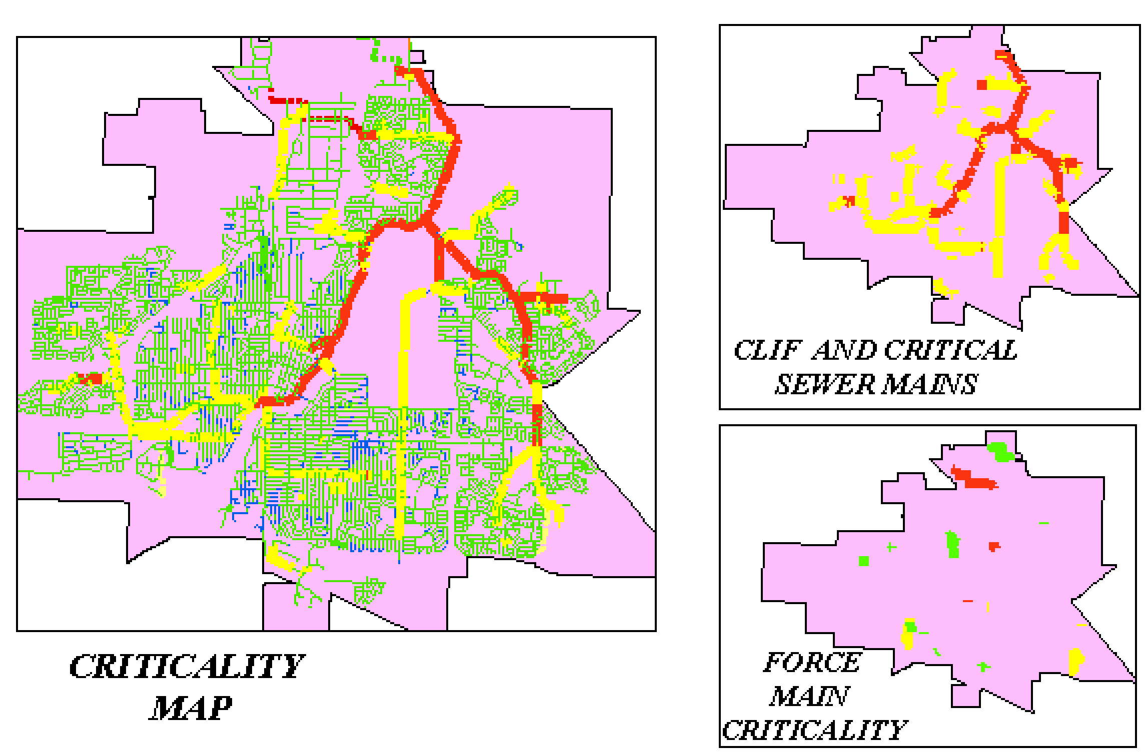

Figure 3: Sanitary Sewer Criticality Map

For sanitary and storm sewer mains, depth is a key consideration. The initial construction of sewers is normally by an open cut method. With the development of an urban environment, the construction of other assets in the right-of-way and the construction of buildings adjacent to the right-of-way significantly increase the impact of failures. Sewer depth is considered in defining CLIF assets. Other CLIF sewers include river crossings and sewers for which the utility does not have sufficient pumping capacity to respond to a sewer failure. These are shown in Figure 3 (left) along with the other categories of sanitary sewer assets as defined in Table 1.

Table 1: Sanitary Sewer System Response Criteria

Asset Category	Assets	Data Source	Colour
CLIF Assets	• Sewage treatment plant. • Interceptor Sewer that carries sewage from large trunks to the sewage treatment plant. • Lift station and force mains where utilities have insufficient emergency pumping capacity or an alternative method to handle flow in an emergency. • River crossings. • Larger sewers where the flow will lead to significant flooding and damage and where the agency does not have the ability to respond. • Deep sewer where repairs using conventional open cut methods are impacted by the buildup of other assets and private property around the potential repair location.	Sanitary Network Inventory Land Use Inventory Sanitary Services Connection Inventory Hydraulic Model	Red
Critical Assets	• Trunk Sewer where the agency can provide emergency pumping only after significant flooding. • Sewers where repairs cost will be significant and where the rehabilitation cost is lower than the cost of an emergency repair.		Yellow
Secondary Assets	• Trunk Sewers with adequate emergency response is planned and capacity is available. • Collection mains with upstream customers. • Service connections to critical customers. • Critical manholes.		Green
FIWIF Assets	• Collection mains with no upstream customers. • Service connections.		Blue

One issue not covered in this analysis is combined sewers. These systems inevitably lead to a combined sewer overflow that impacts the environment and can lead to financial consequences as defined by environment legislation.

Storm Water Collections Systems

Storm sewers systems are, by their very nature, a trade-off between the capital costs of building high capacity systems and the potential future costs as a consequence of storms exceeding the design capacity. Whatever the design standard, engineers know that there will be a storm that will exceed the storm sewer capacity. At some point during a heavy storm, water will begin accumulating on the surface. Where surface grading and planned water retention is incorporated in the design, the combination of pipe capacity, planned surface storage, and overland flow will provide significant additional capacity without incurring significant damage to public and private property.

Table 2: Storm Sewer System Response Criteria

Asset Category	Assets	Data Source	Colour
CLIF Assets	• Large storms sewers with no redundancy and where the capacity will be exceeded (less than a 1 in 2 year storm). • Sections of large sewers that flow through a low area with no overland flow.	Storm Network Inventory Surface Inventory Land Use Inventory Storm Services Connection Inventory Hydraulic Model	Red
Critical Assets	• Large trunk sewer and collectors with marginal overland flow and the risk of damage to public and private property. • Deep sewers where repair costs are prohibitive.		Yellow
Secondary Assets	• Trunk sewers with good overland flow capable of handing large storm, without damage to private or public property. • Collection mains. • Service connections to critical customers. • Critical manholes.		Green
FIWIT Assets	• Collection mains. • Service connections.		Blue

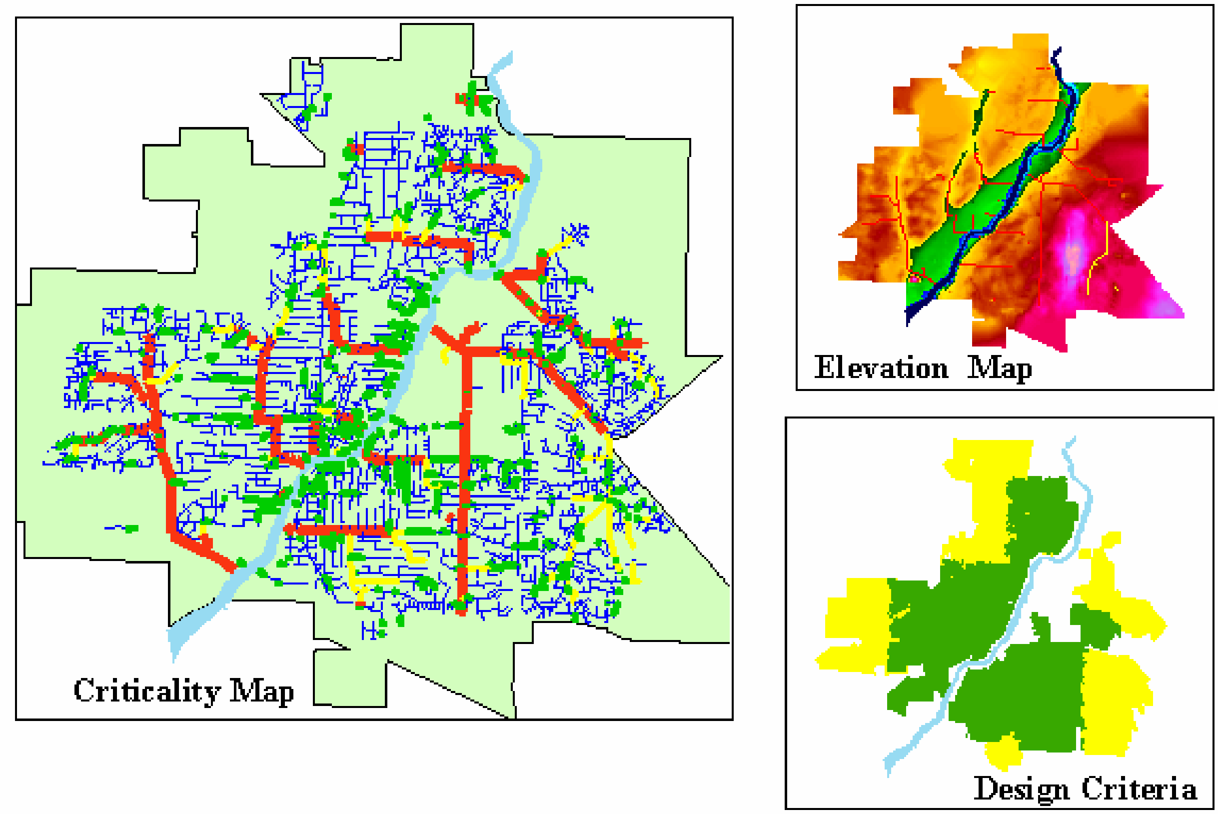

Figure 4: Storm Sewer Criticality

Overland flow is incorporated in the development of newer areas of the city as shown in the lower right of Figure 4. The elevation map (upper right) shows how major storm sewer trunks generally follow the available natural slope.

Water Distribution System

The water distribution system is built with a high degree of redundancy and capacity to meet the peak daily demand that happens during hot summer days. From this point of view, defining asset categories in terms of outcomes is dependent on demand. For colder climates with snow covers during the winter, there is a substantial difference in demand between winter and summer. For the purpose of this analysis, peak daily flow is used. This represents the time of year when the system will be taxed and the consequences would be greatest.

In Figure 5, fill and primary water mains are shown in the upper left. These mains are CLIF assets in red and critical assets in yellow. The failure of these mains will have consequences including significant damage to roads and other underground utilities and reduced or lost service to customers.

The Secondary and FIWIF Assets are shown in the lower right. A database that shows the relationship between water services and water mains allows for the identification of sections of the mains that can be isolated without disrupting service to a customer. These locations are shown in blue in the lower right of Figure 5.

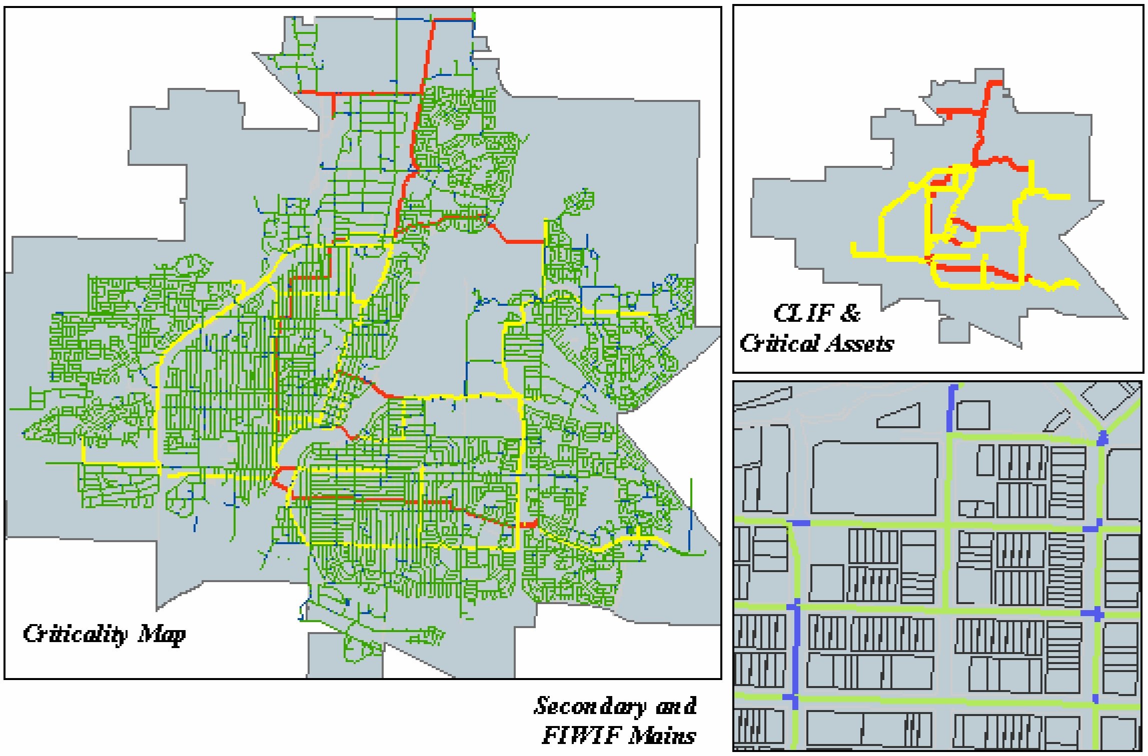

Figure 5: Water Criticality Map

Table 3: Water Distribution System Response Criteria

Asset Category	Assets	Data Source	Colour
CLIF Assets	• Water Treatment plant, and water reservoirs. • Fill mains to two reservoirs. • Primary water main to large subdivision with no redundancy. • Primary water mains close to the water treatment plant and water reservoirs for which redundancy cannot be derived from the distribution system. • River crossings of major primary and fill mains needed to maintain service. • Primary water valves where failure will lead to loss of service and fire suppression during peak demand. • Water mains servicing properties where the disruption of water service is unacceptable. These could include hospitals, level care homes, retirement homes, civic buildings supplying emergency services, companies that are major employers that dependent on water.	Water Network Inventory Land Use Inventory Water Services Inventory Water Hydraulic Model Water Isolation Table Water Service Table (Property to Water Main Table)	Red
Critical Assets	• Primary water mains where failure will impact service and fire suppression. • Distribution mains where there is no redundancy and failure will impact on a significant number of customers. • Water mains servicing properties where the disruption of water service is unacceptable. These could include hospitals, level care homes, retirement homes, and civic building supplying emergency services.		Yellow
Secondary Assets	• Primary water main where sufficient redundancy exists to ensure service and fire suppression. • Distribution mains where failure will impact a small number of customers. Duration of outage can be monitored and replacement can be considered where economical. • Service connections to water-critical customers and water-dependent customers.		Green
FIWIF Assets	• Distribution mains with no customers. • Distribution valves. • Hydrants. • Service connections.		Blue

Roads System

A road system is uniquely redundant as evidenced when a major road is closed for repair or rehabilitation and motorists seek alternative routes. In this context there is normally no road closure that eliminates service unless a key bridge, or the road leading to it, is lost. For the most part within an urban environment, the loss of the road results in traffic jams. However, motorists will eventually get to their destination by an alternative route. Road deterioration will lead to a reduction in service as the road capacity is lowered by motorists forced to reduce speed because of road conditions or by the municipality reducing the posted speed to minimize the risk of an accident.

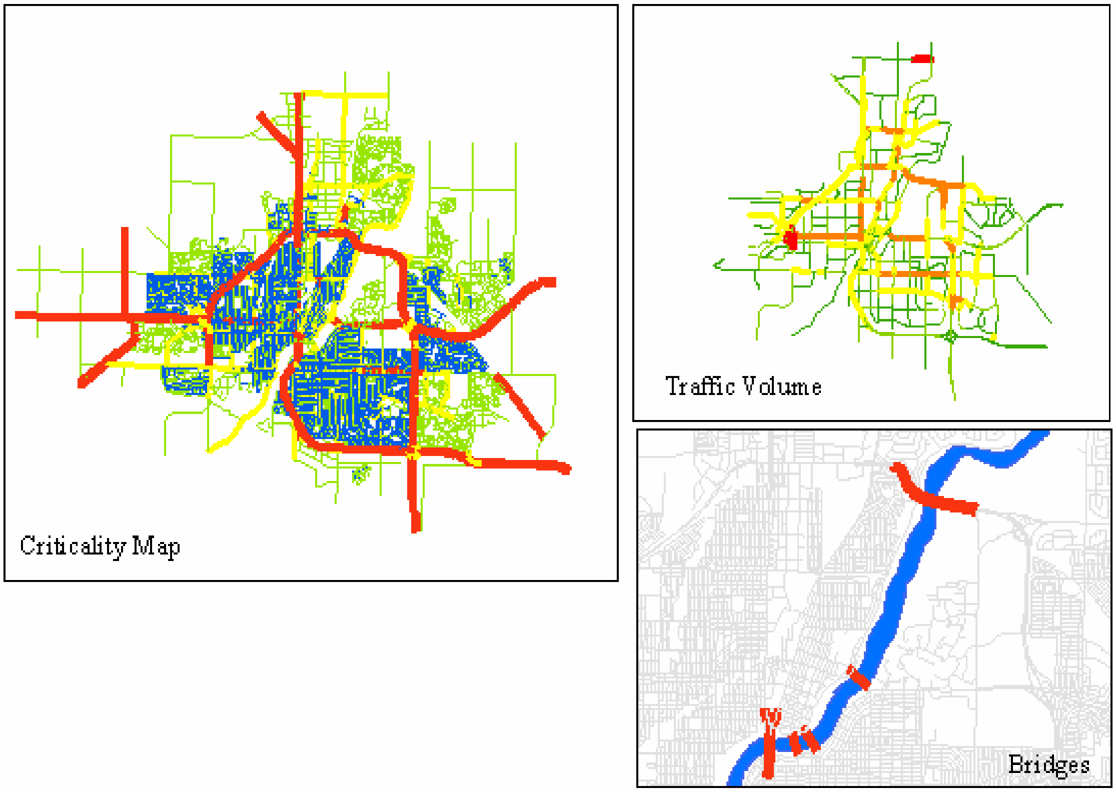

Figure 6: Road Criticality

Table 4: Road System Response Criteria

Asset Category	Asset	Data Source	Colour
CLIF Assets	• **Major river crossings.** • **Major interchanges (Expressways, Freeways and Arterials).**	**Road Inventory** **Intersection Inventory** **Land Use Inventory**	**Red**
Critical Assets	• **Minor river crossing.** • **Interchanges for arterial and collectors.** • **Major intersections arterial and collectors.**		**Yellow**
Secondary Assets	• **Collectors and local roads.** • **Minor intersections.**		**Green**
FIWIF Assets	• **Unpaved local roads.** • **Alleys.**		**Blue**

Road condition is very much about the cost to customers. The loss of a high volume road greatly increases the cost to the customer as motorists take alternative routes to their destination. The consequences of poor road condition include the cost of additional fuel that comes with the additional distance traveled and start, stop, and wait times. There is also the associated environmental effect of additional fuel usage. The consequences also include the damage to vehicle as roads deteriorate and potentially the loss of life associated with road deterioration.

The asset response categorization within each network can initially be done using the broad statements provided above. After this analysis is complete, the impacts of consequences must be considered with respect to private property. This requires a spatial analysis that considers the proximity of underground assets to property lines and to buildings.

This initial process also needs to be reviewed by experts within each agency. Their understanding of the operation of the network will provide insights into refining the consequences of failure. They can best estimate the cost of failure, either through historical expenditures or through their experience and knowledge.

With agreement on the initial criticality plan, there is an opportunity to establish a consequence cube for each network and to report to decision-makers. This information will provide a realistic analysis of the consequences of failure which decision-makers can evaluate to define their initial consequence tolerance. This is an iterative process; in looking at the consequences of multiple asset failures, staff will consider decision-makers' initial consequence tolerance in identifying critical locations.

INTERACTIONS BETWEEN ASSETS

Spatial relationships and interaction between assets quickly become obvious in this consequence analysis. Within an urban right-of-way there are a variety of assets as illustrated in Figure 7. These assets interact when one of the assets fails, resulting in outcomes to consider in defining critical locations. From an engineering point of view, these assets are dependent on their foundation. For water and sewer assets, it is the pipe bedding and soil conditions around the assets that must be considered. The same is true for road assets and sidewalks that are constructed on spread foundations. Other underground utilities such as gas, power, telephones, and telecommunication are less dependent on this support but are subject to failure when there is significant loss of foundation. If the asset's foundation is a key consideration during an asset failure, then water is the key in considering the failure relationship between assets. Water mains are, therefore, the ultimate predator and roads are the ultimate victim. Table 5 gives a perspective on how failures potentially impact on other assets in the right-of-way.

Although not covered specifically in this analysis, gas mains and power lines are significant in their threat to the public safety. Both underground and overhead power lines have the potential to cause damage and death. Ruptured gas mains can cause significant damage, particularly if the natural gas is ignited. These impacts should not be overlooked in considering the potential threat from these assets. Telephones and telecommunication systems do not pose the same threat, but the loss of communication at a critical time can have serious social effects and can seriously impact the community’s response to an emergency.

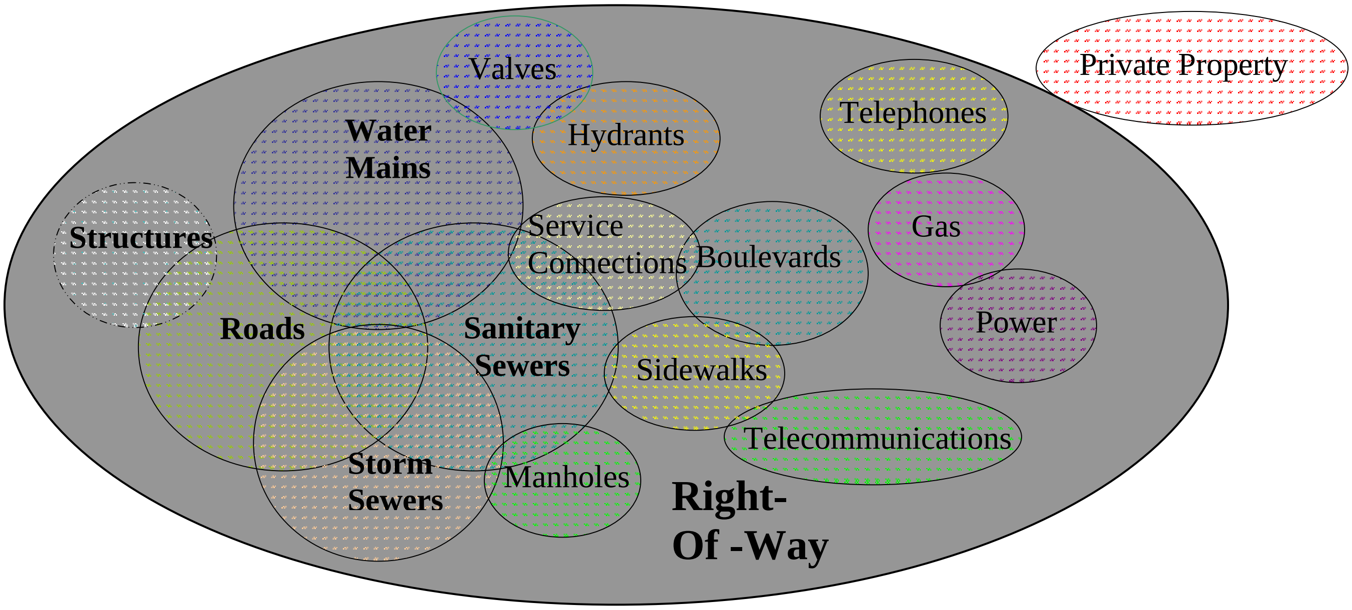

Figure 7: Assets within a Right-of-Way

Assets deteriorate due to corrosion, erosion, settlement, and wear. Beyond the surface impacts, road deterioration occurs with saturation of the road base. This can be from surface runoff penetrating the asphalt mat or saturation due to leakage of water and sewer assets. This leads to consolidation when water is injected during a water main failure. In more severe situations, escaping water can result in large voids that can lead to sewer or road collapse. By far, water main leakage and failures cause the greatest impact on other assets. These lead to erosion of foundations, causes soil loading on other utilities, or increase ground water and deterioration from the resulting corrosion.

Surcharge of sanitary and storm sewers leads to loss of pipe support as water exfiltrates and then infiltrates through poor joints and pipe cracks. As the pipe wall fails, the resulting deterioration leads to voids above the pipe. If the sewer is not blocked off leading to sewer backup, soil will continue to be drawn into the pipe during surcharge. Eventually the loss of soil above the pipe will lead to voids and to secondary asset failures. The sanitary sewer system must also be considered as carrying a dangerous material. Sewage by its very nature is a risk to public health particularly when it is allowed to enter into basements or surfaces onto the road.

Table 5: Potential Impacts of the Failure of Different Assets

		Failure			
		Roads	**Water Mains**	**Sanitary Sewers**	**Storm Sewer**
Impacts	**Private Property**	None	Flooding and lost foundations	Sewer backup and health concerns	Backup and surface flooding
	Roads	N/A	Settlement, alligator cracking, and collapse	Settlement, voids, collapse	Settlement, voids and collapse. Surface flooding impacting asphalt and base
	Water Mains	None	Loss of bedding, increased corrosion, and additional failures	Loss of bedding, increased corrosion of metal components, and failure	Loss of bedding, increased corrosion of metal components, and failure
	Sanitary Sewers	None	Infiltration, loss of bedding, flooding, and collapse	Loss of bedding, additional defects, and collapse	Loss of bedding, increased corrosion of metal components, and failure
	Storm Sewer	None	Infiltration, loss of bedding, flooding, and collapse	Loss of bedding, additional defects, and collapse	Loss of bedding, additional defects, and collapse
	Underground Utilities	None	Loss of support, collapse, and failure	Loss of support, collapse, and failure	Loss of support, collapse, and failure

Given that water seeks the path of least resistance, the horizontal and vertical relationships between assets and the actual distance between assets needs to be considered in defining potential critical locations.

SPATIAL RELATIONSHIPS

To analyze the spatial relationships, assets should be considered as either running perpendicular to, running parallel to, or crossing another asset. Assets also need to be considered in terms of vertical relationship as either being above or below another asset and in terms of relative elevation. For Saskatoon's spatial model, the vertical depths are shown in Table 6. Water and sewer assets are installed at a minimum depth of 2.8 meters to stay below the winter's frost depth.

Table 6: Vertical Depth of Assets

Assets	Depth
Roadways, walks, boulevard	Surface
Gas, power, telecommunication, telephone	1.0 to 1. 5 metres
Water mains	3.0 metres
Storm and sanitary sewers	3.0 to 16.0 metres
Water, sanitary and storm connections	2.8 metres

The influence of one asset over another is dependent on how the asset was originally constructed. Deep buried assets were most likely constructed using open cut methods. However the use of cribbing and less stringent requirements to assure work safety in the past means that the trench width could vary with the age of the assets.

Today trench boxes are used to minimize trench width. With the emergence of boring and tunneling technology, it is possible that the soil above some pipe installations was not disturbed. In this analysis, the removal and reinstatement of soil is a consideration in the settlement of shallower assets that are directly above other assets. In a failure scenario, it is more likely that escaping water will be able to flow through disturbed material more easily than through undisturbed earth.

Roads, sidewalks, boulevards and private property can be impacted when other assets fail. Gas, power, telecommunication and telephones are shallow-bury assets that can also be affected. For deeper assets, it is the relative difference in elevation that needs to be considered.

A means to define the influence that one asset has over another is required due to these relationships. If construction records are available, the method of installation can be used as a proxy to trench width. For this analysis, it is assumed that each asset is installed in open cut and that the walls of the trench were cut at a 1 to 1 slope. The influence that the underground construction has with respect to surface assets is equal to the depth of the asset as illustrated on the left of Figure 8. For comparing the potential impact that underground assets have on surface assets, the influence is the overlap in buffers. Where both assets are below the surface, the influence that the deeper asset has over the shallower will be equal to the difference in depth. In this spatial analysis, where the buffer of the higher asset is completely within the buffer of the lower asset, the assets will interact based on the analysis illustrated in the centre of Figure 8. For crossing assets, the influence can be defined as the intersections of the two buffers. The evaluation of these relationships is accomplished by using the spatial relationship of the Select, Buffer, and Merge features in the ArcToolbox.

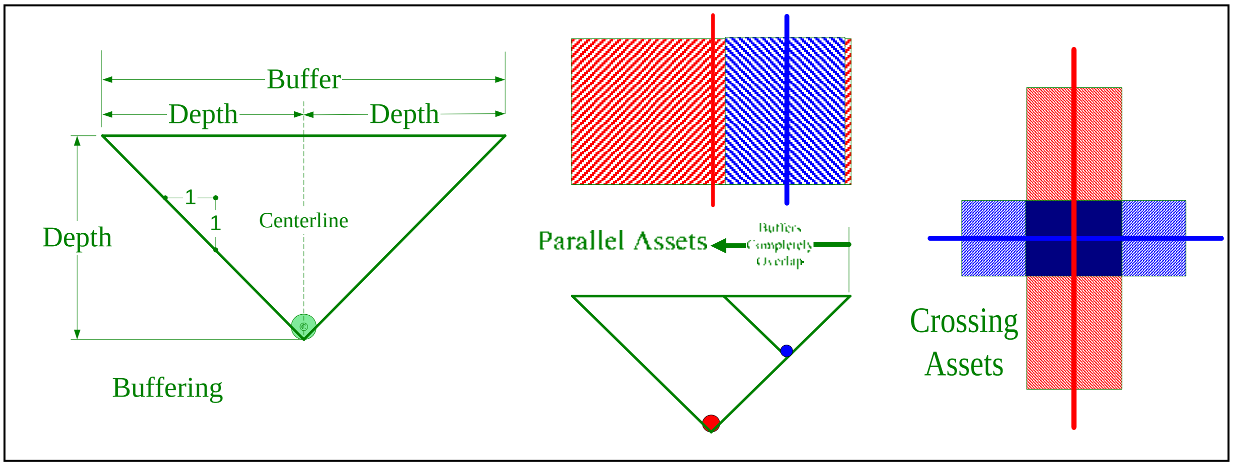

Figure 8: Buffering Linear Assets.

This process can be accomplished programmatically using Model Builder. Figure 9 shows a simplified model based on ArcGIS 9.1.

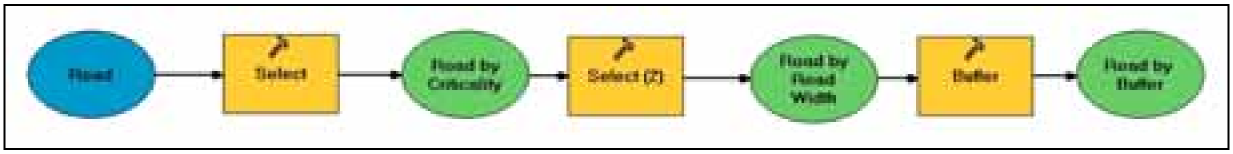

Figure 9: Model Builder Application for Buffering

The City of Saskatoon has spatial records of the boundaries of lots as illustrated in Figure 10. In addition, the locations of buildings within each parcel have been derived from aerial photographs. Parcel attribute data includes land use and property value which can be considered in the analyzing the potential consequences. The impacts of underground assets and the potential impacts to private property are considered in the following spatial relationships:

- Underground assets that are within private property.
- Underground assets that are within private property and near existing buildings.
  - Failure would directly impact the building.
  - Repair by conventional methods would not be possible without impacting the building.
- Underground assets are adjacent to private property.
  - Failure would directly impact the property.
  - Repair by conventional method will intrude on private property.

Using ArcGIS, the Selection by Location tool can be used to determine which assets are located on private property (possibly within an easement), and which assets are potentially under buildings and structures. The buffers created for each of the underground assets can be used to define what underground utilities are in proximity such that failure could impact on the building or property. The closer properties and buildings are to the assets, the greater the potential for interaction. The failure of a deeper asset is the more likely to have significant consequences on private property.

Figure 10: Potential Impact of Utilities on Private Property

Figure 10 illustrates the potential impacts of utilities. In the left diagram the buffer of a CLIF sewer main encroaches on to private property, encroaches on to the building footprint (centre) and, in unusual situations, under an existing building as shown on the right.

DEFINING CRITICAL LOCATIONS

The spatial analysis will lead to further considerations in defining critical locations and the redefining of the asset response levels for the other assets at critical locations. The critical locations are where there are one or more CLIF assets. Where there are two or more CLIF assets in close proximity the possibility of interaction, if one of the assets should fail, needs to be considered in defining the consequence. The possible outcomes are shown in Table 7.

Table 7: Outcomes of the Location Criticality Analysis

Location Criticality	CLIF Assets	Critical Assets	Secondary Assets	FIWIF Assets
Critical Locations	All Assets	N/A		
	1-3 Assets	3-1 Assets	N/A	
	1-3 Assets	3-1 Assets		
Locations of Concern	N/A	All Assets	N/A	
	N/A	1-3 Assets	3-1 Assets	N/A
	N/A	1-3 Assets	3-1 Assets	
Non-Critical Locations	N/A	N/A	1-4 Assets	
	N/A	N/A	N/A	1-4 Assets

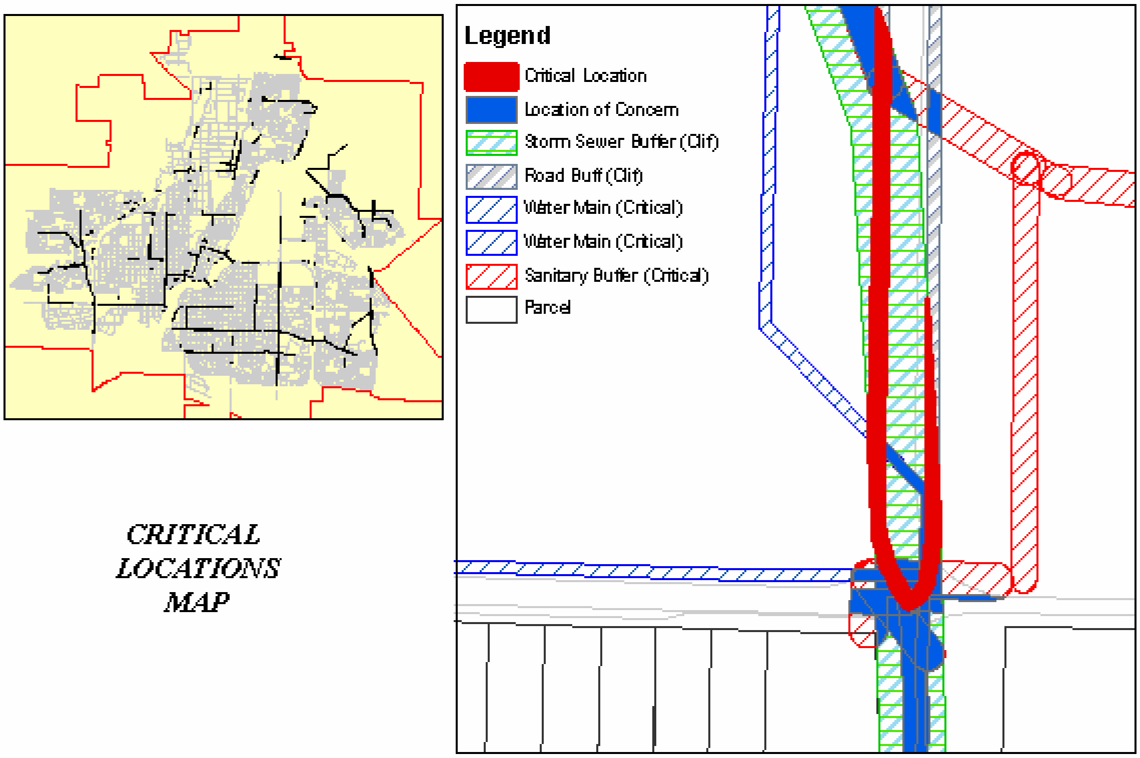

Figure 11: Critical Locations

There may be locations in an urban environment where CLIF or critical assets from many networks are in close proximity, leading to the need to implement an inspection plan that ensures timely inspection, maintenance, and rehabilitation. At the other end of the planning scale are locations where there are only secondary and FIWIF assets that are non-critical. In between these two extremes are locations where there are mixtures of asset categories. These locations are identified iteratively using the Intercept tool in the ArcToolbox. Figure 11 shows the results of the analysis that defines critical locations

It should be noted that the City's road assets model has the various roads culminating at the centre of the intersection. The critical location shown in red in Figure 11 terminates at the centre of the intersection.

Where there are one or more CLIF assets with other assets in proximity, the analysis identifies those assets where the knowledge of the condition of the assets would be worth the cost of inspection. For some assets, the cost of inspections is significant. At this point in the analysis, the question is, "Under what conditions should the agency spend money to obtain information about the condition of the surrounding assets?" For example, the sewer camera inspection layers showing where camera inspections have been completed for the City are shown in Figure 12. By adding the critical locations layer shown blue and using the Select by Location feature for sewer pipes intersecting a critical location, segments that have not been video inspected are identified at critical locations and included in the planned inspection program in Figure 12 (right).

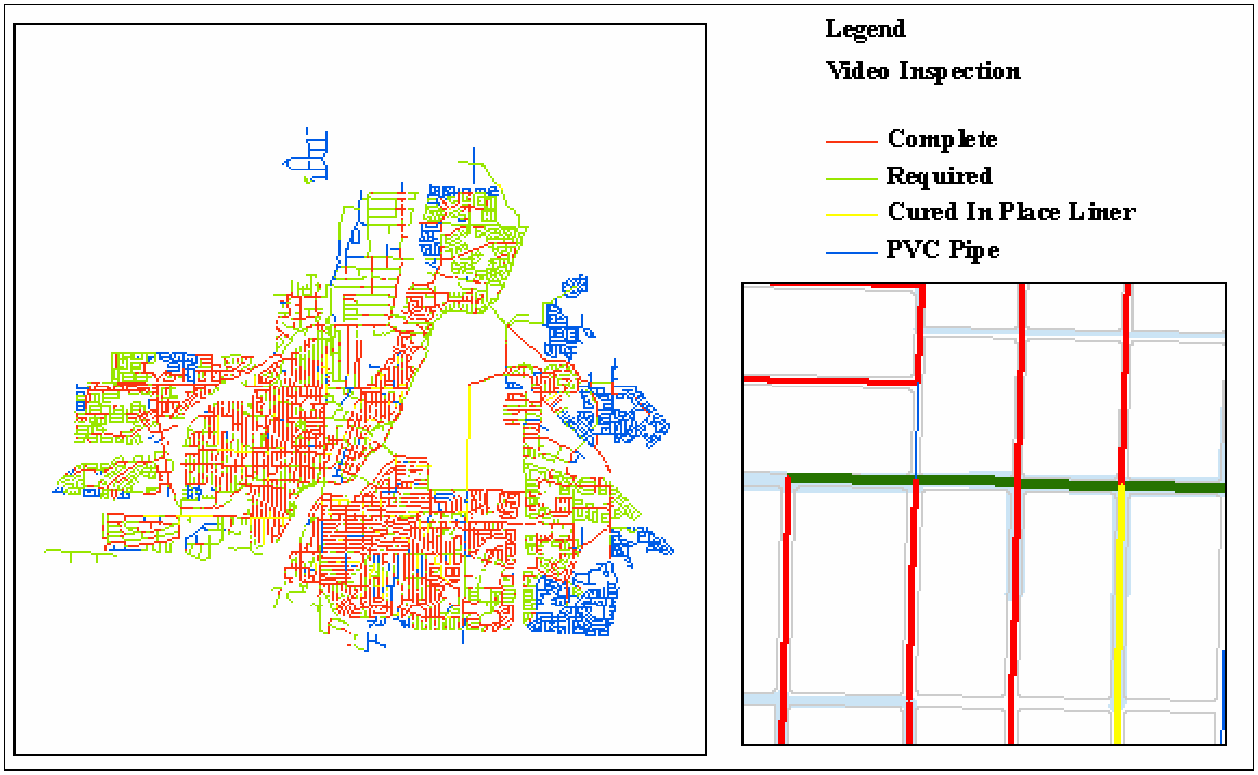

Figure 12: Camera Inspection in Critical Locations

There will be some assets at critical locations and locations of concern where the condition is known as a result of recent inspection and the asset will either be in good shape, in a deteriorated condition, or meets the threshold for rehabilitation or replacement. Figure 13 illustrates locations where water main rehabilitation hotspots, sewer lining candidates, and road rehabilitation candidates have been identified.

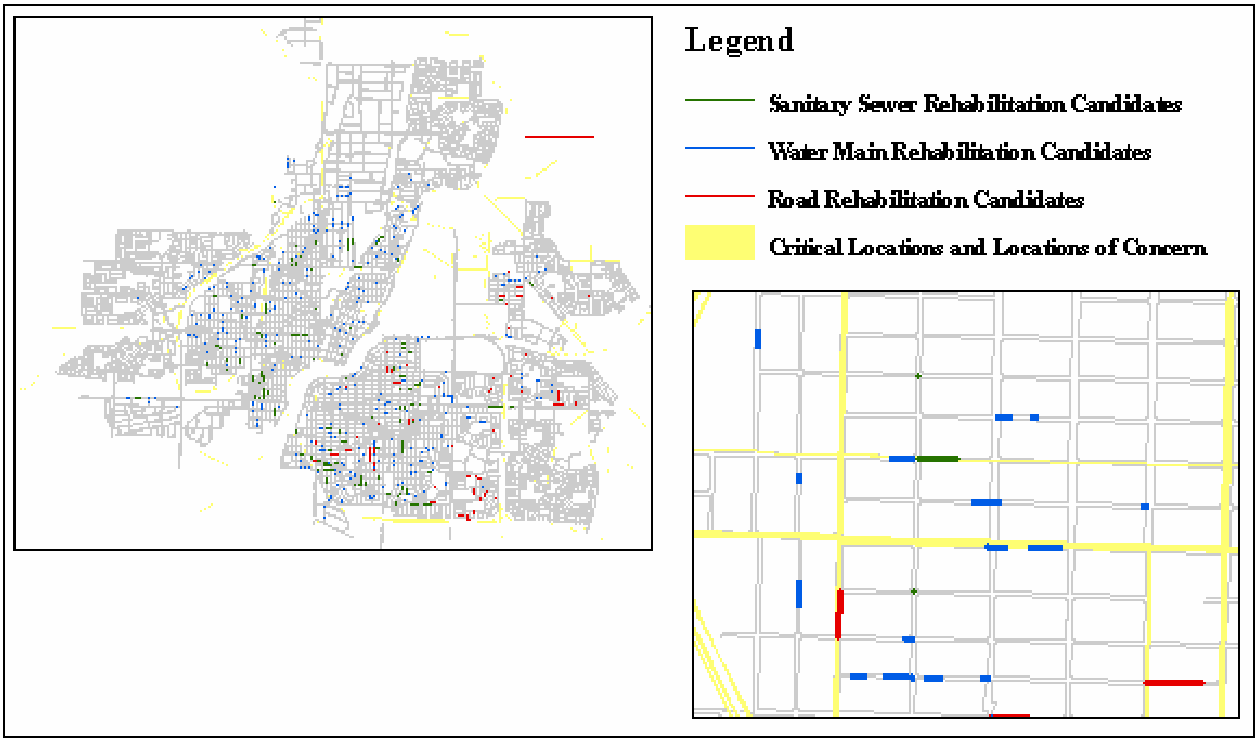

Figure 13: Identified Water and Sewer and Road Programs

Detailed information on the current condition of the assets can also be displayed. The water and sewer assets at an identified location of concern are shown in Figure 14. On the left are water main failures within the location of concern. On the right are the results of a video camera inspection.

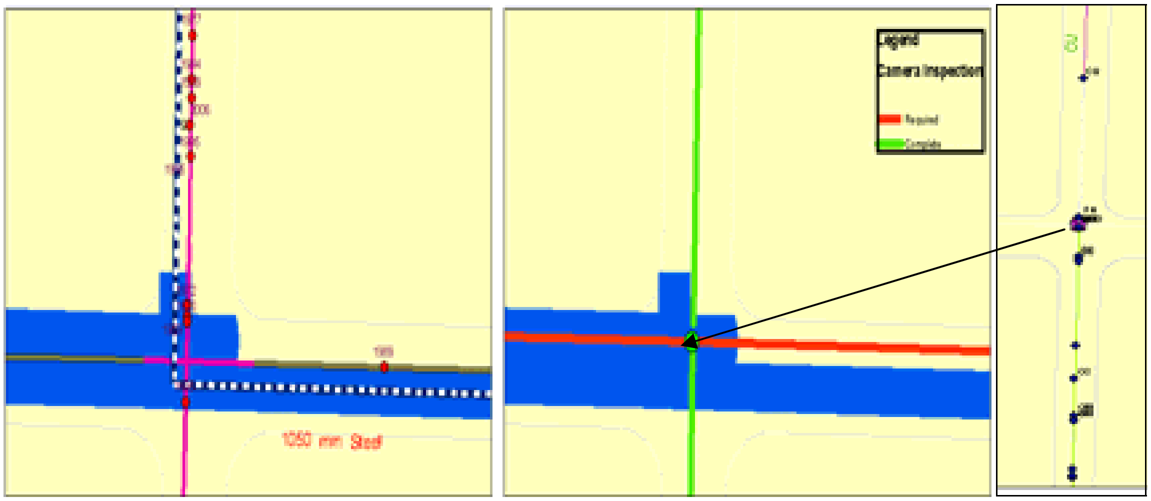

Figure 14: Analysis of Secondary Assets in a Location of Concern

Where an asset that meets the threshold for rehabilitation is at a critical location, consideration should be given to project priority. Even if the asset does not meet the threshold, it may be at a state of deterioration where the risk of failure suggests that undertaking the rehabilitation sooner rather than later would be in the best interest of the agency and the community.

A more interesting question comes when a critical location has assets that have not been inspected or the inspection is not current. Does the agency accept the risk of not knowing the condition of these assets or is this the risk unacceptable? It is likely that a decision will be made to undertake the inspection after reviewing individual situations. Damage to private property is also considered in the decision to inspect assets. Inspection may be undertaken where a failure of a CLIF or critical assets can have serious consequences to private property.

The review of critical locations will lead to a reassessment of the service response for a number of assets as the consequence of failure is reassessed in light of the interaction between assets and the impacts on private property. With the critical locations analysis completed, and a review of the service response, the consequence cube can be revisited in terms of multiple failures. Critical locations where multiple assets could fail and/or be affected by the failures can be evaluated.

CRITICAL LOCATION RISK ANALYSIS

The probability of failure is the other component of risk. Probability is a number between 0 and 1. This is statistical term representing the expectation of an occurrence that is derived from performance and predictive modeling.

To make a risk assessment requires data either in evaluation of the condition of the assets or analysis of actual failures, as well as an understanding of the capacity of the system. This information has been stored on paper and on drawings stored in filing cabinets, but is increasingly being entered into computer databases to meet growing demands for analysis and rehabilitation planning. For secondary and FIWIF assets, this can be accomplished as there are or will be sufficient numbers of failures to permit modeling and consider the risk of failure, and in determining the economical replacement or rehabilitation of the assets. For critical and CLIF assets, the information on failures will not be available. However, where the asset has been periodically inspected, information of the deterioration of the asset is available. Proactive plans can be developed, approved, and funding put in place to ensure that the assets will not fail. For critical assets where some risk is acceptable, alternatives methods can be used in defining risk including calling on expert judgment instead of actual performance models to assess the possibility, rather than the probability, of failure.

CONCLUSION

Defining the probability of failure is an achievable goal, but the real benefit of this analysis is the identification of critical locations that are based on the community’s risk aversion. The identification of these locations will also determine the assets that need to be inspected and possibly rehabilitated. Most communities have undertaken some level of asset renewal and have developed thresholds for rehabilitation. These thresholds are likely general in nature and are applied consistently to assets within an asset category. The consideration of the consequences of failure should lead to a review of the thresholds to include consideration of the consequence and, in some cases, the risk of failure.

In most communities, renewal projects are competing with other projects for limited funding. Limited funding leads to annual backlogs of rehabilitation projects. An outcome of the critical location analysis is a review of the thresholds for rehabilitation to align the decision to not rehabilitate an asset with the community's risk aversion. The condition of the network can then reported back to decision-makers with the requirements for rehabilitation that is consistent with the community values.

Assets in an urban environment cannot be considered independently when these spatial relationships and interactions play an important part in the life cycle of the assets. Understanding the spatial relationships is a must. To develop long term plans, decision-makers must consider the possible consequences of failure and be willing to support staff by providing clear direction in defining the community's tolerance to the risk of not only individual failures but multiple failures that occur in an urban environment. ArcGIS provides the tools for the analysis required to minimize the outcomes of failures at critical locations.

Reference

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