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RESILEINCE PREPAREDNESS-BASED OPTIMIZATION FRAMEWORK FOR WATER AND COMBINED SEWER PIPES: TOWN OF KINDERSLEY

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Abstract: North America's infrastructure is at risk. Water and combined sewer and stormwater systems, representing an important part of the cities' urban infrastructure, are in dire condition state. According to the latest Canadian Infrastructure report card, one-third of the pipes are in fair condition state and below, which requires further attention. Furthermore, more than half of the linear stormwater assets are facing the risk of overflooding due to the increased flow demand/capacity ratio. Even though some scholars developed management systems for pipes to optimize the maintenance and replacement and improve network condition, they ignored the growing effect of urban growth and climate change (i.e. intense and frequent rainfall cause flooding) on the pipes' deterioration. Accordingly, this paper proposes a scheduling and optimization framework that optimizes the pipes' replacement decisions to increase their resiliency while considering the annual expenditures, urban growth and its' future impact on the demand. The framework revolves through five core models: (1) urban and climate change models that simulates the impact of the urban growth and climate change on water and combined sewer pipes; (2) capacity performance model that predicts the future flow demand-capacity ratios based on the estimated population growth, land use changes, and climate change; (3) pipes' deterioration model that calculates the pipes' condition across their service life; (4) financial model that computes the life-cycle costs; and (5) multi-objective optimization model that schedules the replacement decisions to minimize the network's demand-capacity ratio and maximize its condition, while respecting the available budget. The system was applied to the water and combined sewer and stormwater network of Kindersley town, Saskatchewan, Canada. The results showed an optimal intervention schedule with a total of 500 intervention actions across the 25 years planning horizon. Furthermore, it showed an EUAC of $1.7 million and an average condition state of 69% with resilience preparedness of 59% for both networks at the end of the planning horizon. In conclusion, the pipes' resiliency to flooding could be drastically improved while minimizing the life-cycle costs through maintaining acceptable pipes' condition states and demand-capacity ratios, identifying condition/capacity deficient pipes, and taking prompt recovery measures.

1 INTRODUCTION

The infrastructure is crumbling. Everyday natural and man-made challenges arise and adds folds of complexity to the decision-making process. For instance, the Canadian population has doubled in 40 years from 17.9 million in 1960 to reach 35.1 million in 2013 and expecting to be 42.5 million by 2056 (Statistics Canada 2017). The natural increase of population was also attributed to a heavy inflow of rural migrants. The migration towards Canada has been mainly due to the employment opportunities and the major proportion of services it provides. Due to their attractiveness and extremely high population density, various cities were targeted for residency during the first half of the century. However, they lost their attracting elements in the second half of the twentieth century because of the accumulating residency overload and inability to expand their existing infrastructure. The expansion could be either horizontal or vertical. The horizontal expansion could be reached through urbanizing new areas and building solid infrastructure to support the new residents. However, the vertical expansion could be reached through expanding the current services to account for the increasing population. For instance, building a new water treatment plant and installing bigger water main pipe diameters could be an example for vertically expanding the infrastructure capacity to meet the increasing demand. Another challenge is the climate change. The climate change severely impacts the existing infrastructure and urges asset managers to take intervention/replacement decisions earlier than planned/expected. For instance, the increasing the number of freeze and thaw cycles expedites the road deterioration and thus, decreases its' expected service life (Moahmmed et al. 2017). Similarly, the increasing rainfall intensity and frequency might force asset managers to consider replacing the pipes with bigger ones earlier than their physical service life. In that case, the asset will not properly depreciate and will be considered as a waste of the public money.

Research	Domain of application	Scale of application	Optimization type	Optimization tool	Objective(s)
El-Masry *et al.* (2017)	Sewer	Network level	N/A	Benefit/Cost analysis	Maximize the benefit/cost ratio
Abu-Samra *et al.* (2016)	Water	Project level	Single objective	Integrated discrete event simulation and GAs	Minimize the risk index represented by consequences of failure and leak severity
El-Abassy *et al.* (2016)	Water	Project level	N/A	Fuzzy Analytic Network Process (FANP)	Select the optimal trenchless technology type
Zdenko *et al.* (2015)	Water	Network level	Single objective	Decision tree	Maximize network performance
Khan *et al.* (2014)	Water	Network level	Single objective	Decision tree	Prioritize the corridors for repair
Marzouk and Omar (2013)	Sewer	Network level	Multi-objective	GAs	Maximize condition and minimize costs
Mohamed and Zayed (2013)	Water	Network level	Single objective	Integrated MAUT and AHP	Prioritize the corridors for fund allocation
Ward and Savic (2013)	Sewer	Project level	Multi-objective	Integrated AHP and MAUT	Maximize structural condition and minimize costs and risk
Osman *et al.* (2012)	Water and sewer	Phased network level	Multi-objective	GAs with pareto optimization	Minimize risk exposure and condition assessment cost
Alvisi and Franchini (2009)	Water	Network level	Multi-objective	GAs with pareto optimization	Minimize repair costs and water losses
Dridi *et al.* (2008)	Water	Network level	Single objective	GAs	Minimize the life-cycle costs
Alvisi and Franchini (2007)	Water	Network level	Multi-objective	GAs	Minimize cost and maximize performance
Guistolisi *et al.* (2006)	Water	Network level	Multi-objective	Benefit/Cost analysis	Maximize benefit/cost ratio

Table 1: Summary of water and sewer asset management research

Several scholars have developed asset management plans for water and sewer pipes. Table 1 summarizes the most representative work in the domain of water and sewer asset management. For instance, El-Masry et al. 2017 developed a benefit-cost analysis for scheduling the sewer pipes' replacement. Similarly, Abu-Samra et al. developed risk models for minimizing the risk impact of the water pipes' break, repair time and cost. They used discrete event simulation and genetic algorithms (GAs') optimization for scheduling the maintenance actions of the water pipes across 20 years planning horizon. Even though previous scholars utilized different approaches to optimize the decisions to schedule the rehabilitation/replacement of pipes, several limitations were not addressed: (1) absence of research that focuses on augmenting the resilience preparedness of the water and combined sewer pipes to flooding and unmet demands under the evolving climate change and land development; (2) lack of consideration of expanding the pipe's hydraulic capacity while undertaking a replacement decision, which is a major setback when it comes to real-life implementation of the decision-support systems' outcomes.

2 OBJECTIVES

In the lights of the above-mentioned issues, this paper aims at developing a resilience preparedness-based scheduling and optimization framework for water and combined sewer pipes. The framework will assist decision-makers in taking informed and timely pipe replacement decision not only based on the cost and condition, but also the pipes' resilience preparedness for the population growth and climate change. In order to reach this goal, the following objectives need to be achieved:

1. Simulate the impact of climate change and population growth on the infrastructure demand curves.
2. Develop a capacity performance model to forecast the demand/capacity ratio across the planning horizon.
3. Build deterioration models for the pipes to predict their condition across the planning horizon.
4. Construct life-cycle costing model to compute the maintenance and replacement costs across the planning horizon.

3 METHODOLOGY

The resilience preparedness framework supports the transition from a "Reactive" approach, where assets are left until failure, to a "Proactive" approach, where asset management plans are developed to prevent assets from failure and prolong the assets' service lives. It computes the corridors' resiliency with respect to climate change and urbanization. It focuses only on the water and sewer pipes' replacement given their long service lives and lengthy public disruptions. The framework considers the impact of urbanization, represented through land use change and population growth; and climate change, represented through the rainfall intensity and frequency increase, on the water and combined sewer systems. It computes the resilience preparedness, condition, and life-cycle costs across the planning horizon. The framework revolves through four integrated models as shown in Figure 1: (1) demand change model; (2) capacity performance model; (3) future condition prediction model; (4) life-cycle costing model; and (5) optimization model. The demand change model aims at quantifying the impact of population growth, land use change, and increasing rainfall intensity and frequency on the demand of each sub-catchment area. For the water pipes, the impact of land use change and population growth are considered to compute the demand flow increase and the increased rainfall intensity will not be considered given that it does not impact the water pipes. However, in the case of combined sewer and stormwater pipes, the impact of climate change, represented through the increased rainfall intensity, are added to the impact of the land use change and population growth. The result of combining those impacts is the increased demand flow. Thenceforth, the capacity performance computes the demand/capacity ratio to ensure that the supply, which is represented through the pipe diameter, could meet the demand across the planning horizon. A demand-capacity ratio greater than 1 represents the case when the demand flow exceeds the existing capacity. In that case, the existing pipes need to be replaced with bigger diameter ones to meet the increasing demand flow and thus, the pipe replacement decisions for both water and sewer networks will be as follows: (1) replacing the pipe with the same diameter/hydraulic capacity in case the current diameter is enough to operate over its' lifetime and the only trigger to replace the pipe was the deteriorating condition state; and (2) increase the hydraulic capacity through installing a larger diameter pipe to account for growing population, increased rainfall intensity, and pipe condition. In the case of larger diameter replacement, the replacement decision trigger will be either (1) operational; where the hydraulic capacity is no longer sufficient to operate; or (2) physical and operational; where both the condition is deteriorating, and the hydraulic capacity is no longer enough for operation. The financial impact and the extension in the service live of replacing the pipe with a larger diameter is considered in the life-cycle costing and future condition prediction models respectively. Afterwards, the future condition prediction model takes place to compute the deterioration of the pipes across the planning horizon. The model considers the different service lives of different pipe diameters, materials while forecasting the pipes' condition. Subsequently, the life-cycle costing model takes place to calculate the rehabilitation and replacement costs across the planning horizon. The concepts of time value of money were considered to compute the Equivalent Uniform Annual Cost (EUAC) and Net Present Value (NPV). Finally, the optimization model is developed to schedule the rehabilitation and replacement actions across the planning horizon. The optimization trades-off bringing forward or backwards the pipes' interventions based on the goal deviational variables. Non-pre-emptive goal optimization was used to formulate the problem in hand and account for the resilience preparedness, condition, and life-cycle costs while scheduling the pipes' interventions. MOSEK optimization engine was used to solve the problem in hand and REMSOFT software was used for mathematically modelling the resilience preparedness, condition, and life-cycle costs.

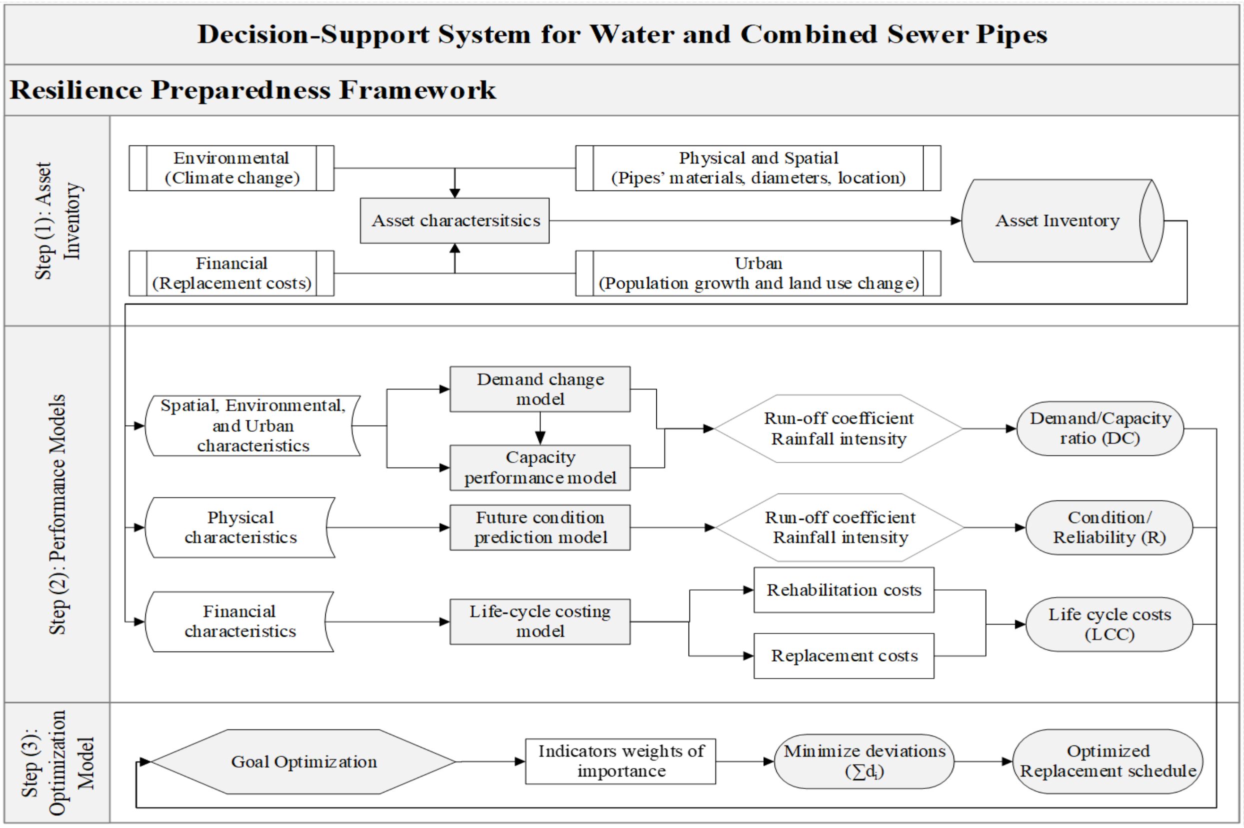


Figure 1: Resilience preparedness framework

3.1 Demand change model

The demand change model aims at computing the rainfall intensity and runoff coefficients of each sub-catchment area to calculate the increase in the demand flow. An urban change and climate change models are developed to compute the runoff coefficient and the rainfall intensity respectively across the planning horizon. For the water pipes, the demand flow will be only affected by the runoff coefficient given the fact that they are not affected by the rainfall intensity. However, for the combined sewer and stormwater pipes, both the rainfall intensity and runoff coefficients are considered while computing the demand flow increase. From a drainage perspective, the most dominant characteristic of the urban landscape is the high degree of impervious ground cover. Population growth and changes in urban land-use affect the extent of imperviousness of urban watersheds, leading to a rapid rate of increase on rainfall runoff. These factors result in more significant changes to the hydrologic regime compared with changes due to drainage works in rural and non-developed areas. Furthermore, the volume and rate of stormwater runoff directly rely on the magnitude of precipitation. Statistical frequency analysis of Canadian global climate models' series has shown that rainfall events' frequency and intensity will, most likely, increase over the next years due to the climate change (Environment Canada 2014). The urban change model used the rational method (Dooge 1957). It computes the runoff coefficient and tributary area (A) that are affected by current and future land use patterns, which respond to urban growth development strategies. Given the fact that there are various land uses for each sub-catchment area, the runoff coefficient of each pipe i is estimated through computing the individual runoff coefficient with respect to each land use type area (Ai). Furthermore, the climate model estimates the changes across time of impervious areas, runoff and flows to the pipe system for an entire catchment based on remotely sensed data and GIS technologies (Gupta et al. 2012). The output of the climate model is the Rainfall Intensity (I). The mathematical formulation of the demand for both runoff coefficient and rainfall intensity could be displayed in the below equations. Thenceforth, the demand of the water and combined sewer and stormwater pipes are computed as shown in the below equations.

$$[1]\ RR_{i_{o_t}} = \frac{\sum_{pc=1}^{PC} A_{pc_{i_o}} \times RR_{pc_{i_{o_t}}}}{A_{i_o}}$$

$$[2]\ A_{i_o} = \sum_{pc=1}^{PC} A_{pc_{i_o}}$$

$$[3]\ Q_{i_{o_t}} = RR_{i_{o_t}} * A_{i_o}$$

where $Q_{i_{o_t}}$ is the design discharge for the recurrence interval of pipe *i* within corridor *o* at point of time *t* (m^3/day); t is the analysis point of time throughout the planning horizon (years); *i* is the pipes counter; $RR_{i_{o_t}}$ is the rational runoff coefficient of pipe *i* within corridor *o* at point of time *t*; I_t is the rainfall intensity at point of time *t* (mm-h); A_{i_o} is the catchment area of pipe *i* within corridor *o* (m^2); $A_{pc_{i_o}}$ is a fraction of pipe *i* area (A_{i_o}) covered within corridor *o* (m^2); and pc and PC are the counter and total number of components (pc) within pipe *i* area (A_{i_o}) respectively.

3.2 Capacity performance model

The capacity performance model aims at computing the demand/capacity ratio (DC) of the network water and sewer pipes. This ratio characterizes the system resilience preparedness as it estimates the flow over the capacity ratio of each pipe over its life-cycle to ensure that the flow demand is met by the given pipe diameter. For instance, a ratio above 100% indicates a pipe facing flow demand superior to its capacity. In that case, the model alerts the decision-makers that the current pipe either (1) will experience overflow, in case of combined sewer and stormwater, or (2) will not fit the demand, in case of water. In both cases, it needs to be replaced with a larger diameter pipe to meet the flow demand, as shown in the below equation.

$$[4]\ DC_{i_{o_t}} = \begin{bmatrix} Do\ Nothing\ or\ replacement\ with\ same\ diameter & \frac{Q_{i_{o_t}}}{CPi_{o_t}} \\ Replacement\ with\ larger\ diameter & \frac{Q_{i_{o_t}}}{CPi_{new_{o_t}}} \end{bmatrix}$$

where $DC_{i_{o_t}}$ is the flow demand-capacity ratio of pipe *i* within corridor *o* at point of time *t* (%); CPi_t is the capacity of pipe *i* within corridor *o* at point of time *t* (m^3/day); $CPi_{new_{o_t}}$ is the capacity of new pipe *i* with a larger diameter within corridor *o* at point of time *t* (m^3/day).

3.3 Future condition prediction model

The future condition prediction model aims at forecasting the pipes' reliability across their service lives. It represents the water and combined sewer pipes' condition evolution while considering both the negative (i.e. aging, pipe break) and positive impacts (i.e. leak repair, rehabilitation, replacement). Given the fact that (1) the service lives of the water and sewer networks are long (i.e. 60-100 years); and (2) inspection and condition assessment is difficult and costly, Weibull-based deterioration model was used to reflect the deterioration pattern of the pipes across the planning horizon. In order to build a Weibull-based deterioration model, the initial date of installation, estimated service life, alpha, and beta distribution parameters need to be present. Weibull analysis is a widely used technique to analyze and predict failures and malfunctions for different types of assets (Jardine and Tsang 2006). It aims at computing the systems' reliability by calculating the probability density and cumulative distribution functions across the system's service life. Thenceforth, the system's reliability is computed as shown in Equation 5. To account for different pipe materials and diameters, a probability distribution function along with its' distribution function parameters is assigned to each pipe category to account for the different pipe failure curves. The key to plotting the cumulative distribution function as well as the reliability function is properly estimating the shape, scale, and location parameters. The shape parameter, sometimes referred to as Beta (β), is the slope of the cumulative distribution curve and the reliability. It simply reflects the rate of failure for the system such that it designates whether the failure rate is increasing, constant or decreasing. For β<1, the system has a decreasing failure rate. This scenario is typical of infant mortality and indicates that the system is failing during its initial burn-in period. For β=1, the system has a constant failure rate. It typically reflects the systems that have survived the initial burn-in period as they will subsequently exhibit a constant failure rate. For β>1, the system has an increasing failure rate, which represents the systems' in their wearing out period. The scale parameter, sometimes referred to as Alpha (α), is the Weibull attribute life or service life adjustment factor. In other words, it is a measure of the range or spread in the distribution of data. The location parameter, sometimes referred to as Gamma (γ), represents the distribution along the planning horizon (time). For γ=0, the distribution starts at t=0 (origin). However, the distribution slides to the left or right for γ<0 or γ>0 respectively. Finally, the impact of replacing the pipe with a same or larger diameter is the same as both return the system to a pristine condition state as displayed in Equation 6.

[5] $R_{i_{o_t}} = 1 - D_{i_{o_t}} = e^{-\left(\frac{t_{i_o}-\gamma}{\alpha}\right)^{\beta}}$ *; For* γ*>0*

[6] $R_{AI_{i_{o_{t+1}}}} = \begin{bmatrix} Do\ Nothing & R_{BI_{i_{o_t}}} - d_{i_{o_t}} \\ Replacement\ with\ same\ or\ larger\ diameter & R_{i_{o_{t_0}}} \end{bmatrix}$

where; t_{i_o} is the age of the system *i* within corridor *o* (years); β is the shape parameter (>0); γ is the location parameter (>0); α is the scale parameter (years); $D_{i_{o_t}}$ is the cumulative distribution function (deterioration) of system *i* within corridor *o* at point of time *t* (%); and $R_{i_{o_t}}$ is the reliability of system *i* within corridor *o* at point of time *t* (%).

3.4 Life-cycle costing model

The life-cycle costing model aims at computing the rehabilitation and replacement costs of each intervention action. Given the diversity of pipe diameters, depths, and materials, replacement costs are estimated at a pipe level. The average unit costs of the different intervention actions could be displayed in Table 2. Those costs could vary within the same pipe at different periods of time given the fact that some pipes might require replacement with larger diameters to account for the increased capacity. For instance, a 300 mm diameter pipe could be replaced either by the same diameter pipe or a larger one (i.e. 375mm) depending on future demand. Thus, a flow demand-capacity replacement threshold of 50% has been defined to guarantee a safety margin of 25 years without overflooding or operational-triggered replacement that makes the current pipe diameter no longer sufficient to meet the increasing demand. For instance, a deteriorating pipe with flow demand-capacity less than 50% would be replaced with the same diameter and a deteriorating pipe with flow demand-capacity more than 50% will be replaced with a larger pipe diameter given that their hydraulic capacity will not be enough to meet the increasing future demand. Finally, the NPV and EUAC of the overall network is computed based on the time value of money basic principles.

3.5 Optimization Model

The existence of ample number of feasible solutions across the study planning horizon adds folds to the problem's complexity. Thus, it is impossible to manually reach an optimal schedule due to the outsized search space. Furthermore, given that there are conflicting objectives (i.e. condition/resilience preparedness vs cost), single objective will not useful for reaching an optimal solution for those objectives. Accordingly, goal programming was used to minimize the life-cycle costs and demand/capacity ratio and maximize the condition. The objective is linked to the variables through “Goal Constraints”. However, the objective is clearly formulated to minimize the sum of deviations for the prescribed goal values defined by the user. To combine the objectives, a percentile ranking approach was utilized by calculating the percentage deviation from a goal rather than the absolute deviation. Finally, the deviational variables are formulated to fit the pre-defined set of KPIs, as shown in the aforementioned equations. In that case, the negative deviations (d_k^-) would be the life-cycle costs and demand/capacity ratio. However, the positive deviation (d_m^+) will be the condition. The model was built on REMSOFT and MOSEK optimization engine was used such that; it features a branch, bound and cut optimization algorithm to solve mixed integer problems. REMSOFT is an asset management and object-oriented modelling software that is capable of undertaking data-driven insights to support decision-making for large fleets of assets. It integrates the spatial geographical information system data into the asset inventory and all through the deterioration, maintenance scheduling, capital/investment planning, and budget allocation. MOSEK, which is an optimization engine that is integrated within REMSOFT, aims at reaching an exact solution for continuous linear, quadratic and conic problems.

$$[7]\ \mathbf{Min}(\mathbf{Z}) = \sum_{\mathrm{i}=1}^{n_s} \sum_{v=1}^{V} \sum_{\mathrm{t}=1}^{T} [\mathrm{W_i} * \mathrm{W_v} * (\mathrm{d}_k^- + \mathrm{d}_m^+)]$$

$$[8]\ \mathrm{d}_{k\,t}^- = \sum_{i=1}^{n_s} \sum_{h=1}^{H} \frac{KPI_{h_{i_t}} - TH_{h_i}}{TH_{h_i}}\ ; \textit{for all k and t}$$

$$[9]\ \mathrm{d}_{m\,t}^+ = \sum_{i=1}^{n_s} \sum_{l=1}^{L} \frac{TH_{l_i} - KPI_{l_{i_t}}}{TH_{l_i}}\ ; \textit{for all m and t}$$

$$[10]\ \textbf{Decision variables} = \begin{bmatrix} I_{t_o} & \cdots & I_{T_o} \\ \vdots & \ddots & \vdots \\ I_{to} & \cdots & I_{TO} \end{bmatrix}$$

$$\text{For } I_{t_o} = 0, 1, \ldots 10$$

$$\mathrm{t} = 1, 2, \ldots \mathrm{T}$$

$$\mathrm{o} = 1, 2, \ldots \mathrm{O}$$

where; Z is the summation of the deviational variables of n_s system throughout the planning horizon T (%); W_v represents the deferential weights among the conflicting goals (%); v is the KPIs’ counter (number); V is the total number of KPIs (number); $\mathrm{d}_{k\,t}^-$ is the summation of all the negative deviational variables at point of time (t) (%); and $\mathrm{d}_{m\,t}^+$ is the summation of all the positive deviational variables at point of time (t) (%); I_{t_o} is the intervention at time (t) and for corridor (o).

Intervention name	Average unit cost ($/unit)	Unit	Notes
Water pipe rehabilitation	$ 1,200.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Water pipe replacement	$ 1,750.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Sewer pipelining	$ 1,450.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth
Sewer pipe replacement	$ 2,200.00	linear meter	Varies according to the pipe material, pipe diameter, and excavation depth

Table 2: Unit costs for the water and combined sewer rehabilitation and replacement activities

4 RESULTS AND ANALYSIS

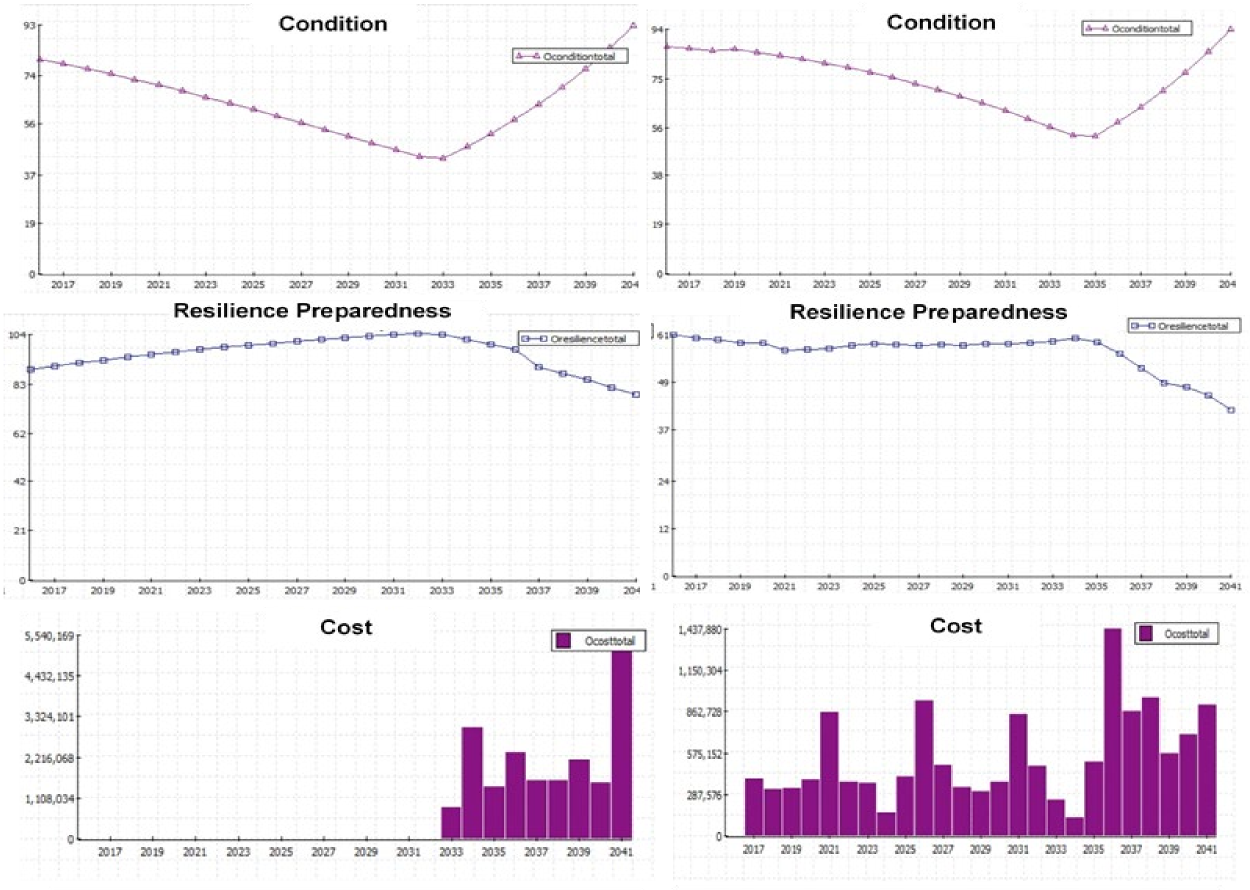
To demonstrate the functionality of the proposed framework, the system was applied to a 53 km stretch from the town of Kindersley roads, water, and sewer networks. The network comprises 120 corridors. Time value of money has been considered with an interest rate of 2%. Furthermore, the study planning horizon was 25 years. The presented multi-objective goal optimization was applied to the case study and displayed promising results in terms of cost, condition, and resilience preparedness. The weights of importance for the financial, physical, and resilience preparedness were 35%, 30%, and 35% respectively. The optimization results could be summarized in Table 3 and Figure 2 (a) and (b) for the water and combined sewer networks respectively. For the water network, the intervention schedule displayed a total of 303 intervention actions split into 3 for rehabilitation, 269 for the replacement for the same diameter, and 31 replacements with a bigger diameter. This distribution is because the network was in an excellent condition state and fair resilience preparedness. Thus, undertaking replacement actions for bigger diameter improved the resilience preparedness by 19% dropping from 61% to 42% demand-capacity ratio as displayed in Figure 2 (a). The average number of interventions per year was 12 interventions for the 125 corridors, which results in an average disruption ratio of 10%. The water network was in a very good initial condition of 87.5%. After running the optimization for 25 years, the condition improved to 94% because of the undertaken replacement actions. Furthermore, the intervention program resulted in NPW of $13.7 million, equivalent to an EUAC of $702,000, for pipelining and replacing the 53 km of Kindersley's water network. Those costs were broken-down to 17% for pipelining, amounting $2.3 million over the 25 years planning horizon, and 83% for replacement, amounting $11.4 million over the 25 years planning horizon. The average annual expenditures were $13,250 $/year/km. For the combined sewer network, the intervention schedule displayed a total of 197 intervention actions split into 28 for pipelining, 108 for the replacement for the same diameter, and 61 replacements with a bigger diameter. This distribution is because the network was in a very good condition state and poor resilience preparedness. Thus, undertaking replacement actions for bigger diameter improved the resilience preparedness by 11% dropping from 89% to 78% demand-capacity ratio as displayed in Figure 2 (b). The average number of interventions per year was 7 interventions for the 125 corridors, which results in an average disruption ratio of 6%. The sewer network was in a very good initial condition of 80%. After running the optimization for 25 years, the condition improved to 93% because of the undertaken replacement actions. Furthermore, the intervention program resulted in NPW of $20 million, equivalent to an EUAC of $1 million, for pipelining and replacing the 53 km of Kindersley's water network. Those costs were broken-down to 6% for pipelining, amounting $1.2 million over the 25 years planning horizon, and 94% for replacement, amounting $18.8 million over the 25 years planning horizon. The average annual expenditures were $19,350 $/year/km. In summary, the intervention program resulted in an EUAC of $1.7 million with an average condition of 69% and average resilience preparedness of 77%, which is 15% improvement compared to the initial one.

KPI	Water	Combined Sewer	Water and Sewer
Cost – Equivalent Uniform Annual Cost (EUAC) ($)	$702,248	$1,025,412	$1,727,660
Cost – Net Present Worth (NPW) ($)	$13,710,317	$20,019,589	$33,729,906
Average Condition (%)	74%	64%	69%
Average Resilience (%)	57%	96%	77%
# of intervention actions	303	197	500
Cost per km per year ($//km/year)	$13,249.97	$19,347.40	$32,597
Average repair length per year (km/year)	5.4	3.0	8.4

Table 3: Town of Kindersley - Optimization summary results

5 CONCLUSIONS

Across the last decade, plentiful decision-making frameworks were developed frameworks for water and combined sewer systems. However, most of the scholars failed to consider the resilience preparedness in their decision-making process. Thus, this paper presented a resilience preparedness-based optimization framework that can be used for scheduling the interventions municipal water and sewer systems. Within the framework, a demand change model was developed to quantify the impact of population growth, land use development, and rainfall intensity and frequency on the demand. Furthermore, a capacity performance model was built to compute the demand/capacity ratio and forecast the optimal timing of expanding the pipes' diameters to accommodate for the increased demand. Thenceforth, a future prediction model was constructed using Weibull to predict the deterioration of the pipes across the planning horizon. Then, a life-cycle costing model was developed to compute the operating and maintenance costs across the planning horizon. Finally, an optimization model was formulated to select the optimal intervention schedule for rehabilitating and replacing the water and sewer pipes either based on the condition or resilience. The system was applied to the town of Kindersley water and combined sewer system. The results showed an optimal intervention schedule with a total of 500 intervention actions across the 25 years planning horizon. Furthermore, it showed an EUAC of $1.7 million and an average condition state of 69% with resilience preparedness of 59% for both networks at the end of the planning horizon. Despite the capabilities and flexibility of the system, the future work is underway to address some of the limitations including but not limited to: (1) coordinating the water and combined sewer interventions given their spatial interdependency; (2) quantifying the indirect/user costs of disrupting the service and its' impact of the public; and (3) calculating the corresponding traffic congestion resulting from the lengthy systems' disruption.



(a) Combined Sewer **(b) Water**

Figure 2: Combined sewer and water network optimization results

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