

A Novel Multi-objective Risk-informed Rehabilitation Framework for Sewerage Systems

By

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Abstract:

Stormwater sewer infrastructure is at risk due to ageing, structural deterioration, population growth, and climate change. Since the consequences of the sewer system failure can adversely impact the community safety, environment and economy, a resilient infrastructure system is of essential importance. However, limited reinvestment budget and insufficient asset management practices impact the rehabilitation of urban sewerage systems. Therefore, an effective and efficient rehabilitation plan is needed to help proper investment decisions. An effective rehabilitation plan will maximize hydraulic performance while minimizing the overall failure risk within a limited budget. The current study aims to address this issue through designing a risk-informed methodology in three steps. First, the hydraulic risk index (obtained using the SWMM model) was combined with the ageing pipe index. The framework uses multi-objective optimization technique to generate solutions under specific sewerage conditions. We named this new framework as Hydraulics and Risk Combined Model (HRCM). Several scenarios including high hydraulic risk, high ageing risk, hydraulic risk and ageing risk (combined problems), and limited budget problems, are used to test the performance of the proposed methodology. The results show that the proposed model could provide a satisfactory solution. Then, in order to increase the calculation speed and improve the accuracy, sensitivity and cost-effectiveness analyses were also conducted for the proposed methodology with different algorithms. The results show that different algorithms offer various benefits. A new calculation method was offered by combining the advantages of the previous methods. Finally, a new optimization method named Phenotype Searching Method, which was enlightened by sexual selection processes, was offered. This method can enhance the selection processes to specific phenotypes (pipes) so that it can increase the convergence speed and increase the performance of the HRCM model.

Keywords: Stormwater Management; Rehabilitation; Hydraulic Performance; Risk-informed Framework; Phenotype Searching Method; Hydraulics and Risk Combined Model

Thanks for my supervisors who teach me what is the love of nature;

thanks for my families who teach me what is the nature of love.

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List of acronyms

CCTV: Closed Circuit Television

HRCM: Hydraulics and Risk Combined Model

MOPSO: Multi-objective Particle Swarm Optimization Algorithm

NSGA-II: Non-dominated Sorting Genetic Algorithm-II

OPDM: Ordered Probit Deterioration Model

PNNDM: Probabilistic neural network deterioration model

PSM: Phenotype Searching Method

PSO: Particle Swarm Method

SWMM: Storm Water Management Model

List of Symbols

N_i : Rating expressed as a percentage of the burial depth of pipe i .

H_i^{US} : Height of maximum surcharge in the manhole.

G_i : Depth at which the pipe i is buried.

N_i^i : Net effect of the surcharge that pipe i causes within itself.

H_i^{DS} : Height of the downstream surcharge in relation to the crown of pipe i .

N_{global} : Systematical overflowing index.

l_i : Length of the pipe i .

S^i : Sum of the rows corresponding to pipe i .

C_i : Consequence of failure of pipe i .

k : Impact factor.

S_k : Classification.

PV_k : Performance value.

W_k : Weighted number.

$P(t)$: Possibility of failure with time t (year).

R_{global} : Systematic risk index.

P_s : Status of a new pipe.

D : Diameter of the new pipe.

M : Rehabilitation method.

I : Rehabilitation index.

\bar{i} : Average intensity.

t_d : Storm duration.

t_p : Time of peak intensity.

Chapter 1 Introduction

1.1 Background

Urban flooding has caused many social impacts and property damages across Canada and the world. The Ottawa spring flooding 2019, urban flooding of Toronto 2013, and Calgary urban flooding 2013 left deep impressions to its victims. From the report of Insurance Bureau of Canada, from 2016-2020, the average annual loss caused by hurricanes, convective storms, winter storms, and floods was estimated at \$4.9 billion (Insurance Bureau of Canada, 2020). From government reports, the flash storm and the melting snow are the main reasons causing the flooding in Canada (Government of Canada, 2013). The combined effect of climate change has increased the impact of storminess in Canada (Vermaire et al., 2013). Reports stated that the increasing temperature could drastically impact the precipitation in a short duration. The variation of precipitation in the winter season could increase the possibility of spring flooding. High-intensity rainfall and extreme weather push demand of city resilience. Therefore, it has become a great challenge in current society (Armenakis and Nirupama, 2014).

This situation promotes the discussion of some topics such as how to build water-sensitive urban (Ashley et al., 2013; Sharma et al., 2012), sustainable urban drainage system, low impact development, and sponge city (Zhang et al., 2019). All of them are systematic problems and need to be built under the consideration of underground sewerage or drainage system. Two kinds of sewer systems, the combined system and separate system, compose the main types of urban drainage systems (Jegatheesan, 2019). Besides, it is common for some cities to use partially separated systems when they transform a combined system to separated sewerage system. Even though there is no final conclusion that which system can solve the urban flooding problem, researchers consider that the separate system has more advantages. Because due to the chemical and biological containment in sanitary sewage, such as hydrogen sulphide (Zhang et al., 2008), heavy metal, nitrate, phosphate (Lee and Bang, 2000), pharmaceutical and personal care products (Ellis, 2006), pathogens (Girones et al., 2010), and nanoparticles (Kaegi et al., 2013), the flooding

caused by combined drainage can containment groundwater (Mohrlök et al., 2008) and impact people's health (Escher et al., 2011).

Some drainage systems lack consideration, and the deterioration of drainage systems is severe. According to the *Canadian Infrastructure Report Card* (CIRC 2019), the unsatisfied pipes, whose status are fair, poor or very poor, have composed one-third of our municipal infrastructure. This situation is not limited to Canada but threatens the world. For example, water and wastewater networks in the United States are in a near failure condition according to *American Society of Civil Engineers's Report Card 2017*, (ASCE, 2017). Some researchers (Elsawah, Bakry and Moselhi 2016) stated that it had been estimated that around 240,000 pipe breaks annually. It had been estimated that at least \$1 trillion dollars should be invested on drainage rehabilitation, and because of aggressive competition among bidding entities, the real condition behind the number could be even worse in some countries (Huang et al. 2018).

The Paris Agreement (United Nations Climate Change, 2015) asked an increasing adaptation and city resilience under the impact of climate change. The agreement also asks governments to improve the resilience of communities, livelihoods and ecosystems. Different countries have different legislations to support water management (Jegatheesan, 2019). In Canada, the management of urban water is considered at the provincial and local governments. The Ontario Development Charges Act (Government of Ontario, 1997) highlights the stormwater drainage and control services management, and the Ontario Water Resources Act (Government of Ontario, 1990) makes significant effort to surface and groundwater protection. In order to help with the government decision, research is well established to study pipe system design from the slope and diameter of a pipe (Moussavi et al., 2017; Shao et al., 2017), the unit pipe performance (Valizadeh et al., 2019), design cost (Maharjan et al., 2009), simulation (Guo et al., 2007), and network structure (Sebti et al., 2014). However, the management of rehabilitation of drainage systems lacks scientific support and the budget is not enough for rehabilitation (CIRC, 2019).

Sewer system rehabilitation is a complex problem that is unique to other drainage questions. The rehabilitation plans need to consider the rehabilitation strategies which are unclear (Baah et al., 2015). Besides, because current pipe rehabilitation is based on closed circuit television (CCTV) (Surendar et al., 2019), pipes may not get fixed in time. Therefore the rehabilitation plan should

not only consider the hydraulic condition but should take the pipe breaking risk into consideration. However, to the best knowledge of authors, in existing rehabilitation plans the hydraulic performance and the risk assessment model are not combined.

There is no optimization method which perfectly designed to solve the drainage rehabilitation problems. Optimization methods have been used to solve engineering problems to know the best design parameters (Dridi et al., 2009; Roshani and Fillion, 2015). And, optimization methods are well established during decades of developments, from linear programming to heuristic method (Gotsis et al., 2011; Vasudevan and Sinha, 2018; Yazdi et al., 2017). The heuristic method is a self-searching method and algorithm usually enlighten by natural processes such as evolutionary algorithms, physics-based algorithms, swarm-based algorithms and human-based algorithms (Mirjalili and Lewis, 2016). The most common optimization method in drainage system design is the genetic algorithm (Afshar et al., 2006), followed by particle swarm method (PSO) (Vasudevan and Sinha, 2018). Yazdi et al. (2017) compared the non-dominated sorting genetic algorithm-II (NSGA-II) and the multi-objective particle swarm optimization algorithm (MOPSO) in solving the rehabilitation problems of a sewer pipe system. They found that the performance of NSGA-II was better than MOPSO in the sewerage system. Many optimization methods were used, such as the ant colony optimization (Afshar, 2010), random forest (Hosseini and Ghasemi, 2012) and hanging gardens algorithm (Bakhshipour et al., 2019). But the question of which method is the best method for drainage design is still under discussion.

Even though there are many optimization methods and there is a drastic discussion about which method is outstanding among drainage problems, current research ignores many optimization methods and are not suitable with drainage systems. The reason is that they can cause parallel results problems at optimization. Parallel results problems mean multiple output results can get the same values on the Pareto Front, which is the imaginary front made by optimum solutions. This happens in the drainage system when the diameter of pipes exceeds the thresholds. The hydraulic performance would only be impacted when the diameter of a pipe settles in a specific range, and the different pipe has a different range. This significantly increases the calculation time and decreases the searchability. Most optimization methods use objective functions to decide their solutions, but this needs to be changed.

1.2 Objective

In summary, considering the current issues in sewer system rehabilitation, three problems have the priority to be addressed.

- The first question is how to combine the hydraulic performance and pipe breaking risk assessment model together.
- The second question is how to design a methodology targeting strategy optimization for drainage rehabilitation questions.
- The third question is how to modify the current optimization methods or provide a new method for drainage system rehabilitation.

In this research, we aim to provide a potential solution for addressing these problems.

1.3 Novelty and Contribution

To the best knowledge of the author, the hydraulic performance and the pipe breaking risk assessment are frequently used in rehabilitation plans but never combined. The first novelty of this research is that we combine hydraulic performance of the drainage system with the pipe breaking assessment model. By using the rehabilitation method as a pivot to link these two topics, the overflowing risk and the pipe breaking risk were linked together. The new framework uses risk-informed multi-objective methods to work on rehabilitation strategies for the first time and this method can find the best rehabilitation method which can consider both overflowing risk and pipe breaking risk. In addition, we found the parallel-results problem, which means that multiple results can get same points on the Pareto Front, at drainage rehabilitation questions. There is no existing research trying to solve this problem. Therefore, we developed ideas based on sexual selection in ecology. Sexual selection means that animals have their preference for specific phenotypes such as color in guppies. This has similarities to our question in drainage systems where we are looking for specific pipes in the system. By taking this method, the performance of optimization methods has been improved dramatically.

1.4 Outline

The Hydraulics and Risk Combined Model (HRCM) includes data claiming, data processing, simulation, expert system, and post-analysis modules. In the beginning, the raw data of the sewer system as well as the rainfall data are required for running the sewer system simulation. The HRCM could simulate the condition of the whole sewerage system and generate solutions such as routine cleaning, shotcrete, or replace the deteriorated pipe, for rehabilitation. The subsequent function for the HRCM model would transform those solution sets to the expert system. By using a general method to evaluate the output results, the cost-effective analysis, which can transform the rehabilitation outcome to cost-benefit, will give the final solution.

This thesis is organized as shown in Figure 1.1. The second chapter illustrates the structure of the HRCM method. Besides, the second chapter answers the validity of the HRCM framework. Then, in order to have a faster calculation speed and more accurate results, the third chapter compared several calculation methods in order to find the best method for drainage system rehabilitation. The fourth chapter talks about the parallel results in rehabilitation. The fourth chapter offers a new method named Phenotype Searching Method (PSM). This method simulates sexual selections which enhances some phenotypes in a species to adapt to the environment. That process has some similarities with pipe rehabilitation problems. The fifth chapter presents the concluding remarks of the research. We summarize our research, and point out the weaknesses and suggestions for the future work of the research.

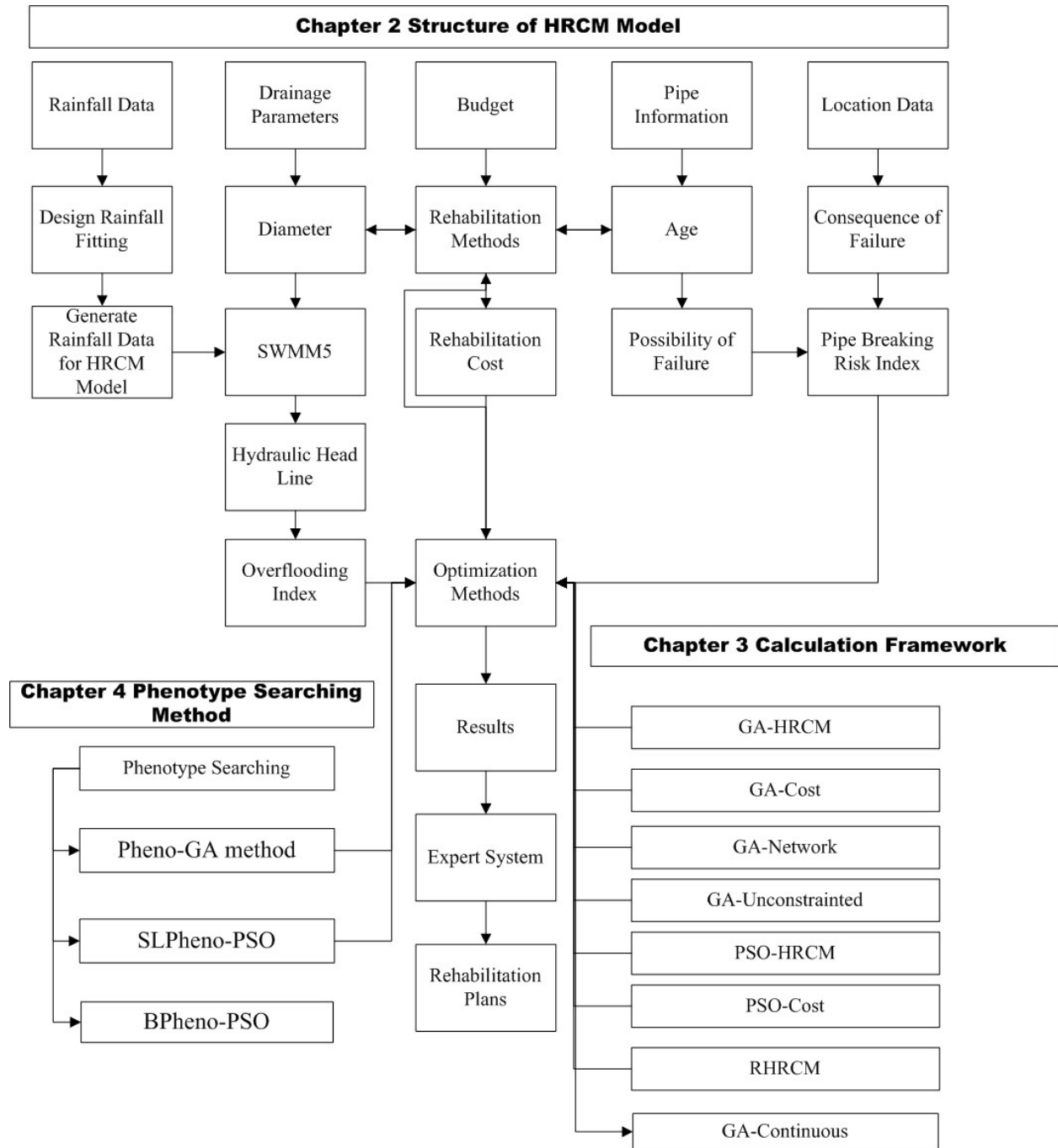


Figure 1.1 The structure of this thesis.

Chapter 2 Risk-Informed Framework for Sewerage System Rehabilitation Management

Abstract

The increasing storm frequency and severity due to climate change, and sewer system degradation due to ageing and corruptions impose higher risk of failure and overflowing to drainage systems. This paper proposes a new risk-informed framework in order to provide optimal strategies for drainage system rehabilitation under limited rehabilitation budgets. The proposed Hydraulics and Risk Combined Model (HRCM) dynamically couples the Storm Water Management Model (SWMM) and a risk model through a multi-objective optimization to maximize the hydraulic performance while minimizing the risk of failure of the sewer system. The sensitivity analysis shows that with a small population size in the genetic algorithm the HRCM is capable of solving complex test cases. In addition, with increasing population size, the Pareto Front converges with several rehabilitation strategies having the same objective function values. The model is examined with several simple and complex scenarios and the results indicated validity and robustness of the model. The results show that the proposed model is capable of providing satisfactory rehabilitation strategies that can inform the drainage system rehabilitation.

Keywords: Rehabilitation; Stormwater Management; Urban Drainage Systems; Risk-informed Framework; Hydraulic Performance

2.1 Introduction

According to the Canada's Changing Climate Report (Bush and Lemmen, 2019), the temperature rise in Canada is about twice of the global average. The temperature rise has changed the climatic processes in the climate system, which in turn has led to intensified storms increasing the stress on drainage systems (Vasiljevic et al., 2012). Adamowski et al., (2010) found that the strength and the frequency of storms has increased by over 10%, and some researchers argued that these unbalanced results will continue to increase the significant summer storms and massive rainfall in the spring (Buttle and Lafleur, 2007).

The increased storms have already caused many disasters and cases of property damage in Canada and around the world (Buttle et al., 2016). Under this situation, the Paris Agreement (United Nations Climate Change, 2015) asked for increasing adaptation and city resilience under the increasing storms. In response to this agreement, many countries have implemented water-sensitive urban design, sponge cities, and sustainable urban drainage systems to increase the resilience of cities to heavy storms (Jegatheesan, 2019).

In addition to the increasing hydraulic demand for drainage systems, additional stresses have been added to sewer system infrastructure due to the ageing, structural deterioration, and corrosion. According to the latest Canadian Infrastructure Report Card (CIRC, 2019), one-third of our municipal infrastructure is composed of the unsatisfactory pipes with fair, poor or very poor condition. According to the ASCE's Report Card for America's Infrastructure in 2017, water and wastewater networks in the United States are in a near failure condition (ASCE, 2017). In China, 72% of the sewer networks were installed in the past 15 years; however, because of the aggressive competition among bidding entities, the construction quality is difficult to guarantee (Huang et al., 2018). Not only in China, but this aggressive

competition also exists worldwide which can bring potential risk to the urban drainage system. Therefore, the government should regulate market competition in a more effective way to insure the quality and sustainability of a project. Dawson et al. (2008) pointed out that in the UK, the sewer problem also needs advanced attention. They argued that currently, in the UK, due to the fragmented management of urban flooding, it is difficult for national, local government agencies and private companies to coordinate for projects. In addition, it has been estimated that urban flooding in Australia caused \$314 million of property damage over the three years before 2001, and the Australian Infrastructure Report Card evaluated the storm-water pipe systems in Australia as being in poor condition as well (Tran et al., 2010). Unfortunately, even though the problem is severe and urgent, the reinvestment is lower than the budget recommended by asset management practitioners (CIRC, 2019); therefore, we should study how to use a limited budget to rehabilitate a drainage system effectively and efficiently.

Sewer system surcharge during a storm can impact people's lives by bringing wastewater to the ground and threaten public health (Girones et al., 2010). Some studies focused on how to improve the hydraulic performance of a drainage system (Yazdi et al., 2017a, 2017b; Ogidan and Giacomoni, 2016). These studies focused on drainage design such as selecting the slope and diameter of a pipe (Moussavi et al., 2017; Shao et al., 2017), improving the unit pipe performance (Valizadeh et al., 2019; Yazdi et al., 2017b), decreasing the design cost (Maharjan et al., 2009), improving the simulation results (Guo et al., 2007; Vasconcelos et al., 2018), and modifying the structure of the pipe system (Jeffers and Montalto, 2018). However, previous studies have not considered a risk-informed supporting system that combines the hydraulic performance of the system with the risk of failure through a multi-objective

optimization.

The rehabilitation of a drainage system becomes complicated when we consider both hydraulic overflowing and pipe aging impact, because of the uncertainty of pipe breaking. Some methods can be used to detect the deterioration of a drainage pipe, such as visual inspection methods, electromagnetic methods, acoustic methods, ultrasound methods (Yin et al., 2020). However, those methods require significant amounts of time and effort to detect the deteriorated condition of each pipe in a drainage system. Modeling can support field detection to make it more efficient. Some models are available for urban managers to predict the deterioration of a drainage system, such as the ordered probit deterioration model (OPDM) and a probabilistic neural network deterioration model (PNNDM). Tran et al. (2008) compared these two models and found that the PNNDM model is more suitable to predict hydraulic deterioration.

Risk-informed method is a decision-supporting method that can provide an assessment for the drainage system to estimate the breaking risk of each pipe (Baah et al., 2015). This method can be used to evaluate the breaking risk of a drainage system and to develop rehabilitation strategies, accordingly. However, those methods are not well combined with hydraulic performance of the drainage system. How to combine different methods into one framework is a challenge in a complex system. In this research, we propose a new framework to dynamically combine the hydraulic performance of the drainage system with the risk of failure to develop optimized rehabilitation methods using multi-objective optimization. We used a simplified sewer network to validate the proposed method, and examine the capability of this framework to identify efficient rehabilitation strategies for various scenarios.

The rest of this paper is organized as follows. We first provide an overview of the proposed framework and the Hydraulics and Risk Combined Model (HRCM). The HRCM model includes submodels for hydraulic simulation (to determine the hydraulic performance index) and the risk assessment. These submodels are dynamically combined through multi-objective optimization. The performance of the HRCM model is examined with various scenarios. We finish the paper with results and discussions on the performance of the proposed framework in different situations.

2.2 Hydraulics and Risk Combined Model

As Fig. 2.1 shows, there are five modules that compose the HRCM: (1) hydraulic performance module, (2) risk assessment module, (3) optimization module, (4) rehabilitation module, and (5) postprocessing module. There are two constraint functions, i.e. the pipe surcharge and budget, and two objective functions, i.e. the system hydraulic performance and system breaking risk. The rehabilitation module can change the deterioration situation of a pipe, and affect the system hydraulic performance. This module also links cost with pipe breaking index and system hydraulic performance.

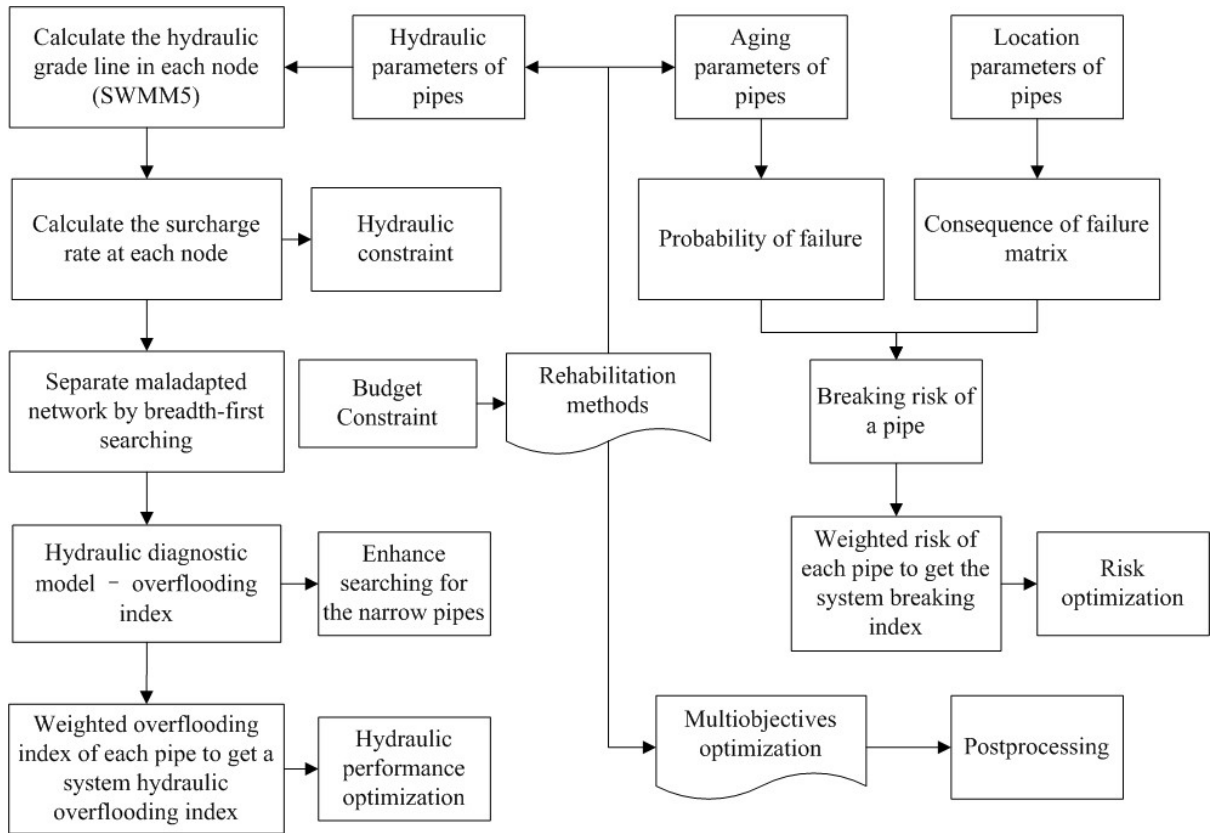


Figure 2. 1 Structure of HRCM.

2.2.1 Rainfall

The Chicago designed storm is a common method for the simulation of sewerage systems and it has been widely used in various studies (Bennis et al., 2003). Here, we use the equation given by Akan and Houghtalen (2003). The average intensity is:

$$\bar{i} = A / (t_d^B + C) \quad (2.1)$$

where:

\bar{i} = the average intensity,

A, B and C = parameters for the curve-fitting,

t_d = the storm duration.

The instantaneous intensities of the designed storm can be calculated by:

$$i = A[(1 - B)(t_b/r)^B + C]/[(t_b/r)^B + C]^2 \quad (2.2)$$

and

$$i = A[(1 - B)(t_a/(1 - r))^B + C]/[(t_a/(1 - r))^B + C]^2 \quad (2.3)$$

where

$$r = t_p/t_d,$$

t_p = the time of peak intensity,

$t_b = t_p - t$, where t is the time,

$$t_a = t - t_p.$$

2.2.2 Hydraulic Model

The Storm Water Management Model (SWMM) developed by the United States Environmental Protection Agency (EPA) is used for hydraulic modelling of the sewer system. The SWMM model is widely used around the world for sewerage system management

2.2.3 Overflowing Index

A proper hydraulic performance index is needed to search for the pipes in the system that contribute to the overflowing and sewer surcharge. In this research, we use the index given by Bennis et al. (2003). They provided a hydraulic diagnostic model that can evaluate the backwater

effect of downstream pipes.

$$N_i = 100\% \times H_i^{US} / G_i \quad (2.4)$$

$$N_i^i = N_{min} + (N_{max} - N_{min}) (H_i^{US} - H_i^{DS}) / G_i \quad (2.5)$$

$$N_i^{DS} = N_i - N_i^i = (N_{max} - N_{min}) H_i^{DS} / G_i \quad (2.6)$$

where:

N_i = surcharge index; the rating expressed as a percentage of the burial depth, varying from N_{min} of 0% to N_{max} of 100%,

H_i^{US} = upstream maximum surcharge; the height of maximum surcharge in the manhole situated immediately upstream from pipe i for the design flow,

H_i^{DS} = downstream maximum surcharge; the height of the downstream surcharge in relation to the crown of pipe i .

G_i = the depth at which the pipe is buried, measured from the ground surface to the upstream crown of pipe i . When H_i^{US} is equal to G_i this means that the height of the surcharge has reached the ground surface and that the pipe will overflow,

N_i^i = net surcharge index; the net effect of the surcharge that pipe i causes within itself,

N_i^{DS} = downstream surcharge index; the surcharge of pipe i caused by downstream pipe.

These parameters are illustrated in Figure 2.2. To calculate N_i^i and N_i^{DS} , the first step is to calculate the N_i .

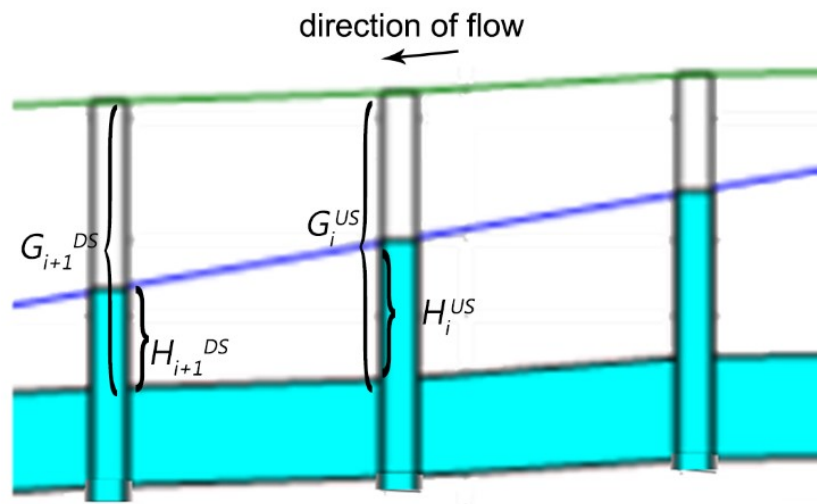


Figure 2. 2 Diagram of the notation of hydraulic parameters.

Table 2.1 presents the calculation procedure for the estimation of the hydraulic diagnostic model for a three-pipe system to estimate the overflowing index. As an example, we presented numerical values to clarify the required steps for the estimation of the overflowing index. The surcharge index N_i and net surcharge index N_i^i need to be calculated first. Then, fill out the table from the p_3 column to p_1 column. The downstream surcharge index can be found after we subtract the net surcharge index from the surcharge index. The amount of downstream surcharge index is assigned to each row according to the number of the previous column. For example, if $N_1 = 40$, $N_1^1 = 10$, $N_2 = 20$, and $N_2^2 = 10$, the value of $N_1^2 = (N_1 - N_1^1) \times (N_2^2/N_2) = 15$. Finally, the hydraulic diagnostic model index of pipe 2 (p_2) equals to $0 + 10 + 15 = 25$. A higher value of the model index means it has a higher impact on the system.

Table 2. 1 The overflowing index calculation method; the number in the bracket is a number for illustration.

Pipe Number	Hydraulic Index Calculation Equation			Hydraulic Diagnostic Model Index
	p_3	p_2	p_1	
p_3	N_3^3 (10)	$N_2 - N_2^2$ (10)	$(N_1 - N_1^1) \times$ $(N_2 - N_2^2)/N_2$ (15)	(S^3) Sum the row p_3 (35)
p_2	0	N_2^2 (10)	$(N_1 - N_1^1) \times$ (N_2^2/N_2) (15)	(S^2) Sum the row p_2 (25)
p_1	0	0	N_1^1 (10)	(S^1) Sum the row p_1 (10)
N_i	N_3^3 (10)	N_2 (20)	N_1 (40)	

The number one in Table 2.1 means the first pipe at the upper stream. In our model, the systematical overflowing index (N_{global}) is calculated with a weighted number of pipe length:

$$N_{global} = \sum l_i S^i / \sum l_i \quad (2.7)$$

where:

l_i = the length of the pipe i ,

S^i = the sum of the rows corresponding to pipe i .

2.2.4 Risk Index

1) *Consequence of Failure*

The consequence of failure in this paper is considered through a weight scoring method (Salman and Salem, 2012). In 2001, the National Research Council of Canada (NRC) published Guidelines for Condition Assessment and Rehabilitation of Large Sewers (Zhao et al., 2001). Based on this and other similar studies (Kleiner et al., 2004; Salman and Salem, 2012), Baah et al., (2015) put forward a risk-based approach to measure the risk assessment as a weighted score (Table 2.2). The consequence of failure will be estimated as follows:

$$C_i = \sum_k S_k \times PV_k \times W_k \quad (2.8)$$

Where:

C_i = the consequence of failure of pipe i ,

k = the impact factor,

S_k = the classification,

PV_k = the performance value,

W_k = the weighted number.

Table 2. 2 Weighted score for the consequence of failure. This table was given by (Baah et al., 2015)

Impact factor (k)	Classification (S_k)	Performance values (PV_k)	Weighted number (W_k)
Roadway type	Intersecting ON road class 2	3	0.2
	Intersecting ON road class 4	2.4	
	Intersecting ON road class 5	1	
Intersecting a railway track	Yes	3	0.2
	No	0	
Pipe size	Diameter > 900 mm	3	0.16
	Diameter > 600 & <=900 mm	2.25	
	Diameter > 300 & <=600 mm	1.5	
	Diameter > 300	1	
Pipe burial depth	Depth > 10m	3	0.16
	Depth <=10 & >3m	1.5	
	Depth <=3m	1	
Located downtown	Yes	3	0.2
	No	0	
Proximity to hospital	Pipe distance <=	3	0.2

	120 m		
	Pipe distance > 120 m	0	
Proximity to school	Pipe distance <= 200m	3	0.2
	Pipe distance > 200m	0	
Distance to building	Distance < 5m	3	0.2
	Distance >= 5 & <= 10 m	1.5	
	Distance > 10m	0	
Proximity to river	Pipe distance <= 15m	3	0.2
	Pipe distance > 15m	0	
Proximity to park or recreational areas	Pipe distance <= 20 m	3	0.16
	Pipe distance > 20m	0	
Proximity to stormwater pipe	Distance <= 10m	3	0.2
	Distance > 10 m	0	

2) Probability of failure

Accurate prediction of the current and future condition of a sewerage system using available assessment data is crucial for developing appropriate strategies for ageing pipe maintenance and rehabilitation.

The exponential model has been justified in several research studies for its accuracy to predict pipe deterioration in both the water distribution system (Kleiner and Rajani, 2001), and

sewerage deterioration system (Duchesne et al., 2013). In those failure model, the probability of failure is decided by the age of a pipe. Some methods such as ordered probit deterioration model, neural network deterioration model (Tran et al., 2009), logistic regression model, and Markov chain models (Malek Mohammadi et al., 2019) are used to predict the deteriorate rate in sewerage systems. In our research, for the sake of simplicity and without losing the generality, we assumed that the deterioration of a pipe follows an exponential relationship. This exponential probability density function can be seen in the survival analysis of sewer pipe deterioration (Duchesne et al., 2013) (Eq. 2.9).

We assumed that the probability of failure for each pipe is (Eq. S1 in Supplemental Materials 1):

$$P(t) = a \times e^{b \times (t-c)} \quad (2.9)$$

Where:

$P(t)$ = the possibility of failure with time t (year).

The a , b and c are fitting parameters.

3) Risk Index

The systematic risk index (R_{global}) will be given by multiplying the consequence of failure and the probability of failure (Eq. 2.10):

$$R_{global} = \sum l_i C_i P^i / \sum l_i \quad (2.10)$$

The probability of failure is the failure probability per unit length. Here, a length weight value has been added to the risk to get the global risk. This systematic risk index combines the

probability of failure (P^i) and the consequence of failure (C_i), and uses the pipe length as the weighted value to evaluate the overall risk of a drainage system.

4) Rehabilitation Methods and Cost

The rehabilitation methods, along with their associated costs are listed in Table 2.3 (Altarabsheh et al., 2018a). When replacing a pipe with a new pipe, the cost also involves the new pipe cost. In this paper, two methods are used for the pipe cost (PC) estimation (see Eq. S2 and S3 in supplemental materials 1).

Table 2. 3 The rehabilitation matrix (Altarabsheh et al., 2018a)

Rehabilitation	Action	Reinforcement Cost (\$/m)	Disruption Cost (\$/m)	Pipe Cost (\$/m)	Benefit (year)
1	Do nothing	0	0		-
2	Routine cleaning	16	0		10
3	Shotcrete	656	0		20
4	Cured-in-place pipe	1558	0		50
5	Reinforced fiberglass sliplining	2231	0		100
6	Dig and replace with concrete pipe	1148	656	PC	50

5) Optimization Method

In this study, two objective functions i.e. the hydraulic performance and risk of failure are combined using a multi-objective optimization method. Three parameters of diameter (D), rehabilitation method (M), and whether to change index (FN) were used for optimization (Eq. 2.11).

$$P_s = \{D, M, FN\} \quad (2.11)$$

where:

P_s = rehabilitation strategy,

D = diameter of the pipe,

M = rehabilitation method,

FN = whether we want to fix the pipe. The index FN is a $\{0,1\}$ set.

The optimization procedure is devised so that the reinforcement methods and replacement methods can have the same probability to be selected. We used the multi-objective optimization nondominated sorting genetic algorithm II (NSGA-II) in MATLAB, which is known as a fast approach, and does not need specifying a sharing parameter (Deb et al., 2002). This method preserves the nondominated solutions on the Pareto Front and provides accurate results in multi-objective optimization. It has been widely used in multi-objective optimization problems including drainage design rehabilitation problems (Bi et al., 2016; Yazdi et al., 2017a). We use the mixed-integer multi-objective genetic algorithm provided by MathWorks (MathWorks, 2018). After several simulation experiments, we set the stall generation limit as 100; the generations as 500; the population size of 100, 500, 1000, 1500, 2000 and 5000; and

the Pareto Fraction equals to 0.35. The mutation and crossover rates are set to 0.5, and based on the case study results, we set the surcharge constraint at each node as 50. The running time is calculated via an Intel® Core™ i7-8750H CPU @2.20GHz, 16.0 GB (RAM).

2.2.5 Postprocessing System

Multi-objective optimization provides several parallel results on the Pareto front. The parallel results are, indeed, multiples independent strategies on the Pareto Front with the same values of objective functions. There is no unique method on how to select rehabilitation solutions from the Pareto front. In this research, we designed a post processing module to remove the replicated results. This expert system selects the minimum cost for each unique hydraulic performance and risk performance of the solution to provide optimal strategies.

2.3 Case Studies

We used nine scenarios to validate this framework. These nine scenarios can be classified into two cases. The details of parameter setting and results can be found in supplemental materials.

2.3.1 Case1

Case1 includes six simple scenarios with known optimal solutions in order to validate the capability of the model. Indeed, using narrow pipes, aged pipes, and extreme design storms the target pipes are easy to identify. We tested the model with this case to answer if: (1) the proposed methodology can successfully and efficiently find the pipe that influences the performance of the system (i.e. narrow pipes), (2) the proposed methodology can detect the high-risk pipe (i.e. aged pipes), and (3) the proposed methodology is capable of detecting the trade-off between the two situations (two scenarios: one pipe is narrow and aged, and one pipe is narrow and another one is aged); (4) the proposed methodology can sufficiently response to

the budget influence (different budgets). The summary of six scenarios under Case1 is listed in Table 2.4. The parameters setting of these six scenarios can be found in Supplemental materials.

It should be noted that to examine the ability of the proposed model to provide different optimal rehabilitation strategies, we also include two other pipes which contribute to the overflowing (i.e. with the net surcharge index (N_i^f) between 0 and 100).

Table 2. 4 Description of test scenarios in Case 1

Classification	Scenario	Scenario description	Function
Hydraulic	Case1-S1	A system with one narrow pipe which causes surcharge.	In this simulation, we verify whether the proposed methodology can detect the narrow pipe.
Ageing risk	Case1-S2	A system with a pipe at high breaking risk but there is not a narrow pipe.	In this simulation, we verify whether the proposed methodology can detect a high breaking risk in a different pipe.
Trade-off	Case1-S3	Two pipes have a problem in this system. The first pipe has a hydraulic problem, and the second pipe has a breaking problem.	In these scenarios, we verify whether the proposed methodology can detect the high breaking risk and hydraulic problems at the same time and distribute the budget.
	Case1-S4	A system has a pipe that has both hydraulic and breaking risk. (Budget 1)	
Budget Limitation	Case1-S5	A system that is the same as scenario 4 except it has a limited budget. (Budget 2)	In these two scenarios we evaluate how the proposed methodology

Case1-S6	A system that is the same as scenario 4 except it has a limited budget. (Budget 3)	solves the budget limit problem.
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2.3.2 Case 2

Case2 aims to test whether the proposed model can solve the rehabilitation problem in a more complex situation. The first scenario of Case2 is used to compare the results with those obtained in Case1-S1. The Case2-S1 is a narrow pipe scenario but the diameter of that narrow pipe is larger than the Case1-S1. Case2-S1 has also different rainfall and cost settings to validate whether the model can detect the problematic pipe in a different configuration. The Case2-S2 includes multiple pipes with higher risk. We set the age of pipes from 5 to 95. This scenario can validate how the model rehabilitates a more complex system. The Case1-S3 has multiple narrow pipes at the downstream of the network. Since those pipes are at main chain they can impact the entire chain routes. The scenarios descriptions under case 2 are presented in Table 5.

Table 2. 5 Description of Scenarios in Case 2

Classification	Scenario	Scenario description	Function
Sensitivity Comparison	Case2-S1	This scenario has three narrow pipes. Only if the program replaces all the three pipes the overflowing can be solved. (Budget = 1000000 \$)	This scenario was used to compare with Case-S1. Different diameters, rainfall, can cost setting can test the capacity of the framework.

Regular Ageing	Case2-S2	A gradient of deteriorated years was assigned to each pipe. (Without budget constraint)	This scenario can validate how the framework solves a complex aged system.
Multiple narrow pipes	Case2-S3	Multiple narrow pipes were assigned after congestion. Those pipes can impact all the drainage instead of only one chain (Without budget constraint).	This scenario can test whether this framework can solve the narrow pipe problem in the main chain.

2.4 Results and Discussion

2.4.1 Sensitivity analysis

We used Case1-S1 and Case2-S1 to conduct a sensitivity analysis on the population size. The results of the HRCM model include the pipe diameter (will not change if pipe is not replaced) and the rehabilitation method. The model provides different optimal strategies among which the end users can select the strategy based on their own set of requirements and budget constraints. For Case1-S1, using the population size of 100, the model provides eight different strategies, each corresponding to one point on the Pareto Front. Table 2.6 presents the pipe diameters and rehabilitation methods for the first five pipes in the network. The complete results can be found in Table S8 in supplemental materials 1. The results determine which rehabilitation method should be used and if we replace a pipe, what size of the pipe should we use.

Table 2. 6 HRCM results for C1-S1 scenario (first five pipes).

Ordinal number	Pipe Diameters (m)					Rehabilitation Methods				
	d p1*	d p2	d p3	d p4	d p5	s p1**	s p2	s p3	s p4	s p5

for the strategies										
1	0.7203	2.2061	0.46	0.915	2.2061	6	6	2	2	6
2	0.305	0.5515	0.46	0.915	2.2061	2	6	2	2	6
3	0.305	0.7203	1.9022	0.915	2.2061	3	6	6	2	6
4	0.305	0.7203	0.46	0.915	2.2061	3	6	2	2	6
5	0.305	2.2061	0.46	0.915	2.2061	3	6	2	2	6
6	1.6208	0.303	0.46	0.915	2.2061	6	4	3	2	6
7	0.305	0.303	0.46	0.915	1.9022	3	3	2	2	6
8	0.305	0.303	0.46	0.915	2.2061	3	3	2	2	6

* d_p: pipe diameter.

** s_p: rehabilitation method.

The number of final strategies depends on the number of population and the Pareto fraction parameter in the GA method. The number of optimal strategies equals to the population size times the Pareto fraction. However, we only obtained a limited number of points on the Pareto Front. That is, there are many strategies with the same results of the objective functions for both the hydraulic overflowing index and the pipe breaking index. In our model, we have a postprocessing module, which only keeps the cheapest strategies on the Pareto Front. These criteria for the selection of the optimal solution from the Pareto Front may change in different situations.

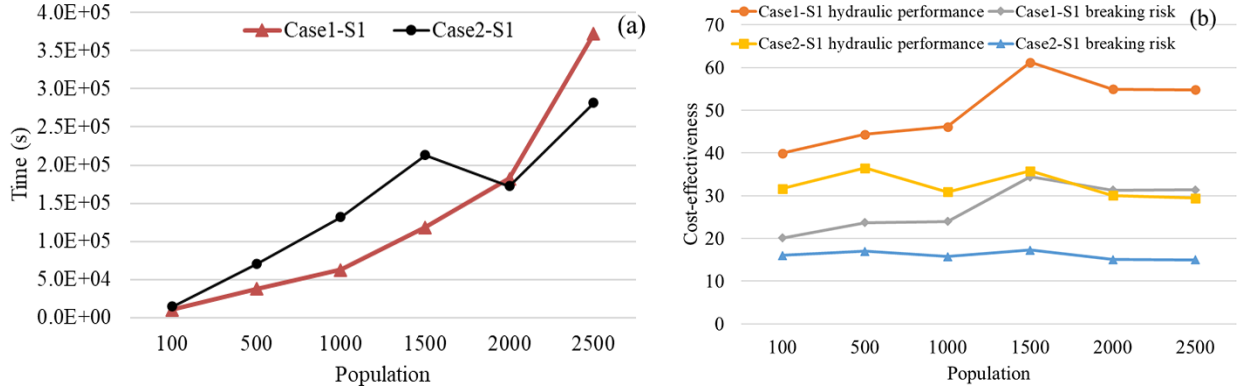


Figure 2. 3 Sensitivity analysis on population size for Case1-S1 and Case2-S1 for (a) time competition, and (b) cost-effectiveness

We compared the calculation time (Fig. 2.3a), cost-effectiveness (Fig. 2.3b), and the Pareto Front (Fig. 2.4) to determine the appropriate population size for optimization. The cost-effectiveness analysis can evaluate the cost and its benefit (Irfan et al., 2009; Yao et al., 2019). It is defined as the index in Eq. 2.12 to evaluate the efficiency of each method.

$$Ce = \frac{1}{j} \sum_j (I_j^p - I_j^a) / C_j^r \quad (2.12)$$

Where Ce is the cost-effectiveness index. This index equals to the average of the difference between the original overflowing/risk index I_p , and the overflowing/risk index after the rehabilitation I_a , over the rehabilitation cost C_r .

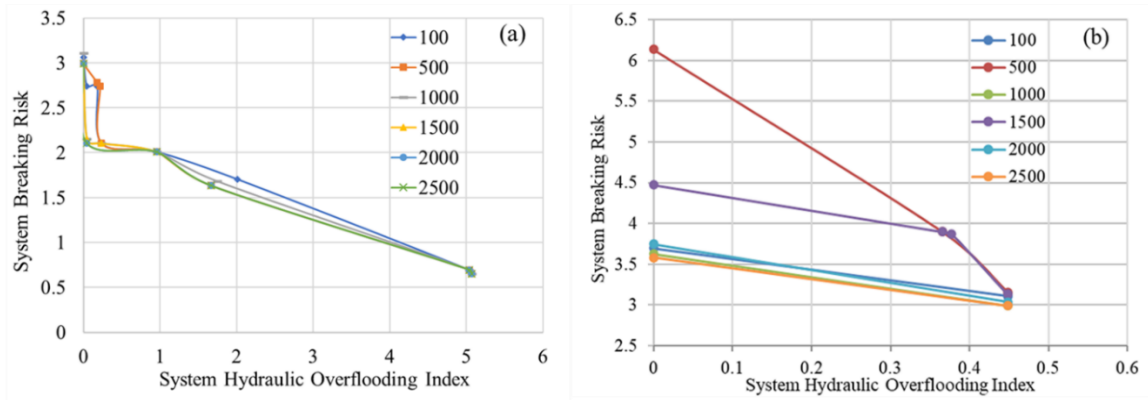


Figure 2. 4 Optimum results of the system breaking risk and system hydraulic overflooding index for (a) Case1-S1, and (b) Case2-S1.

Fig. 2.3a presents the time competition of Case1-S1 and Case2-S1. The figure plots the population size in NSGA-II against the computational time, and as can be seen there is no convergence in computational time. Fig. 2.3b shows that the cost-effectiveness doesn't change with the population size. That is, when we increase the population to search for the optimum value, the cost-benefit effect of our model will not change.

The curves in Fig. 2.4 are the Pareto Front outputs obtained using different population sizes. Fig. 2.4a, and Fig. 2.4b show the results of Case1-S1 and Case2-S1, respectively. It can be seen that the population size can change the solutions on the Pareto Front. The larger populations result in better results on the Pareto Front. When the population size is higher than 2000, the Pareto Front becomes stable. However, the results for Case1-S1 and Case2-S1 obtained with population size of 1000 and 100, respectively are similar to those obtained with the population size of 2000. Considering both cases, we selected population size of 2000 to run other simulations.

2.4.2 Scenario Results

The HRCM model gives the rehabilitation solutions (Tables S8-S16 in supplemental materials 1), and their corresponding system overflowing index and system breaking index are in Tables S17-S26 in supplemental materials 1.

Case1-S1: Hydraulics scenario

The objective of the first scenario was to verify whether the proposed model can find the narrow pipe and replace it with a larger pipe to solve the overflowing problem. The original system hydraulic performance index was 29.72 and the risk index was 16.24 (Table S7 in supplemental materials 1). The model selected the narrow pipe precisely and replaced it with a pipe of larger diameter. In this scenario, pipe C4 and C5 were narrow but they were not remarkable. Our model provided strategies to replace these two pipes successfully.

Case1-S2: Ageing risk scenario

The objective of the second scenario in case 1 is to verify whether the HRCM can find the aged pipe and reinforce it with a rehabilitation method. The original overflowing index and the risk index were 5.07 and 22.68, respectively (Table S7 in supplemental materials 1). The proposed framework changed the ageing pipe with the rehabilitation method - reinforced fiberglass sliplining, to decrease the potential risk.

Case1-S3: Trade-off scenario-two pipe failure

This scenario is designed to examine the performance of the HRCM model in finding rehabilitation plans for relatively more complex situations where both narrow and aged pipes in the sewer network. In this scenario, one pipe is narrow and the other one is aged. We expect that the model can solve this problem by detecting both narrow and aged pipes. The original indexes for overflowing and risk were 29.72 and 23.92 (Table S7 in supplemental materials

1), respectively. The results showed that the pipe length can significantly impact the overflowing and risk indexes. We found that this framework can detect the pipe with a hydraulic problem or a risk problem. The model can change the narrow pipe with the rehabilitation method sixth in Table 2.3, where it digs and replaces the pipe with another concrete pipe. It can use reinforced fiberglass sliplining to revise the aged pipe. These two processes can impact hydraulics and risk at the same time. The original two indexes were 37.53 to 19.46 (Table S7 in supplemental materials 1), and they were decreased to acceptable values.

Case1-S4: Trade-off scenario-one pipe failure

Scenario C1-S4 is used to obtain the trade-off between hydraulic performance and the risk. There is an aged narrow pipe in the system with the original overflowing index and the risk index of 37.53 and 19.46 (Table S7 in supplemental materials 1), respectively. Because the length of a pipe can impact the hydraulic performance and the risk index, the risk index in this scenario is relatively lower compared to other scenarios. In the proposed method, only one rehabilitation method can be applied on a pipe, such that if the HRCM chose to dig and replace the pipe, it cannot be reinforced by fibreglass. That explains why in this scenario, the risk is higher than other scenarios. Because, when the HRCM replaces the pipe, it can have a shorter benefit year than reinforced pipe.

These two scenarios showed that the proposed HRCM can have a good performance in the trade-off scenarios. Indeed, the model can detect pipes with both hydraulic and risk problems either for two different pipes or the same pipe in the system. The results of this scenario showed that the proposed model is capable of solving complex problems.

Case1-S5 and Case1-S6 - The budget limitation scenarios

In this section, we examine how the budget can change the performance of the HRCM model. The Case1-S4 includes a pipe with both hydraulic and ageing problems. As for the poor hydraulic performance and high-risk pipe, the model will replace the pipe. The original overflowing index and the risk index were same as Case1-S4. We set a budget limitation to explore the impact on this framework. The results showed that when the budget was limited, the framework will select the less expensive rehabilitation method to solve this problem, and when it cannot solve the hydraulic problem, it will first solve the risk problem. Compared with Case1-S4, we found that there is a threshold for the budget. When the budget meets the minimum requirement, the proposed HRCM can find the method to decrease the overflowing and the risk index. However, when the budget does not meet the threshold, the HRCM cannot give promising rehabilitation strategies.

C2-S1: Multiple narrowed pipe in the chain route

Case2-S1 scenario is similar to Case1-S1 but with different pipe diameters. In that discharge, there will have a severe surcharge if we only replace pipe C8. From our design, only if the program replaces pipe C4, C5, and C8, the surcharge will not occur. It should be noted that the model replaced pipe C6 as well. It is because we did not replace pipes and calculate the index in order, therefore, the program may replace an extra pipe to meet the requirement. We think this can be improved if we can update the program to calculate the overflowing index and pipe breaking index in order.

Case2-S2: Multiple deteriorated pipes.

In this scenario, every pipe was assigned an age. And there was one narrow pipe (C8) which caused the overflowing in the system. In this scenario, even though the pipe C8 was a

narrow pipe but the water discharge was smaller than other narrow pipe scenarios. Therefore, only one strategy replaced the pipe (C8). The model selected higher benefit year strategies for the more deteriorated pipes.

Case2-S3: Multiple narrow pipes after the congestion.

In this scenario, the narrow pipes were settled after congestion. The narrow pipes will impact all the chain route and cause surcharge. The model can detect the pipes and replace those pipes to solve the surcharge in every chain route.

2.5 Parallel Solution Problem

It is important to discuss why we can have multiple solutions, but those solutions only have one value on the Pareto Front. The number of solution a drainage rehabilitation problem will be:

$$2^n < \text{Number of Solutions} = \sum_{i=1,2,\dots,n} \{psd + psr\}_i < (sd + sr)^n \quad (2.13)$$

Where n = number of pipes,

psd = number of possible replacement solutions which can get the same value on the Pareto Front for pipe i ;

psr = number of possible reinforcement solutions, which can get the same value on the Pareto Front for pipe i ;

sd = total number of replacement solutions;

rs = total number of reinforcement solutions.

That means the final number of solutions will increase with the number of pipes. This will

decrease the calculation speed and optimization efficiency. We used the postprocessing module to select final solutions from the solution pool; however, that didn't increase the calculation speed and efficiency. That should be improved in the future.

2.6 Limitations

Through the sensitivity analysis, we found that when the population size was larger than 2000, the results converged on the Pareto Front. However, this model can give applicable rehabilitation plans at a smaller population size; we think it is because of the constraint functions which can only keep satisfying solutions. The output of the HRCM model is a set of rehabilitation plans. We expect that managers select a plan according to their own criteria. Even though this model can provide optimal rehabilitation plans, we can mention three limitations for this framework: (1) the calculation speed is slow, (2) the cost-effectiveness of this model needs to be improved, and (3) each module in this model, without losing the generality, is simplified.

The first two limitations may come from one reason. From data based on the results, we found that with the increase of population size, more rehabilitation plans on the Pareto Front can have the same value for the objective functions of overflowing index and breaking index. That means there can be multiple optimal solutions that have the same result on the Pareto Front. The optimization model can solve the drainage rehabilitation problems, but it may have low efficiency in such questions. In addition, we found that the cost-effectiveness will not increase with larger population size. This limitation is out of the scope for the current study and will be addressed in our future research.

2.7 Conclusion

The failure or overflowing of urban drainage systems adversely impacts people's life and health as well as the environment and built infrastructure. Therefore, it is essential to ensure that drainage systems are in good condition. However, the rehabilitation of sewer systems is highly limited by the budgetary constraints, which makes it essential to have optimal rehabilitation strategies in place. In this study, we developed a new framework that combines the sewer system hydraulic performance and breaking risk to support decision making for drainage system rehabilitation.

The proposed risk-informed framework was validated by sensitivity analysis and several case studies. The sensitivity analysis on the population size of NSGA-II showed that: (1) rehabilitation strategies increased with increased population size; (2) multiple rehabilitation strategies have the same objective function values on the Pareto Front and that impacts the calculation speed, which we referred to as parallel results problem; (3) The Pareto Front can converge after the population size higher than 2000; (4) the cost-effectiveness did not improve with the increased population size; and (5). these results did not change with scenarios.

The HRCM model was applied to various case studies to validate its capability in solving problems in various situations. In case 1, six scenarios were applied to test whether this model can identify the narrow or aged pipe in a simple system. Indeed, we tested the model in terms of whether it can replace or reinforce the pipe as we expected. In case 2, more complex situations were presented to examine the performance of the proposed model. The framework can find narrow or aged pipe in single or mixed scenarios. It will replace the extremely narrow pipes to satisfy surcharge constraint, and provide compromise strategies which can get the non-dominant results on the Pareto Front. In severely deteriorated scenarios, the framework

will reinforce the pipe or replace it with a new pipe. The proposed risk-informed framework can detect the narrow pipes at the branch of the drainage system or at the main chain of the system to solve the local or global overflowing. It was shown that the parallel results may affect the performance of that model. The results exhibited that by combining the hydraulic and risk models, the HRCM can improve the hydraulic performance and minimize the failure risk of the system. This decision support tool can provide a set of rehabilitation plans which can assist decision making for efficient drainage system rehabilitation.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request: HRCM model source code, input data files, and output results files.

Acknowledgments

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Chapter 3 An efficient framework for multi-objective risk-informed decision support systems for urban drainage rehabilitation

Abstract

Combining multiple modules into one framework is an important step in modelling a complex system. In this study, rather than focusing on modifying a specific model, we studied the performance of different calculation structures in a multi-objective optimization framework. The objective was to answer an essential question about whether a different framework structure can have a significant impact on the simulation results, and what the most adequate approach is to organize different modules in order to improve the simulation performance. The Hydraulic and Risk Combined Model (HRCM) combines hydraulic performance and pipe breaking risk in a drainage system to provide optimal rehabilitation strategies. We evaluated different framework structures for the HRCM. Results showed the conventional framework including (1) constraint functions; (2) objective functions; and (3) multi-objective optimization, is not efficient. The conventional framework can be significantly improved in terms of the calculation speed and cost-effectiveness. It was shown that removing the constraint function and adding more objective functions will not substantially help with the calculation speed but can improve the model's performance remarkably. Besides, we found that the mixed-integer optimization can decrease the optimization performance compared with using continuous variables and adding a

postprocessing module at the last stage to remove the unsatisfying results. If the optimization method is strong enough to find the optimal solution in a complex system, an extra diagnostic model is not necessary. This study highlights the importance of evaluating the framework structure to solve engineering problems efficiently, and provides a simplified framework for optimization problems.

Keywords: Optimization; Framework; Drainage Rehabilitation; Overflowing; Pipe Breaking

3.1 Introduction

Urban flooding usually happens when the capacity of a municipal sewerage system cannot satisfy the amount of water that emerges in a short period of time (Jegatheesan, 2019). Such a large amount of water can be either resulted from an intensified storm due to climate change (Adamowski et al., 2010; Buttle et al., 2016; Buttle and Lafleur, 2007), or freshets that amplify the stress on the sewerage system (Government of Canada, 2013). In order to release the stress of overflowing in cities, building a smart urban sewerage system can be a priority to increase the resilience of cities.

Computational simulations have been used for urban planning, including underground infrastructure design and pipe rehabilitation in recent years (Ogidan and Giacomoni, 2016; Yazdi et al., 2017a). The essential idea is to build an optimization framework and apply it to a set of variables, which can be the diameter of the pipe, the slope of the pipe or the depth of the pipe, to optimize the objective function, which can be the system hydraulic performance or system pipe breaking risk (Moussavi et al., 2017; Shao et al., 2017). Previous studies focused on various aspects such as the cost of flooding damage (Barreto et al., 2010), and integrated 1D/2D hydraulic modelling, where the SWMM5 was used as the 1D hydraulic model for

sewer system simulations and a 2D model was employed to analyze the overflowing consequences in the drainage basin to obtain more accurate results on the damage of urban flooding (Vojinovic et al., 2014). These studies resulted in frameworks to improve the hydraulic performance of a drainage system.

Except for the surcharge, drainage systems face more challenges such as ageing due to natural and human impacts (CIRC, 2019). Furthermore, the threat of drainage pipes breaking cannot be ignored at locations across the world (Dawson et al., 2008; Elsayah et al., 2016; Huang et al., 2018). Canada's Infrastructure Card (2019), reported that nearly one-third of potable water and sewerage pipes underground are imposed to breaking risk (CIRC, 2019). The pipe breakage can contaminate groundwater and soil severely. Due to the ageing of the pipe system, the breakage of water supply pipes and sewerage pipes can introduce secondary pollutants into potable water and threaten human health (Haller et al., 2007).

Accurate predictions of the current and future conditions of a sewerage system using available assessment data are crucial for developing appropriate strategies for ageing pipe maintenance and rehabilitation. Ahmad Altarabsheh et al. (2018a and 2018b) conducted research based on the whole lifecycle assessment, genetic algorithm, and Monte Carlo simulation to maximize network condition and serviceability while minimizing network risk of failure and total lifecycle cost for the entire planning period. State transition in a Markov chain can simulate the life of a pipe and predict the whole life risk of a pipe (Baik and Abraham 2006). Other methods such as evolutionary polynomial regression (Berardi et al. 2008); ordinal regression model (Younis and Knight 2010) flexible fuzzy model (Hosseini and Ghasemi 2011) are promising methods. Researchers have also concentrated on deciding

the consequences of failure, such as the analytical hierarchy process (Rudiono, 2018; Tarigan et al., 2018). However, this line of research has not been applied to drainage rehabilitation and design.

Cai et al. (in review, 2020) combined hydraulic performance and breaking risk via multi-objective optimization. By building a relationship between rehabilitation and hydraulic performance, as well as rehabilitation and risk, they provided a novel decision support system for drainage systems rehabilitation. In their methodology, they used the traditional three-element optimization method: (1) set constraint functions to allow the system meet basic requirements; (2) set objective function to improve the performance of the system; (3) use a linkage module to link different modules in the system. They used one constraint function to control the overflowing in an urban system, and used a hydraulic performance objective function to optimize the rehabilitation methods. In their paper, they used a breadth-first searching algorithm to separate the problematic system and then optimized the system by a hydraulic diagnostic model (Bennis et al., 2003) from the high impact drainage chain route to the low impact drainage chain route. This method provides good results for various drainage systems. However, there are some limitations in their framework. The overflowing is solved by constraint function which means they add many logistic judgments in their algorithm, and that will decrease the calculation speed. Second, this hydraulic diagnostic model is designed to search for a narrow pipe in a chain route in a drainage system. Therefore, it may decrease the speed when they apply this method chain by chain to search for all the narrow pipes in the drainage network.

In this research, we are looking for the possibility to improve the three elements optimization framework and create a faster and more accurate framework. We improve their first-generation rehabilitation methodology from four aspects. (1) Enlightened by a multiple-stage decision support system (Amador et al., 2020), we improve their framework to get accurate results by adding a new objective function to optimize the budget distribution. (2) We test whether the constraint function can be removed, and the final results can be selected by a filter to increase the speed. (3) We examine whether it is accurate enough to use the overflowing index in each node for optimization. In this way, the new algorithm does not need to search the network chain by chain. (4) We compare whether particle swarm optimization can have better results than the genetic algorithm in this problem. This is because, in the literature, there is a debate on which method has a better performance in drainage systems.

This paper is organized as follows: first, the structure of our new algorithms has been introduced; subsequently, we specify the new algorithms in a computational model, Hydraulics and Risk Combined Model (HRCM). Then, two scenarios are studied to verify those new methods. Finally, we provide a combined methodology to replace/rehabilitate pipes in the drainage system for urban flooding control and pipe breaking precaution.

3.2 Materials and Methods

3.2.1 Introduction to HRCM Model

In this research, we used the Hydraulics and Risk Combined Model (HRCM) (in review, Cai et al., 2020) to calculate the hydraulic performance, risk, and maintenance cost of a drainage system. There are five modules in the HRCM model:

(1) Hydraulic simulation module: In this module, SWMM5 model calculates hydraulic grade line in the drainage system. Then, the hydraulic diagnostic model is applied to this system to calculate the hydraulic performance index (flooding index) for the drainage;

(2) Risk assessment module: In the risk assessment module, the probability of failure for each pipe is calculated according to the age of each pipe. Then, a statistical exponential equation will give the probability of breaking for each pipe. The breaking probability of each pipe will multiply the consequence of failure of that pipe to get the breaking risk of that pipe;

(3) Rehabilitation module: In this module, different rehabilitation methods are connected to the age and diameter of a pipe. That can change the values of breaking risk index and overflowing index in a drainage system;

(4) Multi-objective optimization module: There are two objective functions in this multi-objective optimization. First, a set of constraint functions on hydraulics performance, breaking risk, and budget constraints the minimum requirements for rehabilitation methods. Second, they used a non-dominated sorting genetic algorithm (NSGA-II) to optimize hydraulic performance and decrease breaking risk in this system;

(5) Postprocessing filter (expert system): This module can select results from the Pareto Front according to the cost.

The structure of the HRCM model can be seen in Fig. 3.1, and the calculation process of the HRCM model can be found in the supplemental material 2.

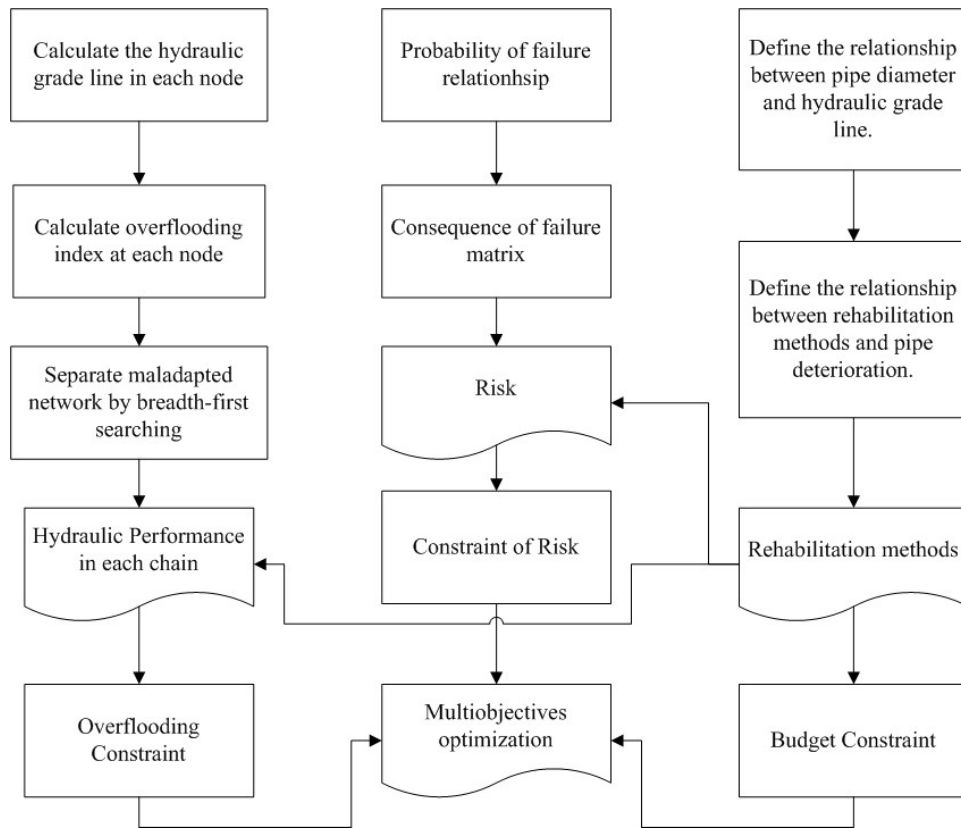


Figure 3. 1 Structure of the HRCM model.

3.3 Rehabilitation Methodologies

3.3.1 Alternative methodologies for pipe rehabilitation

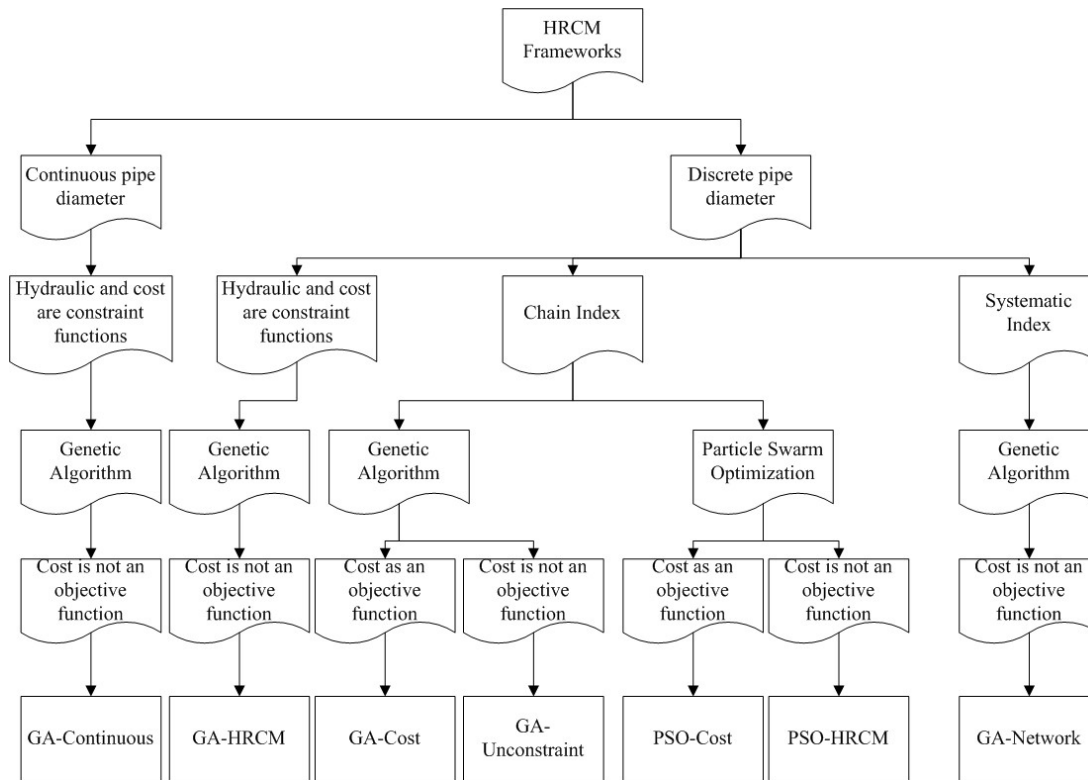


Figure 3. 2 The differences between different algorithms.

We considered six alternative methodologies for pipe rehabilitation. The GA-HRCM is the method which was presented in Cai et al. (in review, 2020). We used this method as our control group to compare with other methods. Explanations of other alternative algorithms: GA-Continuous, GA-Cost, GA-Unconstraint, PSO-Cost, PSO-HRCM, and GA-Network are in Fig.3.2.

GA-Continuous uses a continuous diameter for pipes during and, after optimization, the continuous pipe diameters were transformed to the nearest discrete pipe diameters which are used in engineering. GA-Cost uses the rehabilitation cost as another objective function. We use this group to understand whether this can improve the rehabilitation strategy results by increasing the cost-effectiveness. The GA-Unconstraint method removes the hydraulic

constraint in rehabilitation as well as the budget constraint. The output results were filtered and we only kept the results that satisfied our expectations after the optimization process.

The particle swarm optimization (PSO) and genetic algorithm (GA) methods have been widely used in sewerage pipe design and rehabilitation (Afshar et al., 2006; Vasudevan and Sinha, 2018) and they have shown good results in predicting the hydraulic performance. However, it is still unclear which method is suitable for drainage optimization (Surendar et al., 2019; Vasudevan and Sinha, 2018; Yazdi et al., 2017a, 2017b). We revised the code given by (Yarpiz, 2020), in order to solve the mixed integers problem. We employed two (PSO) methods to compare their performance with the employed genetic algorithm. The PSO-HRCM method replaces the NSGA-II to non-dominant sorting PSO method. Upon this replacement, PSO-Cost method adds cost as another objective function to the PSO-HRCM method.

A drainage system involves a complex structure (Haghighi, 2013). In the research of Bennis et al. (2003), they provided a hydraulic diagnostic model. To distinguish it from other indexes, we named it as chain route index in this study. In their model, they recognized the narrow pipes by calculating an index to evaluate backwater effects from downstream to upstream. Their method, can separate the surcharge effect into two categories: (1) surcharge caused by the pipe itself; (2) surcharge caused by the downstream narrow pipes. Therefore, a computational model can detect the pipe which affects the system easily. The GA-HRCM method used this hydraulic diagnostic model to optimize the overall overflowing index. It is accurate it is debatable whether this strong searching model is necessary to find the narrow pipe (Cai et al., in review). Dion and Bennis (2010) introduced a global modeling approach to

evaluate hydraulic performances in a drainage system. Instead of calculating the chain route index, they directly used the hydraulic grade line in each junction to evaluate the hydraulic performance of the drainage system. To distinguish this index from the chain route index, this index will be called the network index in the present study. The procedure of GA-HRCM model used the chain route index. It has high efficiency when the drainage system is simple, but it is not efficient when the drainage system becomes complex, because this chain route index needs to calculate the index from one branch of the system to another branch (Cai et al., in review). In this research, we evaluated this speed-accuracy compromise by comparing the GA-HRCM method and GA-Network method, using the global hydraulic index.

The GA-HRCM framework, simulates a real rehabilitation circumstance that the decision of rehabilitation should be made under a budget constraint. The surplus budget can be distributed to the drainage to enhance the system further. However, this method doesn't consider rehabilitation cost as an objective function. Therefore, this framework will randomly distribute budget to pipes only if a strategy can solve hydraulics and pipe-breaking problems. In this study, we considered adding a new objective function (cost), and validated whether this method can have higher cost-effectiveness performance. In GA-Cost and PSO-Cost method, there are three objective functions: overflowing index, pipe breaking index, and rehabilitation cost.

3.4 Case Study

Because the validation of the HRCM model was evaluated by Cai et al. (2020, in review) and the objective of this study is to compare the performance of different frameworks, in this study, we assumed two idealized scenarios in which it is easy to recognize the narrow pipe

and aged pipe. Therefore, we can easily evaluate the performance of different frameworks.

The configuration of the drainage system used the system in Bennies et al. (2003) (Fig. 3.3).

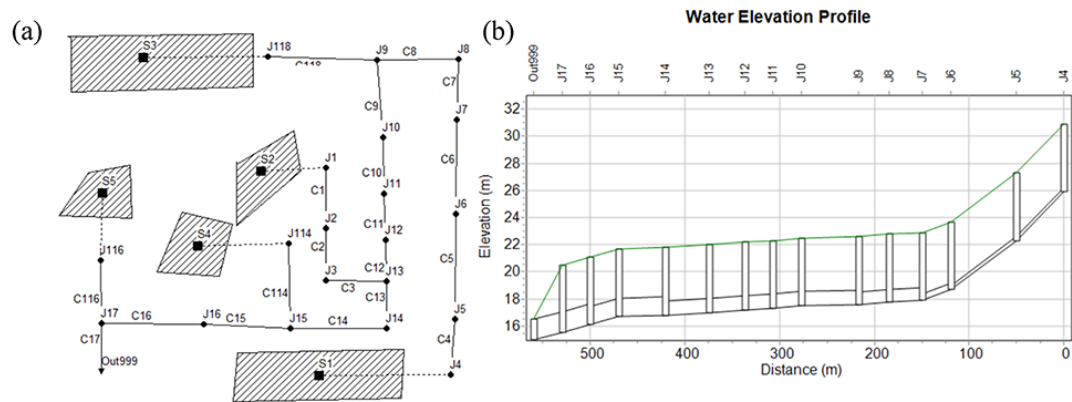


Figure 3. 3 The drainage system configuration: (a) the structure of the drainage system; (b) schematic view of the pipe diameter, length, and depth. [Data from Bennies et al. (2003)]

In this paper, we considered two scenarios (Table 3.1) to evaluate these seven methods in Figure 3.2. The first scenario represented a narrow pipe scenario, and the second scenario represented an aged pipe scenario.

Table 3. 1 The simulation scenarios

Classification	Scenario	Description	Function
Hydraulic	1	A system with one narrow pipe (poor hydraulic performance) at the chain route. The diameter of pipe (C8) is replaced to	In this simulation, it was tested whether the method can detect the narrow pipe.

0.1 m. The age setting of all the pipes are zero.

Ageing risk	2	A system with a pipe at high risk but there is no hydraulic risk. The diameters of pipes are presented in Fig. 3b. The age of pipe C9 was 60, and other pipes' ages are zero.	In this simulation, it was tested whether the method can detect an aged pipe.
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The first scenario is used to test whether those methods can choose the correct pipe and replace it with a larger pipe. In the first scenario, three narrow pipes were placed in the system, and all the pipes were at the same age. In the three narrow pipes, one pipe was an extremely narrow pipe, which means the model must find and replace this pipe, then the overflowing constraint can be satisfied. The other pipes will affect the overflowing index but they were not necessary to satisfy requirements. The second scenario includes an aged pipe and two narrow pipes. The aged pipe was severely deteriorated than other pipes, and the narrow pipes were not severely narrow. The second scenario was used to test whether these methods can find the aged pipe and use a reasonable rehabilitation method to solve the ageing problem. The drainage system was set as in Fig. 3a. This is the same as that in Cai et al. (in review, 2020) study, for comparison purposes. Chicago designed rainfall is a common case

for the simulation of sewerage systems (Akan and Houghtalen, 2003; Bennis et al., 2003; Marsalek and Watt, 1984).

3.5 Cost-effectiveness Analysis

The cost-effectiveness analysis can quantify the rehabilitation performance of a rehabilitation strategy at per unit cost (Irfan et al., 2009; Yao et al., 2019). This method can evaluate the effectiveness of our rehabilitation method, as it provides information on which method can best improve the performance of a system under the unit cost. It is defined as the index in Eq. 3.1 to evaluate the efficiency of each method.

$$Ce = \frac{1}{j} \sum_j \frac{I_j^p - I_j^a}{C_j^r} \quad (3.1)$$

Where Ce = cost-effectiveness index;

I_p = average of the difference between the original overflowing/risk index;

I_a = overflowing/risk index after the rehabilitation;

C_r = cost for rehabilitation.

3.6 Results

3.6.1 Computational Time Competition

Fig. 3. 4 shows the time competition of the seven methods. The computational time will increase with an increased population. However, that trend was not monotonic.

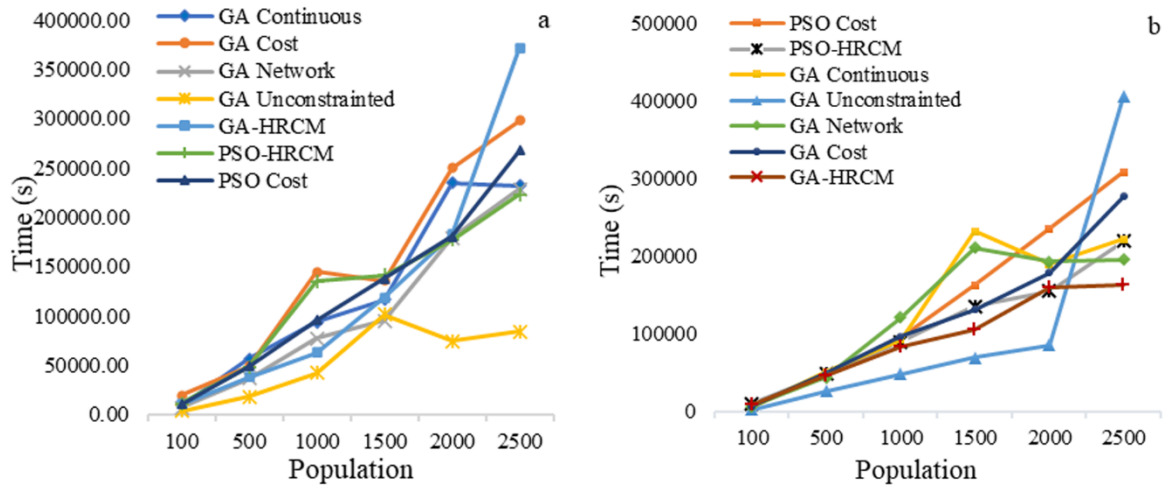


Figure 3. 4 **The time competition of the seven methods** (a) scenario 1; (b) scenario 2.

Different methods exhibited discrepancies in the calculation speed under the various scenarios. The GA-Unconstrained had the minimum calculation time in the first scenario, but its computational cost became enormous in the second scenario. There is a bump up when the population equals 2500. Then, we generated two simulations for GA-Unconstrained with the population size being equal to 2200 and 3000. The calculation times were 77286 s and 89393 s, respectively. Therefore, we inferred that the high computational time for GA-Unconstrained at the population size (equal to 2500) is because of the fluctuations of the program. The GA-Continuous method had a fast convergence speed for both scenarios. It was found that the GA-HRCM method was the slowest method.

3.6.2 Hydraulic performance, breaking risk and cost

The original overflowing index and the risk index of scenario 1 were 29.72 and 16.24, respectively. The overflowing index and risk index of scenario 2 were 5.07 and 22.68, respectively.

Fig. 3.5 show the breaking risk index and overflooding index of each method. The results showed that all the methods can improve the drainage system by decreasing the overflooding index and breaking risk index. GA-Cost and PSO-Cost methods show that using cost as another objective function can improve the searching results with both optimization methods.

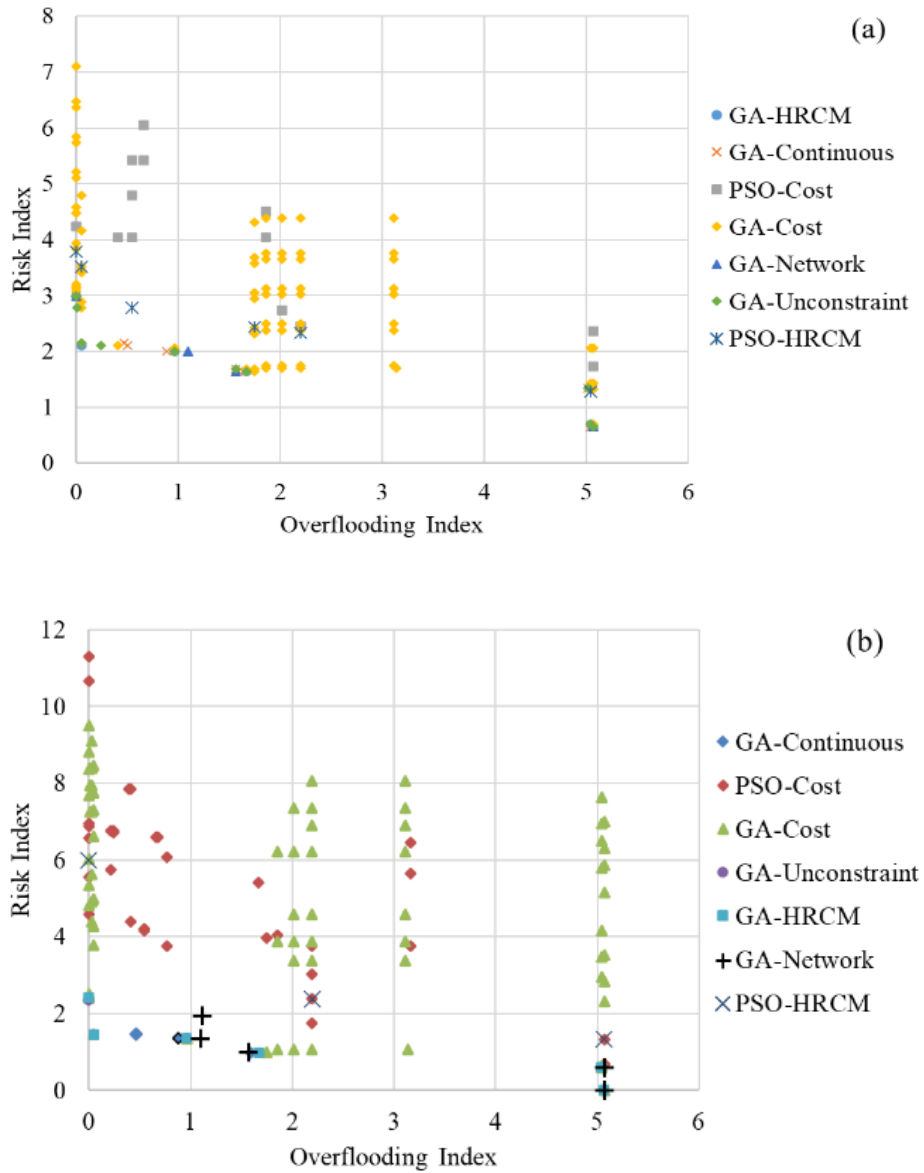


Figure 3. 5 The overflooding index, risk and the cost of all the methods when the population equals 2000. (a) scenario 1 and (b) scenario 2.

Haji Agha Mohammad Zarbaf et al. (2017) compared the PSO method and the GA method for the calculation of cable tension estimate. They found that both methods can evaluate the tensioned cable, but the PSO method was more accurate than the GA method. Surendar et al. (2019) compared the GA and PSO methods in predicting the Brazilian tensile strength. They found that even though the two methods can predict the value, PSO had better performance in fitting the result. Vasudevan and Sinha (2018) showed that the PSO method had better performance than GA in the distribution system. However, in the sewerage system, one study showed that GA methods can give similar results to PSO method (Kumar et al., 2019). In our research, we find the PSO method was not as good as the GA method. The PSO method uses the best values in one generation to guide the algorithm to generate next generation. This will be efficient in searching for an optimum value in a continuous function. However, to rehabilitate drainage systems, there are many parallel solutions. For example, even though the hydraulic performance will be improved when we enlarge the diameter of a pipe, after enlarging the diameter and exceeding a threshold, the results won't be improved. That means in one generation, there will be many optimum values. This will impact the performance of the PSO method in searching for the optimum value.

3.7 Methods Evaluation

3.7.1 Scenario 1 – Narrow pipe

We assessed the results by evaluating the converged population, convergence time, number of the solutions, and the cost-effectiveness at a population of 2000 (Table 3.2). The cost-effectiveness value was calculated by dividing the difference between the original hydraulic/risk index and the new hydraulic/risk index by the cost (million \$) (Table 3.2).

Table 3. 2 The summarized results of the seven methods with scenario 1

Method	Converge population	Converg e Time	2500 Time	2500 Number s	2500	2500 Cost	Hydro ^a	Risk ^b
					Average cost (million \$)	Effectiveness		
GA-HRCM	2000	182334	372035	6	0.67	54.81	31.36	
GA- Continuous	1500	116374	232122	5	0.44	62.65	33.60	
GA-Cost	N/A	N/A	298599	34	0.30	138.26	73.92	
GA-Network	500	36696	229006	4	0.70	43.97	23.82	
GA- Unconstrained	N/A	N/A	84157	8	0.78	47.81	24.64	
PSO-HRCM	N/A	N/A	223591	5	1.03	28.16	13.99	
PSO-Cost	N/A	N/A	268340	13	0.61	45.24	22.18	

^{a.} Hydro is the cost-effectiveness of the overflowing index.

^{b.} Risk is the cost-effectiveness of the breaking index.

After adding the cost as another objective function, the expense on rehabilitation decreased significantly. Compared with the original HRCM method, we found that the GA-Cost method had less chance to select fiberglass reinforcement. That can reduce the cost on unnecessary rehabilitation. The GA-Network method showed a fast convergence speed in this scenario. Results converged when the population equaled to 500.

The slow convergence speed can be attributed to different factors. First, the slow computational speed can be due to the optimization of rehabilitation strategies itself. For example, consider a case in which there is a pipe in a drainage system leading to a surcharge, such as C8 in Fig. 3.3b, and the critical diameter is δ (which is enough to solve the surcharge). When the program assigns diameter values larger than δ , they can get the same results for the overflowing index. That means, even though there are limited points on the Pareto Front, there are many strategies that can get the exact same value on the Pareto Front. Therefore, this seriously affects the convergence speed of optimization. Second, the reason is because of the setting of the model. In our model, we assumed the rehabilitation is a flat time rehabilitation, therefore, we didn't consider the impact of rehabilitation on the following years. The slow convergence speed may be improved after we evaluate the long term impact of rehabilitation.

The GA-Network gave fewer strategies than using the chain route index. The GA-Unconstrained method has the fastest calculation speed for the same population size as the other methods. However, from the framework aspects, there was no convergence when we compared the results at different population sizes. In this research, the word convergence means the results of the number of strategy sets, the overflowing index and the pipe breaking

index in each strategy set don't change with the population size. The parallel solutions may explain this nonconvergence in the framework. That motivated us to study how to evaluate the performance of optimization in rehabilitation problems in the future.

The computational time of the GA-Unconstrained method varies considerably; it has the highest computational speed compared with other methods. It was found that GA-Continuous had a faster convergence speed than the original HRCM method as well. However, the number of results was smaller than the original HRCM method.

3.7.2 Scenario 2 – Ageing pipe

In scenario 2, there is an aged pipe. The results for the second scenario are listed in Table 3.3. The seven methods showed that the GA-Cost method produced the best cost-effective results with the highest value of both hydraulic performance and breaking risk. This is the same as scenario 1. Genetic Algorithm had better performance than the PSO method in this case. The PSO-Cost method was better than the PSO-HRCM method based on cost-effectiveness analysis. That shows that the framework will have better performance when the cost is added as an objective function instead of a constraint.

GA-Unconstrained was not outstanding in this scenario. One possible reason is the property of our case, where only one pipe is in aged condition. From the calculation method of the probability of failure, only if the program detects the aged pipe and reinforces it with a proper strategy, the breaking risk index will be changed. In the risk assessment module, the probability of failure is decided by the age of a pipe. To distinguish the difference between installing a new pipe and reinforcing an existing pipe, we made a scheme in the probability of failure. Estimation of the failure probability of a drainage system is a challenging task. There

are few general equations to predict the probability of failure of a drainage pipe. Some methods such as ordered probit deterioration model, neural network deterioration model (Tran et al., 2009), logistic regression model, and Markov chain models (Malek Mohammadi et al., 2019) are used to predict the deterioration rate in sewerage systems. In our research, for convenience, we assumed that the deterioration of a pipe follows an exponential relationship. This exponential probability density function can be seen in the survival analysis of sewer pipe deterioration (Duchesne et al., 2013). Replacing a pipe can change the age of the deteriorated pipe to 0. However, according to the cost of rehabilitation strategies' table in Altarabsheh et al. (2018), reinforcing a pipe by fiberglass is cheaper than replacing it with a new pipe. Then, the program will always select to replace a pipe instead of reinforcing it, even though reinforcing a pipe can make it serve longer than replacing it. Kleiner and Rajani (2001) mentioned that there is a burn-in place in the probability of failure curve, which means there is a high breaking risk after installing a new pipe due to some problems during installation. That can happen in a drainage system, too. Therefore, we assumed an installation breaking risk for replacing a pipe. We also assumed if the number of operational years of reinforcement are longer than the current age of the pipe, the breaking risk is 0. That method solves the dilemma of whether to replace or reinforce a pipe.

Table 3. 3 The summarized results of seven methods with scenario 2

Method	Convergence	Convergence Time	2500 Time	2500 Number	Average cost (million\$)	2500 Cost Effectiveness	
						Hydro ^a	Risk ^b
GA-HRCM	N/A	N/A	163519	6	0.65	4.46	40.77
GA-Continuous	1500	232415	222536	6	0.67	3.64	39.66
GA-Cost	N/A	N/A	277206	40	0.24	13.92	129.50
GA-Network	N/A	N/A	196281	6	0.66	3.69	41.07
GA-Unconstrained	2000	86322	406361	6	0.73	4.40	36.62
PSO-HRCM	N/A	N/A	219888	5	1.00	3.30	19.87
PSO-Cost	N/A	N/A	309305	33	0.63	4.29	27.17

^{a.} Hydro is the cost-effectiveness of the overflowing index.

^{b.} Risk is the cost-effectiveness of the breaking index.

3.8 Revised-HRCM (RHRCM)

3.8.1 Introduction of the RHRCM model

In previous sections, seven methods were applied to the HRCM model to verify how the seven calculation methods can affect the framework. The seven alternative frameworks can affect the rehabilitation results by cost and computational time, but all the methods obtain similar overflowing and pipe breaking indexes. In this section, we combined the advantage of the seven calculation methods in our previous research to improve the calculation speed and cost-effectiveness. The revised framework is presented in Figure. 6. In this new framework, we simplified the three-element framework as: (1) optimization; (2) linkage; (3) postprocessing. The new framework removes constraint functions and adds cost as another objective function. And it removes the hydraulic diagnostic model and integers to represent each pipe diameter. Distinguished from other studies that used optimization directly without improving the structure of optimization, we first propose to study the optimization condition in each step for drainage optimization. This framework can be applied to other pipe systems and solve similar problems. The method with fastest convergence (GA-Continuous) was selected to improve the convergence speed. The GA-Network method was selected to enhance the performance of the HRCM model on the network drainage system and improve the efficiency. Besides, GA-Continuous method and the GA-Network method can give fewer strategies than the original HRCM method. In order to compensate for the weakness of the original HRCM in efficient budget distribution to rehabilitate each pipe, we selected the GA-Cost method to increase the accuracy of the framework.

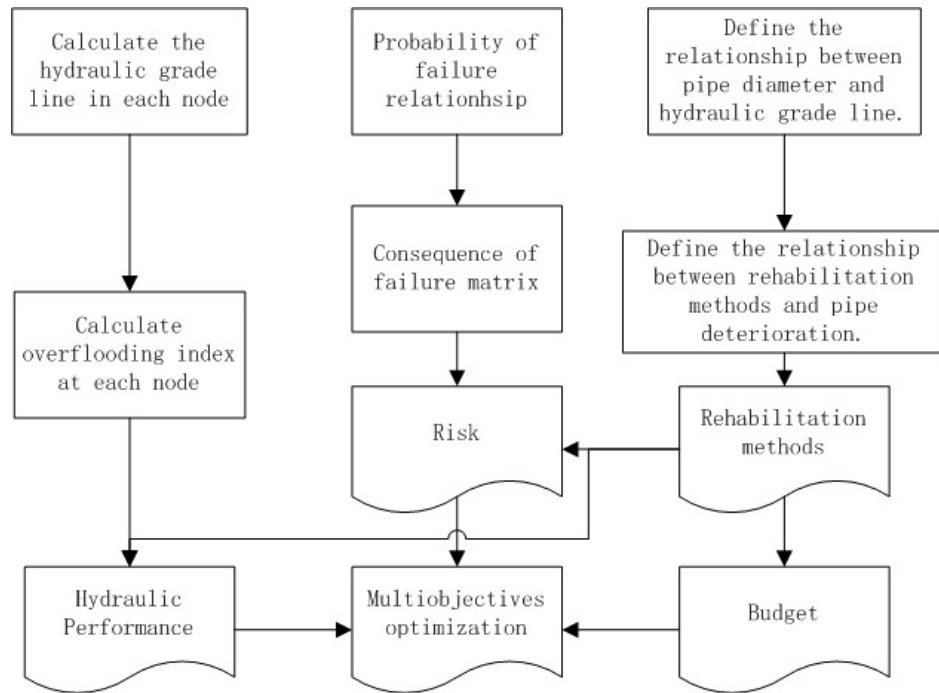


Figure 3. 6 Diagram of the revised framework (RHRCM).

3.8.2 The computational time comparison between the revised HRCM (RHRCM) and other methods

The computational time comparison between the RHRCM method and the other seven modified methods is presented in Fig. 7. The RHRCM method exhibited the fastest speed compared with the other seven methods, and it was stable with respect to the increase in population in scenario 1. This property can also be seen from the computational time comparison of scenario 2. The RHRCM was relatively stable compared with the GA-Unconstrained because it did not have a significant jump point when the population size equaled to 2000. The RHRCM method showed a significant advantage than HRCM model.

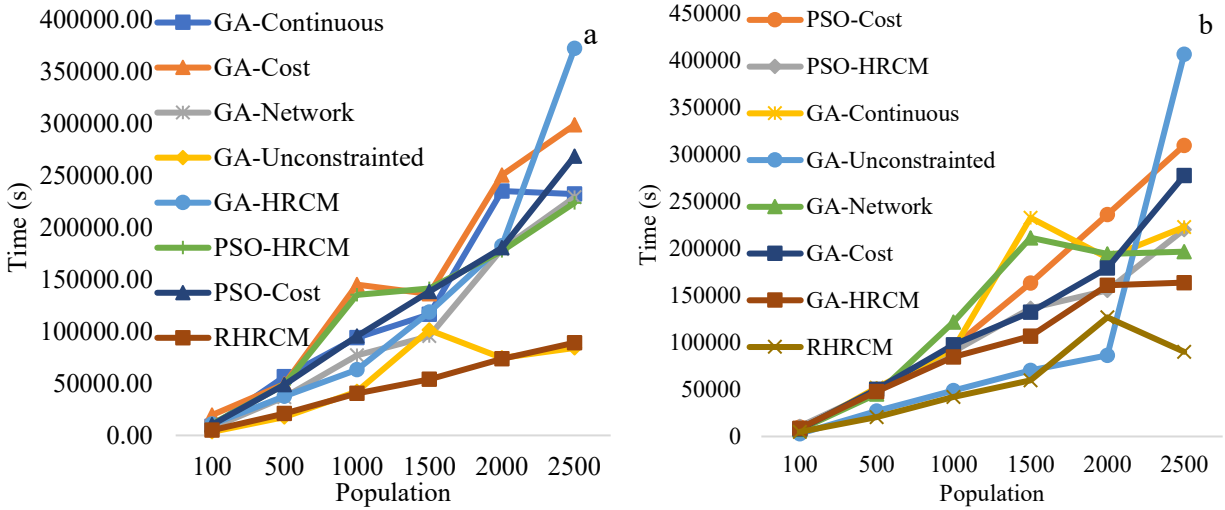


Figure 3. 7 Time competition of different methods for various population sizes: (a) scenario 1 and (b) scenario 2.

3.8.3 Cost-effectiveness of the RHRCM method

The cost-effectiveness of the RHRCM method is reported in Table 4. The evaluation results demonstrated that the RHRCM method can combine the strengths of previous frameworks. First, the cost-effectiveness value was increased dramatically. The RHRCM method gave the highest cost-effectiveness value. Even though there was slow convergence, we found the obtained strategies were good enough to solve the overflowing problem and the pipe breaking risk problem at a small population size. Besides, the number of strategies obtained with RHRCM was acceptable. It demonstrated to be a balance between the GA Cost method and other methods. The evaluation results showed that the RHRCM method has significantly faster computational speed and leads to results with higher cost-effectiveness than other methods.

Table 3. 4 The evaluation results of the RHRCM method

Method	Convergence	Convergence Time	2500 Time	2500 Numbers	Average cost (million)	2500 Cost Effectiveness	
						Hydro ^a	Risk ^b
Scenario 1	N/A	N/A	89182	10	0.30	177.29	87.82
Scenario 2	N/A	N/A	89863	30	0.26	11.70	137.31

^{a.} Hydro is the cost-effectiveness of the overflowing index.

^{b.} Risk is the cost-effectiveness of the breaking index.

3.9 Discussion

3.9.1 Advantage and limitation of RHRCM method

The refined HRCM model is faster because of removing the unnecessary parts in the original HRCM model. We also acquire higher cost-effectiveness by adding cost as another objective function, as it can remove the parallel solutions.

We believe there is a convergence of optimum value in an optimum question because the Pareto Front is the set of optimum values. However, are there optimum strategies in a rehabilitation problem? The answer is no. The reason is that the two types of situations can cause the same value on the Pareto Front with different strategies. First, if there are two pipes

which have the same breaking risk and hydraulic performance in this network, one will get the same result when replacing the first pipe or the second pipe. That means one will have two solutions which can get the same result on the Pareto Front and both of these solutions are the optimum solutions. The second type is that if one can replace a pipe to a diameter of 0.305 m to 1 m, it may solve the surcharge problem; however when one changes the diameter to 2 m, it can get the same surcharge index at that junction. That means every pipe has a threshold; when the diameter of the pipe goes beyond that threshold, all of the rehabilitation strategies are the same in the optimization program. In the HRCM model, we used a postprocessing strategy to select solutions from the set of rehabilitation plans. In the RHRCM model, the new dimension (cost) can help to partly solve parallel results problem because different diameters have different costs. That can improve the performance of an optimization method. But, this method doesn't increase the searching speed on hydraulic performance and breaking risk. How to solve the parallel solution problem and increase the searching speed can be a topic for future study.

3.9.2 Discrete versus continuous data

In engineering, some parameters are not continuous. For example, the diameter of the pipe in a real case should be a discrete value, based on manufacturing standards. Therefore, although, the mixed-integer optimization method is widely used in many engineering problems, there should be a discussion that whether mixed-integer is always better than continuous optimization. In our research, we found the GA-Continuous has a faster convergence speed in scenario 1 than GA-HRCM. However, GA-Continuous is slower than GA-HRCM in scenario 2. We found both continuous and discrete methods can solve the problem well. Therefore, mixed-integer optimization is not always better than continuous

optimization. In the context of optimization algorithms, the continuous optimization method can have a higher sensitivity to the variables which are changed continuously, and they don't have the process to transform a continuous number to an integer. However, it may be easy to get the local optimum value. So, it is a competition between these two situations, and we should adjust it according to different situations.

3.9.3 Parallel computing and other potential parameters which can be included

We found that when we add the cost into our framework our program can have better results. That provided the initial idea to solve the parallel solution problem. We can add more parameters to this system. The GA-Unconstraint and RHRCM show that there is no significant difference in the calculation speed when we have two or three objective functions. The GA-Cost and GA-HRCM showed that the case of three objective functions needs more time for calculation. That means when we remove the constraint function, the calculation time won't increase significantly even though we add more objective functions. Therefore, we can add more parameters to this framework to make it more resistant to the parallel solutions. Besides, we believe, this framework can have a higher calculation speed when we use parallel computing.

In this study, we use the GA and PSO methods because they are the most widely used methods in engineering. Many kinds of optimization algorithms, such as ant colony optimization algorithm (Afshar, 2010), random forest (Hosseini and Ghasemi, 2012), cellular automata (Afshar et al., 2011), hanging gardens algorithm (Bakhshipour et al., 2019), and whale optimization (Mirjalili and Lewis, 2016) should be tested in the future to see whether they are more suitable for this framework.

3.9.4 Framework

Distinguishing our research from other studies, and improving the performance of an optimization model by using different optimization methods, we studied whether the simplified calculation framework can improve the performance. In our research, we found that by our new framework, the calculation speed and the cost-effectiveness of the HRCM model have been improved significantly. That emphasizes the importance of studying how to improve the calculation methodology of an optimization question. A multi-objective optimization model is a complex system, because it has complex calculation structure and involves many modules to solve one question. Therefore, current optimization methods should be simplified to achieve higher performance. However, to the best knowledge of authors previous research did not study simplifying the framework structure to improve calculation performance. The research on framework structure thus needs to be paid more attention.

3.10 Conclusion

How to develop rehabilitation strategies in order to obtain maximum benefit for solving urban flooding and reducing pipe breaking risk at the same time, is an important question in urban drainage systems. In this paper, seven potential frameworks were compared. The results showed that the calculation speed and accuracy were improved when continuous variables were used, and the constraint functions are removed. A post-processing filter was added at the end to transform pipe diameter to discrete value and remove the unsatisfying strategies which give high overflowing index or breaking risk index. Multi-objective optimization was found to be adequate in finding the solution. Furthermore, the calculation accuracy can increase when the cost is selected as an objective function. We also found that the GA algorithm had a better performance than PSO method in drainage optimization problems. Simulation results

showed those methods can significantly improve the decision support system for drainage rehabilitation. A new method was proposed (RHRCM) which exhibited remarkably higher computational speed and was able to find results with higher cost-effectiveness than other methods. We found that a simplified framework can significantly improve the calculation performance of the original model; therefore further research should put more effort into the framework study.

Chapter 4 Phenotype Searching Method - A Novel Method to Solve Drainage Rehabilitation

Abstract

In a multi-objective optimization it is hard to find the optimum value in a complex system because multiple solutions can have the same results on the Pareto Front, which is denoted as parallel results problem in this study. The parallel results issue can adversely affect the optimization efficiency. In order to address this issue we propose a novel optimization method: Phenotype Searching method (PSM). This method simulates a selection process in nature, where the selection acts on phenotypes. Drainage systems are a kind of complex system, and they are prone to the parallel results problem in finding optimal rehabilitation strategies. In a drainage rehabilitation problem, the phenotype can be analogized to the sensitivity when changing each pipe to the improvement of system performance. This method can be integrated with some optimization methods to overcome the parallel results problem. To illustrate this process, we integrate the PSM method with the genetic algorithm (GA) and particle swarm optimization (PSO) to develop the Pheno-genetic algorithm optimization (Pheno-GA), Self-Learning Phenotype Searching -Particle Swarm Optimization (SLPheno-PSO), and Boundary Searching Pheno-particle swarm optimization (BPheno-PSO) methods. We apply the proposed novel methods to case studies in the drainage system rehabilitation problem to evaluate the performance of the PSM method. The results showed that the PSM method can improve the performance of the GA and PSO methods to overcome the parallel results problems.

Keywords: Phenotype Searching Method; Parallel Results Problem; Drainage System; Rehabilitation; HRCM

4.1 Introduction

Optimization methods have been widely used in solving pipe system rehabilitation (Dridi et al., 2009; Roshani and Fillion, 2015). There are four major types of optimization methods: evolutionary algorithms, physics-based algorithms, swarm-based algorithms and human-based algorithms (Mirjalili and Lewis, 2016). The optimization of sewer systems began with linear programming in the last century (Gotsis et al., 2011), and developed into nonlinear programming in recent years (Rep et al., 2008). The difference between these two methods is whether the constraint function and the objective function are linear or non-linear. After that, dynamic programming and differential dynamic programming (Li and Matthew, 1990; Rashid and Hayes, 2011) have been used to solve the pipe network design problem. These two methods improved the previous methods by dividing one optimization problem into several sections and solving them together.

In this century, with the development of computers, heuristic optimization has become popular. Many kinds of optimization algorithms, such as ant colony optimization algorithm (Afshar, 2010), random forest (Hosseini and Ghasemi, 2012), genetic algorithm (GA) (Afshar et al., 2006), cellular automata (Afshar et al., 2011), hanging gardens algorithm (Bakhshipour et al., 2019), and particle swarm method (PSO) (Vasudevan and Sinha, 2018) have become popular in pipe system design. They have been used to assisting the parameters setting of a single pipe, such as the slope or diameter of a pipe (Shao et al., 2017); it can modify the structure of a pipe system as well (Haghighi, 2013). Besides, some research combined heuristic optimization with

numerical modelling (Rao et al., 2017) or fuzzy sets to improve model performance (calculation speed/uncertainty prediction) (Sabzkouhi and Haghghi, 2016).

A drainage system is a kind of complex system which has specific characteristics. Yazdi et al. (2017a) compared three optimization methods: the non-dominated sorting genetic algorithm-II (NSGA-II), the multi-objective particle swarm optimization algorithm (MOPSO) and the non-dominated sorting harmony search algorithm (NSHS) in solving the rehabilitation problems of a sewer pipe system. They found that NSHS was superior among these three methods. In addition, the performance of NSGA-II was better than MOPSO in the sewerage system. Their results were the same as the results of Cai et al. (unpublished, 2020 a and 2020 b). However, these results were different from other research, which studies other problems outside a complex system (Surendar et al., 2019; Vasudevan and Sinha, 2018).

One of the reasons for that discrepancy is the parallel results issue. The parallel results problem is that multiple multi-objective solutions have the same values on the Pareto Front, and that means there is no global optimum solution in the complex system. For example, when we want to enhance the performance of a drainage system (system hydraulic performance index) by replacing the narrow pipe to an appropriate pipe, the index will not change when the diameter of the new pipe is larger than a threshold. Therefore, the multi-objective optimization will preserve all the solutions which can solve the overflowing, indiscriminately. This problem is obvious in a non-dominated sorting optimization because each objective function is optimized, separately (Cai et al., 2020b in review).

This research is distinctive in that it offers a novel method to improve the performance of an optimization method to solve a problem under a parallel results scheme. We got the idea through

eco-evolutionary dynamics research, where the selections are assumed, including the sexual selection and natural selection, and applied to phenotypes. Distinguishing this method from GA method is that the GA method selects the solutions based on the objective function, but the Phenotype Searching method selects the solutions based on the sensitivity of each variable to the objective function. Besides, it can be understood as an enhanced searching module and can be added to other optimization methods to increase their performance in detecting problematic pipes in the sewer system. The structure of this paper is as follows. First, we introduce the model we used-the Hydraulics and Risk Combined Model (HRCM) to build our questions on drainage system rehabilitation. Second, the concept of the phenotype searching method is present. Third, few examples of how to combine optimization algorithms with the phenotype searching method are introduced. Fourth, case studies were applied to a drainage system to validate the performance of the phenotype searching method against the one which did not apply.

4.2 Hydraulic and Risk combined Model (HRCM)

The urban drainage system can impact the resilience of a city (Vasiljevic et al., 2012). A good drainage system can considerably relieve the stress of flooding caused by storm and extreme weather (Adamowski et al., 2010; Buttle and Lafleur, 2007). However, reports showed that some drainage systems are not in good condition (CIRC, 2019; Yazdi et al., 2017a). The overflowing stress can even become severe when cities are using combined sewerage systems that use the same systems for both sanitary sweage and stormwater (Huang et al., 2018; Jegatheesan, 2019). Because sewer water contains many toxic components such as heavy metals (Lee and Bang, 2000), pharmaceutical personal care products (Ellis, 2006) and pathogens (Girones et al., 2010); overflowing due to intense storms can threaten human health.

In this paper, the performance of the PSM is validated using the HRCM model in a drainage system. The HRCM model combines the hydraulic performance and pipe breaking risk in a drainage system to provide rehabilitation strategies. It is a multi-objective model and has parallel results problem. We used two internal optimization configuration methods in the HRCM, revised HRCM and PSO-Cost (see Supplemental Materials 3) to compare with the PSM modified optimization methods.

4.3 Phenotype Searching Method

4.3.1 Introduction to the phenotype searching method

The parallel results problem is relevant to the strategy optimization, and it happens when multiple strategies have the same performance in a complex system. In a drainage system with a narrow pipe or a deteriorated pipe, the parallel results issue occurs when the optimal rehabilitation strategies are sought. When the diameter of the new pipe is small or exceeds a threshold, the system hydraulic performance will not be affected. And when the benefit year of a reinforcement method longer than the deteriorated year, the rehabilitation methodology cannot distinguish different rehabilitation methods. The parallel results problem can be relieved when the cost is implemented in the rehabilitation framework; however, this approach does not directly optimize the hydraulic performance or pipe deterioration, so it is less efficient.

Enlightened by the natural and sexual selection of guppies (Blondel et al., 2019; Dargent et al., 2019; Labonne and Hendry, 2010), a new optimization was created in the current research. Natural selection or sexual selection usually happens when the phenotype cannot adapt to the environment or attract a partner. In most evolutionary algorithms, the new generation is selected

by calculating the objective functions, which simulate this natural selection. However, those algorithms ignore sexual selection in the mating process. Contradictory to the natural selection, which is the objective function in an optimization, sexual selection is the selection of each phenotype. In a drainage system, the phenotype is the hydraulic or aged situation of each pipe and the contribution (hydraulic or aging) of the pipe to the drainage system. Sexual selection is the preference for the optimization of each pipe. By adding the sexual selection on phenotype, it can guide heuristic methods to converge and find practical optimal solutions.

4.3.2 Modified optimization methods based on phenotype searching method

There are many optimization methods used to solve drainage related problems. Two methods have stood out among those methods in drainage system design: (i) the GA method and (ii) the PSO method. Research has shown that multi-objective evolutionary algorithms can quickly solve the multi-objective problem; for example, they can assist in urban drainage network design (Lin et al., 2016; Shao et al., 2017; Yazdi et al., 2017b), replacement, and rehabilitation (Ogidan and Giacomoni, 2016; Risch et al., 2015; Selvakumar et al., 2015; Yazdi et al., 2017a). Barreto et al. (2010) found that NSGA-II exhibited better performance in a small-scale system, but performance decreased when the system became larger. However, the epsilon multi-objective evolutionary algorithm was not sensitive to the scale of the system. The GA method and PSO method can optimize the drainage system for design and rehabilitation (Cai et al. 2020a, 2020b), but it is not efficient to search at a parallel results situation. In this study, we used the novel phenotype searching method to modify the GA and PSO methods and applied these modified methods to the Hydraulic and Risk Combined Model (HRCM) to validate the performance of this new method. The HRCM model (Cai et al. 2020 in review) is a rehabilitation decision

support model that can provide rehabilitation strategies to solve overflowing and pipe breaking problems in drainage systems (Supplemental Materials 3).

4.3.3 Pheno-GA method

The GA method randomly creates a series of variables to represent an individual. GA will calculate the objective function of each individual and rank the individual based on the value of the objective function. Then, computer will select the parents' series via the specific method and let the exchange part of their series calculate the result based on the new series. Finally, this algorithm will remove the individual with lower fitness. The GA method begets the next generation by crossing the parents' gene series (variables series), but it uses the objective function to decide the mating process.

The PSM method can enhance the searching capability of GA by adding an enhanced searching matrix for each variable. The pre-defined matrix can decrease the complexity to search for the optimum results in a complex system. A new structure for the GA method can be built by adding the PSM method to the original GA method. For drainage problems, the sensitivity matrix was calculated first by changing the diameter of each pipe to the maximum diameter, and calculating the variation of hydraulic performance. The same procedure was applied to the age of the pipe. The variation was stored in a matrix and this matrix was normalized. The mutation processes are changed in the GA method. The mutation will happen according to the value of the sensitivity matrix (sexual selection matrix). The details of the calculation method can be seen in Fig. 4.1.

```

Calculate initial overflowing index ( $N_{global}$ ) and pipe breaking risk index
( $R_{global}$ ).
for each variable
  if pipe diameter variable
    replace the variable to the largest diameter
  else
    replace the variable to the most beneficial rehabilitation method
  end
  calculate rehabilitated overflowing index ( $r_{N_{global}}$ ) and pipe breaking risk
  index ( $r_{R_{global}}$ ).
  if pipe diameter variable
    calculate the weight index  $N_{global} - r_{N_{global}}$ 
  else
    calculate the weight index  $R_{global} - r_{R_{global}}$ 
  end
normalize weight index
mating matrix = normalized weight matrix
change the mutation rate in GA method to the mating matrix
run HRCM

```

Figure 4. 1 The calculation processes of Pheno-GA method

4.3.4 Self-Learning Pheno-Particle Swarm Optimization (SLPheno-PSO)

The PSO method searches the optimum value by generating points first. It searches the optimum global value by comparing the optimum local value and the temporary optimum global value to guide the swarm of particles to converge to the optimum global value. The same idea can also be applied to the PSO method, and the PSM method can combine with a self-learning process to simulate the feedback or to simulate the teaching process from parents to children. To simulate sexual selection or natural selection of a phenotype, we used the mating matrix to represent the possibility that the individual will move in that direction. This matrix multiplied the original velocity vector to obtain the final position of an individual. By adding the learning processes of SLPheno-PSO, the mating matrix is recalculated according to the value calculated in each generation. The value in the mating matrix will be amplified if the drainage performance

had been improved. If the new generation did not improve the drainage performance, the value in the mating matrix will be decreased. Fig. 4.2 presents the calculation processes of the SLPheno-PSO method.

To distinguish our SLPheno-PSO method from some non-standard PSO methods, such as the δ -PSO method (Ivić et al., 2017), which gave a variable δ added to the position of a swarm linearly, the characteristic of the gene flow algorithm is that it changes the mating possibility of an individual.

```

Calculate initial overflowing index ( $N_{global}$ ) and pipe breaking risk index ( $R_{global}$ ).
for each variable
  if the variable is pipe diameter variable
    replace the variable to the largest diameter
  else
    replace the variable to the most beneficial rehabilitation method
  end

calculate rehabilitated overflowing index ( $r_{N_{global}}$ ) and pipe breaking risk index
( $r_{R_{global}}$ ).

if the variable is pipe diameter variable
  calculate the weight index  $N_{global} - r_{N_{global}}$ 
else
  calculate the weight index  $R_{global} - r_{R_{global}}$ 
end

normalize weight index
mating matrix = normalized weight matrix
change the PSO velocity = position + velocity .* (mating matrix)
run HRCM model
for each iteration, change the matring matrix after after each iteration according to
whether the hydraulic performance and pipe breaking risk have been modified.
if all the index has been modified
  change the mating matrix to mating matrix = mating matrix .*exp(abs(mating
matrix));
  normalize the mating matrix
else
  mating matrix = [mating matrix./ exp(mating matrix)]
  normalize the mating matrix
end

```

Figure 4. 2 The calculation processes of SLPheno-PSO method

4.3.5 Boundary Searching Phenotype-PSO (BPheno-PSO)

In the SLPheno-PSO method, the mating matrix will be changed according to the calculation results, but there is another possibility to improve the optimization performance. Another phenotype searching method to solve the parallel results problem is the boundary searching phenotype-PSO method. Because we want to get the rehabilitation strategies within the threshold, in contrast to the method searching for the global optimum values, we want to get the rehabilitation strategies that can remove all the strategies outside the threshold. Therefore, we can apply a small searching distance at first and increase the searching distance in each iteration step. We can apply the equal searching weight number to each pipe at the beginning, and then enhance the searching to pipe according to the generated mating matrix. The non-dominant method will replace the global best value if the new value is better than the previous value; therefore, the final results will still keep previous results, even though we still enlarge the pipe diameter or the reinforcing solutions. The program will automatically remove the parallel results in this way (Fig. 4.3).

Calculate initial overflowing index (N_{global}) and pipe breaking risk index (R_{global}).
for each variable

if the variable is pipe diameter variable
 replace the variable to the largest diameter
else
 replace the variable to the most beneficial rehabilitation method
end

calculate rehabilitated overflowing index ($r_{N_{global}}$) and pipe breaking risk index ($r_{R_{global}}$).

if the variable is pipe diameter variable
calculate the weight index $N_{global} - r_{N_{global}}$
 else
 calculate the weight index $R_{global} - r_{R_{global}}$
end

normalize weight index
mating matrix = normalized weight matrix
change the PSO velocity = position + velocity .* (mating matrix)
run HRCM model
for each iteration, change the mating matrix after after each iteration according to the original mating matrix.
 change the mating matrix to mating matrix = mating matrix .*exp(abs(mating matrix));
 normalize the mating matrix
end

Figure 4. 3 The algorithm of the Boundary Searching Pheno-PSO method.

4.4 Case Study

We used two scenarios (Table 4.1), the narrow pipe scenario and the aged pipe scenario, to test these optimization methods. These two scenarios were used to evaluate whether the calculation method can detect the narrow pipe and aged pipe, and replace the pipe using a fast and cost-effective method.

Table 4. 1 The simulation scenarios

Classification	Scenario	Case description	Function
Hydraulic	1	A system with a very narrow pipe.	In this simulation, it tested whether this method can detect the narrow pipe.
Ageing risk	2	A system with a highly aged pipe.	In this scenario, it tested whether the method can detect the aged pipe.

These two scenarios have the same drainage structure but vary with different pipe diameter and age. The drainage structure comes from Bennis et al. (2003). The first scenario has one extremely narrow pipe which should be replaced to solve the surcharge (to the ground) problem. Besides, there are two pipes in the system, which are lightly narrow and can cause slight overflowing. These two kinds of overflowing validate the performance of different methods to give satisfying strategies. The age of pipes are zero in this scenario (Fig. 4.4).

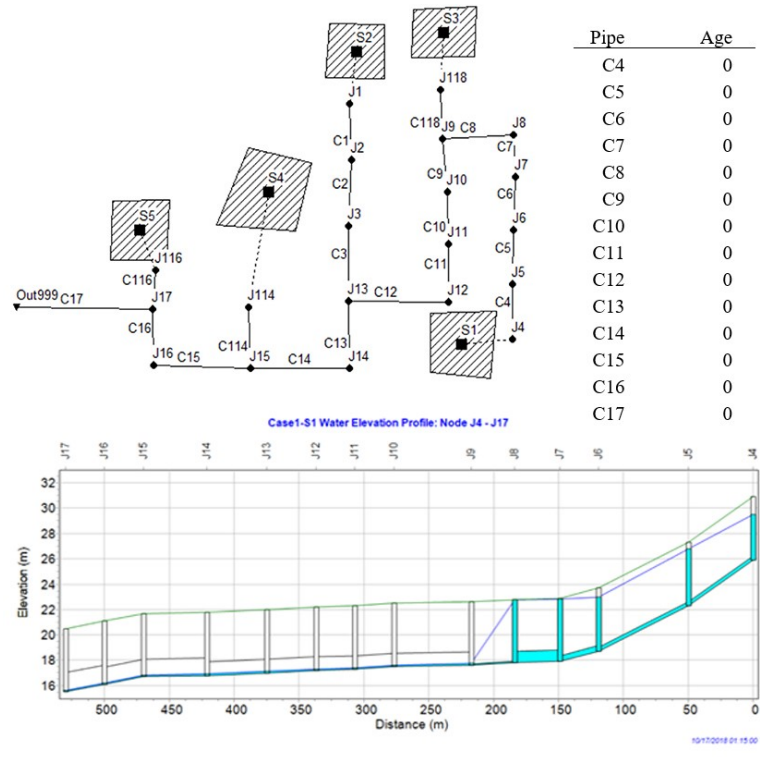


Figure 4. 4The configuration of scenario 1: the drainage structure, age of pipes and the cross profile of pipes.

The second scenario is used to test whether the method can find the aged pipe. One pipe C9 is significantly deteriorated. There are two light narrow pipes in this scenario, which can be seen from the hydraulic grade line in Fig. 4.5.

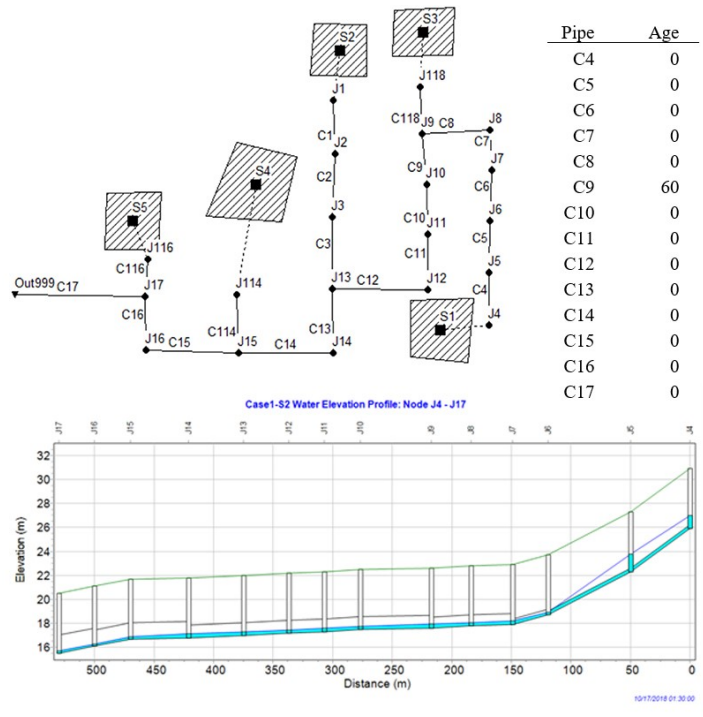


Figure 4. 5 The configuration of scenario 2: the drainage structure, age of pipes and the cross profile of pipes.

The sensitivity analyses were applied under the population size equal to 100, 500, 1000, 1500, 2000 and 2500. The time competition and the cost-benefit analysis were used to evaluate the Phenotype searching method. The results were calculated with an Intel® Core™ i7-8750H CPU @2.20GHz, 16.0 GB (RAM).

4.5 Results

4.5.1 Time competition and rehabilitation results

The time competition is to test the calculation speed of these five methods. The results indicate that except for the PSO-Cost method, other methods are competitive in terms of the calculation speed. From the research of Cai et al. (2020 b), the RHRCM method is the

recommended method in the HRCM model because it is fast and effective. We found the BPSM-PSO has a higher calculation speed than the RHRCM method in both scenarios (Fig. 4.6).

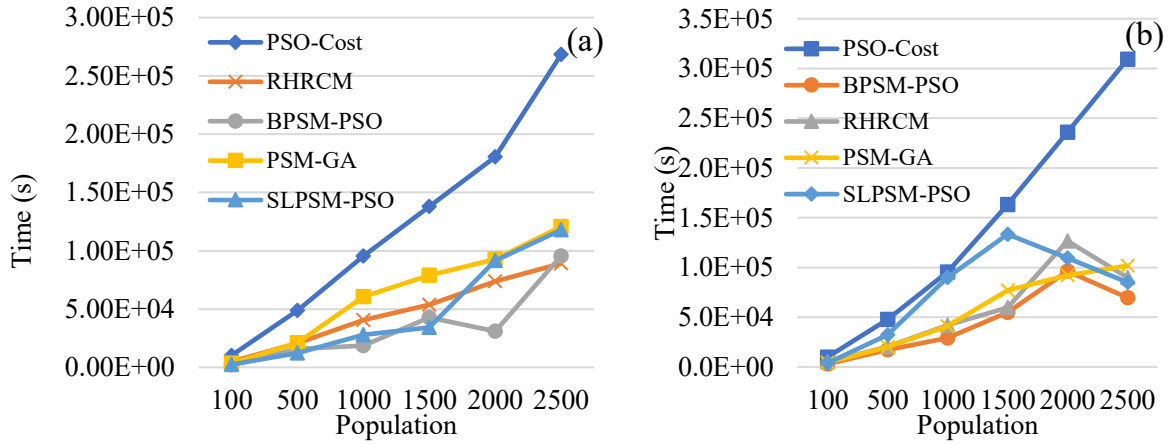


Figure 4. 6 Time competition of the five methods for (a) Scenario 1, and (b) Scenario 2.

The original system overflowing index and system breaking index for scenario one are 29.72 and 16.24; the indexes for scenario two are 5.07 and 22.68, respectively. After applying the decision support system, the rehabilitation strategies of these five methods can decrease the overflowing index of scenario one to 5.07, which means there is not an overflowing (to the ground) in that drainage system. After applying this model, the five methods gave rehabilitation strategies that decreased the pipe breaking risk (Fig. 4.7).

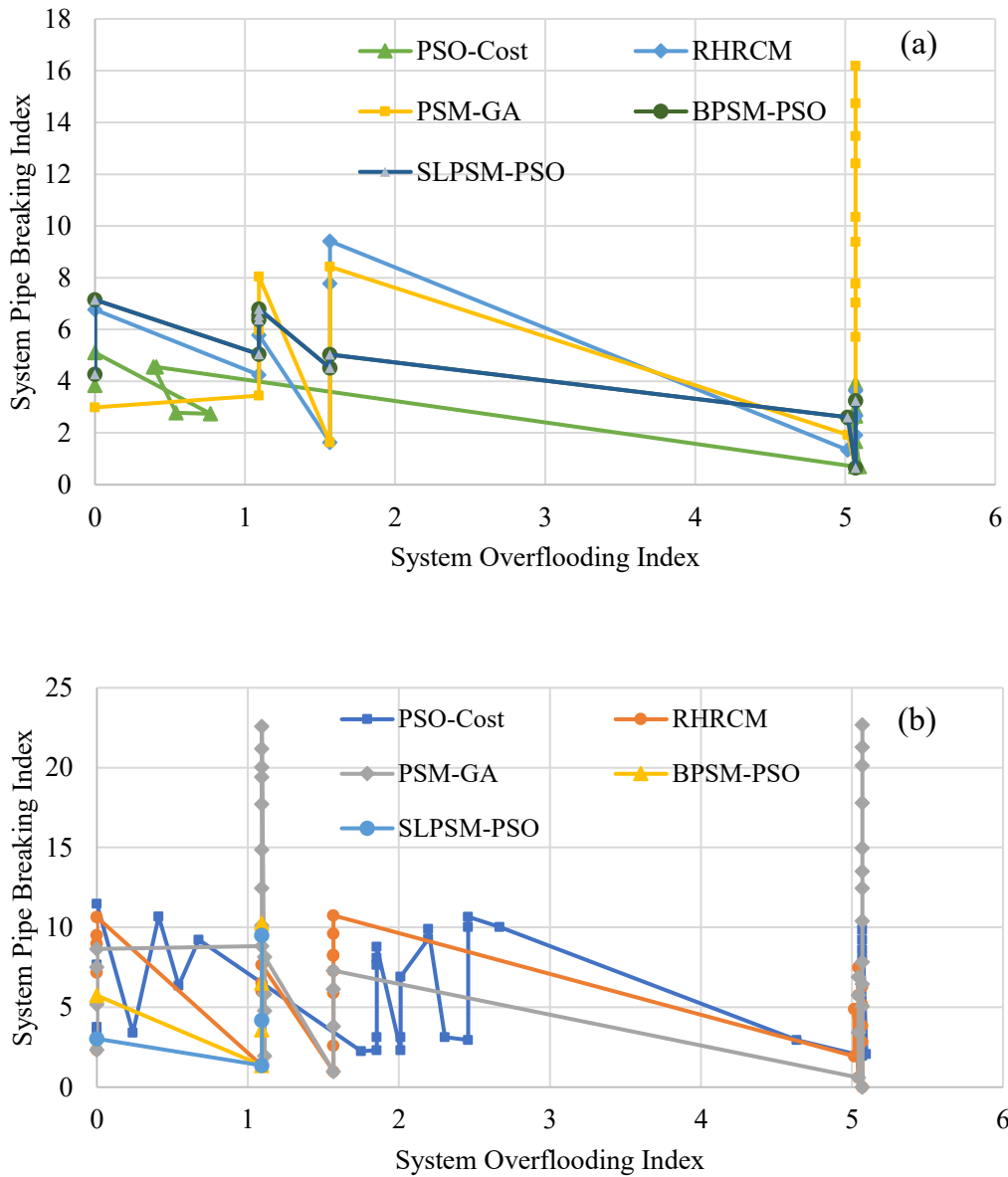


Figure 4. 7 System pipe breaking index against system overflooding index of each method at population size equals to 2500 for (a) Scenario 1, and (b) Scenario 2.

In scenario one, the PSM-GA method and PSO-Cost method have the advantages to find the better Pareto Front. However, both methods find the optimum solutions to solve the overflooding and pipe breaking problem. The significant difference between those methods is the number of solutions. PSM-GA method can find more solutions than the RHRCM method, which used the

GA method as well. That means the PSM-GA method can improve the searching performance of the GA method. In scenario two, the PSM-GA method and SLPSM-PSO have the advantages to find the better Pareto Front. The PSO-GA method is the best method in this scenario. We found that the modified PSO methods (SLPSM-PSO and BPSM-PSO) have a faster calculation speed, but they only provide few solutions compared with the PSO-Cost method. Two modified PSO methods can quickly provide highly efficient results by only providing the strategies which can decrease the two indexes as much as possible. The SLPSM-PSO has fewer and better solutions than the BPSM-PSO method, but it spends more time to calculate the results.

4.5.2 Cost-Effectiveness Analysis

The cost-effectiveness analysis can evaluate the rehabilitation effectiveness at a unit cost. We define this index as the average value of the index (overflowing or pipe breaking) difference before and after rehabilitation divided by the cost (Rep et al., 2008).

The modified GA method significantly improved the cost-effectiveness of the HRCM method in scenario one; however, it did not show that advantage in scenario two. The modified PSO methods improved the PSO-Cost in scenario two but did not in scenario one. These differences show the different capacities of these two methods. The cost-effectiveness shows even the modified PSO methods can improve the performance of the PSO method in the drainage rehabilitation problem, but the GA method still has a better performance than the PSO method.

Table 4. 2 Cost-effectiveness results of each method

Scenario	Index	PSO-Cost	RHRC M	PSM-GA	BPSM-PSO	SLPSM-PSO
Scenario 1	System overflowing index	45.24	177.29	$\frac{263.4}{5}$	50.64	49.76

	System pipe breaking index	22.18	87.82	94.63	21.98	21.43
Scenario 2	System overflowing index	4.29	11.70	11.48	8.23	8.45
	System pipe breaking index	27.17	137.31	112.9 8	33.81	35.97

4.6 Discussion

In this study, we presented a new framework that can apply to an optimization method to enhance its ability to find the optimum solution in parallel results situations. There are three modified optimization methods by the phenotype searching method: (1) the Pheno-GA method: this method changes the mutation rate of each pipe according to the effectiveness of changing the pipe to the drainage system; (2) the SLPheno-PSO method: this method has a self-learning process. It will change the mating matrix in every iteration to adjust the optimization; (3) the BPheno-PSO method: this method enlarges the searching space in each iteration. That is different from other optimization methods which narrow the searching space in each iteration.

In scenario 1, it is shown that the Pheno-GA method has better performance in terms of cost-effectiveness compared to the optimization method used in the HRCM model. In our model, we first generate the mating matrix, and when a pipe has a high mating matrix value (a high sensitivity to impact the performance of the system) to cause the overflowing, the model will force the program to replace the narrow pipe with a new pipe. But we did not set criteria to assign a reinforcement method which has a higher rehabilitation performance to the severe deteriorated pipe. That explained why the PSM-GA did not increase the cost-effectiveness of RHRCM at the second scenario.

In PSM-PSO based methods, even though PSM-PSO methods have the same criteria to force pipe replacing, but there was feedbacks in each iteration. That can lead to the different outcomes. We found even though PSO-based method did not have a better cost-effectiveness than GA based method, but the PSM-PSO-based methods can significantly increase the cost-effectiveness of PSO method in both scenarios. Two PSO methods, the BPheno-PSO and SLPheno-PSO method are equivalent, but the SLPheno-PSO method has a better performance to search for the results. We found a possibility to use this Phenotype Searching Method to enhance the optimization method. It is an easy and flexible method, but more studies need to be applied to identify the best compound model and how to select different modified methods.

4.7 Conclusion

In this research, we presented the concept of a new method to improve the optimization performance in drainage rehabilitation problems, and we named that method the phenotype searching method. The idea is based on natural selection and sexual selection in nature. Upon the objective function in the optimization method, we added a new pre-defined criteria matrix to each pipe. This matrix can affect the optimization process and change the performance of exist optimization methods. This study provides three phenotype searching modified optimization methods- Pheno-GA, SLPheno-PSO and BPheno-PSO. Those three methods show the possibility to use the concept of phenotype searching method to improve the current widely used optimization method to improve the optimum results further. We applied those three modified methods and compared them with the PSO and GA method in the Hydraulic and Risk Combined Model (HRCM) to solve drainage overflowing and deteriorated problems by case studies. The results show that the modified method can further improve some characteristics of original optimization methods. The Pheno-GA method has better performance than the GA method at the

narrow pipe scenario; and the SLPheno-PSO method and BPheno-PSO method have better performance than the PSO method in scenario two. The SLPheno-PSO method has better performance than the BPheno-PSO method. The Pheno-GA and GA methods have better performance than PSO related methods.

Chapter 5 Concluding Remarks

5.1 Summary

The damage of the storm is estimated to be around two billion dollars per year in Canada and over one-third of sewerage pipes are severely deteriorated and at the edge of breaking. The sewerage system needs to be fixed immediately, but there is not enough budget. This problem is not limited to Canada and concerns many other countries worldwide. Therefore, there is a need to investigate the sustainable sewer infrastructure that improves community resilience to storms and provides policymakers alternatives of pipe replacement plan underbudgets constrains. Here, we propose a new model, the Hydraulics and Risk Combined Model (HRCM), to fill the gaps and is optimized to target rehabilitation problems.

In the second chapter, we introduced the structure of the HRCM model and tested its validity. The HRCM method is an optimization method targeted rehabilitation strategies instead of designing parameters. This model allows the combining of hydraulic performance, risk assessment, rehabilitation method, and optimization into one framework. By building a linkage between the rehabilitation method and hydraulic parameters and the age of pipe, the optimization module can change the overflowing index and pipe breaking index by revising rehabilitation methods. The expert system could communicate the best results to policymakers. We applied our model to a small urban drainage and simulated the scenarios about the narrow pipe, aged pipe and narrow and aged combined situations, and the limited budget cases. The results showed that our model could detect the problem pipe successfully and provide reasonable suggestions to users.

The third chapter offered the modified calculation method for the HRCM model to improve the calculation speed and the accuracy of the model. We offered a revised HRCM model in this chapter. The essential updates of the new model are: (1) adding cost as the third objective function; (2) Removing the constraint function, but use the expert system to remove the

unsatisfied results. (3) changing the chain hydraulic index to network hydraulic index to enhance the ability to solve more complex drainage systems; (4) use continuous pipe diameter type to replace the discrete diameter. The new method could increase the performance of the HRCM method.

Since many rehabilitation methods could get the same objective results, the parallel results could impact the calculation speed and the optimization method. In the third chapter, we want this model to provide an optimization method specialized in drainage system rehabilitation, so we added a matrix that can store the information on the subsequent influence of replacing pipes one at a time to the system. This unique matrix was inspired by the sexual selection, a process that enhances the natural selection on special, favored phenotype in a population. This process is similar to the selection on a specific pipe in the drainage system. After adding the matrix, the HRCM model was found to have outstanding performance in various scenarios. The new method named Gene Flow method and this method can be built with kinds of optimization methods to enhance their optimization performance on solving drainage rehabilitation questions.

5.2 Limitations of the Present Project and Suggestions for Future Studies

The HRCM offered a framework for drainage rehabilitation; however, there are some limitations with the current HRCM model. First, the HRCM model cannot support parallel computing which is needed for practical applications with a large number of pipes and several rehabilitation strategies. By our method, we use the SWMM5 to calculate the overflowing index, and that means we need to use the input file of SWMM5. However, the existing parallel computing code has a racing problem during the calculation. Therefore, a multi-thread method should be provided for this method to increase the speed of the current HRCM model.

Second, in our research, we compared the GA algorithm and the PSO method for optimization. It is unclear whether other optimization methods are better than the two methods. Besides, even though we offered the gene flow method to build a bridge for optimization methods with drainage rehabilitation problems, but there are still some points needed to be improved, such as how to modify the feedback processes in this methods, and how to modify the Phenotype Searching method to other optimization methods. We are also looking into how to use

other functions on the SWMM5 model to link the sewerage erosion model, climate model and other models into our HRCM model to improve the performance of our method. We believe the HRCM model will have more and more functions and a large community in the future.

In addition, the proposed methodology is flat in time; that is, it does not provide rehabilitation strategies over the course of the infrastructure design service life. Indeed, it provides a one-time optimized rehabilitation strategy which makes the best use of the available budget to minimize the risk of failure and maximize the system performance.

References

- Adamowski, J., Adamowski, K., Bougadis, J., 2010. Influence of Trend on Short Duration Design Storms. *Water Resour. Manag.* 24, 401–413. <https://doi.org/10.1007/s11269-009-9452-z>
- Afshar, M.H., 2010. A parameter free Continuous Ant Colony Optimization Algorithm for the optimal design of storm sewer networks: Constrained and unconstrained approach. *Adv. Eng. Softw.* 41, 188–195. <https://doi.org/10.1016/j.advengsoft.2009.09.009>
- Afshar, M.H., Shahidi, M., Rohani, M., Sargolzaei, M., 2011. Application of cellular automata to sewer network optimization problems. *Sci. Iran.* 18, 304–312. <https://doi.org/10.1016/j.scient.2011.05.037>
- Afshar, M.H., Afshar, A., Mariño, M.A., Darbandi, A.A.S., 2006. Hydrograph-based storm sewer design optimization by genetic algorithm. *Can. J. Civ. Eng.* 33, 319–325. <https://doi.org/10.1139/105-121>
- Akan, A.O., Houghtalen, R.J., 2003. Urban hydrology, hydraulics, and stormwater quality.
- Altarabsheh, A., Kandil, A., Ventresca, M., 2018a. New Multiobjective Optimization Approach to Rehabilitate and Maintain Sewer Networks Based on Whole Lifecycle Behavior. *J. Comput. Civ. Eng.* 32, 04017069. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000715](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000715)
- Altarabsheh, A., Ventresca, M., Kandil, A., 2018b. New Approach for Critical Pipe Prioritization in Wastewater Asset Management Planning. *J. Comput. Civ. Eng.* 32, 04018044. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000784](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000784)
- Armenakis, C., Nirupama, N., 2014. Urban impacts of ice storms: Toronto December 2013. *Nat. Hazards* 74, 1291–1298. <https://doi.org/10.1007/s11069-014-1211-7>
- Ashley, R., Lundy, L., Ward, S., Shaffer, P., Walker, L., Morgan, C., Saul, A., Wong, T., Moore, S., 2013. Water-sensitive urban design: opportunities for the UK. *Proc. Inst. Civ. Eng. - Munic. Eng.* 166, 65–76. <https://doi.org/10.1680/muen.12.00046>
- ASCE, 2017. ASCE Infrastructure Report 2017.

- Baah, K., Dubey, B., Harvey, R., McBean, E., 2015. A risk-based approach to sanitary sewer pipe asset management. *Sci. Total Environ.* 505, 1011–1017.
<https://doi.org/10.1016/j.scitotenv.2014.10.040>
- Bakhshipour, A.E., Bakhshizadeh, M., Dittmer, U., Haghghi, A., Nowak, W., 2019. Hanging Gardens Algorithm to Generate Decentralized Layouts for the Optimization of Urban Drainage Systems. *J. Water Resour. Plan. Manag.* 145, 04019034.
[https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0001103](https://doi.org/10.1061/(ASCE)WR.1943-5452.0001103)
- Barreto, W., Vojinovic, Z., Price, R., Solomatine, D., 2010. Multiobjective Evolutionary Approach to Rehabilitation of Urban Drainage Systems. *J. Water Resour. Plan. Manag.* 136, 547–554. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000070](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000070)
- Bennis, S., Bengassem, J., Lamarre, P., 2003. Hydraulic Performance Index of a Sewer Network. *J. Hydraul. Eng.* 129, 504–510. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2003\)129:7\(504\)](https://doi.org/10.1061/(ASCE)0733-9429(2003)129:7(504))
- Bi, W., Dandy, G.C., Maier, H.R., 2016. Use of Domain Knowledge to Increase the Convergence Rate of Evolutionary Algorithms for Optimizing the Cost and Resilience of Water Distribution Systems. *J. Water Resour. Plan. Manag.* 142, 04016027.
[https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000649](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000649)
- Blondel, L., Baillie, L., Quinton, J., Alemu, J.B., Paterson, I., Hendry, A.P., Bentzen, P., 2019. Evidence for contemporary and historical gene flow between guppy populations in different watersheds, with a test for associations with adaptive traits. *Ecol. Evol.* 9, 4504–4517. <https://doi.org/10.1002/ece3.5033>
- Bush, E. and Lemmen, D.S., editors (2019): *Canada's Changing Climate Report*; Government of Canada, Ottawa, ON. 444 p.
- Buttle, J.M., Allen, D.M., Caissie, D., Davison, B., Hayashi, M., Peters, D.L., Pomeroy, J.W., Simonovic, S., St-Hilaire, A., Whitfield, P.H., 2016. Flood processes in Canada: Regional and special aspects. *Can. Water Resour. J. Rev. Can. Ressour. Hydr.* 41, 7–30.
<https://doi.org/10.1080/07011784.2015.1131629>

- Buttle, J.M., Lafleur, P.M., 2007. Anatomy of an Extreme Event: The July 14–15, 2004 Peterborough Rainstorm. *Can. Water Resour. J.* 32, 59–74. <https://doi.org/10.4296/cwrj3201059>
- Cai, X., Mohammadian, M., Shirkhani, H., 2020a. An Evaluation of seven calculation methods for the Hydraulics and Risk Combined Model. submitted.
- Cai, X., Shirkhani, H., Mohammadian, M., 2020b. A New Risk-Based Approach for Sewerage Flooding and Ageing Rehabilitation Management --The Structure of Hydraulics and Risk Combined Model (HRCM). Submitted
- CIRC, 2019. Canada Infrastructure Report Card 2019.
- Dargent, F., Chen, L., Fussmann, G.F., Ghalambor, C.K., Hendry, A.P., 2019. Female preference for novel males constrains the contemporary evolution of assortative mating in guppies. *Behav. Ecol.* 30, 646–657.
- Dawson, R.J., Speight, L., Hall, J.W., Djordjevic, S., Savic, D., Leandro, J., 2008. Attribution of flood risk in urban areas. *J. Hydroinformatics* 10, 275–288. <https://doi.org/10.2166/hydro.2008.054>
- Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans. Evol. Comput.* 6, 182–197. <https://doi.org/10.1109/4235.996017>
- Dion, Y., Bennis, S., 2010. A global modeling approach to the hydraulic performance evaluation of a sewer network. *Can. J. Civ. Eng.* 37, 1432–1436. <https://doi.org/10.1139/L10-082>
- Dridi, L., Mailhot, A., Parizeau, M., Villeneuve, J.-P., 2009. Multiobjective Approach for Pipe Replacement Based on Bayesian Inference of Break Model Parameters. *J. Water Resour. Plan. Manag.* 135, 344–354. [https://doi.org/10.1061/\(ASCE\)0733-9496\(2009\)135:5\(344\)](https://doi.org/10.1061/(ASCE)0733-9496(2009)135:5(344))
- Duchesne S, Beardsell G, Villeneuve J-P, et al (2013) A Survival Analysis Model for Sewer Pipe Structural Deterioration: A sewer deterioration model. *Computer-Aided Civil and Infrastructure Engineering* 28:146–160. <https://doi.org/10.1111/j.1467-8667.2012.00773.x>

- Ellis, J.B., 2006. Pharmaceutical and personal care products (PPCPs) in urban receiving waters. *Environ. Pollut.* 144, 184–189. <https://doi.org/10.1016/j.envpol.2005.12.018>
- Elsawah, H., Bakry, I., Moselhi, O., 2016. Decision Support Model for Integrated Risk Assessment and Prioritization of Intervention Plans of Municipal Infrastructure. *J. Pipeline Syst. Eng. Pract.* 7, 04016010. [https://doi.org/10.1061/\(ASCE\)PS.1949-1204.0000245](https://doi.org/10.1061/(ASCE)PS.1949-1204.0000245)
- Escher, B.I., Baumgartner, R., Koller, M., Treyer, K., Lienert, J., McArdell, C.S., 2011. Environmental toxicology and risk assessment of pharmaceuticals from hospital wastewater. *Water Res.* 45, 75–92. <https://doi.org/10.1016/j.watres.2010.08.019>
- Girones, R., Ferrús, M.A., Alonso, J.L., Rodriguez-Manzano, J., Calgua, B., de Abreu Corrêa, A., Hundesa, A., Carratala, A., Bofill-Mas, S., 2010. Molecular detection of pathogens in water – The pros and cons of molecular techniques. *Water Res.* 44, 4325–4339. <https://doi.org/10.1016/j.watres.2010.06.030>
- Gotsis, D., Spiliotis, M., Giakoumakis, S., 2011. Reuse of drainage water in irrigation with the aid of 0-1 linear programming. *Irrig. Drain. Syst.* 25, 385–394. <https://doi.org/10.1007/s10795-012-9131-8>
- Government of Canada, 2019. Canada’s Changing Climate Report Executive Summary.
- Government of Canada, 2013. Causes of flooding. URL <https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/causes-of-flooding.html>
- Government of Ontario, 1997. Development Charges Act.
- Government of Ontario, 1990. Ontario Water Resources Act.
- Guo, Y., Walters, G.A., Khu, S.T., Keedwell, E., 2007. A novel cellular automata based approach to storm sewer design. *Eng. Optim.* 39, 345–364. <https://doi.org/10.1080/03052150601128261>
- Haghighi, A., 2013. Loop-by-Loop Cutting Algorithm to Generate Layouts for Urban Drainage Systems. *J. Water Resour. Plan. Manag.* 139, 693–703. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000294](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000294)

- Haji Agha Mohammad Zarbaf, S.E., Norouzi, M., Allemang, R.J., Hunt, V.J., Helmicki, A., 2017. Stay Cable Tension Estimation of Cable-Stayed Bridges Using Genetic Algorithm and Particle Swarm Optimization. *J. Bridge Eng.* 22, 05017008.
[https://doi.org/10.1061/\(ASCE\)BE.1943-5592.0001130](https://doi.org/10.1061/(ASCE)BE.1943-5592.0001130)
- Haller, L., Hutton, G., Bartram, J., 2007. Estimating the costs and health benefits of water and sanitation improvements at global level. *J. Water Health* 5, 467–480.
<https://doi.org/10.2166/wh.2007.008>
- Hosseini, S.M., Ghasemi, A., 2012. Hydraulic performance analysis of sewer systems with uncertain parameters. *J. Hydroinformatics* 14, 682–696.
<https://doi.org/10.2166/hydro.2011.129>
- Huang, D., Liu, X., Jiang, S., Wang, H., Wang, J., Zhang, Y., 2018. Current state and future perspectives of sewer networks in urban China. *Front. Environ. Sci. Eng.* 12, 2.
<https://doi.org/10.1007/s11783-018-1023-1>
- Ivić, S., Družeta, S., Hreljac, I., 2017. S-Lay pipe laying optimization using specialized PSO method. *Struct Multidisc Optim* 56, 297–313.
- Insurance Bureau of Canada, 2020. Investing in Canada's Future: The Cost of Climate Adaptation at the Local Level.
- Jegatheesan, V., 2019. Urban stormwater and flood management: enhancing the liveability of cities. Springer Berlin Heidelberg, New York, NY.
- Kaegi, R., Voegelin, A., Ort, C., Sinnet, B., Thalmann, B., Krismer, J., Hagendorfer, H., Elumelu, M., Mueller, E., 2013. Fate and transformation of silver nanoparticles in urban wastewater systems. *Water Res.* 47, 3866–3877.
<https://doi.org/10.1016/j.watres.2012.11.060>
- Kleiner, Y., Rajani, B., 2001. Comprehensive review of structural deterioration of water mains: statistical models. *Urban Water* 3, 131–150. [https://doi.org/10.1016/S1462-0758\(01\)00033-4](https://doi.org/10.1016/S1462-0758(01)00033-4)
- Kleiner, Y., Sadiq, R., Rajani, B., 2004. Modeling Failure Risk in Buried Pipes Using Fuzzy Markov Deterioration Process, in: Pipeline Engineering and Construction. Presented at

- the Pipeline Division Specialty Congress 2004, American Society of Civil Engineers, San Diego, California, United States, pp. 1–12. [https://doi.org/10.1061/40745\(146\)7](https://doi.org/10.1061/40745(146)7)
- Kumar, S., Kaushal, D.R., Gosain, A.K., 2019. Evaluation of evolutionary algorithms for the optimization of storm water drainage network for an urbanized area. *Acta Geophys.* 67, 149–165. <https://doi.org/10.1007/s11600-018-00240-8>
- Labonne, J., Hendry, A.P., 2010. Natural and Sexual Selection Giveth and Taketh Away Reproductive Barriers: Models of Population Divergence in Guppies. *Am. Nat.* 176, 26–39. <https://doi.org/10.1086/652992>
- Lee, J.H., Bang, K.W., 2000. Characterization of Urban Stormwater Runoff. *Water Res.* 34, 1773–1780.
- Li, J., Deng, C., Li, H., Ma, M., Li, Y., 2018. Hydrological Environmental Responses of LID and Approach for Rainfall Pattern Selection in Precipitation Data-Lacked Region. *Water Resour. Manag.* 32, 3271–3284. <https://doi.org/10.1007/s11269-018-1990-9>
- Li, G., Matthew, R.G.S., 1990. New Approach for Optimization of Urban Drainage Systems. *J. Environ. Eng.* 116, 927–944. [https://doi.org/10.1061/\(ASCE\)0733-9372\(1990\)116:5\(927\)](https://doi.org/10.1061/(ASCE)0733-9372(1990)116:5(927))
- Lin, Y.-H., Chen, Y.-P., Yang, M.-D., Su, T.-C., 2016. Multiobjective Optimal Design of Sewerage Rehabilitation by Using the Nondominated Sorting Genetic Algorithm-II. *Water Resour. Manag.* 30, 487–503. <https://doi.org/10.1007/s11269-015-1173-x>
- Marsalek, J., Watt, W.E., 1984. Design storms for urban drainage design. *Can. J. Civ. Eng.* 11, 574–584. <https://doi.org/10.1139/184-075>
- Maharjan, M., Pathirana, A., Gersonius, B., Vairavamoorthy, K., 2009. Staged cost optimization of urban storm drainage systems based on hydraulic performance in a changing environment. *Hydrol Earth Syst Sci* 9.
- Marzouk, M., Omar, M., 2013. Multiobjective optimisation algorithm for sewer network rehabilitation. *Structure and Infrastructure Engineering* 9, 1094–1102. <https://doi.org/10.1080/15732479.2012.666254>

- MathWorks, 2018. exampleIntGAMULTIOBJ. exampleIntGAMULTIOBJ. URL
<https://www.mathworks.com/matlabcentral/answers/103369-is-it-possible-to-solve-a-mixed-integer-multi-objective-optimization-problem-using-global-optimizati>
- Mirjalili, S., Lewis, A., 2016. The Whale Optimization Algorithm. *Adv. Eng. Softw.* 95, 51–67.
<https://doi.org/10.1016/j.advengsoft.2016.01.008>
- Mohrlok, U., Wolf, L., Klinger, J., 2008. Quantification of infiltration processes in urban areas by accounting for spatial parameter variability. *J. Soils Sediments* 8, 34–42.
<https://doi.org/10.1065/jss2007.05.225>
- Moussavi, A., Samani, H.M.V., Haghghi, A., 2017. A framework for optimal reliability-based storm sewer network design in flat areas. *Can. J. Civ. Eng.* 44, 139–150.
<https://doi.org/10.1139/cjce-2016-0244>
- MTO, 2010. IDF Curve Lookup-Ottawa. URL
http://www.mto.gov.on.ca/IDF_Curves/results_out.shtml?coords=45.429047,-75.672204
- Ogidan, O., Giacomoni, M., 2016. Multiobjective Genetic Optimization Approach to Identify Pipe Segment Replacements and Inline Storages to Reduce Sanitary Sewer Overflows. *Water Resour. Manag.* 30, 3707–3722. <https://doi.org/10.1007/s11269-016-1373-z>
- Rao, C.J., Jothiprakash, V., Eldho, T.I., 2017. Design of a Pipe Network Using the Finite-Element Method Coupled with Particle-Swarm Optimization. *J. Pipeline Syst. Eng. Pract.* 8, 04017019. [https://doi.org/10.1061/\(ASCE\)PS.1949-1204.0000282](https://doi.org/10.1061/(ASCE)PS.1949-1204.0000282)
- Rashid, Md.M., Hayes, D.F., 2011. Dynamic Programming Methodology for Prioritizing Sewerage Projects. *J. Water Resour. Plan. Manag.* 137, 193–204.
[https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000107](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000107)
- Rep, K.R., Kompare, B., Ros̃, M., Kravanja, S., 2008. Cost Optimization of Integrated Wastewater Drainage and Treatment Systems. *Water Environ. Res.* 80, 581–595.
<https://doi.org/10.2175/106143007X221472>
- Risch, E., Gutierrez, O., Roux, P., Boutin, C., Corominas, L., 2015. Life cycle assessment of urban wastewater systems: Quantifying the relative contribution of sewer systems. *Water Res.* 77, 35–48. <https://doi.org/10.1016/j.watres.2015.03.006>

- Rossman, L.A., 2017a. Storm Water Management Model Reference Manual Volume II – Hydraulics. U. S. Environ. Prot. Agency 190.
- Rossman, L.A., 2017b. Storm Water Management Model Reference Manual Volume II – Hydraulics 190.
- Rossman, L.A., 2015. Storm Water Management Model User’s Manual Version 5.1. U. S. Environ. Prot. Agency 353.
- Roshani, E., Filion, Y.R., 2015. Water Distribution System Rehabilitation under Climate Change Mitigation Scenarios in Canada. *J. Water Resour. Plan. Manag.* 141, 04014066.
[https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000450](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000450)
- Rudiono, J., 2018. Priority Scale of Drainage Rehabilitation of Cilacap City. *IOP Conf. Ser. Mater. Sci. Eng.* 333, 012111. <https://doi.org/10.1088/1757-899X/333/1/012111>
- Sabzkouhi, A.M., Haghghi, A., 2016. Uncertainty Analysis of Pipe-Network Hydraulics Using a Many-Objective Particle Swarm Optimization. *J. Hydraul. Eng.* 142, 04016030.
[https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001148](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001148)
- Salman, B., Salem, O., 2012. Risk Assessment of Wastewater Collection Lines Using Failure Models and Criticality Ratings. *J. Pipeline Syst. Eng. Pract.* 3, 68–76.
[https://doi.org/10.1061/\(ASCE\)PS.1949-1204.0000100](https://doi.org/10.1061/(ASCE)PS.1949-1204.0000100)
- Selvakumar, A., Matthews, J.C., Condit, W., Sterling, R., 2015. Innovative research program on the renewal of aging water infrastructure systems. *J. Water Supply Res. Technol.-Aqua* 64, 117–129. <https://doi.org/10.2166/aqua.2014.103>
- Sebti, A., Bennis, S., Fuamba, M., 2014. Cost Optimization of Hydraulic and Structural Rehabilitation of Urban Drainage Network. *J. Infrastruct. Syst.* 20, 04014009.
[https://doi.org/10.1061/\(ASCE\)IS.1943-555X.0000180](https://doi.org/10.1061/(ASCE)IS.1943-555X.0000180)
- Shao, Z., Zhang, X., Li, S., Deng, S., Chai, H., 2017. A Novel SWMM Based Algorithm Application to Storm Sewer Network Design. *Water* 9, 747.
<https://doi.org/10.3390/w9100747>

- Sharma, A.K., Cook, S., Tjandraatmadja, G., Gregory, A., 2012. Impediments and constraints in the uptake of water sensitive urban design measures in greenfield and infill developments. *Water Sci. Technol.* 65, 340–352. <https://doi.org/10.2166/wst.2012.858>
- Shao, Z., Zhang, X., Li, S., Deng, S., Chai, H., 2017. A Novel SWMM Based Algorithm Application to Storm Sewer Network Design. *Water* 9, 747. <https://doi.org/10.3390/w9100747>
- Shamir, U., Howard, C.D.D., 1979. An analytic approach to scheduling pipe replacement. *J. AWWA* 71, 248–258.
- Surendar, A., Kuzichkin, O.R., Kanagarajan, S., Hashemi, M.H., Khorami, M., 2019. Applying two optimization techniques in evaluating tensile strength of granitic samples. *Eng. Comput.* 35, 985–992. <https://doi.org/10.1007/s00366-018-0645-z>
- Tarigan, A.P.M., Rahmad, D., Sembiring, R.A., Iskandar, R., 2018. An application of the AHP in water resources management: a case study on urban drainage rehabilitation in Medan City. *IOP Conf. Ser. Mater. Sci. Eng.* 309, 012096. <https://doi.org/10.1088/1757-899X/309/1/012096>
- Tran, D.H., Ng, A.W.M., Mcmanus, K.J., Burn, S., 2008. Prediction models for serviceability deterioration of stormwater pipes. *Struct. Infrastruct. Eng.* 4, 287–295. <https://doi.org/10.1080/15732470600792236>
- Tran, D.H., Perera, B.J.C., Ng, A.W.M., 2010. Hydraulic Deterioration Models for Storm-Water Drainage Pipes: Ordered Probit versus Probabilistic Neural Network. *J. Comput. Civ. Eng.* 24, 140–150. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000020](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000020)
- United Nations Climate Change, 2015. The Paris Agreement.
- Valizadeh, N., Shamseldin, A.Y., Wotherspoon, L., 2019. Quantification of the hydraulic dimension of stormwater management system resilience to flooding. *Water Resour. Manag.* 33, 4417–4429. <https://doi.org/10.1007/s11269-019-02361-1>
- Vasiljevic, B., McBean, E., Gharabaghi, B., 2012. Trends in rainfall intensity for stormwater designs in Ontario. *J. Water Clim. Change* 3, 1–10. <https://doi.org/10.2166/wcc.2012.125>

- Vasudevan, B., Sinha, A.K., 2018. Reliability improvement of reconfigurable distribution system using GA and PSO. *Electr. Eng.* 100, 1263–1275. <https://doi.org/10.1007/s00202-017-0580-9>
- Vermaire, J.C., Pisaric, M.F.J., Thienpont, J.R., Courtney Mustaphi, C.J., Kokelj, S.V., Smol, J.P., 2013. Arctic climate warming and sea ice declines lead to increased storm surge activity: WARMING LEADS TO ARCTIC STORM SURGES. *Geophys. Res. Lett.* 40, 1386–1390. <https://doi.org/10.1002/grl.50191>
- Vojinovic, Z., Sahlou, S., Torres, A.S., Seyoum, S.D., Anvarifar, F., Matungulu, H., Barreto, W., Savic, D., Kapelan, Z., 2014. Multi-objective rehabilitation of urban drainage systems under uncertainties. *J. Hydroinformatics* 16, 1044–1061. <https://doi.org/10.2166/hydro.2014.223>
- Yarpiz, 2020. Multi-Objective Particle Swarm Optimization (MOPSO). MATLAB Cent. File Exch. URL <https://www.mathworks.com/matlabcentral/fileexchange/52870-multi-objective-particle-swarm-optimization-mopso>
- Yazdi, J., Sadollah, A., Lee, E.H., Yoo, D.G., Kim, J.H., 2017a. Application of multi-objective evolutionary algorithms for the rehabilitation of storm sewer pipe networks: Comparison of MOEAs. *J. Flood Risk Manag.* 10, 326–338. <https://doi.org/10.1111/jfr3.12143>
- Yazdi, J., Yoo, D.G., Kim, J.H., 2017b. Comparative study of multi-objective evolutionary algorithms for hydraulic rehabilitation of urban drainage networks. *Urban Water J.* 14, 483–492. <https://doi.org/10.1080/1573062X.2016.1223319>
- Yin, X., Chen, Y., Bouferguene, A., Zaman, H., Al-Hussein, M., Kurach, L., 2020. A deep learning-based framework for an automated defect detection system for sewer pipes. *Autom. Constr.* 109, 102967. <https://doi.org/10.1016/j.autcon.2019.102967>
- Zhao, J.Q., McDonald, S.E., Kleiner, Y., 2001. Guidelines for Condition Assessment and Rehabilitation of Large Sewers 90.
- Zhang, C., He, M., Zhang, Y., 2019. Urban Sustainable Development Based on the Framework of Sponge City: 71 Case Studies in China. *Sustainability* 11, 1544. <https://doi.org/10.3390/su11061544>

Zhang, L., De Schryver, P., De Gusseme, B., De Muynck, W., Boon, N., Verstraete, W., 2008. Chemical and biological technologies for hydrogen sulfide emission control in sewer systems: A review. *Water Res.* 42, 1–12. <https://doi.org/10.1016/j.watres.2007.07.013>

Supplemental Materials 1

1. Structure

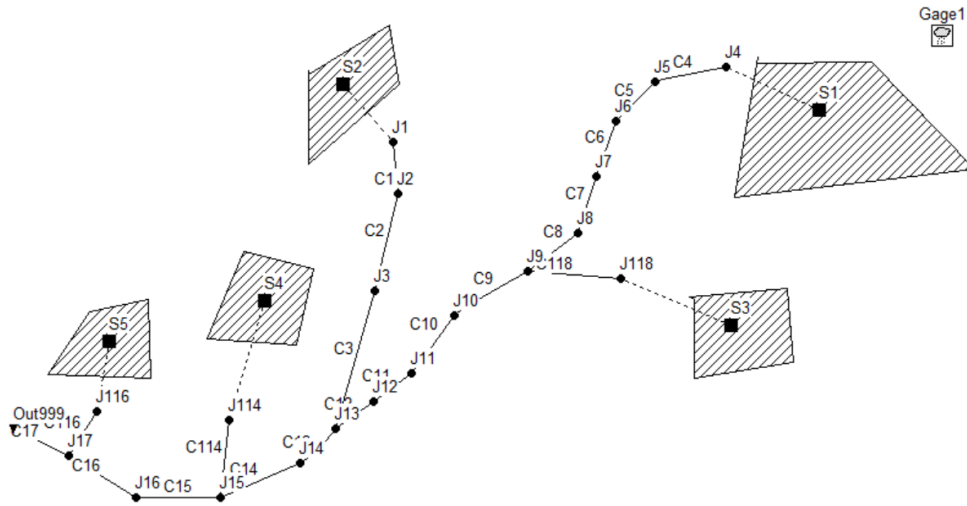


Figure S1. The setting of the drainage structure for Case1 and Case2 (Bennis et al. 2003).

2. Rainfall

2.1 Case 1

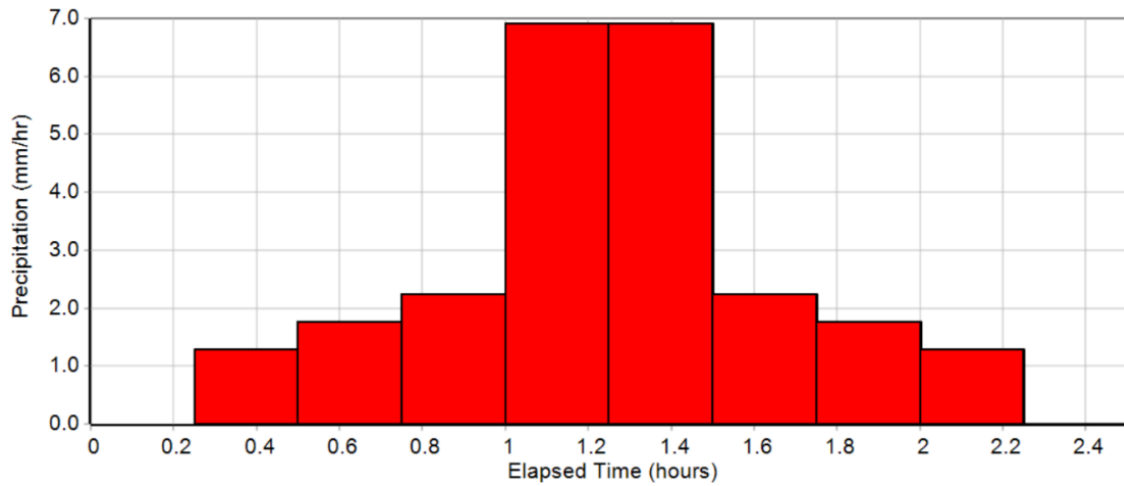


Fig. S2 Precipitation data of Case1

2.2 Case 2

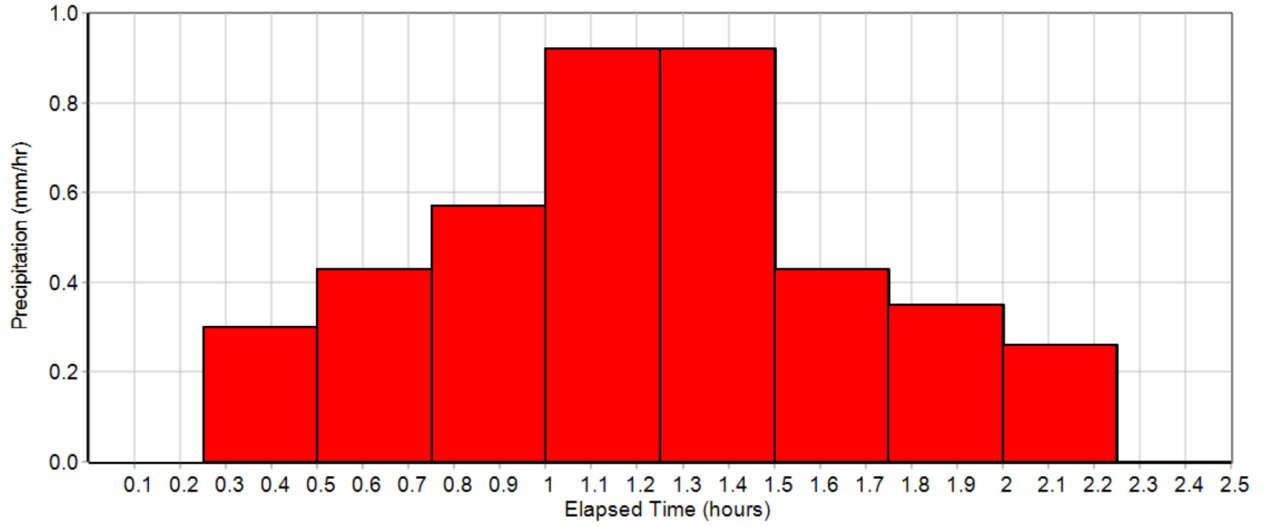


Fig. S3 Precipitation data of Case2

3. Probability of Failure

$$P(t) = 100 \times e^{0.02 \times (t-100)} \quad (\text{eq. S1})$$

When the age reaches 100 years, the probability will equal 100, and when the value of age is smaller than zero years, which will only happen when the benefit year is longer than the aged year, the probability will be zero. The possibility of failure is not zero when the age equals to zero, because the pipe may break during installation, or there may be some flaws of that pipe which have not been found and could make the pipe break after the installation (Kleiner and Rajani 2001).

4. Age

Table S1. Age settings of each pipe in each scenario.

Pipe	Case1-S1	Case1-S2	Case1-S3	Case1-S4	Case1-S5	Case1-S6	Case2-S1	Case2-S2	Case2-S3
C4	0	0	0	0	0	0	0	0	0
C5	0	0	0	0	0	0	0	5	0

C6	0	0	0	0	0	0	0	10	0
C7	0	0	0	0	0	0	0	15	0
C8	0	0	0	0	0	0	0	20	0
C9	0	60	0	0	0	0	0	25	0
C10	0	0	0	60	60	60	0	30	0
C11	0	0	0	0	0	0	0	35	0
C12	0	0	0	0	0	0	0	40	0
C13	0	0	80	0	0	0	0	45	0
C14	0	0	0	0	0	0	0	50	0
C15	0	0	0	0	0	0	0	55	0
C16	0	0	0	0	0	0	0	60	0
C17	0	0	0	0	0	0	0	65	0
C118	0	0	0	0	0	0	0	70	0
C1	0	0	0	0	0	0	0	75	0
C2	0	0	0	0	0	0	0	80	0
C3	0	0	0	0	0	0	0	85	0
C114	0	0	0	0	0	0	0	90	0
C116	0	0	0	0	0	0	0	95	0

Table S2. Pipe breaking risk of each pipe in each scenario before rehabilitation.

Pipe	Case1-S1	Case1-S2	Case1-S3	Case1-S4	Case1-S5	Case1-S6	Case2-S1	Case2-S2	Case2-S3
C4	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
C5	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.61	1.46
C6	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.77	0.63
C7	0.74	0.74	0.74	0.74	0.74	0.74	0.74	1.00	0.74
C8	0.70	0.70	0.70	0.70	0.70	0.70	0.70	1.04	0.70
C9	1.27	7.70	1.27	1.27	1.27	1.27	1.27	2.09	1.27
C10	0.63	0.63	0.63	3.85	3.85	3.85	0.63	1.15	0.63
C11	0.63	0.63	0.63	0.63	0.63	0.63	0.63	1.27	0.63
C12	0.80	0.80	0.80	0.80	0.80	0.80	0.80	1.78	0.80
C13	0.97	0.97	8.81	0.97	0.97	0.97	0.97	2.39	0.97
C14	1.03	1.03	1.03	1.03	1.03	1.03	1.03	2.81	1.03
C15	0.63	0.63	0.63	0.63	0.63	0.63	0.63	1.90	0.63
C16	0.63	0.63	0.63	0.63	0.63	0.63	0.63	2.10	0.63
C17	0.63	0.63	0.63	0.63	0.63	0.63	0.63	2.32	0.63
C118	0.70	0.70	0.70	0.70	0.70	0.70	0.70	2.82	0.70
C1	0.63	0.63	0.63	0.63	0.63	0.63	0.63	2.84	0.63
C2	0.63	0.63	0.59	0.63	0.63	0.63	0.63	3.13	0.63
C3	0.80	0.80	0.75	0.80	0.80	0.80	0.80	4.39	0.80
C114	1.03	1.03	0.96	1.03	1.03	1.03	1.03	6.25	1.03

C116	0.63	0.63	0.63	0.63	0.63	0.63	0.63	4.23	0.63
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5. Cost

5.1 Case 1

Table S3 The rehabilitation matrix

Rehabilitation	Action	Reinforcement Cost (\$/m)	Disruption Cost (\$/m)	Pipe cost	Benefit (year)
1	Do nothing	0	0		-
2	Routine cleaning	16	0		10
3	Shotcrete	656	0		20
4	Cured-in-place pipe	1558	0		50
5	Reinforced fiberglass sliplining	2231	0		100
6	Dig and replace with concrete pipe	1148	656	PCI	50

The pipe cost in *PCI* is:

$$PCI = Diameter * Length \text{ (eq. S2)}$$

5.2 Case 2.

Table S4 The rehabilitation matrix

Rehabilitation	Action	Cost (\$/m)	Disruption Cost	Pipe cost	Benefit (year)
----------------	--------	-------------	-----------------	-----------	----------------

)	(\$/m)		
1	Do nothing	0	0		-
2	Routine cleaning	16	0		10
3	Shotcrete	656	0		20
4	Cured-in-place pipe	1558	0		50
5	Reinforced fiberglass sliplining	2231	0		100
6	Dig and replace with concrete pipe	1148	656	PC2	50

An empirical equation was given by (Zhang et al. 2017):

$$PC2 = 0.01 \times L \times (425.339 + 4903.395H + 69.895H^2 + 1.434DH - 18.692D + 0.062D^2) \text{ (Eq. S3)}$$

where:

L = length of a new pipe (m);

H = depth of the pipe (m);

D = diameter of the pipe (m).

6. Hydraulic Flooding

Case1-S1

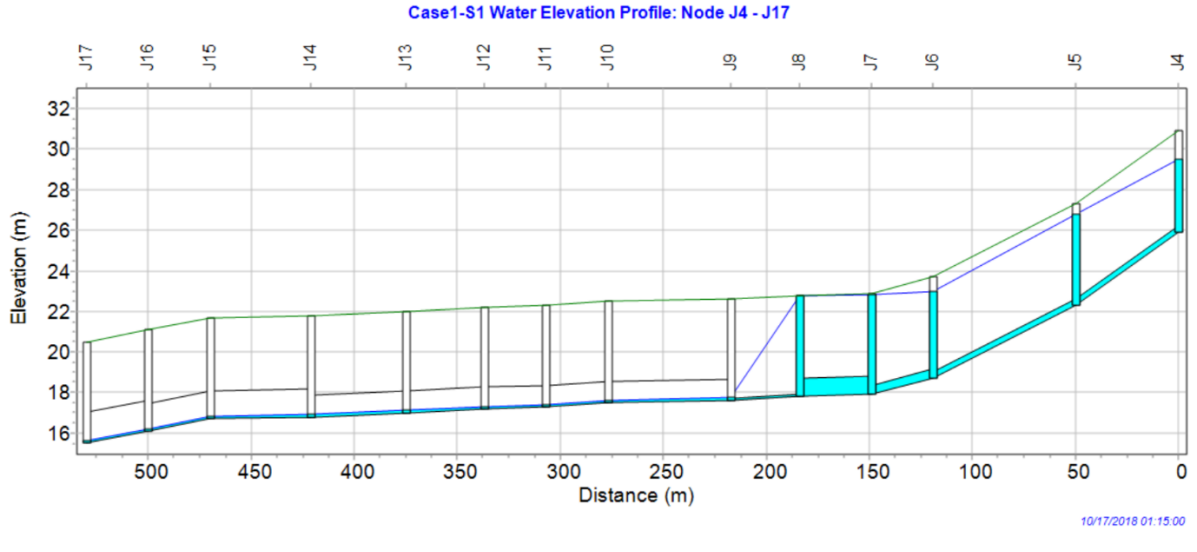


Figure S4. Water Elevation Profile for Case1-S1.

Case1-S2

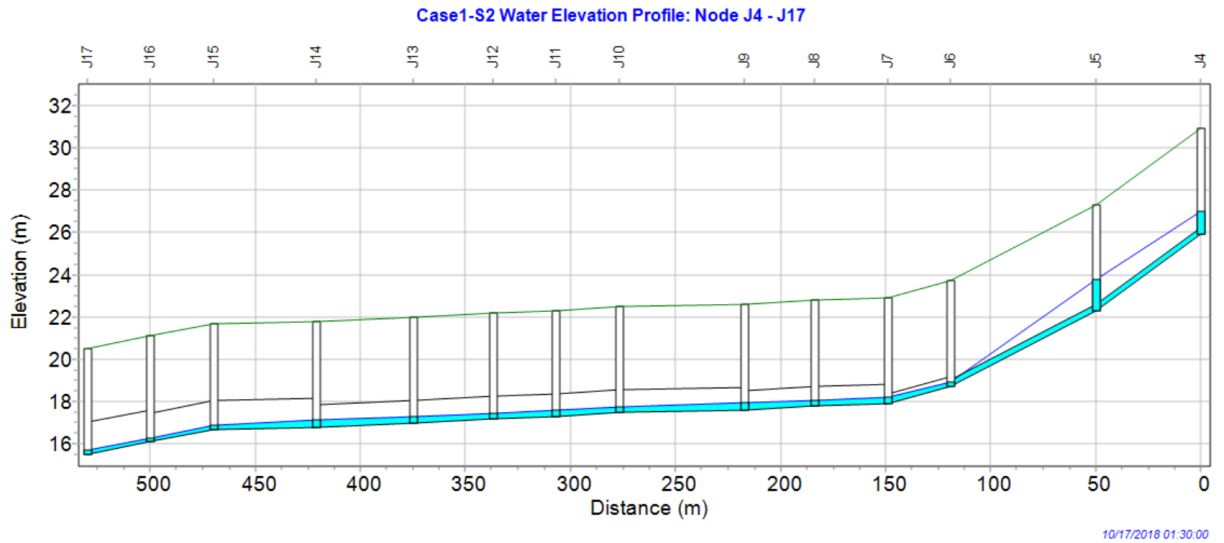


Figure S5. Water Elevation Profile for Case1-S2.

Case1-S3

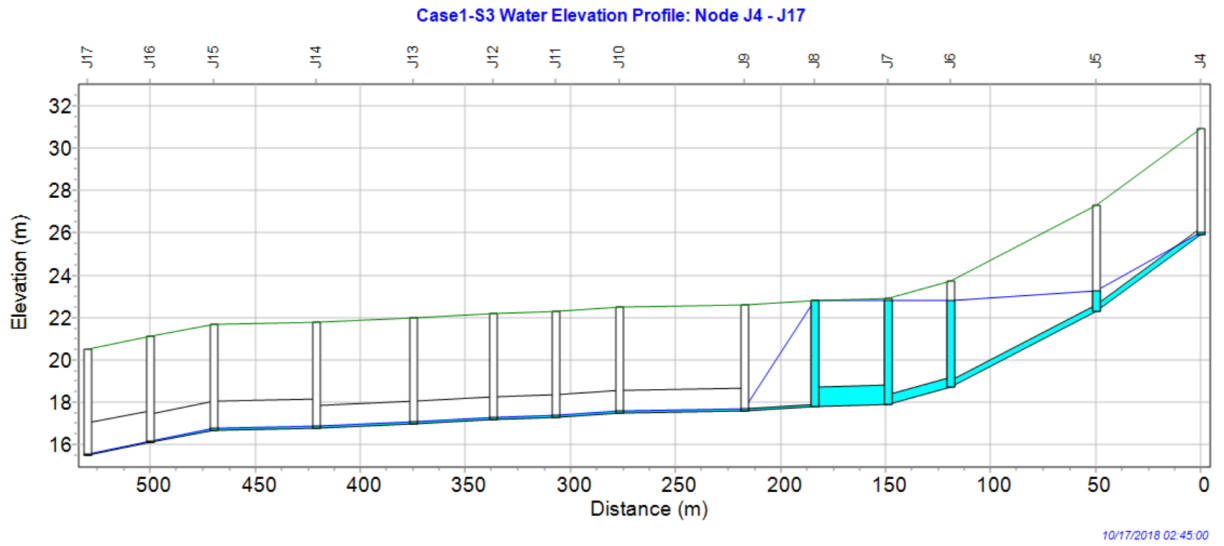


Figure S6. Water Elevation Profile for Case1-S3.

Case1-S4-S6

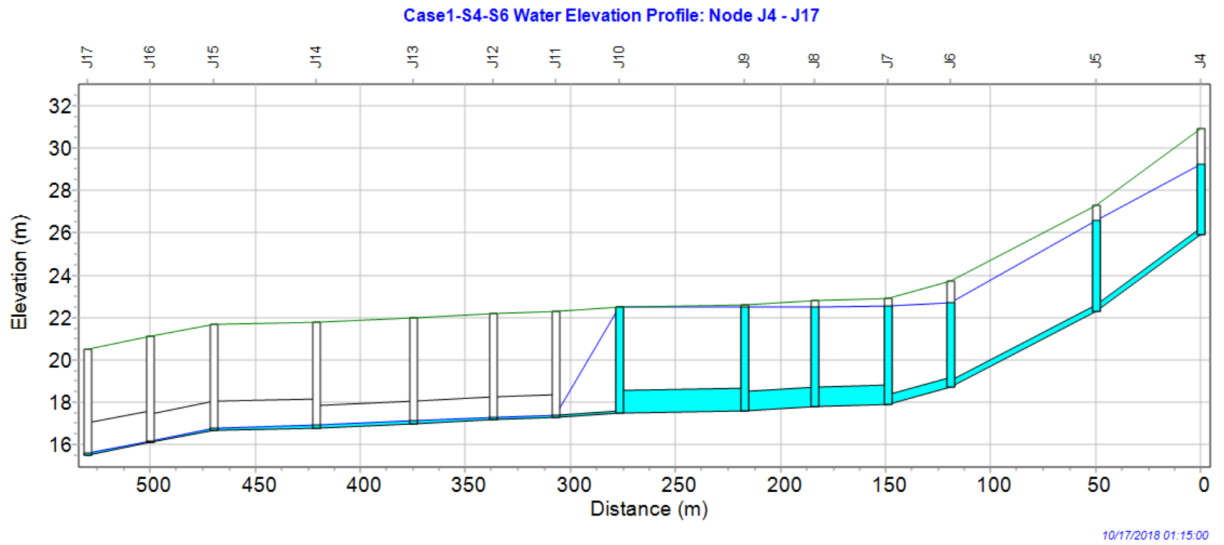


Figure S7. Water Elevation Profile for Case1-S4, Case1-S5, and Case1-S6.

Case2-S1

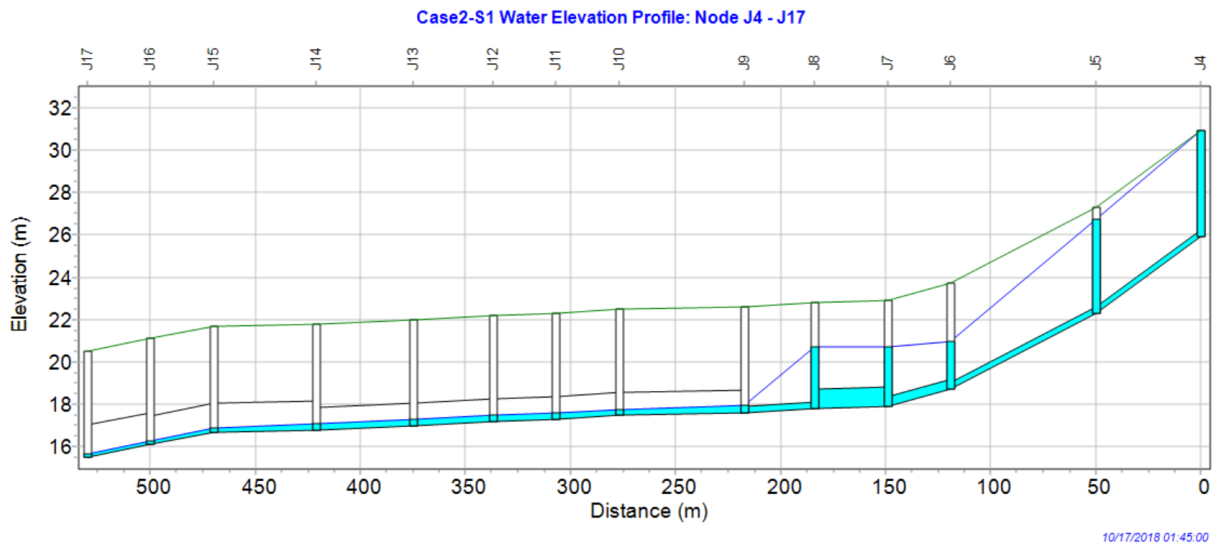


Figure S8. Water Elevation Profile for Case2-S1

Case2-S2

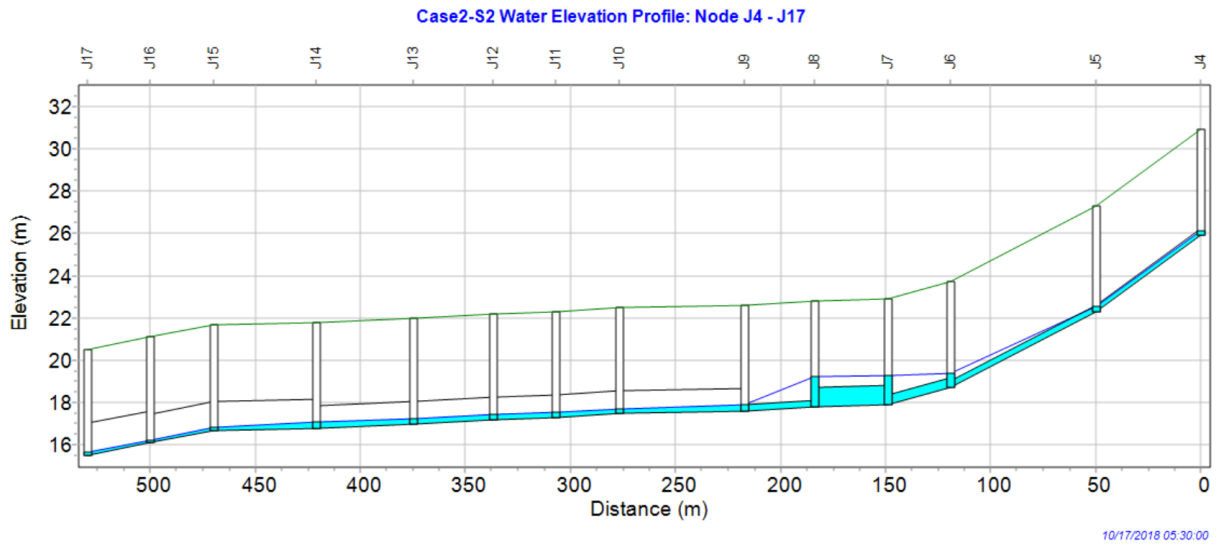


Figure S9. Water Elevation Profile for Case2-S2

Case2-S3

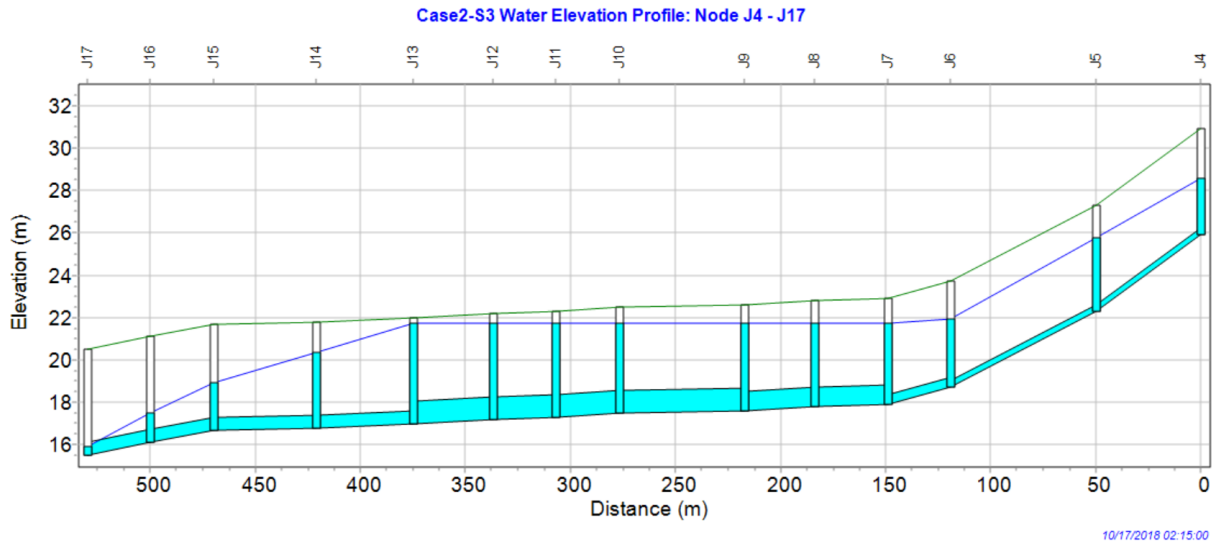


Figure S9. Water Elevation Profile for Case2-S3

Table S5. The hydraulic diagnostic index of each pipe in scenario before rehabilitation

Pipe	Case1-S1	Case1-S2	Case1-S3	Case1-S4	Case1-S5	Case1-S6	Case2-S1	Case2-S2	Case2-S3
J4	0.00	0.00	0.00	0.00	0.00	0.00	11.93	0.00	0.00
J5	28.07	41.14	28.07	38.63	38.63	38.63	91.59	0.00	9.29
J6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
J7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
J8	445.59	0.00	445.59	0.00	0.00	0.00	226.53	44.64	0.00
J9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
J10	0.00	0.00	0.00	611.76	611.76	611.76	0.00	0.00	0.00
J11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
J12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
J13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	206.84
J14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	271.54
J15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	184.85
J16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	198.56
J17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S6. The surcharge index of each pipe in each scenario before rehabilitation

N overflowing	Case1- S1	Case1- S2	Case1- S3	Case1- S4	Case1- S5	Case1- S6	Case2- S1	Case2- S2	Case2- S3
J4	91.05	16.08	91.05	90.63	90.63	90.63	100.00	0.00	50.16
J5	100.00	25.06	100.00	99.57	99.57	99.57	88.07	0.00	67.41
J6	84.80	0.00	84.80	78.63	78.63	78.63	40.31	6.61	60.79
J7	97.80	0.00	97.80	90.70	90.70	90.70	46.39	12.36	71.60
J8	100.00	0.00	100.00	93.15	93.15	93.15	55.27	25.67	73.81
J9	0.00	0.00	0.00	97.71	97.71	97.71	0.00	0.00	77.89

J10	0.00	0.00	0.00	100.00	100.00	100.00	0.00	0.00	80.18
J11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	85.26
J12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	87.80
J13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	93.62
J14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	67.43
J15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	36.90
J16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.22
J17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S7 The system overflooding index and system breaking index of each scenario before rehabilitation

Index	Case1 -S1	Case1 -S2	Case1 -S3	Case1 -S4	Case1 -S5	Case1 -S6	Case2 -S1	Case2 -S2	Case2 -S3
System overflooding index	29.72	5.07	29.72	37.53	37.53	37.53	25.70	2.63	62.43
System breaking index	16.24	22.68	23.92	19.46	19.46	19.46	16.24	46.95	16.24

7. Results after rehabilitation

7.1 Rehabilitation solutions

Table S8 Case1-S1 Rehabilitation solutions given by the HRCM model.

	solution	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C118	C1	C2	C3	C114	C116	
Diameter	1	2.21	1.36	0.46	0.92	2.21	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53	
	2	0.31	0.55	1.36	0.92	0.91	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53	
	3	0.31	0.55	0.46	0.92	2.21	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53	
	4	0.31	2.21	0.46	0.92	2.21	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53	
	5	2.21	0.30	0.46	0.92	2.21	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53	
	6	0.31	0.30	0.46	0.92	1.90	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53	
	7	0.31	0.30	0.46	0.92	2.21	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53	
Rehabilitation	1	6	6	3	3	6	3	3	4	4	3	3	3	3	4	2	3	2	3	3	3	
	2	3	6	6	4	6	3	3	4	3	3	2	3	3	2	3	3	4	4	2	3	
	3	3	6	3	3	6	2	3	3	3	3	3	3	3	3	3	3	2	4	3	4	
	4	3	6	3	3	6	3	4	5	4	3	2	4	4	4	3	3	3	4	2	4	
	5	6	4	3	4	6	3	3	3	3	3	2	2	3	3	4	3	3	3	2	3	
	6	3	3	2	3	6	3	3	3	3	3	2	3	3	3	3	2	2	3	3	2	2
	7	3	3	4	3	6	2	3	3	3	2	3	3	3	3	2	3	4	5	3	3	3

Table S9 Case1-S2 Rehabilitation solutions given by the HRCM model.

	solution	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C118	C1	C2	C3	C114	C116
Diameter	1	1.36	2.53	0.46	0.92	0.92	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	2	0.31	0.55	0.46	0.92	0.92	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	3	0.31	2.21	0.46	0.92	0.92	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53

	4	2.53	0.3	0.46	0.92	0.92	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	5	0.31	0.3	0.46	0.92	0.92	1.07	1.07	1.07	1.07	1.07	1.37	1.37	2.21	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	6	0.31	0.3	0.46	0.92	0.92	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
Rehabilitation	1	6	6	4	5	3	5	3	4	3	3	2	3	4	3	4	5	4	4	3	3
	2	2	6	2	3	3	5	2	2	5	2	2	3	2	4	4	3	2	2	2	3
	3	2	6	2	3	3	5	4	3	3	3	2	2	3	3	3	3	4	3	3	2
	4	6	3	5	5	3	5	4	3	3	4	3	5	3	3	3	3	4	3	3	5
	5	3	3	2	2	3	5	3	2	3	3	2	3	6	3	3	3	4	3	2	4
	6	2	2	2	2	3	5	2	2	2	2	2	2	2	2	2	3	3	3	3	3

Table S10 Case1-S3 Rehabilitation solutions given by the HRCM model.

	solution	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C118	C1	C2	C3	C114	C116
Diameter	1	2.21	2.21	0.46	0.92	1.62	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	2	0.31	0.55	0.46	0.92	1.9	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	3	0.31	0.72	0.46	0.92	2.21	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	4	0.31	2.21	0.46	0.92	2.21	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	5	2.21	0.3	0.46	0.92	2.21	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	6	0.31	0.3	0.46	0.92	1.9	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	7	0.31	0.3	0.46	0.92	2.21	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
Rehabilitation	1	6	6	3	3	6	3	4	3	3	5	3	5	4	3	4	4	3	4	3	4
	2	3	6	3	2	6	2	2	3	3	5	3	2	2	3	3	2	2	3	3	3
	3	3	6	3	3	6	3	2	3	3	5	3	2	3	3	4	2	2	3	4	3
	4	4	6	3	3	6	3	4	4	3	5	4	3	5	3	3	3	4	5	3	4
	5	6	3	3	3	6	3	3	4	3	5	2	3	4	3	4	4	5	3	4	4
	6	2	2	2	2	6	2	3	2	2	5	3	2	2	2	3	2	3	2	2	2
	7	4	3	2	2	6	2	2	2	2	5	2	3	2	2	2	3	2	2	3	3

Table S11 Case1-S4 Rehabilitation solutions given by the HRCM model.

C1-S4	solution	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C118	C1	C2	C3	C114	C116
Diameter	1	2.21	2.21	0.46	0.92	0.92	1.07	2.21	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	2	0.31	0.55	0.46	0.92	0.92	1.07	0.55	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	3	0.31	0.72	0.46	0.92	0.92	1.07	2.21	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	4	0.31	2.21	0.46	0.92	0.92	1.07	2.21	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	5	2.53	0.3	0.46	0.92	0.92	1.07	2.53	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	6	0.31	0.3	0.46	0.92	0.92	1.07	2.21	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	2.21	1.07	1.37	1.53
	7	0.31	0.3	0.46	0.92	0.92	1.07	2.21	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
Rehabilitation	1	6	6	3	3	3	5	6	3	3	3	3	4	3	5	4	4	3	3	3	3
	2	2	6	2	4	3	3	6	3	3	2	2	4	3	3	3	2	2	3	3	3
	3	3	6	3	3	3	3	6	4	4	3	3	3	4	4	4	3	3	3	3	3
	4	3	6	3	4	3	4	6	3	3	2	3	3	3	4	3	3	4	3	3	3
	5	6	3	3	4	4	5	6	3	3	3	4	4	4	5	4	3	3	4	2	3
	6	4	3	3	4	3	4	6	3	4	4	3	3	3	2	4	2	6	4	4	2
	7	2	2	2	2	3	2	6	2	2	2	2	2	2	2	2	3	2	2	2	2

Table S12 Case1-S5 Rehabilitation solutions given by the HRCM model.

C1-S5	solution	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C118	C1	C2	C3	C114	C116
Diameter	1	0.31	0.3	0.46	0.92	0.92	1.07	0.91	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	0.91	1.07	1.07	1.37	1.53
	2	0.31	0.3	0.46	0.92	0.92	1.07	0.91	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
Rehabilitation	1	2	2	2	2	2	2	6	2	2	2	2	2	2	2	2	6	2	2	2	2
	2	2	2	2	2	2	2	6	2	2	2	2	2	2	2	2	2	2	2	2	2

Table S13 Case1-S6 Rehabilitation solutions given by the HRCM model.

C1-S6	solution	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C118	C1	C2	C3	C114	C116
Diameter	1	0.31	0.3	0.46	0.92	0.92	1.07	0.1	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
Rehabilitation	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	2

Table S14 Case2-S1 Rehabilitation solutions given by the HRCM model.

	solution	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C118	C1	C2	C3	C114	C116
Diameter	1	1.36	0.91	2.21	0.92	2.21	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	2	2.53	2.21	0.46	0.92	1.36	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
Rehabilitation	1	6	6	6	4	6	3	3	3	3	2	2	4	2	3	4	3	3	2	3	3
	2	6	6	5	3	6	5	2	3	5	4	3	3	4	2	3	4	2	2	4	3

Table S15 Case2-S2 Rehabilitation solutions given by the HRCM model.

C2-S1	solution	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C118	C1	C2	C3	C114	C116
Diameter	1	0.31	0.31	0.46	0.92	1.36	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.36	1.62	0.92	1.07	1.07	1.62	1.37	2.21
	2	0.31	0.31	0.46	0.92	0.31	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.13	1.62	0.92	1.07	1.07	1.36	1.37	1.62
	3	0.31	0.31	0.46	0.92	0.31	1.07	1.07	1.07	1.07	1.07	1.37	1.37	1.53	1.62	0.92	1.07	1.07	1.36	1.37	1.36

	1	4	4	4	4	6	4	4	4	4	4	5	5	6	6	5	5	5	6	5	6
Rehabilitation	2	3	4	4	4	4	4	4	4	4	4	5	5	6	6	5	5	5	6	5	6
	3	4	4	4	4	4	4	4	4	4	4	5	5	5	6	5	5	5	6	5	6

Table S16 Case2-S2 Rehabilitation solutions given by the HRCM model.

	solution	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C118	C1	C2	C3	C114	C116
Diameter	1	0.31	0.31	0.46	0.92	0.92	1.07	1.07	1.07	1.07	2.53	2.53	2.21	2.53	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	2	0.31	0.31	0.46	0.92	0.92	1.07	1.07	1.07	1.07	2.21	2.53	0.61	1.13	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	3	0.31	0.31	0.46	0.92	0.92	1.07	1.07	1.07	1.07	2.21	2.21	0.61	2.21	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	4	0.31	0.31	0.46	0.92	0.92	1.07	1.07	1.07	1.07	2.53	0.61	1.13	1.62	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	5	0.31	0.31	0.46	0.92	0.92	1.07	1.07	1.07	1.07	2.53	0.61	1.36	2.21	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	6	0.31	0.31	0.46	0.92	0.92	1.07	1.07	1.07	1.07	2.53	0.61	2.21	2.21	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	7	0.31	0.31	0.46	0.92	0.92	1.07	1.07	1.07	1.07	2.53	2.53	0.61	0.61	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	8	0.31	0.31	0.46	0.92	0.92	1.07	1.07	1.07	1.07	2.21	0.61	1.36	0.61	1.53	0.92	1.07	1.07	1.07	1.37	1.53
	9	0.31	0.31	0.46	0.92	0.92	1.07	1.07	1.07	1.07	2.53	0.61	2.21	0.61	1.53	0.92	1.07	1.07	1.07	1.37	1.53
Rehabilitation	1	3	3	4	4	5	4	4	4	3	6	6	6	6	4	5	3	4	3	5	3
	2	4	4	4	4	3	4	4	4	4	6	6	4	6	4	4	3	3	4	4	4
	3	3	3	4	3	4	3	3	4	3	6	6	3	6	4	5	3	3	3	4	3
	4	3	4	4	4	4	3	4	4	4	6	4	6	6	4	3	3	3	4	4	3
	5	2	2	3	4	4	4	2	4	4	6	2	6	6	4	4	2	4	4	4	3
	6	3	3	3	4	5	3	3	4	3	6	3	6	6	4	4	3	4	3	4	3
	7	2	3	3	4	5	3	3	4	3	6	6	3	2	4	5	2	4	3	5	2
	8	3	3	3	2	3	3	3	3	3	2	6	3	6	3	3	3	3	3	2	3
	9	3	4	4	4	4	4	4	4	4	4	6	3	6	4	4	4	3	4	4	3

7.2 System overflowing index and system breaking risk index after rehabilitation

Table S17 System overflowing index and system breaking risk after rehabilitation.

Scenario	Solution	System overflowing index	System breaking risk	Cost
Case1-S1	1	0.00	3.09	727986.08
	2	0.01	2.78	694827.99
	3	0.05	2.10	626080.85
	4	0.96	2.01	810841.02
	5	1.75	1.63	629313.11
	6	5.04	0.70	403565.77
	7	5.07	0.65	562545.80
Case1-S2	1	0.00	2.41	979789.80
	2	0.05	1.46	551085.05
	3	0.96	1.36	612163.22
	4	1.67	0.98	949652.60
	5	5.04	0.59	564745.18
	6	5.07	0.00	260440.00
Case1-S3	1	0.00	3.04	971931.01
	2	0.05	2.15	537984.83
	3	0.24	2.10	691970.50
	4	0.96	2.01	999547.02
	5	1.75	1.63	871149.11
	6	5.04	0.70	264175.77
	7	5.07	0.65	383525.80
Case1-S4	1	0.00	3.46	902153.71
	2	0.05	2.62	527074.60
	3	0.24	2.57	764127.88
	4	0.96	2.48	729378.40
	5	1.67	2.10	931266.56
	6	5.04	1.71	831348.37
	7	5.07	1.12	108285.18
Case1-S5	1	5.04	1.79	119672.70
	2	5.07	1.16	66006.35
Case1-S6	1	37.53	4.19	11556.00
Case2-S1	1	0.00	3.75	747920.91
	2	0.45	3.04	980680.47

Case2-S2	1	0.00	3.35	1432041.21
	2	2.62	2.70	1369802.91
	3	2.63	2.07	1419509.25
Case2-S3	1	0.00	3.05	1127562.76
	2	0.88	2.50	1180717.34
	3	0.95	2.46	889930.47
	4	3.99	2.17	1044570.91
	5	4.08	2.13	849038.13
	6	4.41	2.09	894492.26
	7	5.04	1.87	844442.12
	8	5.16	1.54	535086.94
	9	6.87	1.50	1078594.39

Table S18 Case1-S1 Hydraulic diagnostic index after rehabilitation

Index	Pip e	Solutio n 1	Solutio n 2	Solutio n 3	Solutio n 4	Solutio n 5	Solutio n 6	Solutio n 7
	C4	0.00	0.11	0.53	10.76	0.00	0.00	0.00
	C5	0.00	0.00	0.00	0.00	14.20	40.93	41.14
	C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydraulic diagnostic index	C15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0.00	0.11	0.53	10.76	0.00	15.87	16.08
	C5	0.00	0.00	0.00	0.00	14.20	25.06	25.06
	C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Surcharge index	C16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0.98	0.00	0.00	0.00	0.98	0.00	0.00
	C5	1.46	1.46	1.46	1.36	0.00	0.00	0.00
	C6	0.00	0.63	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	0.65	0.70	0.65	0.65	0.65	0.70	0.65
	C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pipe breaking index	C12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C13	0.00	0.00	0.00	0.00	0.00	0.00	0.00

C14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C118	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C114	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C116	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S19 Case1-S2 Hydraulic diagnostic index after rehabilitation

Index	Pipe	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6
	C4	0.00	0.53	10.76	0.00	0.00	0.00
	C5	0.00	0.00	0.00	13.56	40.93	41.14
	C6	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00	0.00
	C11	0.00	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	0.00	0.00	0.00
	C13	0.00	0.00	0.00	0.00	0.00	0.00
	C14	0.00	0.00	0.00	0.00	0.00	0.00
	C15	0.00	0.00	0.00	0.00	0.00	0.00
Hydraulic diagnostic index	C16	0.00	0.00	0.00	0.00	0.00	0.00
	C17	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0.00	0.53	10.76	0.00	15.87	16.08
	C5	0.00	0.00	0.00	13.56	25.06	25.06
	C6	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00	0.00
	C11	0.00	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	0.00	0.00	0.00
	C13	0.00	0.00	0.00	0.00	0.00	0.00
	C14	0.00	0.00	0.00	0.00	0.00	0.00
	C15	0.00	0.00	0.00	0.00	0.00	0.00
	C16	0.00	0.00	0.00	0.00	0.00	0.00
Surcharge index	C17	0.00	0.00	0.00	0.00	0.00	0.00
	C4	1.05	0.00	0.00	0.98	0.00	0.00
	C5	1.36	1.46	1.36	0.00	0.00	0.00
	C6	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00	0.00
	C11	0.00	0.00	0.00	0.00	0.00	0.00
Pipe breaking index	C12	0.00	0.00	0.00	0.00	0.00	0.00
	C13	0.00	0.00	0.00	0.00	0.00	0.00

C14	0.00	0.00	0.00	0.00	0.00	0.00
C15	0.00	0.00	0.00	0.00	0.00	0.00
C16	0.00	0.00	0.00	0.00	0.59	0.00
C17	0.00	0.00	0.00	0.00	0.00	0.00
C118	0.00	0.00	0.00	0.00	0.00	0.00
C1	0.00	0.00	0.00	0.00	0.00	0.00
C2	0.00	0.00	0.00	0.00	0.00	0.00
C3	0.00	0.00	0.00	0.00	0.00	0.00
C114	0.00	0.00	0.00	0.00	0.00	0.00
C116	0.00	0.00	0.00	0.00	0.00	0.00

Table S20 Case1-S3 Hydraulic diagnostic index after rehabilitation

Index	Pipe	Solutio n 1	Solutio n 2	Solutio n 3	Solutio n 4	Solutio n 5	Solutio n 6	Solutio n 7	
Hydraulic diagnostic index	C4	0.00	0.53	2.66	10.76	0.00	0.00	0.00	
	C5	0.00	0.00	0.00	0.00	14.20	40.93	41.14	
	C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	Surcharge index	C4	0.00	0.53	2.66	10.76	0.00	15.87	16.08
		C5	0.00	0.00	0.00	0.00	14.20	25.06	25.06
		C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C7		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C8		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C9		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C10		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C11		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C12		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C13		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C14		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C15		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C16		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C17		0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Pipe breaking index		C4	0.98	0.00	0.00	0.00	0.98	0.00	0.00
		C5	1.36	1.46	1.46	1.36	0.00	0.00	0.00
		C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C8	0.70	0.70	0.65	0.65	0.65	0.70	0.65	
	C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	C10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C11	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
C12	0.00	0.00	0.00	0.00	0.00	0.00	0.00		

C13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C118	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C114	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C116	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S21 Case1-S4 Hydraulic diagnostic index after rehabilitation

Index	Pipe	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7
	C4	0.00	0.53	2.66	10.76	0.00	0.00	0.00
	C5	0.00	0.00	0.00	0.00	13.56	40.93	41.14
	C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydraulic diagnostic index	C15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0.00	0.53	2.66	10.76	0.00	15.87	16.08
	C5	0.00	0.00	0.00	0.00	13.56	25.06	25.06
	C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Surcharge index	C16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0.98	0.00	0.00	0.00	0.98	0.00	0.00
	C5	1.36	1.46	1.46	1.36	0.00	0.00	0.00
	C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C10	1.12	1.16	1.12	1.12	1.12	1.12	1.12
Pipe breaking index	C11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C13	0.00	0.00	0.00	0.00	0.00	0.00	0.00

C14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C118	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2	0.00	0.00	0.00	0.00	0.00	0.59	0.00
C3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C114	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C116	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S22 Case1-S5 Hydraulic diagnostic index after rehabilitation

Index	Pipe	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
	C4	0.00	0.53	2.66	0.00	0.00
	C5	0.00	0.00	0.00	40.93	41.14
	C6	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00
	C11	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	0.00	0.00
	C13	0.00	0.00	0.00	0.00	0.00
	C14	0.00	0.00	0.00	0.00	0.00
	C15	0.00	0.00	0.00	0.00	0.00
Hydraulic diagnostic index	C16	0.00	0.00	0.00	0.00	0.00
	C17	0.00	0.00	0.00	0.00	0.00
	C4	0.00	0.53	2.66	15.87	16.08
	C5	0.00	0.00	0.00	25.06	25.06
	C6	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00
	C11	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	0.00	0.00
	C13	0.00	0.00	0.00	0.00	0.00
	C14	0.00	0.00	0.00	0.00	0.00
	C15	0.00	0.00	0.00	0.00	0.00
	C16	0.00	0.00	0.00	0.00	0.00
Surcharge index	C17	0.00	0.00	0.00	0.00	0.00
	C4	1.05	0.00	0.00	0.00	0.00
	C5	1.46	1.46	1.46	0.00	0.00
	C6	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00
	C8	0.70	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00
	C10	1.16	1.16	1.16	1.16	1.16
	C11	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	0.00	0.00
Pipe breaking index	C13	0.00	0.00	0.00	0.00	0.00

C14	1.03	0.00	0.00	0.00	0.00
C15	0.63	0.00	0.00	0.00	0.00
C16	0.00	0.00	0.00	0.00	0.00
C17	0.00	0.00	0.00	0.00	0.00
C118	0.00	0.00	0.00	0.00	0.00
C1	0.00	0.00	0.00	0.63	0.00
C2	0.00	0.63	0.00	0.00	0.00
C3	0.00	0.00	0.00	0.00	0.00
C114	0.00	0.00	0.00	0.00	0.00
C116	0.00	0.00	0.00	0.00	0.00

Table S23 Case1-S6 Hydraulic diagnostic index after rehabilitation

Index	Pipe	Solution	
Hydraulic diagnostic index	C4	0.00	
	C5	38.63	
	C6	0.00	
	C7	0.00	
	C8	0.00	
	C9	0.00	
	C10	611.76	
	C11	0.00	
	C12	0.00	
	C13	0.00	
	C14	0.00	
	C15	0.00	
	C16	0.00	
	C17	0.00	
	Surcharge index	C4	90.63
		C5	99.57
		C6	78.63
C7		90.70	
C8		93.15	
C9		97.71	
C10		100.00	
C11		0.00	
C12		0.00	
C13		0.00	
C14		0.00	
C15		0.00	
C16		0.00	
C17		0.00	
Pipe breaking index		C4	0.00
		C5	0.00
		C6	0.00
	C7	0.00	
	C8	0.00	
	C9	0.00	
	C10	3.15	
	C11	0.00	
	C12	0.00	
	C13	0.00	
C14	0.00		

C15	0.00
C16	0.00
C17	0.00
C118	0.00
C1	0.00
C2	0.00
C3	0.00
C114	1.03
C116	0.00

Table S24 Case2-S1 Hydraulic diagnostic index after rehabilitation

Index	Pipe	Solution 1	Solution 2
	C4	0.00	0.00
	C5	0.00	0.00
	C6	0.00	8.37
	C7	0.00	0.00
	C8	0.00	0.00
	C9	0.00	0.00
	C10	0.00	0.00
	C11	0.00	0.00
	C12	0.00	0.00
	C13	0.00	0.00
	C14	0.00	0.00
	C15	0.00	0.00
Hydraulic diagnostic index	C16	0.00	0.00
	C17	0.00	0.00
	C4	0.00	0.00
	C5	0.00	0.00
	C6	0.00	8.37
	C7	0.00	0.00
	C8	0.00	0.00
	C9	0.00	0.00
	C10	0.00	0.00
	C11	0.00	0.00
	C12	0.00	0.00
	C13	0.00	0.00
	C14	0.00	0.00
	C15	0.00	0.00
	C16	0.00	0.00
Surcharge index	C17	0.00	0.00
	C4	1.05	0.98
	C5	1.46	1.36
	C6	0.59	0.00
	C7	0.00	0.00
	C8	0.65	0.70
	C9	0.00	0.00
	C10	0.00	0.00
	C11	0.00	0.00
	C12	0.00	0.00
	C13	0.00	0.00
	C14	0.00	0.00
Pipe breaking index	C15	0.00	0.00

C16	0.00	0.00
C17	0.00	0.00
C118	0.00	0.00
C1	0.00	0.00
C2	0.00	0.00
C3	0.00	0.00
C114	0.00	0.00
C116	0.00	0.00

Table S25 Case2-S2 Hydraulic diagnostic index after rehabilitation

Index	Pipe	Solution 1	Solution 2	Solution 3
	C4	0.00	0.00	0.00
	C5	0.00	0.00	0.00
	C6	0.00	0.00	0.00
	C7	0.00	0.00	0.00
	C8	0.00	44.39	44.64
	C9	0.00	0.00	0.00
	C10	0.00	0.00	0.00
	C11	0.00	0.00	0.00
	C12	0.00	0.00	0.00
	C13	0.00	0.00	0.00
	C14	0.00	0.00	0.00
	C15	0.00	0.00	0.00
Hydraulic diagnostic index	C16	0.00	0.00	0.00
	C17	0.00	0.00	0.00
	C4	0.00	0.00	0.00
	C5	0.00	0.00	0.00
	C6	0.00	6.61	6.61
	C7	0.00	12.12	12.36
	C8	0.00	25.67	25.67
	C9	0.00	0.00	0.00
	C10	0.00	0.00	0.00
	C11	0.00	0.00	0.00
	C12	0.00	0.00	0.00
	C13	0.00	0.00	0.00
	C14	0.00	0.00	0.00
	C15	0.00	0.00	0.00
	C16	0.00	0.00	0.00
Surcharge index	C17	0.00	0.00	0.00
	C4	0.00	0.00	0.00
	C5	0.00	0.00	0.00
	C6	0.00	0.00	0.00
	C7	0.00	0.00	0.00
	C8	0.70	0.00	0.00
	C9	0.00	0.00	0.00
	C10	0.00	0.00	0.00
	C11	0.00	0.00	0.00
	C12	0.00	0.00	0.00
Pipe breaking index	C13	0.00	0.00	0.00

C14	0.00	0.00	0.00
C15	0.00	0.00	0.00
C16	0.63	0.63	0.00
C17	0.63	0.63	0.63
C118	0.00	0.00	0.00
C1	0.00	0.00	0.00
C2	0.00	0.00	0.00
C3	0.80	0.80	0.80
C114	0.00	0.00	0.00
C116	0.59	0.63	0.63

Table S26 Case2-S3 Hydraulic diagnostic index after rehabilitation

Index	Pipe	Soluti on 1	Soluti on 2	Soluti on 3	Soluti on 4	Soluti on 5	Soluti on 6	Soluti on 7	Soluti on 8	Soluti on 9
	C4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	21.86	22.87	26.54	34.86	24.52	41.51
	C13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydraulic diagnostic index	C14	0.00	0.00	0.00	28.70	28.93	29.84	0.00	29.38	32.80
	C15	0.00	16.40	17.77	0.00	0.00	0.00	17.08	0.00	0.00
	C16	0.00	0.00	0.00	0.00	0.00	0.00	32.80	17.31	22.10
	C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.10
	C8	0.00	0.00	0.00	0.00	0.00	0.37	2.08	0.12	3.30
	C9	0.00	0.00	0.00	0.38	0.64	1.65	3.18	1.14	4.45
	C10	0.00	0.00	0.00	2.92	3.18	3.94	5.72	3.68	6.73
	C11	0.00	0.00	0.00	8.01	8.26	9.02	10.80	8.51	11.82
	C12	0.00	0.00	0.00	10.55	10.80	11.56	13.09	11.05	14.10
	C13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C14	0.00	0.00	0.00	28.70	28.93	29.84	0.00	29.38	32.80
	C15	0.00	16.40	17.77	0.00	0.00	0.00	33.49	0.00	0.00
Surcharge index	C16	0.00	0.00	0.00	0.00	0.00	0.00	16.40	17.31	22.10
	C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pipe breaking index	C11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C13	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91

C14	0.96	0.96	0.96	0.00	0.00	0.00	0.96	0.00	0.00
C15	0.59	0.00	0.00	0.63	0.63	0.59	0.00	0.63	0.59
C16	0.59	0.63	0.59	0.63	0.59	0.59	0.00	0.00	0.00
C17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C118	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C114	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C116	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Reference

- Bennis, S., Bengassem, J., and Lamarre, P. (2003). "Hydraulic Performance Index of a Sewer Network." *Journal of Hydraulic Engineering*, 129(7), 504–510.
- Kleiner, Y., and Rajani, B. (2001). "Comprehensive review of structural deterioration of water mains: statistical models." *Urban Water*, 3(3), 131–150.
- Zhang, C., Wang, Y., Li, Y., and Ding, W. (2017). "Vulnerability Analysis of Urban Drainage Systems: Tree vs. Loop Networks." *Sustainability*, 9(3), 397.

Supplemental Materials 2

1. Hydraulic Model

1.1 Surcharge index

The surcharge index (N_i) represents the ratio between the water elevation and the maximum depth at one manhole (Bennis et al. 2003).

$$N_i = 100\% \times \frac{H_i^{US}}{G_i} \quad (S1)$$

Where N_i is the rating expressed as a percentage of the burial depth, varying from N_{min} of 0% to N_{max} of 100%. H_i^{US} is the height of maximum surcharge in the manhole situated immediately upstream from pipe i for the design flow; G_i is the depth at which the pipe is buried, measured from the ground surface to the upstream crown of pipe i .

1.2 Overflowing Index

The overflowing index is a hydraulic diagnostic model given by Bennis et al. (2003). In this indexes system, the surcharge at a manhole has two sources. The first index is a net surcharge (N_i^i) at that manhole. The second index is the downstream effects (N_i^{DS}). After separating the surcharge to this two sources, we can multiple the surcharge effects of a pipe (S^i) to other pipes in order to know which pipe needs to be fixed.

$$N_i^i = N_{min} + (N_{max} - N_{min}) \frac{(H_i^{US} - H_i^{DS})}{G_i} \quad (S2)$$

$$N_i^{DS} = N_i - N_i^i = (N_{max} - N_{min}) \frac{H_i^{DS}}{G_i} \quad (S3)$$

Where H_i^{US} is equal to G_i this means that the height of the surcharge has reached the ground surface and that the pipe will overflow. N_i^i is the net effect of the surcharge that pipe i causes within itself; and H_i^{DS} is the height of the downstream surcharge in relation to the crown of pipe i .

1.3 System overflowing index

In this study, following the system overflowing given by Hosseini and Ghasemi (2012), we used that index to optimize the system hydraulic performance in a drainage system. We applied two system overflowing indexes. The first one used the multiple overflowing indexes of each manhole (S^i). The second one used the surcharge index at each manhole (Dion and Bennis 2010). The first system overflowing index should have a higher sensitivity to the narrow pipe than the second one. From the comparison of these two indexes, we can know whether an extra hydraulic diagnostic model is necessary to solve the overflowing problem.

The first systematical overflowing index (N_{S-I}) is calculated with a weighted number of pipe length (S4):

$$N_{S-I} = \frac{\sum l_i S^i}{\sum l_i} \quad (S4)$$

Where l_i is the length of the pipe i , and S^i is the multiple overflowing index of pipe i .

The second system overflowing index is N_{S-II} :

$$N_{S-II} = \frac{\sum l_i N^i}{\sum l_i} \quad (S5)$$

In this equation, l_i = length of pipe i ; N^i = hydraulic overflow index of pipe i .

2. Risk Index

2.1 Pipe Risk Assessment

In our research, we assumed that the deterioration of a pipe follows an exponential relationship (Duchesne et al. 2013). The assumed equation is (Eq.S6):

$$P^i = 100 \times e^{0.02 \times (t-100)} \quad (S6)$$

Where P^i = the possibility of failure of the pipe i , and t = the time of that pipe (year). If the aged year is over 100, $P^i = 1$; and if the the benefit year is longer than the aged year, $P^i = 0$.

The consequence of failure (Baah et al. 2015) was calculated by (Eq. S8) :

$$C_i = \sum_k S_k \times PV_k \times W_k \quad (S8)$$

Where C_i = the consequence of failure of pipe i ; k = the impact factor, S_k = the classification of impact factors; PV_k = the performance value of each classification; and W_k = the weighted number of each impact factor. The indexes values are in Table S1.

Table S1 Weighted score for the consequence of failure. This table was given by (Baah et al., 2015)

Impact factor (k)	Classification (S_k)	Performance values (PV_k)	Weighted number (W_k)
Roadway type	Intersecting ON road class 2	3	0.2
	Intersecting ON road class 4	2.4	
	Intersecting ON road class 5	1	
Intersecting a railway track	Yes	3	0.2
	No	0	
Pipe size	Diameter > 900 mm	3	0.16
	Diameter > 600 & <=900 mm	2.25	
	Diameter > 300 & <=600 mm	1.5	
	Diameter > 300	1	

	Depth > 10m	3	
Pipe burial depth	Depth <=10 & >3m	1.5	0.16
	Depth <=3m	1	
Located downtown	Yes	3	0.2
	No	0	
Proximity to hospital	Pipe distance <= 120 m	3	0.2
	Pipe distance > 120 m	0	
Proximity to school	Pipe distance <= 200m	3	0.2
	Pipe distance > 200m	0	
Distance to building	Distance < 5m	3	
	Distance >= 5 & <=10 m	1.5	0.2
	Distance > 10m	0	
Proximity to river	Pipe distance <= 15m	3	0.2
	Pipe distance >15m	0	
Proximity to park or recreational areas	Pipe distance <= 20 m	3	0.16
	Pipe distance > 20m	0	
Proximity to stormwater pipe	Distance <= 10m	3	0.2
	Distance > 10m	0	

The system breaking risk index is (Eq.S7):

$$R_S = \frac{\sum l_i C_i P^i}{\sum l_i} \quad (S7)$$

where R_S = the risk of the system; C_i = the consequence of a failure of pipe i ; P^i = the possibility of failure of pipe i ; and l_i = the length of pipe i .

3. Rehabilitation Methods

Drainage rehabilitation is a complex process, but it is commonly simplified to six rehabilitation methods (Altarabsheh et al. 2018a; b): 1 refers to doing nothing, 2 is routine cleaning, 3 is shotcrete, 4 is using cured-in-place pipe technique, 5 is to reinforce with fiberglass sliplining, and 6 is to dig and replace with a concrete pipe. The ordinal number 1-5 can reinforce the pipe to decrease the aging, and the ordinal number 6 can replace the pipe to relieve the aging and overflowing problems (Table S2). It is hard to define the expense at a different diameter of a new pipe. In order to let the model distinguish the difference between the different diameters of the pipe, we add a pipe cost that relates to the diameter and length of a new pipe.

Table S2 The rehabilitation matrix (Altarabsheh et al. 2018a)

Rehabilitation	Action	Cost (\$/m)	Disruption Cost (\$/m)	Pipe Cost (\$/m)	Benefit (year)
1	Do nothing	0	0	0	-
2	Routine cleaning	16	0	0	10
3	Shotcrete	656	0	0	20
4	Cured-in-place pipe	1558	0	0	50

5	Reinforced fiberglass sliplining	2231	0	0	100
6	Dig and replace with concrete pipe	1148	656	<i>Diameter</i> \times <i>Length</i>	50

4. Postprocessing

A postprocessing submodel can transform the results given by different frameworks to a comparable value. Besides, this module can select results from the Pareto Front according to the cost.

5. References

- Approach to Rehabilitate and Maintain Sewer Networks Based on Whole Lifecycle Behavior.” *Journal of Computing in Civil Engineering*, 32(1), 04017069.
- Altarabsheh, A., Ventresca, M., and Kandil, A. (2018b). “New Approach for Critical Pipe Prioritization in Wastewater Asset Management Planning.” *Journal of Computing in Civil Engineering*, 32(5), 04018044.
- Baah, K., Dubey, B., Harvey, R., and McBean, E. (2015). “A risk-based approach to sanitary sewer pipe asset management.” *Science of The Total Environment*, 505, 1011–1017.
- Bennis, S., Bengassem, J., and Lamarre, P. (2003). “Hydraulic Performance Index of a Sewer Network.” *Journal of Hydraulic Engineering*, 129(7), 504–510.
- Dion, Y., and Bennis, S. (2010). “A global modeling approach to the hydraulic performance evaluation of a sewer network.” *Canadian Journal of Civil Engineering*, 37(11), 1432–1436.
- Duchesne, S., Beardsell, G., Villeneuve, J.-P., Toumbou, B., and Bouchard, K. (2013). “A Survival Analysis Model for Sewer Pipe Structural Deterioration: A sewer deterioration model.” *Computer-Aided Civil and Infrastructure Engineering*, 28(2), 146–160.
- Hosseini, S. M., and Ghasemi, A. (2012). “Hydraulic performance analysis of sewer systems with uncertain parameters.” *Journal of Hydroinformatics*, 14(3), 682–696.

Supplemental Materials 3

1. Hydraulics and Risk Combined Model (HRCM)

The HRCM model is a decision support system that combines hydraulic overflowing and pipe breaking into one framework to provide rehabilitation strategies. This model has five sections: (1) hydraulic model, which calculates the hydraulic grade line and the system overflowing index; (2) risk assessment model, which calculate the pipe breaking risk and the system pipe breaking index; (3) rehabilitation module, which includes some rehabilitation strategies which can fix the drainage system by replacing or reinforcing pipes; (4) multi-objective optimization, which assigns rehabilitation methods to different pipes and finds the optimal rehabilitation strategies to enhances the performance of the system; and (5) post-processing modul, which selects the final rehabilitation strategy among the optimal strategies according to a set of pre-defined criteria.

1.1 Hydraulic calculation

The HRCM employs two indexes to calculate the system overflowing index (Eq. S1) (Dion and Bennis 2010), and chain flooding index (Eq. S2-S3) (Bennis et al. 2003).

$$N_i = 100\% \times \frac{H_i^{US}}{G_i} \quad (S1)$$

$$N_i^i = N_{min} + (N_{max} - N_{min}) \frac{(H_i^{US} - H_i^{DS})}{G_i} \quad (S2)$$

$$N_i^{DS} = N_i - N_i^i = (N_{max} - N_{min}) \frac{H_i^{DS}}{G_i} \quad (S3)$$

where,

N_i = overflowing index of the i^{th} manhole;

H_i^{US} = height of maximum surcharge at the manhole situated immediately upstream from pipe i for the design flow;

G_i = depth at which the pipe is buried, measured from the ground surface to the upstream crown of pipe i ;

N_i^i = net effect of the surcharge that pipe i causes within itself;

H_i^{DS} = height of the downstream surcharge in relation to the crown of pipe i .

N_i^{DS} = effect of surcharge on pipe i originating from downstream.

In order to obtain a single index for the entire network, we employ the system index N_s to calculate the final index as in Eq. S4 (Hosseini and Ghasemi, 2012):

$$N_s = \frac{\sum l_i N_i^i}{\sum l_i} \quad (\text{S4})$$

where, l_i = length of pipe i ;

N^i = hydraulic overflow index of pipe i .

1.2 Pipe Risk Assessment

The consequence of failure and the probability of failure compose the risk index. The risk index is noted as R_{global} and estimated by Eq. S5:

$$R_{global} = \frac{\sum l_i C_i P^i}{\sum l_i} \quad (\text{S5})$$

where, R_{global} = risk of the system;

C_i = consequence of a failure of pipe i ;

P^i = possibility of failure of pipe i , and l_i is the length of pipe i .

An exponential equation is used in the HRCM model to calculate the possibility of failure of a pipe (Duchesne et al. 2013).

The consequence of failure was calculated by Eq. (S6) (Baah et al. 2015):

$$C_i = \sum_k S_k \times PV_k \times W_k \quad (S6)$$

where, C_i = consequence of failure of pipe i ;

k = impact factor;

S_k = classification;

PV_k = performance value;

W_k = weighted number.

Table S1 Weighted score for the consequence of failure. This table was given by (Baah et al., 2015)

Impact factor (k)	Classification (S_k)	Performance values (PV_k)	Weighted number (W_k)
Roadway type	Intersecting ON road class 2	3	0.2

	Intersecting ON road class 4	2.4	
	Intersecting ON road class 5	1	
Intersecting a railway track	Yes	3	0.2
	No	0	
Pipe size	Diameter > 900 mm	3	0.16
	Diameter > 600 & <=900 mm	2.25	
	Diameter > 300 & <=600 mm	1.5	
	Diameter > 300	1	
Pipe burial depth	Depth > 10m	3	0.16
	Depth <=10 & >3m	1.5	
Located downtown	Depth <=3m	1	0.2
	Yes	3	
Proximity to hospital	No	0	0.2
	Pipe distance <= 120 m	3	
Proximity to school	Pipe distance > 120 m	0	0.2
	Pipe distance <= 200m	3	
Distance to building	Pipe distance > 200m	0	0.2
	Distance < 5m	3	
	Distance >= 5 & <=10 m	1.5	

	Distance > 10m	0	
Proximity to river	Pipe distance <= 15m	3	0.2
	Pipe distance >15m	0	
	Pipe distance <= 20 m	3	
Proximity to park or recreational areas	Pipe distance > 20m	0	0.16
	Distance <= 10m	3	
Proximity to stormwater pipe	Distance > 10m	0	0.2

1.3 Rehabilitation methods

Six rehabilitation methods are used in the HRCM: (1) do nothing; (2) routine cleaning; (3) shotcrete; (4) cured-in-place pipe technique; (5) reinforce with fibreglass sliplining; and (6) dig and replace with a concrete pipe (Altarabsheh et al., 2018). The cost in the HRCM is calculated based on the rehabilitation method, diameter and length of pipes (Cai et al. 2020). The rehabilitation methods can change the probability of failure of a pipe to change the pipe breaking risk index (Table S2).

Table S2 The rehabilitation matrix

Rehabilitation	Action	Cost (\$/m)	Disruption Cost (\$/m)	Pipe Cost (\$/m)	Benefit (year)
1	Do nothing	0	0	0	-

2	Routine cleaning	16	0	0	10
3	Shotcrete	656	0	0	20
4	Cured-in-place pipe	1558	0	0	50
5	Reinforced fiberglass sliplining	2231	0	0	100
6	Dig and replace with concrete pipe	1148	656	<i>Diameter</i> \times <i>Length</i>	50

References

- Altarabsheh A, Kandil A, Ventresca M (2018) New Multiobjective Optimization Approach to Rehabilitate and Maintain Sewer Networks Based on Whole Lifecycle Behavior. *Journal of Computing in Civil Engineering* 32:04017069. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000715](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000715)
- Baah K, Dubey B, Harvey R, McBean E (2015) A risk-based approach to sanitary sewer pipe asset management. *Science of The Total Environment* 505:1011–1017. <https://doi.org/10.1016/j.scitotenv.2014.10.040>
- Bennis S, Bengassem J, Lamarre P (2003) Hydraulic Performance Index of a Sewer Network. *Journal of Hydraulic Engineering* 129:504–510. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2003\)129:7\(504\)](https://doi.org/10.1061/(ASCE)0733-9429(2003)129:7(504))
- Cai X, Shirkhani H, Mohammadian M (2020) A New Risk-Based Approach for Sewerage Flooding and Ageing Rehabilitation Management --The Structure of Hydraulics and Risk Combined Model (HRCM). revision request
- Dion Y, Bennis S (2010) A global modeling approach to the hydraulic performance evaluation of a sewer network. *Can J Civ Eng* 37:1432–1436. <https://doi.org/10.1139/L10-082>
- Duchesne S, Beardsell G, Villeneuve J-P, et al (2013) A Survival Analysis Model for Sewer Pipe Structural Deterioration: A sewer deterioration model. *Computer-Aided Civil and Infrastructure Engineering* 28:146–160. <https://doi.org/10.1111/j.1467-8667.2012.00773.x>

Hosseini SM, Ghasemi A (2012) Hydraulic performance analysis of sewer systems with uncertain parameters. *J Hydroinform* 14:682–696.
<https://doi.org/10.2166/hydro.2011.129>