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A Decision Support System to Optimize Water Distribution Systems Maintenance and Rehabilitation under Changing Climate:
Literature Review

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Executive Summary

The National Research Council of Canada (NRC) and Infrastructure Canada (INFC), in partnership with collaborators and stakeholders are tasked with developing decision support tools, including codes, guides, and models for the design of resilient new Core Public Infrastructure (CPI) and rehabilitation and maintenance of existing CPI to ensure adequate capacity against existing climate variability, climate change, and extreme weather events. Within this effort, water/wastewater systems management has been identified as one of the most significant areas likely to be impacted by climate change through changes in temperature, precipitation, freeze/thaw cycles, etc. In an earlier NRC/INFC-funded project, the likely impact of a changing climate on the demand, hydraulic capacity and water quality in Water Distribution Systems (WDS) was described and approaches to quantify this impact were articulated. The main objective of this current project is to incorporate these impacts into the decision process on WDS operation, maintenance and renewal planning.

The current report is the first step toward mapping the state of the art in the field of WDS asset renewal planning and addresses the problem from the perspectives of WDS design, expansion, and rehabilitation. Multi-objective optimization models seem to be the most suited to solving asset renewal problems where factors that are difficult to monetize (e.g., environmental impacts, quality of life) are to be explicitly considered. Among the several optimization algorithms reviewed, the Non-dominated Sorting Genetic Algorithm (NSGA) appears to perform well, especially on very high-dimensionality problems with a relatively large number of decision variables. Therefore, NSGA is the preferred technique for model development in the next phase of this project.

1 Introduction

Canada's buildings, bridges, roads, water and wastewater systems are at risk due to the effects of climate change and extreme weather. There are limitations in current approaches to design and rehabilitation of Core Public Infrastructure (CPI), which are based on past climatic loads rather than on expected future climatic loads. This may lead to early failure of CPI, long service disruption, high rehabilitation and replacement costs, and considerable negative socio-economic impacts. The consequences of failure of existing and new CPI, including, buildings, bridges, roads, water and wastewater systems can be quite significant and could include fatalities, injuries and illnesses, increased costs to infrastructure owners, and unforeseen costs to the infrastructure users, to insurers, and to municipal, provincial/territorial and federal governments.

The National Research Council of Canada (NRC) and Infrastructure Canada (INFC), in partnership with collaborators and stakeholders are tasked with developing decision support tools, including codes, guides, and models for the design of resilient new CPI and rehabilitation and maintenance of existing CPI to ensure adequate capacity against existing and future climate change and extreme weather events. Within this effort, water/wastewater systems management has been identified as one of the most significant areas likely to be impacted by climate change through changes in temperature, precipitation, freeze/thaw cycles, etc. Our work in the Climate Resilient Buildings and Core Public Infrastructure (CRB-CPI) project indicated that both water main breaks and system demands could be impacted by climate change (Roshani E. , Kleiner, Colombo, & Salomons, 2022). This has also been shown in the literature. For instance, current research indicates that per capita demand may increase from 0.5% to 5% per one degree of temperature increase (Staats, 2018) and (Akuoko-Asibey, Nkemdirim, & Draper, 2013).

Billions of dollars are spent annually on maintaining and rehabilitating water distribution systems, mostly on replacing buried mains to a) reduce costs associated with breaks of deteriorating water mains and b) increase network hydraulic capacity to satisfy increasing demands. Decisions on replacement or rehabilitation of water mains are often made in a reactive mode, without the anticipation of future performance and without proper holistic planning. This is especially true for small and medium water utilities that lack the resources available to large utilities to deploy (often-proprietary) sophisticated break prediction models and long-term planning. One common denominator to most small and large water utilities is their failure (so far) to consider future climate change impact on their pipe renewal decision making.

In an earlier NRC/INFC-funded project the likely impact of a changing climate on the demand, hydraulic capacity and water quality in WDS was described and approaches to quantify this impact were articulated. The main objective of this project is to incorporate this impact into the decision process on WDS operation, maintenance and renewal planning.

The optimization model and decision support system (DSS, a computer tool) developed in this project will aid in pipe renewal decision making while considering climate change impact on pipe deterioration, breakage frequency, and demand growth. The tool will help decision makers make more informed decisions on system renewal and reduce overall capital and operational costs while extending asset service life and accounting for the climatic variables. Finally, a guideline document was developed to assist asset managers in prioritising rehabilitation investments to maximise system resilience, functionally and efficiency.

1.1 Background

Constructing, maintaining, and rehabilitating water infrastructure is a costly and important endeavor for cities around the world (United Nations Human Settlements Programme (UN Hbitat), 2012). A study by (EPA Office of Water, 2018) indicated that $472.6 billion is needed to rehabilitate drinking water systems in the USA to maintain current service levels in the next 20 years. An equivalent Canadian study indicated that $12 to 15 billion is spent annually on municipal infrastructure, including water, wastewater, roads, etc. (Federation of Canadian Municipalities and National Research Council, 2006). Most of the need is in replacing and rehabilitating deteriorated water mains in water distribution systems. In North America, water distributions systems leak at an average rate of 10-30% (Brothers, 2001), (Farley, 2001), (Folkman, 2018) and at comparable rates in Europe (European Environment Agency, 2010). Water loss through leaks as well as increase in pipe roughness due to deteriorated inner surfaces of water mains, increase energy use and energy costs of pumping in water distribution systems.

Climate change and its negative impacts is seen as a major concern in both developed and developing countries. Water distribution and transmission systems are affected by climate change. The impacts of climate change on water consumption was studies by (Maidment & Miaou, 1986), (Mote, et al., 1999), (Protopapas, Katchamart, & Platonova, 2000), (Downing, et al., 2003), , (Sadiq & Karney, 2004), (Neale, Carmichael, & Cohen, 2007), (Praskievicz & Chang, 2009), (Akuoko-Asibey, Nkemdirim, & Draper, 2013), (Staats, 2018), (Dimkić, 2020), (Rasifaghihi, Li, & Haghighat, 2020), and (Roshani E. , Kleiner, Colombo, & Salomons, 2022). In all of these studies, authors indicated that the changing climate would lead to increasing demand in water distribution systems. Impacts on water distribution systems (WDS) capacity was studied by (Roshani & Filion, 2013), (Roshani & Filion, 2014) and (Basupi & Kapelan , 2015), (Roshani, Kleiner, & Colombo, 2018). These authors also indicated the risks associated with uncertain WDS demands could result in undersized water main (requiring replacement or reinforcement) due to extra demands caused by climate change.

The structural deterioration of buried water mains is also likely to be affected by the changing climate. This effect can act to accelerate or decelerate deterioration, however, in cold countries such as Canada, where many pipe breaks are associated with cold temperatures inducing frost heave, the likely net effect is deceleration of pipe deterioration. Unfortunately, there is a lack of knowledge on quantifying the relation between climate change and watermain deterioration (UKWIR, 2012). The impacts of local climate on pipe breaks was studied by (Clark, 1970), (Newport, 1981), (Lochbaum, 1993), (Habibian, 1994), (Rajani & Kleiner, 2001) and others. These authors often showed that water main break rates would be affected by parameters such as temperature and precipitations. Others researchers also investigated proxy climate variables such as freezing index and rainfall deficit (Kleiner & Rajani, 2002) (Hu & Hubble, 2007) (Kleiner & Rajani, 2010), (Kleiner & Rajani, 2012), (Rajani, Kleiner, & Sink, 2012), (Laucelli, Rajani, Kleiner, & Giustolisi, 2014), (Wols & Van Thienen, 2014), (Wols & Van Thienen, 2016). Their outcomes indicated that these variables also affect break rates.

The literature also reflects that other water distribution factors such as energy consumption and water quality could be influenced by climate variables. (Dandy, Roberts, Hewitson, & Chrystie, 2006), (Dandy, Bogdanowicz, Craven, Maywald, & Liu, 2008), (Wu, Simpson, & Maier, 2010a), (Wu, Maier, & Simpson, 2010b), (Roshani, MacLeod, & Filion, 2012), (Wu W. , Simpson, Maier, & Marchi, 2012), and (Wu, Simpson, & Maier, 2012) studied energy consumptions, and (Casas-Monroy, et al., 2018), (Kimbrough, 2019), (Fish, Reeves-McLaren, Husband, & Boxall, 2020) studied water quality under climate change.

In some countries, governments started imposing taxes on GHG emissions, including those deemed to be caused by WDSs, in an attempt to to mitigate greenhouse gas (GHG) emissions towards curbing climate change. These can be construed as economic impact of climate change (Stern, et al., 2006). The water sector is a heavy consumer of electricity for raw water pumping in transmission systems and for pumping treated drinking water in distribution networks. For example, in the UK, roughly 3% of generated electricity is consumed by the water industry (Ainger, et al., 2009). Another estimate indicates that the energy used to pump, and heat water is approximately 13% of all US electricity generation (Griffiths-Sattenspiel & Wilson, 2009) in which 80% is used to move water (EPRI, 2002). Worldwide, more than 54% of electricity is generated through the combustion of fossil-fuels (International Energy Agency (IEA) , 2022) which releases GHGs such as carbon dioxide into the atmosphere. Considerable portion of these GHG emissions is generated by the water industry. One study estimated that water provision and water heating accounts for 6% of GHGs emitted in the UK (Clarke, Grant, & Thornton, 2009). Comparing this study with (Ainger, et al., 2009) indicates that the water industry’s GHG emission is double its share of electricity consumption, which could be attributed to the heating system’s inefficiencies and pumping water during peak electricity consumption, where electricity is generated more by burning fossil fuel. It is worth noting that these numbers are much smaller in Canada, as more than 80% of electricity in Canada is generated from renewable and nuclear sources (this ratio varies among provinces).

Considering the existing literature and the economic size of water industry, it is fair to conclude that water distribution networks are affected by the changing climate and they could be part of the solution. Hence ensuring their long-term sustainability under climate change is a key in our endeavor to adapt and an effective tool to mitigate its impacts. Billions of dollars are spent annually to make sure that water distribution networks are staying up-to-date and capable of supplying safe and adequate flow of water to their communities. Wise planning and investment during a WDS rehabilitation process, that accounts for the long-term climate variables, could led into a system with higher adaptability to the climate change and achieve a higher level of GHG emission mitigations. It is worth noting that even medium size cities such as Ottawa has thousands of kilometers of buried water mains. It is only through a long-term gradual investment that these systems could adapt to the changing climate. Therefore, having access to such models that would account for the climatic variable would greatly help with optimized investment leading to adaptive assets.

Now that the impact of climate variables on water distribution systems are established, in the next sections, this report will focus on the extensive review of the literature pertaining to water distribution system design, expansion and rehabilitation planning.

2 WDS design, expansion and rehabilitation

2.1 Problem definition

From the underground stone water canals in Persepolis and aqueducts in Athens to advanced water distributions systems in large modern cities, supplying clean water with an affordable cost has always been a concern of human societies. Water distribution systems are at the heart of this concern. The purpose of a WDS is to convey and distribute - at acceptable pressures - water that is of acceptable quality to meet user demands. Specifically, a minimum pressure must typically be met under average day, peak demand and fire flow conditions and a disinfectant residual must be maintained in the bulk water in the pipe and at the user's faucet (Lansey, Basnet, Mays, & Woodburn, 1992). Network design, operation, and rehabilitation planning (in the case of existing systems) is required to meet these hydraulic and water quality performance standards.

Water network design/expansion, operation and rehabilitation have different meanings in the field of water distribution systems analysis. Water network design and expansion optimization is concerned with locating and sizing system components such as pipes, pumps, and tanks to provide pressure at or above a minimum required to meet peak and off-peak demands, to meet fire flow requirements, and to meet water quality requirements while minimizing construction and operational costs of the system (Boulos, Lansey, & Karney, 2004). In the design/expansion problem, component selection and sizing occur only at the start of the planning period of the system. Follow-up maintenance and system upgrades are often not (but should be) considered in the design problem.

What distinguishes the rehabilitation problem from the design/expansion problem is the time-dependent nature of decision variables in network rehabilitation. In aging networks, pipe wall condition tends to deteriorate with time (wall roughness increases and inner diameter decreases), while leakage and pipe failures tend to increase with time. The rehabilitation problem seeks to optimize the type and timing of pipe replacement, repair, and lining interventions that will minimize overall system costs. System costs include the capital cost of pipe renewal/replacement/rehabilitation and operation and maintenance costs that include pumping, repair, disinfection, etc. Pipe replacement/renewal, and renovation (lining) activities are subject to constraints on minimum pressure and demand requirements, annual budgetary limits, and water quality and reliability requirements (Engelhardt, Skipworth, Savic, Saul, & Walters, 2000). Unlike in the design/expansion problem, rehabilitation considers recurring replacement, and lining interventions throughout the entire planning period of a water distribution system. Since this project focuses on existing infrastructure, we only briefly explore the literature on design and expansion and mainly focus on literature related to solving the system rehabilitation/renewal planning problem while accounting for the impact of climate change.

2.1.1 Single and multi-objective optimization

The literature reflects that early efforts to optimize WDN-related decisions started in the mid-to late 1970s and focused on cost-minimization. These costs included capital costs and/or operation costs and/or renewal costs. Such minimization costs could also involve various constraints, such as total budget, annual budget, etc. These cost-minimization formulations were, as their name suggests, single-objective formulations, where the objective is to minimize total cost.

As the field advanced, researchers came to realize that a well-performing WDN has in fact more than one objective. Additional objectives could be maximizing reliability, minimizing water quality injuries/deaths, maximizing resilience, minimizing energy footprint, etc. It is clear that these objectives generally conflict with each other (e.g., maximizing reliability involves higher capital costs for redundancy therefore it is impossible to minimize cost while maximizing reliability) therefore problem formulation had to be adjusted. There are three manners with which this optimization problem can be adjusted, each with its benefits and limitations.

a. Maximize (or minimize) for one (presumably the most important) objective, while adding additional objectives as constraints. For example, minimize cost subject to an acceptable level of reliability (or an acceptable level of injuries), etc. This formulation has the drawback that often the set level of a constraint is arbitrary and may not provide the most suitable solution. This could be remedied by examining the sensitivity of the solution to perturbations in the constraint level (which would also provide the tradeoff between the single objective and the constraint objective), but this would require much more computational effort, especially when there are multiple constraints to be examined.
b. Bring all the considered objectives into one common set of units (cost or dollar values are often used. For example, when quantifying the consequences of pipe failure (towards the minimization of lifecycle costs) there are monetary costs (repair, replace, compensate for damage, etc.) and non-monetary costs (injuries, deaths, loss of time, loss of quality of life, etc.). To solve a problem involving these consequences, as a single objective problem (i.e., minimize cost), one would have to monetize all these costs. While there are several techniques to objectively monetize non-monetary costs/benefits, such as willingness to pay, surveys, and others, all have issues that detract from their objectivity and there is no one standard method that is globally accepted. Moreover, this issue can also create moral problems, such as trying to monetize the loss of life, for instance.
c. Formulate the optimization problem as a multi-objective one. As described earlier, one cannot simultaneously minimize or maximize conflicting objectives. However, one can find the tradeoff between conflicting objectives, i.e., what quantity of objective *x* would have to be given up in order to improve objective *y* by one unit. An efficient solution is defined as a non-dominated solution, where an objective cannot be improved without

giving up a (positive) quantity of a conflicting objective. As a consequence, each multi objective problem will have several (sometimes many or even infinite number of) efficient solutions. The collection of all efficient solutions it called the Pareto front. The solution of a multi-objective optimization thus provides a Pareto front, where all efficient solutions are presented as well as the tradeoffs amongst the various objectives. The decision maker (as opposed to the analyst) is the entity that decides which point on the Pareto front is appropriate for the particular asset owner. This approach is quite comprehensive, however there exists only a very limited number of mathematical techniques that can be deployed to solve such a problem and these techniques are heuristic, therefore cannot guarantee optimal solution (only near-optimal).

In the following discussion the term “optimal solution” refers to maximum/minimum for formulations described in Items a. or b. above and to a Pareto front for formulations described in Item c.

2.2 Literature review: Design and Expansion

A number of optimization algorithms have been developed to search the large decision space in the pipe design/expansion, operation and rehabilitation problems. A large number of the early optimization approaches such as linear programming (Gupta, Hussan, & Cook, 1969), (Jacoby, 1968), (Watanatada T., 1973), (Kally E., 1971a), (Morgan & Goulter, 1985) continuous gradient formulation (Featherstone & El-Jumaily K., 1983), direct search techniques (Ormsbee & Contractor, 1981), dynamic programming (Yang, Liang, & Wu, 1975), (Kally. E., 1971b), discrete gradients (Lam C., 1973) and integer programming (Rowell & Barnes, 1982), (Oron & Karmeli, 1979) have been reported to solve the WDS design/expansion in the literature before 1990. Although pipes are only available in discrete commercial diameters, most of these approaches considered the pipe diameter as a continuous variable for ease of computation and to avoid a discrete combinatorial solution space. The main decision variable in these papers is often pipe diameter. Other WDS components such as the pumps, tanks, and valves have also been considered in the literature (Shamir U., 1974) (Alperovits & Shamir, 1977) (Deb & Sarkar, 1971), (Deb A. K., 1976), (Calhoun, 1971), (Kareliotis, 1984), (Swamee, Kumar, & Khanna, 1973), (Duan, Mays, & Lansey, 1990). (Gessler, 1985) proposed the selective enumeration method to reduce the number of solutions that need to be simulated and evaluated. In his method, a heuristic algorithm was used to eliminate fewer appealing solutions before simulation. The proposed approach had two major problems; a) the computational requirement increased dramatically with the size of the network (the curse of dimensionality); and b) there is a higher likelihood that potential optimal candidate solutions are ignored (Simpson & Goldberg, 1994).

Early mathematical optimization techniques were based on differentiation of the objective (and constraint) function(s) and as such were limited to a continuous and smooth (differentiable) solution space. They were also limited when multi-objective optimization was required (Deb K. , 2002), (Coello Coello, 2005). For instance, some prior problem knowledge is required in all of these methods. The development (late 1980s) of heuristic methods, such as evolutionary based (genetic algorithms, genetic programming), and nature based (bee hive, ant colony) were coupled with advances in computational power. Evolutionary Algorithms (EAs), opened the possibilities to perform both single and multi-objective optimization in a discrete (and combinatorial) solution space (Deb K. , 2002).

(Simpson, Dandy, & Murphy, 1994) were the first to apply Genetic Algorithm (GA) to WDS design problem. The model was applied on a simple network that consists of 14 pipes and 2 reservoirs. The GA outcomes were compared with several other techniques such as complete enumeration and nonlinear programming. The results suggested that GA can find the global optimum with relatively few evaluations. (Simpson & Goldberg, 1994) investigated the factors that influence the performance of the simple GA in finding the optimal solution for a simple two-reservoir looped network. The results indicated that the use of a tournament selection scheme and the population size are the most critical aspects of successfully applying the GA.

(Dandy, Simpson, & Murphy, 1996) modified the simple GA by applying fitness scaling, creeping mutation, and Gray coding. They solved the New York tunnel problem using the proposed modified GA. Although the new approach could find the least-cost solution, the major drawback of the approach was the tuning procedure for GA parameters (e.g., the population size, probability of the mutation and crossover). The modified GA outperformed the other traditional optimization methods including the linear, nonlinear and dynamic programming. (Savic & Walters, 1997) were the first to combine GA with the EPANET hydraulic solver (Rossman, 1994). They applied the proposed model on three benchmark networks (The two-reservoir looped network, Hanoi network, and New York City network). They successfully found the least-cost solutions for the design and expansion of these benchmarks. The outcomes showed the optimization results were sensitive to the Hazen-Williams coefficients used in the hydraulic modelling. (Abebe & Solomatine, 1998) also linked EPANET with the global optimization tool (GLOBE). Four algorithms including the Controlled Random Search (CRS2) (Price, 1983), CRS4 (Ali & C., 1994), Genetic Algorithm (Goldberg, 1989) and Adaptive Cluster Covering with Local Search (ACCOL) (Solomatine, 1998) were used and compared. They concluded that GA and ACCOL outperform the other algorithms.

(Halhal, Walters, & Ouazar, 1997) solved the WDS design and expansion problem with the structured messy multi-objective GA optimization model. They maximized the benefit of WDS pipe replacement and lining subject to a limited available budget and minimized the capital costs. The model was applied to two networks. The authors concluded that the structured messy GA performed better than the simple GA. (Wu & Simpson, 2001) applied the messy genetic algorithm to solve the WDS design and expansion problem. The proposed model was applied to a real water distribution system. They showed that the number of design trials required by the messy GA is considerably smaller than the other GAs. One of the important aspects of their work was to account for most of the network components including, the pipes, pumps, tanks, and valves.

(Babayan, Kapelan, Savic, & Walters, 2005) considered demand uncertainty in solving the WDS design. They combined Monte Carlo Simulations (MCS) with GAs. Since MCS require a large number of evaluations, the authors converted the original stochastic model to a deterministic formulation that uses standard deviation as the measure of input variability. Using this approach, they were able to quantify the impacts of uncertainty on the robustness of the system.

The proposed model was then applied to the New York tunnel and Anytown benchmarks. The authors concluded that neglecting the uncertainty in the design process may lead to a serious under estimation of the design variables. A comprehensive review of optimization algorithms developed to solve the pipe design/expansion problem is found in (Lansey & and Mays, 1989a) and (Lansey K. E., 2006).

More recently, (Reca, Martínez, Gil, & Baños, 2008) evaluated the performance of several meta-heuristic optimization models including GA, simulated annealing, Tabu search, and iterative local search. They first applied the models to the small Hanoi benchmark network. The models were then applied to a much larger irrigation network. They concluded that in the small Hanoi network, the GA outperformed the other algorithms, while in the larger network, the simulated annealing and Tabu searches performed better.

Because of the high costs of WDS construction, the main objective in the optimal design problem has been to minimize the capital costs of the project. Most of the aforementioned early studies) only considered construction costs in their objective function. In later work, other objectives such as the operation and maintenance costs have also been incorporated in the WDS problems. (Walski, et al., 1987) considered the network maintenance cost and energy cost in the objective function. In another study, the operational costs of WDS were minimized as a separate single objective (Boulos, et al., 2001), (Bounds, Kahler, & Ulanicki, 2006). Since it is important to have a reliable and robust system in the long term, network reliability has also been considered as an objective or sometimes as a constraint in the WDS optimization frameworks (Mays, et al., 1989), (Schneiter, Haimes, Li, & Lambert, 1996), (Wagner, Shamir, & Marks, 1988), (Todini, 2000), (Ostfeld, Kogan, & Shamir, 2002), (Savic D. , 2002), (Keedwell & Khu, 2004), (Jourdan, Corne, Savic, & Walters, 2005), (Kapelan, Savic, & Walters, 2005); (Jayaram & Srinivasan, 2008). Since the WDS reliability is not the focus of this research these works are not reviewed here in detail.

2.3 Literature review: water main renewal

Water distribution system renewal planning is defined as the identification of the best timing to implement the most appropriate renewal option (replace/renovate/retrofit) for every component in the WDS. In order to achieve one or more objectives (e.g., minimize cost, maximize reliability, etc.). This is subject to hydraulic performance, construction, time, and budgetary constraints. In other words, network renewal is concerned with choosing the optimal set of interventions that satisfy one or multiple objectives. Quite often WDS renewal focuses on the water main renewal options (e.g. pipe replacement (same or larger diameter), hydraulic reinforcement (add pipe in parallel), lining, retrofit with cathodic protection, etc.). The total cost comprises the cost of pipe replacement, pipe lining, installing new pipes in the expansion areas, pipe break repair, pipe leakage, and energy costs for pumping to overcome static lift and energy losses in the system. The search for optimal rehabilitation interventions that minimize the cost is subject to a number of constraints. The availability of financial resources, materials and components, and hydraulic performance of the system are among these constraints. The most common objective in the rehabilitation problem is the cost.

The water distribution network rehabilitation problem was initially formulated by (Alperovits & Shamir, 1977), (Bhave, 1978), and (Deb A. K., 1976). These researchers framed network rehabilitation as a single-objective optimization problem with the objective to minimize the total cost of construction and operation. This is often referred to as the least-cost optimization problem. (Shamir & Howard, 1979) developed a model to schedule pipe replacements based on the forecasted number of existing pipe breaks (as an exponentially increasing function), repair and replacement cost, and the discount rate. The least-cost criterion was used by (Walski, 1986), (Walski, 1985); and (Walski & Pelliccia, 1982) to replace pipes with break rates greater than the critical break rate. This criterion specifies that a pipe should be rehabilitated if the cost to rehabilitate is lower than the pumping cost without rehabilitation. They also concluded that the (Shamir & Howard, 1979) approach is useful to analyze the replacement of the entire group of pipes while their approach is more suitable in analyzing the economic replacement on pipe-by-pipe bases.

Building on the least-cost criterion, (Day, 1982) was the first to propose that hydraulic information should also be considered in the decision process regarding water network rehabilitation. Following this proposal, rehabilitation-planning algorithms were developed to link hydraulic solvers with optimization codes. The hydraulic solver continuously updates the optimization engine with up-to-date hydraulic data of the pipe performances in the system.

(Su, Mays, Duan, & Lansey, 1987) proposed the basic framework for the model that can find the least-cost design of WDS rehabilitation. This model was subjected to the mass and energy conservation, nodal pressure bounds, and reliability constraints. Reliability was defined as the probability of satisfying the demands and pressure bounds for various possible pipe failures (breaks). The hydraulic simulator, KYPIPE by (Wood, 1980), the reliability model based on the minimum cut set method, and the optimization engine based on the generalized reduced-gradient method were combined to find the optimal planning. This was the first time that a pipe break model and a hydraulic simulator were incorporated directly into the optimization engine to solve the WDS rehabilitation planning. Using the continuous pipe diameter rather than commercial discrete diameter was the biggest disadvantage of the proposed model.

(Woodburn, Lansey, & Mays, 1987) and (Lansey, Basnet, Mays, & Woodburn, 1992) proposed a model to determine the minimum cost solution in the WDS rehabilitation. The model was solved for the rehabilitation or replacement of the pipes in the system to meet the specific demand and pressure requirements while minimizing the costs. They included the cost of pipe replacement, pipe relining, expected repair cost, and energy cost in their approach. They used an algorithm called the operations research scheme to find the optimal solution. Instead of pipe diameter, the pipe length was used as the decision variable in the model therefore this model allowed for the rehabilitation and replacement of a portion of a pipe, which is not realistic.

(Kim & Mays, 1994) continued the work by (Lansey, Basnet, Mays, & Woodburn, 1992) and proposed a new methodology that can select the pipes to be rehabilitated or replaced in an existing WDS while the total rehabilitation and energy costs is minimized. They combined the KYPIPE hydraulic simulator with the generalized reduced gradient (GRG2) optimizer. The rehabilitation options such as pipe replacement, lining, and do-nothing were included in the proposed model. The advantage of this model over the (Lansey, Basnet, Mays, & Woodburn, 1992) model was that the integer variables algorithm was used to simulate the decisions for rehabilitation or replacement instead of pipe length which solved the partial pipe rehabilitation issue. The concept of Significance Index, SI, was introduced by (Arulraj & Suresh H. R., 1995) SI is an optimality criterion which can be used in heuristic optimization models to prioritize rehabilitation activities for existing pipes or to design a new WDS. (Schneiter, Haimes, Li, & Lambert, 1996), used the concept of capacity reliability (defined as the probability that a carrying capacity of the system meets the flow demand) and proposed a decision-making platform for maintenance and rehabilitation of pipes in the network.

(Kleiner, Adams, & Rogers, 1998a), and (Kleiner, Adams, & Rogers, 1998b) developed a rehabilitation framework based on the dynamic programming and partial and implicit enumeration schemes to minimize the cost of rehabilitation (pipe replacement or relining) in a predefined time horizon. In their approach, network economics and hydraulic capacity were analyzed simultaneously (hydraulic capacity was quantified using EPANET). Up until this point, optimization was done either on structural consideration (i.e., cost of break repair versus pipe replacement) or energy consideration (i.e., when friction losses increase due to pipe internal deterioration to the point where total energy loss was more expensive than pie replacement). (Kleiner, Adams, & Rogers, 1998a) were the first to consider both simultaneously. The Kleiner et al. model also considered the time-dependent deterioration of pipe structural integrity and pipe hydraulic capacity. (Dandy & Engelhardt, 2001) applied the genetic algorithm to minimize the present value of capital, repair and pipe damage costs for a real pipe network in Adelaide, Australia. They showed that GA could be a powerful tool to assist in planning for the WDS rehabilitation.

(Lansey, Duan, & Mays, 1989), (Lansey, Basnet, Mays, & Woodburn, 1992), (M.Z & Mays, 2002), and (Farmani, Walters, & and Savic, 2005) considered the system reliability as a separate objective in the multi-objective framework. Multi-objective approaches to optimize the rehabilitation timing of water main assets have also been suggested. (Halhal, Walters, Savic, & Ouazar, 1997) used a messy genetic algorithm to solve the rehabilitation timing problem. The model was applied to a simple case study in which the benefits of improved system performance are weighed against the costs, subject to an available budget constraint. They also examined the sensitivity of the optimal solution to uncertainties in interest rate and inflation rate. (Farmani, Walters, & and Savic, 2005) investigated the trade-off characteristics between the total cost and reliability of WDSs. A wide range of decision variables, including pipe rehabilitation decisions, tanks sizing and setting, and pump operation schedules were considered in their approach and the model was applied to the Anytown benchmark network. The costs include the capital cost of pipes and tanks, and the present value of the energy during the specific period. The resilience index (which they considered as a surrogate measure for the network reliability) was considered as the second objective. They concluded that the optimal solution on the payoff curve shows a poor performance under the random pipe failure or pump being out of service.

(Alvisi & Franchini, 2006) proposed a procedure based on multi-objective GA to find the near optimal rehabilitation planning. The first objective was to minimize the overall cost of the repair and replacement of pipes and the second objective was to maximize the hydraulic performance of the network. They also considered the annual budget constraint. A head-driven hydraulic simulator was linked to a GA engine to simulate the various hydraulic and pipe break scenarios. They concluded that the multi-objective GA has the potential to be a useful tool for water main rehabilitation scheduling. (Dandy & Engelhardt, 2006) proposed a multi-objective framework to minimize the rehabilitation costs and maximize network reliability simultaneously. In their work, the economic costs of rehabilitation were converted to the present value and reliability was measured as the expected number of customer interruptions per year. Their work provided the starting point that can be extended to include other performance measures which affect customers' level of service.

(Jayaram & Srinivasan, 2008) considered the life-cycle cost of pipe rehabilitation in a multi-objective GA framework to minimize the cost and maximize the hydraulic performance of a WDS. The life-cycle costs included the initial cost of the pipes, the pipe replacement cost, cleaning and lining cost, break repair cost, and the salvage value of the replaced pipes. A modification of the resilience index was used to maximize the reliability. The results indicated that the modified resilience index is a good indicator of the uncertainty handling ability of the system. (Dridi, Parizeau, Mailhot, & Villeneuve, 2008) used and compared several evolutionary optimization techniques including IGA, NPGA-II, and NSGA-II to schedule the optimal water pipe renewal for short planning periods. Their results confirmed that using evolutionary algorithms could be useful to solve the pipe renewal scheduling problem. In particular, they recommended the use of NSGA-II to optimize large networks.

(Nafi & Kleiner, 2010) and (Nafi & Kleiner, 2011) incorporated the asset management strategies into a model which optimized the timing of pipe renewal in a WDS. They considered the discounts that account for the adjacency of infrastructure works to the newly installed pipes and volume discounts on large quantities (economies of scale) of purchased pipe for installation in networks. The (Nafi & Kleiner, 2010) optimization model minimized cost that include the pipe replacement and break repair and maximizes the usage of the available budget. The proposed model does not account for pipe roughness growth and background leakage, which can increase the cost of energy to overcome energy losses and to pump larger amounts of water due to water losses.

(Roshani & Filion, 2013) developed and examined a multi-objective framework to find the optimal WDS rehabilitation plan. They developed a complicated framework to solve WDS rehabilitation planning that included five different models: the optimization engine, pipe roughness model, pipe break model, pipe leak model, and a hydraulic simulator. This is for the first time that all of these models are considered simultaneously to find the optimal WDS rehabilitation plan. A trade-off between the capital costs of network rehabilitation and the network operating costs were explored. The capital costs included the pipe replacement costs, lining costs, duplication costs, and installing new pipes costs, while the operational costs accounted for the break repair cost, energy cost, and water loss cost. The proposed model was applied to the Fairfield WDS which is a fairly complicated system. They also proposed a new approach for gene coding to solve the WDS rehabilitation. In the traditional approach each year of the project life span is modelled by the one gene for instance to model one pipe in its life span of 50 years, 50 genes are required. Note that if the pipe duplication is among the decision options, the number of the required genes should be doubled to account for the second pipe rehabilitation planning. This causes several problems including the memory and computational issues. The proposed approach reduced the number of the genes by 80 percent. It allows including all of the rehabilitation options in the decision domain. (Roshani & Filion, 2013) included asset management strategies such as the adjacency to public works discount, quantity discount, and annual budgetary limits. Appling these strategies can potentially reduce the construction costs. They also investigated the effects of considering these strategies on the distribution of the rehabilitation decisions over the time and location.

The main rehabilitation decision option in the literature is pipe replacement and in rare cases pipe lining. This is mainly done to simplify the problem. In reality a full range of rehabilitation options for pipes including pipe duplication, replacement, various lining techniques, and installing new pipes utility managers consider in future growth areas. The lack of a comprehensive range of rehabilitation options in the proposed models sacrifices the practicality of the approach. There are several other assumptions in the previous approaches to simplify the complexity of the problem, which compromise the outcomes.

In recent years, public environmental awareness has increased and so have concerned about the possible impacts of climate change. This is due to fears that climate change may pose a serious threat to mankind (Erwin, Magnuson, Parsons, & Tadjdeh, 2012). Governments of many developed and developing countries have started campaigns to mitigate GHG emission, which is the main cause of climate change. Financial tools are considered as an effective measure to mitigate GHG emission consequences (Stern, et al., 2006). Carbon tax, cap-and-trade system, and discounting are various financial instruments that have been proposed in the literature to reduce GHG emissions. In the carbon tax approach, the governments levy tax on the GHG emissions while in cap-and-trade system the governments issue a permit to each industry section, allowing them to produce a specific amount of GHG emissions. If the permit holder’s emission exceeds the permitted limit, the holder should buy the extra permit from those who sell their permit in the market.

Taxing and cap-and-trade systems potentially can increase the electricity cost directly. Governments also use indirect methods to reduce the GHG emissions through controlling social discount rate. The social discount rate (SDR) is the minimum real rate of return that public projects must earn if they are to be worthwhile undertakings (Boardman, Moore, & Vining, 2008). SDR has a significant impact on the projects’ economic analysis, especially in the projects with long-life and carbon footprints. If SDR is set to a high percentage, the effect of future costs would decrease in the economic analysis and vice versa. Since the energy cost and the extra costs from tax or cap-and-trade system are a part of the annual costs in water distribution projects, therefore SDR influences them.

Only recent decades, environmental considerations have been included in the WDS design. (Filion, MacLean, & Karney, 2004) were the first to include life-cycle-energy-analysis to quantify energy expenditure in the fabrication, use, and end-of-life of the pipes, in WDS. The proposed approach incorporated the environmental input-output life-cycle-analysis to quantify the energy required to manufacture pipes. They have combined the EPANET hydraulic model with a pipe aging model and exponential pipe break model to calculate the theoretical energy recovery in the use stage. Then the energy required to dispose and recycle pipes was formulated. The final model was applied to New York tunnel benchmark with various pipe replacement frequencies from 10 to 100 years. The pipe replacement period close to 50 years produced the lowest overall energy expenditure in all of the life stages.

(Dandy, Roberts, Hewitson, & Chrystie, 2006) and (Dandy, Bogdanowicz, Craven, Maywald, & Liu, 2008) were the first to incorporate sustainability as a key objective in WDS optimization. A multi-objective GA was used to identify the Pareto optimal trade-off between cost and total energy for a simple WDS design. The total energy included the embedded energy of the materials and consumed energy in the system operation, while the capital cost only included the cost of pipes. (Wu, Simpson, & Maier, 2008) and (Wu, Maier, & Simpson, 2010b) incorporated GHG emissions as the second objective in a multi-objective optimization framework, and used GA to find the optimal WDS design. The model was used to investigate trade-off between the traditional minimum cost objective and an additional environmental objective of minimizing GHG emissions. The model was applied to a simple WDS. Results demonstrated that a significant trade-off exists between economic objective and environmental objective. They also concluded that the Pareto front is very sensitive to discount rate.

(Wu, Maier, & Simpson, 2010b) compared the use of single-objective and multi-objective approaches to investigate trade-off between economic objectives and GHG emission. In (Wu, Simpson, & Maier, 2010a) the authors used GHG emissions as one objective, while in (Wu, Maier, & Simpson, 2010b) GHG emissions were converted to GHG cost using the carbon tax model. This made it possible to investigate the environmental aspects of the WDS design in a single-objective (monetary) framework. Two simple WDSs were analyzed. The results indicated that the single-objective approach produced less trade-off information between the GHG emission and system costs. They recommended the multi-objective approach to find the optimal WDSs design while accounting for the GHG emissions over the single-objective approach.

In another study (Wu W. , Simpson, Maier, & Marchi, 2012) investigated the effects of considering variable speed pumps (VPS) and fixed speed pumps (FSP) in water transmission systems to reduce the energy consumption and GHG emission. A pump power estimation method was developed and used to incorporate the VSP. The proposed method was combined with a multi-objective optimization framework to minimize the total cost and GHG emissions. They indicated that the use of VSP could significantly save the operational costs and reduce GHG emissions.

Previous studies have incorporated environmental objectives in the water distribution system design problem mainly to understand the effect of climate change mitigation scenarios on design decisions and on energy use and GHG emissions (Filion, MacLean, & Karney, 2004), (Dandy, Roberts, Hewitson, & Chrystie, 2006), (Dandy, Bogdanowicz, Craven, Maywald, & Liu, 2008), (Wu, Simpson, & Maier, 2008), and (Wu, Simpson, & Maier, 2010a). Hypothetical, simplified networks have been used in most of these studies. The research results obtained with these simple networks are not directly transferable to real, complex networks and this is a current limitation of the previous research.

(Roshani, MacLeod, & Filion, 2012) addressed the aforementioned limitation and analyzed a real WDS. They formulated the WDS design/expansion under climate change mitigation strategies in a single-objective framework while using a more comprehensive problem definition and modeling. The major contribution of this publication was to use optimization approach in a parametric analysis to explore the impacts of discounting and carbon pricing on the GHG emission reduction in the WDS design and expansion for the first time. Time-varying carbon pricing and time-varying GHG emission factors were considered in the evaluation procedure for the design and expansion of a relatively complex (real) system. Additionally, the effectiveness of the GHG mitigation strategies was examined in a real network that is not otherwise accessible through case studies of simplistic systems. Pipe construction materials have various surface roughness and they follow different roughness growth rates, which can affect the energy requirement for pumping water into the system. Another major contribution of this work was to investigate and compare the effects of various pipe materials (e.g. the cement-mortar ductile iron and polyvinyl chloride pipe materials) on the energy and GHG mass reduction in WDSs.

(Roshani & Filion, 2013) explored the effects and consequences of considering the GHG mitigation scenarios in the WDS rehabilitation planning. They formulated the WDS rehabilitation planning under the climate change strategies for the first time. They also investigated the effects of the uncertain GHG tax and discount rates not only on the energy consumption and GHG emission but also on parameters such as the water loss costs, break repair cost, and the distribution of the decision options. They studied the trade-off between the capital cost minimization and operational cost minimization. The proposed model was applied to the real Fairfield WDS in Amherstview, Ontario, and the effects of various GHG pricing and discount rate on the shape and location of the optimal Pareto fronts was studied. It is worth noting that, the multi-objective framework that was used in this study was unique. It accounted for the fullest range of decision variables (e.g., the pipe duplication, replacement, relining, and installing new pipes). It applied pipe-aging models such as the roughness growth, leakage, and pipe break to fully simulate the aging effects on the pipes performance in the system. In the previous works mainly the pipe replacement was considered to update the current WDSs and rarely the pipe cleaning and lining was considered. In reality a wider range of options are used by utility managers. The proposed model included all of the common options to update the system including the pipe replacement, pipe cleaning and lining, and pipe duplication. It also considered new pipe installations for the future growth areas which make the problem more complicated.

A more recent work by (Muhammed, Farmani, Behzadian, Diao, & Butler, 2017) used graph theory clustering concept to reduce the computation load required for optimizing WDS rehabilitation planning. The authors used connectivity properties to partition the WDS into a number of clusters, and then they identified pipes that might have direct impact on system performance and considered them for rehabilitation planning. To identify the pipes with higher impacts they used three difference strategies (i.e., 1- rehabilitation of some of the pipes inside the clusters, 2- rehabilitation of pipes in the path supplying water to the clusters, and 3- a combination of Strategies 1 and 2). Their results indicated that the third strategy is able to generate solutions with similar performance that are cheaper by around 53% and 35% in comparison with the full search space and engineering judgment-based optimization strategies, respectively. The results also demonstrate that the cluster-based approach can reduce the computational efforts for achieving optimum solutions compared to the other optimization strategies.

2.4 Conclusion

Water distribution system renewal optimization has been addressed in the literature mainly by focusing on pipe replacement (with same or larger diameter pipe) and, in some rare cases, pipe lining. This has been done mostly to simplify what is a complex optimization problem. In reality, utility owners and managers often select among several options such as pipe duplication, pipe replacement, pipe lining (several technologize possible, e.g., cement-mortar lining, cured-in-place liners and others), and installing new pipes in areas slated for new growth. Eliminating decision options to simplify the problem sacrifices the practicality of the approach.

Further, previous approaches have attempted to reduce the complexity of the rehabilitation problem by grouping pipes in cohorts or groups and applying replacement scheduling decisions to all pipes in a cohort. In the cohort method, a decision is made for a group of pipes which share some common properties. The number of decisions needed to schedule rehabilitation is fewer in this approach. However, since all pipes in the same group are treated in exactly the same way, these algorithms cannot guarantee that a decision is optimal for each individual pipe in the group. Another limitation of many of previous approaches is the assumption that an individual pipe should be replaced strictly if its maintenance cost (e.g., break repair cost) is greater than the replacement cost (Nafi & Kleiner, 2010) and (Nafi & Kleiner, 2011) without considering system-wide effects. Replacing an individual pipe strictly based on its maintenance cost and regardless of the effect of this single pipe on the long term financial and hydraulic performance of the entire system is neither accurate nor will it guarantee that the final solution will be optimal.

Most of the literature reviewed in the previous sections, focused on either formulating and solving the rehabilitation planning problem for a small unrealistic network or studied the impact of GHG mitigation policies on rehabilitation. To the best of our knowledge, none has accounted for the impact of changing climate and or adaptation measures on water distribution system rehabilitation planning or asset management. This seems to be a clear gap in the current knowledge.

Amongst various optimization approaches investigated in the literature, multi-objective optimization models seem to be the most suited to solving asset renewal problem where factors that are difficult to monetize (e.g., environmental impacts, quality of life) are to be explicitly considered. This is mainly because, in renewal planning, often several objectives such as costs, performance indicators, and GHG emissions should be optimized simultaneously. Although it is feasible to combine all of these objectives and formulate a single objective problem but this will introduce many other factors such as objective and penalty weights that would add significant and unnecessary uncertainties to the problem which could be avoided by employing a multi-objective optimization technique. Several multi-objective optimization techniques have been used by various researchers to solve the rehabilitation planning problem. The Non-dominated Sorting Genetic Algorithm (NSGA) seems to perform well, especially on very high-dimensionality problems with a relatively high number of decision variables. The long-term planning of the renewal of even a moderate-size WDN presents a very high dimensionality challenge. A simple water distribution system with 400 water mains creates a rehabilitation planning problem with thousands of decision variables if planned for next 20 to 30 years. Therefore, NSGA seems to be the well-suited choice for our model development.

References

Abebe, A. J., & Solomatine, D. (1998). Application of global optimization to the design of pipe networks. *Proc., Int. Conf. on Hydroinformatics-98.* Balkema, Rotterdam, The Netherlands.

Ainger, C., Butler, D., Caffor, I., Crawford-Brown, D., Helm, D., & Stephenson, T. (2009). *A Low Carbon Water Industry in 2050.* Bristol, UK, : UK Environment Agency. Retrieved from UK Environment Agency.

Akuoko-Asibey, A., Nkemdirim, L., & Draper, D. (2013). The impacts of climatic variables on seasonal water consumption in Calgary, Alberta. *Can. Water Resour. J.*, 107–116.

Ali, M., & C., S. (1994). Modified controlled random search algorithms. *International Journal of Computer Mathematics*, 53, 229-235.

Alperovits, E., & Shamir, U. (1977). Design of optimal water distribution systems. *Water Resource Research*, 885-900.

Alvisi, S., & Franchini, M. (2006). Near-optimal rehabilitation scheduling of water distribution systems based on a multi-objective genetic algorithm. *Civil Engineering Environmental Systems*, 143-160.

Arulraj, G. P., & Suresh H. R. (1995). Concept of significancein dex for maintenance and design of pipe networks. *Journal of Hydraulic Engineering*, 121, 833-837.

Babayan, A., Kapelan, Z., Savic, D., & Walters, G. (2005). Least-Cost Design of Water Distribution Networks under Demand Uncertainty. *Journal of Water Resources Planning and Management*, 131(5), 375-382.

Basupi , I., & Kapelan , Z. (2015). Flexible Water Distribution System Design under Future Demand Uncertainty. *Journal of Water Resources Planning and Management*.

Bhave, P. R. (1978). Noncomputer Optimization of Single-Source Networks. *ASCE Journal of Environmental Engineering Division*, 799-814.

Boardman, A. E., Moore, M. A., & Vining, A. R. (2008). Social discount rates for canada. *John Deutsch Institute Conference: Discount Rates for the Evaluation of Public Private Partnerships.* Kingston, Ontario, Canada.

Boulos, P. F., Lansey, K. E., & Karney, B. W. (2004). *Comprehensive Water Distribution Systems Analysis Handbook for Engineers and Planners.* Colorado, USA: MWHSoft Press.

Boulos, P. F., Wu, Z., Orr, C. H., Moore, M., Hsiung, P., & Thomas, D. (2001). ptimal Pump Operation of Water Distribution Systems using Genetic Algorithms. *Proceedings of AWWA Distribution System Symposium, .* Denver.: American Water Works Association.

Bounds, P., Kahler, J., & Ulanicki, B. (2006). Efficient energy management of a large-scale water supply system. *Civil Engineering and Environmental Systems*, 23(3), 209-220.

Brothers, K. (2001). Water leakage and sustainable supply-truth or consequences? *Journal of American Water Works Association*, 93(4), 150-152.

Calhoun, C. (1971). Optimization of Pipe Systems by Linear Programming. *Control of Flow in Closed Conduits, J.P. Tullis. Ed., Colorado State University*, (pp. 175-192.). Ft. Collins, CO .

Canadian Water and Wastewater Association (CWWA). (1997). *Municipal Water and Wastewater Infrastructure: Estimated Investment Needs 1997-2012.* Ottawa, Canada.

Casas-Monroy, O., Byllaardt, J. V., Bradie, J., Sneekes, A., Kaag, K., & Bailey., S. A. (2018). Effect of temperature on chlorine treatment for elimination of freshwater phytoplankton in ballast water: bench-scale test. *Canadian Journal of Fisheries and Aquatic Sciences*.

Clark, C. M. (1970). EXPANSIVE-SOIL EFFECT ON BURIED PIPE. *American Water Works Association, ISSN: 0003-150X, Volume: 63,*, 424-427.

Clarke, A., Grant, N., & Thornton, J. (2009). *Quantifying the Energy and Carbon Effects of Water Saving.* Rotterdam, UK.: Environment Agency.

Coello Coello, C. A. (2005). *Twenty Years of Evolutionary Multi-Objective Optimization: A Historical View of the Field. No. 2508.* Col. San Pedro Zacatenco, Mexico.: Evolutionary Computation Group, Departamento de Ingenier´ıa El´ectrica, Secci´on de Computaci´on.

Dandy, G. C., Simpson, A. R., & Murphy, L. J. (1996). An improved genetic algorithm for pipe network optimization. *Water Resource Research*, 32(2), 449–458.

Dandy, G., & Engelhardt, M. (2001). Optimal scheduling of water pipe replacement using genetic algorithms. *Journal of Water Resources Planning and Management*, 214-223.

Dandy, G., & Engelhardt, M. (2006). Multi-objective trade-offs between cost and reliability in the replacement of water mains. *Journal of Water Resources Planning and Management*, 79-88.

Dandy, G., Bogdanowicz, A., Craven, J., Maywald, A., & Liu, P. (2008). Optimizing the Sustainability of Water Distribution Systems. *10th Water Distribution Systems Analysis Symposium.* Kruger National Park, South Africa.

Dandy, G., Roberts, A., Hewitson, C., & Chrystie, P. (2006). Sustainability objectives for the optimization of water distribution networks. *8th Annual Water Distribution Systems Analysis Symposium.* Cincinnati, Ohio, USA.

Day, D. K. (1982). Organizing and Analyzing Leak and Break Data for Making Main Replacement Decisions. *Journal of American Water Works Association*, 588-594.

Deb, A. K. (1976). Optimization of Water Distribution Network Systems. *ASCE Journal of Environmental Engineering Division*, 837-851.

Deb, A., & Sarkar, A. (1971). Optimization of Desing of Hydraulic Networks. *ournal of Sanitary Division, ASCE*, 97(SA2) 141-159.

Deb, A., Grablutz, F., Hasit, Y., Snyder, J., Loganathan, G., & N., A. (2002). *Prioritizing Water Main Rehabilitation and Replacement.* Denver CO: American Water Works Association Research Foundation.

Deb, K. (2002). *Multi-Objective Optimization Using Evolutionary Algorithms.* West Sussex, England.: John Wiley & Sons, Ltd., .

Dimkić, D. (2020). Temperature Impact on Drinking Water Consumption. *Environmental Sciences Proceedings* (p. 12). MDPI.

Downing, T., Butterfield, R., Edmonds, B., J.W.Knox, S.Moss, Piper, B., . . . team, t. C. (2003). *Climate change and the demand for water.* Oxford: Stockholm Environment Institute, Oxford Office.

Dridi, L., Parizeau, M., Mailhot, A., & Villeneuve, J. P. (2008). Using Evolutionary Optimization Techniques for Scheduling Water Pipe Renewal Considering a Short Planning Horizon. *Computer-Aided Civil and Infrastructure Engineering*, 23, 625-635.

Duan, N., Mays, L. W., & Lansey, K. E. (1990). Optimal Reliability-Based Design of Pumping and Distribution Systems. *Journal of Hydraulic Engineering*, 116(2), 249-268.

Engelhardt, M. O., Skipworth, P. J., Savic, D. A., Saul, A. J., & Walters, G. A. (2000). Rehabilitation strategies for water distribution networks: a literature review with a UK perspective. *Urban Water*, 153-170.

EPA Office of Water. (2018). *Drinking Water Infrastructure Needs Survey and Assessmen: Sixth Report to Congress.* Washington, D.C. : EPA.

EPRI. (2002). *U.S. Electricity Consumption for Water Supply and Treatment: The Next Half Century. Vol. 4.* Palo Alto: Electric Power Research Institute.

Erwin, S. I., Magnuson, S., Parsons, D., & Tadjdeh, Y. (2012). *Top Five Threats to National Security in the Coming Decade*. Retrieved from National Defense Magazine: http://www.nationaldefensemagazine.org/archive/2012/November/Pages/TopFiveThreatstoNationalSecurityintheComingDecade.aspx

European Environment Agency. (2010). *Indicator Fact Sheet, WQ06, Water Use Efficiency (In Cites): Leakage*. Retrieved from http://www.eea.europa.eu/data-andmaps/indicators/water-use-efficiency-in-cities-leakage/water-use-efficiency-in-cities-leakage

Farley, M. (2001). *Leakage Management and Control.* Geneva, Switzerland: WHO.

Farmani, R., Walters, G., & and Savic, D. (2005). Trade-off between total cost and reliability for Anytown water distribution network. *Journal Water Resources Planning and Managment-ASCE*, 161-171.

Featherstone, R., & El-Jumaily K. (1983). Optimal Diameter Selection for Pipe Networks. *Journal of Hydraulic Division, ASCE*, 109(HY2) 221-233.

Federation of Canadian Municipalities and National Research Council. (2006). *InfraGuide - Water and Sewer Rates: Full Cost Recovery .* Ottawa.

Filion, Y., MacLean, H., & Karney, B. (2004). Life-cycle energy analysis of a water distribution system. *Journal of Infrastructure Systems*, 120-130.

Fish, K. E., Reeves-McLaren, N., Husband, S., & Boxall, J. (2020). Unchartered waters: the unintended impacts of residual chlorine on water quality and biofilms. *npj Biofilms and Microbiomes*.

Folkman, S. (2018). *Water Main Break Rates In the USA and Canada: A Comprehensive Study.* Utah State University, Buried Structures Laboratory.

Gessler, J. (1985). Pipe network optimization by enumeration. *Proceeding, Special Conf. on Computer Applications/Water Resources* (pp. 572-581.). New York, : ASCE.

Goldberg, D. (1989). *Genetic Algorithms in Search, optimization & Machine Learning.* Reading: Addison-Wesley Publishing Co.

Griffiths-Sattenspiel, B., & Wilson, W. (2009). *The Carbon Footprint of Water*. Retrieved from http://www.rivernetwork.org/resource-library/carbon-footprint-water

Gupta, I., Hussan, M., & Cook, J. (1969). Linear Programming Analysis of a Water Supply System. *Transactions of the American Institute of Industrial Engineers*, Vol. 1, No. 1, 200-214.

Habibian, A. (1994). Effect of temperature changes on water-main breaks. *Journal of Water Resources Planning & Management*, ASCE 120(2), 312–321.

Halhal, D., Walters, G. A., & Ouazar, D. (1997). Water network rehabilitation with structured messy genetic algorithm. *Journal of Water Resource Planning and Management*, 123, 137-146.

Halhal, D., Walters, G. A., Savic, D. A., & Ouazar, D. (1997). Scheduling of water distribution system rehabilitation using structured messy genetic algorithm. *Evolutionary Computation*, 7(3), 311-29.

Hu, Y., & Hubble, D. W. (2007). Factors contributing to the failure of asbestos cement water mains. *Canadian Journal of Civil Engineering 34(5)*, 608–621.

International Energy Agency (IEA) . (2022). *Monthly Electricity Statistic*. Retrieved from https://www.iea.org/reports/monthly-electricity-statistics-overview/highlights

Jacoby, S. (1968). Design of Optimal Hydraulic Networks. *Journal of Hydraulic Division, ASCE*, 94(HY3) 641-661.

Jayaram, N., & Srinivasan, K. (2008). Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing. *Water Resource Research*.

Jourdan, L., Corne, D. W., Savic, D., & Walters, G. (2005). LEMMO: Hybridising rule induction and NSGA II for Multi-Objective Water Systems design. *Computation and Control in Water Industry CCWI.* Exeter, UK.

Kally E. (1971a). Automatic Planning of Least-Cost Water Distribution Networks. *Water and Water Engineering*, 148-152.

Kally. E. (1971b). Pipeline Planning by Dynamic Computer Programmin. *Journal of American Water Works Association*, 114-118.

Kapelan, Z. S., Savic, D. A., & Walters, G. A. (2005). Multiobjective design of water distribution systems under uncertainty. *Water Resources Research*, 41(11), W11407.

Kareliotis, S. (1984). Optimization of Tree-Like Water Supply Systems. *Journal of Hydrology*, 68 419-429.

Keedwell, E., & Khu, S. T. (2004). Hybrid genetic algorithms for multiobjective optimisation of water distribution networks. *Genetic and Evolutionary Computation GECCO 2004*, (pp. 1042-1053).

Kim, J. H., & Mays, L. W. (1994). Optimal rehabilitation model for water-distribution systems. *Journal Water Resources Planning and Managment-ASCE*, 674-692.

Kimbrough, D. E. (2019). Impact of local climate change on drinking water quality in a distribution system. *Water Quality Research Journal*, 179-192.

Kleiner, Y., & Rajani, B. (2002). Forecasting variations and trends in water-main breaks. *Journal of Infrastructure Systems 8(4)*, 122–131.

Kleiner, Y., & Rajani, B. (2010). I-warp: Individual water main renewal planner. *Drink. Water Eng. Sci. 3(1)*, 71–77.

Kleiner, Y., & Rajani, B. (2012). Comparison of four models to rank failure likelihood of individual pipes. *Journal of Hydroinformatics (2012) 14 (3)*, 659–681.

Kleiner, Y., Adams, B. J., & Rogers, J. S. (1998a). Long-term planning methodology for water distribution system rehabilitation. *Water Resource Research*, 2039-2051.

Kleiner, Y., Adams, B. J., & Rogers, J. S. (1998b). election and scheduling of rehabilitation alternatives for water distribution systems. *Water Resource Research*, 2053-2061.

Lam C. (1973). Discrete Gradient Optimization of Water Systems. *Journal of Hydraulic Division*, 99(HY6) 863-872.

Lansey K. E. (2006). The Evolution of Optimizing Water Distribution System Applications. *8th Annual Water Distribution Systems Analysis Symposium.* Cincinnati, Ohio, USA: ASCE.

Lansey, K. E., & and Mays, L. W. (1989a). Optimization model for design of water distribution systems. *Reliability analysis of water distribution systems.* New York: ASCE, .

Lansey, K. E., & Mays, L. W. (1989b). Optimization model for water distribution system design. *Journal of Hydraulic Engineering*, 1401-1418.

Lansey, K. E., Basnet, C., Mays, L. W., & Woodburn, J. (1992). Optimal Maintenance Scheduling for Water Distribution Systems. *Civil Engineering Environmental Systems*, 211-226.

Lansey, K. E., Duan, N., & Mays, L. W. (1989). Water distribution system design under uncertainties. *Journal Water Resources Planning and Management-ASCE*, 630-645.

Laucelli, D., Rajani, B., Kleiner, Y., & Giustolisi, O. (2014). Study on relationships between climate-related covariates and pipe bursts using evolutionary-based modelling. *Journal of Hydroinformatics 16(4)*, 743–757.

Lochbaum, B. S. (1993). PSE&G develops models to predict main breaks. *Pipeline and Gas J.*, 20(9), 20-27.

M.Z, E., & Mays, L. W. (2002). *Chapter 6. Water Price and Drought Management. in Water Supply Handbook.* Ohio, USA.: McGraw Hill. .

M.Z., E., & Mays, L. W. (2002). *Chapter 6. Water Price and Drought Management. in Water Supply Handbook.* Ohio, USA.: McGraw Hill.

Maidment, D. R., & Miaou, S.-P. (1986). Daily Water Use in Nine Cities. *Water Resources Research*, 845-851.

Mays, L. W., Bao, Y., Brion, L., Cullinane, L., Duan, N., Lansey, K., . . . Woodburn, J. (1989). *New methodologies for the reliabilitybased analysis and design of water distribution systems.* Austin: Center for Resaerch for Water Resources, the University of Texas.

Morgan, D., & Goulter, I. (1985). Optimal Urban Water Distribution Desgin. *Water Resources Research*, 21(5) 642-652.

Mote, P., Canning, D., Fluharty, D., Francis, R., Franklin, J., Hamlet, A., . . . Snover, A. (1999). *Impacts of Climate Variability and Change, Pacific Northwest.* Seattle,Washington: NationalAtmospheric and OceanicAdministration, Office of Global Programs, and JISAO/SMAClimate ImpactsGroup.

Muhammed, K., Farmani, R., Behzadian, K., Diao, K., & Butler, D. (2017). Optimal Rehabilitation of Water Distribution Systems Using a Cluster-Based Technique. *Journal of Water Resources Planning and Management*.

Nafi, A., & Kleiner, Y. (2010). Scheduling Renewal of Water Pipes While Considering Adjacency of Infrastructure Works and Economies of Scale. *Journal of Water Resources Planning and Management*, 136(5), 519-530.

Nafi, A., & Kleiner, Y. (2011). “A Comprehensive approach to long and short term planning of water main renewal. *Conference in Computation and Control in Water Industry.* Exeter, England.

Neale, T., Carmichael, J., & Cohen, S. (2007). Urban Water Futures: A Multivariate Analysis of Population Growth and Climate Change Impacts on Urban Water Demand in the Okanagan Basin, BC. *Canadian Water Resources Journal*, 315-330.

Newport, R. (1981). Factors influencing the occurrence of bursts in iron water mains. *Water Supply and Management*, 274–278.

Ormsbee, L., & Contractor, D. (1981). Optimization of Hydraulic Networks. *International Symposium on Urban Hydrology, Hydraulics, and Sediment Control*, (pp. 255-281.). Lexington, KY.

Oron, G., & Karmeli, D. (1979). Procedure for Economic Evaluation of Water Networks Parameters. *Water Resources Bulletin*, 15(4) 1050-1060.

Ostfeld, A., Kogan, D., & Shamir, U. (2002). Reliability simulation of water distribution systems - single and multiquality. *Urban Water*, 4(1), 53 - 61.

Praskievicz, S., & Chang, H. (2009). Identifying the Relationships Between Urban Water Consumption and Weather Variables in Seoul, Korea. *Physical Geography*, 324-337.

Price, W. (1983). Global optimization by controlled random search. *Journal of Optimization Theory & Applications*, (40), 333-348.

Protopapas, A. L., Katchamart, S., & Platonova, A. (2000). Weather Effects on Daily Water Use in New York City. *Journal of Hydrologic Engineering*, 332-338.

Rajani, B. B., & Kleiner, Y. (2001). *Comprehensive review of structural deterioration of water mains: physical based models.* Ottawa: NRC Publications.

Rajani, B., Kleiner, Y., & Sink, J.-E. (2012). Exploration of the relationship between water main breaks and temperature covariates. *Urban Water Journal*, 67-84.

Rasifaghihi, N., Li, S. S., & Haghighat, F. (2020). Forecast of urban water consumption under the impact of climate change. *Sustainable Cities and Society*.

Reca, J., Martínez, J., Gil, C., & Baños, R. (2008). Application of Several Meta-Heuristic Techniques to the Optimization of Real Looped Water Distribution Networks. *Water Resources Management, 22(10), 1367-1379.*, 22(10), 1367-1379.

Roshani, E., & Filion, Y. (2013). Event-Based Approach to Optimize the Timing of Water Main Rehabilitation While Considering Asset Management Strategies. *Journal of Water Resources Planning and Management, ASCE*, Jun 2014, Vol. 140, No. 6.

Roshani, E., & Filion, Y. (2013). Water Distribution System Rehabilitation Under Climate Change Mitigation Scenarios in Canada. *Journal of Water Resources Planning and Management*.

Roshani, E., & Filion, Y. (2014). The Effects of Future Water Demand Reduction on WDS Rehabilitation Planning. *16th Water Distribution System Analysis Conference.* Bari, Italy.

Roshani, E., Kleiner, Y., & Colombo, A. (2018). Water Distribution System Capacity under Uncertain Climate Change. *1st International WDSA/CCWI Joint Conference.* Kingston, Ontario.

Roshani, E., Kleiner, Y., Colombo, A., & Salomons, E. (2022). *Water Distribution Systems Climate Change Risks and Opportunities.* Ottawa: National Research Council.

Roshani, E., MacLeod, S., & Filion, Y. (2012). Evaluating the Impact of Climate Change Mitigation Strategies on the Optimal Design and Expansion of the Amherstview, Ontario Water Network: A Canadian Case Study. *Journal of Water Resources Planning and Management, ASCE, Vol 138, Issue 2*, 100-110.

Roshani, E., MacLeod, S., & Filion, Y. (2012). Evaluating the Impact of Climate Change Mitigation Strategies on the Optimal Design and Expansion of the Amherstview, Ontario Water Network: A Canadian Case Study. *Journal of Water Resources Planning and Management, ASCE*, Vol 138, Issue 2, P 100-110.

Rossman, L. A. (1994). *EPANET User's Manual.* Cincinnati.: Risk Reduction Engrg. Lab., Off. of Res. and Devel., U.S. Environmental Protection Agency.

Rowell, W., & Barnes, J. (1982). Obraining Layout of Water Distribution Systems. *Journal of Hydraulic Division, ASCE*, 108(HY1), 137-148.

Sadiq, & Karney. (2004). Modeling Water Demand Considering Impact of Climate Change – a Toronto Case Study. *Journal of Water Management Modeling* .

Savic, D. (2002). Single-objective vs. Multiobjective Optimisation for Integrated Decision Support. *Integrated Assessment and Decision Support: Proceedings of the First Biennial*

Meeting of the International Environmental Modelling and Software Society. Lugano, Switzerland.

Savic, D. A., & Walters, G. A. (1997). Genetic algorithms for leastcost design of water distribution networks. *Journal of Water Resources Planning and Management, ASCE*, 123(2), 67–77.

Schneiter, C. R., Haimes, Y. Y., Li, D., & Lambert, J. H. (1996). Capacity reliability of water distribution networks and optimum rehabilitation decision making. *Water Resources Research*, 32(7), 2271 - 2278.

Shamir U. (1974). Optimal Design and Operation of Water Distribution Systems. *Water Resources Research*, 10(1) 27-35.

Shamir, U., & Howard, C. (1979). An analytic approach to scheduling pipe replacement. *Journal of American Water Works Association*, 71(5), 248–258.

Simpson, A. R., & Goldberg, D. E. (1994). Pipeline optimization via genetic algorithms: From theory to practice. *Proc., 2nd Int. Conf. on Pipeline Syst.* Edinburgh, U.K.

Simpson, A. R., Dandy, G. C., & Murphy, L. J. (1994). Genetic algorithms compared to other techniques for pipe optimization. *Journal of Water Resources Planning and Management, ASCE*, 120(4), 423-443.

Solomatine, D. (1998). Genetic and other global optimization algorithms-comparison and use in calibration problems. *Proc. Int. Conf. Hydroinformatics-98.* COPENHAGEN, DENMARK.

Staats, M. (2018, 04 24). *Chapman Creek Water System, Water Availability and Climate Change* . Retrieved from ubc.ca: http://blogs.ubc.ca/mstaats8/

Stern, N., Peters, S., Bakhshi, V., Bowen, A., Cameron, C., Catovsky, S., . . . Stock, M. (2006). *tern review: The economics of climate change.* London, UK.: HM Treasury.

Su, Y. C., Mays, L. W., Duan, N., & Lansey, K. E. (1987). Reliability-based optimization model for water distribution system. *Journal of Hydraulic Engineering*, 1539-1556.

Swamee, P., Kumar, V., & Khanna, P. (1973). Optimization of Dead End Water distribution Systems. *Journal of Environmental Engineering, ASCE*, 99(EE2) 123-134.

Todini, E. (2000). Looped water distribution networks design using a resilience index based heuristic approach. *Urban Water*, 2, 115 - 122.

UKWIR. (2012). *Impact of climate change on asset management planning, Technical Report 12/CL/01/16.* UKWIR.

United Nations Human Settlements Programme (UN Hbitat). (2012, 01 20). *State of the World's Cities Report 2012/2013: Prosperity of Cities.* Retrieved from www.zaragoza.es: http://www.zaragoza.es/ciudad/medioambiente/onu/en/detallePer_Onu?id=507

Wagner, J. M., Shamir, U., & Marks, D. H. (1988). Water Distribution Reliability - Analytical Methods. *Journal of Water Resources Planning and Management-Asce*, 114(3), 253-275.

Walski, T. M. (1985). Cleaning and lining versus parallel mains. *Journal Water Resources Planning and Managment-ASCE*, 43-53.

Walski, T. M. (1986). Predicting costs of pipe cleaning and lining projects. *Journal of Transportation Engineering*, 317-327.

Walski, T. M., & Pelliccia, A. (1982). Economic Analysis of Water Main Breaks. *Journal of American Water Works Association*, 140-147.

Walski, T. M., Brill, J. E., Gessler, J., Goulter, I. C., Jeppson, R. M., Lansey, K., . . . Ormsbee, L. (1987). Battle of the Network Models: Epilogue. *Journal of Water Resources Planning and Management*, 113(2), 191-203.

Watanatada T. (1973). Least-Cost Design of Water Distribution Systems. *Journal of Hydraulic Division, ASCE*, 99(HY9) 1497-1513.

Wols, B. A., & Van Thienen, P. (2014). Impact of weather conditions on pipe failure: A statistical analysis. *Journal of Water Supply: Research and Technology - AQUA 63(3)*, 212–223.

Wols, B. A., & Van Thienen, P. (2016). Impact of climate on pipe failure: predictions of failures for drinking water distribution systems. *EJTIR Issue 16(1)*, 240 □ 253.

Wood, D. J. (1980). *Computer analysis of flow in pipe networks including extended period simulations.* Lexington, Ky.: Reference material for three-day short course and correspondence course, Office of Continuing Education and Extension of the College of Engineering, University of Kentucky.

Woodburn, J., Lansey, K., & Mays, L. W. (1987). Model for the Optimal Rehabilitation and Replacement of Water Distribution System Components. *Hydraulic Engineering, Proceedings of the 1987 National Conference* (pp. 606-611). New York, NY, USA: ASCE.

Wu, W., Maier, H., & Simpson, A. (2010b). Single-Objective versus Multi-Objective Optimization of Water Distribution Systems Accounting for Greenhouse Gas Emissions by Carbon Pricing. *Journal of Water Resources Planning and Management, 136(5)*, 555-565.

Wu, W., Simpson, A., & Maier, H. (2008). Multi-objective genetic algorithm optimization of water distribution systems accounting for sustainability. *10th Annual Symposium on Water Distribution Systems Analysis.* Krueger National Park, South Africa.

Wu, W., Simpson, A., & Maier, H. (2010a). Accounting for Greenhouse Gas Emissions in Multiobjective Genetic Algorithm Optimization of Water Distribution Systems. *Journal of Water Resources Planning and Management, 136(2)*, 146-155.

Wu, W., Simpson, A., & Maier, H. (2012). Sensitivity of Optimal Tradeoffs between Cost and Greenhouse Gas Emissions for Water Distribution Systems to Electricity Tariff and Generation. *Journal of Water Resources Planning Management, 138(2)*, 182–186.

Wu, W., Simpson, A., Maier, H., & Marchi, A. (2012). Incorporation of Variable-Speed Pumping in Multiobjective Genetic Algorithm Optimization of the Design of Water Transmission Systems. *Journal of Water Resources Planning Management, 138(5)*, 543–552.

Wu, Z. Y., & Simpson, A. R. (2001). Competent Genetic-Evolutionary Optimization of Water Distribution Systems. *Journal of Computing in Civil Engineering*, 15(2), 89-101.

Yang, K., Liang, T., & Wu, I. (1975). Design of Conduit System with Diverging Branches. *Journal of Hydraulic Division, ASCE*, 01(HY1) 167-188.