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The Effect of Future Water Demand Reduction on WDS Rehabilitation Planning

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Abstract

The aim of this paper is to examine the impact of demand reduction on energy cost, pipe replacement, lining, and duplication costs, etc. in a medium-sized water distribution system. The model is applied to simulate nine water demand reduction scenarios in the Fairfield water distribution system. Results indicate that water production cost is not effected by a reduction in demand. Moreover, the annual capital cost and annual overall cost do not significantly change until demand is reduced by 25%. Based on these results, it is concluded that a demand reduction plan is not an economically viable option for the Fairfield water distribution system.

Peer-review under responsibility of the Organizing Committee of WDSA 2014

Keywords: Water distribution systems, water conservation, water main asset rehabilitation planning, optimization, demand reductio

1. Introduction

Environment Canada estimates that water demand could be reduced by 40% [1] in many Canadian cities with targeted water conservation programs. Several water conservation programs are already in place to achieve this goal. Despite these lofty conservation goals, water distribution systems are often designed, built and rehabilitated to satisfy specific forecasted demands. These systems are often optimized to work efficiently on a specific demand point, whereby changing the demand point will change the optimized design point of the system. This can potentially influence the expected energy and maintenance cost of the optimized system design.

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The dichotomy between water conservation goals and practical system rehabilitation planning and optimization raises a number of research questions, namely: (1) How does a reduction in demand change optimal water main rehabilitation decisions? (2) How does a reduction in demand affect pumping and energy use in a system? (3) Is reducing water demand a financially sustainable option? (4) To what extent is a reduction in demand optimal when all of the system costs are accounted for?

Bishop et al. (1996) [2], examined the effect of demand reduction on capital and operational costs in water distribution systems. The authors collected extensive statistical data from seven US municipalities from 1993 to 1994. The data related to network operational & maintenance costs, capital costs and revenue losses. The results suggested that, in the short term, water conservation reduced cost far below revenues because water rates covered all utility costs and water rates were higher than the marginal cost of water production. The authors also claimed that the real benefits of water conservation is most evident in the long run adjustment to capital spending, whereby existing facilities can be used for a longer period of time before their capacity must be expanded.

It is noted that Bishop et al. (1996) [2] did not consider system re-design and/or modification in their study and thus their results can only be taken as optimistic. The current paper examines the link between water conservation and an attendant reduction in demand and the design of a water distribution system in relation to energy, capital costs, and operational. The aim of this paper is to examine the effect of a demand reduction on the optimization of water main asset rehabilitation decisions. Specifically, the relationship between demand reduction and energy use, capital and operational costs in optimized system designs, is examined. A multi-objective genetic algorithm (GA) is used to generate optimized solutions for various demand conservation scenarios. These optimized solutions are compared on the basis of energy use, capital costs, and operational costs to ascertain the impact of water conservation on water main asset rehabilitation decisions.

2. Methodology

WDS rehabilitation planning is a classic optimization problem. Water distribution system rehabilitation planning is defined as finding the best place, the best time, and the best option to rehabilitate and replace WDS components (e.g. pipes, pumps, tanks etc.) in order to achieve one or more objectives. The optimization approach is designed to minimize the capital and operational costs of the network (1)-(2). A fast-elitist non-dominated sorting genetic algorithm (NSGA-II) by Deb et al. (2002) [3] is used to search the large decision space efficiently and minimize two objectives:

$$Obj1 = Min(CC) = \sum_{t=0}^{T}\sum_{p=1}^{np}\left(RC_{t,p} + DC_{t,p} + LC_{t,p} + NP_{t,p}\right) \tag{1}$$

$$Obj2 = Min(OC) = \sum_{t=0}^{T}\sum_{p=1}^{np}BC_{t,p} + \sum_{t=0}^{T}\left(EC_{t} + WTC_{t} - CW_{t}\right) \tag{2}$$

In which CC is the capital cost, OC is the operational cost, t is time in year, T is the life time span of the project, p is the pipe number, np is the maximum pipe number, $RC_{t,p}$ is replacement cost for pth pipe in tth year, $DC_{t,p}$ is pipe duplication cost, $LC_{t,p}$ is lining cost, $NC_{t,p}$ is New pipe cost, $BC_{t,p}$ is break repair cost, EC_t is the energy cost, WTC_t is the water treatment cost, and CW_t is the benefit from charged water. This optimization is subject to velocity and pressure constraints and accounts for pipe roughness growth, pipe break growth, and leakage growth. The decisions include pipe replacement, pipe lining, duplicating the current pipe, and installing the new pipes in the future growth area. The second pipes in the duplicated pipes also could be rehabilitated with the same set of options except the duplication. The proposed model is called OptiNet. OptiNet was previously introduced by Roshani and Filion (2013) [4]. OptiNet is able to simulate various demand scenarios for each solution in each year of its lifespan. This include, average day demand, fire demand, maximum day demand, and maximum hourly demand.

2.1. Case Study: Fairfield Water Distribution Network

The multi-objective optimization approach is applied to the Fairfield water distribution system (Fig. 1) in Amherstview, Ontario, Canada. The Fairfield system has 400 pipes and supplies water to approximately 15,000 people. It consists of established residential and industrial areas as well as future growth regions (shaded area in Fig. 1). These areas are added to the system at Year 10 and Year 20. The predicted 20-year demand for the entire network is 76 l/s which is calculated by the consultant engineering firm, CH2MHILL. The multi-objective approach is run for nine scenarios to examine the effect of water conservation policies on water main asset rehabilitation in the Fairfield water distribution system. In each run, the 20-year rehabilitation planning is conducted based on the predicted demand growth rate. First, the 'status quo' scenario where no conservation is applied is run in the Fairfield network. In the remaining 8 scenarios, the future demand is reduced from 5% to 40% by 5% intervals (Fig. 2) and rehabilitation plans are selected by the multi-objective approach accordingly. Each scenario is run three times and the best Pareto front of all found solutions are selected for further investigation.

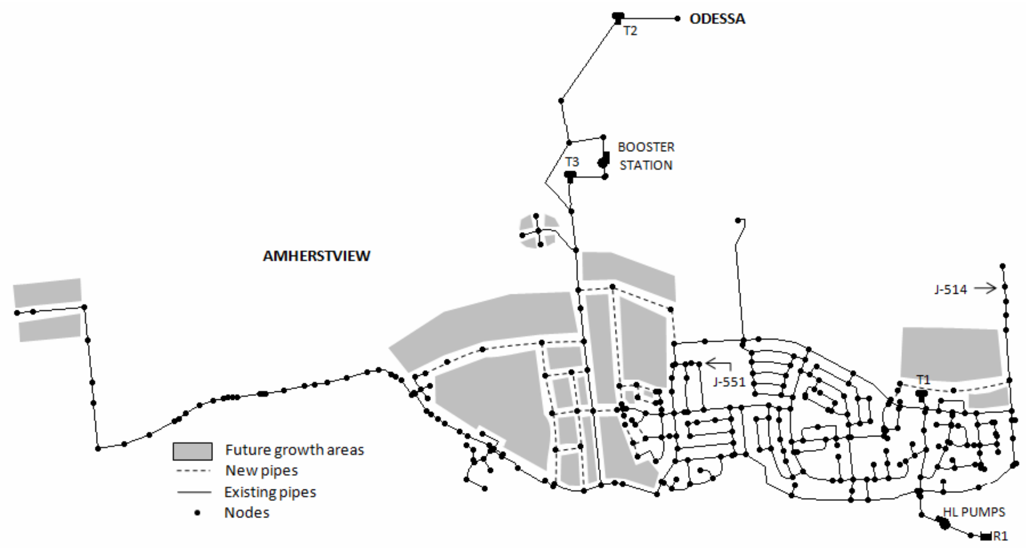

Fig. 1. Fairfield water distribution system.

Each run includes 10,000 populations and each population has 120 solutions. Each solution has 8,000 decision variables. Each solution is simulated 32 times to evaluate its hydraulic performance. For each year a 24-hour extended period simulation is performed by EPANET2 (20 in total for the entire project lifespan). A maximum day demand simulation is performed in three discrete years: the first year, the tenth year, and the twentieth year of the rehabilitation planning period. Additionally, the fire demand simulation is performed for three critical junctions at the same time as maximum day demand simulations. For the optimization, the crossing probability is 0.9, mutation probability is 0.15, crossing distribution index is 0.15 and mutation distribution index is 0.05. All of these values are held constant for all scenarios. Simulations were run on a cluster machine with five nodes (i.e., computer). Each node has 24 cores, and there are thus 120 cores. Each machine runs Windows HPC server 2008R2 with 48 GB RAM. Each simulation took approximately 96 hours to finish.

Leakage loss was simulated with the method proposed by Alvisi (2009)[5]. The exponential break model of Shamir and Howard (1979)[6] was used to predict pipe breaks. The exponential roughness growth model by Sharp and Walski (1988)[7] was used to model the time-varying Hazen-Williams pipe 'C' factor. These models are not described here due to space limitation. The interested reader can find these details in Roshani et al (2014)[8].

Table 1. Projected annual growth rates and current and projected average day water demands in the Fairfield distribution system

Water Use	Land Use (%)	Annual Growth Rate (%)	Present Water Demand (L/s)	Projected 20-Year Water Demand (L/s)
Residential	68	3.5	20	40
Multi-residential	18	3.5	6	12
Commercial	2	2.0	1	2
Institutional	8	2.0	2	3.7
Industrial	10	1.0	3	4.1
New Industrial	-	-	0	8.8
Total	100		32	70.6

Simulated demands are illustrated in Fig. 2. The two jumps in the demand (i.e. one at the middle and one at the end) are due to adding the future growth areas to the current system. The demand for future growth areas are estimated by the consultant firm and it reflects the demands requirement of the system while no demand conservation strategy is considered. Currently there is no ongoing buy-back program for the Fairfield network; therefore, to estimate the impacts of such programs the current buy-back policy for the city of Toronto is applied to the case study network. In this program for every cubic meter of reduction in water consumption 30 cents are paid back to the costumer.

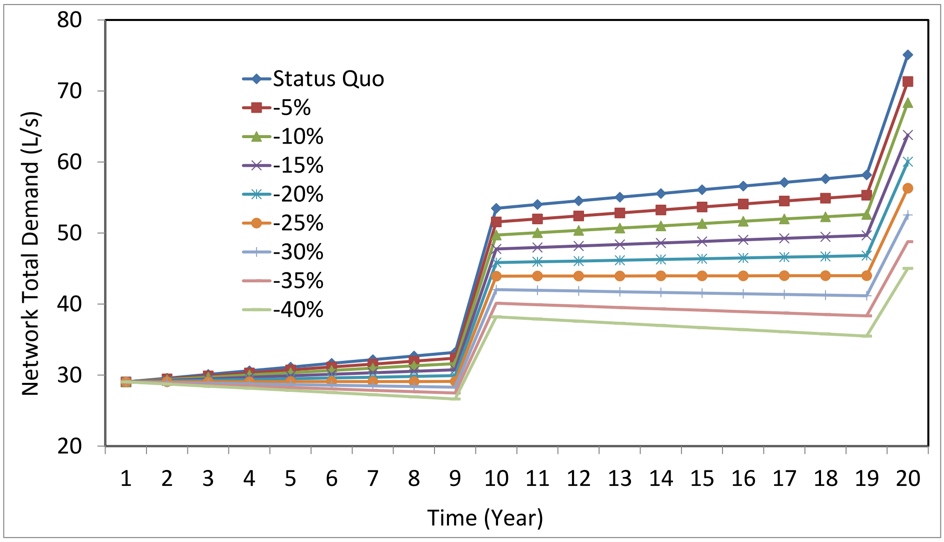

Fig. 2. Predicted and reduced demands for Fairfield network.

3. Results

The proposed model is applied to the nine demand scenarios. In this paper, the solutions generated in the last generation of the optimization were selected and the desired values (i.e. costs and water volumes, etc.) were averaged on all of the solutions. This averaging procedure also reduces the effect of stochasticity of the optimization engine on the final solutions. These averaged values were compared for various scenarios.

3.1. Capital Costs

Average annual capital costs of the system are shown in Fig. 3. The largest capital cost on this particular network is pipe replacement. Pipe duplication is the second by a wide margin, while installing new pipes and lining existing pipes rank third and fourth, respectively. Pipe replacement costs does not significantly change when the demand is reduced by less than 25% of baseline. After this point, pipe replacement cost decrease with an additional reduction in demand. This could be attributed to the fact that the actual demand value for the system is increasing until the demand reduction is more than 25 percent (Fig. 2). When the demand reduction is more than 25 percent, the reduced demand in each year is smaller than the amount of the demand from the previous year. As a result, the need to increase the pipe diameter to meet future demand growth diminishes and thus so does the pipe replacement cost.

Pipe duplication, lining and the installation of new pipes in the future growth area (Fig. 1) are not affected by the reduction in demand. These costs are marginal in comparison to the pipe replacement cost. On the other hand, these costs are mainly driven by other factors in the network such as break repair costs and energy, which are not changing significantly for this particular network. Considering the fact that the pipe replacement is the most significant portion of the total annual capital costs, therefore the total capital cost follows the same trend as pipe replacement cost due to the same reasons.

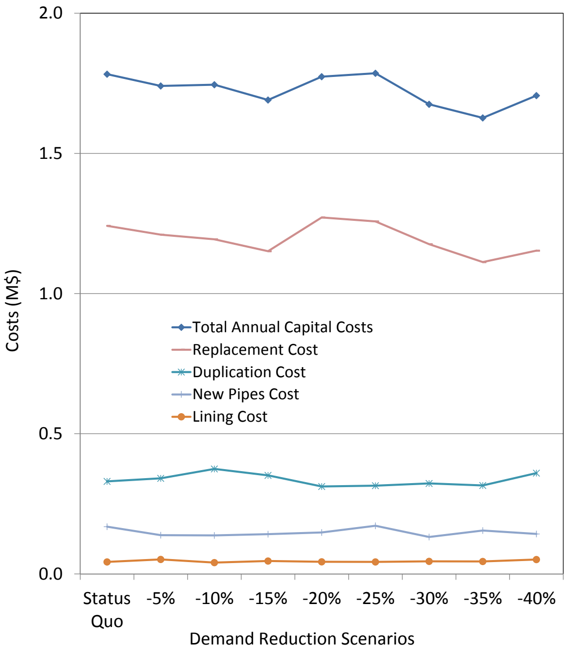

Fig. 3. Average annual capital costs for various demand reduction scenarios

3.2. Energy Cost, Break Repair Cost and Greenhouse Gas Emission

Annual energy cost and annual GHG emission follow the same trend because GHG emissions are based on energy use and a GHG intensity factor. The details surrounding the calculation of GHG emissions is found in Roshani and Filion (2014)[8]. Energy use does not show a significant change until demand is reduced by 20% after which energy use decreases rapidly. Reducing demand reduces the need to update (replace, duplicate, or re-line) the pipes therefore aged pipes stay in use for a longer time. Since most of pipes in Fairfield system are either ductile iron or cast iron that tend to lose their hydraulic conductivity as they age and deteriorate (i.e. the Hazen-Williams coefficient is reduced), energy use increases. On the other hand, because of a reduction in demand, less water is pumped and therefore less energy is used. The results indicate that these two factors have equal effect on the system up to a point of 20% demand reduction. Past this point, the reduction in energy use by pumping less water is more pronounced than the increase in energy use due to aging/deteriorating pipes. Break repair cost increases as water demand is reduced. This is owing to the fact that older pipes tend to stay in service for a longer time when the demand is reduced, and the number of breaks increase with age.

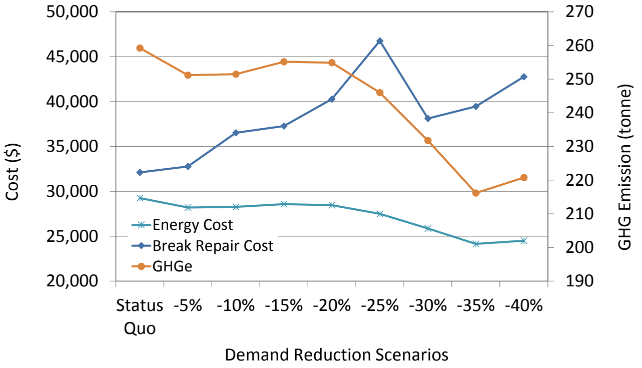

Fig. 4. Average annual energy cost, break repair cost and GHG emission versus various demand reduction scenarios

3.3. Water and Leakage

Due to the reduction in the demand, the volume of water that is being treated is reduced. At the same time, the volume of revenue water is also reduced. In contrary to treated water and revenue water, the volume of water that is lost to leakage also increases. This is due to the fact that by decreasing the future demand, the capital investment to replace aged pipes decreases (Fig. 3). Therefore more aged leaky pipes stay in the system for a longer period of time and leakage increases.

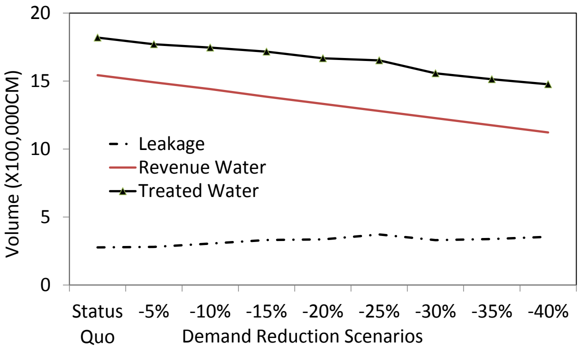

Fig. 5. Annual leakage, revenue water, and treated water volume versus various demand reduction scenarios

While water treatment costs decrease with a reduction in demand, the overall cost of water production (after accounting for revenue and adding buy-back costs) stays the same. This is clearly shown in Fig. 6 and is because a reduction in the demand will reduce the revenue of the utility with the same order.

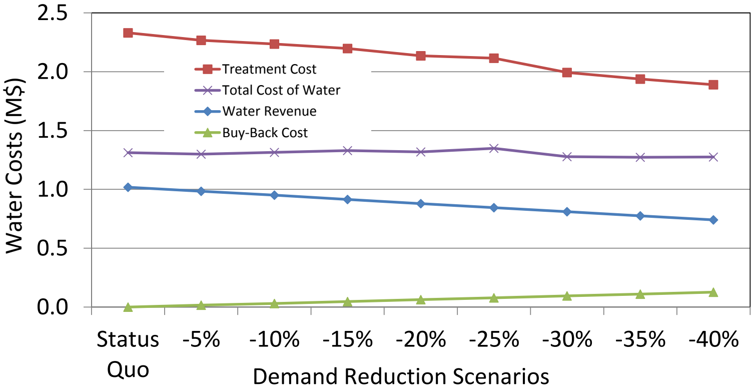

Fig. 6. Annual cost of water treatment, buy-back expenses, and water revenue versus various demand reduction scenarios

3.4. Overall Costs

The impacts of demand reduction on the total annual costs of the Fairfield network maintenance and operation (which includes all of the costs such as pipe replacement, pipe duplication, lining, installing new pipes in the future growth area, energy, treatment, buy-back, break repair cost minus water revenue) are indicated in Fig. 7. The total annual cost varies between $2.95 M to $3.22 M. No significant difference is seen until a 25% reduction in the demand. After this point, the total annual costs tend to decrease. Water treatment cost (Fig. 6) and total annual capital cost (i.e., pipe replacement cost plus duplication cost plus lining and installing new pipes, see Fig. 3) are the largest portion of the overall annual cost. Therefore, the annual cost tends to follow the same trend as these two costs for the same reason.

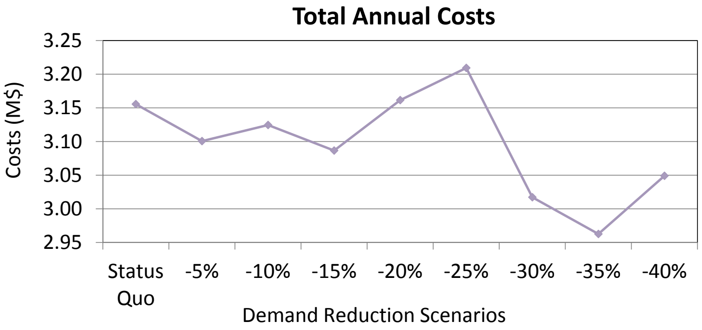

Fig. 7. Overall annual cost of the network versus various demand reduction scenarios

4. Conclusions

The aim of this paper was to examine the effect of a demand reduction on the optimization of water main asset rehabilitation decisions and system costs. The paper examined the relationship between demand reduction and energy use, capital and operational costs in optimized system designs in the Fairfield water distribution network in Amherstview, Ontario, Canada. A multi-objective genetic algorithm (GA) was used to generate optimized solutions for various demand conservation scenarios. These optimized solutions were compared based on energy use, capital costs, and operational costs to ascertain the impact of water conservation on water main asset rehabilitation decisions. Additionally, the impacts of pipe aging on leakage, pipe breaks incidence, and roughness growth were accounted for in OptiNet. Various water demand reduction scenarios were simulated and results indicated that water production cost was not affected by a reduction in demand. Moreover, the annual capital cost and annual overall cost did not significantly change until demand was reduced by 25%. Based on these results, it is concluded that a demand reduction plan, which reduces the demand by less than 25 percent, is not an economically viable option for the Fairfield water distribution system.

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