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Effect of storage tank size on the minimization of water distribution system cost and greenhouse gas emissions while considering time-dependent emissions factors

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Supplementary material:

1. Diurnal water demand curves for Case Studies 1 and 2.
2. Component costs and greenhouse gas emissions for the optimal solutions for Case Studies 1 and 2.

ABSTRACT

The importance of reducing greenhouse gas (GHG) emissions, which have been linked to human-induced climate change, is gradually being recognized by water utilities. While multi-objective optimization has been applied by previous literature to minimize cost and GHG emissions associated with water distribution systems (WDSs), this has mainly been achieved by considering design options of pipe size and pump type. Little consideration has been given to the appropriate sizing of storage tanks. As such, this paper aims to investigate the effect of storage tank size on the minimization of cost and GHG emissions associated with WDSs. Increases in storage tank size are considered by increasing the tank reserve size (TRS); the portion of the storage tank available for system balancing purposes. As storage tanks are critical to the operation of a WDS, it is necessary to accurately model the operation of a WDS. While electricity tariffs (ETs) are used to consider the time-dependency of pumping operational cost, no such consideration has been given to pumping operational GHG emissions. As such, time-dependent emissions factors are used to calculate pumping operational GHG emissions. In order to investigate the effect of TRS on the minimization of cost and GHG emissions associated with a WDS, the multi-objective optimization of two case study WDSs is performed. The results show that using different TRSs can affect the optimal pumping operational management of a WDS, and that increasing the TRS can result in GHG emissions reductions. However, using a very large TRS is likely to be associated with prohibitive costs.

1 INTRODUCTION

As water distribution systems (WDSs) can emit significant amounts of greenhouse gases (GHGs), they are contributors to human-induced climate change. In order to minimize this impact, the objective of minimizing greenhouse gas (GHG) emissions has recently been incorporated into the optimization of WDSs (Stokes et al. 2014b). This can be achieved both directly (Basupi et al. 2013; Basupi et al. 2014; Du et al. 2013; Kang and Lansey 2012; MacLeod and Filion 2011; Marchi et al. 2014; Roshani et al. 2012; Wu et al. 2010a; Wu et al. 2012a; Wu et al. 2013; Wu et al. 2010b; Wu et al. 2012b) and indirectly by considering GHG emissions as part of a wider array of environmental objectives (Herstein et al. 2011; Herstein and Filion 2011; Herstein et al. 2009).

When optimizing WDSs, previous literature has focused on using pipe sizes and pump types as decision variables in order to find solutions of minimized cost and GHG emissions (Basupi et al. 2013; Basupi et al. 2014; Dandy et al. 2006; Du et al. 2013; Herstein et al. 2011; Herstein and Filion 2011; Herstein et al. 2009; Kang and Lansey 2012; MacLeod and Filion 2011; Marchi et al. 2014; Roshani et al. 2012; Wu et al. 2010a; Wu et al. 2012a; Wu et al. 2013; Wu et al. 2010b; Wu et al. 2012b). Both pipe size and pump type are important factors to consider, as they not only explicitly affect the cost and GHG emissions associated with a WDS's design, but also affect the hydraulic performance of a system, affecting pumping electrical energy requirements and therefore the cost and GHG emissions associated with the pumping operation of a WDS (Dandy et al. 2006; Herstein et al. 2011; Herstein et al. 2009; Roshani et al. 2012; Wu et al. 2010a; Wu et al. 2012a; Wu et al. 2013; Wu et al. 2010b; Wu et al. 2012b).

However, available storage is also an important factor that can affect the cost and GHG emissions associated with a WDS. Storage tanks, as well as providing emergency water storage for fires and system failures, are a critical link between a system’s water source and demand. Without adequate storage, pumps must be operated to coincide with the occurrence of water demands, which may not be desirable when attempting to reduce pump energy usage (Batchabani and Fuamba 2012; Walski 2000). Hence, adequate storage size can benefit the minimization of cost and GHG emissions due to the greater flexibility and control of pumping operations they are able to provide.

An increased storage tank size can allow pumping to occur during low electricity tariff (ET) times, reducing the cost associated with electricity usage when a time-of-use pricing system is in place. However, using fewer pumps but for a greater proportion of the day is one way to reduce GHG emissions; reducing pump flow can reduce pipe velocities, leading to reduced pipe friction. This can reduce pump energy usage and therefore also reduce GHG emissions. Thus the need for larger storage sizes is diminished, as the difference between pump flow and system demand is reduced. Hence, the sizing of storage tanks can be critical when considering the minimization of, and trade-offs between, cost and GHG emissions, as the optimal size of a storage tank may be different when considering either cost or GHG emissions. Furthermore, storage tanks must be adequately sized to take full advantage of possible cost and GHG emissions reductions, while decreasing the likelihood of negative effects associated with over-sizing, such as increased tank capital cost and reduced water quality (Farmani et al. 2006; Gibbs et al. 2009).

However, while storage tank size has been considered with respect to minimizing WDS costs (Batchabani and Fuamba 2012; Farmani et al. 2006; Farmani et al. 2005; Lansey and Mays 1989; Ostfeld and Tubaltzev 2008; Prasad 2010; Vamvakeridou-Lyroudia et al. 2007; Vamvakeridou-Lyroudia et al. 2005; Walters et al. 1999; Wu et al. 2010b), less consideration has been given to this issue when considering the minimization of GHG emissions (Basupi et al. 2013; Basupi et al. 2014; Herstein et al. 2011; Herstein and Filion 2011; Marchi et al. 2014; Wu et al. 2010b). Additionally, little consideration has been given to the GHG emissions directly associated with storage tanks (Herstein et al. 2011; Herstein and Filion 2011).

As noted above, the minimization of GHG emissions can be achieved by operating pumps at a consistent rate, thereby reducing excessive pipe velocities and frictional energy losses. However, the emissions intensity associated with electricity is not always static. Like ETs, emissions factors (EFs) that are used to calculate the GHG emissions associated with the use of electricity can also be time-dependent (Stokes et al. 2014a; Stokes et al. 2014b). This is due to the nature of the electricity grid used to supply a WDS with electricity during operation. Generally, an electricity grid is connected to multiple electricity generation sources, each with their own emissions intensity (e.g. high intensity fossil fuel electricity sources and low or zero intensity renewable energy electricity sources). As the contribution of each electricity generation source differs, the emissions intensity of electricity changes over time. With the increasing usage of renewable energy, such as wind farms, which are the fastest growing non-hydro renewable energy type, the emissions intensity of electricity can fluctuate to a significant extent (Stokes et al. 2014a). Currently, many regions globally use significant amounts of wind generation, including Denmark (28% of total electricity generation), Spain (22%), South Australia (27%) and several states in Germany (over 40%)

and the United States of America (up to 27%) (Stokes et al. 2014a). If the minimization of GHG emissions associated with the operation of a WDS is to be considered, then it is necessary to consider the time-dependency of EFs, as this can possibly affect the optimal operation of pumps and, as discussed previously, the optimal sizing of storage tanks. However, there has been little consideration to either long-term reductions of EFs, such as over the life of a WDS in response to climate change policies (Roshani et al. 2012; Wu et al. 2012a), or the short term time-dependency of EFs, such as the fluctuation of EFs occurring each day (Ramos et al. 2011; Stokes et al. 2014a; Stokes et al. 2014b), with no application considering the optimal sizing of storage tanks.

In order to address the research gaps discussed above, there is a need to consider both optimal operational management and system design together with tank sizing options when considering the minimization of costs and GHG emissions associated with WDSs. Additionally, there is a need to consider the time-dependency of emissions factors associated with electricity used for pumping purposes. In order to address these shortcomings, the aims of this study are:

Aim 1. To investigate the effect of changing the storage tank balancing volume on optimal design and operational options when minimizing both the cost and GHG emissions for two case study WDSs with different levels of complexity.

Aim 2. To investigate the effect that using either time-varying EFs, represented by the use of an estimated 24-hour EF curve, or an average EF to calculate operational GHG emissions, has on both the options chosen during optimization and the cost and GHG emissions of the non-dominated solutions for the two case study WDSs used for objective 1.

The remainder of the paper is organized as follows. Two case study WDSs, which are minimized for costs and GHG emission while considering tank size variations and the use of time-dependent emissions factors, are introduced in the next section. This is followed by an outline of the methodology and specific details about the optimization algorithm used; the objectives of minimizing cost and GHG emissions; time-dependent emissions factors and storage tank sizing. Finally, the results from the optimization of the two case studies are presented and discussed, and conclusions are drawn.

2 CASE STUDIES

The first case study uses a two pump, single storage tank WDS (Figure 1) and considers the minimization of costs and GHG emissions associated with a new WDS. Therefore, the optimization of both design (pipes, pumps and storage tank) and operational management (pump schedule) options are considered. As shown in Figure 1, the pumping main is 600m long, the tank main is 300m long and the distribution network consists of 19x200m long pipes and 2x280m long (diagonal) pipes. This system is chosen as its single pressure zone, relative simplicity due to its small number of pipes, and single storage tank make it ideal for analyzing the complexity of design and operational control trade-offs, while still incorporating the fundamental complexity of a pumped WDS. The relatively small search space also makes the simultaneous optimization of both design and operational control options feasible. As shown in Figure 1, the first case study WDS consists of 23 pipes, one pumping station with two pumps and one storage tank.

The second case study uses a modified version of the D-town network from the Battle of the Water Networks II (Marchi et al. 2014; Salomons et al. 2012) (Figure 2) and considers the minimization of costs and GHG emissions associated with an existing WDS. Consequently, only operational management (pump scheduling) options of storage tanks of different sizes are considered as decision variables. As shown in Figure 2, the second case study WDS consists of 348 non-zero demand nodes, 443 pipes, 7 storage tanks and 12 pumps in 5 pumping stations. The original BWN-II problem called for the infrastructure upgrade and operational management optimization of the WDS. As this paper is concerned only with the operational management of the system, the original D-Town WDS has been altered to accommodate the increased water demands of the upgrade problem, allowing the network to be used without significant design issues that may influence pumping operations. The alterations include increasing the diameters of 4 pipes (IDs P22, P23, P100 and P995), which heavily restrict flows in the original design; placing an extra pump in addition to the original 3 pumps in pumping station 1, which uses the same pump curve as the original pumps; and increasing the size of 3 of the 7 storage tanks (IDs T4, T5 and T7) to allow a minimum balancing storage size equivalent to 12 hours under average day water demand loadings. Pipe P22 is changed in diameter from 406mm to 610mm, pipe P23 from 508mm to 610mm, pipe P100 from 406mm to 610mm and pipe P995 from 152mm to 203mm. The increase in diameter is from 11.64m to 26.03m for tank T4, from 11.89m to 16.82m for tank T5 and from 7.14m to 17.48m for tank T7. These alterations are among the most widely made changes by the participants of the BWN-II competition (Marchi et al. 2014). This system is chosen for its real-world complexity of having multiple tanks supplying multiple pressure zones, with the subsequent need to control multiple pump stations.

Water demand curves for both case studies are available as supplementary material. While pipe and storage tank requirements for fire and power outage scenarios are an important part of the design of a WDS, this study is concerned with the tradeoffs between costs and GHG emissions. Therefore, the additional pipe size and storage tank size requirements of fire and power outage were not taken into account.

3 METHODOLOGY

The methodology used to meet the aims outlined in the Introduction is outlined in Figure 3 and is based on the Water distribution system Cost-Emissions Nexus (WCEN) conceptual framework introduced by Stokes et al. (2012; 2014b). As can be seen, the computational structure consists of a number of components that follow the traditional steps of evolutionary optimization, including the selection of design (O1) and operational (O2) options (i.e. decision variable values (Op2)), which have an impact on the water distribution system (WDS) and electrical energy generation (EEG) infrastructure components. The magnitude of these impacts on the objectives and constraints is then quantified in the analysis component (OF1, OF2, Cstr1, Cstr2), which drives the selection of the next generation of decision variable values via the selected multi-objective optimization algorithm (Op3) in the optimization component.

The impact of changing the storage tank balancing volume (Aim 1) and time-varying emissions factors (Aim 2) on the Pareto optimal solutions (Op4) is investigated via a number of scenarios / cases, which alter some of the inputs to the optimization, options and infrastructure components (Figure 3). In relation to Aim 1, different storage tank balancing volumes are represented by four different tank reserve size (TRS) scenarios (TRS1-TRS4) in order to observe the effect of tank volume for a set of known size intervals. In relation to Aim 2, two different emissions factor cases, including an estimated 24-hour (typical) time-varying EF curve (EEF), which represents the average diurnal change in emissions factors intensity over the time period of time-varying EFs, and an average EF (AEF), which represents the average value of the time-varying EFs, are used. Further details of the optimization process, the way objectives and constraints are calculated and the TRS scenarios / EF cases are given in subsequent sections.

3.1 Optimization Approach

In order to find solutions of minimized costs and greenhouse gas (GHG) emissions, the state-of-the-art Borg Multi-Objective Evolutionary Algorithm (MOEA) (Hadka and Reed 2013) is used. Borg MOEA has been employed for its previously demonstrated superior performance when compared with more traditionally used evolutionary algorithms for a range of problems (Hadka and Reed 2013). Each case study WDS is optimized for each TRS scenario/EF case combination using a maximum solution evaluation limit of 100,000 evaluations (Eval, Figure 3). Initial testing showed this maximum evaluation limit to allow for solution convergence. As a general recommendation made by Hadka and Reed (2013), initial and minimum population sizes of 100 solutions are used. (Pop, Figure 3). Initial testing showed that these values allow for solution convergence for both case studies. As the seed (Seed, Figure 3), which is used to initialize the pseudo random number generator to generate the initial population of solutions, influences the ability of the optimization algorithm to find non-dominated solutions, each case study WDS using each TRS scenario/EF case combination is optimized thirty times using thirty randomly chosen seeds, resulting in a total of 480 optimization runs. All dominated solutions are disregarded from the final non-dominated set of solutions for each scenario.

For the first case study WDS, the design is optimized for the minimization of *construction* costs and GHG emissions. As part of this case study, 24 discrete decision variables are considered, including 23 pipes (pumping main, tank main and distribution system) and one pump (with both pumps being restricted to the same type). Design options for these decision variables include 12 pipe diameters and 11 pump types. For both case studies, the operations of the WDSs are optimized for the minimization of operational costs and GHG emissions. Operational optimization of pumping schedules consists of 8 continuous, independent decision variables for each pump (4 on times and 4 off times). For each pump scheduling decision variable, options range from 0 to 86,400 (seconds per day). This form of scheduling allows each pump to be switched on and off a maximum of 4 times each day (chosen as a compromise between an efficient number of decision variables and pumping flexibility for effective objective function optimization), without the need to discretize pump scheduling options into specific time segments. For the first case study, the operation of both of the system's pumps is optimized, while the operation of eight of the second case study's 12 pumps are optimized, with the remaining 4 pumps running continuously.

3.2 Calculation of Objectives and Constraints

As stated previously, the two objective functions include (1) the economic cost and (2) the climate change impact, measured as the released mass of GHG emissions, associated with the water distribution system (WDS). In order to enable these objective function values to be calculated, an extended period simulation, using the EPANET 2.0 (Rossman 2000) hydraulic simulation program (EPS, Figure 3), is performed. For the first case study where 24 hour (one day) long water demand curve, time-dependent emissions factors and electricity tariff structures are used, a 24 hour long EPS is employed. For the second case study where 168 hour (one week) long water demand curve and electricity tariff structures are used, a 168 hour long EPS is employed. For both case studies, an additional 24 hour "warm up" time is employed to reduce the effects of initial conditions. This allows calculation of pump electrical energy usage, which is then converted into costs and GHG emissions associated with (i) pumping operations, using operational cost analysis (OCA, Figure 3) and emissions factor analysis (EFA, Figure 3) respectively, and (ii) design, using design cost analysis (DCA, Figure 3) and embodied energy analysis (EEA, Figure 3), respectively.

Hydraulic simulation (EPS, Figure 3) is also used to calculate any violation of constraints (Cstr1 and Cstr2, Figure 3). A solution is deemed feasible if:

1. The zero and non-zero demand node pressures are maintained above 0m (Marchi et al. 2014) and 20m (Water Services Association of Australia 2002), respectively, during the EPS period (Cstr1, Figure 3). These pressure limits are chosen to prevent cavitation in the pipe network and to allow for the operation of most water demanding appliances (e.g. washing machines), respectively.
2. The total volume of water pumped into the system from the source is equal to or above the total volume consumed by all demand nodes during the EPS period (Cstr2, Figure 3).

3.2.1 Calculation of Economic Costs

For the first case study, where design optimization is performed, construction costs are associated with the cost of pipes, pumps and storage tank used to construct the WDS. For the second case study, where only operational optimization is considered, the construction costs associated with increasing the storage tanks (for each TRS scenario) are considered as the sole construction cost component. For the first case study, pipes are priced according to their length and chosen diameter and pump costs incorporate both the initial pump station cost and pump replacement cost. Both pipe and pump costs used in this study can be found in Wu et al

(2010b). For the first case study, pump replacement is considered every 20 years (Wu et al. 2010b). For both case studies, costs associated with each TRS are based on investigation costs for ground level concrete storage tanks used by South Australia's primary water utility company, SA Water (SA Water, unpublished data, January 2014). Refer to Table 1 for storage tank cost information for each TRS scenario.

For both case studies, operational costs associated with the WDSs are evaluated, and are due to the cost of electricity being used for pumping. In order to calculate electricity costs, an electricity tariff (ET, Figure 3) is used to convert the amount of electrical energy consumed into an economic cost. A peak/off-peak ET is used for both case studies. The peak ET, used between the hours of 7am and 11pm, is valued at 0.121 AUD per kilowatt hour ($/kWh). The off-peak ET, used between 11pm and 7am, is valued at 0.037 $/kWh. As the electricity tariff paid by the water utility in South Australia is undisclosed, applicable peak/off-peak ET rates used in this paper are taken from the SA Power Networks' (previously ETSA Utilities) Network Tariffs for FY2009 rate 2 business rate for South Australia (SA) (ETSA Utilities 2009). The cost of electricity is calculated by multiplying the energy (kWh) consumed for pumping purposes over the extended period simulation (EPS) by the appropriate ET rate ($/kWh).

3.2.2 Calculation of GHG Emissions

For the first case study, construction GHG emissions associated with the pipes and storage tank used to construct the WDS are considered. For the second case study, where operational optimization only is considered, the only construction GHG emissions considered are those associated with the embodied energy of increasing the storage tank sizes. In order to calculate construction GHG emissions, embodied energy analysis is used (EEA, Figure 3). The embodied energy, as megajoules per kilogram (MJ/kg), of a product is multiplied by an appropriate emissions factor (EF), as metric tonnes of carbon dioxide equivalents per megajoule (t CO_2-e/MJ), and the product's mass (t), to calculate its associated GHG emissions (t CO_2-e).

For the first case study, pipe unit mass data from Wu et al. (2010b) are used and an embodied energy value of 40.2 MJ/kg for ductile iron cement mortar lined (DICL) pipes is used (Ambrose et al. 2002). An EF of 0.16 kg CO_2-e/MJ is used to calculate pipe GHG emissions. This value is based on the average emissions factor value for electricity generation sources in South Australia for the period of January 2011 to February 2012 (converted from t CO_2-e/MWh to t CO_2-e/MJ). This value is used as no up-to-date pipe production specific emissions factor data are available for SA. Pipe GHG emissions are an estimate only, as other factors besides the manufacturing of the materials (e.g. transportation and installation) are not considered. It is noteworthy that pipe materials account for 35-45% of embodied energy, with trenching material, excavation and transportation accounting for the remainder (Prosser et al. 2013).

For both case studies, GHG emissions associated with the TRS are based on the balancing volume of the storage tank/s, and are calculated by considering the mass of reinforced concrete required for each TRS. Each storage tank is assumed to be circular in plan, with a 200mm thick reinforced concrete base and a 150mm thick reinforced concrete wall. The dimensions of each tank are based on standard reinforced concrete storage tank designs from several Australian tank manufacturers for tanks with similar applied hydrostatic forces. As for pipes, the TRS GHG emissions are an estimate only, as other factors besides the manufacturing of the materials (e.g. transportation and installation) are not considered.

As with the calculation of GHG emissions associated with DICL pipes, TRS GHG emissions are calculated using embodied energy. An embodied energy value of 0.95 MJ/kg is used, based on the value given for general strength construction concrete by Hammond and Jones (2008). As with the calculation of GHG emissions for DICL pipes (discussed above), an EF of 0.16 kg CO2-e/MJ is used to calculate TRS GHG emissions. Refer to Table 1 for TRS scenario GHG emissions information.

For both case studies, GHG emissions associated with the operation of the WDSs are evaluated, and are due to generation of electricity used for pumping purposes (EEG, Figure 3). In order to calculate operational GHG emissions, an emissions factor (t CO_2-e/MWh) (EF, Figure 3) is used to convert the amount of electrical energy consumed into associated GHG emissions. Operational GHG emissions are calculated by multiplying the energy (kWh) consumed for pumping purposes over the extended period simulation (EPS) by the appropriate EF (t CO_2-e/MWh). A detailed discussion of the operational EFs used in this study is provided below.

In order to be able to directly compare design and operations, present value analysis (PVA) is used to convert all future values (being either costs or GHG emissions) to a present value. In order to use PVA, a discount rate must be selected. Previous WDS GHG emissions optimization literature has used a conventional economic rate of 8% and a GHG emissions discount rate of zero (Roshani et al. 2012; Wu et al. 2010a; Wu et al. 2010b; Wu et al. 2012b). Consequently, these values are chosen for this study. It is noted that, while GHG emissions are a physical and not an economic property, their production does lead to both present benefits (e.g. the production of electricity) and future costs (e.g. the increase in atmospheric CO_2 levels). Hence, PVA can be used to weight the desire between increasing present benefits and reducing future costs (Simpson 2008). As with the calculation of GHG emissions for DICL pipes (discussed above), an EF of 0.16 kg CO2-e/MJ is used to calculate TRS GHG emissions. Based on values used in previous studies (Wu et al. 2010a; Wu et al. 2012a; Wu et al. 2013; Wu et al. 2010b; Wu et al. 2012b), a project life of 100 years is assumed for pipes, and is consistent with industry practice in Australia (Water Services Association of Australia 2002) and is used for calculating both electricity costs and GHG emissions and pump replacement costs. It is noted that a design life of 100 years may be considered excessive and may increase the level of uncertainty in the results.

3.3 Emissions Factor Cases

As stated previously, two emissions factor (EF) cases, using an estimated 24-hour EF curve (EEF, Figure 3) and an average EF (AEF, Figure 3), are used for the evaluation of operational GHG emissions. The estimated 24-hour EF curve case considers the diurnal time-dependency of emissions factors associated with the use of electricity. The average EF case represents the current standard of operational GHG emissions evaluation in the WDS optimization literature, where the time-dependency of emissions factors associated with the use of electricity is not considered. Both the estimated 24-hour EF curve and average EF (see Figure 4) are obtained using time-varying EF data that are developed from raw electrical energy generation data collected for each generation source supplying electrical energy to the South Australian electricity grid from February 2011 to January 2012 (Australian Energy Market Operator 2013). As discussed by Stokes et al. (2014a), the magnitude and timing of wind energy, which effects the time-variations of EFs, can affect the optimal operation of a WDS when considering the minimization of GHG emissions. The proportion of wind energy considered in this study is representative of wind energy penetration in several regions globally where wind generation has been widely adopted (Stokes et al. 2014a). For this study, the time-varying EFs, with an average value of 0.574 t CO_2-e per MWh, are calculated from electricity generated by wind farms (27%), gas-turbines (open-cycle, combined cycle) and gas fired steam turbines (49%) and coal fired steam turbines (24%). The proportion of electricity being produced by each generation type is responsible for the temporal fluctuations in the time-varying EF data. On average over the period from January 2011 to February 2012, the proportions of generation fuel sources at low EF times (between 20:00 and 8:00) were from wind (30%), gas (45%) and coal (25%) and at high EF times (between 8:00 and 20:00) were from wind (22%), gas (54%) and coal (24%). A detailed methodology for the calculation of time-dependent emissions factors is presented by Stokes et al. (2014a) and is therefore used in this paper.

3.4 Tank Reserve Size Scenarios

As stated previously, the TRS is the volume of water in the storage tank/s able to be used for system balancing purposes. Each storage tank's TRS is calculated as the volume of water required to supply the system under average-day demand for a specified length of time (e.g. the 6 hour TRS will hold enough balancing storage to supply the WDS for 6 hours). For the second case study, which uses multiple storage tanks, the TRS for each tank is the volume required to supply the demand for that tank's district metering area (DMA). The TRS volumes and associated cost and GHG emissions for each TRS scenario used for each case study are detailed in Table 1. The TRS volumes are altered by changing the diameter of each tank. The lower and upper water levels of each tank are not altered, as this would alter the hydraulic properties of the system.

4 RESULTS & DISCUSSION

4.1 Effect of Tank Reserve Size on Optimal System Design and Operation while using the Estimated 24-hour Emissions Factor Curve

4.1.1 Minimization of Costs and GHG emissions

The results for both case studies show that, when using the estimated 24-hour EF curve (EEF), increasing the tank reserve size (TRS) can result in reduced total GHG emissions. For case study 1, using the 12 hour TRS results in solutions with lower GHG emissions and similar costs, compared to using either the 3 or 6 hour TRSs (Figure 5a). For example, while solution EEF12.18 (12 hour TRS, lower GHG emissions solution) and solution EEF3.13 (3 hour TRS, lower GHG emissions solution) have similar costs ($6.48M and $6.49M respectively), solution EEF12.18 has GHG emissions 1.7 kt CO_2-e (3.7%) lower than those for solution EEF3.13, with GHG emissions of 42.9 kt CO_2-e and 44.6 kt CO_2-e respectively. For case study 2, using the 6 hour TRS results in solutions with reduced GHG emissions compared to using the original TRS (Figure 6a). However, using a TRS that is too large can also result in increased costs. For case study 1, using the 24 hour TRS results in significantly increased costs, with little benefit to reducing GHG emissions, compared to using the 12 hour TRS. For case study 2, using the 12 or 24 hour TRSs results in significantly increased costs, with no additional reductions in GHG emissions (Figure 6a). Component costs and GHG emissions for the optimal solutions for both case studies are available as supplementary material.

4.1.2 Optimal Pumping Operational Management

When a sufficiently large TRS is used, pumping operational optimization can help to minimize pumping operational costs and GHG emissions by moving pump usage to off-peak electricity tariff (ET)/lower EF times of the day. This effect is seen when both cost minimization (Figures 7a and 8a) and GHG emissions minimization (Figures 7c and 8c) are prioritized. Conversely, when using the 3 hour TRS (case study 1, Figures 7a and 7c) or original TRS (case study 2, Figures 8a and 8c), the developed solutions for both case studies have pump schedules that show less regard to the off-peak ET/low EF times of the day. Instead, pump usage is maintained in order to stop the small storage tank/s from emptying. These results suggest that moving pumping to the off-peak ET/low EF times of the day is an effective way to reduce pumping operational costs/GHG emissions, respectively. However, for the presented case studies, while this strategy works to reduce total GHG emission, it does not reduce total costs. Instead, increasing the TRS and hence storage tank cost can result in increased total costs.

As a zero GHG emissions discount rate is used, the small increase in construction GHG emissions associated with an increase in TRS is outweighed by the high present value of pumping operational GHG emissions reductions. However, as a high (8%) economic discount rate is used, the increase in construction costs associated with an increase in TRS outweighs the low present value of pumping operational cost reductions. Therefore, the values of both GHG emissions and economic discount rates used to evaluate the present worth of pumping operational GHG emissions and costs, respectively, may significantly alter the benefits of increasing the TRS.

4.1.3 Optimal Design

The results for the first case study show that while the choice of pipe diameters has a significant effect on the costs and GHG emissions of solutions, pipe sizes do not change significantly when using different TRSs. As such, the results suggest that the choice of TRS does not have a significant effect on the choice of pipe diameters. Additionally, the results show that the same pump type is chosen for all solutions, regardless of TRS, suggesting that pump type is not a significant factor to utilizing different TRSs. For the lower cost solutions, smaller pipe diameters are used to reduce construction costs at the expense of a small increase in pumping operational costs (an effect of the previously discussed high economic discount rate). For lower GHG emissions solutions, pipe diameters are increased to reduce pumping operational GHG emissions at the expense of a small increase in construction GHG emissions (an effect of the previously discussed zero GHG emissions discount rate). These results suggest that the selection of larger pipe diameters is more heavily influenced by the need to reduce pipe frictional losses in order to reduce pump electrical energy consumption and therefore pumping operational GHG emissions, instead of by the need to fill the storage tank more quickly to utilize the TRS balancing volume.

4.2 Effect of Tank Reserve Size on Optimal System Design and Operation while using the Average Emissions Factor

The results for both case studies suggest that using the average emissions factor (EF), instead of the estimated 24-hour EF curve, reduces the benefit of using a larger TRS in relation to minimizing GHG emissions. For the first case study, by using the average EF, increasing the storage tank beyond the smallest TRS results in similar or higher costs and GHG emissions (Figure 5b). For the second case study, by using the average EF, any benefits from increasing the TRS with regard to reducing GHG emissions are not as large as when the estimated 24-hour EF curve is used (Figure 6b). For both case studies, similar to when the estimated 24-hour EF curve is used to evaluate solutions, using the average EF to develop solutions while using the smallest TRS results in pump schedules that are developed to keep the storage tank/s from emptying (e.g. Figures 7b and 7d for case study 1 and Figures 8b and 8d for case study 2). For solutions developed while using the larger TRSs, pump usage is moved towards off-peak ET times of the day in an attempt to reduce pumping operational costs. However, pumping operational GHG emissions are minimized by pumping more consistently throughout the day in order to reduce pipe frictional energy losses (e.g. Figure 7d for case study 1 and Figure 8d for case study 2). This occurs because the average EF does not consider the time-dependency of EFs and hence the only way to reduce pumping operational GHG emissions is to reduce pump energy usage. As such, greater trade-offs between costs and GHG emissions and reduced benefits to reducing GHG emissions by using a larger TRS are seen when using an average EF than when using time-dependent EFs to evaluate pumping operational GHG emissions.

4.3 Discussion of Real World Implications

The general characteristics of the results suggest that increasing TRS can help to reduce GHG emissions. This is achieved by utilizing the larger water storage to move the majority of pumping operations to only the off-peak ET/low EF times of the day. However, this can only reduce GHG emissions to a certain extent, as past a certain TRS, the reduction in pumping operational GHG emissions will be outweighed by an increase in construction GHG emissions associated with the larger TRS itself. Additionally, using a larger TRS significantly increases construction costs, which in some cases could be prohibitively high. The general characteristics of the results also suggest that the selection of economic and GHG emissions discount rate values is important. In general, decreasing the economic/GHG emissions discount rate can increase the benefit of using a larger TRS with respect to minimizing cost and GHG emissions.

However, the above findings are only applicable when the estimated 24-hour EF curve is used, as when the average EF is used, decreased or no benefits associated with using a larger TRS are seen. Instead, the results suggest that using a smaller TRS may be beneficial to the minimization of costs and GHG emissions. Additionally, the results suggest that using the average EF increases the trade-offs between costs and GHG emissions of the developed solutions, as pump schedules prioritizing the minimization of costs move pumping to off-peak ET times, while pump schedules prioritizing the minimization of GHG emissions pump more consistently throughout the day. As such, it is suggested that when designing a WDS, the engineer should use the best available EF data when analyzing TRS requirements.

The general characteristics of the results suggest that when the emissions intensity of electricity fluctuates on a daily basis, there may be benefit to selecting a larger TRS in order to reduce GHG emissions. These benefits are due to the larger TRSs’ ability to store water for longer periods without pumping, therefore allowing for an operational management strategy whereby pumping is moved to the low EF times of the day. As shown by Stokes et al. (2014a), the effectiveness of this strategy increases as the magnitude of time-dependent EF fluctuations increase, such as when large amounts of wind generation capacity are present within an electricity grid. As many regions around the world, such as in Denmark, Spain and several states in Germany and the United States of America, have wind generation capacity at similar or higher levels than the South Australian electricity grid used in this study (Stokes et al. 2014a), considering the use of increased tank volumes may be beneficial for reducing the carbon footprints of water utilities in these regions.

It should be noted that the results presented in this paper are case study dependent. For example, this study is focused on the time-of-use of pumping, with the resultant minimization of costs and GHG emissions being dependent on the timing and structure of the electricity tariff and time-dependent emissions factors used. As these properties are regionally dependent, results are likely to be affected by the region where the study originates, and it is therefore important to consider this dependency. While timing of the case study time-dependent emissions factors align with those of the electricity tariffs, this may not always be the case. Increased differences between these are likely to increase the tradeoffs between pumping costs and GHG emissions and potentially affect the optimal choice of storage tank size. Additionally, the costs and GHG emissions associated with the storage tank can affect the resulting minimization of costs and GHG emissions of using a different TRS, and must therefore be carefully considered. While the costs and GHG emissions associated with each TRS used in this paper are calculated using the assumption of a ground level, circular reinforced concrete structure, other storage tank designs are in use by different water utilities and this can change the costs and GHG emissions associated with the storage tank.

While the results of this study relate to the minimization of costs and GHG emissions, the effect of TRS on water quality and system reliability have not been considered. For example, longer water detention times associated with larger storage volume can increase water age and consequently reduce water quality, due to the degradation of residual disinfectant which can lead to microbiological growth (Walski 2000). Conversely, a larger storage volume can also increase the reliability of a WDS, due to additional water being available in the event of pump failure or pipe burst (Walski 2000). These factors are important and should also be considered when selecting the size of water storage tanks.

5 SUMMARY

In this paper, the effect of changing tank reserve size (the volume of water used for hydraulic balancing under normal conditions) on the optimal design and operational of water distribution systems for the minimization of costs and GHG emissions is considered (refer to Aim 1). Additionally, this effect is investigated when using either an estimated 24-hour emissions factor curve, which allows consideration of the time-dependency of EFs, or an average EF, which does not (refer to Aim 2).

In summary, the results show that when the emissions intensity of electricity fluctuates during each day, using a larger TRS can help to reduce GHG emissions. While this reduction may not be large, with the results suggesting GHG emissions reductions of 2-4% for a new WDS, they occur with no increase in cost. This occurs because the larger TRS allows pumping to be moved to the low EF times of the day, which is also when the off-peak tariff is in effect. As previously discussed, when larger EF fluctuations are seen, such as when large amounts of wind generation capacity are installed within an electricity grid, the effect of moving pumping to low EF times of the day is intensified and therefore resulting reductions of GHG emissions could be increased (Stokes et al. 2014a). However, these results are not seen when an average EF is used to evaluate pumping operational GHG emissions. As such, the general characteristics of the results suggest that when time-varying EF fluctuations occur over each day, using a larger EF may help to reduce GHG emissions. However, when these fluctuations do not occur, or are not considered when evaluating pumping operational GHG emissions, no cost or GHG emissions reduction benefits will result from increasing the TRS.

While water quality was not considered in this study, it is an important factor that can be affected by storage tank size. As such, water quality analysis could also be considered as an objective for selecting storage tank size.

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REFERENCES

Ambrose, M. D., Salomonsson, G. D., and Burn, S. (2002). "Piping Systems Embodied Energy Analysis." *CMIT Doc. 02/302*, CSIRO Manufacturing and Infrastructure Technology, Highett, Australia.

Australian Energy Market Operator. (2013). "Electricity NEM Data." Melbourne, Australia.

Basupi, I., Kapelan, Z., and Butler, D. (2013). "Reducing life-cycle carbon footprints in the redesign of water distribution systems." *Journal of Water and Climate Change*, 4(3), 176-192, 10.2166/wcc.2013.004.

Basupi, I., Kapelan, Z., and Butler, D. (2014). "Reducing life-cycle carbon footprint in the (re) design of water distribution systems using water demand management interventions." *Urban Water Journal*, 11(2), 91-107, Batchabani, E., and Fuamba, M. (2012). "Optimal tank design in water distribution networks: review of literature and perspectives." *Journal of Water Resources Planning and Management*, 140(2), 136-145, 10.1061/(ASCE)WR.1943-5452.0000256.

Dandy, G. C., Roberts, A., Hewitson, C., and Chrystie, P. "Sustainability objectives for the optimization of water distribution networks." *Proceedings of 8th Annual Water Distribution Systems Analysis Symposium*, Cincinnati, USA.

Du, F., Woods, G. J., Kang, D., Lansey, K. E., and Arnold, R. G. (2013). "Life cycle analysis for water and wastewater pipe materials." *Journal of Environmental Engineering*, 139(5), 703-711, 10.1061/(ASCE)EE.1943-7870.0000638.

ETSA Utilities. (2009). "Notice of change to ETSA Utilities' distribution tariffs from 1 July 2009." South Australia.

Farmani, R., Walters, G., and Savic, D. (2006). "Evolutionary multi-objective optimization of the design and operation of water distribution network: total cost vs. reliability vs. water quality." *Journal of Hydroinformatics*, 8(3), 165-179, 10.2166/hydro.2006.019.

Farmani, R., Walters, G. A., and Savic, D. A. (2005). "Trade-off between total cost and reliability for Anytown water distribution network." *Journal of Water Resources Planning and Management*, 131(3), 161-171, 10.1061/(ASCE)0733-9496(2005)131:3(161).

Gibbs, M. S., Dandy, G. C., and Maier, H. R. (2009). "Calibration and optimization of the pumping and disinfection of a real water supply system." *Journal of Water Resources Planning and Management*, 136(4), 493-501, 10.1061/(ASCE)WR.1943-5452.0000060

Hadka, D., and Reed, P. (2013). "Borg: an auto-adaptive many-objective evolutionary computing framework." *Evolutionary Computation*, 21(2), 231-259, 10.1162/EVCO_a_00075.

Hammond, G. P., and Jones, C. (2008). "Embodied energy and carbon in construction materials." *Proceedings of the Institution of Civil Engineers-Energy*, 161(2), 87-98,

Herstein, L., Filion, Y., and Hall, K. (2011). "Evaluating the environmental impacts of water distribution systems by using EIO-LCA-based multiobjective optimization." *Journal of Water Resources Planning and Management*, 137(2), 162-172, 10.1061/(ASCE)WR.1943-5452.0000101

Herstein, L. M., and Filion, Y. R. (2011). "Life-cycle assessment of common water main materials in water distribution networks." *Journal of Hydroinformatics*, 13(3), 346-357, 10.2166/hydro.2010.127.

Herstein, L. M., Filion, Y. R., and Hall, K. R. (2009). "Evaluating environmental impact in water distribution system design." *Journal of Infrastructure Systems*, 15(3), 241-250,

Kang, D., and Lansey, K. (2012). "Dual water distribution network design under triple-bottom-line objectives." *Journal of Water Resources Planning and Management*, 138(2), 162-175, 10.1061/(ASCE)WR.1943-5452.0000161.

Lansey, K. E., and Mays, L. W. (1989). "Optimization Model for Water Distribution System Design." *Journal of Hydraulic Engineering-Asce*, 115(10), 1401-1418,

MacLeod, S. P., and Filion, Y. R. (2011). "Issues and implications of carbon-abatement discounting and pricing for drinking water system design in Canada." *Water Resources Management*, 26(1), 44-61, 10.1007/s11269-011-9900-4.

Marchi, A., Salomons, E., Ostfeld, A., Kapelan, Z., Simpson, A. R., Zecchin, A. C., Maier, H. R., Wu, Z. Y., Elsayed, S. M., Song, Y., Walski, T., Stokes, C., Wu, W., Dandy, G. C., Alvisi, S., Creaco, E., Franchini, M., Saldarriaga, J., Páez, D., Hernández, D., Bohorquez, J., Bent, R., Coffrin, C., Judi, D., McPherson, T., van Hentenryck, P., Matos, J. P., Monteiro, A. J., Matias, N., Yoo, D. G., Lee, H. M., Kim, J. H., Iglesias-Rey, P. L., Martínez-Solano, F. J., Mora-Meliá, D., Ribelles-Aguilar, J. V., Guidolin, M., Fu, G., Reed, P., Wang, Q., Liu, H., McClymont, K., Johns, M., Keedwell, E., Kandiah, V., Jasper, M. N., Drake, K., Shafiee, E., Barandouzi, M. A., Berglund, A. D., Brill, D., Mahinthakumar, G., Ranjithan, R., Zechman, E. M., Morley, M. S., Tricarico, C., de Marinis, G., Tolson, B. A., Khedr, A., and Asadzadeh, M. (2014). "The Battle of the Water Networks II (BWN-II)." *Journal of Water Resources Planning and Management*, 140(7), 04014009-1-14, 10.1061/(ASCE)WR.1943-5452.0000378.

Ostfeld, A., and Tubaltzev, A. (2008). "Ant colony optimization for least-cost design and operation of pumping water distribution systems." *Journal of Water Resources Planning and Management*, 134(2), 107-118, 10.1061/(ASCE)0733-9496(2008)134:2(107).

Prasad, T. D. (2010). "Design of pumped water distribution networks with storage." *Journal of Water Resources Planning and Management*, 136(1), 129-132, 10.1061/(ASCE)0733-9496(2010)136:1(129).

Prosser, M. E., Speight, V. L., and Filion, Y. R. (2013). "Life-cycle energy analysis of performance-versus age-based pipe replacement schedules." *Journal-American Water Works Association*, 105(12), E721-E732, Ramos, H. M., Kenov, K. N., and Vieira, F. (2011). "Environmentally friendly hybrid solutions to improve the energy and hydraulic efficiency in water supply systems." *Energy for Sustainable Development*, 15(4), 436-442, 10.1016/j.esd.2011.07.009.

Roshani, E., MacLeod, S. P., and Filion, Y. R. (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*, 138(2), 100-110, 10.1061/(ASCE)WR.1943-5452.0000158.

Salomons, E., Ostfeld, A., Kapelan, Z., Zecchin, A., Marchi, A., and Simpson, A. R. (2012). "The Battle of the Water Networks II." 14th Water Distribution Systems Analysis Conference, Engineers Australia, Adelaide, Australia.

Simpson, A. R. "Selecting a Discount Rate for Evaluating Water Distribution Projects — The Sustainability Controversy." *Proceedings of Water Distribution Systems Analysis 2008*, Kruger National Park, South Africa.

Stokes, C. S., Maier, H. R., and Simpson, A. R. (2014a). "Water Distribution System Pumping Operational Greenhouse Gas Emissions Reduction by Considering Time-Dependent Emissions Factors." *Journal of Water Resources Planning and Management*, 10.1061/(ASCE)WR.1943-5452.0000484.

Stokes, C. S., Simpson, A. R., and Maier, H. R. (2012). "An Improved Framework for the Modelling and Optimisation of Greenhouse Gas Emissions Associated with Water Distribution Systems." 6th International Congress on Environmental Modelling and Software (iEMSs), International Environmental Modelling and Software Society, Leipzig, Germany.

Stokes, C. S., Simpson, A. R., and Maier, H. R. (2014b). "The cost-greenhouse gas emission nexus for water distribution systems including the consideration of energy generating infrastructure: An integrated conceptual optimization framework and review of literature." *Earth Perspectives*, 1(1), 1-17, 10.1186/2194-6434-1-9.

Vamvakeridou-Lyroudia, L., Savic, D., and Walters, G. (2007). "Tank simulation for the optimization of water distribution networks." *Journal of Hydraulic Engineering*, 133(6), 625-636, 10.1061/(ASCE)0733-9429(2007)133:6(625).

Vamvakeridou-Lyroudia, L., Walters, G., and Savic, D. (2005). "Fuzzy multiobjective optimization of water distribution networks." *Journal of Water Resources Planning and Management*, 131(6), 467-476, 10.1061/(ASCE)0733-9496(2005)131:6(467).

Walski, T. M. (2000). "Hydraulic design of water distribution storage tanks." *Water distribution systems handbook*, 10, 10.1-10.20,

Walters, G. A., Halhal, D., Savic, D., and Ouazar, D. (1999). "Improved design of “Anytown” distribution network using structured messy genetic algorithms." *Urban Water*, 1(1), 23-38,

Water Services Association of Australia. (2002). "Water Supply Code of Australia, Version 2.3." Water Services Association of Australia, Melbourne, Australia.

Wu, W., Maier, H. R., and Simpson, A. R. (2010a). "Single-objective versus multiobjective optimization of water distribution systems accounting for greenhouse gas emissions by carbon pricing." *Journal of Water Resources Planning and Management*, 136(5), 555-565, 10.1061/(ASCE)WR.1943-5452.0000072.

Wu, W., Maier, H. R., and Simpson, A. R. (2012a). "Sensitivity of optimal tradeoffs between cost and greenhouse gas emissions for water distribution systems to electricity tariff and generation." *Journal of Water Resources Planning and Management*, 138(2), 182-186, DOI: 10.1061/(ASCE)WR.1943-5452.0000169.

Wu, W., Maier, H. R., and Simpson, A. R. (2013). "Multiobjective optimization of water distribution systems accounting for economic cost, hydraulic reliability, and greenhouse gas emissions." *Water Resources Research*, 49, 1211-1225, 10.1002/wrcr.20120.

Wu, W., Simpson, A. R., and Maier, H. R. (2010b). "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, DOI: 10.1061/(ASCE)WR.1943-5452.0000020.

Wu, W., Simpson, A. R., Maier, H. R., and Marchi, A. (2012b). "Incorporation of variable-speed pumping in multiobjective genetic algorithm optimization of the design of water transmission systems." *Journal of Water Resources Planning and Management*, 138(5), 543-552, DOI: 10.1061/(ASCE)WR.1943-5452.0000195.

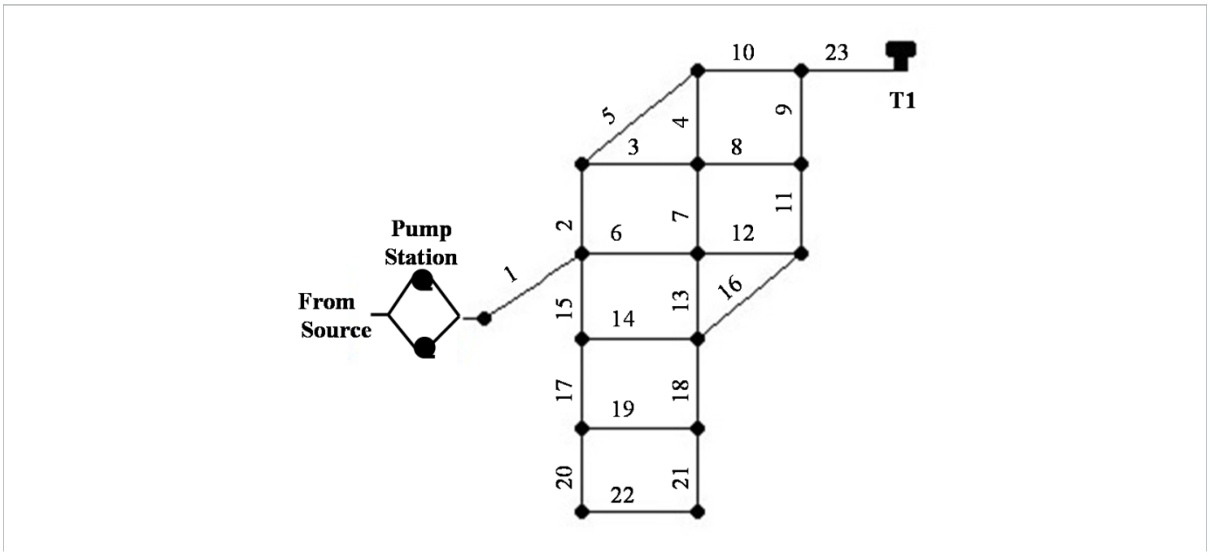

Figure 1. The two pump, one tank WDS used for the first case study, with pipe identification numbers shown

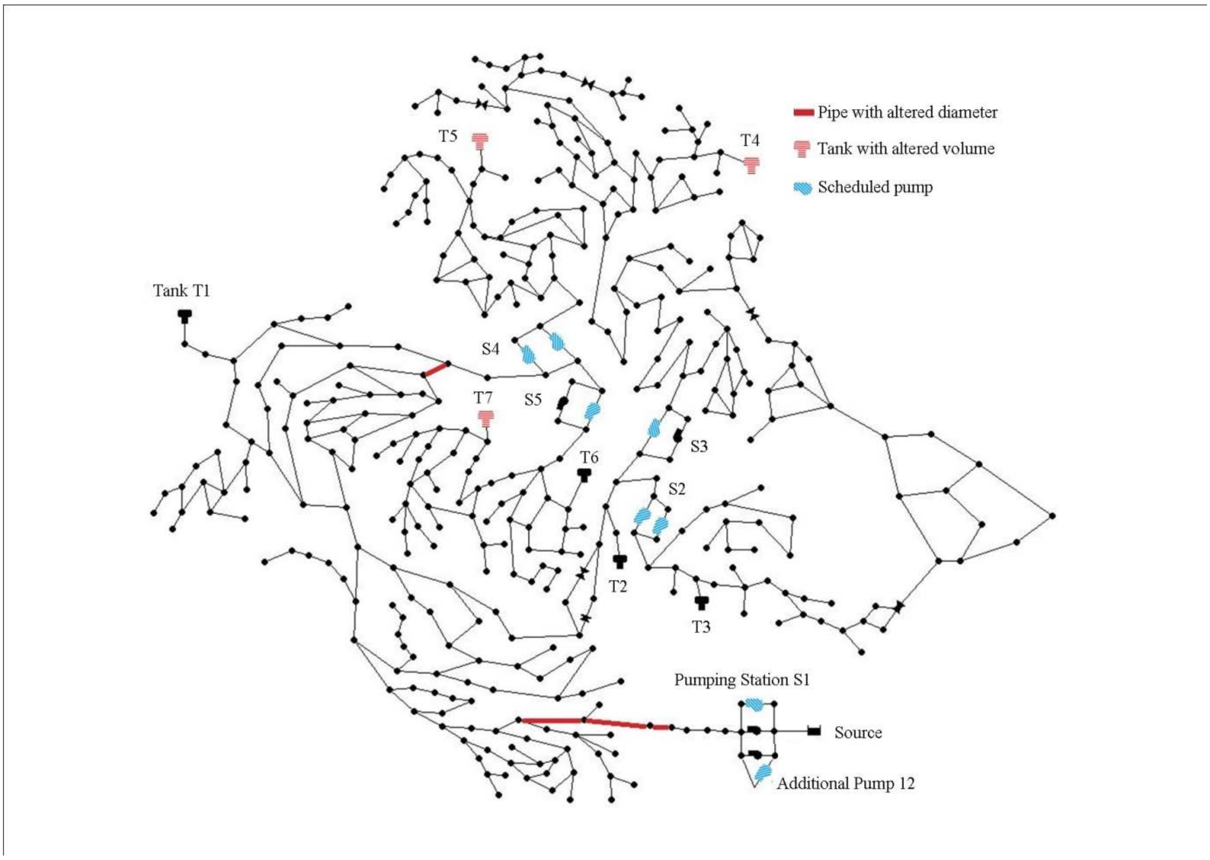

Figure 2. The D-town WDS, modified from the original Battle of the Water Networks II system, as used for the second case study

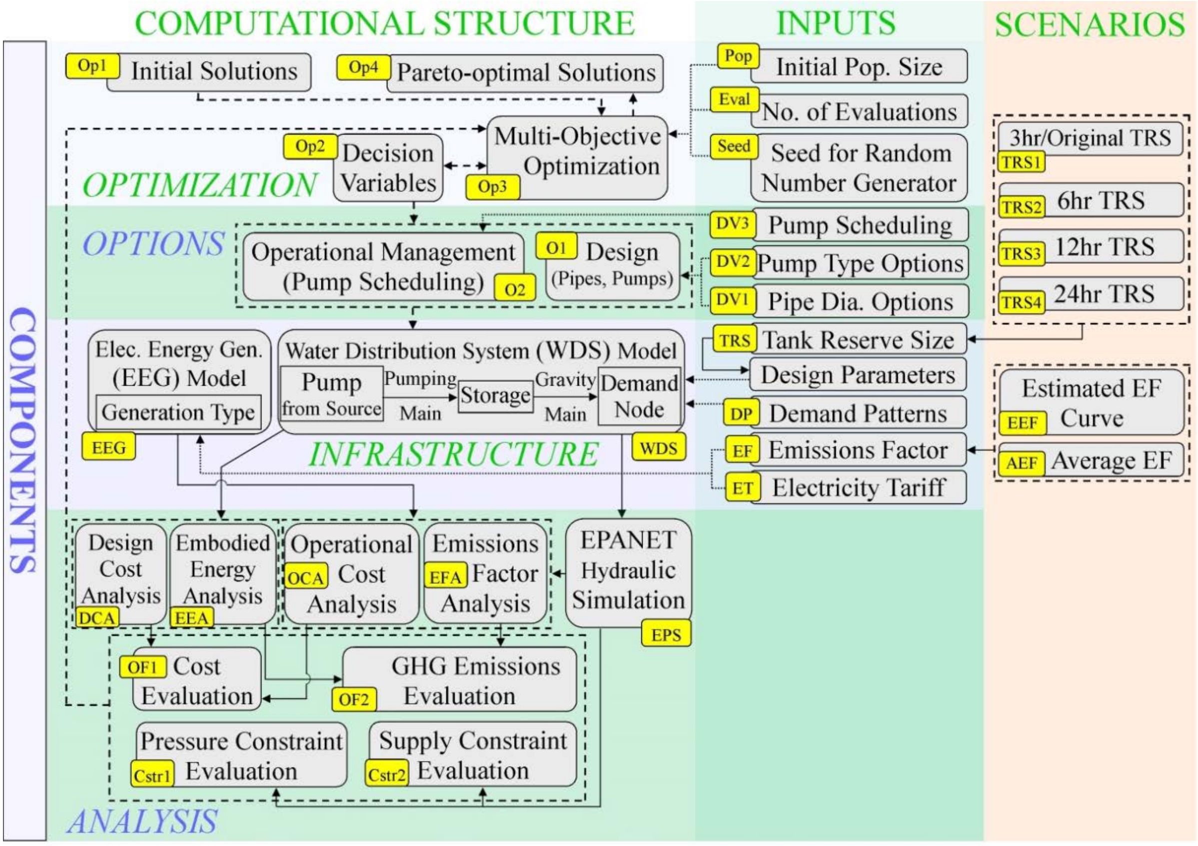

Figure 3. Outline of the methodology used for the multi-objective optimization of the case study WDSs for the minimization of costs and GHG emissions

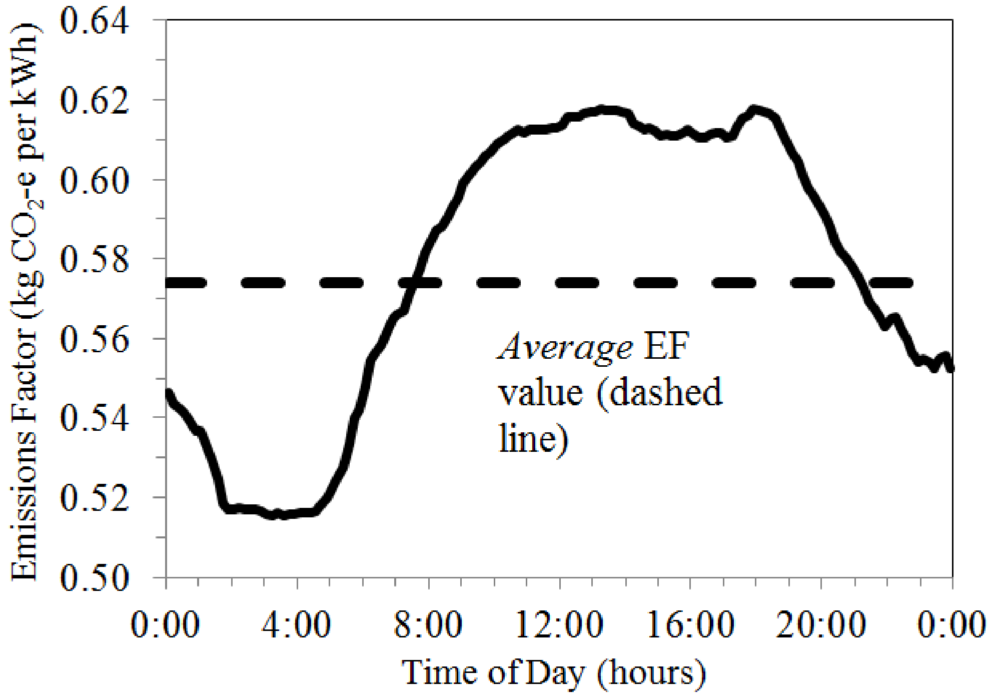

Figure 4. Estimated 24-hour EF curve [taken from Stokes et al. (2014a)] used to calculate operational GHG emissions associated with the use of electricity (solid line). The average EF value is shown for comparison (dashed line).

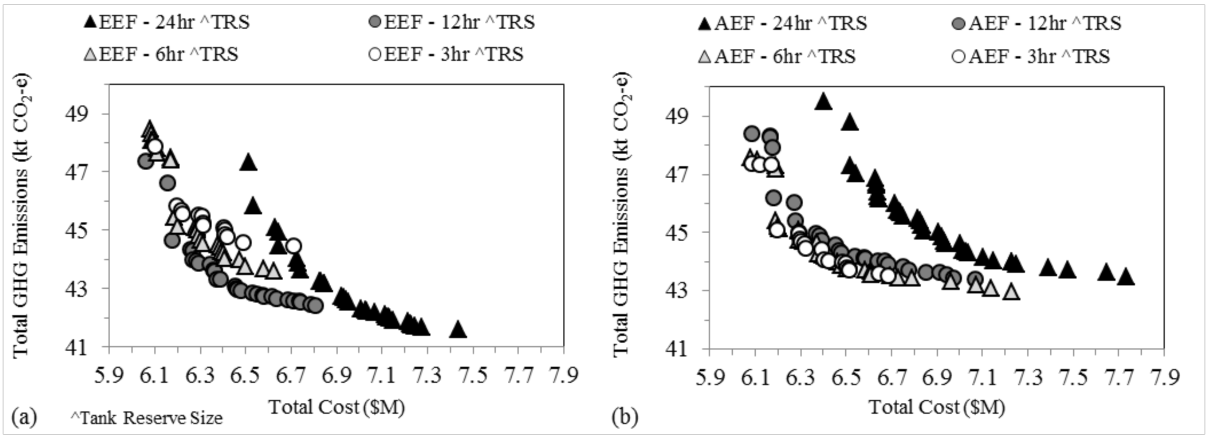

Figure 5. Case study 1 non-dominated solutions for each TRS scenario using (a) the estimated 24-hour EF curve and (b) the average EF to evaluate pumping operational GHG emissions

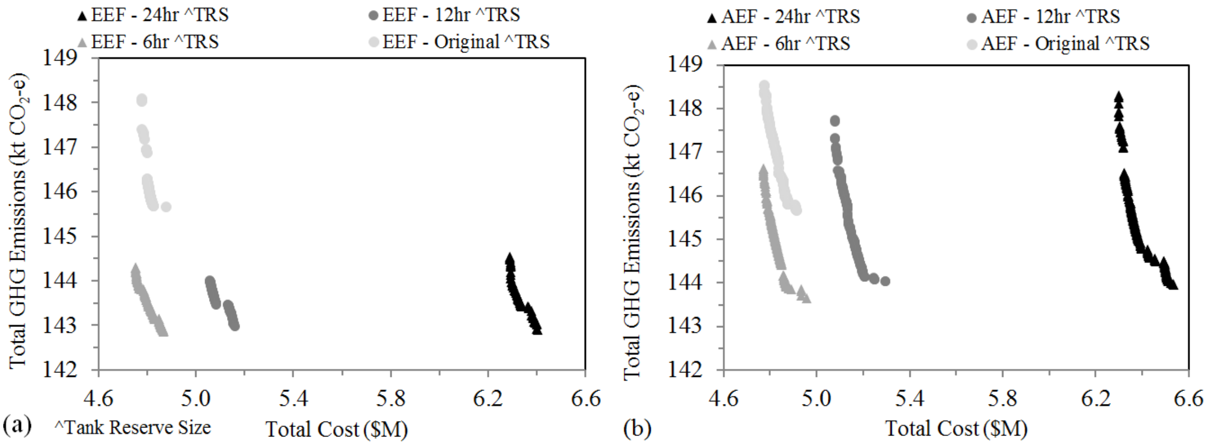

Figure 6. Case study 2 non-dominated solutions for each TRS scenario using (a) the estimated 24-hour EF curve and (b) the average EF to evaluate pumping operational GHG emissions

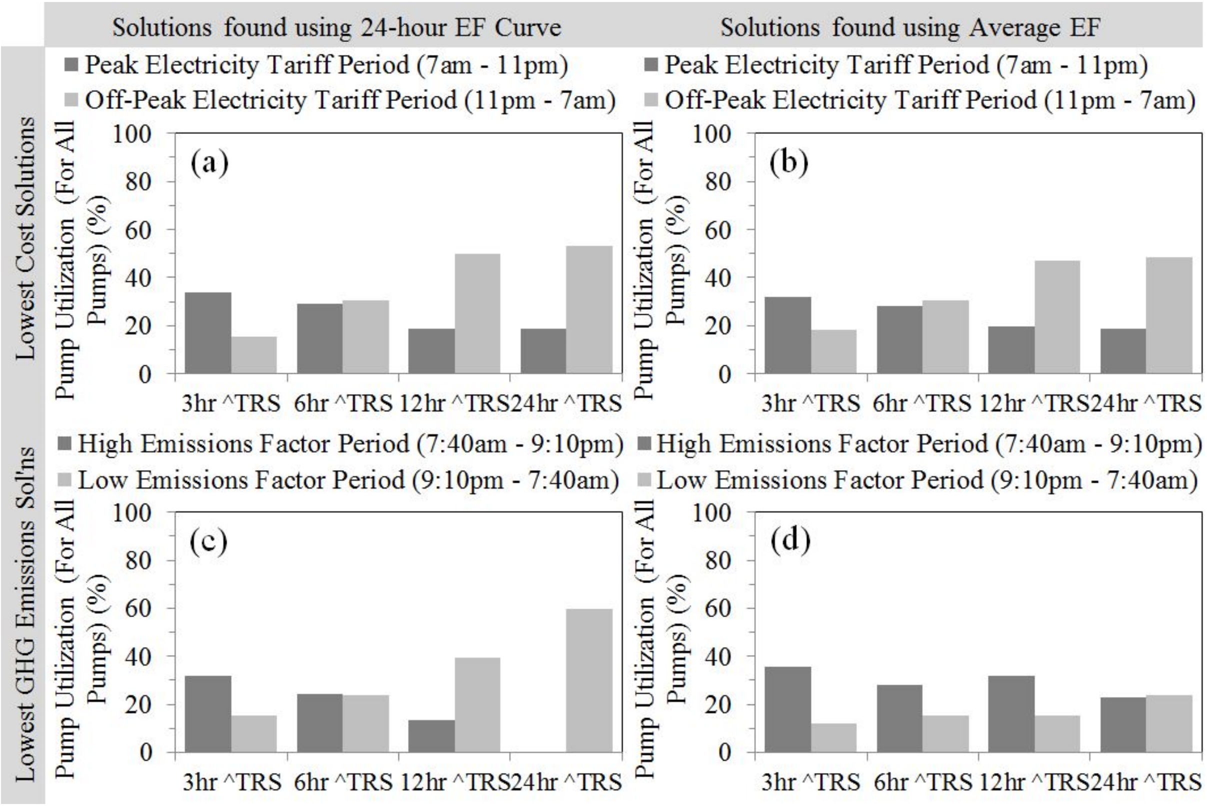

Figure 7. Pump utilization for lowest cost solutions (a, b) and lowest GHG emissions solutions (c, d) for the first case study, found while using the estimated 24-hour EF curve (a, c) and the average EF (b, d)

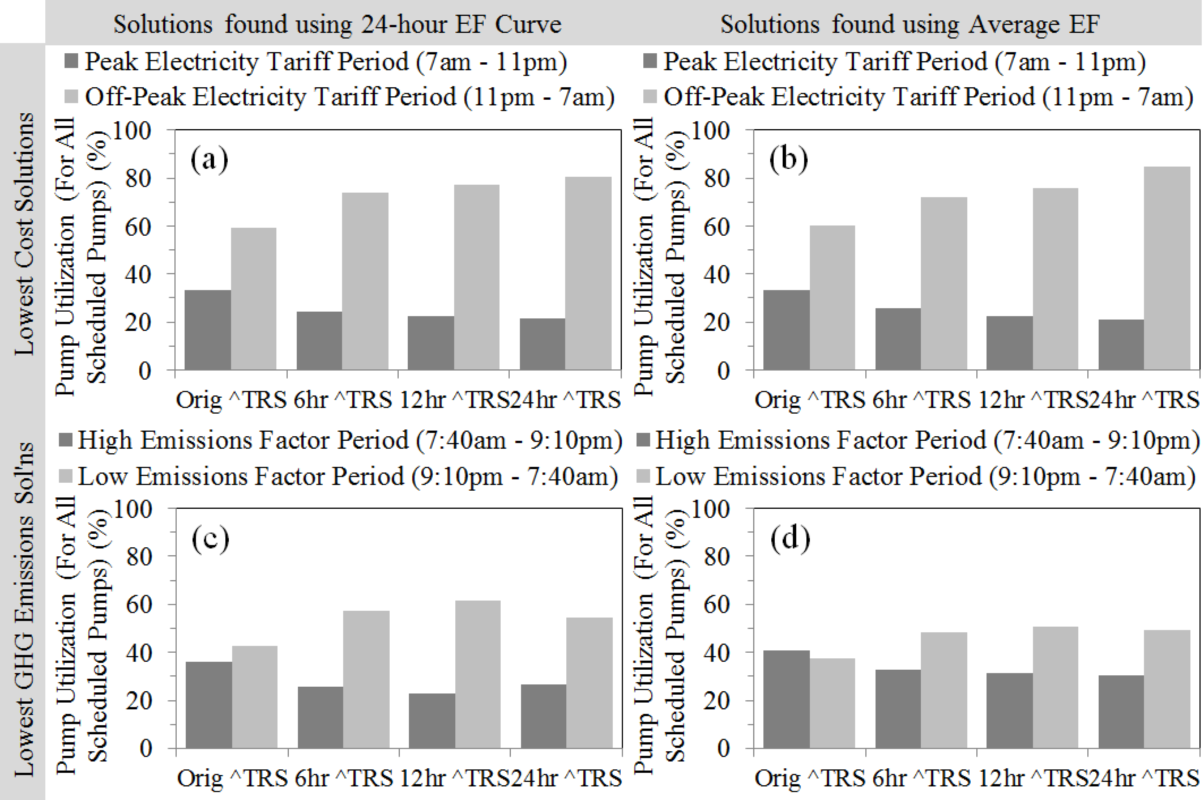

Figure 8. Pump utilization for lowest cost solutions (a, b) and lowest GHG emissions solutions (c, d) for the second case study, found while using the estimated 24-hour EF curve (a, c) and the average EF (b, d)

Table 1. Tank reserve size volumes and associated costs and GHG emissions for each tank reserve size scenario used for each case study. Tank volumes do not include emergency or fire storage.

Case Study 1				Case Study 2			
TRS^ Scenario	Tank Volume (m^3)	Estimated Cost ($M)	Estimated Emissions^^ (kt CO_2-e)	TRS^ Scenario	Vol. of Tank(s) (m^3)	Estimated Cost ($M)	Estimated Emissions^^ (kt CO_2-e)
3 hour	754	0.93	0.02	Original*	9500	1.96	0.29
6 hour	1496	1.02	0.04	6 hour	11083	2.15	0.34
12 hour	3017	1.20	0.07	12 hour	14017	2.50	0.43
24 hour	6026	1.55	0.12	24 hour	24560	3.74	0.69

^Tank Reserve Size

^^Based on the embodied energy of materials used to construct the storage tank

*Based on tank sizes of the original D-town WDS for the Battle of the Water Networks II, which gives a TRS of 2.5 hours