A Framework for the Minimization of Greenhouse Gas Emissions Associated with Water Distribution Systems Considering the Time-Dependency of Emissions Factors Associated with the Generation of Electricity

by

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Thesis submitted to The University of Adelaide,
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in fulfilment of the requirements for the degree of
Doctor of Philosophy

Submitted July 2014

Abstract

While water distribution systems (WDSs) form an integral part of modern cities, it is desirable to minimize the considerable costs that can be associated with their design and pumping operations. However, WDSs are complex systems and complete enumeration of all possible alternative solutions as a way of minimizing costs is generally not possible. As such, formal optimization algorithms have become a popular way to minimize the cost of WDSs within reasonable computational timeframes. Another important objective, minimizing the environmental impact of WDSs, has only more recently been considered. Human-induced climate change caused by greenhouse gas (GHG) emissions has become one of the most significant problems faced by human-kind. Water distribution systems contribute to the release of GHG emissions through both their design/construction and pumping operations.

When electricity used for pumping purposes is generated by fossil fuel generation sources, a significant amount of GHG emissions can be released over the project life of a WDS. This occurs to the extent where the majority of GHG emissions can be associated with electricity consumed for pumping purposes. However, within the literature considering the minimization of costs and GHG emissions associated with WDSs, most research has focused on design optimization, with less consideration being given to the pumping operations of a WDS. Therefore, there remains a need to consider the important aspects of pumping operations so that their associated costs and GHG emissions can be evaluated with the same level of accuracy as those associated with the design of a WDS. Consequently, this research incorporates the elements that are necessary to accurately evaluate costs and GHG

emissions associated with the pumping operations of WDS into a single framework for the minimization of costs and GHG emissions.

The major research contributions are presented in four journal publications. Firstly, the water distribution cost-emissions nexus (WCEN) conceptual framework is presented, which represents the nexus of elements required to accurately model and evaluate costs and GHG emissions when optimizing the design and pumping operation of a WDS. Secondly, in order to facilitate the practical application of these concepts, the WCEN computational software framework, which combines hydraulic simulation with multi-objective heuristic optimization, is presented. In particular, the WCEN computational software framework allows the design and pumping operations of a WDS to be optimized while considering both the short and long-term time-dependency of operational conditions, such as emissions factors associated with electricity generation, of which generally only average values have been considered. Thirdly, a methodology for calculating time-dependent emissions factors from electricity generation data is presented. Finally, a study on the effect of water storage tank size on the optimal design and pumping operations of a WDS is presented. While other design parameters can affect the costs and GHG emissions of WDS, storage tank size has been given little consideration in the past, especially when the time-dependency of emissions factors is also considered. It is hoped that this research will lead to the greater consideration of minimizing both costs and GHG emissions when developing designs and pumping operational management strategies for WDSs in the real world.

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Statement of Originality

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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A list of works contained within this thesis is given in Section 6.3.

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Acknowledgements

Firstly, I would like to thank my supervisors, Angus Simpson and Holger Maier, for all of their dedication and exhaustive effort in helping me to achieve my goals. I am especially grateful to Angus for the opportunity to undertake my postgraduate study, his guidance and his belief in my abilities. I am also grateful to Holger for his tireless efforts in helping me to improve my writing and publications, and the ever interesting and enlightening conversations.

I would also like to thank the two examiners of this thesis, who’s suggestions have added to its quality.

I am grateful to Stephen Carr for his help with debugging my code. Without this, I may never have had the ability to complete my research. I am also grateful to Wenyan Wu for her technical knowledge and constant willingness to help. I would also like to acknowledge the Goyder Institute for Water Research and all of their helpful staff for their support through my studies.

I would especially like to thank Bree Bennett for putting up with working next to me for over three years and the ever entertaining and unproductive conversations. I would like to thank Nicole Arbon, Phil Visintin and Angela Marchi for passing on their expert knowledge in all things academically related. I would like to thank Julie Ligertwood for her support, ever enthusiastic help and constant fruit related encouragement. I would like to thank all of my fellow postgraduate students for their friendship throughout our shared study experience. I would also like to thank all of the staff within The School for all of their help and support.

I would like to thank all of my friends (a special mention to Adam, Brett, Dali, Nina, Tessa and the undergrad gang) for their years of support and encouragement. I would also like to thank my grandparents for their love and support. Finally and most importantly, I would like to thank my mum, for without her persistent love and support, I would have never come this far.

Chapter 1

1.1 Introduction

Water distribution systems (WDSs) form an integral part of modern cities, supplying potable water for the majority of our activities, from the manufacture of goods and cultivation of agricultural products to the basic human-necessity of clean, drinkable water. However, considerable costs can be associated with the design and pumping operations of WDSs [*Zessler and Shamir*, 1989; *Simpson et al.*, 1994]. As such, it is desirable to minimize these costs while maintaining an adequate supply of water to meet the water demands placed on the WDS. However, WDSs are complex systems and complete enumeration of all possible alternatives as a way of minimizing costs is generally not possible [*Simpson et al.*, 1994]. As such, formal optimization algorithms have become a popular way to minimize the cost of WDSs within reasonable computational timeframes. While deterministic approaches have been used [*Alperovits and Shamir*, 1977; *Quindry et al.*, 1981], non-deterministic heuristic optimization algorithms, including population based methods (e.g. evolutionary and Ant Colony Optimization) and single-point based methods (e.g. simulated annealing), have become popular for their efficient and robust search methods [*Dandy et al.*, 1996; *Maier et al.*, 2014].

In the past three decades, a large amount of literature has been devoted to the minimization of costs associated with WDSs by way of evolutionary algorithm optimization [*Simpson et al.*, 1994; *Dandy et al.*, 1996; *Savic and Walters*, 1997; *Walters et al.*, 1999; *Wu and Simpson*, 2001; *Zecchin et al.*, 2007]. However, with the more recent advent of multi-objective evolutionary optimization algorithms, the optimization of more than one objective has become a practical possibility. While reference to the multi-objective optimization of WDSs was first made in the 1960s [*Schaake and Lai*, 1969], the use of MO optimization algorithms has only become prevalent over the past 15 years. Evolutionary based algorithms have become popular for the multi-objective optimization of WDSs and other water resources problems, and include such algorithms as the Structured Messy Genetic Algorithm (SMGA) [*Halhal et al.*, 1997], Strength Pareto Evolutionary Algorithm (SPEA) [*Zitzler and Thiele*, 1999], SPEA2 [*Zitzler et al.*, 2001], Elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II) [*Deb et al.*, 2000], ε-Dominance Multi-Objective Evolutionary Algorithm (ε-MOEA) [*Deb et al.*, 2003], ε-NSGA-II [*Kollat and Reed*, 2006], Multialgorithm Genetically Adaptive Multiobjective Method (AMALGAM) [*Vrugt and Robinson*, 2007], Multi-Objective Hybrid Optimization (MOHO) [*Moral and Dulikravich*, 2008] and Borg MOEA [*Hadka and Reed*, 2013]. Recent algorithms, such as AMALGAM and Borg MOEA, which assimilate design components from other MOEAs, have shown promise for the efficient optimization of many-objective problems [*Vrugt and Robinson*, 2007; *Hadka and Reed*, 2013]. However, SPEA2 and the more widely developed NSGA-II, while being over a decade old, are currently the most popular multi-objective evolutionary algorithms for the optimization of WDSs [*Wu*, 2012].

With the advent of these multi-objective evolutionary algorithms, along with the minimization of costs, other objectives have been considered. These have mainly included objectives based on maximizing the security of water supply, such as by maximizing hydraulic reliability [*Todini*, 2000; *Devi Prasad and Park*, 2004; *Tolson et al.*, 2004; *Farmani et al.*, 2005; *Kapelan et al.*, 2005; *Farmani et al.*, 2006; *Jayaram and Srinivasan*, 2008; *Wu et al.*, 2009b], maximizing mechanical reliability [*Dandy and Engelhardt*, 2006; *Fu et al.*, 2012] and maximizing water quality [*Farmani et al.*, 2006; *Fu et al.*, 2012]. However, another important objective, minimizing the environmental impact of WDSs, has only more recently been considered. Human-induced climate change caused by greenhouse gas (GHG) emissions has become one of the most significant problems faced by human-kind [*Stern*, 2006; *Sterner and Persson*, 2007]. The importance of climate change mitigation via the reduction of GHG emissions has become increasingly recognized by the scientific, commercial and political sectors [*National Round Table on the Environment and the Economy*, 2007; *Department of Resources Energy and Tourism*, 2009]. Within the literature considering the minimization of GHG emissions associated with WDSs, this has been achieved by considering carbon dioxide equivalents (CO_2-e) directly [*Dandy et al.*, 2006; *Wu et al.*, 2010a; *Wu et al.*, 2010b; *Kang and Lansey*, 2012; *Roshani et al.*, 2012; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Basupi et al.*, 2013; *Du et al.*, 2013; *Wu et al.*, 2013; *Basupi et al.*, 2014; *Marchi et al.*, 2014] or as part of a wider array of environmental and climate change objectives [*Herstein et al.*, 2009b; *Herstein and Filion*, 2011; *Herstein et al.*, 2011].

Water distribution systems contribute significantly to the release of GHG emissions through the different phases of their life-cycles. These GHG emissions can be associated with the design/construction, maintenance and decommissioning of the system. The processes of raw material extraction, material processing, component manufacture, transportation and component assembly for the components used during the initial construction and replacement of old components, such as for pipes, pumps and storage tanks can all contribute to releases of GHG emissions [*Herstein and Filion*, 2011]. GHG emissions can also be associated with the operation of a WDS. When electricity used for pumping purposes is generated by fossil fuel generation sources, a significant amount of GHG emissions can be released over the project life of a WDS, to the extent where the majority of GHG emissions can be associated with electricity consumed for pumping purposes [*Herstein et al.*, 2009b; *Wu et al.*, 2010a; *Wu et al.*, 2010b; *Herstein and Filion*, 2011; *Herstein et al.*, 2011; *Kang and Lansey*, 2012; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Wu et al.*, 2013; *Basupi et al.*, 2014]. In order to accurately evaluate the design and pumping operations of a WDS for the minimization of costs and GHG emissions, it is important to consider the following:

1. The important elements of the infrastructure being analyzed, including elements of the WDS infrastructure that affect the hydraulic behavior of the system and elements of the electrical energy generation infrastructure that affect the cost and GHG emissions associated with the use of electricity (Infrastructure, Figure 1.1).
2. The options that can be selected in order to minimize costs and GHG emissions, including the design options (e.g. pipe material and diameters, pump types and storage tank sizes) and pumping operational management options (e.g. pump schedules and trigger levels) (Options, Figure 1.1).
3. The analysis processes used to evaluate the costs and GHG emissions, including those associated with the design of a WDS and the electricity used for pumping operational purposes (Analysis, Figure 1.1).
4. The optimization process used to find solutions of minimized costs and GHG emissions (Optimization, Figure 1.1).
5. The information required to accurately model and evaluate the costs and GHG emissions associated with both the design and pumping operations (Inputs, Figure 1.1).
6. The simulation parameters that are available to evaluate pumping operational costs and GHG emissions as accurately as is possible with the information and computational resources that are available (Simulation Choices, Figure 1.1).

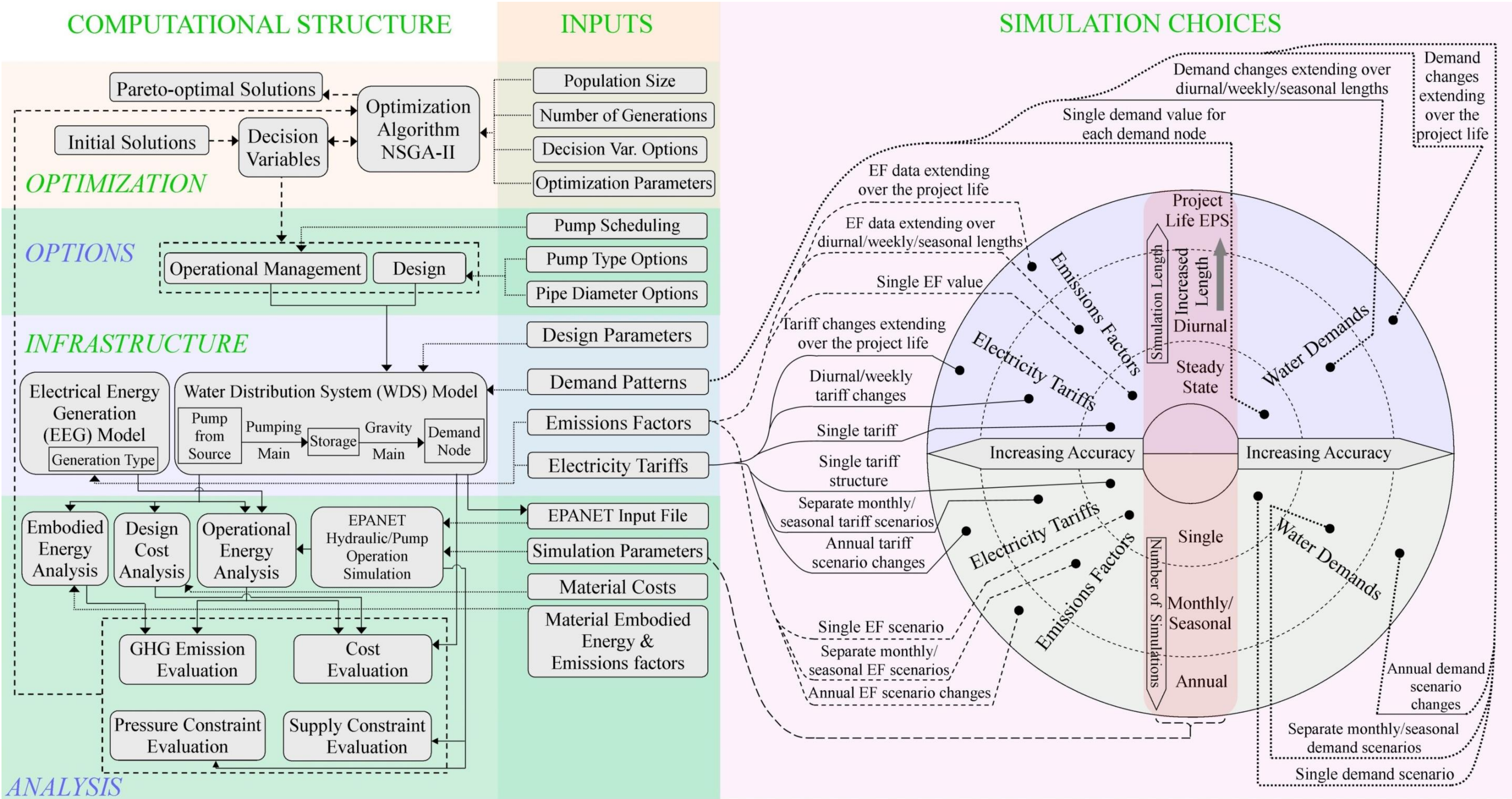

Figure 1.1. Representation of the nexus of elements important for the accurate evaluation of costs and GHG emissions when optimizing the design and pumping operations of a water distribution system (adapted from *Stokes et al.* [2012]).

1.2 Minimization of Costs and Greenhouse Gas Emissions Associated with Water Distribution Systems

Within the literature that considers the minimization of costs and GHG emissions associated with WDSs, most research has focused on the design, with less consideration being given to the pumping operations of a WDS. There remains the need to consider certain aspects of the modelling, evaluation and optimization processes, especially those concerned with the pumping operations of a WDS. Therefore, six key research requirements are outlined. A full review of the relevant literature is provided in Chapter 2.

Firstly, there remains a need to consider the time-dependency of emissions factors (EFs) associated with the generation of electricity used for pumping purposes. EFs are used to quantify the GHG emissions intensity of electrical energy used to drive pumps within a WDS. When electrical energy consumed by a WDS is supplied by multiple generation sources through an electricity grid, the emissions intensity of electricity can vary over time. This is because the emissions intensity of electrical energy is proportional to the individual emissions intensities of the different generation sources supplying electricity and the contribution of each source at any point in time. For example, an electricity grid supplied predominantly by fossil fuel generation (e.g. coal and gas fired generation) will supply electrical energy with a greater emissions intensity than a grid supplied predominantly by renewable energy sources (e.g. wind farms and solar arrays). As electricity grids are increasingly being supplied by a mix of both fossil fuel and renewable generation sources, and the contribution of these generation sources can change over time, the emissions intensity will also change over time. These time periods can be short, as the contributions of different generators can change within each hour of each day as the generating ability and profitability of each generation source changes (e.g. reducing expensive gas fired generation during off-peak electricity demand times and the reduced generating ability of wind farms during low wind times). Emissions intensities can also change over mid- and long-term time periods, as the contributions of different generation sources changes over different months within a year (e.g. decreased sunlight during winter months will decrease the generating ability of solar arrays) or over consecutive years, as new generation sources are commissioned and old generation sources are decommissioned. As such, the emissions intensity, and therefore EFs associated with the consumption of electrical energy, can change over both short and long time periods. While previous literature has used EFs to evaluate GHG emissions associated with the operation of WDSs, most have used an average EF, which does not consider the time-dependency of EFs [*Stokes et al.*, 2014c; *Stokes et al.*, 2014a]. As discussed by Stokes et al. [2014c], some literature has considered the long-term reduction in EFs in response to climate change policy, reducing EFs in line with those expected over the project life of a WDS. However, little consideration of the short- and mid-term time-dependency of EFs has yet been made. Time-variations of EFs, such as variations over the hours of a day and the months of the year, can affect the optimal pumping operational management of a WDS, as pumping during low EF times can help to minimize pumping operational GHG emissions without minimizing the amount of electrical energy that is consumed. Annual variations in EFs can also affect the total pumping operational GHG emissions associated with a WDS over its project life, thereby affecting the trade-offs that occur between minimizing design GHG emissions by reducing pipe diameters and minimizing pumping operational GHG emissions by reducing frictional energy losses within the pipe network. As such, the time-dependency of EFs constitutes an important consideration.

Secondly, as the evaluation of pumping operational GHG emissions while considering time-dependent EFs is introduced, it is important to also consider the time-dependency of water demands when evaluating the pumping operations of a WDS. As the consideration of time-dependent EFs affects the optimal time-of-use of pumps, considering the changes in water demands allows the developed pumping operational management strategies (discussed below) to more accurately represent the real-world operation of the WDS. This is important for three reasons, including (i) better control of system hydraulics can be maintained if water demands are more accurately represented; (ii) pumping operational management strategies can be specifically chosen to take advantage of the changes in water demands with respect to reducing pumping operational GHG emissions; and (iii) optimal selection of design components can be more accurately chosen in order to achieve the best trade-off between design and pumping operational GHG emissions. Recent literature considering the minimization of GHG emissions associated with WDSs has considered the short-term variability of water demands by using diurnal water demand curves to represent the changes in water demands over a 24 hour time period [*Stokes et al.*, 2014c]. However, limited consideration has been given to the time-dependency of water demands beyond diurnal variations [*Stokes et al.*, 2014c]. As such, there is a need to better consider the time-dependency of water demands when reducing GHG emissions associated with WDSs.

Thirdly, as the time-dependency of EFs is considered, it is important to also consider the time-dependency of electricity tariffs in order to evaluate both costs and GHG emissions with the same level of accuracy. While electricity tariffs are not directly related to the generation of electricity, the electricity tariff can be set to change according to the time-of-use of electrical energy. This can be used by an electricity grid regulator to reduce the consumption of electricity during higher demand periods, such as reducing demands during the highest daily demand periods or reducing demands over the higher demand months of the year. As the pumping operational management of a WDS can be chosen to take advantage of low emissions intensity electrical energy times, consideration should also be extended to the use of pumps during off-peak electricity tariff times. While consideration of the long-term time-dependency of electricity tariffs considered in the literature helps to more accurately evaluate pumping operational costs, it has no effect on the optimal pumping operational management of a WDS, as this is not made in conjunction with the consideration of pumping operational management options [*Stokes et al.*, 2014c]. Little consideration of the short-term variations of electricity tariffs, which can affect the optimal pumping operational management, while considering the reduction of both the costs and GHG emissions associated with pumping in WDSs, has been made [*Stokes et al.*, 2014c]. As such, there remains a need to consider the time-variability of electricity tariffs and its effect on the optimal operation of a WDS.

Fourthly, if the time-dependency of EFs, water demands and electricity tariffs are to be considered, then the ability to change the WDS to benefit from this information should also be considered. Considering the time-of-use of pumps allows electrical energy to be consumed during low EF and off-peak electricity tariff times, helping to further reduce both the costs and GHG emissions associated with pumping in a WDS. As the operational management of a WDS is restricted by the hydraulic capability of the system, it is important to jointly consider the design and pumping operation phases. While literature considering the minimization of costs and GHG emissions has considered both design and operational aspects, and other literature has considered how pumping operations can help to minimize costs, limited consideration has been given to the optimization of pumping operational management while minimizing GHG emissions [*Stokes et al.*, 2014c; *Stokes et al.*, 2014a]. Hence, there remains a need to consider pumping operational management strategies when minimizing the costs and GHG emissions associated with WDSs.

Fifth, if the time dependency of EFs, water demands and electricity tariffs and pumping operational management strategies are to be considered, then it is important to consider the effect of water storage within a WDS. Storage tanks are commonly used to provide a hydraulic balancing service, thereby separating the direct connection between pumps that supply water into the WDS and demand nodes that demand water from the WDS. As such, the available balancing volume of storage tanks can affect the time-of-use of pumps. However, in the literature considering the minimization of pumping costs and GHG emissions, little consideration has been given to the balancing volume of storage tanks or their subsequent effect on the time-of-use of pumps [*Stokes et al.*, 2014c]. Hence, there remains a need to consider the balancing volume of storage tanks when minimizing the costs and GHG emissions associated with WDSs.

Finally, if the time-dependency of EFs, water demands and electricity tariffs, pumping operational management strategies and the effect of storage tank balancing volumes are to be considered, then the WDS must be simulated in a way that allows these considerations to be made. Hence, the ability to simulate a WDS for short and long term time-variations is required. While some have considered the use of extended period simulations (EPSs) to evaluate the pumping operations, the use of steady-state hydraulic simulations has predominantly been considered [*Stokes et al.*, 2014c]. Hence, there remains a need to consider both the length and number of simulations used to evaluate the pumping operations of a WDS, particularly when the time-dependency of EFs, water demands and electricity tariffs is considered.

1.2 Objectives

With consideration of the research requirements outlined above, the aim of the research presented within this thesis is to investigate the nexus of elements required to accurately evaluate the design and pumping operations of WDSs for the minimization of costs and GHG emissions. This is done while considering the time-dependency of emissions factors, water demands and electricity tariffs, pumping operational management strategies, storage tank balancing volumes and the simulation parameters that these require. In order to do this (i) a framework that integrates the nexus of elements required to accurately evaluate and minimize costs and GHG emissions and (ii) a method of calculating time-varying emissions factors associated with the generation of electricity are both required. In order achieve this, the following four objectives and six sub-objectives are used. A summary of these objectives is shown in Figure 1.2.

Objective 1. To develop a conceptual framework that identifies and shows the interactions between the various modelling elements that have an impact on WDS design and pumping operational costs and GHG emissions evaluation and optimization, including those from energy generating infrastructure, in an integrated fashion. Furthermore, to identify the knowledge gaps with respect to the simplification of the modelling processes and the research required to address these gaps (**Chapter 2**).

Objective 2. To develop a computational software simulation and multi-objective optimization framework based on the conceptual framework described in **Objective 1** that can be used to help address the identified knowledge gaps. Importantly, this framework must incorporate the considerations of both the short- and long-term time-dependency of emissions factors, water demands and electricity tariffs, pumping operational management strategies and the simulation parameters that these require (**Chapter 3**).

> ***Sub-objective 2.1.*** *To demonstrate the importance of developing solutions of minimized costs and GHG emissions, while considering both the short- and long-term time-dependency of emissions factors, water demands, electricity tariffs and pumping operational management strategies, afforded by the use of the developed computational software framework for a case study WDS.*

Objective 3. To develop a method for the calculation of time-dependent EFs associated with the consumption of electricity generated by multiple electrical energy generation sources with different individual associated emissions intensities (**Chapter 4**).

> ***Sub-objective 3.1.*** *To test the impact of considering the time-dependency of EFs by comparing solutions found using actual EFs over a one-year period, which consider the actual variations in emissions intensity, with those found using an average EF for a hypothetical case study WDS.*

> ***Sub-objective 3.2.*** *To develop an estimated (typical) 24-hour EF curve that can be used for day-to-day operational purposes, which aims to replicate the important characteristics of the time-dependency of actual EFs, and compare the solutions found using the estimated 24-hour EF curve with those found using actual EFs over a one-year period for a hypothetical case study WDS.*

> ***Sub-objective 3.3.*** *To test the sensitivity of solutions found while considering different amounts of renewable energy penetration by comparing solutions found using three modified estimated (typical) 24-hour EF curves, which aim to replicate the diurnal time-dependency of EFs for different (hypothetical) renewable*

energy (wind generation) penetration possibilities, with solutions found using the estimated (typical) 24-hour EF curve, for a hypothetical case study WDS.

Objective 4. To investigate the effect of the storage tank size (balancing volume), while considering design (pipe diameter and pump type) and pumping operational management options, on the development of non-dominated optimized solutions while considering the time-dependency of emissions factors (**Chapter 5**).

Sub-objective 4.1. *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.*

Sub-objective 4.2. *To investigate the effect that using either time-varying EFs, represented by the use of an estimated 24-hour EF curve (from Sub-objective 3.2), 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 4.1.*

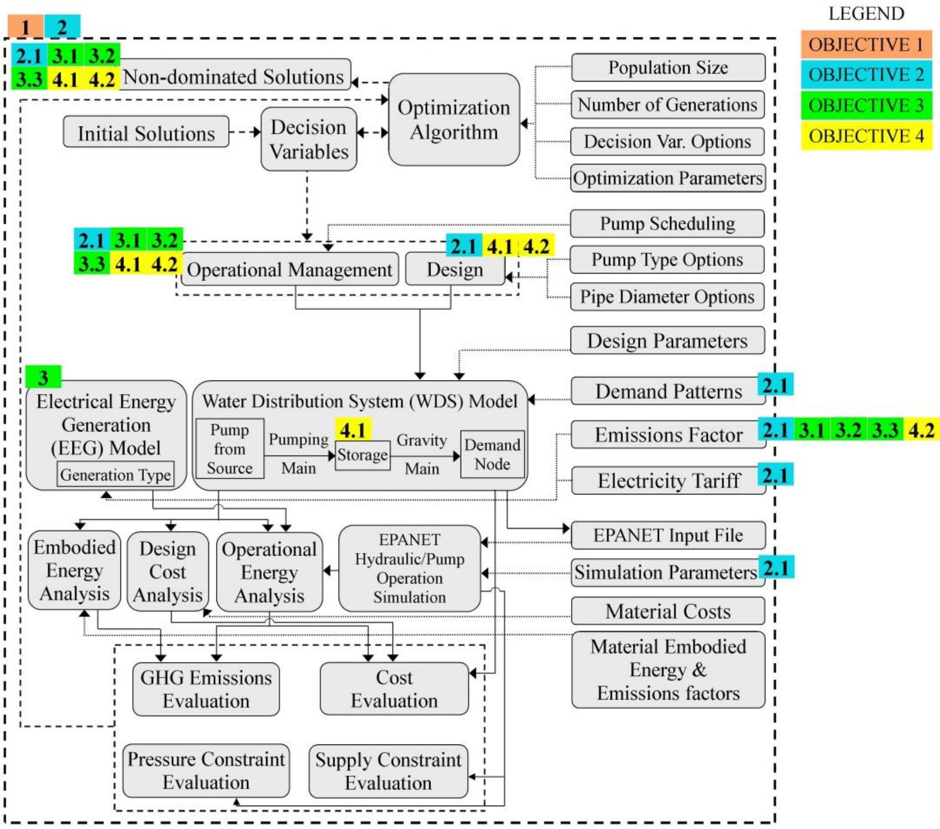

Figure 1.2. Projection of research objectives onto the water distribution cost-emissions nexus framework developed as part of this research.

1.3 Computing Resources Used for Optimization

In order to achieve the previously outlined objectives, multi-objective optimization is used. For this research, two multi-objective evolutionary algorithms have been modified and were subsequently used for the research undertaken and presented in Chapters 3 to 5. For the research presented in Chapters 2 and 3, the Elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II) [*Deb et al.*, 2000]. NSGA-II is used for its efficient solution space search ability, ease of implementation and because it has been successfully applied to recent WDS cost and GHG emissions optimization problems [*Stokes et al.*, 2014a]. NSGA-II is modified to allow the use of integer decision variables for selecting design choices (e.g. pipe diameters and pump types) and pumping operational choices (e.g. pump schedule times). For the research presented in Chapter 5, the state of the art Borg Multi-Objective Evolutionary Algorithm (MOEA) [*Hadka and Reed*, 2013] is used. As with NSGA-II, Borg MOEA is modified to allow integer decision variables to be used.

Computational optimization used for this research is undertaken using the eResearch South Australia (ERSA) Corvus (decommissioned in February 2014) and Tizard high performance computing facilities [*eResearch South Australia*, 2014]. These computing facilities are used as they allow multiple optimization runs to be performed in unison. Each optimization run is performed using a single thread on a multi-core processor (2.66 GHz Intel Clovertown quad core or 2.6 GHz AMD 6238 12-core processor). Computational information for the optimization runs that are undertaken is shown in Table 1.1. As can be seen, a large amount of computational time is devoted to the research and this is beyond the feasible capabilities of a desktop PC. In total, optimization performed for this research takes nearly 13,000 hours (approximately 1.5 years) of computational time (e.g. over 1.5 years to run using a single desktop PC). Hence, the capabilities of the ERSA high performance computing facilities are utilized.

Table 1.1. Computational information for the optimization runs performed for this research.

	Number of Optimization Runs	Optimization Time (per Run)	Total Computational Time
Chapter 3 (Paper 2)	*960*	*Approx. 80 mins (1.2 hrs) for 48 hour EPS* (n.b. multiple EPSs required when considering multiple operational scenarios)*	*76,800 mins (1,280 hrs)*
Chapter 4 (paper 3)	*180*	*Approx. 270 mins (4.5 hrs) for 7 day EPS* to 15,600 mins (260 hrs) for 365 day EPS**	*508,500 mins (8,475 hrs)*
Chapter 5 (Paper 4)	*480*	*Approx. 80 mins (1.2 hrs) for case study 1 (48 hour EPS*) to 720 mins (12 hrs) for case study 2 (168 hour EPS*)*	*192,000 mins (3,200 hrs)*
Total	*1,620*		*777,300 mins (12,955 hrs)*

*EPS refers to the extended period hydraulic simulation used to evaluate water distribution system objectives and constraints as part of the optimization process.

1.4 Thesis Overview

This thesis is organized into six chapters. In the main body of this thesis (**Chapters 2 to 5**), four journal papers are presented [*Stokes et al.*, 2014a; *Stokes et al.*, 2014b; *Stokes et al.*, 2014c; *Stokes et al.*, 2014d]. In **Chapter 6**, the thesis conclusions are drawn and research contributions, limitations and recommendations for future work are discussed. The following outlines the material covered in **Chapters 2 to 5** and links each to the research objectives outlined in **Section 1.2** (see Figure 1.3):

> **Chapter 2 (Paper 1)** [*Stokes et al.*, 2014c] presents the water distribution cost-emissions nexus (WCEN) conceptual framework, which describes the nexus of elements required to accurately simulate and optimize WDSs for the minimization of

costs and GHG emissions while considering knowledge gaps including the time-dependency of EFs, water demands, electricity tariffs and operational management strategies and the simulation parameters that these require. A review of literature considering the minimization of costs and GHG emissions associated with WDSs and based around the concepts presented in the conceptual framework is presented, knowledge gaps in previous research are identified and recommendations are made for research requirements (**Objective 1**) which are subsequently addressed in **Chapters 3 to 5**.

Chapter 3 (Paper 2) [*Stokes et al.*, 2014d] presents the water distribution cost-emissions nexus (WCEN) computational software framework (developed by the authors), based on the WCEN conceptual framework developed in **Chapter 2**, which is used to find solutions of minimized costs and GHG emissions associated with WDSs while considering the time-dependency of EFs, water demands, electricity tariffs and operational management strategies and the simulation parameters that these require (**Objective 2**). The utility of the WCEN computational software framework is demonstrated by comparing non-dominated solutions found, while using EFs, water demands, electricity tariffs and operational management strategies that consider different combinations of short- and long-term time-dependency, for a case study WDS (**Sub-objective 2.1**).

Chapter 4 (Paper 3) [*Stokes et al.*, 2014a] presents a methodology for calculating time-dependent emissions factors associated with the consumption of electricity generated by multiple electrical energy generation sources with different individual associated emissions intensities (**Objective 3**). A case study WDS is optimized to test the impact of considering the time-dependency of EFs by comparing non-dominated solutions found using actual EFs, which consider the actual variations in emissions intensity, with those found using an average EF (**Sub-objective 3.1**). An estimated (typical) 24-hour EF curve, which aims to replicate the important aspects of the time-dependency of actual EFs, is developed and a case study WDS is optimized to compare the non-dominated solutions found using the estimated 24-hour EF curve with those found using actual EFs (**Sub-objective 3.2**). Three modified estimated 24-hour EF curves, which represent the average diurnal changes in emissions intensity over the period of the actual EFs for three different (hypothetical) amounts of renewable energy (wind generation) penetration, are developed. A case study WDS is optimized and the non-dominated solutions found using the three modified estimated 24-hour EF curves are compared with those found using the estimated 24-hour EF curve (**Sub-objective 3.3**).

Chapter 5 (Paper 4) [*Stokes et al.*, 2014b] presents a methodology to investigate the effect of the storage tank balancing volume, while considering design (pipe diameter and pump type) and pumping operational management options, on the development of non-dominated solutions while considering the time-dependency of emissions factors (**Objective 4**). Both new (design and pumping operational management optimization) and existing (pumping operational management optimization only) case study WDSs are optimized to test the impact of considering the storage tank balancing volume on the development of non-dominated solutions while using an estimated 24-hour EF curve to consider the time-dependency of EFs (**Sub-objective 4.1**). A new and an existing case study WDS are optimized to test the impact of considering the time-dependency of EFs by comparing the non-dominated solutions found while using an estimated 24-hour EF curve to those found while using an average EF (**Sub-objective 4.2**).

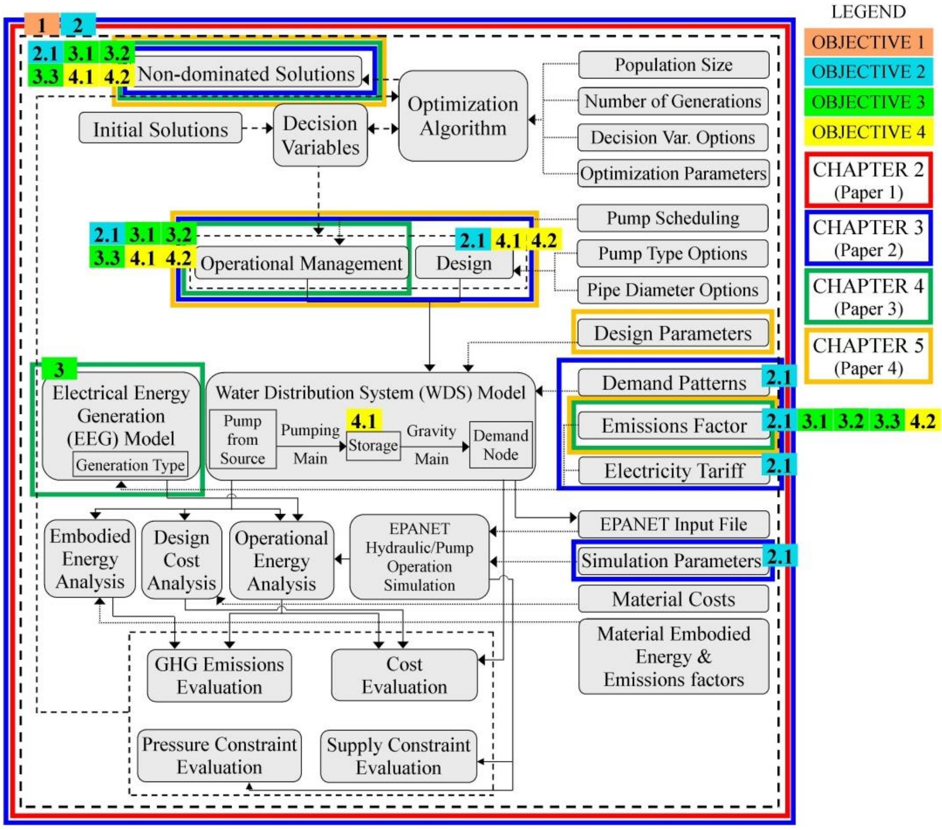

Figure 1.3. Linkage of publications and research objectives.

Chapter 2

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

Statement of Authorship

Title of Paper	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
Publication Status	Published
Publication Details	Stokes, C. S., A. R. Simpson, and H. R. Maier (2014), The cost-greenhouse gas emission nexus for water distribution systems including the consideration of energy generating infrastructure: An integrated optimization framework and review of literature, Earth Perspectives, 1(9), 1-17.

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

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Abstract

The increased release of greenhouse-gas (GHG) emissions associated with human activities causing climate change is one of the most significant problems faced by human-kind. Water distribution systems (WDS), whilst providing an essential service to society, are responsible for the generation of significant amounts of GHGs. In response, the minimization of GHG emissions associated with WDSs has become a research focus. In this paper, a critical review of previous research is provided, summarizing research progress and highlighting research needs in this emergent and important area. This is done within the context of the water distribution system cost-emissions nexus (WCEN) conceptual framework, which is a novel conceptual framework that considers the interaction between all components required to accurately evaluate the costs and greenhouse gas (GHG) emissions associated with water distribution systems (WDSs) in an integrated fashion. Key findings from this review indicate that future research should (1) include the use of time-dependent emissions factors (EFs), which would allow the scheduling of pumps at times of lower emissions intense energy to be considered; (2) include the modeling of seasonally variable water demands; (3) include greater consideration of the hydraulic simulation process, such as using seasonal extended period simulations; (4) include greater consideration of the management of pumping operations at the design stage, instead of solely focusing on changes in infrastructure design to reduce costs and GHG emissions; (5) include consideration of the effects that external policies, such as carbon taxes and present value discounting, have on the trade-offs between costs and GHG emissions

2.1 Introduction

The increased release of greenhouse-gas (GHG) emissions associated with human activities causing climate change is one of the most significant problems faced by human-kind [*Stokes et al.*, 2012]. Greenhouse gas (GHG) releases through human-related activities have been identified as a major cause of human-induced climate change. The importance of mitigating climate change by reducing GHG emissions has been widely recognized by the scientific, commercial and political sectors. Water distribution systems (WDSs) provide an essential service to modern cities. However, they also contribute significantly to the release of GHG emissions through activities related to their construction and operation, especially when pumping operational energy is sourced from fossil fuel electricity generation sources. WDSs are also complex systems, with many different design and operational options being available to a decision maker. Thus, it is often impractical or even impossible for a decision maker to evaluate and consider the combination of all available options. As such, optimizing the design and operation of WDSs via the use of optimization algorithms has become a popular way of considering these many available options. In order to evaluate the performance of the many potential design and operation combinations during evolutionary algorithm based optimization processes, WDSs must be modeled (i.e. simulated). However, the modeling of WDSs can be computationally expensive. As such, simplifications are often made during the modeling process in order to reduce both the problem complexity and the computational time required to evaluate each solution in the optimization process (in the case where evolutionary algorithms or similar metaheuristics are used). This can include simplifications to the decision variables, such as limiting the types and number of options considered; simplifications to input data, such as replacing actually time-dependent input information with steady-state or approximate values; and simplifications to the simulation process, such as hydraulically simulating a limited number of water demand scenarios compared to what will be encountered during real-life operations [*Stokes et al.*, 2012]. The optimization of costs associated with water distribution systems has been covered extensively in the past three decades [*Wu et al.*, 2010b]. As such, simplifications made to the modeling of WDSs have been well established. Consideration of optimizing WDSs for the minimization of GHG emissions has only occurred more recently. Commonly, GHG emissions (both capital emissions and operational emissions from fossil fueled electricity sources) have been optimized along with costs by using multi-objective (MO) optimization algorithms. As such, modeling simplifications applied when evaluating costs are also applied when evaluating GHG emissions. These simplifications have the potential to affect the possible solutions and their corresponding evaluations. In addition, the primary focus of optimization has been on the selection of WDS infrastructure design options (e.g. pipe sizes and pump types). Only limited consideration has been given to the impact of pump operational management, interactions between water supply infrastructure and energy generating infrastructure and how policy drivers may affect the optimal trade-offs between cost and GHG emissions. Therefore, there remains a need to review the current literature considering the optimization of WDSs for the minimization of GHG emissions in order to establish what modeling simplifications have been made and to identify gaps in current modeling and evaluation processes. In order to achieve this, a conceptual framework is required to identify and show the nexus of modeling elements that can impact on the optimization of costs and GHG emissions associated with WDSs. Additionally, this conceptual framework should include consideration of energy generating infrastructure that affects pumping operational GHG emissions, as well as policy drivers that can impact the trade-offs between costs and GHG emissions associated with WDSs. Such a framework was first presented by Stokes et al. [2012]. As such, the objectives of this paper are as follows:

1. To develop a conceptual framework, based on the framework presented by Stokes et al. [2012], that identifies and shows the interactions between the various modeling elements that have an impact on WDS cost and GHG emissions optimization, including those from energy generating infrastructure, in an integrated fashion.

2. To review existing literature considering the minimization of GHG emissions associated with WDSs in the context of the proposed conceptual framework in order to identify the research gaps with respect to the simplification of the modeling processes and future research required to address these gaps.

The water distribution system cost-emissions nexus (WCEN) conceptual framework (Objective 1), is presented in Section 2.2. The evaluation of existing literature in the context of the WCEN conceptual framework (Objective 2) is presented in Section 2.3, leading to the identification of current research gaps and future research directions required to progress this field of research (Sections 2.4 and 2.5).

2.2 Water Distribution Cost-emissions Nexus (WCEN) Conceptual Framework

The WCEN conceptual framework (Figures 2.1 and 2.2) is based on the similarly named framework presented by Stokes et al. [2012]. While not an analytical tool itself, the WCEN conceptual framework represents the nexus of elements required to accurately model and evaluate costs and GHG emissions when optimizing the design and operation of a WDS.

The conceptual framework is separated into four distinct components (Figure 2.1). These include an infrastructure component (WDS and electricity generation infrastructure), options component (design and operations of the WDS), analysis component (simulation and evaluation), and government policy sub-component, each of which consists of a number of related elements. The components are linked to one another to represent the flow of information through the system. A list of components and sub-components of the conceptual framework is given in Table 2.1. In addition, the framework also consists of a simulation dynamics component (Figure 2.2), as the most appropriate simulation duration and number of simulations performed can have a significant impact on accuracy and computational efficiency, and are likely to be different for the evaluation of costs and GHG emissions. The various sub-components of the WCEN conceptual framework are described in detail in the subsequent sections.

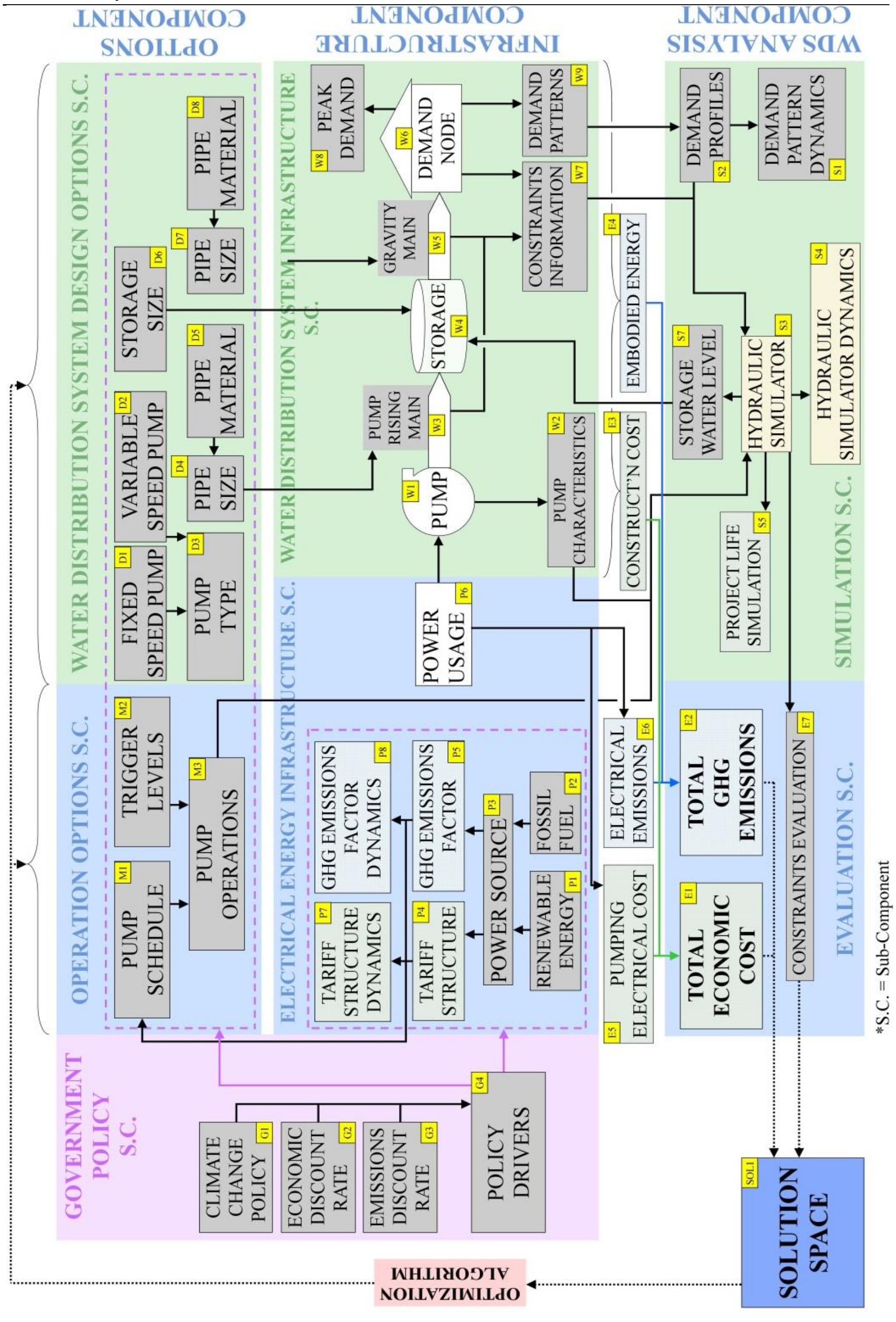

Figure 2.1. The water distribution system cost-emissions nexus framework (modified from *Stokes et al.* [2012]). Refer to Appendix A for an enlarged image.

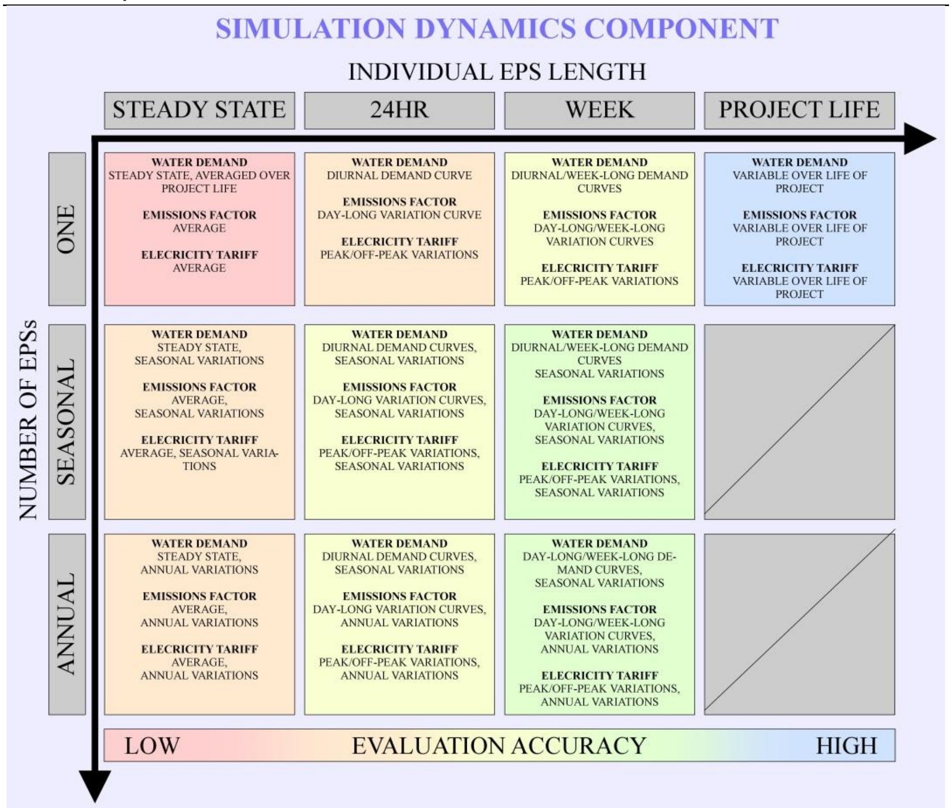

Figure 2.2. The simulation dynamics component. Refer to Appendix B for an enlarged image.

Table 2.1. Components and sub-components, water distribution system cost-emissions nexus framework.

Component	Sub-Component (SC)
Options Component	*Operation Options SC*
	WDS Design Options SC
	*Government Policy SC**
Infrastructure Component	*Electrical Energy Infrastructure SC*
	WDS Infrastructure SC
	*Government Policy SC**
WDS Analysis Component	*Simulation SC*
	Evaluation SC

*While the Government Policy sub-component is associated with both the Options and Infrastructure components, it is discussed separately from these components in the text

2.2.1 Infrastructure Component

In order to obtain accurate estimations of the costs and GHG emissions when optimizing the design and operation of a WDS, it is important to consider the real-world infrastructure that is being modelled. The infrastructure component within the WCEN conceptual framework represents this real-world infrastructure. Two critical infrastructure types are important to consider. These include the WDS being modeled, as represented by the WDS infrastructure sub-component, and the sources of generation of electricity being used by pumps during the operation of WDSs, as represented by the electrical energy generating infrastructure sub-component. While simplifications to both systems are required, each system's critical aspects, as related to the conceptual framework's purpose, should be retained.

Modeling of the WDS infrastructure is used to represent the physical WDS elements that allow water to be supplied from sources to consumers. An accurate representation of the critical elements of the actual WDS is required if costs and GHG emissions are to be estimated accurately. These elements are represented within the WDS infrastructure sub-component, and include the pumps that supply water to the system [W1 – See Figure 2.1]; the pump rising mains [W3] that connect the pumps to the distribution pipe network; the water storage systems [W4], which can include either reservoirs or tanks; the gravity mains that distribute water from water storages to the demand nodes [W5]; and the demand nodes, which represent the consumer demands placed on the WDS [W6]. Water demand patterns [W9] of the WDS being modeled are used within the hydraulic simulation process to consider the real-world water demands. A water demand profile [S2] can represent multiple water demand patterns for different demand node requirements (e.g. residential, commercial and industrial). A combination of multiple water demand patterns can also be used to represent different water demand scenarios, such as different seasons in a year. While peak and average water demand flows are commonly used when simulating a WDS, it can be important to consider a range of operational conditions in order to obtain the most accurate estimate of operational costs and GHG emissions. Additionally, it can also be important to consider exceptional water demand circumstances, such as fire loadings and pipe breakages. As water demands drive the system hydraulics, an accurate representation of both water demands and the physical infrastructure can help to obtain an accurate estimation of the pumping operational energy required to meet the demands. Additionally, accurate representation of the physical infrastructure is important if design related costs and GHG emissions are to be accurately estimated. Other aspects of a WDS, such as infrastructure maintenance and replacement, miscellaneous running costs (e.g. electricity for lighting at pump stations) and labor costs are not usually able to be included as part of the hydraulic simulation and are therefore not represented by the WDS infrastructure sub-component of the conceptual framework presented in this paper.

The electrical energy infrastructure sub-component represents the elements of electricity generation and supply infrastructure that are required to accurately evaluate pumping operational costs and GHG emissions associated with a WDS. The cost of electricity for pumping is commonly calculated by using an electricity tariff, which is represented by a tariff structure [P4]. The tariff structure dynamics [P7] represent the different possible tariff structures, such as flat rate or peak/off-peak rates. In order to accurately estimate the cost of pumping operational energy consumption, it is important to consider the variability in electricity tariffs during each day and/or week, as well as possible seasonal and annual variability. Pumping operational GHG emissions can be calculated by considering the generation rate and emissions factors of individual generators feeding into the grid. As such, both renewable [P1] and fossil fuel (non-renewable) [P2] generation types are represented in the conceptual framework. In order to accurately estimate the overall emissions factor [P5] of the electricity supplied to the WDS, the amalgamation of all individual generators supplying into the grid, represented as the electrical source [P3], should be considered. The use of emissions factors is represented by the emissions factors dynamics [P8]. Emissions factors can range from the use of a single, average value, to the use of multiple emissions factors used to represent the change in emission intensities over the period of a day, between each month/season in a year, or between each year over the operational life-span of the WDS. As a WDS is just one of many users consuming electricity from a grid, careful consideration should be given to how emissions factors associated with the consumption of electricity by the WDS [P5] are calculated (e.g. whether emissions factors values consider all generated electricity, or only the generation of electricity used by the

WDS). While the consideration of how emissions factor values are calculated is beyond the scope of this paper, the application of the emissions factor values must also be carefully considered. The way in which emissions factors are used can affect the evaluation of emissions.

2.2.2 Options Components

In order to find solutions of minimized costs and GHG emissions when optimizing the design and operation of a WDS, it is important to consider the options available to decision makers. These options are represented within the options component by two sub-components; the water distribution system design options (WDS design options) sub-component and the operation options sub-component.

The WDS design options sub-component is used to represent the options related to the design of the hydraulic infrastructure. Design phase considerations commonly include the selection of sizes of pipes, storage tanks/reservoirs and pumps, and are generally assumed to be fixed after the construction (or redevelopment/rehabilitation) of the system. Chosen pump types [D3], both variable-speed pumps (VSPs) [D2] and fixed-speed pumps (FSPs) [D1], pipe sizes [D4, D7], material types [D5, D8] and water storage sizes [D6] can significantly affect design costs and GHG emissions associated with the products themselves and operational costs and GHG emissions, through their effect on system hydraulics. While design costs may be evaluated from pricing information gained from commercial sources, design GHG emissions must be calculated directly from the materials used. Embodied energy is commonly used to calculate these GHG emissions. A widely used definition of embodied energy has been given by Treloar [1994].

Options available for the operational management of WDSs are represented by the operation options sub-component. Pumping operations can be explicit (using pump scheduling) and/or implicit (using storage trigger levels). Pump scheduling [M1] can be used to control the timed status and speed of pumps, while trigger levels [M2] can be used to control storage levels. Chosen control options are represented as pump operation information [M3]. This information can be used to represent operational scenarios via the use of hydraulic simulation [S3], allowing pumping operational energy consumption to be calculated. While average conditions can be used to estimate pumping operational energy consumption, more accurate estimations can be achieved by considering multiple operational scenarios.

2.2.3 Water Distribution System Analysis Components

In order to obtain more accurate trade-offs between costs and GHG emissions when optimizing the design and operation of a WDS, it is important to consider both the simulation and evaluation options available. To do this, the water distribution system analysis component of the conceptual framework uses two sub-components; the simulation sub-component, which represents the operational simulation of the WDS, and the evaluation sub-component, which represents the evaluation of costs and GHG emissions associated with the WDS. Evaluation of costs and GHG emissions can be achieved both directly from the design options, represented by the options component, and indirectly through operational simulation, represented by the simulation sub-component. The evaluation of objective functions using infrastructure design and hydraulic simulation information has been used extensively within the field of WDS optimization.

Hydraulic simulation [S3] is used to evaluate both design constraint satisfaction and objective function performance of each developed solution. Project life simulation [S5] represents the simulation of the WDS over the life of the project, including consideration of both construction and operation phases. Project life simulation can incorporate both infrastructure design information (from the options component) and information gained from the hydraulic simulation. Information outputted from an extended period simulation (EPS) can include the storage levels [S7], pipe flows and node pressure information at each time-step, which can be used for constraint evaluation [E7], and pump electrical energy consumption [P6] used for operational evaluation purposes. Hydraulic simulation requires water demand profiles [S2], pump characteristics (pump and efficiency curves) [W2] and pump operation information [M3]. Constraint information [W7], such as water balance and node pressure requirements, is used for the evaluation of constraints. Demand profiles can be used to simulate water demand changes over different seasons and years, as represented by the demand pattern dynamics [S1], to better represent the true nature of water demands. The hydraulic simulator requires a representation of the physical system; this information is commonly a simplified model of the real-life WDS, as represented by the WDS infrastructure sub-component, and includes design options information, as represented by the WDS design options sub-component. The total hydraulic simulation length can be controlled by modifying the EPS length and the number of different EPSs used (e.g. used for changes of input data values, such as emissions factors and water demands, over different months/seasons or years), which are represented by the hydraulic simulator dynamics [S4].

Evaluation of each objective function, namely total life cycle economic cost [E1] and total life cycle GHG emissions [E2], is represented by the evaluation sub-component. This sub-component is also used to represent constraint evaluation [E7], which is used to penalize designs that violate user-defined design constraints (such as node pressure and water balance violations). Design and operational information represented by both the water distribution system and electrical energy infrastructure sub-components is used to evaluate the fitness of each solution. Infrastructure construction costs [E3] and pumping electrical costs [E5] are used to evaluate total life cycle economic costs. GHG emissions from electrical energy consumption [E6] and from embodied energy [*Treloar*, 1994] associated with infrastructure construction [E4] are used to evaluate total life cycle GHG emissions.

2.2.4 Simulation Dynamics Components

The simulation dynamics component (Figure 2.2) is used to represent the temporal dynamics of the hydraulic simulation. This includes representation of the number of EPSs (e.g. for different seasons) and the length of each EPS. The dynamics of the water demand model, the emissions factor model and the electricity tariff model are represented as variables used to adjust the level of accuracy achieved by the simulation process. The EPS dynamics are represented as a function of the other dynamic variables; the requirements for the number of EPSs and length of each EPS are dependent on how the water demands, emissions factors and tariffs are to be modeled. The EPS dynamics represent the transition of input data accuracy into hydraulic simulation and evaluation accuracy. In order to accurately estimate costs and GHG emissions, input data must be accurate, which in turn requires appropriate hydraulic simulations in order to account for this accuracy (e.g. using a 24 hour EPS to account for the use of diurnal water demands). In this way, each variable can be modeled to replicate the real-life operational environment as accurately as possible. However, this way of simulating the WDS requires a single EPS running over the length of the project life, which is computationally expensive and would usually be time prohibitive for use with optimization. This would also require future water demands, emissions factors and electricity tariffs to be known for the entire length of the project life, which would not be possible when modeling such complex systems.

In order to achieve accurate evaluation, particularly for electrical energy consumption, which is cumulative over the lifespan of the WDS as discussed earlier, while minimizing the time taken to perform the optimization, a compromise must be made. The most common way of increasing simulation accuracy whilst minimizing computational expense is to use a single EPS, where short term (daily) changes to the water demand and tariff are modeled. However, this does not consider longer term changes, such as seasonal and yearly variations. In order to accurately estimate operational costs and GHG emissions, it is important to consider both short and long term variations by considering different EPS lengths and numbers of EPSs used. While four different EPS lengths and three different numbers of EPSs are shown, other lengths and numbers of EPSs can also be used, depending on the requirements of the modeled demand, emissions factor and tariff data used.

2.2.5 Government Policy Sub-components

Policies and governance external to the control of a water utility can have a significant effect on both the design and operation of a WDS and the evaluation of its associated costs and GHG emissions. These policies are represented by the government policy sub-component. Three policy types are focused on, including climate change policy [G1], economic discount rate policy [G2] and emissions discount rate policy [G3]. These policies can significantly affect the operational costs and GHG emissions of a WDS when accumulated over longer time-periods. Therefore, it is important to consider the effects of policies over the entire life of a WDS, including both design and operational phases. This component has been included to highlight the importance of being able to consider the effects of policy on the optimal design and operation of a WDS.

2.3 Review of Methods used for Greenhouse Gas Emissions Reductions Associated with Water Distribution Systems

In this section, papers that have focused on the minimization of GHG emissions associated with water distribution systems using formal optimization approaches are reviewed in the context of the WCEN conceptual framework introduced in the previous section, discussing the achievements that have been made within this field and the aspects that require further research. Additional papers that focus on the minimization of GHG emissions associated with WDSs from an analysis or simulation perspective are also included in the review. In total, thirty one journal papers, eighteen conference papers and one report have been included in the review (see Appendix C). While the WCEN conceptual framework focuses on the minimization of GHG emissions, papers considering energy reduction have also been included. It should be noted that while many papers that focus on the reduction of costs associated with WDSs exist, only those explicitly considering the reduction of either energy (within the context of reducing environmental impact) or GHG emissions are reviewed in this paper. The components of the WCEN conceptual framework considered in each paper are summarized in Appendix C and discussed in detail in the subsequent sections.

2.3.1 Consideration of Options

The papers that have considered aspects represented within the options component of the WCEN framework are presented in Appendix C. As can be seen, the most widely used options associated with the design of WDSs are pipe sizing [Appendix C, Column C7] (Pr3, Pr4, Pr5, Pr10, Pr11, Pr12, Pr15, Pr16, Pr23, Pr24, Pr25, Pr26, Pr27, Pr31, Pr32, Pr33, Pr34, Pr35, Pr36, Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45, Pr46, Pr47, Pr48, Pr49 – See Appendix C) and the selection of pipe material type [C6] (Pr3, Pr5, Pr10, Pr11, Pr12, Pr15, Pr16, Pr23, Pr24, Pr25, Pr26, Pr27, Pr31, Pr32, Pr33, Pr34, Pr35, Pr36, Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45, Pr46, Pr47, Pr48, Pr49). Other options, such as storage tank size and location [C5] (Pr4, Pr5, Pr19, Pr23, Pr24, Pr26, Pr33, Pr40, Pr44) and pump type selection [C3] (Pr2, Pr10, Pr27, Pr33, Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45, Pr46, Pr47, Pr48, Pr49) were also used. Operational management options (pump scheduling [C1] and trigger levels [C2]) were not used as frequently (Pr5, Pr9, Pr14, Pr31, Pr33, Pr34, Pr36, Pr46).

Trade-offs can occur between the design and operational phases which can be affected by the options chosen for each phase. For example, a major trade-off can occur between the minimization of pipe sizes to minimize capital costs/GHG emissions and the minimization of pump energy consumption to minimize operational costs/GHG emissions. Similarly, trade-offs can occur between the objectives of minimizing costs and GHG emissions. For example, similar to electricity tariffs, the emissions intensity of electricity is time-dependent. Therefore changing the time-of-use of pumps can alter both the GHG emissions and costs associated with the electricity consumed, even if the amount of electricity consumed does not change. If the rise and fall of emissions factors and electricity tariffs do not coincide, trade-offs will be seen between operational costs and GHG emissions. While these examples are easy to grasp, other trade-offs may be more implicit, requiring more thorough analysis in order to understand their causes and effects.

2.3.1.1 Pipe Size Selection

As can be seen in Appendix C, pipe size selection [C7] is the most common option considered. Twenty eight of the reviewed papers considered the pipe sizes used in a WDS. Twenty five of these used the pipe size option as a decision variable for optimization, with twenty considering the reduction of GHG emissions. The majority of these showed a trade-off between construction and operational GHG emissions and while reduced pipe sizes also reduced GHG emissions associated with pipe construction, total GHG emissions (construction and operation) increased due to an increase in pumping energy required to overcome the higher friction losses of the smaller pipe sizes. However, some other interesting results were reported. Herstein et al. [2009b] (Pr25) showed that an increase in pipe size resulted in an increase in environmental impact (using the environmental index (EI) measurement). The use of larger pipes in this system allowed more water to be pumped to the storage tank instead of directly to the demand node. However, as the tank was located further away from the pump location, this resulted in greater energy losses, and thus an increase in energy usage, resulting in the reported increase in EI value. Results from Wu et al. [2010d] (Pr45) showed a trade-off between construction and operational GHG emissions that result in an optimal design that uses a relatively small pipe size (compared to the choices available). This is probably due to a low demand, with larger pipe sizes resulting in a relatively low pump energy usage reduction compared to the increase in construction emissions associated with the additional material required for larger pipes. Dandy et al. [2008] (Pr11) used multi-objective optimization to reduce the pipe costs and energy of a gravity fed system. As there was no operational energy expenditure, the lowest energy solution corresponded to the lowest pipe embodied energy solution.

From the reviewed literature, it is clear that a trade-off exists between construction and operational GHG emissions due to the sizes of pipes used in WDSs. A general trend of reducing pipe sizes (lower construction GHG emissions) resulting in increased pump energy requirements (higher operational GHG emissions) has been noted. However, other factors such as system layout, system hydraulic capacity and consumer water demands directly affect the point at which an optimal trade-off is found. While the area of WDS GHG emissions optimization is relatively new, the majority of research focused on the option of pipe size selection, with results showing a clear benefit of considering GHG emissions when sizing pipes for both WDS design and upgrade scenarios.

2.3.1.2 Pipe Material Selection

Twenty eight of the reviewed papers considered the type of material used for the construction of pipes. The majority of these used the concept of embodied energy to evaluate the environmental impact of pipe material type selection [C6]. Ambrose et al. [2002] (Pr3) considered the specific values for pipe embodied energy for different material types. While embodied energy values vary between each material type, it was noted that the quoted embodied energy value for a specific material type is also dependent on the level of detail used during the calculation of the embodied energy. While many pipe material types are available, the option of material type was commonly limited to either ductile iron cement mortar lined (DICL), polyvinyl chloride (PVC) or polyethylene (PE) pipes (Pr10, Pr11, Pr23, Pr32, Pr36), though Du et al. [2013] (Pr12) also compared these along with concrete, reinforced concrete and cast iron pipe materials. However, many papers considered the selection of only one material type (Pr4, Pr5, Pr24, Pr25, Pr26, Pr27, Pr31, Pr32, Pr33, Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45, Pr46, Pr47, Pr48, Pr49). Wu et al. [2008c] (Pr40) noted that while DICL has a relatively low embodied energy value when compared to that of PVC and PE based pipes, it also has a relatively high unit mass, which can also affect a pipe's associated GHG emissions and needs to be considered. Ambrose et al. [2002] (Pr3) showed that despite the apparent benefit of DICL, it contained an embodied energy up to five times that of PVC and PE based pipes when the unit mass and hydraulic performance of each pipe type was considered. Du et al. [2013] (Pr12) found that ductile iron had the greatest (worst) global warming potential (GWP, based on embodied energy analysis) for smaller pipe diameters, while PVC had the greatest GWP for larger pipe diameters due to the pipe wall thickness used for these larger diameters. Despite high production energy demands and carbon dioxide emissions, concrete pipes were found to have the lowest (best) GWP between pipe diameters of 102mm and 1219mm. Case study results by MacLeod et al. [2010] (Pr32) and Roshani et al. [2012] (Pr36) both showed little difference in GHG emissions of optimal designs using PVC or DICL pipes, although the construction costs of PVC pipes were considerably lower than those of DICL pipes. Dandy et al. [2006] (Pr10) considered both PVC and DICL pipe materials for the energy reduction optimization of a WDS and found that the optimal design used only PVC pipes. While Roshani et al. [2012] (Pr36) and MacLeod et al. [2010] (Pr32) only evaluated GHG emissions associated with operations, Dandy et al. [2006] (Pr10) evaluated energy associated with both capital (construction) and operations.

While only six of the reviewed papers focusing on optimization considered multiple material type choices for the construction of pipes, different studies showed different pipe materials to be beneficial for the reduction of GHG emissions. The work by Ambrose et al. [2002] (Pr3) showed a large difference in the embodied energy of DICL and PVC material types. PVC pipes have been shown to have a lower embodied energy value per unit length of pipe, which would suggest that they also have a lower environmental impact with respectively lower GHG emissions over DICL pipes. This finding was also shown by Dandy et al. [2006] (Pr10). However, the literature also suggested that pipe material type has little effect on the hydraulics of a WDS, resulting in little difference in operational GHG emissions. This suggests that while the difference in hydraulic performance (i.e. frictional losses) between material types may only be small, the differences in embodied energy values of the pipes can have a substantial effect on the overall GHG emissions associated with a particular design.

2.3.1.3 Pump Type Selection

Of the reviewed papers, fourteen considered the option of pump type selection during optimization. Pump type selection [C3] has been used in conjunction with pipe size selection by Wu et al. [2008a; 2008c; 2008b; 2009a; 2010a; 2010b; 2010d; 2010c; 2012a; 2012b; 2013] (Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45, Pr46, Pr47, Pr48, Pr49), Kang and Lansey [2012] (Pr27) and Marchi et al. [2014] (Pr33), while using multi-objective optimization to find the optimal trade-off between construction and operational GHG emissions. Additionally, Richardson and Hodkiewicz [2011] (Pr35), while not considering pump type selection per se, considered the effect of pump overhaul scheduling, and hence the trade-offs between pump replacement capital and loss of efficiency due to wear, on the minimization of cost and GHG emissions. This study showed that similar trade-offs exist between costs and GHG emissions when considering pump overhaul scheduling as when considering other more often used options, such as selecting pipe sizes and pump types. Wu et al. [2010a] (Pr46) and used trigger levels to control the operation of a pump over a 48-hour EPS, while Marchi et al. [2014] (Pr33) considered the use of both pump scheduling and trigger levels to control pump operations. These studies highlighted the importance of considering both pump type selection and pump operational management together. The other studies stated above used steady-state analysis without the use of pump operational management, with the range of GHG emissions corresponding to optimal solutions being far smaller than those obtained while incorporating pump operational management. The ability to reduce GHG emissions by considering pump type selection and pump operational management options together has not been considered in depth in the reviewed literature. However, results showed that this consideration may lead to further reductions in GHG emissions, and it is therefore recommended that this be further explored.

2.3.1.4 Pump Operational Management

Eight of the reviewed papers considered the use of pump operational management. Of these, seven used storage trigger levels [C2] to implicitly control pumps, while four considered the use of pump scheduling [C1] to explicitly control the time of operation. Ertin et al. [2001] (Pr14) and Ramos et al. [2011] (Pr34) used both pump schedules and trigger levels, comparing the energy efficiency of each management type. Ertin et al. [2001] (Pr14) showed that a 12.5% energy saving can be made by using pump scheduling instead of storage tank trigger levels. Conversely, Ramos et al. [2011] (Pr34) reported that while no pump electrical energy savings were made by using pump scheduling instead of trigger levels, operational costs can be significantly reduced by pumping at off-peak electricity times and hence reducing the average unit cost of consumed electrical energy. Trigger level options were also used for the purpose of reducing GHG emissions (Pr31, Pr33, Pr34, Pr36, Pr46) and energy usage (Pr9, Pr14). While literature considering operational management options has suggested a benefit to the consideration of pump operational management for the reduction of GHG emissions, little work has been undertaken to consider the effects of time-dependent operational factors, such as time-dependent emissions factors, on the optimal operational management of WDSs. However, as considering the time-dependency of electricity tariffs has been shown to help select operational management choices that reduce operational costs [*Ramos et al.*, 2011] (Pr34), by extension, consideration of the time-dependency of emissions factors could help to reduce operational GHG emissions. As pumps use the majority of consumed energy during WDS operation, careful consideration of pump control represents a possibility for further GHG emissions reduction and therefore warrants further research.

2.3.2 Infrastructure Considerations

2.3.2.1 Water Distribution System Complexity

WDSs have been represented within the literature in different forms, from simple single pipe systems to complex, real-world networks. As can be seen from Appendix C, of the reviewed literature using multi-objective (MO) optimization and the objective of GHG emissions reduction, eleven examples used complex WDSs [C16], while fourteen of the reviewed papers used only simplified WDSs [C15] for case-studies. Simplified networks have been used for proof of concept and assessment of the impact of policy factors, such as discount rates. More complex networks were used for both initial design and system upgrade scenarios. Case-studies by Abadia Sanchez et al. [2008] (Pr1), Cabrera et al. [2010] (Pr9) and Filion et al. [2004] (Pr17) used simplified representations of WDSs for the purpose of system energy analysis. Ertin et al. [2001] (Pr14), Filion [2007; 2008] (Pr15, Pr16) and MacLeod and Filion [2011] (Pr31) used simplistic systems in order to analyze the effects of specific factors, such as pump scheduling, population density and urban form, on the energy usage and/or GHG emissions associated with a WDS. Herstein et al. [2009b] (Pr25) used a one pump, one tank and one demand node WDS in order to test the concept of the environmental impact index; used to rank a WDS based on several sustainability criteria, including the release of GHG emissions. This was later applied to an MO optimization problem using the Anytown WDS (Pr26), as described by Walski et al. [1987]. Biehl and Inman [2010] (Pr5), Boulos and Bros [2010] (Pr7), Ektesabi et al. [2009] (Pr13) and Young [2010] (Pr50) discussed possible energy reduction and GHG emissions abatement strategies, and the considerations that need to be made when applying them to real-world systems. Ghimire [2010] (Pr21) and Ghimire and Barkdoll [2008; 2009; 2010] (Pr18, Pr19, Pr20) simulated a number of WDSs ranging in size and complexity, analyzing the effects of various factors on energy usage, such as pump power, storage tank parameters and water demands. Wu et al. [2013] (Pr49) optimized a South Australian WDS, among others, for the minimization of costs and GHG emissions and the maximization of hydraulic reliability. MacLeod et al. [2010] (Pr32) and Roshani et al. [2012] (Pr36) optimized the Amherstview, Canada, WDS as an upgrade problem, looking at the effect of pipe selection on GHG emissions, while Dandy et al. [2006] (Pr10) optimized the Anabranch rural WDS in Australia as a design problem, looking at the effect of pipe selection on capital and operational energy usage, with comparison to an original design, which focused on the reduction of capital and operational costs.

In summary, there has been limited consideration of complex WDSs. While they were used for the simulation and analysis of energy usage and the analysis of GHG emissions, only eleven of the reviewed papers used complex systems in case-studies for the optimization of GHG emissions (Pr4, Pr5, Pr12, Pr23, Pr24, Pr26, Pr27, Pr32, Pr33, Pr36, Pr49). While simple case-studies have shown the benefits of considering GHG emissions, only the use of more complex case study systems will be able to show the feasibility of considering GHG emissions associated with real-world WDSs outside of the research arena. Therefore, further research should be undertaken in order to understand the implications of considering GHG emissions on more complex systems.

2.3.2.2 Water Demands

Daily water demand patterns [C17], also known as diurnal curves, were incorporated by nineteen of the reviewed papers into the simulation and optimization of energy usage and GHG emissions associated with WDSs (Pr2, Pr4, Pr5, Pr8, Pr9, Pr14, Pr19, Pr21, Pr22, Pr23, Pr24, Pr25, Pr31, Pr32, Pr33, Pr34, Pr36, Pr46, Pr49). Diurnal curves have become a popular way to increase the accuracy of modeling the time-dependency of water demands seen in the real world. This time dependency has become an important part of modeling the cost of operating WDSs, especially with the consideration of peak/off-peak electricity tariffs, where it is not only the total time of pump operation that is important, but also the time of use. Ertin et al. [2001] (Pr14) demonstrated a reduction in energy usage of 12.5% when considering pump time of use. This was done by careful consideration of storage tank levels, which required the use of diurnal curves to accurately simulate the change in tank levels over time. While the majority of literature considering GHG emissions opted for the use of steady-state water demands, Herstein et al. [2009b; 2009a] (Pr24, Pr25), MacLeod and Filion [2011] (Pr31) and Wu et al. [2010a] (Pr46) included the use of diurnal curves while using extended period simulations (EPSs) when evaluating operational energy usage. While not commonly in use, demand variations [C18] over extended periods of time, such as monthly, seasonal and annual variations, have also been incorporated. Alandi et al. [2005] (Pr2) used monthly demand variations in order to evaluate pump energy usage for each month in the year and Filion et al. [2004] (Pr17) used demands that were assumed to increase on a decade by decade basis. The demand variations were used to consider the difference in system requirements at each stage of pipe replacement during the life of the system. Wu et al. [2012b] (Pr47) incorporated seasonal demand variations as a way of assessing the benefits of using variable speed pumps. In this study, the benefit of being able to reduce the pump's speed was seen by a reduction in frictional energy loss, which in turn equated to a reduction in GHG emissions.

Nineteen of the reviewed papers used diurnal water demand patterns as a consideration of the time-dependency of consumer demands. This is important, as it allows the time-dependency of real-life water demands to be represented more accurately. The time-dependency of water demands over longer time periods is still rarely used, with only two optimization papers considering this (Pr17, Pr47). However, as shown by Filion et al. [2004] (Pr17) and Wu et al. [2012b] (Pr47), considering longer term water demand variations can affect the choice of optimal design options. Consideration of water demand variability is important for the accurate analysis of GHG emissions, as a WDS is a demand driven system and thus this consideration can directly affect the energy usage requirements of the system. Water demands may change over the operational life of a WDS (e.g. diurnal changes, seasonal changes and/or yearly changes) and these changes must be incorporated in order to more accurately reflect actual energy consumption. In order to achieve greater accuracy, future research will need to incorporate longer-term water demand changes along with the shorter-term changes that are presently used.

2.3.2.3 Electricity Tariffs

Single, average tariff values [C12] have been predominantly considered when analyzing the operational costs associated with WDSs (Appendix C). Of the reviewed papers, only four considered peak/off-peak time-dependent tariffs [C13] (Pr6, Pr8, Pr33, Pr34). Biehl and Inman [2010] (Pr6) discussed the ways in which electricity is charged to the consumer, and suggested ways in which both energy usage and its associated costs can be reduced. Both time dependent charges, including peak and off peak tariffs, which charge for the actual amount of electricity used with a rate based on the time of usage, and time-independent charges, including demand charges, which charge for the highest demand reached over either the billing period, or a prescribed period of time, were considered. While a demand charge can account for 10-20% of a water utility's electricity costs, it is suggested that the majority of these costs can be attributed to tariff charges (Pr6). Ramos et al. [2011] (Pr34) showed that optimizing pump operations while considering peak/off-peak electricity tariffs can result in cost reductions by pumping during off-peak times. One study also looked at the effect of longer term changes to electricity costs. Wu et al. [2012a] (Pr48) used a fixed rate tariff, adjusted annually to model the effect of electricity price increases caused by the possible effects of carbon taxes and carbon trading schemes imposed on the electricity generation industry.

While literature using peak/off-peak electricity tariffs has shown that consideration of the time-dependency of electricity tariffs can be used to reduce operational costs (Pr34), there has been little research to assess the effects of time-dependent tariffs on the trade-offs between costs and GHG emissions. Although tariffs are only used to calculate costs associated with electricity usage, the trade-offs that often occur between costs and GHG emissions mean that the accurate analysis of operational costs is an important part of analyzing this trade-off. As with GHG emissions, operational costs are accumulated over the life of a WDS and as such, both the short-term and long-term time-dependencies of electricity tariffs must be considered if these costs are to be assessed accurately.

2.3.2.4 Greenhouse Gas Emissions Factors

As can be seen from Appendix C, all of the reviewed papers which used emissions factors used single, average GHG emissions factors [C10] instead of considering short-term (e.g. diurnal) emissions factor variations. The only consideration of time-dependent emissions factors [C11] in the reviewed literature was by Roshani et al. [2012] (Pr36) and Wu et al [2012a; 2013] (Pr48, Pr49). In these studies, emissions factors were assumed to reduce annually, due to an increase in the proportion of renewable energy sources for electricity generation. However, short-term (e.g. daily) variations of emissions factors were not considered. Within the literature, there has been little discussion of the short-term variability of emissions factors, which considers the varying contribution of different generation types for different demand loads during the day. However, similar to electricity tariffs, emissions factors can vary over shorter (e.g. daily) time periods. Similar to the effect of electricity tariffs on costs (Pr34), these changes to emissions factors have the potential to affect the optimal operation of pumps when considering the minimization of GHG emissions. GHG emissions are accumulated over the life-time of a WDS's operation. As such, the time of use of electricity generated from fossil fuel sources has the potential to considerably alter the GHG emissions associated with the operation of a WDS. For WDS optimization, there lies a potential to find reduced GHG emissions operational strategies by considering the impact of time-dependent GHG emissions factors. However, this has not been studied thus far.

2.3.2.5 Sources of Electrical Energy Generation

While the analysis of pump energy usage was widely considered, only seven of the papers reviewed considered the source of electricity [C9] consumed by pumping activities (Pr25, Pr26, Pr30, Pr34, Pr36, Pr38, Pr48). These papers commonly accounted for the types of electricity generation by considering their associated emissions factors. This consideration allows the emissions factor for a specific electricity generation region to be evaluated, allowing for increased accuracy when evaluating GHG emissions. Stokes and Horvath [2006] (Pr38) used life cycle analysis (LCA) to evaluate the energy use and GHG emissions for two case-study WDSs in California. GHG emissions were evaluated for multiple activities throughout the life of the WDSs; including through the use of electricity for pumping, which was calculated considering the mix of electricity generation types for the state of California. Lundie et al. [2004] (Pr30) also used LCA to evaluate the environmental impacts of Sydney Water's activities, including the WDS used to supply the city. In this study, both conventional and alternative power sources, including the combustion of biosolid remains from wastewater treatment, were considered. Ramos et al. [2011] (Pr34) compared operational management optimization while considering different power sources, including from the electricity grid, a water turbine used to recover energy normally lost through a pressure reducing device and a wind turbine used to provide renewable energy generation. The results of this study concluded that using renewable energy (in the form of a wind turbine) can significantly reduce GHG emissions, as significantly less electricity is sourced from the electricity grid. Herstein et al. [2009b; 2011] (Pr25, Pr26) included the consideration of electricity generation sources during the optimization of case-study WDSs, in which system cost and environmental impact were evaluated. The environmental impact objective used considers several factors, including air pollution and non-renewable resource depletion, associated with the use of electricity. The consideration of electricity generation source was used in the evaluation of these factors, where the type of generation impacts the amount of pollution and resource depletion.

Pump energy usage [C14] is often calculated as part of the analysis of a WDS. While the energy usage of a pump is generally considered, the consideration of where this energy has come from is often overlooked. This is important if the GHG emissions associated with the usage of electricity are to be calculated more accurately. However, only seven of the reviewed papers considered different sources of electricity generation (Pr25, Pr26, Pr30, Pr34, Pr36, Pr38, Pr48). While consideration was given to the location of electricity generation sources (generally on a regional basis), little research has been conducted into the influence of time on these sources. A WDS can operate over many decades, with GHG emissions associated with its operation being accumulated over this period. Because of this, accurate calculation of these GHG emissions will require consideration of the source of electricity generation in terms of both location and time. In order to accurately estimate GHG emissions, greater consideration needs to be given to the sources of electricity generation in order to increase the accuracy of GHG emissions analysis.

2.3.3 Water Distribution System Analysis Considerations

2.3.3.1 Extended Period Simulations

Of the reviewed papers that used hydraulic simulation, thirty six used either single steady state or extended period simulation [C19], of no more than 96 hours in length, to evaluate energy use over the projected lifespan of the WDS. The majority of these have not considered variable lengths of EPS and the effect this can have on the accuracy of evaluation. However, two papers have discussed EPS length [C21]. Cabrera et al. [2010] (Pr10) used two EPS lengths during a WDS energy audit; one day and one year, with energy inputs and outputs being evaluated using both simulation lengths. The proportion of total input/output energy associated with each source/consumer was compared over the different EPS periods. Hernandez et al. [2010] (Pr22) also used various EPS lengths while conducting a WDS energy audit. In this case, short-term and long-term EPSs of one day and one month, respectively, were used.

The use of multiple hydraulic simulations [C22] can also help to improve the accuracy of evaluation. For example, the simulation of different demand patterns over multiple seasons within a year can be used to reflect the changing demands that occur in the real world; however, this requires a separate EPS for each demand pattern, which will increase the computational time required to run an optimization algorithm. Most of the reviewed literature has used a single hydraulic simulation in order to evaluate pump energy requirements. Exceptions to this include Alandi et al. [2005] (Pr2), who simulated multiple demand scenarios for each month in the year; and Wu et al. [2012b] (Pr47), who simulated the use of both FSPs and VSPs over four demand scenarios to represent seasonal variation, using the demand variations to show the energy saving benefits of using VSPs over FSPs. Filion et al. [2004] (Pr18) also used multiple simulations for the purpose of analyzing multiple demand scenarios. Increases in demand were used at each system upgrade juncture, which require possible pipe size changes in order to fulfil hydraulic demands for the next maintenance period.

Few papers have considered the length and number of EPSs used to analyze the operation of a WDS. However, these constitute important considerations. As discussed in Section 2.2.4, the use of water demand, electricity tariff and GHG emissions factor data that consider time-dependent variations will require simulations that encompass these time variations. Without considering these, the increased accuracy of the input data will not be translated into more accurate analysis. As such, research must consider the length and number of EPSs used, with consideration given to the requirements of the input data used.

2.3.4 Government Policy Considerations

2.3.4.1 Economic Discounting

As can be seen from Appendix C, twelve papers considered the effects of economic discounting [C28], using discount rates ranging from 1.4% to 10%. Comparisons were also made between the results found by using different discount rates (Pr31, Pr32, Pr36, Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45). Results commonly showed higher annual operating cost designs resulting from the use of higher discount rates. This result is expected, as a higher discount rate will place less value on future (operating) costs compared to present (construction) costs, resulting in a bias towards lower construction cost designs. This results in designs that require the use of more electrical energy for pumping requirements. The use of higher discount rates translates to greater pump energy requirements, with an associated increase in GHG emissions. The largest proportion of GHG emissions commonly results from electricity usage during operations. Reducing total GHG emissions can often be achieved by reducing operational GHG emissions, which has been seen with the use of lower discount rates. In practice, higher discount rates are applied to economic cost analyzes for water distribution systems (Pr43), however, the results shown within the reviewed literature would suggest that a lower discount rate should be applied to economic costs if importance is also to be placed on reducing GHG emissions.

Eleven of the sixteen papers which used optimization to reduce GHG emissions also considered the use of economic discount rates, which represents the majority of papers. Present value analysis (PVA), used to evaluate the present worth of future activities, is critical to the analysis of trade-offs between construction and operational costs, as the discount rate used can have a dramatic effect on the weighting given to operation. As such, sensitivity analyzes of economic discount rates will still be necessary in order to analyze these trade-offs in a robust fashion.

2.3.4.2 Greenhouse Gas Emissions Discounting

While not as commonly considered as economic discounting, PVA was also applied directly to the evaluation of GHG emissions [C29] in nine of the reviewed papers. A discount rate of zero is often used for GHG emissions impact evaluation (Pr44), placing an equal weighting on present GHG emissions and those produced in the future. Use of positive discount rates was also suggested (reducing the value of future emissions), which reflects the belief that future technology will be able to better abate the impact of higher GHG emission concentrations in the atmosphere (Pr44). Of the reviewed papers that considered GHG emission discounting, the majority used a rate of zero. Wu et al. [2008b] (Pr41) used two discounting scenarios; economic costs and GHG emissions costs (using a carbon tax) were discounted at the same rate for the first scenario, while GHG emissions costs were given a zero discount rate in the second scenario. The results of this study show that the second scenario leads to results where a higher proportion of total costs are due to GHG emissions. Another study by Wu et al. [2010b] (Pr44) used the same scenarios as described above, while GHG emissions were discounted directly, however, a direct comparison between the two scenarios was not presented.

As with economic discount rates, the direct application of discount rates to GHG emissions is an important aspect of the analysis process. Trade-offs exist between construction and operational GHG emissions and also between costs and GHG emissions. As such, careful consideration needs to be given to the discount rates applied to GHG emissions. However, as discussed above, few studies have taken the effects of GHG emissions discounting into account. As with economic PVA, there remains a need to consider the effects of GHG emissions PVA with the use of sensitivity analyzes and the consideration of the effects different discount rates have on the trade-offs between the construction and operation phases, and the objectives of cost and GHG emission reduction.

2.3.4.3 Carbon Costing

Carbon tax and carbon trading policies [C27] have been analyzed in six of the reviewed papers. This was done by applying a monetary cost to each unit of GHG emissions produced, including that from construction, calculated from embodied energy, and operation, calculated from electricity usage. Roshani et al. [2012] (Pr36) used three carbon tax scenarios as proposed by the Canadian National Round Table on the Environment and the Economy [2007], comparing optimization results for each. However, this study found little evidence that the use of a carbon tax will result in GHG emissions benefits, concluding that for the system upgrade problem considered, there was already adequate hydraulic capacity, suggesting that upgrading the system would do little to reduce pump energy requirements. MacLeod and Filion [2011] (Pr31) used the same carbon tax scenarios as Roshani et al. [2012] (Pr36), applied to a water transfer main design scenario. Results of this study showed that a larger pipe diameter was chosen for the two higher taxed scenarios when the lowest discount rate was used, resulting in fewer GHG emissions being produced during operation over the lifetime of the project. Wu et al. [2008b] (Pr41) applied five different carbon taxes to a WDS optimization problem. As with MacLeod and Filion [2011] (Pr31), a higher carbon tax showed some propensity to result in the selection of larger pipe diameters, thus reducing pump energy requirements. Wu et al. [2012a] (Pr48) used an increase in electricity costs to simulate the effect of a carbon trading scheme, with electricity tariffs increasing annually by a set percentage. Results from this study suggest that no significant GHG emissions reductions would be seen by considering higher electricity costs, as the use of higher electricity tariffs increased the operational cost of each design solution, however, it did not affect the order of the solutions.

The results from the above studies suggest that the use of carbon taxes and carbon trading schemes may help to reduce GHG emissions, however, there are other factors that need to be considered, which may also play a significant role in the choice of optimal solutions. These include the use of different discount rates, the emissions factors applied to the use of electricity and the impact of changing pipe sizes on a system's hydraulic capacity. While these studies have helped to recognise the benefits of carbon taxes and carbon trading schemes, more research is needed to understand what level of carbon tax and carbon costing is required to see optimal benefits in relation to the reduction of GHG emissions, and whether this can be applied to all cases or is case-study specific.

2.4 Summary and Conclusions

The rising level of GHG emissions within the atmosphere of the Earth is a common problem faced by human-kind, with no easy solutions yet to be discovered. As such, it is the responsibility of each sector of industry to help reduce their contribution of GHG emissions released into the atmosphere. Water utilities are no exception. Research into the GHG emissions associated with WDSs is a new, yet important field. There remain many aspects of GHG emissions reduction that are yet to be properly researched. The importance of the field, coupled with the responsibility of water utilities to reduce their carbon footprint, means that these areas should become a priority for future research efforts.

Water distribution systems (WDSs), whilst providing an essential service to modern cities, contribute significantly to the release of GHG emissions. Optimization has been used as a way to more efficiently design and operate WDSs by reducing both costs and GHG emissions. This paper has presented the WCEN conceptual framework (Section 2.2), a conceptual tool used to analyze the components which affect the costs and GHG emissions associated with WDSs, and has reviewed current literature which considers the use of formal optimization methods for the reduction of GHG emissions (and energy usage, which is linked directly to GHG emissions in most cases) associated with WDSs (Section 2.3). The review of the selected papers has outlined gaps in the current literature, which are summarized in Section 2.5.

While not an analytical tool itself, the WCEN conceptual framework provides a representation of all the components required to accurately evaluate the GHG emissions and costs associated with WDSs. This includes the integration of electricity generation infrastructure, used to more accurately represent the factors affecting GHG emissions associated with electricity usage; the introduction of more accurate, time-dependent input data, including water demands, electricity tariffs and GHG emissions factors; the ability to modify the hydraulic simulation process to fit the requirements made by the use of more accurate input data; the analysis of outside policies such as present value discounting policy and carbon trading policy; and the integration of these aspects into one complete framework.

2.5 Recommendations for Future Research

The literature reviewed in this paper has shown the benefits of reducing climate change effects that have come with the explicit consideration of GHG emissions in the optimization of WDSs. While trade-offs often exist between costs and emissions, it has been shown that the consideration of GHG emissions does not need to be at the detriment to cost savings. While the reviewed literature has introduced the concept of evaluating the GHG emissions associated with a WDS, there is scope for improvements to be made in the field of WDS simulation and optimization. Improvements need to be made so that GHG emissions are evaluated with the same degree of accuracy as costs. Greater accuracy will be found by both improving the input data used and careful consideration of the modeling process. An increase in accuracy will not only allow solutions to be viewed with greater confidence, but will also allow better solutions to be found.

Based on the review of the forty-one papers on the reduction of energy usage and GHG emissions associated with the construction and operation of water distribution systems considered in this paper, the following recommendations for future research are made.

1) Costs, associated with both the design and operation of WDSs, have been well considered within the literature. Similarly, GHG emissions associated with the design of WDSs have been well considered, both in terms of factors affecting design GHG emissions (e.g. embodied energy analysis) and the choices available to control design GHG emissions (e.g. choosing pipe diameters). However, GHG emissions associated with the operation of WDSs have been given little consideration beyond simplistic evaluation. While considerations of material types and their

respective production methods have been made in order to accurately evaluate design GHG emission, similar accuracy has not been afforded to operational GHG emissions. Considering the sources of electricity used for pumping purposes is critical, as they can have a significant impact on the emissions intensity of electricity being consumed. Future research should focus on the consideration of the sources of electricity, so that operational GHG emissions can be evaluated as accurately as costs and design GHG emissions.

2) Consideration should be given to the time-dependency of GHG emissions factors used for the evaluation of operational GHG emissions resulting from the operation of pumps. As discussed in Section 2.3.2.4, current research predominantly treats emissions factors used to calculate GHG emissions as a single, average value. The sources of electricity (see recommendation 1) need to be considered if the time-dependency of emissions factors is also to be considered. However, as discussed in Section 2.3.2.5, there is a lack of consideration of the source(s) of electricity used for pumping. Both of these gaps mean that the GHG emissions associated with electricity usage are not being accurately evaluated, with little consideration being given to both the time and place of electricity usage. In reality, emissions factors fluctuate with time and location according to the contribution of different generation types supplying to the electricity grid. As discussed previously, the time-variability of electricity tariffs has been successfully used to reduce the cost of WDS operations. Similar to this, the modeling of time-variability of emissions factors could not only increase the accuracy of operational GHG emissions evaluation, but could allow pump operational strategies to be explored, using potential times of low emissions energy as a way to reduce GHG emissions without the necessity of reduced energy consumption. While emissions factors may be difficult to accurately model due to the complex nature of the electricity generation industry, they may be modeled using similar ideas to those employed for water

demands. These could include diurnal curves for hourly fluctuations through the day; multipliers used to adjust the peaks for different times of the year; and predictions for future increases/decreases over the coming years and decades.

3) If the time-dependency of emissions factors is to be considered, then it is also necessary to consider the time-dependency of water demands. As water demands affect the timing and magnitude of water requirements placed on the WDS, they can directly affect the energy requirements of pumps and as such, affect the optimal use of pumps. Additionally, as the driver for the entire system, the accuracy of modeling a WDS is dependent on the modeling accuracy of water demands. As discussed in Section 2.3.2.2, while diurnal curves are now widely used to model the variation in water demands over the length of a day, other demand variations have not been widely considered within the reviewed literature. As GHG emissions are accumulated over the life of a WDS, longer term variations, such as seasonal and annual variations, should be modeled in order to accurately simulate the effect that changing water demands have on the amount of GHG emissions produced over the operational lifetime of a system.

4) In order to benefit from the additional accuracy afforded by considering time-dependent emissions factors and water demands, the time-of-use of pumps also needs to be considered. Pumps can be controlled to both reduce energy usage through unnecessary friction losses due to high pipe velocities and to use electricity during low emissions factor times to reduce operational GHG emissions. However, pumps also need to be controlled so that the ever-changing water demands placed on the WDS are met, without storage tanks running empty or below a minimum acceptable level. As such, the complex task of operating pumps to minimize costs and GHG emissions is ideally

suited to formal optimization techniques. However, as discussed in Sections 2.3.1.4, little consideration has been given to pump operational management options for the reduction of GHG emissions associated with WDSs. As the majority of GHG emissions (in a pumped system) are commonly associated with the use of pumps, there exists an opportunity to further reduce GHG emissions by considering optimal operational management of pumps within WDSs.

5) As discussed in Section 2.3.3.1, little consideration has been given to the hydraulic simulation processes used for the evaluation of GHG emissions. Few improvements in the simulation processes applied to WDSs (including simulation length and the number of simulations used) have been considered in the reviewed papers. If the use of more accurate information, such as time-dependent GHG emissions factors and seasonal/annual water demand variations is to be considered, careful consideration of the simulation process is also required. The necessity to modify simulation practices when incorporating new input data has been highlighted in Figure 2.2, where the addition of input information complexity is matched against simulation requirements necessary to fully exploit the additional information. As such, if recommendations 1 to 4 are to be considered, it will also be necessary to further consider the requirements of the simulation processes used to evaluate operational costs and GHG emissions.

6) As discussed in Section 2.3.4, government policies have been considered in the reviewed papers by including such factors as discount rates for both economic and GHG emissions discounting, and carbon pricing by considering carbon taxes and carbon trading schemes. While one or more of these factors have been included by thirteen of the sixteen papers that have used optimization to reduce GHG emissions, they have a significant effect on the evaluation of costs and GHG

emissions. As such, it is important that policy factors are continually considered.

2.6 Acknowledgements

The authors would like to thank the anonymous reviewers for their valuable contributions to this paper. The authors would also like to thank the University of Adelaide and the Goyder Institute for Water Research for their financial support of this research.

Chapter 3

A Computational Software Tool for the Minimization of Costs and Greenhouse Gas Emissions Associated with Water Distribution Systems

Statement of Authorship

Title of Paper	A computational software tool for the minimization of costs and greenhouse gas emissions associated with water distribution systems
Publication Status	Submitted for publication
Publication Details	Stokes, C. S., A. R. Simpson, and H. R. Maier (2014), A computational software tool for the minimization of costs and greenhouse gas emissions associated with water distribution systems, Environmental Modelling & Software (submitted).

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author (Candidate)	Christopher S. Stokes		
Contribution to the Paper	Coded computational software framework, undertook numerical evaluation and wrote manuscript		
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Abstract

While evolutionary algorithms have been applied extensively to water resource problems, there remains a need to unify and consolidate computational and software approaches to solving these problems. The minimization of costs and greenhouse gas (GHG) emissions from water distribution systems (WDSs) is one area where this is required. While the minimization of GHG emissions has been actively researched over the last decade, approaches to the simulation and optimization of WDSs have changed little, with average operational conditions (e.g. emissions factors, water demands and electricity tariffs) being used to evaluate WDSs. Consideration of time-dependent operational conditions, operational management choices and the simulations parameters that these require have been identified as key areas of required improvement. Importantly, no practical, freely available, application based framework considering these improvements has been developed. The water distribution cost-emissions nexus (WCEN) computational software framework has been developed as a freely available computational software framework that incorporates these improvements. In this paper, the WCEN computational software framework is presented and a case study WDS is optimized to demonstrate its utility.

3.1 Introduction

The application of evolutionary optimization algorithms to water resources problems has been covered extensively over the last 20 years [*Nicklow et al.*, 2010; *Maier et al.*, 2014]. However, there is a need to better unify and consolidate the computational and software implementation of these approaches in order to facilitate a level platform on which studies can be performed, to allow researchers to easily access algorithms and benchmark studies [*Maier et al.*, 2014]. In order to facilitate these improvements, it is necessary to develop computational software frameworks that are applicable to a range of real-world studies, can be easily integrated with existing research needs and can be easily segmented and upgraded as new technology and approaches become available [*Maier et al.*, 2014; *Robson*, 2014].

The minimization of greenhouse gas (GHG) emissions associated with water distribution systems (WDSs) is a key example of where these improvements are required. As a result of the recognition of the potentially negative impact GHG emissions due to the construction and operation of WDSs can have on the environment, research focusing on the minimization of GHG emissions from WDSs, in addition to the minimization of costs, has gained popularity [*Stokes et al.*, 2014c]. However, much of this research has emerged from optimization studies focusing solely on cost minimization. Consequently, many of the computational methods used for cost minimization have been adopted for the minimzation of costs and GHG emissions. However, this has resulted in the simplified representation of some aspects of the underlying system, particularly in relation to the temporal variation of emissions factors, electricity tariffs and water demands [*Stokes et al.*, 2014c].

In order to highlight these issues, [*Stokes et al.*, 2014c] developed the water distribution cost-emissions nexus (WCEN) conceptual framework, which considers the nexus of elements required to accurately simulate a WDS for the purposes of minimizing costs and GHG emissions. In particular, the WCEN conceptual framework includes consideration of both short-term (e.g. daily) and long-term (e.g. monthly and annual) time-dependency of operational conditions (e.g. emissions factors, water demands and electricity tariffs), the consideration of pumping operational management choices, including those for multiple operational conditions, and consideration of the simulation requirements necessary to apply these to multi-objective (MO) optimization of WDSs for the minimization of costs and GHG emissions.

In order to facilitate implementation of the elements of the WCEN conceptual framework in practice, and to enable this to be done in a consistent manner, the WCEN conceptual framework needs to be converted into a computational software framework. In order to achieve this, the objectives of this paper are (1) to present some general considerations for the development of computational software frameworks (2) to introduce the structure, features and benefits of the WCEN computational software framework and (3) to use a case study to demonstrate how the WCEN framework can be used to address some of the knowledge gaps identified in Stokes et al. [2014c] by providing a platform with which a range of time-dependent operational conditions (e.g. emissions factors, electricity tariffs, water demands, pumping operational management options) can be considered. The WCEN computational software framework introduced in this paper (refer to Appendix E) integrates hydraulic and pumping operational simulation, cost and GHG emissions calculation and MO heuristic optimization tools into one freely available, easy to use and easily accessible package. Importantly, specific components of the software framework (e.g. the optimization algorithm) can be updated and integrated into other computational software frameworks, as required. The WCEN computational software framework allows the user to optimize a WDS for the reduction of costs and reduction of GHG emissions, while considering real-world operational conditions, by using the most accurate emissions factor, water demand and electricity tariff information available, while incorporating operational management strategies that can take full advantage of this information.

The remainder of this paper is organized as follows. In the next section, some general considerations for the development of computational software frameworks are presented. Next, the novelty of the WCEN computational software framework, developed with consideration of these guidelines, is explained in detail, followed by a detailed discussion of the software architecture used for the WCEN computational software framework. Following this, the case study WDS and methodology used to demonstrate the capabilities and benefits of the WCEN computational software framework are introduced. Finally, results from the case study are discussed and conclusions are drawn.

3.2 General Considerations for the Development of Computational Software Frameworks

The application of computational software frameworks is an important part of addressing water resources problems. While these frameworks can be case study specific, it is preferable that they are developed with broader application in mind, facilitating the benchmarking of problems and approaches used to solve these problems [*Maier et al.*, 2014]. The broader application of these frameworks can allow more direct comparison between studies and results, allowing better understanding as to whether case study specific approaches are required or whether more generic approaches can be employed when solving these problems [*Maier et al.*, 2014]. As such, it is important to consider general methods or steps to the development of simulation and optimization components, the application of uncertainty assessment and the implementation of the framework itself. Ultimately, the broad application and longevity of a framework may rest on its ability to be adapted to different situations, such as the requirement of high evaluation accuracy or high computational efficiency. Therefore, it is desirable that a computational software framework be developed with flexibility in mind.

3.2.1 Simulation and Optimization

Simulation models can be critical to the understanding and evaluation of complex, real-world water resources systems. It is important to select a simulation model appropriate for the application. Consideration should be given to why a simulation model is required (e.g. how it links to the purpose and objectives of the study), what the model is required to do (e.g. required features of the model, possible integration with other simulation models, availability of data, simulation parameters and performance criteria), how output is resolved (e.g. trial and error, analytical, optimization), how and whether uncertainty is quantified and how to validate the model to ensure robustness [*Jakeman et al.*, 2006; *Refsgaard et al.*, 2007; *Bennett et al.*, 2013; *Kelly et al.*, 2013]. Simulations can sometimes be computationally expensive. Therefore, it can also be desirable to consider the computational resources and time availability. For example, when absolute accuracy is important, the use of more complex yet computationally time-consuming simulation may be required. However, if computational time is limited, it may be necessary to reduce simulation complexity at the expense of accuracy [*Robson*, 2014]. If computational expense is a likely burden, such as when optimization or uncertainty assessment (discussed below) are incorporated, surrogate meta-models, such as artificial neural networks, may be able to be used to reduce the computational time of simulation while retaining the evaluation accuracy of a more complex simulation model [*Razavi et al.*, 2012; *Kelly et al.*, 2013; *Maier et al.*, 2014; *Wu et al.*, 2014]. In order to facilitate broader application of computational software frameworks, it is desirable that the simulation model can be flexibly applied with respect to the above considerations and can be easily upgraded or exchanged with a different model without the need to redevelop the entire framework.

3.2.2 Optimization

Optimization (when based on evolutionary algorithm techniques) requires the repetitive use of simulation models, which may severely limit the computational effort afforded to the simulation model. Appropriate choice of optimization technique (e.g. search ability and computational efficiency of the optimization algorithm), limitations to search space size and the employment of surrogate meta-models can help to reduce the burden of computational constraints [*Razavi et al.*, 2012; *Kelly et al.*, 2013; *Maier et al.*, 2014; *Wu et al.*, 2014]. Optimization techniques, especially those involving heuristics (e.g. evolutionary optimization), have been significantly improved over the past two decades with respect to their search ability and computational efficiency [*Maier et al.*, 2014]. Optimization techniques may be improved upon and updated over time, and so it is desirable for the longevity of a computational framework that the optimization algorithm component be easily interchangeable without redeveloping the entire framework.

3.2.3 Uncertainty

Uncertainty assessment can involve the use of various methods, including expert and stakeholder involvement, error propagation analysis, scenario analysis and inverse modeling (e.g. parameter estimation and predictive uncertainty) [*Refsgaard et al.*, 2007]. More formal quantification of uncertainty typically involves the use of Monte Carlo simulation analysis [*Refsgaard et al.*, 2007; *Castelletti et al.*, 2012] and can range from simple procedures, such as Generalized Likelihood Uncertainty Estimation (GLUE), based on the random selection of model parameter values [*Beven and Binley*, 1992], to more complex Bayesian analysis [*Castelletti et al.*, 2012; *Robson*, 2014]. However, these numerical methods are computationally expensive and this can limit their application with complex simulation models and optimization when the available run times are limited [*Maier et al.*, 2014; *Robson*, 2014]. While uncertainty measures can be implicitly incorporated into optimization to reduce this computational expense [*Kapelan et al.*, 2005], the incorporation of uncertainty assessment can require the use of more simplistic simulation models or surrogate meta-models (discussed above) in order to reduce the run times.

3.2.4 Framework Implementation

Ideally, computational software frameworks should be made freely available in a format that is compatible with standard operating systems (e.g. such as using the C programming language). Ease of use, ease of integration into existing frameworks and the ability to be applied to a range of studies are also important if a framework is to be more broadly applied within the water resources field. These attributes can be seen in existing computational software frameworks that deal with both water resources and wider environmental problems [*Bogdos and Manolakos*, 2013; *Guzman et al.*, 2013; *Holguin-Gonzalez et al.*, 2013; *Ou et al.*, 2013; *Thorp and Bronson*, 2013; *Zambrano-Bigiarini and Rojas*, 2013; *Zhang et al.*, 2013].

3.3 The Water Distribution System Cost and Greenhouse Gas Emissions Nexus Computational Software Framework

The WCEN computational software framework is an open-source software package that integrates both hydraulic and pumping operational simulation and multi-objective (MO) heuristic/evolutionary algorithm optimization packages into a computer program that can be used to control the accuracy with which a WDS is simulated and for which both costs and GHG emissions are evaluated. In response to the considerations outlined in Section 3.2, the WCEN computational software framework is developed as a freely available, easily integrated framework with segmented software components (e.g. for user control, optimization, options/infrastructure/analysis and hydraulic simulation, as shown in Figure 3.1) to allow easy update and modification by others. Interactions between components exist through commonly defined variables/header files for sharing information and through function calls, such as for executing the optimization component through the user control component (Figure 3.1). While not all of the considerations discussed in Section 3.2 are explicitly incorporated into the WCEN computational software framework (e.g. uncertainty assessment), it is developed with a key emphasis on flexibility so that these considerations can be easily integrated in the future. In order to make modification/integration of the software possible, the commonly utilized C programming language is used. This also allows the NSGA-II MO optimization algorithm and EPANET 2.0 Toolkit, both written in C, to be easily utilized within the software.

The WCEN computational software framework is so named as it is a computational software platform used for evaluating the costs and GHG emissions of WDSs and is based on the WCEN conceptual framework introduced by Stokes et al. (2014b). It allows consideration of the time-dependency of operational conditions (emissions factors (EFs), electricity tariffs (ETs) and water demands), operational management strategies and in-turn the simulation parameters they require, in order to accurately evaluate and optimize costs and GHG emissions. While many of the elements contained within the WCEN computational software framework have been previously considered within the literature (e.g. hydraulic and pumping operational simulation, optimization, cost evaluation and GHG emissions evaluation), other elements have only rarely, if at all, been considered within previous literature. These elements, as discussed in detail by Stokes et al. [2014c], are outlined below.

Firstly, previous literature has generally used an average emissions factor, which does not consider the time-dependency of EFs [*Herstein et al.*, 2009b; *Wu et al.*, 2010a; *Wu et al.*, 2010b; *Herstein et al.*, 2011; *MacLeod and Filion*, 2011; *Wu et al.*, 2012b; *Wu et al.*, 2013]. While some literature has considered long-term variations of EFs [*Wu et al.*, 2012a; *Wu et al.*, 2013], little consideration of the short- and mid-term time-dependency of EFs has yet been made [*Stokes et al.*, 2014c]. Secondly, while recent literature has considered the short-term variability of water demands by using diurnal water demand curves to represent the changes in water demands over a 24 hour time period [*Herstein et al.*, 2009b; *Wu et al.*, 2010a; *Herstein and Filion*, 2011; *Herstein et al.*, 2011; *MacLeod and Filion*, 2011; *Ramos et al.*, 2011; *Roshani et al.*, 2012; *Basupi et al.*, 2013; *Wu et al.*, 2013; *Basupi et al.*, 2014; *Marchi et al.*, 2014], limited consideration has been given to the time-dependency of water demands beyond diurnal variations [*Stokes et al.*, 2014c]. Thirdly, little consideration has been given to either the short-term [*Marchi et al.*, 2014] or long-term [*MacLeod and Filion*, 2011; *Roshani et al.*, 2012; *Wu et al.*, 2012a] time-dependency of EFs. Fourthly, most literature has only considered the optimization of design options [*Dandy et al.*, 2006; *Dandy et al.*, 2008; *Herstein et al.*, 2009b; *Wu et al.*, 2010a; *Wu et al.*, 2010b; *Herstein et al.*, 2011; *MacLeod and Filion*, 2011; *Roshani et al.*, 2012; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Wu et al.*, 2013], with only limited consideration being given to the optimization of pumping operational management while minimizing GHG emissions [*Bunn and Hillebrand*, 2008; *Basupi et al.*, 2014; *Marchi et al.*, 2014]. Finally, while some have considered the use of extended period simulations (EPSs) to evaluate the pumping operational costs and GHG emissions of a WDS [*Wu et al.*, 2010b; *Herstein and Filion*, 2011; *Ramos et al.*, 2011; *Roshani et al.*, 2012; *Basupi et al.*, 2013; *Basupi et al.*, 2014; *Marchi et al.*, 2014], the use of steady-state hydraulic simulations is more commonly considered [*Dandy et al.*, 2006; *Dandy et al.*, 2008; *Herstein et al.*, 2009b; *Wu et al.*, 2010a; *Wu et al.*, 2010b; *Herstein et al.*, 2011; *MacLeod and Filion*, 2011; *Kang and Lansey*, 2012; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Du et al.*, 2013; *Wu et al.*, 2013].

As discussed by Stokes et al. [2014c], there remains a need to consider the time-dependency of EFs, water demands, ETs and pumping operational management strategies, as well as the use of simulation parameters (length and number of simulations) that allow these considerations to be made. The WCEN computational software framework allows the user to define the number and length of hydraulic and pumping operational simulations, dependent on the accuracy of EF, water demand and ET information available, and the pumping operational management choices used to optimize the pumping operation of the WDS. For example, both short- and longer-term operational conditions can be considered by simulating multiple daily pumping operation scenarios, while using diurnally time-dependent EFs, water demands and ETs for different months of the year.

In order to accurately evaluate costs and GHG emissions by including the considerations discussed above, the WCEN computational software framework is structured as shown in Figure 3.2. As can be seen, the framework is separated into specific tasks and components. The tasks are used to outline the considerations that are made when using the WCEN computational software framework. The simulation choices task outlines the available simulation options that can be selected by the user, including the length and number of hydraulic and pumping operational simulations used. As shown in Figure 3.2, the use of time-dependent EFs, water demands and ETs is considered when selecting the simulation choices. The inputs task outlines the information inputs required for the computational process. These inputs are selected by the user and are inputted into the computational software framework by the use of onscreen inputs and two input files; the WCEN input file used directly by the computational software framework; and the EPANET input file required to run the EPANET 2.0 Toolkit used to perform the hydraulic simulations [*Rossman*, 2000]. The computational structure task outlines the computational software structure itself, and is separated into different components that represent the different computational processes performed. These components include the optimization component, which outlines the process of solution development for the minimization of costs and GHG emissions; the options component, which outlines the design and operation options to change the WDS; the infrastructure component, which outlines the infrastructure being modelled; and the analysis component, which outlines the analysis process used in order to evaluate each developed solution. Each of the tasks and components are described in detail in the following sections.

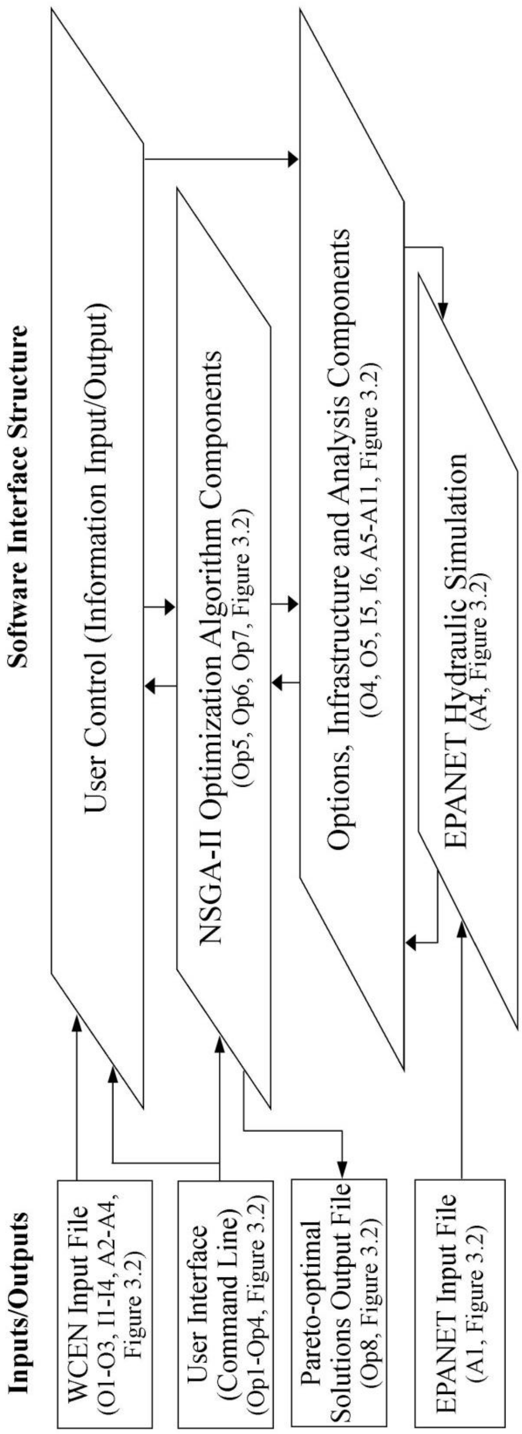


Figure 3.1. Software interface structure used for the WCEN computational software framework, showing separation of components and flow of information. Note the optimization component can be bypassed to allow direct evaluation for any single solution.

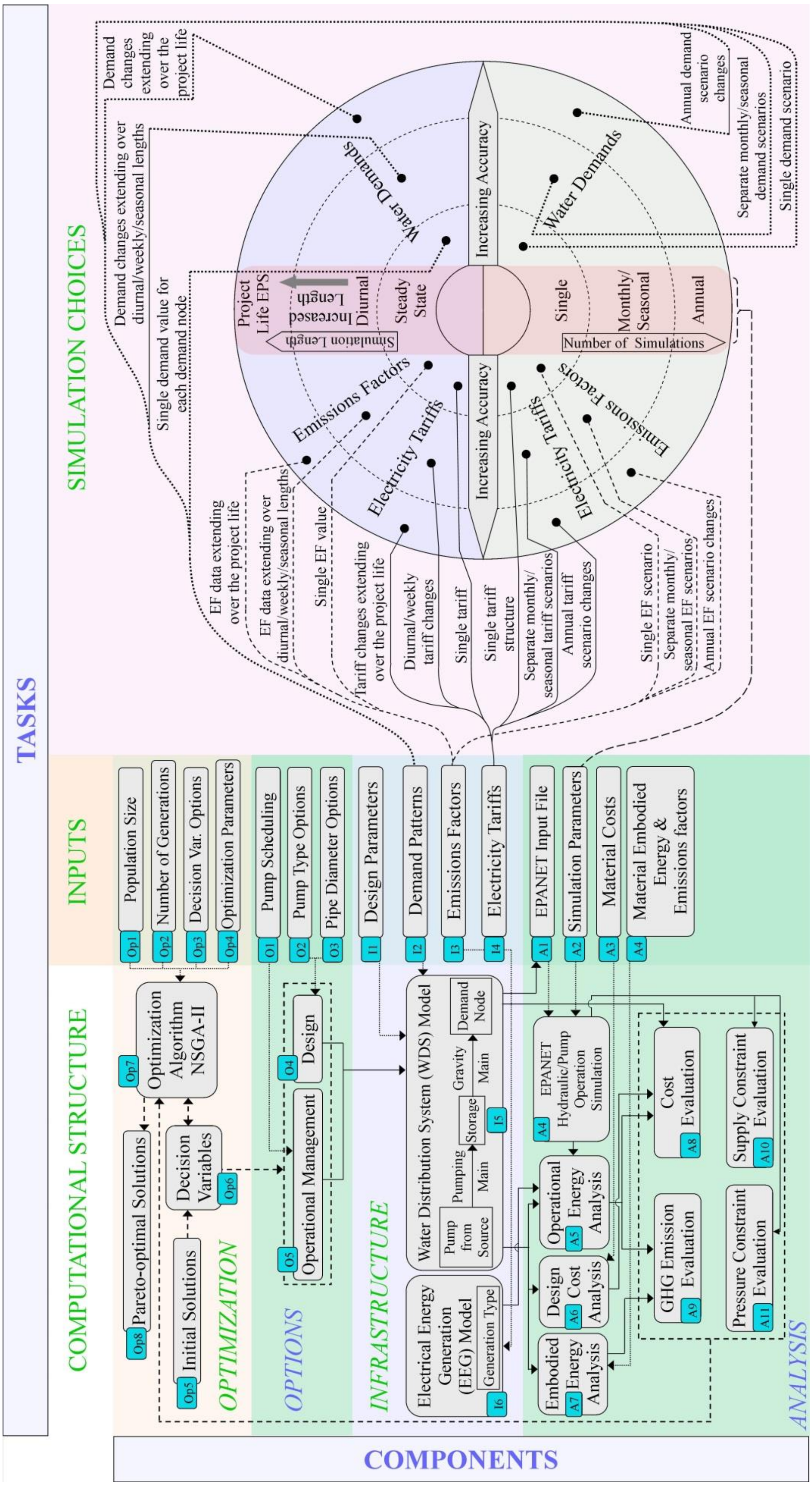


Figure 3.2. Representation of the computational structure of the water distribution cost-emissions nexus (WCEN) computational software framework.

3.3.1 Simulation Choices

The simulation choices task (Figure 3.2) describes the simulation choices that are made by the user and implemented into the computational process. The simulation choices affect input information used to describe the infrastructure (EFs, water demands and ETs), and thus reflect the level of accuracy of evaluation. When selecting the simulation choices, consideration should be given to the available EF, water demand and ET information, and the operational management structure required. While using a single, average EF, water demand and ET results in low computational expense with only a single, steady-state hydraulic simulation being required, the level of accuracy used to evaluate costs and GHG emissions is low and pumping operational management options cannot be considered. Alternatively, using real-life (i.e. considering actual variations that have occurred) EFs, water demands and ETs over the operational life of the WDS gives the highest level of evaluation accuracy, however, this results in high computational expense. Additionally, knowing the variations in EFs, water demands and ETs for the operational life of a WDS in advance is not possible, and so an estimate of this information needs to be made. In order to balance the required accuracy and computational expense with the availability of information, considering the time-dependency of EFs, water demands and ETs over both short and long time-periods can be made. The consideration of diurnal, weekly, monthly, seasonal and/or annual variations can be made by using multiple hydraulic and pumping operational simulations of an appropriate length. For example, diurnal variations in EFs, water demands and ETs can be considered by using a 24 hour long extended period simulation (EPS), while monthly variations can also be considered by running an EPS for each month of the year. Additionally, in this example, different pumping operational management choices can be made for each month of the year, enabling the pumping operational management to be adapted to requirements in each of the months being simulated.

3.3.2 Inputs

Once the simulation choices have been made, input information is compiled and placed into the input files. Two input files are used by the WCEN computational software framework. The first is the EPANET input file (Figure 3.2, A1), which is required by the EPANET 2.0 Toolkit used to perform the hydraulic and pumping operational simulations. This input file contains all the information necessary to hydraulically simulate the pumping operation of a WDS, and can be created by using the freely available EPANET 2.0 interface software [*Rossman*, 2000]. The second is the WCEN input file, which is directly used by the WCEN computational software framework. The WCEN input (comma delimited) file stores information used to evaluate the WDS, including information regarding design and operational management options; the infrastructure being represented; and the analysis of the WDS. Information stored in the WCEN input file is read at the user control level and subsequently distributed to the options, infrastructure and analysis components (Figures 3.1 and 3.2). Information in the WCEN input file is stored and read in through a separate subroutine in a linear fashion (an example WCEN input file is provided as supplemental material in Appendix D) to enable easier inclusion of additional information as required by the user. This information is distributed directly to the options/infrastructure/analysis components by the use of commonly defined variables.

Options information determines the different options available to modify the WDS. This includes the identification of each pump schedule and total number of pump schedules applied to each pump (e.g. using 4 pump schedules to simulate the operational management of a pump over 4 different seasons of the year) (O1); the number and identification (ID) of each available pump type (O2); and the number and ID of the available pipe diameters (O3).

Infrastructure information describes the infrastructure being modelled. WDS design parameters (I1) include information necessary to evaluate the WDS, including the EPANET specific ID for each pipe, pump, node and storage tank; pipe lengths for each pipe; minimum required pressures for each node; average day (base) water demands for each node; and peak day and peak hour demand factors for calculating pump flow and pressure constraints. Water demand patterns (I2) are also included to quantify the changes in water demands over the simulation period. Additionally, information describing the electrical energy generation (EEG) infrastructure used to supply electricity to the WDS is included. This includes EF (I3) and ET (I4) values used to evaluate the costs and GHG emissions associated with the pumping operation of the WDS.

Analysis information is used to simulate the WDS and evaluate the costs and GHG emissions associated with its design and pumping operation. Simulation parameters (A2) include the number and length of hydraulic and pumping operational simulations used to evaluate the pumping operation of the WDS. Material embodied energy and EFs (A4) are used to evaluate pipe GHG emissions, while material costs (A3) are used to evaluate pipe and pump costs. Note that pump GHG emissions are not included in the evaluation process due to the lack of pump embodied energy information available.

High level control and additional information used to control the optimization process is input by the user via command line interface (example provided as supplemental material). The MO heuristic optimization algorithm used by the WCEN computational software framework is the Elitist Non-dominated Sorting Genetic Algorithm

(NSGA-II) [*Deb et al.*, 2000], which is described in detail in the subsequent section. This information includes the population size (Op1), which defines the maximum number of solutions that are created during each iteration (referred to as a generation) of the optimization process; the maximum number of generations (Op2), which, with the population size, defines the maximum number of solution evaluations that are performed during the optimization process; the decision variable options (Op3), which include the number of decision variables, depending on the number of design and operational management elements (pipes, pumps and pump schedules) that can be changed, and the bounds of each decision variable. Other optimization parameters (Op4) are also defined by the user, including the type and probability of solution crossover, probability of mutation, and the starting random number seed that initiates the pseudo random number generator used during the optimization process. As the development of all operations within the computational process that rely on randomly selected numbers are dependent on the random number seed, the exact solutions developed by the WCEN computational software framework can be re-developed at any time by using the same starting random number seed value.

3.3.3 Computational Structure – Optimization

At the start of the computational process, initial solutions are developed (Figure 3.2, Op5). Within the optimization algorithm, solutions are represented as a series of integer coded decision variables (Op6), each representing a changeable aspect of either the design or pumping operational management of the WDS being evaluated. The initial solutions are randomly chosen, with the population of solutions representing a range of design and pumping operation option choices for the WDS being modelled.

Once a population of initial solutions is chosen, new solutions of minimized costs and GHG emissions are then developed by using the MO heuristic optimization algorithm, NSGA-II (Op7) [*Deb et al.*, 2000]. While NSGA-II has been shown to be outperformed in some situations, such as for many-objective problems [*Purshouse and Fleming*, 2003; *Hadka and Reed*, 2012], it is chosen for its efficient solution space search ability, its ease of implementation and because it has previously been applied successfully to the bi-objective optimization of WDSs [*Wu et al.*, 2010a; *Wu et al.*, 2010b; *Herstein et al.*, 2011; *Kang and Lansey*, 2012; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Basupi et al.*, 2013; *Wu et al.*, 2013; *Basupi et al.*, 2014]. As the user control component interacts with the optimization component through a single function call, the MO optimization algorithm can be easily replaced. The Borg Multi-objective Evolutionary Algorithm (MOEA) [*Hadka and Reed*, 2012] has also been successfully integrated within the WCEN computational software framework (without modification to the wider componentry), however this cannot be made publically available due to licensing agreements associated with its use. The processes employed by NSGA-II and subsequently used within the WCEN computational software framework are described in detail by Deb et al. [2000; 2002]. MO heuristic optimization generates progressively better solutions over a number of iterations, referred to as generations. In each generation, each individual in the population of solutions is evaluated (discussed below) and the solutions in the population are modified based on evolutionary operators (e.g. crossover and mutation for genetic algorithms) until the computational budget is expended (i.e. the maximum number of generations is reached). Once the computational budget is expended, Pareto-optimal solutions (Op8), which represent the set of non-dominated solutions with minimized costs and GHG emissions, developed by MO heuristic optimization, are outputted. As certain operations within the optimization process rely on random selection, a pseudo-random number generator is employed. However, this is affected by initial conditions (i.e. the use of a “seed” value to initialize the pseudo-random generation of numbers). In order to help overcome this effect, multiple optimization runs are used and subsequently multiple non-dominated solution sets are outputted. The final non-dominated solution set is constructed as the "subset" of non-dominated solutions from the entire set of solutions outputted from the multiple optimization runs, which is displayed to the user in an (comma delimited) output file.

3.3.4 Computational Structure – Infrastructure

Two infrastructure systems are represented; the water distribution system (WDS) model (Figure 3.2, I5), which represents the WDS being designed and operated, and electrical energy generation (EEG) model (I6), which represents the source(s) of electricity used by the WDS during its operation. While each system is simplified, they contain the critical elements that are required to accurately evaluate the costs and GHG emissions associated with the design and pumping operation of a WDS.

The WDS model (I5) is comprised of the physical infrastructure that allows water to be supplied from the source to consumers. This includes representation of the critical infrastructure, with information (e.g. design and operational parameters) regarding the WDS infrastructure being considered by the design parameters (I1). As previously discussed, the design parameters include information regarding pumping from the water source; the pumping (transfer) mains pipes; water storage(s), which can be tanks or reservoirs; the gravity (distribution) mains pipes that feed from the storage(s); the demand nodes that represent points of consumer water demands; and other necessary infrastructure, such as valves. Design option choices (O4) (i.e. pump types and pipe diameters) are used in conjunction with design parameters (I1) to evaluate the design costs and GHG emissions. Both design (O4) and pumping operation (O5) option choices (i.e. pump types, pipe diameters and pump schedule times) are input into the EPANET input file (A1) to simulate the pumping operation of the WDS in order to evaluate pumping operational costs and GHG emissions, and hydraulically simulate the WDS in order to evaluate water supply (A10) and nodal pressure (A11) constraints. The WDS model (I5) is also used to represent the water demand patterns, which are inputted as part of the WCEN input file (I2) and inputted into the EPANET input file (A1). As discussed previously, the accuracy of water demands can be defined by the user by selecting the appropriate length of each water demand pattern and the number of patterns (I2). While the level of water demand accuracy used to simulate WDSs is generally restricted by the availability of water demand information, the WCEN computational software framework allows the user to vary the accuracy of water demand information to make the most of what is available. This can be done by using separate diurnal water demand curves for each month/season of the year and by using multiplier values to vary the magnitude of the water demand curves to replicate projected variations in water use over the life of a WDS.

The electrical energy generation (EEG) model (I6) represents the electrical generation infrastructure that supplies the WDS with electrical energy for pumping purposes. This representation is made by the costs and GHG emissions associated with the consumption of electrical energy. As previously discussed, the GHG emissions intensity of generated electrical energy, quantified by EFs, is dependent on the contribution of the different generation types (e.g. coal and gas fired, solar arrays and wind generation) supplying electricity. As the contribution of each generation type changes over time, so does the emissions intensity associated with the electrical energy being consumed by the WDS. EFs inputted from the WCEN input file (I3) are used to quantify the emissions intensity of electricity. As detailed in the simulation choices component, the accuracy of EFs can be changed to suit the level of information available. While a single average EF value can be used, EF patterns detailing the changes in EFs over shorter time periods (daily, weekly, etc.) or multiple values detailing changes over longer time periods (months, years, etc.) can be used by the WCEN computational software framework to increase the accuracy of operational GHG emissions evaluation.

As with emissions factors, electricity tariffs (I4) are used by the EEG model (I6) to calculate the pumping operational cost of electricity being consumed by the WDS. While other operational costs can be attributed to WDSs, such as those associated with labor and lighting at substations, these costs are not proportional to the hydraulic properties of the WDS and are therefore not considered. While not directly resulting from the generation of electricity, ETs are set by the market operator and can be set to vary between different hours of the day, days of the week or over different months/seasons of the year. ETs can also be subject to annual changes. Like EFs, it is beneficial to model the change in ETs as accurately as possible, so that the calculation of pumping operational costs matches the reality of pumping operational costs as closely as possible. As detailed in the simulation choices component, the accuracy of ETs can be changed to suit the level of information available. While a single average ET value can be used, peak/off-peak ETs detailing the changes in ETs over shorter time periods (daily, weekly, etc.) and multiple ET values detailing changes over longer time periods (months, years, etc.) can be used by the WCEN computational software framework to increase the accuracy of operational cost evaluation. While other forms of ETs, such as block/peak consumption related charges, can be used, they are not currently considered within the framework.

3.3.5 Computational Structure – Options

In order to evaluate each solution developed using the optimization process, decision variable values are translated into design and pumping operational management choices. Both design (O4) and operational management (O5) options are represented as integer coded decision variables. Discrete design options considered in the WCEN computational software framework include the choice of both pipe diameter for specific (user defined) pipes in the WDS and pump type for specific (user defined) fixed-speed pumps. Discrete pumping operational management options considered in the WCEN computational software framework include the scheduling of pumps. Pump schedules options represent the times at which a pump is turned on and off, using a time-step of 30 minutes. An example pump schedule (Figure 3.3) shows the translation of a pump schedule from decision variable values to resultant pump control. The number of pump on/off switches made each day should be limited by the user for both computational reasons, such as to reduce the search space size for optimization, and real-world effects, such as increased cost associated with excessive wear of pump components due to excessive pump switches. As previously discussed, multiple pump schedules can be chosen for each pump to simulate the differences in pumping operational strategies used for different months/seasons of the year. Depending on the requirements of the user, other design and operational management options, such as tank capacity and location, pipe material type and system rehabilitation options, can be important to consider. While not included, the framework source code is made freely available so that these can be integrated in the future.

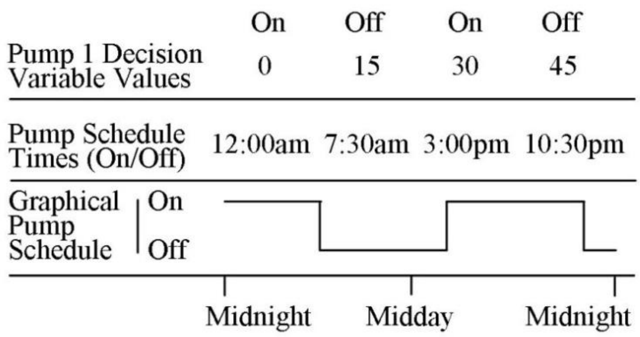


Figure 3.3. Example pump scheduling decision variable values (in one-half hour increments), corresponding pump on/off scheduling times and graphical representation of the pump schedule.

3.3.6 Computational Structure – Analysis

The aim of analysis is to input information regarding the design options (Figure 3.2, O4) and pumping operational management options (O5) in order to evaluate the costs and GHG emissions associated with the WDS. In order to do this, infrastructure information considering both the WDS (I5) and EEG (I6) is used in conjunction with embodied energy analysis (A7), in which GHG emissions associated with the design are considered; design cost analysis (A6), in which costs associated with the design are considered; and pumping operational energy analysis (A5), in which both the electricity costs and GHG emissions associated with pumping operations are considered. Additionally, constraint violations (A10, A11) are considered in order to recognize the developed solutions with design and/or operational management choices that lead to potentially inadequate WDS hydraulic capacity.

Embodied energy analysis (A7) is used to calculate capital GHG emissions associated with the design of the WDS (GHG_d). This is done by considering embodied energy, which is defined as the total life-cycle energy required to convert a raw material into a finished product

[*Treloar*, 1994]. To calculate embodied energy, the unit mass as kilograms per meter length (kg/m) of each pipe is multiplied by an embodied energy value. The embodied energy (EE) value, as megajoules per kilogram (MJ/kg), of a product is dependent on multiple factors, such as the materials used to make the product and how and where it is made [*Hammond and Jones*, 2008] and as such, is case specific. Once embodied energy is calculated, unit GHG emissions for each pipe diameter can be calculated by multiplying the embodied energy by its respective unit mass (M_P), as kilograms per meter (kg/m), and an appropriate material emissions factor (MEF), as metric tonnes of carbon-dioxide equivalent per kilowatt hour (t CO_2-e/kWh). For Equation 3.1, a MJ to kWh conversion value of 1/3.6 is applied. Design GHG emissions for the entire WDS are calculated by multiplying the appropriate unit GHG emissions value (as t CO_2-e/m) for each pipe (P) for its chosen diameter by its length (L_P), such that

$$GHG_d = \sum_P EE \times M_P \times \frac{MEF}{3.6} \times L_P \tag{3.1}$$

Design cost analysis (A6) is used to calculate costs associated with the design of the WDS (C_d). Costs associated with pumps and pipes are considered. Pump costs are calculated based on the unit cost of each pump. The unit cost of each pipe (C_P), as dollars per meter ($/m), is dependent on the diameter of the respective pipe. Pipe costs are case specific and should consider the availability and cost of the chosen type of pipe (e.g. polyvinyl chloride, polyethylene or ductile iron cement mortar lined), as well as the of-the-shelf availability of different pipe diameters. Pipe design costs are calculated by multiplying the appropriate unit cost (as $/m) for each pipe for its chosen diameter by its length (L_P), such that

$$C_d = \sum_P C_P \times L_P \tag{3.2}$$

Pumping operational energy analysis (A5) is used to calculate the electricity costs and GHG emissions associated with the pumping operation of the WDS. Hydraulic and pumping operational simulation (A4), performed using the EPANET 2.0 Toolkit, is required to calculate the electrical energy consumption for pumping purposes. The WCEN computational software framework's hydraulic and pumping operational simulation structure calculates electrical energy consumption for each time-step of the pumping operational simulation, allowing electricity costs and GHG emissions to be calculated while considering the time-dependency of the WDS's operation. As discussed previously, the consideration of time-dependency includes the use of time-dependent EFs (I3), water demands (I2), ETs (I4) and the pump schedules used to control each pump (O5). Pumping operational electricity GHG emissions ($GHG_{op,s}$) for each pumping operational simulation (s) are calculated using the electrical energy consumption ($E_{t,p}$), as kilowatt hours (kWh), of each pump (p) for each time-step (t) of the hydraulic simulation, and the appropriate EF (EF_t), as metric tonnes of carbon dioxide equivalent per kilowatt hour (t CO_2-e/kWh), such that

$$GHG_{op,s} = \sum_t \sum_p E_{t,p} \times EF_t \tag{3.3}$$

The hydraulic simulation time-step (t) is user defined and should be the same or smaller than the time-steps used for time-dependent EF and ET information. Additionally, an initial simulation period in which no evaluation is undertaken can be specified by the used to help prevent the effects of initial hydraulic conditions. Pumping operational electricity costs ($C_{op,s}$) for each pumping operational simulation (s) are calculated using the electrical energy consumption ($E_{t,p}$) of each pump (p) for each time-step (t), and the appropriate ET (ET_t), as dollars per kilowatt hour ($/kWh), such that

$$C_{op,s} = \sum_t \sum_p E_{t,p} \times ET_t \tag{3.4}$$

Where multiple hydraulic simulations are used (e.g. for different months/seasons of the year or different years over the project life of the WDS), pumping operational electricity costs ($C_{op,s}$) and GHG emissions ($GHG_{op,s}$) are calculated using information from each pumping operational simulation ($s \geq 1$, $\sum s = n$). Pumping operational costs and GHG emissions calculated over multiple (to a total of n) months/seasons are used to find the average annual costs ($C_{op,y}$) and GHG emissions ($GHG_{op,y}$) for each year of operation, such that

$$GHG_{op,y} = \frac{\sum_{h=1}^{n} GHG_{op,s}}{n} \tag{3.5}$$

and

$$C_{op,y} = \frac{\sum_{h=1}^{n} C_{op,s}}{n} \tag{3.6}$$

Pumping operational costs and GHG emissions over the project life of the WDS are calculated using present value analysis, in which a discount rate for costs (i_C) and GHG emissions (i_{GHG}) is applied to the average annual costs ($C_{op,y}$) and GHG emissions ($GHG_{op,y}$), respectively, for each year of operation ($y \geq 0 + y_0$, where $y = 0 + y_0$ is the first year of operation and y_0 is the time delay between the start of the WDS's construction and the first year of operation). The calculation of total pumping operational costs (C_{op}) and GHG emissions (GHG_{op}) are shown in Equation 3.7 and Equation 3.8 respectively.

$$C_{op} = \sum_{y=0+y_0}^{n+y_0} \frac{C_{op,y}}{(1+i_C)^y} \tag{3.7}$$

and

$$GHG_{op} = \sum_{y=0+y_0}^{n+y_0} \frac{GHG_{op,y}}{(1+i_{GHG})^y} \tag{3.8}$$

Total costs (A8) (Equation 3.9) and total GHG emissions (A9) (Equation 3.10) are calculated as the sum of design and pumping operational costs and design and pumping operational GHG emissions, respectively. This information is then used by the optimization algorithm (Op7) to evaluate the costs and GHG emissions associated with each solution.

$$C_{TOTAL} = C_d + C_{op} \tag{3.9}$$

$$GHG_{TOTAL} = GHG_d + GHG_{op} \tag{3.10}$$

Constraint violations are evaluated by considering nodal pressures and total water supply delivered to the WDS. Where steady-state hydraulic simulations are used to evaluate constraints (detailed below), storage tank water levels are defined by the user by selecting storage tank "initial levels" in the EPANET input file. The nodal pressure constraint violation ($CSTR_{Press}$) is evaluated using a steady-state hydraulic simulation (A4) using peak hour water demand loadings to ensure pressure minimums are not exceeded during worst-case demand events. Minimum allowable nodal pressures ($P_{N,min}$) are provided as part of the WDS design parameter information (I1). Node pressure constraint evaluation (A11) is performed by calculating the difference between the required minimum allowable nodal pressure and the actual node pressure (P_N) for each node (N), such that

$$CSTR_{Press} = \sum_{N} \left(P_{N,min} - P_N\right), only\ for\ P_N < P_{N,min} \tag{3.11}$$

where the actual node pressure (P_N) is below the required minimum node pressure ($P_{N,min}$) for a node (N). The node pressure constraint is also evaluated during the pumping operational energy analysis (A5) hydraulic simulation to prevent node pressures becoming lower than the required minimum pressures due to inadequate storage tank water levels. This is done by calculating the difference between the required minimum node pressure and the actual node pressure (Equation 3.11) at each time-step.

The total water supply constraint violation ($CSTR_{Supply}$) is evaluated using a steady-state hydraulic simulation (A4) using peak day water demand loadings to ensure adequate supply can be met during peak water demand times. Supply constraint evaluation (A10) is performed by calculating the difference between the sum of the instantaneous node water demands under peak day demand loadings (D_N) for each node (N) and the sum of the instantaneous pump supply (S_P) from the water source(s) that is/are supplying the WDS with water (with all pumps turned on) for each pump (P), such that

$$CSTR_{Supply} = \sum_{N} D_N - \sum_{P} S_P \tag{3.12}$$

where the sum of the instantaneous water demands ($\sum D_N$) is greater than the sum of the instantaneous pump supply ($\sum S_P$). It is important to note that this constraint will only ever be violated when non-fixed-head storage tanks are used to store water within the WDS (such as for hydraulic balancing purposes).

Node pressure constraint evaluation (A11) and total water supply constraint evaluation (A10) are used by the optimization algorithm (Op7) to evaluate constraint violations for each solution. Along with the previously discussed total costs and total GHG emissions, constraint violations are used to evaluate each solution in order to compare the solutions developed in each iteration (generation) of the optimization process. This process of solution development, evaluation and comparison is continued until the maximum number of generations is reached and the Pareto-optimal solutions are presented. While solutions with constraint violations can be used to populate the next generation of solutions, the Pareto-optimal solutions (Op8) presented at the end of optimization do not violate any constraints.

3.4 Demonstration of Utility of WCEN Computational Software Framework

In the previous section, the WCEN computational software framework is presented as a way to use optimization to minimize the costs and GHG emissions of WDSs, while considering the trade-off between simulation accuracy and computational efficiency. In this section, application of the WCEN computational software framework is demonstrated by minimizing the costs and GHG emissions for a case study WDS. The WCEN computational software framework allows the presented case study WDS to be optimized under a selection of operational scenarios that consider a variety of modeling and simulation complexity. As such, the trade-offs that occur between costs and GHG emissions evaluation accuracy and the computational time taken to optimize the WDS are demonstrated. Additionally, the benefit of allowing these trade-offs to be considered, as offered by the WCEN computational software framework, are assessed.

3.4.1 Case Study

A relatively simple WDS, first presented by Stokes et al. [2014c], is chosen as the case study for illustrating the utility of the WCEN computational software framework. This is because it enables the complexity of design and pump operational management trade-offs to be analyzed, while still incorporating the fundamental complexity of a loop network and pumped WDS with integrated water storage. Example input files for this case study are provided as supplemental material.

The case study WDS consists of 23 pipes, one pumping station containing two pumps and one storage tank (Figure 3.4). A 600 m long pressure main connects the pumping station (elevation of 0m) to the distribution system. The distribution system consists of 19x200 m long pipes and 2x280 m long pipes that connect each of the 14 demand nodes, with a 300 m long pipe connecting the distribution system to a 10 m tall storage tank at a base elevation of 90 m. Each demand node has an average day water demand of 5 liters per second (L/s), giving a total WDS average day demand of 70 L/s. Design optimization considers the choice of pipe diameters for each of the 23 pipes; and pump type used for each of the two pumps in the pump station. Available pipe diameters and pump and efficiency curves for each pump type are taken from Wu et al. [2010b]. Operational control of the two pumps in the pumping station is managed by the use of pump schedules. Each pump is controlled by its own schedule. The pump schedules consist of four on/off times; meaning that each pump is limited to turning on and off two times each day.

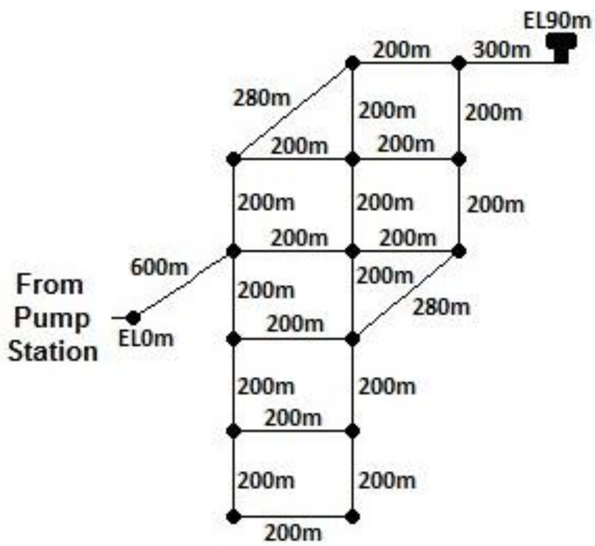


Figure 3.4. Case study water distribution system layout used to demonstrate the utility of the WCEN computational software framework.

3.4.2 Methodology

The methodology for the optimization of the case study WDS follows that outlined in Figure 3.2 and discussed in Section 3.3. In order to optimize the case study WDS under a range of operational conditions that consider a variety of modeling and simulation complexity, four operational scenarios are used, as shown in Table 3.1 and Figure 3.5. These four scenarios are used to compare the results of using "standard practice" with those of using the additional simulation complexity and flexibility afforded by the WCEN computational software framework. The average simulation (AS) scenario represents the "minimum" level of simulation complexity used within the literature, and provides a benchmark against which the other three scenarios can be compared. The AS scenario uses a single steady state hydraulic and pumping operational simulation, in which average emissions factor (EF), electricity tariff (ET) and water demand values are used to evaluate each solution. As the AS scenario uses a steady state pumping operational simulation, only design, and not pumping operational, optimization can be considered. 25 decision variables (23 for pipe diameter and 2 for pump type) are used. The diurnal simulation (DS) scenario uses a 24 hour long single extended period hydraulic and pumping operational simulation (EPS), in which diurnal EF, ET and water demand patterns are used to evaluate each solution. For the DS scenario, both design and pumping operational optimization are considered. 33 decision variables (25 for design and 8 for scheduling both pumps) are used. The monthly, diurnal simulations (MDS) scenario uses twelve 24 hour EPSs to simulate the pumping operation of the case study WDS for each month of the year. As such, diurnal EF, ET and water demand patterns are used for each EPS for each month of the year. For the MDS scenario, pumping operational optimization for each month of the year is considered. The annual, diurnal simulations (ADS) scenario uses ten 24 hour EPSs to simulate the pumping operation of the case study WDS for ten consecutive 10 year-long operational periods over the project life of 100 years. As such, diurnal EF, ET and water demand patterns are used for each EPS for each 10 year-long operational period. For the ADS scenario, pumping operational optimization for each 10 year period is considered.

Large solution spaces resulting from the simultaneous optimization of design and multiple pumping operation schedules preclude convergence on near-optimal solutions from occurring. For this reason, design optimization is precluded for the MDS and ADS scenarios. Additionally, optimization of the multiple pumping operation schedules for each solution developed using the MDS and ADS scenarios is completed separately (Figure 3.6). As such, 8 decision variables (for scheduling both pumps) are used for each simulated operational period for both the MDS (totaling 96 decision variables) and ADS scenarios (totaling 80 decision variables). Design costs and GHG emissions are considered when evaluating solutions developed using the MDS and ADS scenarios. Design choices (e.g. pipe diameters and pump types) used for the MDS and ADS scenarios are taken from solution number 16 (see Figure 3.13), developed using the DS scenario. Further details about design and pumping operational optimization, the evaluation of GHG emissions and costs, consideration of water demands and the use of present value analysis to calculate future (pump operational) costs and GHG emissions are discussed below.

Table 3.1. The four scenarios used when optimizing the case study water distribution system. Each scenario represents a different level of time-dependency consideration.

Scenario	Number of Hydraulic/Pump Operational Simulations	Simulation Length	Emissions Factors	Electricity Tariff	Water Demands
AS	*1*	*Steady-State*	*Average*	*Average*	*Average*
DS	*1*	*24 h*	*Diurnal*	*Peak/Off-Peak*	*Diurnal*
MDS	*12*	*24 h*	*Monthly, Diurnal*	*Monthly, Peak/Off-Peak*	*Monthly, Diurnal*
ADS	*10*	*24 h*	*Annual, Diurnal*	*Annual, Peak/Off-Peak*	*Annual, Diurnal*

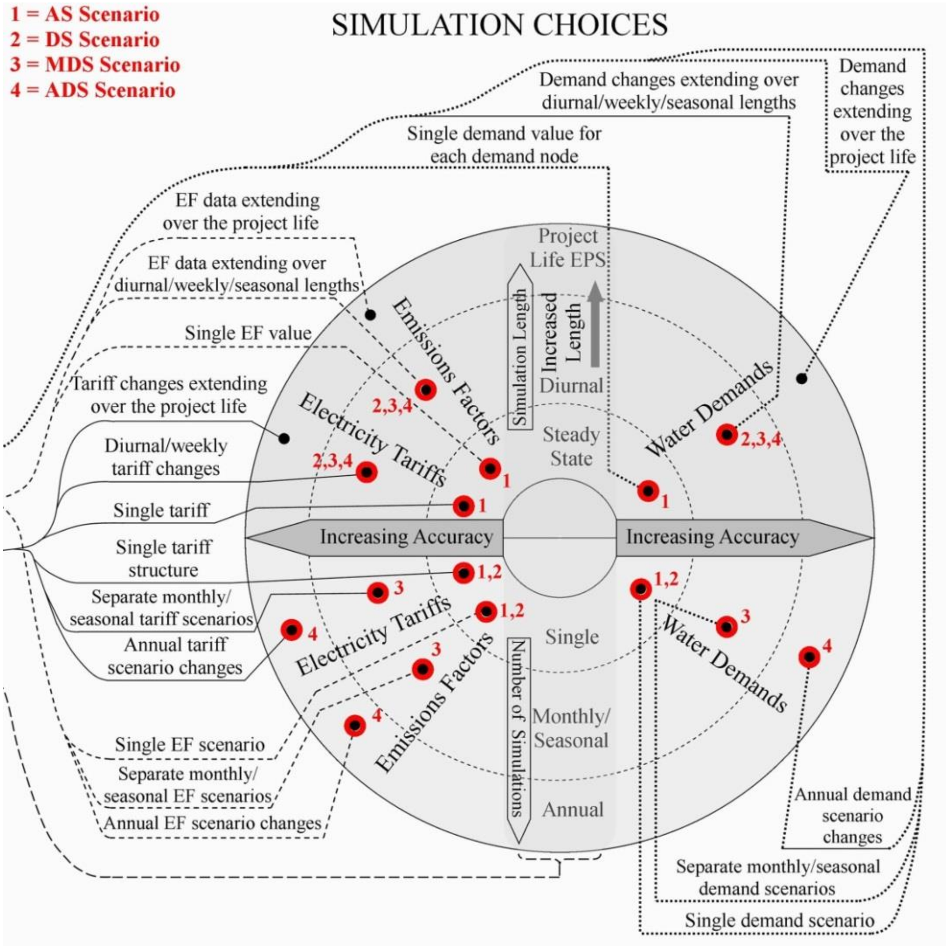


Figure 3.5. Alignment of the considerations made with each scenario to the simulation choices, as described within the representation of the WCEN computational software framework (see Figure 3.2).

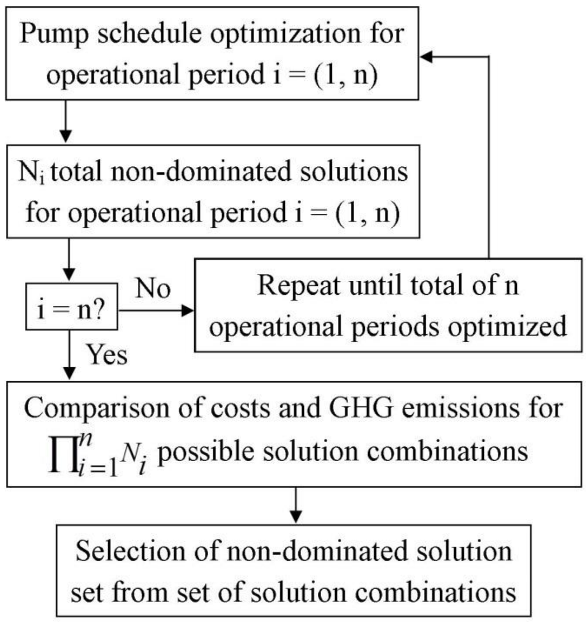


Figure 3.6. Optimization process employed for both the MDS and ADS scenarios, where multiple (n) operational periods are optimized separately.

3.4.2.1 Optimization Algorithm

As discussed in Section 3.3, the case study WDS for each scenario is optimized using NSGA-II [*Deb et al.*, 2000]. A population of 400 individual solutions used over 1000 generations was shown to be adequate for solution convergence for each scenario. As discussed in Section 3.3, NSGA-II uses crossover and mutation operators as part of the optimization process. A single-point crossover probability of 0.8 and chromosome mutation probability of 0.1 are used. These parameter values are informed by the recommendations made by Deb et al. [2000] and initial testing showed them to be preferable. In order to reduce the effect of pseudo random numbers used by the optimization algorithm, the WDS for each simulation case is optimized 40 times using 40 different pseudo random number seed values. The non-dominated solutions contained within all the solutions found using the 40 optimization runs are used to form the final non-dominated set of solutions for each simulation case.

3.4.2.2 Evaluation of Greenhouse Gas Emissions

In order to evaluate the GHG emissions associated with the design and pumping operation of a WDS, analysis of the sources of GHG emissions must be performed. As discussed in Section 3.3, GHG emissions associated with the design of a WDS are calculated using embodied energy analysis (Figure 3.2, A7). An embodied energy value of 40.2 megajoules per kilogram (MJ/kg) for ductile iron cement mortar lined (DICL) pipes is used [*Ambrose et al.*, 2002]. Pipe unit mass information for each available pipe diameter is taken from Wu et al. [2010b]. A material emissions factor value of 0.16 metric tonnes of carbon dioxide equivalents per megajoule (t CO_2-e/MJ) is used to convert embodied energy into GHG emissions. This value is based on electricity generation EF data for South Australia (SA) over a two year period from February 2011 to June 2013 (converted from t CO_2-e/kWh to t CO_2-e/MJ). It is noted that the mix of generation sources in operation during the embodied energy analysis of Ambrose et al. [2002] is different to that related to the EF data for SA. This is due to the increase in renewable energy generation in SA between 2002 and 2011. As explained in Section 3.3, the design GHG emissions associated with pumps are not considered due to a lack of available embodied energy data.

As discussed in Section 3.3, pumping operational GHG emissions are calculated using pumping operational energy analysis (Figure 3.2, A5). GHG emissions associated with the pumping operation of a WDS are due to the consumption of electrical energy by pumps within the system. In order to calculate pumping operational GHG emissions, EFs are used. As this study is concerned with the simulation abilities afforded by the

WCEN computational software framework, different EFs are required for each of the operational scenarios used when optimizing the case study WDS. For the AS scenario, an average EF of 0.57 kilograms of carbon dioxide equivalents per kilowatt hour of electrical energy (kg CO_2-e/kWh) is used. For the diurnal simulation (DS) scenario, an estimated EF curve with an average EF value of 0.57 kg CO_2-e/kWh is used to simulate the annual average change in EFs over the time period of one day (Figure 3.7). As previously explained, these time-dependent EFs are representative of electricity generation in South Australia between February 2011 and June 2013. The diurnal variations of these EFs are due to the changing mix of electricity generation sources over each day. In SA, a higher proportion of renewable generation (wind turbines) is in operation overnight while more fossil fuel generation is in operation during the day to compensate for the increased demand for electricity during this time. For the MDS scenario, used to optimize the pumping operations of the case study WDS for each month of the year, separate estimated EF curves are used to describe the monthly average diurnal change in EFs (Figures 3.8a and 3.8b). The changes in time-dependent EF variations for each month are mainly explained by the different timing of electricity demands for the different seasons during the year. For the hotter seasons (predominantly December to March), more electricity demand is placed during the hottest periods of the day. This leads to a peak in fossil fuel generation and subsequently higher EFs between approximately 12pm and 4pm. For the colder seasons (predominantly June to August), more electricity demand is placed during the evening, when people increase the use of household heating systems. This leads to a peak in fossil fuel generation and subsequently higher EFs between approximately 6pm and 9pm. For the ADS scenario, used to optimize the pumping operations of the case study WDS for each 10 year-long operational period over the 100 year project life (starting from 2012), annual EF multiplier values (Figure 3.9) are used in conjunction with the estimated EFs curve (Figure 3.7). The annual EF multiplier values are based on the “5% by 2020” baseline emissions reduction (from 2000 levels) target in Australia [*Department of Climate Change and Energy Efficiency*, 2010]. All EFs used in this paper are based on electricity generation EF data for South Australia (SA) over a period from February 2011 to June 2013.

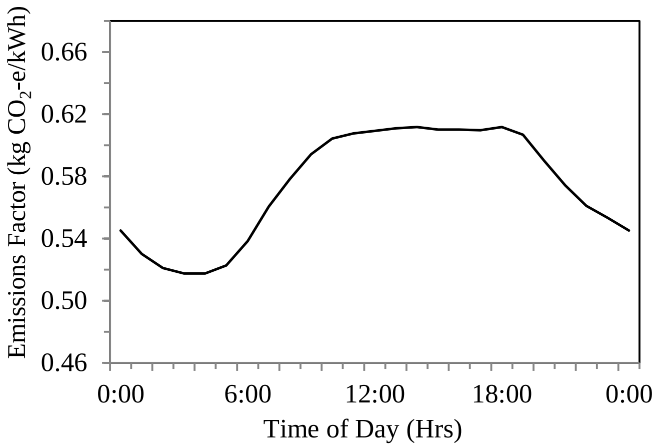


Figure 3.7. Estimated emissions factors curve used to consider the annual average diurnal variation of emissions factors (used for DS and ADS scenarios).

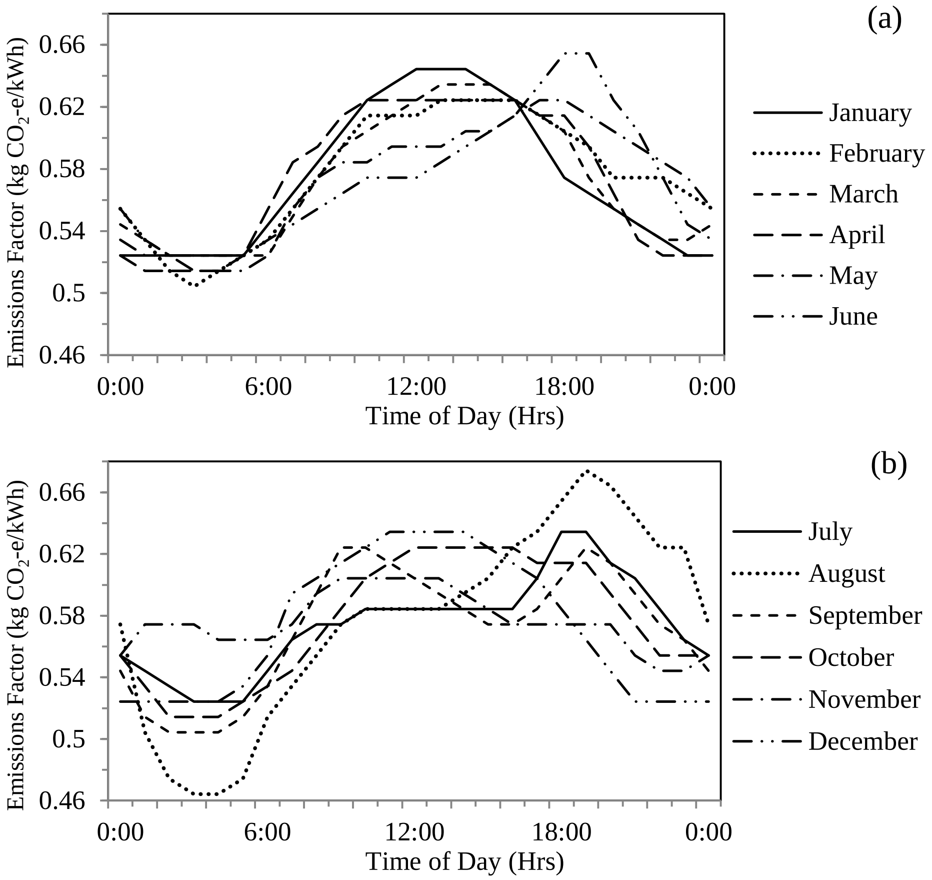


Figure 3.8. Estimated emissions factor curves used to consider the monthly average diurnal variation of emissions factors (used for MDS scenario) for the months of January to June (a) and July to December (b).

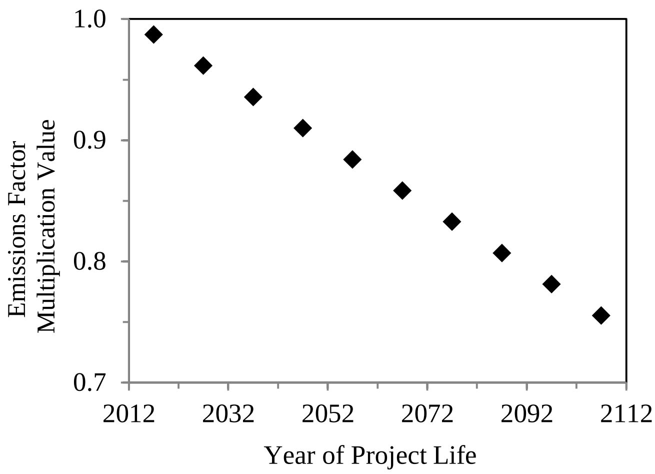


Figure 3.9. Emissions factor multiplier values used to consider the variation of emissions factors for each 10 year-long operational period over the project life of the water distribution period (used for ADS scenario).

3.4.2.3 Evaluation of Costs

In order to evaluate the cost associated with a WDS, the sources of costs must be considered. As discussed in Section 3.3, design costs are calculated using design cost analysis (Figure 3.2, A6). Costs associated with both pipes and pumps used to construct the WDS are considered. Available pipe diameter and pump type cost information is taken from Wu et al. [2010b]. As discussed in Section 3.3, pumping operational energy analysis (Figure 3.2, A5) is used to calculate the amount of electricity consumed for pumping purposes. Pumping energy requirements, measured as kilowatt hours (kWh), are converted into an associated cost by using an ET, as dollars per kilowatt hour ($/kWh). For the AS scenario, where the time-of-use of electricity is not considered, an averaged ET of 0.093 Australian dollars (AUD) per kWh is used. For the DS scenario, a peak/off-peak ET is used. A peak ET of 0.121 AUD/kWh, charged between the hours of 0700 and 2300, is used. An off-peak ET of 0.037 AUD/kWh, charged between the hours of 2300 and 0700, is used. For the MDS scenario, the peak/off-peak ET structure described above is used. A summer peak ET of 0.133 AUD/kWh, replacing the original peak ET is applied for the months from January to March, inclusive (the summer off-peak ET does not change). The summer peak ET increase is calculated using standard ET contract rates from various electricity suppliers in South Australia. For the ADS scenario, annual ET multiplier values (Figure 3.10) are used in conjunction with the peak/off-peak ET structure described above. The annual ET multiplier values are based on a 3% per annum increase in ETs as used by Wu et al. [2012a]. All ETs used in this paper are based on the SA Power Networks' (previously ETSA Utilities) Network Tariffs for FY2009 rate 2 business rate for South Australia [*ETSA Utilities*, 2009].

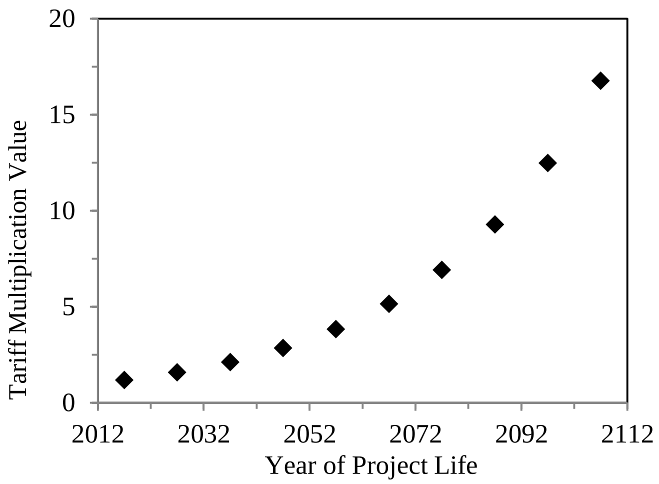


Figure 3.10. Electricity tariff multiplier values used to consider electricity tariff variations for each 10 year-long operational period over the project life of the water distribution system (used for ADS scenario).

3.4.2.4 Water Demands

As discussed in Section 3.3, water demands are used when evaluating both the operation of the WDS and the nodal pressures (Figure 3.2, A11) and supply constraints (Figure 3.2, A10) applied to the WDS. Water demands used to evaluate the pumping operation of the WDS are based on the annual average water demand. For the AS scenario, where the time-of-consumption of water is not considered, the base water demand of 5 L/s per demand node is applied. For the DS scenario, diurnal water demand variations are considered by applying a diurnal water demand multiplier curve (Figure 3.11) to the base water demand. Due to a lack of available diurnal water demand variation information for South Australia, diurnal variation data are based on a 2008 study of water demands for the residential suburb of Torquay, Queensland [*Turner et al.*, 2010]. For the MDS scenario, monthly water demand multiplier values (Figure 3.12) are applied to the base demand in combination with the diurnal water demand multiplier curve (Figure 3.11). Monthly water demand multiplier values are based on monthly water treatment plant flow data for Adelaide, SA, between July 1999 and June 2010 [*SA Water*, 2010]. For the ADS scenario, annual water demand multiplier values (Figure 3.13) are applied to the base water demand in combination with the diurnal water demand multiplier curve (Figure 3.11). Annual water demand multiplier values are based on the projected total urban water consumption values for Adelaide, South Australia [*Water Services Association of Australia*, 2010].

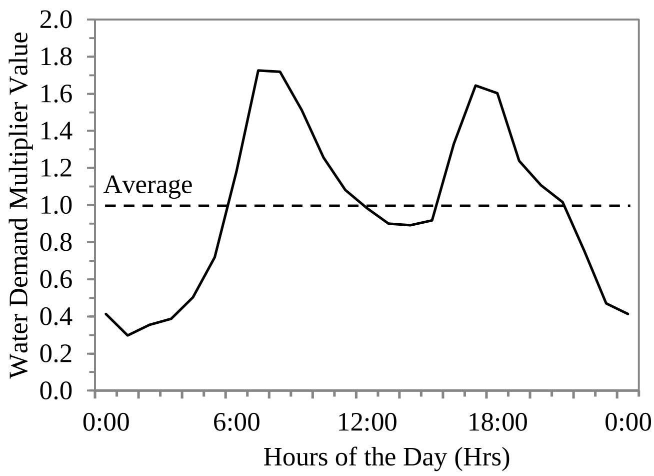


Figure 3.11. Diurnal water demand multiplier curve (used for the DS, MDS and ADS scenarios).

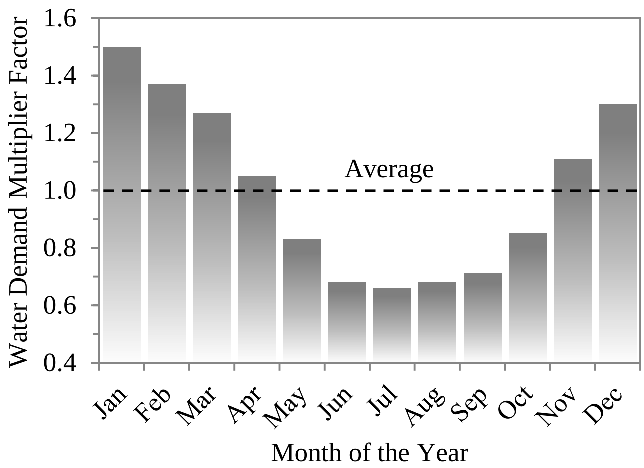


Figure 3.12. Monthly water demand multiplier values used to consider the variation of water demands for each month of the year (used for MDS scenario).

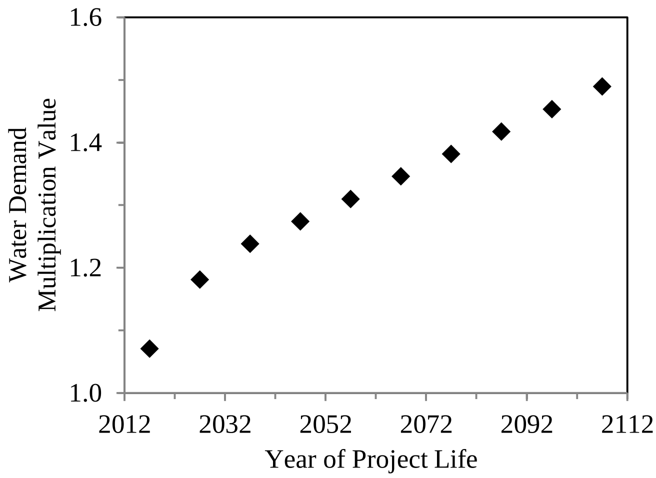


Figure 3.13. Water demand multiplier values used to consider water demand variations for each 10 year-long operational period over the project life of the water distribution system (used for ADS scenario).

As discussed in Section 3, the nodal pressure constraints (Figure 3.2, A11) are evaluated using a peak hour water demand, while the supply constraints (Figure 3.2, A10) are evaluated using the water demands pumped on the peak day. For all scenarios, a peak day demand multiplier of 2.0 is used [*Water Services Association of Australia*, 2002]. For all scenarios, a peak hour demand multiplier of 1.73 is used. The peak hour multiplier value is based on the peak hour demand from the diurnal water demand multiplier curve (Figure 3.11). In order to calculate the peak hour demand, the base demand is multiplied by both the peak hour and peak day water demand multipliers.

3.4.2.5 Present Value Analysis

As discussed in Section 3.3, present value analysis (PVA) is used to calculate the present worth of pumping operational costs and GHG emissions accumulated over the project life of the WDS. In order to use PVA, a discount rate is required. Based on previous WDS cost and GHG emissions minimization literature, an economic discount rate of 8% and a GHG emissions discount rate of zero are chosen for this study [*Wu et al.*, 2010a; *Wu et al.*, 2010b; *Roshani et al.*, 2012; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Wu et al.*, 2013]. 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]. they are Based on the project life used by previous WDS cost and GHG emissions minimization literature, a projected project life of 100 years is used for calculating both pump electricity consumption costs and GHG emissions and pump replacement costs [*Wu et al.*, 2010a; *Wu et al.*, 2010b; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Wu et al.*, 2013].

3.4.3 Results and Discussion

3.4.3.1 Optimization using Average Simulation (AS) and Diurnal Simulation (DS) Scenarios

Solution costs and GHG emissions for the average simulation (AS) scenario, which represents standard simulation practices (steady state hydraulic simulation using average input data values) [*Dandy et al.*, 2006; *Wu et al.*, 2010b; *Kang and Lansey*, 2012; *Du et al.*, 2013; *Wu et al.*, 2013; *Basupi et al.*, 2014], and the diurnal simulation (DS) scenario, which represents the consideration of short-term time-dependency of operational conditions (24 h EPS using time-varying input data values), are shown in Figure 3.14. As can be seen, both costs and GHG emissions are significantly higher for all solutions developed using the AS scenario, compared to the solutions developed using the DS scenario. These results suggest that by using the WCEN computational software framework to consider the short-term time-dependency of operational conditions (EFs, ETs, water demands), while optimizing pumping operational management choices, both costs and GHG emissions can be significantly reduced.

Pumping operations are not optimized for the AS scenario as they are for the DS scenario. Therefore, the only way to reduce GHG emissions for the AS scenario is by changing the design. Additionally, as an average EF is used for the AS scenario to evaluate pumping operational GHG emissions, the only way to reduce pumping operational GHG emissions is by reducing friction energy losses in pipes, by increasing their diameters, which results in less pump energy expenditure. As such, pipe diameters are increased significantly for solutions developed using the AS scenario in order to reduce GHG emissions. As larger pipes are more expensive to manufacture than smaller pipes, solution costs for the AS scenario increase significantly compared to those for the DS scenario.

When solutions are developed using the DS scenario, the time-dependency of EFs is considered and pumps can be operated during lower EF times of the day to reduce pumping operational GHG emissions. The results suggest that this is a more efficient way to reduce GHG emissions than by increasing pipe diameters. As such, solutions developed using the DS scenario use smaller pipe diameters than those developed using the AS scenario. Therefore, the results suggest that by using the WCEN computational software framework to consider the short-term time-dependency of operational conditions (DS scenario), both the design and pumping operation choices of solutions are significantly different compared to those developed when considering standard simulation practices (AS scenario).

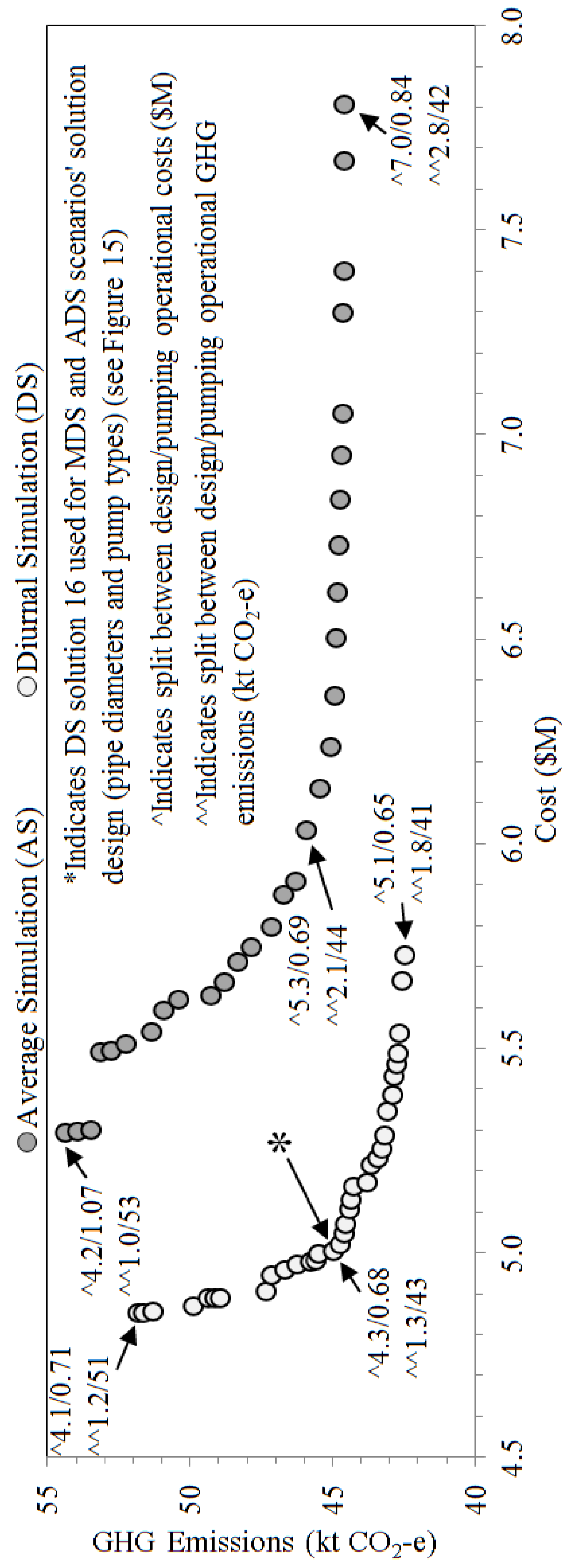


Figure 3.14. Costs and GHG emissions for the solutions developed using both the average simulation (AS) and diurnal simulation (DS) scenarios.

3.4.3.2 Optimization using Monthly, Diurnal Simulations (MDS) and Annual, Diurnal Simulations (ADS) Scenarios

Solution costs and GHG emissions for the monthly, diurnal simulations (MDS) scenario, which represents the consideration of both the short-term (diurnal) and longer-term (monthly) time-dependency of operational conditions, are shown in Figure 3.15. Solution costs and GHG emissions for the annual, diurnal simulations (ADS) scenario, which represents the consideration of both the short-term (diurnal) and long-term (annual) time-dependency of operational conditions, are shown in Figure 3.15. Solution costs and GHG emissions for both scenarios are significantly different compared to when solutions are developed while considering standard simulations practices (AS scenario, see Figure 3.14). For the MDS scenario, solution costs and GHG emissions are reduced compared to solutions developed for the AS scenario and are similar to those developed for the DS scenario. Similar to solutions developed using the DS scenario and as discussed above, optimizing pumping operations while considering the time-dependency of EFs and ETs allows both costs and GHG emissions to be further reduced than when optimizing only the design of the WDS. For the ADS scenario, a 32% larger total volume of water is considered to be consumed over the project life which results in increased solution costs and GHG emissions compared to solutions developed for the DS scenario. Despite this increase in water consumption and an overall increase in GHG emissions (Figure 3.15) compared to DS solution 16 (Figure 3.14), fewer GHG emissions are emitted per gigaliter (GL) of water consumed (between 170 and 178 t CO_2-e/kWh compared to 196 t CO_2-e/kWh for DS solution 16). This is due to the predicted decrease in electricity emissions intensity of the project life of 100 years. However, as electricity costs are predicted to increase over the project life, the total cost (Figure 3.15) and cost per GL of water consumed significantly increases compared to DS solution 16 (between $4650 and $5150 per GL compared to $3100 per GL for DS solution 16). These results for both the MDS and ADS scenarios suggest that costs and GHG emissions can be significantly affected by the consideration of both the short-term and long-term time-dependency of operational conditions, compared to when only standard simulation practices are considered.

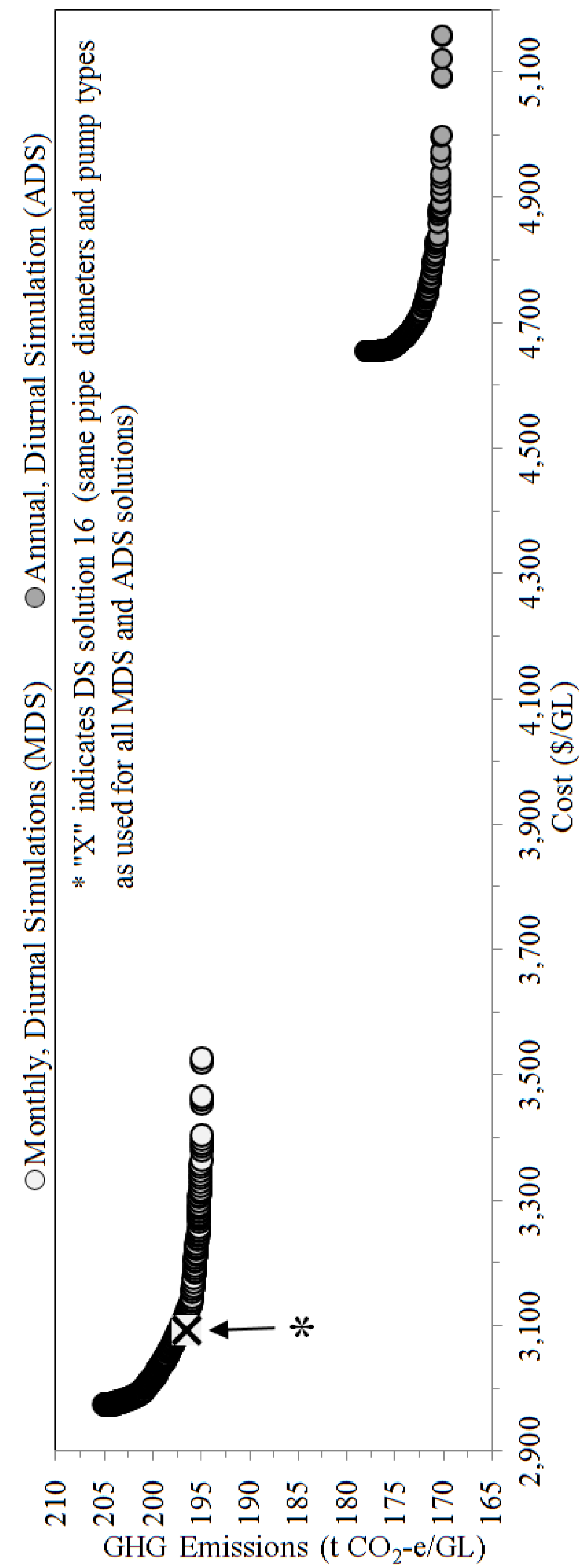


Figure 3.15. Costs and GHG emissions for the solutions developed using the monthly, diurnal simulations (MDS) scenario and the annual, diurnal simulations (ADS) scenario.

When developing solutions for the MDS scenario, different pump schedules are utilized for each month of the year. This occurs for two reasons. Firstly, the changes in water demands for each month affect the amount of water that needs to be pumped. As such, pump schedules respond to this by changing the amount of time each pump is operated for. As shown in Figure 3.16, pump utilization closely follows the monthly water demand multipliers (which represent the changes in water demands for each month). Secondly, the diurnal changes of EFs and ETs vary for each month. As such, pump schedules also respond to these changes in order to reduce pumping operational costs and GHG emissions by pumping at the off-peak ET and low EF times, respectively. When developing solutions for the ADS scenario, different pump schedules are utilized for each 10 year-long operational period over the project life of the WDS. This occurs as the increases in water demands seen in each consecutive period increase the amount of time that pumps must be operated for. This is shown by the increase in pump utilization for each 10 year-long operational period over the project life of 100 years (Figure 3.17). As can be seen, pump utilization closely follows the increase in annual water demand multipliers (which represent the increase in water demands over the project life). These results suggest that considering both the short-term and long-term time-dependency of operational conditions can significantly affect the development of pumping operational management. As such, the results suggest that by using the WCEN computational software framework to consider both the short-term and long-term time-dependency of operational conditions, optimal pumping operations of solutions can be significantly different compared to those developed when considering only standard simulation practices.

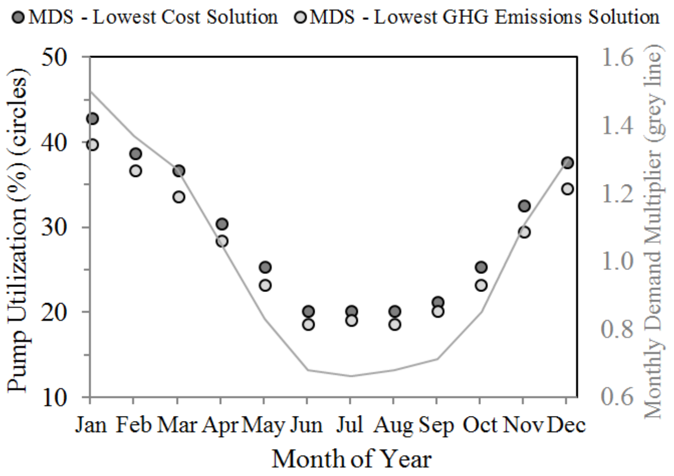


Figure 3.16. Pump utilization (percentage of time pumps are operated) for each month of the year for the lowest cost and lowest GHG emissions solutions developed using the monthly, diurnal simulations (MDS) scenario.

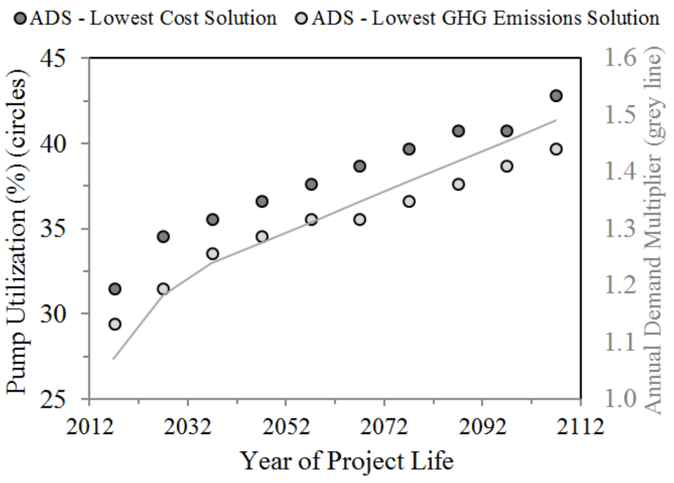


Figure 3.17. Pump utilization (percentage of time pumps are operated) for each 10 year-long operational period for the lowest cost and lowest GHG emissions solutions developed using the annual, diurnal simulations (ADS) scenario.

3.4.3.3 Summary of Results

From the optimization of the case study WDS, the results suggest that considering both the short-term (DS scenario) and long-term (MDS and ADS scenarios) time-dependency of operational conditions can significantly affect the optimization of both the design and pumping operational management choices of solutions, compared to when only standard simulation practices are considered (AS scenario). Additionally, costs and GHG emissions associated with the developed solutions can be significantly affected by these considerations, as a result of both the accuracy of evaluation and the selection of optimal design and pumping operational management choices. However, considering short-term and long-term variations can come at a cost of increased computation time. For the AS and DS scenarios, an optimization run using a single seed value takes less than one hour using a 2.6 GHz processor. However, for the MDS and ADS scenarios, optimization using a single seed value takes 13.0 hours and 15.6 hours, respectively. The general characteristics of the results suggest that considering variations over both short-term and long-term periods, such as over months and years, by considering multiple operational conditions, can significantly affect solution development. However, careful consideration of which operational conditions to simulate is important, as these can considerably add to the computational time required for optimization. This demonstrates the benefits of the WCEN computational software framework, as it enables the impact of different operational conditions and subsequently required simulation parameters to be explored, and their trade-off with computational time to be analyzed, which would otherwise not be possible.

3.5 Summary and Conclusions

Currently, most WDS design and operational optimization literature concerned with the reduction of costs and GHG emissions use simplifications of the real-world elements that affect the system being considered. Specifically, most studies use standard simulation practices, which consider only average operational conditions (emissions factors, electricity tariffs and water demands) and without considering pumping operational management choices when evaluating pumping operational costs and GHG emissions. However, operational conditions vary over time and these variations are likely to have an impact on the optimal trade-offs between costs and GHG emissions. In order to enable the impact of these issues to be investigated in a consistent manner, a water distribution cost-emission nexus (WCEN) computational software framework is presented in this paper. As previously discussed, it is important that such a framework is made freely available and can be easily integrated into research in order to facilitate consistency of modeling, simulation and evaluation within studies. By developing the WCEN computational software framework as an open source software package and with consideration of the previously discussed guidelines (Section 3.2), it allows the framework to be freely accessed and integrated into research, enabling researchers to apply the framework to studies beyond that presented in this paper.

In order to demonstrate the application and benefits of the WCEN computational software framework and the types of analyses it facilitates, a case study WDS is optimized while considering four different scenarios that consider different levels of time-dependency. The general characteristics of the case study optimization results show that considering both short-term (e.g. daily) and long-term (e.g. monthly and annual) variations can significantly affect both the chosen design and pumping operational management options of developed solutions, as well as their costs and GHG emissions, compared to when only standard simulation practices are considered. As WDSs operate under a range of conditions during their project life, it is important to account for these ranges of conditions when modeling and simulating a WDS for the minimization of costs and GHG emissions by considering both short-term and long-term variations. Subsequently, design and pumping operational management can be developed with consideration of these variations, allowing costs and GHG emissions to be minimized by taking advantage of these variations. This can help to develop solutions of reduced costs and GHG emissions that are evaluated accurately with respect to real life operating conditions. Conversely, not considering these variations can mean solutions are developed without accounting for the possible range of operational conditions encountered in real life, leading to design and pumping operational management choices that may be unsuitable to operational conditions outside of the average conditions that are often only considered. By using the WCEN computational software framework, different levels of evaluation accuracy, and the effect these have on solution development and the minimization of costs and GHG emissions, can be considered, which is not possible when considering only standard simulation practices.

In conclusion, the WCEN computational software framework is presented and demonstrated as an effective way to analyze the effect of considering different operational conditions and required simulation parameters on the development of solutions for the minimization of costs and GHG emissions associated with WDS, which would otherwise not be possible. As such, the WCEN computational software framework allows the most accurate available operational information to be used, instead of only the average values considered when using standard simulation practices. As cost and GHG emission minimization is becoming increasingly important for water utilities, the WCEN computational software framework and the considerations that it allows will become important ways to help further minimize the costs and GHG emissions associated with WDSs.

3.6 Acknowledgements

This research was supported by resources supplied by eResearch SA. Electricity generation data was provided by the Australian Energy Market Operator (AEMO). Funding for this research was provided by the University of Adelaide and the Goyder Institute for Water Research. These funding sources had no other involvement in this research. The authors would like to thank Stephen Carr for his help with modifying and debugging the NSGA-II optimization algorithm used for this study. The authors would also like to thank the three anonymous reviewers for their time and valuable input which helped to improve the quality of this research.

Chapter 4

Water Distribution System Pumping Operational Greenhouse Gas Emissions Reduction by Considering Time-Dependent Emissions Factors

Statement of Authorship

Title of Paper	Water distribution system pumping operational greenhouse gas emissions reduction by considering time-dependent emissions factors
Publication Status	Submitted for publication
Publication Details	Stokes, C. S., H. R. Maier, and A. R. Simpson (2014), Water distribution system pumping operational greenhouse gas emissions reduction by considering time-dependent emissions factors, Journal of Water Resources Planning and Management (submitted).

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author (Candidate)	Christopher S. Stokes		
Contribution to the Paper	Developed time-dependent emissions factor calculation method, undertook numerical evaluation and wrote manuscript		
Signature		Date	7/7/14

Name of Co-Author	Holger R. Maier		
Contribution to the Paper	Supervised manuscript preparation and reviewed draft		
Signature		Date	28/05/2014

Name of Co-Author	Angus R. Simpson		
Contribution to the Paper	Supervised manuscript preparation and reviewed draft		
Signature		Date	8/7/2014

Abstract

Human-induced climate change caused by greenhouse gas (GHG) emissions has become a significant concern. While water distribution systems (WDSs) provide an essential service, they also contribute to the release of GHG emissions through the use of electricity from fossil fuel sources for pumping purposes. In this paper, the reduction of both costs and GHG emissions associated with the pumping operation of WDSs is considered. Actual (time-varying) emissions factors (EFs) for the South Australian electricity grid from February 2011 to January 2012 with a 5 minute time-step are used to evaluate pumping operational GHG emissions and compared with the use of an average EF, which does not consider the time-dependency of EFs. An estimated (typical) 24-hour EF curve, which aims to replicate the important aspects of the time-dependency of actual EFs, is developed and compared for use in place of actual EFs, for when the actual variations in EFs cannot be accurately predicted for the future. Additionally, modified estimated 24-hour EF curves, representing different amounts of renewable energy (wind generation) penetration are considered to test the sensitivity of solution development to the magnitude of the variations of time-dependent EFs. Through the multi-objective optimization of pumping operations of a case study WDS, it is shown that solutions found using actual EFs can reduce GHG emissions by moving pumping to low EF times of the day. Conversely, solutions found using an average EF can only reduce GHG emissions by pumping more consistently during the day. Additionally, solutions found using the estimated 24-hour EF curve are very similar to those found using the actual EFs, suggesting that the estimated 24-hour EF curve can accurately replicate the important characteristics of the time-dependency of EFs and can be used in place of actual EFs to find solutions of reduced pumping operational costs and GHG emissions. Furthermore, solutions found using the modified estimated 24-hour EF curves show that the development of solutions is dependent on the magnitude of the variations of time-dependent EFs.

4.1 Introduction

Human-induced climate change caused by greenhouse gas (GHG) emissions and its associated effects have become a significant concern for human-kind. The importance of climate change mitigation as one way of addressing this issue is being increasingly recognized by the scientific, commercial and political sectors [*National Round Table on the Environment and the Economy*, 2007; *Department of Resources Energy and Tourism*, 2009]. While water distribution systems (WDSs) provide an essential service to modern populations, they also contribute to the release of GHG emissions. As a result, careful investigation of potential climate change mitigation options is required. In response, recent literature has included the consideration of the minimization of GHG emissions as one of the objectives in the optimization of WDSs. The majority of these studies have focused on the *design* of the system [*Dandy et al.*, 2006; *Herstein et al.*, 2009b; *Wu et al.*, 2010a; *Wu et al.*, 2010b; *Herstein and Filion*, 2011; *Herstein et al.*, 2011; *MacLeod and Filion*, 2011; *Kang and Lansey*, 2012; *Wu et al.*, 2012a; *Basupi et al.*, 2013; *Du et al.*, 2013]. Other studies have considered *pumping operational* management, such as the use of trigger levels to control pump on and off status [*MacLeod et al.*, 2010; *Roshani et al.*, 2012; *Marchi et al.*, 2014] or the use of variable speed pumps to minimize frictional energy losses [*Wu et al.*, 2012b]. While much literature has considered the minimization of pumping operational *costs* [*Zessler and Shamir*, 1989; *Ormsbee and Lansey*, 1994; *Mackle et al.*, 1995; *Kazantzis et al.*, 2002; *McCormick and Powell*, 2004; *Barán et al.*, 2005; *Lopez-Ibanez et al.*, 2008], comparatively few studies have considered the sources of pumping operational *GHG emissions* [*Herstein et al.*, 2009b; *Herstein and Filion*, 2011; *Herstein et al.*, 2011] and the availability of pumping operational options that can be used to minimize them [*Ramos et al.*, 2011; *Wu et al.*, 2012b; *Basupi et al.*, 2014; *Marchi et al.*, 2014]. This is despite the fact that the majority of GHG emissions from WDSs have been shown to be associated with the operational phase [*Herstein et al.*, 2009b; *Wu et al.*, 2010b; *Herstein and Filion*, 2011; *Herstein et al.*, 2011; *Wu et al.*, 2012b].

Pumping operational GHG emissions associated with WDSs occur when the electricity used for pumping is consumed by fossil fuel electricity generation sources. The emissions intensity associated with the generation of electricity is dependent on the type of electricity generation fuel source used by the various sources in an electrical grid. As most WDSs draw electrical energy from an electricity grid serviced by many different generation sources, emissions intensity can change over time as a response to the changes in contributions from these sources. While fossil fuel electricity generation sources (e.g. gas and coal fired power stations) are responsible for electricity GHG emissions, other electricity generation sources, such as renewable zero-emissions sources (e.g. wind farms and solar arrays), can also affect the emissions intensity of electricity. This occurs because an increase in zero-emissions electricity generation acts to decrease the overall emissions intensity of electricity supplied to the electrical grid. For example, wind generation, globally the fastest growing energy resource [*Geoscience Australia and Australian Bureau of Agriculture and Resource Economics*, 2010], varies with wind speed and can therefore cause significant emissions intensity variations. Consequently, water utilities operating pumps in regions with large amounts of wind generation may consume electricity with high emissions intensity variability over short time-periods (e.g. daily). While previous literature has considered the contributions from different generation sources [*Herstein et al.*, 2009b; *Herstein and Filion*, 2011; *Herstein et al.*, 2011], little consideration has been given to the time-dependency of these contributions [*Ramos et al.*, 2011].

The accuracy of calculating GHG emissions is dependent on the accuracy of the emissions factors (EFs) used to estimate the emissions intensity of electricity. An *average* EF cannot replicate the fluctuations of emissions intensities that occur over time. As pumps can be controlled to operate at specific times, *time-dependent* emissions factors, which aim to replicate the fluctuations of emissions intensities, are required to accurately calculate pumping operational GHG emissions. While some consideration has been given to the *time-dependency* of EFs [*Roshani et al.*, 2012; *Wu et al.*, 2012a], this has rarely been done while also considering pumping operational options [*Ramos et al.*, 2011].

As renewable electricity generation sources are being used increasingly to mitigate GHG emissions associated with fossil fuel generation sources, the *time-dependency* of emissions intensities associated with electricity generation will become an important consideration for many water utilities [*Stokes et al.*, 2014c]. Wind power is the most widely used non-hydro zero-emissions renewable generation type in the world and is also the fastest growing energy resource, increasing globally at an average annual rate of nearly 30% between 2000 and 2008 [*Geoscience Australia and Australian Bureau of Agriculture and Resource Economics*, 2010]. Many locations already have a high penetration of wind power. For example, in 2011, wind generation supplied 28% of Denmark's electricity [*Asea Brown Boveri Ltd*, 2013], while in 2013, it supplied 22% of Spain's electricity [*Red Eléctrica de España*, 2013]. In the United States of America, many states have high installed wind generation capacity, such as Iowa (27%), South Dakota (26%), Kansas (19%), Idaho (16%) and Minnesota (16%) [*American Wind Energy Association*, 2013]. In Germany, in 2011, the states of Sachsen-Anhalt, Brandenburg, Schleswig-Holstein and Mecklenburg-Vorpommern used more than 40% wind generation [*Molly*, 2011]. In 2012, South Australia's wind generation represented 27% of total installed capacity [*Australian Energy Market Operator*, 2013a]. As such, there remains a need to consider the *time-dependency* of emissions factors and to determine how this consideration can affect the optimal *pumping operation* of an existing WDS for the minimization of both costs and GHG emissions.

However, as there is currently no way to accurately predict the actual changes in EFs associated with electricity produced in the future, there is also a need to develop and test the utility of a *typical EF curve*, that can be used to approximate actual fluctuations of EFs for *operational pumping* purposes. As the amount of renewable energy (particularly wind generation) varies between regions, there is also a need to test the sensitivity of *pumping operational options* to different amounts of renewable energy penetration within an electricity grid. In order to address these shortcomings, the objectives of this paper are:

1. To test the impact of considering the *time-dependency* of EFs by comparing solutions found using *actual* EFs over a one-year period, which consider the actual variations in emissions intensity, with those found using an *average* EF for a hypothetical case study WDS.
2. To develop an *estimated* (typical) 24-hour EF curve that can be used for day-to-day operational purposes, which aims to replicate the important characteristics of the time-dependency of *actual* EFs, and compare the solutions found using the *estimated* 24-hour EF curve with those found using *actual* EFs over a one-year period for a hypothetical case study WDS.
3. To test the sensitivity of solutions found while considering different amounts of renewable energy penetration by comparing solutions found using three *modified estimated* (typical) 24-hour EF curves (*modified* EF curves), which aim to replicate the diurnal time-dependency of EFs for three different (hypothetical) renewable energy (wind generation) penetration possibilities,

with solutions found using the *estimated* (typical) 24-hour EF curve (from 2), for a hypothetical case study WDS.

The remainder of this paper is organized as follows. Firstly, the case study WDS used to address the objectives is introduced. Following this, the methodology used to optimize the case study WDS is outlined, which is followed by an analysis and discussion of the results. Finally, conclusions are drawn and recommendations are given.

4.2 Case Study

The case study is aimed at minimizing the costs and GHG emissions associated with the pumping operation of a hypothetical WDS adapted from The Battle of the Water Networks II (BWN-II) [*Salomons et al.*, 2012; *Marchi et al.*, 2014]. Known as D-Town, the network is realistically sized, containing over 400 pipes, over 350 demand nodes, 7 storage tanks and 12 pumps in 5 pumping stations (see Figure 4.1). The original BWN-II problem called for the infrastructure upgrade and operational management optimization of the WDS. As the paper here is concerned with only the pumping operational management of an assumed existing system, the original D-Town WDS has been altered to accommodate the increased water demands of the system upgrade problem. The alterations include increasing the diameters of 4 pipes, with IDs P22 (406mm to 610mm), P23 (508mm to 610mm), P100 (406mm to 610mm) and P995 (152mm to 203mm), 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 diameters of 3 of the 7 storage tanks, with IDs T4 (11.64m to 26.03m), T5 (11.89m to 16.82m) and T7 (7.14m to 17.48m), to allow a minimum balancing storage size equivalent to 12 hours under average day water demand loadings. These alterations are among the most commonly made changes by the participants of the BWN-II competition [*Marchi et al.*, 2014]. The original 168 hour duration water demand multipliers for each of the five demand management areas are used. The EPANET 2.0 input files used for this study are available as supplemental material.

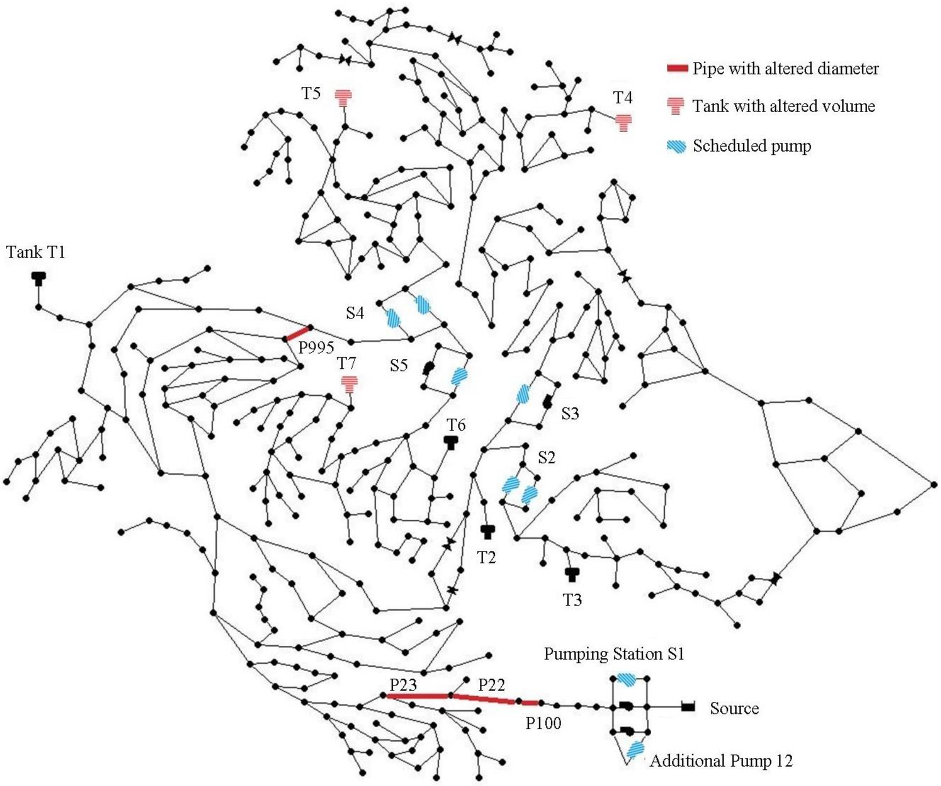


Figure 4.1. The modified D-town water distribution system used for the case study presented in this paper. Pumping schedules for 8 lighter colored pumps are optimized (S1, S2, S3, S4 and S5), while 4 black pumps are run full time (S1, S3 and S5). Pipes and tanks (highlighted) that have been altered from the original D-town network are indicated.

4.3 Methodology

4.3.1 Introduction

In order to address the objectives of the paper outlined previously, three emissions factor (EF) scenarios and three hypothetical EF scenarios for sensitivity analysis are considered for the evaluation of operational GHG emissions, as outlined below and summarized in Table 4.1:

1. In Scenario 1, *actual* EFs from February 2011 to January 2012, which consider the actual changes in emissions intensity over time, are used (S1, Table 4.1 and Figure 4.2).
2. In Scenario 2, an *average* EF, which represents the average value of the actual EFs, is used (S2, Table 4.1 and Figure 4.2).
3. In Scenario 3, an *estimated* (typical) 24-hour time-varying EF curve, which represents the average diurnal change in emissions intensity over the time period of the *actual* EFs, is used (S3, Table 4.1 and Figure 4.2).
4. In Scenarios 4.1, 4.2 and 4.3, three *modified* EF curves, which represent the average diurnal changes in emissions intensity over the period of the *actual* EFs for three different (hypothetical) amounts of renewable energy (wind generation) penetration, are used (S4.1, S4.2 and S4.3, Table 4.1 and Figure 4.2).

Table 4.1. Details for each of the three scenarios.

Scenario	Pump Schedule	Emissions Factor Type	Emissions Factor Value
Actual EFs (S1)	*24hr long*	*365 days*	*0.574 kg CO2-e per kWh (Average)*
Average EF (S2)	*24hr long*	*Average value*	*0.574 kg CO2-e per kWh*
Estimated 24-hour EF Curve (S3)	*24hr long*	*24 hour curve*	*0.574 kg CO2-e per kWh (Average)*
Modified EF Curve (S4.1) 3% Wind	*24hr long*	*24 hour curve*	*0.829 kg CO2-e per kWh (Average)*
Modified EF Curve (S4.2) 15% Wind	*24hr long*	*24 hour curve*	*0.703 kg CO2-e per kWh (Average)*
Modified EF Curve (S4.3) 40% Wind	*24hr long*	*24 hour curve*	*0.439 kg CO2-e per kWh (Average)*

Note: All scenarios used peak/off-peak electricity tariffs and a 168hr long water demand multiplier curve

For each emissions factor scenario, multi-objective (MO) optimization is used to optimize the pump schedules for the case study WDS (see Section 4.2) and the results are used to address the objectives of the paper as follows:

1. In order to investigate the impact of considering the time-dependency of EFs, optimal operational management solutions found using the *actual* EFs (S1) over a one-year period and the *average* EF (S2) are compared.
2. In order to investigate the ability of the *estimated* 24-hour EF curve to effectively represent the time-dependency of *actual* EFs for the purposes of making optimal operational decisions, solutions found using the *estimated* 24-hour EF curve (S3) are compared with those found using the *actual* EFs over a one-year period (S1).
3. In order to investigate the sensitivity of solutions found while considering different (hypothetical) amounts of renewable energy penetration, solutions found using three *modified* 24-hour EF

curves (S4.1, S4.2 and S4.3) are compared with those found using the *estimated* 24-hour EF curve (S3).

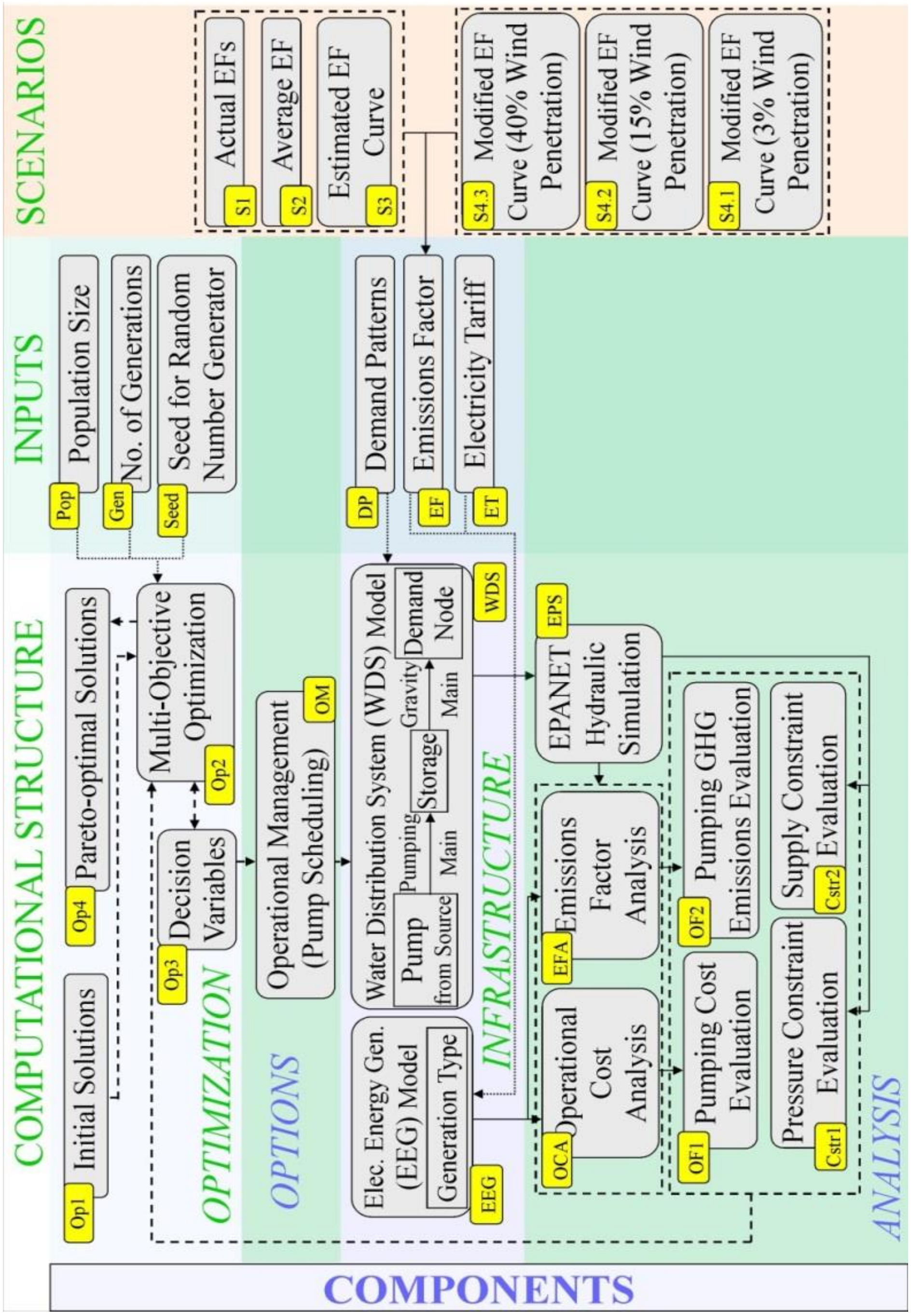


Figure 4.2. Flowchart presenting the methodology used in this study.

4.3.2 Overview

The detailed methodology used to evaluate and minimize the pumping operational costs and GHG emissions for the case study WDS is based on the water distribution system cost-emissions nexus (WCEN) conceptual framework (Stokes et al., 2014) and outlined in Figure 4.2. The first step involves the selection of initial solutions (Op1, Figure 4.2). Each solution represents a possible operational management strategy (OM, Figure 4.2), with decision variables (Op2, Figure 4.2) representing the pump schedules. Multi-objective (MO) optimization (Op3, Figure 4.2) is then used to develop new solutions of minimized pumping operational costs and GHG emissions. In order to calculate the pumping electricity costs and GHG emissions associated with each developed solution, a WDS model (WDS, Figure 4.2) is used to represent the critical elements of the WDS required to calculate its associated pumping operational costs and GHG emissions. Additionally, the electrical energy generation (EEG) model (EEG, Figure 4.2) is used to represent the critical elements of the electrical energy generation infrastructure that is used to supply the WDS with electricity for pumping purposes, including its associated EFs (EF, Figure 4.2) and electricity tariffs (ET, Figure 4.2). The operation of the WDS is hydraulically simulated using an extended period simulation (EPS, Figure 4.2), performed using EPANET 2.0 [*Rossman*, 2000]. This serves to both calculate the electrical energy used for pumping operations, which is used to calculate pumping operational costs and GHG emissions, and to check if there is any violation of the constraints. Two constraints are imposed to ensure the available hydraulic capacity of the WDS can meet the water demands:

1. Minimum pressures of 20m at non-zero demand nodes and 0m at zero demand nodes (Cstr1, Figure 4.2). These pressure limits are chosen to allow for the operation of most water demanding

appliances (e.g. washing machines) and to prevent cavitation in the pipe network, respectively;

2. The total volume of water pumped into each district metered area (DMA) must be equal or above the demand for that DMA over the course of the extended period simulation (Cstr2, Figure 4.2).

The objective functions of operational costs (OF1, Figure 4.2) and operational GHG emissions (OF2, Figure 4.2) are calculated from the energy usage evaluated during the EPS by the use of operational cost analysis (OCA, Figure 4.2) and emissions factor analysis (EFA, Figure 4.2) respectively. Once the objective functions and constraints are calculated, this information is passed to the MO optimization algorithm in order to develop subsequent solutions of minimized pumping operational costs and GHG emissions. As per normal optimization procedures, this process is continued until either the convergence of solutions or the expenditure of computational budget.

Details of the pump schedule optimization, and operational costs and greenhouse gas emissions evaluation processes specific to the presented case study are given in the following subsections. Following this, details of how *time-varying* emissions factors are obtained and how the emissions factor scenarios are derived are also given.

4.3.3 Details of Pump Schedule Optimization Process

4.3.3.1 Multi-Objective Optimization Algorithm

The Elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II), developed by Deb et al. (2000), is used as the optimization engine. While more recent MOGAs are available [*Deb et al.*, 2003; *Kollat and*

Reed, 2006; *Vrugt and Robinson*, 2007; *Hadka and Reed*, 2013], NSGA-II is used for its efficient solution space search ability, its ease of implementation and because it has been successfully applied to recent WDS cost and GHG emissions optimization problems [*Wu et al.*, 2010a; *Wu et al.*, 2010b; *Herstein and Filion*, 2011; *Herstein et al.*, 2011; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Wu et al.*, 2013]. A population size of 100 (Pop, Figure 4.2) and a maximum of 400 generations (Gen, Figure 4.2) are used, as preliminary results showed that solution convergence is achieved by using these values. Each EF scenario is optimized thirty times using different pseudo random number generator seeds (Seed, Figure 4.2) to reduce the stochastic effects of heuristic optimization. The non-dominated solutions contained within all the solutions found using the thirty optimization runs are used to form the final non-dominated set of solutions for each EF scenario.

4.3.3.2 Decision Variables

Each solution is represented as a set of integer value decision variables (DVs) (Op3, Figure 4.2) that represent pump schedules used to control the times at which the pumps are turned on and off (OM, Figure 4.2). In order to meet the minimum water demand requirements, it is assumed that 4 of the 12 pumps can be run continuously. As such, 8 pumps are operated by 8 optimized pump schedules. Each pump schedule is optimized to control each pump over a period of 24 hours. For EPS durations of longer than 24 hours, pump schedules are repeated for each day of the EPS. Each pump is limited to up to 4 on and 4 off selections each day. Therefore, each solution uses 8 DVs (on/off times) to represent the pump schedule assigned to each pump, with a total of 64 DVs per solution.

4.3.3.3 Pumping Operational Costs and Greenhouse Gas Emissions Evaluation

Both objective functions (OF1 and OF2, Figure 4.2) are evaluated with respect to the volume of water supplied. As such, costs are expressed as Australian Dollars ($) per gigaliter (GL) and GHG emissions are expressed as metric tonnes (t) CO_2-e per GL. This enables results from the simulations of different durations required to meet the objectives of this paper to be compared. It should be noted that because the maximum duration considered is 1 year and only operational costs of an existing system are calculated, there is no need to discount costs and GHG emissions.

Pumping Operational Costs

Operational costs are evaluated as the cost of electricity used to operate pumps, calculated using operational cost analysis (OCA, Figure 4.2). OCA uses an electricity tariff (ET, Figure 4.2) to convert consumption of electrical energy into an economic cost. Two electricity tariffs are used; a peak electricity tariff, from 7am to 11pm (16 hours per day) of $0.121 per kWh, and an off-peak electricity tariff, from 11pm to 7am (8 hours per day) of $0.037 per kWh. As the actual electricity tariff paid by the water utility in South Australia is undisclosed, an applicable electricity tariff structure is taken from the SA Power Networks (previously ETSA Utilities) Network Tariffs for FY2009 rate 2 business rate [*ETSA Utilities*, 2009] for South Australia. The cost of electricity is calculated by multiplying the electrical energy (kWh) consumed for pumping purposes over the extended period simulation (EPS) by the appropriate electricity tariff rate ($ per kWh). While other costs can be associated with the operation of WDSs, electricity costs represent the majority of costs for municipal water processing and distribution, with the majority of electricity being attributed to the operation of pumps

[*Boulos and Bros*, 2010]. While the amount of renewable energy generation may affect electricity tariffs, this association can be complicated by the indirect link between these two factors and has therefore not been considered in this study [*Cutler et al.*, 2011; *Australian Energy Regulator*, 2012].

Pumping Operational Greenhouse Gas Emissions

Emissions factor analysis (EFA, Figure 4.2) is used to evaluate the amount of GHG emissions associated with the consumption of electricity used for pumping purposes. EFA uses emissions factors (EFs) to calculate the mass of GHG emissions from the total amount of electrical energy consumed. EFs, measured as kilograms of carbon dioxide equivalent per kilowatt hour (kg CO_2-e per kWh), have previously been used to evaluate GHG emissions from both the embodied energy in the manufacture, transport and installation of materials, such as pipes (capital emissions), and the electrical energy (pumping operational emissions) sourced from generating facilities used for pumping purposes [*Wu et al.*, 2010a; *Wu et al.*, 2010b; *MacLeod and Filion*, 2011; *Roshani et al.*, 2012; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Marchi et al.*, 2014].

Emissions factor data from the South Australian electricity grid are used for the evaluation of GHG emissions. South Australia (SA) has an almost isolated electricity grid, with imports and exports via interstate interconnectors accounting for about only 3% of consumption [*Cutler et al.*, 2011]. From 2011 to 2012, SA's electricity generation sources included wind (27%), open-cycle gas turbines (OCGT) and gas fired stream turbines (gas ST) (20%), combined-cycle gas turbines (CCGT) (29%) and coal fired steam turbines (24%). This gives SA one of the highest penetrations of wind power in the world [*Cutler et al.*, 2011].

Because of this, emissions factors associated with the generation of electricity fluctuate on an hourly/daily and monthly/seasonal basis. GHG emissions associated with the use of electricity are calculated by multiplying the electrical energy (kWh) consumed for pumping purposes over the extended period simulation (EPS) by the appropriate EF (kg CO_2-e per kWh).

4.3.4 Details of Emissions Factors Scenarios

The operational management of the case study WDS is optimized for the six EF scenarios stated previously. The *time-varying* EF values used in the six scenarios are based on the raw electricity generation data and individual generation source emissions factor data collected for each electricity generation source supplying electrical energy to the South Australian electricity grid from February 2011 to January 2012 [*Australian Energy Market Operator*, 2013b], as detailed in subsequent sections.

In order to calculate *time-varying* EFs from the raw electricity generation data, individual emissions factors for each electricity generation source (which do not vary significantly over time for electricity generation types used in South Australia) are used in conjunction with the raw electricity generation data in order to calculate the weighted average of emissions factors over each time period, such that:

$$AWEF_t = \frac{\sum_{i=1}^{n} EE_{i,t} \times EF_i}{\sum_{i=1}^{n} EE_{i,t}} \tag{4.1}$$

where $AWEF_t$ is the average weighted *time-dependent* emissions factor (i.e. the emissions factor accounting for the weighted average of GHG emissions from each individual electricity generation source) for the South Australian electricity grid for the time period (Δt); $EE_{i,t}$ is the electrical energy generation for electricity generation source (i) for the time period (Δt); EF_i is the individual emissions factor attributed to the electricity generation source (i); and Δt is the time period from t to t+1. Each emissions factor is calculated for a 5 minute time period, as electrical energy generation data used for this study are provided in 5 minute intervals. The resulting *time-dependent* EFs ($AWEF_t$) are shown in Figure 4.3 (these raw data are available as supplemental material). The data have an average value of 0.574 kg CO_2-e per kWh, with minimum and maximum values of 0.208 kg CO_2-e per kWh and 0.903 kg CO_2-e per kWh respectively. Hence, the range is 0.695 kg CO_2-e per kWh. The standard deviation of the data is 0.121 kg CO_2-e per kWh.

As can be seen in Figure 4.3, the emissions factors vary considerably over both shorter (e.g. hours and days) and longer time periods (e.g. months and seasons). These variations are complex and result from multiple contributing factors, including (i) varying contributions of different generators (e.g. coal and gas fired, and wind farm electricity generation) over time, (ii) varying total demand of electrical energy, and (iii) the availability of wind farm electricity generation. As electricity demand increases, so do EFs, as readily available and higher emissions intensity (coal and gas fired) electricity generation is used to increase supply. As demand decreases, so do the contributions of higher emissions intensity electricity generation, leading to a decrease in EFs. EFs also tend to decrease overnight, as electrical energy demand decreases and the availability of wind farm electricity generation increases in proportion to the higher emissions intensity electricity generation types. However, the variations in EFs are not always consistent and can fluctuate according to many other influencing factors, including supply and demand ratios and the resulting changes in economic (spot) prices of electricity [*Cutler et al.*, 2011], weather conditions (related to both electrical energy demand and wind farm electricity generation), and the responses of power plant operators to all of these changes.

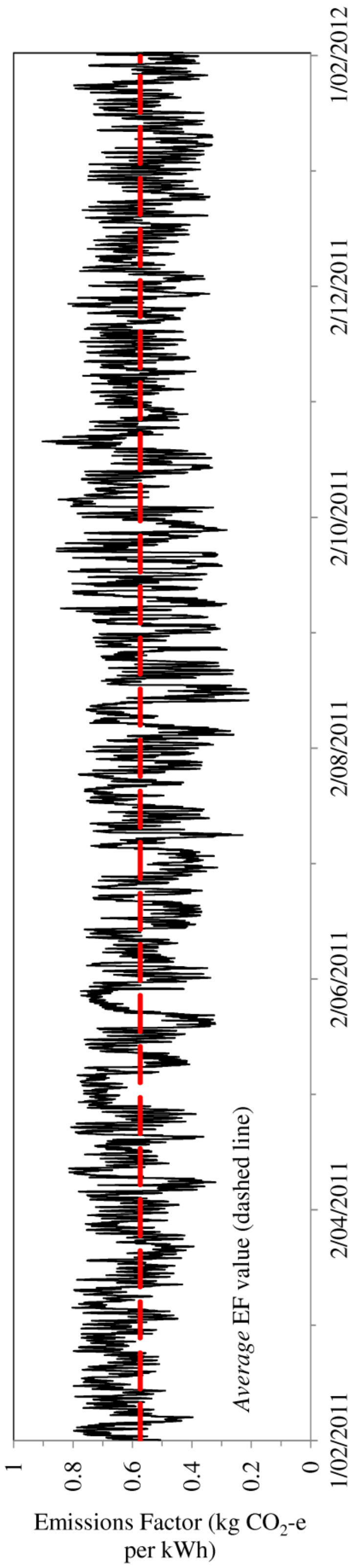


Figure 4.3. Time-varying emissions factor data for the period from February 2011 to January 2012 (solid line). Average emissions factor value is shown for comparison (dashed line).

4.3.4.1 Actual Emissions Factors Scenario (S1)

The *actual* EFs scenario (S1) directly uses the *time-varying* EFs data presented in Figure 4.3, thus representing the actual continuous variations in the emissions intensity of electrical energy that occurred over the period of time considered. The time period of one year is chosen as it allows emissions factor variations over longer time periods (e.g. monthly and seasonal variations) to be considered along with variations over shorter time periods (e.g. diurnal variations). As the case study WDS is optimized while using *actual* EFs with a duration of one year, an EPS (EPS, Figure 4.2) running for one year (365 days) is required.

4.3.4.2 Average Emissions Factors Scenario (S2)

The *average* EF scenario (S2) represents the use of emissions factors that do not consider the time-dependency of EFs and uses the average value of the *time-varying* EFs data used in S1 (from February 2011 to January 2012), which is equal to 0.574 kg CO_2-e per kWh. For this scenario, a 168 hour (seven day) EPS duration is used (EPS, Figure 4.2), as this is the length of the water demand curves used to represent the changes in water demands over a period of one week. By comparing the results from S1 and S2, the impact of using time-varying EFs, rather than constant EFs, on optimal solutions can be assessed. This provides an indication whether time varying EFs should be considered in the determination of optimal operational strategies, or whether the use of average EFs is sufficient.

4.3.4.3 Estimated 24-Hour Emissions Factor Curve Scenario (S3)

The emissions factors for the *estimated* 24-hour EF curve scenario (S3) represent the consideration of short-term (diurnal) emissions intensity variations that occur within the *time-varying* EF data. This enables time-varying EF data to be considered in routine operational settings in which actual, real-time EF data are not available. Consequently, *estimated* 24-hour EF curves are akin to diurnal demand curves. By comparing the results from S1 and S3, an assessment can be made in relation to how well the solutions obtained using the *estimated* 24-hour demand curves match the solutions obtained using the actual time varying EFs. This provides an indication of whether the *estimated* 24-hour EF curve provides an adequate representation of the actual dynamics of EF variation.

The *estimated* 24-hour EF curve scenario has an average EF of 0.574 kg CO_2-e per kWh with a diurnal variation (Figure 4.4) and aims to replicate the average diurnal fluctuation in the *time-varying* EFs data used in S1 (from February 2011 to January 2012). Overall contributions of electricity generation sources considered are shown in Figure 4.5. In order to obtain EF values for the *estimated* 24-hour EF curve, the estimated (averaged) EF values for each time of the day over the one year of *time-varying* EF data are calculated, such that:

$$EEF_t = \frac{\sum_{d=1}^{D} AWEF_{t,d}}{D} \tag{4.2}$$

where EEF_t is the estimated (averaged) emissions factor for the time of day (t); $AWEF_{t,d}$ is the *time-dependent* emissions factor for the South Australian electricity grid for the time of day (t) for the day (d) represented in the *time-varying* EF data; and D is the total number of days represented in the *time-varying* EF data. Each estimated emissions factor used in the *estimated* 24-hour EF curve is calculated for a 5 minute time period, as the *time-varying* EFs are calculated using 5 minute intervals. The *estimated* 24-hour EF curve data are available as supplemental material (see Appendix E).

When optimizing the case study WDS using the *estimated* 24-hour EF curve, a 168 hour (seven day) EPS duration is used. This is because the *estimated* 24-hour EF curve has a duration of 24 hours, which means that the required EPS duration is governed by the length of the water demand curves, as was the case for S2. As the *estimated* 24-hour EF curve has a duration of 24 hours (one day), it is repeated seven times over the duration of the EPS (EPS, Figure 4.2).

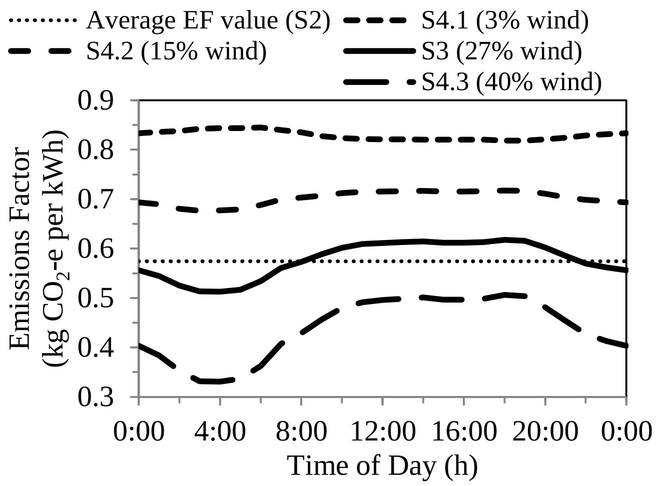


Figure 4.4. Diurnal emissions factor curves, representing the average daily fluctuation of emissions factors for South Australia (time-varying EFs) for a period of one year from February 2011 to January 2012, used for the estimated 24-hour emissions factor curve (S3) and modified emissions factor curves (S4.1, S4.2 and S4.3). The average emissions factor value for S2 is shown for comparison (dotted line).

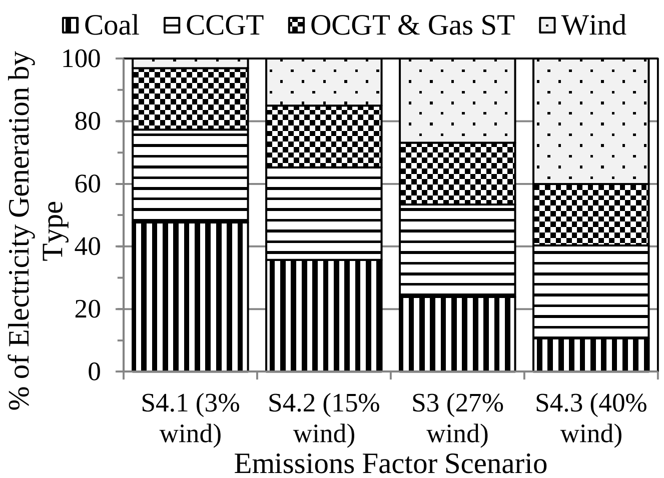


Figure 4.5. Mix of electricity generation types for the estimated 24-hour EF curve for S3 and the modified EF curves for S4.1, S4.2 and S4.3 (sensitivity analysis).

4.3.4.4 Modified Emissions Factor Scenarios (S4.1, S4.2 and S4.3) for Sensitivity Analysis

The emissions factors for the *modified* EF curves represent the consideration of short-term (diurnal) emissions intensity variations that occur within the *time-varying* EF data while considering different amounts of renewable energy (wind generation) penetrations. As water utilities in different regions can consume electricity generated with different amounts of renewable energy penetration, it is important to consider the effect of these differences on the solutions found using optimization, and their evaluated costs and GHG emissions. Time-dependent EFs used to develop each *modified* EF curve are calculated using the method described in Section 4.3.4, although with modified generation values. Each *modified* EF curve is developed using the method described for Scenario S3 (Section 4.3.4.3). Wind generation data are modified to reflect penetration percentages of 3% (S4.1), similar to the average percentage of wind generation in the United States of America and Canada over 2011 and 2012 [*US Energy Information Administration*, 2012; *National Energy Board*, 2013]; 15% (S4.2), the average between S4.1 (3% wind) and the current percentage of wind penetration in SA of 27% (S3) and similar to the values in Kansas, Idaho and Minnesota; and 40%, similar to wind penetration projections for SA by 2020 [*Australian Energy Market Operator*, 2011] and those in some parts of Germany (see Figure 4.5). As coal has traditionally been used in Australia as an inexpensive and plentiful fuel source, wind generation for S4.1 and S4.2 (where wind penetration is reduced) is offset by coal fired generation. As projections show coal generation to substantially reduce in SA by 2020 [*Australian Energy Market Operator*, 2011], wind generation for S4.3 (where wind penetration is increased) is offset by coal generation. The resulting *modified* EF curves are shown in Figure 4.4, and the data of the different *modified* EF curves are available as supplemental material.

4.4 Results and Discussion

4.4.1 Comparison of Solutions Found using Average and Actual Emissions Factors

Optimization of the case study WDS results in non-dominated solution sets with some difference in costs, yet little difference in GHG emissions when using either the *average* EF (S2) or *actual* EFs (S1) (Figure 4.6). The solutions found using the *average* EF have associated pumping GHG emissions between 172.1 and 175.6 t CO_2-e per GL and associated pumping costs between \$25,061 and \$28,105 per GL. In comparison, the solutions found using the *actual* EFs have associated pumping GHG emissions between 171.3 and 173.8 t CO_2-e per GL and associated pumping costs between \$25,107 and \$25,857 per GL.

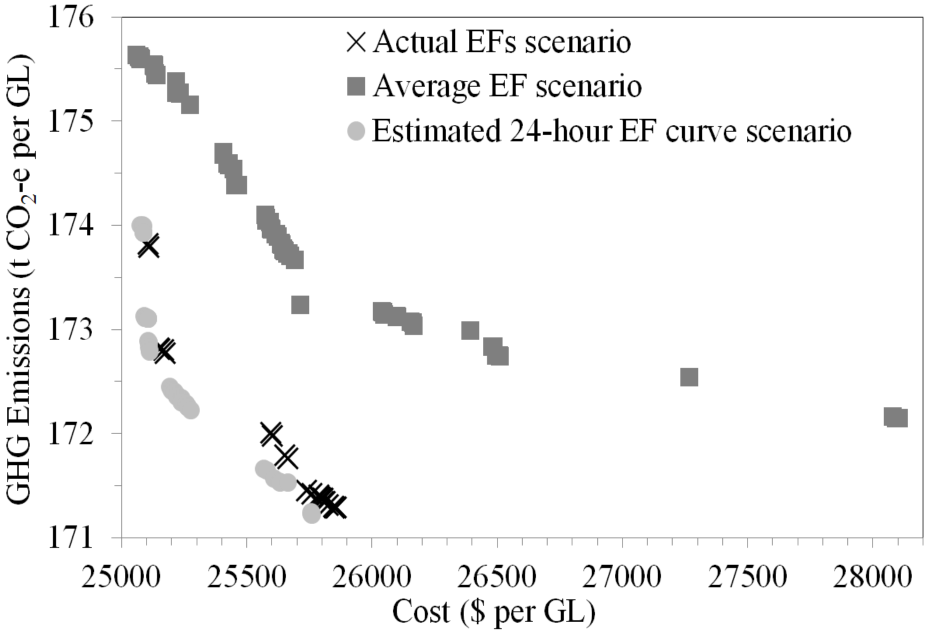
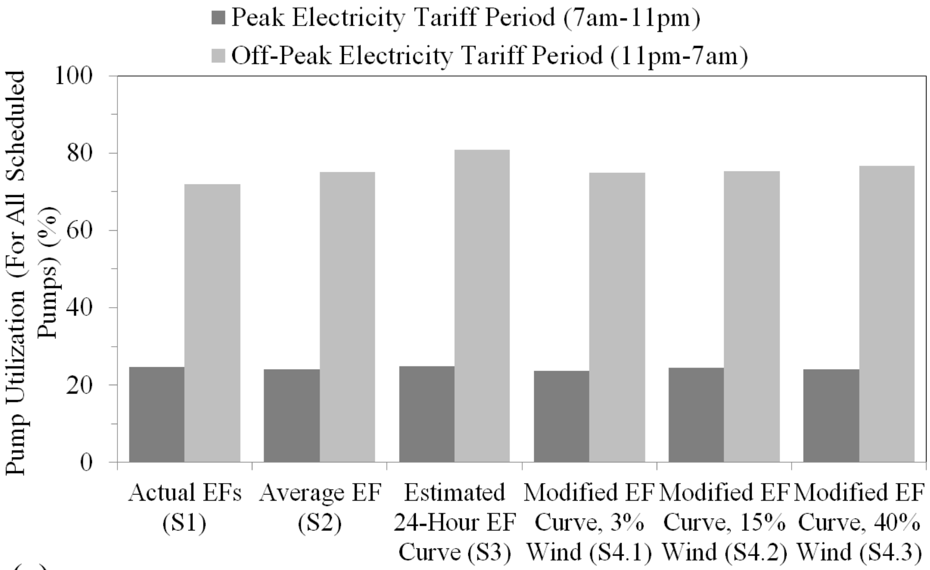


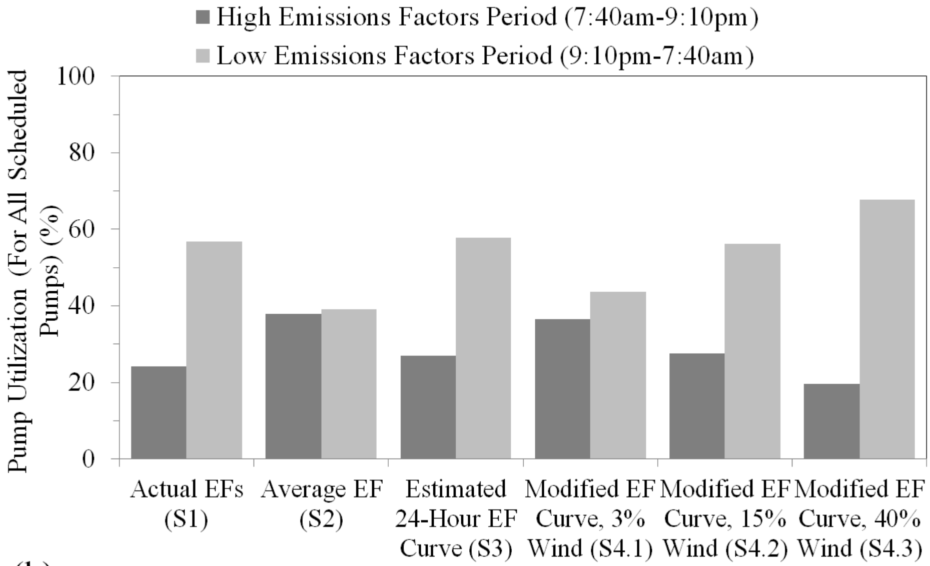
Figure 4.6. Costs and GHG emissions for the non-dominated solutions found using the actual EFs (S1), average EF (S2) and estimated 24-hour EF curve (S3).

The results suggest that when *time-varying* EFs fluctuate over time, considering these variations by using *actual* EFs can result in the development of pumping operational management solutions that are significantly different to when an *average* EF is used. When optimized using the *average* EF, solutions have pump schedules that operate pumps at different times of the day, dependent on whether pumping cost or pumping GHG emissions minimization is prioritized. When the minimization of costs is prioritized (lower cost solutions), pump schedules concentrate pumping to the off-peak ET times (e.g. see Figure 4.7a). However, when GHG emissions minimization is prioritized (higher cost solutions), pump schedules spread pumping more evenly over the day (e.g. see Figure 4.7b). This occurs because solutions that prioritize the minimization of GHG emissions do so by reducing frictional energy losses and hence electrical energy consumption by pumping more consistently throughout each day.

When optimized using the *actual* EFs, solutions that prioritize the minimization of pumping GHG emissions could either minimize GHG emissions by reducing electrical energy usage, as is the case the when the *average* EF is used, or by considering the *time-dependency* of EFs and pumping during low EF times. The results show that the latter mechanism is actually used. As the emissions intensity of electricity and hence EFs are lower overnight (when wind generation output is generally highest), at the same time as when the off-peak electricity tariff (ET) is used, the found solutions minimize both pumping costs and pumping GHG emissions in similar ways. Hence, the pump schedules for all of the found solutions are similar (e.g. see Figures 4.7a and 4.7b).



(a)



(b)

Figure 4.7. Pump utilization for the (a) lowest cost/highest GHG emissions solutions and (b) the highest cost/lowest GHG emissions solutions found using the actual EFs (S1), average EF (S2), estimated 24-hour EF curve (S3) and modified EF curves for different amounts of renewable energy (wind generation) penetration (S4.1, S4.2 and S4.3). Note the low and high EF times are defined by when the estimated 24-hour EF curve EF values are above and below the average EF value, respectively.

4.4.2 Comparison of Solutions Found using Estimated 24-Hour EF Curve and Actual Emissions Factors

Optimization of the case study WDS using the *estimated* 24-hour EF curve results in non-dominated solutions similar to those found using the *actual* EFs scenario. While solution pumping costs and pumping GHG emissions are similar to those for solutions found using the *actual* EFs and *average* EFs (Figure 4.6), operational management choices are similar to those found using the *actual* EFs (e.g. see Figures 4.7a and 4.7b). Solutions prioritizing the minimization of pumping GHG emissions found using the *estimated* 24-hour EF curve use similar pump schedules to those found using the *actual* EF curve, where pumping is moved to the lower emissions intensity times of the day. These solutions are significantly different from those found using the average EF, where GHG emissions are reduced by more evenly pumping throughout the length of each day. Hence, the results suggest the *estimated* 24-hour EF curve accurately reflects the aspects of the time-dependency of *actual* EFs important for the selection of operational management choices that are not reflected by the *average* EF.

4.4.3 Comparison of Solutions Found using Modified EF Curves considering Different Penetrations of Renewable Energy

Optimization of the case study WDS using the three *modified* EF curves representing different levels of renewable energy (wind generation) penetration results in similar pumping costs, yet each have comparatively different pumping GHG emissions to each other and to when the *estimated* 24-hour EF curve is used (Figure 4.8). However, these differences are consistent with the difference of the average EF values of each of the *modified* EF curves (scenarios S4.1, S4.2 and S4.3), as well as the estimated 24-hour EF curve (S3), suggesting they are not due to differences between the time-variations of EFs used for each scenario.

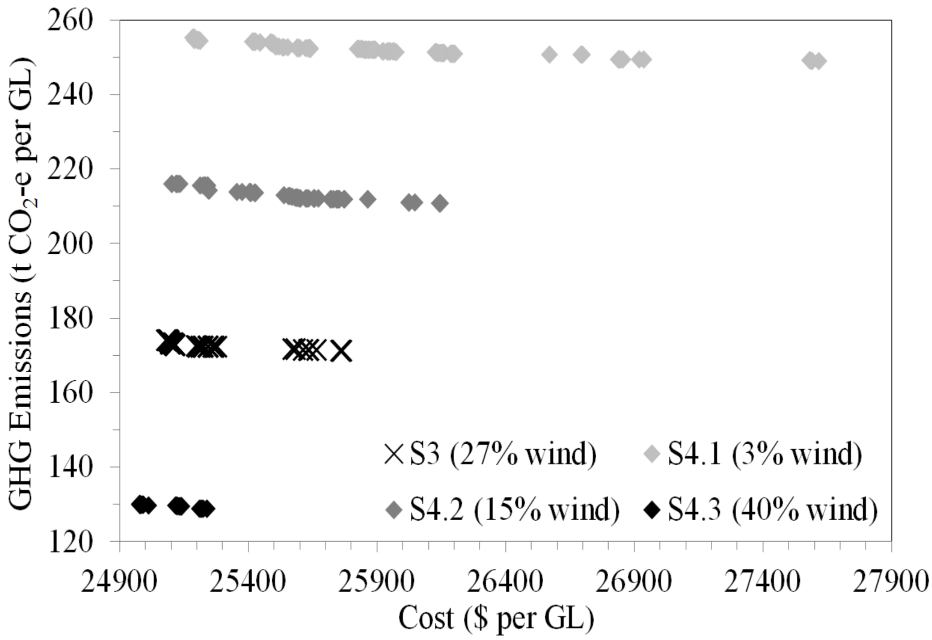


Figure 4.8. Costs and GHG emissions for the non-dominated solutions found using the three modified EF curves (S4.1, S4.2 and S4.3) and the estimated 24-hour EF curve (S3).

The optimal pump management choices for solutions found using the *modified* EF curves vary, depending on what percentage of wind penetration is considered and whether the minimization of pumping costs or pumping GHG emissions is prioritized. For solutions that prioritize the minimization of costs, pump schedules for all scenarios (S4.1, S4.2 and S4.3) concentrate most pumping to off-peak times of the day (e.g. see Figure 4.7a). This is similar to when solutions are found using the *estimated* 24-hour EF curve (S3). For solutions that prioritize the minimization of GHG emissions, the pump schedules for each scenario schedule the use of pumps differently, depending on what percentage of renewable energy (wind generation) penetration is considered. For S4.1 (3% wind), pumps are utilized more evenly throughout the length of each day, as there is little difference between the lowest and highest EF values (e.g. see Figure 4.7b). Hence, pumps are scheduled to reduce pipe frictional losses and hence reduce pump energy usage, rather than concentrating pumping during low EF times. For S4.2 and S4.3 (15% and 40% wind, respectively), pump schedules concentrate pump usage to the low EF times of the day (e.g. see Figure 4.7b). This is similar to the way GHG emissions are minimized for solutions using the *estimated* 24-hour EF curve (S3). These results suggest that the difference in pump utilization between low and high EF times becomes more pronounced as the difference between the lowest and highest EF values increases.

4.4.4 Discussion of Real-World Implications

The results suggest that use of *actual* EFs, rather than *average* EFs, allows pumping GHG emissions to be reduced by considering the *time-dependency* of EFs, rather than by simply reducing electrical energy usage. This is achieved by pumping during the low EF times of the day, in the same way that pump schedules are developed to reduce costs when peak/off-peak electricity tariffs are considered. In contrast, when constant EFs are used, pump schedules are developed to pump more evenly throughout the length of each day.

The results suggest that the *estimated* 24-hour EF curve is able to capture the most important dynamics of the *actual* EFs, as the characteristics of the optimal solutions obtained using the *actual* EF data and the *estimated* 24-hour EF curve are the same, in that pump usage is moved to low EF/electricity tariff times. While this result cannot be generalized to all real-world environments, it is likely that when *time-varying* EFs behave in a similar manner to those used for the presented study (i.e. EFs vary with repeating diurnal fluctuations), an *estimated*

24-hour EF curve, which only represents the average diurnal variations in *time-varying* EFs, provides enough information to develop solutions that consider the actual *time-dependency* of emissions intensity, which cannot be considered when using the *average* EF.

The results of the scenarios with different degrees of wind penetration indicate that as larger amounts of renewable energy (wind generation) penetration are considered (e.g. near or above 15%), GHG emissions are minimized by concentrating pumping to low EF times of the day. Conversely, as smaller amounts of renewable energy (wind generation) penetration are considered (e.g. near or below 3%), GHG emissions are minimized by spreading pumping out more evenly throughout the length of each day in order to minimize pump energy usage, similar to when the *average* EF is used. This suggests that there is probably no need to change operational practices when the time variability of EFs is relatively low, but that there are benefits in changing operational practices once wind penetration of around 15% is achieved. However, this threshold value is likely to be case dependent.

While the results suggest that the *time-dependency* of EFs can have a significant effect on the development of pump schedules, it should be noted that these can also be affected by the hydraulic characteristics of a WDS. For example, a WDS with a steeply rising system curve (e.g. where a small increase in pipe water velocity results in a large increase in frictional energy loss) may be better suited to reducing GHG emissions by reducing pump flows and hence energy losses, rather than pumping during low EF times, even when time-varying EFs are considered.

As discussed previously, the varying contributions of different electricity generation sources with different emissions intensities control the rise and fall of EFs. In a system where base load electricity generators are more emissions intensive than those used to help meet peak demand requirements (e.g. fossil fuel derived base load with renewable energy electricity generation used only during peak demand times), emissions factors are likely to reduce when electricity tariffs increase (as peak tariff values are generally used to help reduce peak electrical energy demands), leading to a situation where considering the *time-dependency* of EFs can lead to solutions that prioritize the minimization of either costs or GHG emissions, utilizing significantly different pump schedules.

4.5 Conclusions

The results obtained in this study indicate that the development of solutions of minimized costs and GHG emissions can be significantly affected by the consideration of *time-varying* EFs (refer to Objective 1). In addition, the important aspects of the *time-dependency* of *actual* EFs can be considered by using an *estimated* 24-hour EF curve that represents the average diurnal fluctuations in EFs, without the associated problems of using the *actual* EFs (refer to Objective 2). However, the amount of renewable energy penetration can affect the magnitude of the time-variations of EFs and hence the development of solutions (refer to Objective 3). Therefore, when renewable energy (wind generation) penetration is high (e.g. near or above 15%), it is recommended that an *estimated* 24-hour EF curve be used when optimizing the operation of water distribution systems for the reduction of GHG emissions, especially when the sources of electricity that are used are known to vary in emissions intensity, and that these variations are well documented.

4.6 Acknowledgements

This research was supported by resources supplied by eResearch SA. Electricity generation data were provided by the Australian Energy Market Operator (AEMO). Funding for this research was provided by the University of Adelaide and the Goyder Institute for Water Research. The authors would like to thank Stephen Carr for his help with modifying and debugging the optimization algorithm used for this study. The authors would also like to thank the three anonymous reviewers, whose comments helped to improve the quality of this paper.

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Chapter 5

Effect of Storage Tank Size on the Minimization of Water Distribution System Cost and Greenhouse Gas Emissions while Considering Time-Dependent Emissions Factors

Statement of Authorship

Title of Paper	Effect of storage tank size on the minimization of water distribution system cost and greenhouse gas emissions while considering time-dependent emissions factors
Publication Status	Publication style (not yet submitted for publication)
Publication Details	Stokes, C. S., H. R. Maier, and A. R. Simpson (2014b), Effect of storage tank size on the minimization of water distribution system cost and greenhouse gas emissions while considering time-dependent emissions factors, not submitted.

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author (Candidate)	Christopher S. Stokes		
Contribution to the Paper	Undertook numerical evaluation and wrote manuscript		
Signature		Date	7/7/'14

Name of Co-Author	Holger R. Maier		
Contribution to the Paper	Supervised manuscript preparation and reviewed draft		
Signature		Date	29/05/2014

Name of Co-Author	Angus R. Simpson		
Contribution to the Paper	Supervised manuscript preparation and reviewed draft		
Signature		Date	8/7/14

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.

5.1 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.*, 2014c]. This can be achieved both directly [*Wu et al.*, 2010a; *Wu et al.*, 2010b; *MacLeod and Filion*, 2011; *Kang and Lansey*, 2012; *Roshani et al.*, 2012; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Basupi et al.*, 2013; *Du et al.*, 2013; *Wu et al.*, 2013; *Basupi et al.*, 2014; *Marchi et al.*, 2014] and indirectly by considering GHG emissions as part of a wider array of environmental objectives [*Herstein et al.*, 2009b; *Herstein and Filion*, 2011; *Herstein et al.*, 2011].

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 [*Dandy et al.*, 2006; *Herstein et al.*, 2009b; *Wu et al.*, 2010a; *Wu et al.*, 2010b; *Herstein and Filion*, 2011; *Herstein et al.*, 2011; *MacLeod and Filion*, 2011; *Kang and Lansey*, 2012; *Roshani et al.*, 2012; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Basupi et al.*, 2013; *Du et al.*, 2013; *Wu et al.*, 2013; *Basupi et al.*, 2014; *Marchi et al.*, 2014]. 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.*, 2009b; *Wu et al.*, 2010a; *Wu et al.*, 2010b; *Herstein et al.*, 2011; *Roshani et al.*, 2012; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Wu et al.*, 2013].

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 [*Walski*, 2000; *Batchabani and Fuamba*, 2012]. 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, energy usage, and therefore GHG emissions, can be reduced by pumping more consistently throughout the day, as a result of reduced frictional energy losses. This can reduce the need for larger storage sizes, 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 [*Lansey and Mays*, 1989; *Walters et al.*, 1999; *Farmani et al.*, 2005; *Vamvakeridou-Lyroudia et al.*, 2005; *Farmani et al.*, 2006; *Vamvakeridou-Lyroudia et al.*, 2007; *Ostfeld and Tubaltzev*, 2008; *Devi Prasad*, 2010; *Wu et al.*, 2010b; *Batchabani and Fuamba*, 2012], less consideration has been given to this issue when considering the minimization of GHG emissions [*Wu et al.*, 2010b; *Herstein and Filion*, 2011; *Herstein et al.*, 2011; *Basupi et al.*, 2013; *Basupi et al.*, 2014; *Marchi et al.*, 2014]. Additionally, little consideration has been given to the GHG emissions directly associated with storage tanks [*Herstein and Filion*, 2011; *Herstein et al.*, 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.*, 2014c; *Stokes et al.*, 2014a]. 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.*, 2014c], 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 objectives of this study are:

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.
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.

5.2 Case Studies

The first case study uses a two pump, single storage tank WDS (Figure 5.1) 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 5.1, 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 5.1, 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 [*Salomons et al.*, 2012; *Marchi et al.*, 2014] (Figure 5.2) 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 5.2, 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 with only the operational management of the system, the original D-Town WDS has been altered to accommodate the increased water demands of the upgrade problem. 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.

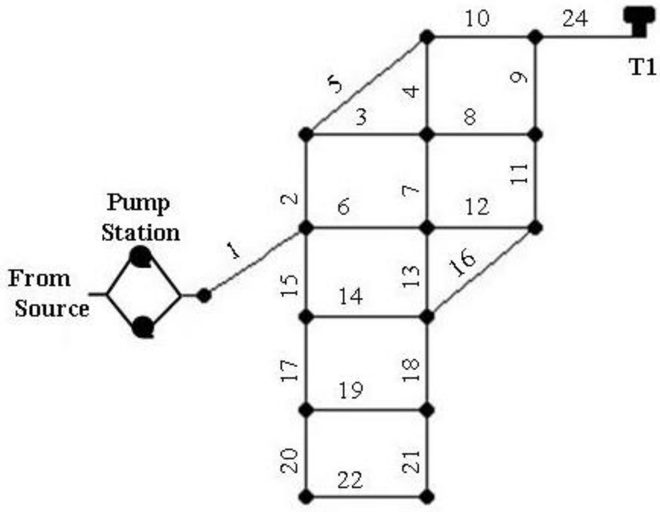


Figure 5.1. The two pump, one tank WDS used for the first case study, with pipe identification numbers shown.

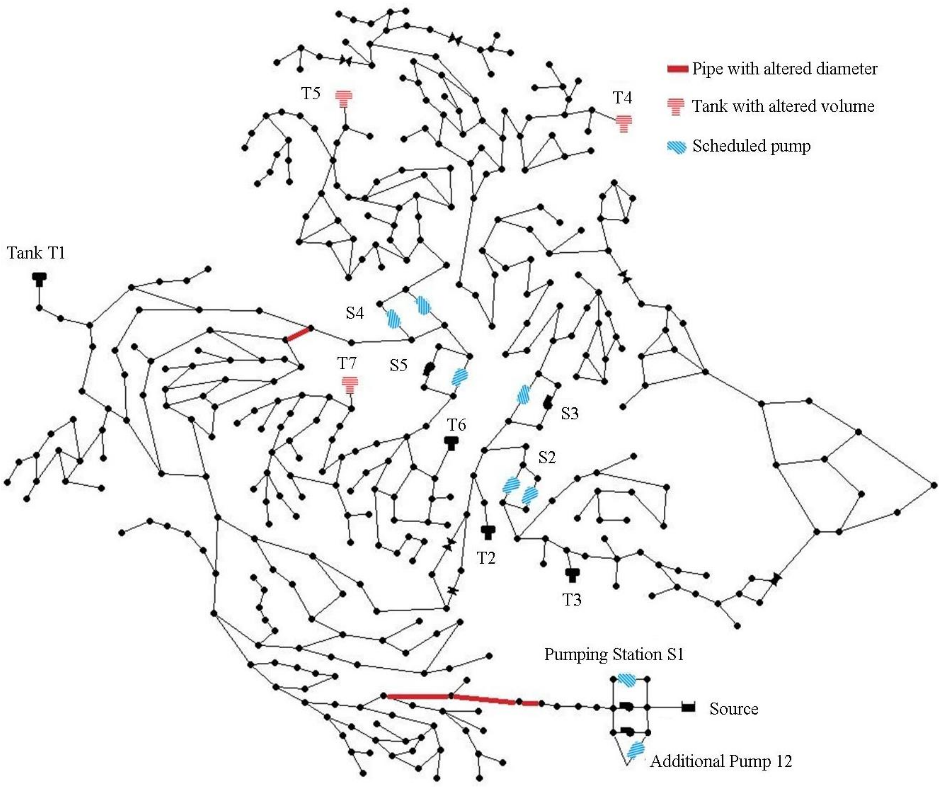


Figure 5.2. The D-town WDS, modified from the original Battle of the Water Networks II system, as used for the second case study.

5.3 Methodology

The methodology used to meet the objectives outlined in the Introduction is outlined in Figure 5.3 and is based on the Water distribution system Cost-Emissions Nexus (WCEN) conceptual framework introduced by Stokes et al. [*Stokes et al.*, 2012; 2014c]. 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 (objective 1) and time-varying emissions factors (objective 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 5.3). In relation to objective 1, different storage tank balancing volumes are represented by four different tank reserve size (TRS) scenarios (TRS1-TRS4). In relation to objective 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 (SEF), 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.

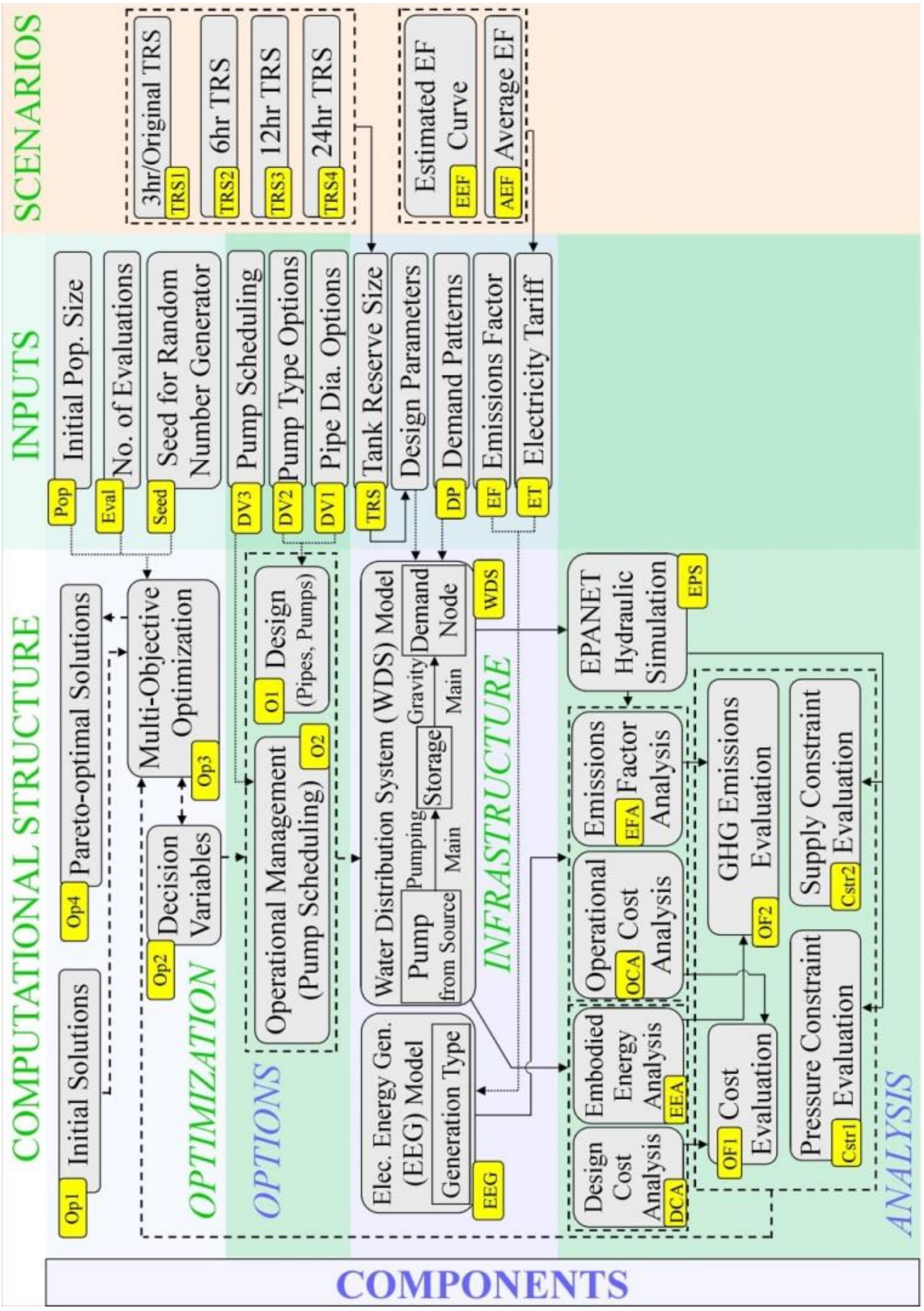


Figure 5.3. Outline of the methodology used for the multi-objective optimization of the case study WDSs for the minimization of costs and GHG emissions.

5.3.1 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 (n.b. this algorithm was not previously available for use with other research conducted for this thesis). 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 5.3). Initial testing showed this maximum evaluation limit to allow for solution convergence. As recommended by Hadka and Reed [2013], initial and minimum population sizes of 100 solutions are used (Pop, Figure 5.3). As the seed (Seed, Figure 5.3), 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 *design* costs and GHG emissions. As part of this case study, 23 discrete decision variables are considered, including 22 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 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, 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 is optimized, with the remaining 4 pumps running continuously, as discussed previously.

5.3.2 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 5.3), is performed. 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 5.3) and emissions factor analysis (EFA, Figure 5.3) respectively, and (ii) design, using design cost analysis (DCA, Figure 5.3) and embodied energy analysis (EEA, Figure 5.3), respectively.

Hydraulic simulation (EPS, Figure 5.3) is also used to calculate any violation of constraints (Cstr1 and Cstr2, Figure 5.3). A solution is deemed feasible if:

1. The zero and non-zero demand node pressures are maintained above 0m and 20m, respectively, during the EPS period (Cstr1, Figure 5.3). 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 5.3).

5.3.2.1 Calculation of Economic Costs

For the first case study, where design optimization is performed, design costs are associated with the cost of pipes, pumps and storage tank used to construct the WDS. For the second case study, where operational optimization only is considered, the design costs associated with increasing the storage tanks are considered are the sole design 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 5.1 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 ET (Figure 5.3) 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).

5.3.2.2 Calculation of GHG Emissions

For the first case study, design 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, only the design GHG emissions associated with increasing the storage tanks are considered. In order to calculate design GHG emissions, embodied energy analysis is used (EEA, Figure 5.3). 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 February 2012 to January 2011 (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.

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, an EF of 0.16 kg CO_2-e/MJ is used to calculate TRS GHG emissions. Refer to Table 5.1 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 (Op5, Figure 5.3). In order to calculate operational GHG emissions, an emissions factor (t CO_2-e/MWh) (Op4, Figure 5.3) 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 [*Wu et al.*, 2010a; *Wu et al.*, 2010b; *Roshani et al.*, 2012; *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]. Based on values used in previous studies [*Wu et al.*, 2010a; *Wu et al.*, 2010b; *Wu et al.*, 2012a; *Wu et al.*, 2012b; *Wu et al.*, 2013], a project life of 100 years is used for calculating both electricity costs and GHG emissions and pump replacement costs.

5.3.3 Emissions Factor Cases

As stated previously, two emissions factor (EF) cases, using an estimated 24-hour EF curve (EEF, Figure 5.3) and an average EF (AEF, Figure 5.3), 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 5.4) 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*, 2013b]. 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%). 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.

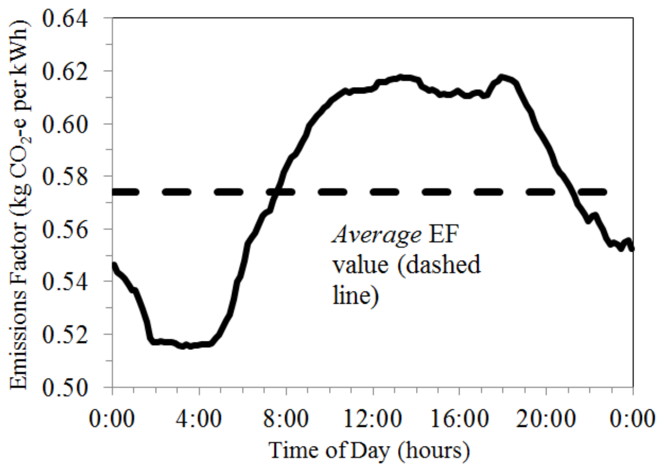


Figure 5.4. Estimated 24-hour EF curve [taken from Stokes et al. [2014a]] used to calculate operational GHG emissions associated with the use of electricity (solid line). The average EF value is shown for comparison (dashed line).

5.3.4 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 5.1. 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.

Table 5.1. Tank reserve size volumes and associated costs and GHG emissions for each tank reserve size scenario used for case study 1. Tank volumes do not include emergency or fire storage.

Case Study 1			
TRS^ Scenario	Tank Volume (m^3)	Estimated Cost ($M)	Estimated Emissions (kt CO_2-e)
3 hour	*754*	*0.93*	*0.02*
6 hour	*1496*	*1.02*	*0.04*
12 hour	*3017*	*1.20*	*0.07*
24 hour	*6026*	*1.55*	*0.12*

^Tank Reserve Size

Table 5.2. Tank reserve size volumes and associated costs and GHG emissions for each tank reserve size scenario used for case study 2. Tank volumes do not include emergency or fire storage.

Case Study 2			
TRS^ Scenario	Vol. of Tank(s) (m^3)	Estimated Cost ($M)	Estimated Emissions (kt CO_2-e)
Original*	*9500*	*1.96*	*0.29*
6 hour	*11083*	*2.15*	*0.34*
12 hour	*14017*	*2.50*	*0.43*
24 hour	*24560*	*3.74*	*0.69*

^Tank Reserve Size

*Based on tank sizes of the original D-town WDS for the Battle of the Water Networks II

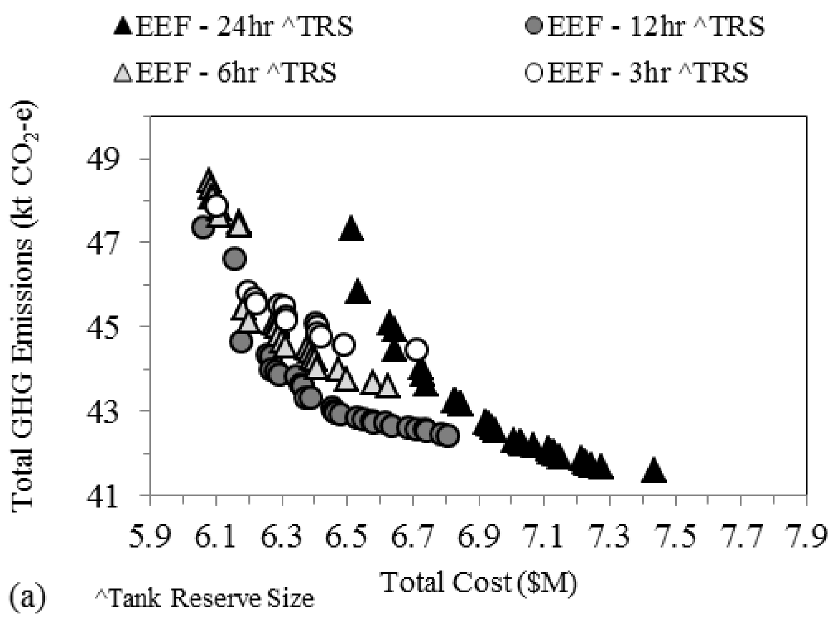
5.4 Results and Discussion

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

5.4.1.1 Minimization of Costs and GHG emissions

The results for the 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 5.5a). 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 5.6a). 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 5.6a).



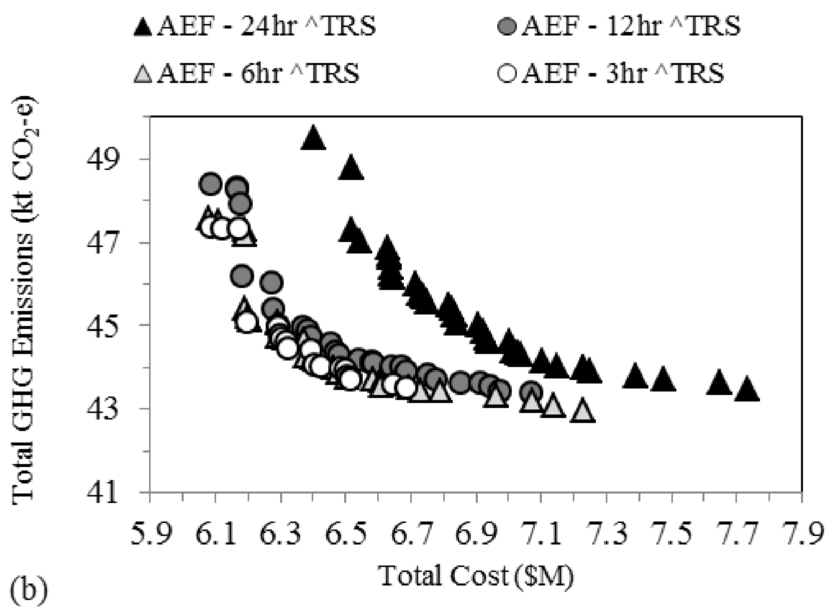
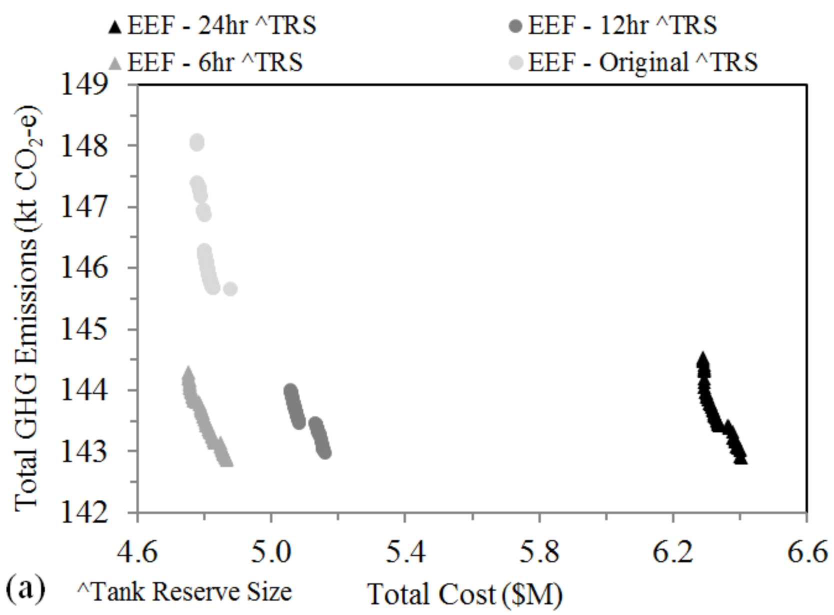


Figure 5.5. Case study 1 non-dominated solutions for each TRS scenario using (a) the estimated 24-hour EF curve and (b) the average EF to evaluate pumping operational GHG emissions.



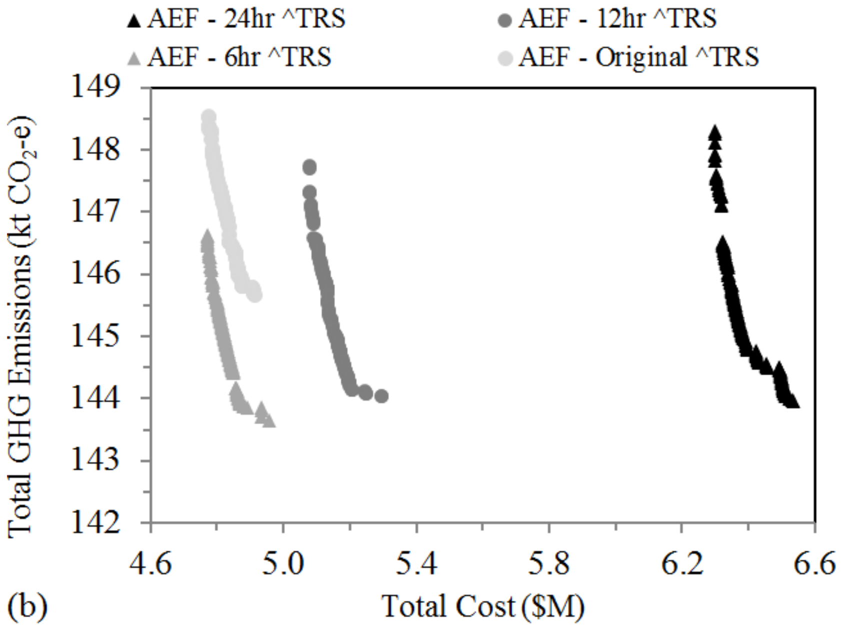


Figure 5.6. Case study 2 non-dominated solutions for each TRS scenario using (a) the estimated 24-hour EF curve and (b) the average EF to evaluate pumping operational GHG emissions.

5.4.1.2 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 5.7a and 5.8a) and GHG emissions minimization (Figures 5.7c and 5.8c) are prioritized.. Conversely, when using the 3 hour TRS (case study 1, Figures 5.7a and 5.7c) or original TRS (case study 2, Figures 5.8a and 5.8c), 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 design 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 design 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.

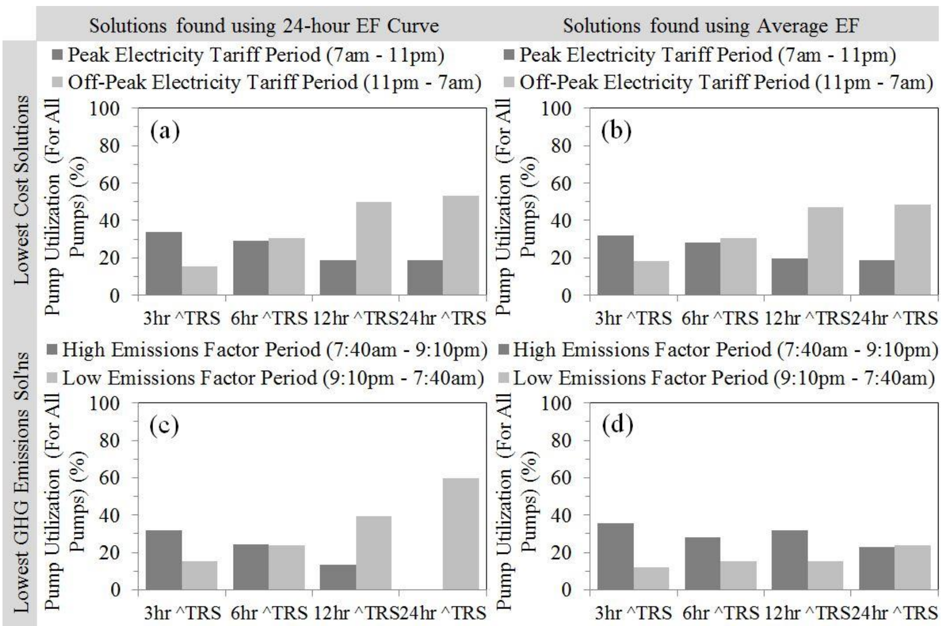


Figure 5.7 Pump utilization for lowest cost solutions (a, b) and lowest GHG emissions solutions (c, d) for the first case study, found while using the estimated 24-hour EF curve (a, c) and the average EF (b, d).

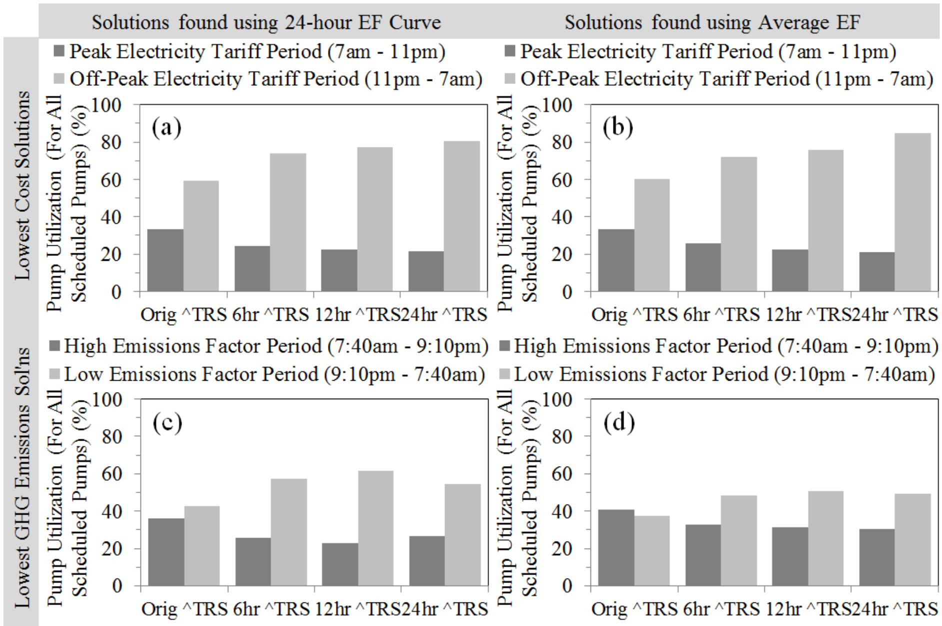


Figure 5.8 Pump utilization for lowest cost solutions (a, b) and lowest GHG emissions solutions (c, d) for the second case study, found while using the estimated 24-hour EF curve (a, c) and the average EF (b, d).

5.4.1.3 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 design 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 design 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.

5.4.2 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 5.5b). 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 5.6b). 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 5.7b and 5.7d for case study 1 and Figures 5.8b and 5.8d 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 5.7d for case study 1 and Figure 5.8d 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.

5.4.3 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 design GHG emissions associated with the larger TRS itself. Additionally, using a larger TRS significantly increases design 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. 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.

5.5 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 Objective 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 Objective 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.

5.6 Acknowledgements

This research was supported by resources supplied by eResearch SA. Electricity generation data was provided by the Australian Energy Market Operator (AEMO). Funding for this research was provided by the University of Adelaide and the Goyder Institute for Water Research.

Chapter 6

6.1 Thesis Summary and Conclusions

The multi-objective optimization of WDSs for the minimization of costs and GHG emissions is critical to understanding how the mitigation of climate change effects can be achieved and what trade-offs occur between this and the economics of constructing and operating WDSs. Within the literature, predominant consideration has been given to the minimization of costs and GHG emissions by optimizing the design of a WDS. However, less consideration has been given to the optimization of pumping operations and the processes required to accurately evaluate these while considering the range of operational conditions encountered over the life of a WDS. In order to address the knowledge gaps within the current literature, key research requirements are identified. Based on these research requirements, the objectives of this research are formed. These objectives centre on investigating and practically implementing the nexus of elements required to accurately evaluate the design and pumping operations of WDSs into a framework that can be used to minimize costs and GHG emissions.

In order to achieve the objectives of this research, two frameworks are developed. Firstly, a conceptual framework is developed to investigate the nexus of elements required to accurately evaluate the design and pumping operations of WDS for the minimization of costs and GHG emissions. Secondly, a computational software framework is developed to implement these as part of a practical optimization tool. Additionally, methods for calculating time-dependent emissions factors and an estimated 24-hour emissions factor curve, akin to a diurnal water demand curve, are developed. Through this research, it is shown that by using the developed computational software framework while considering the time-dependency of emissions factors associated with the use of electricity for pumping purposes, design and pumping operational management solutions can be explored for a range of operational conditions likely to be encountered during the operational life of a WDS. As such, it is hoped that this research will help to make GHG emissions minimization in addition to cost minimization more desirable and more easily implemented into the design and operation of WDSs in the real world.

6.2 Research Contributions

The overall contribution of this research is to highlight the need to consider the accurate evaluation of both costs and GHG emissions, especially those associated with pumping operations, and provide a practical method by which these considerations can be implemented. From the research presented in **Chapters 2 to 5** of this thesis, the following key contributions are made:

1. The first contribution of this research is the development of the water distribution cost-emissions nexus (WCEN) conceptual and computational software frameworks. The WCEN conceptual framework is developed to identify and show the interactions between the various modelling elements that have an impact on WDS design and pumping operational costs and GHG emissions evaluation and optimization, including those from energy generating infrastructure, in an integrated fashion. Following from this, the WCEN conceptual framework is used to identify the knowledge gaps with respect to the simplification of the

modelling processes and future research required to address these gaps (**Objective 1**). The WCEN computational software framework is then developed in order to practically apply the considerations made within the WCEN conceptual framework to the computational simulation and optimization of WDSs for the minimization of costs and GHG emissions (**Objective 2**). The ability to optimize the design and pumping operational management of WDSs while considering short- and long-term time-variability of pumping operations is demonstrated using a hypothetical case study WDS, including the consideration of time-dependent emissions factors, water demands and electricity tariffs for South Australia (**Sub-objective 2.1**). While the WCEN computational software framework is demonstrated for this particular case study, the generic nature of the framework means that it could easily be applied to other water distribution systems around the world.

2. The second contribution of this research is the development of a method for calculating the actual time-variations of emissions factors for electricity supplied from multiple generation sources with different individual emissions intensities (**Objective 3**). By using periodic electricity generation data with a small time-step (e.g. a 5 minute time-step) from generating sources with known emissions intensities, actual time-varying emissions factors associated with electricity used for pumping purposes can be calculated. While the time-varying emissions factors used for this research are developed from electricity generation data for South Australian electrical energy generation sources, the general nature of this method means it can be applied to other regions of the world. Following from this, the effect of using actual time-varying emissions factors is compared to using the traditionally considered average emissions factor value. This research shows that the choice of whether to use actual emissions factors or an

average emissions factor can significantly affect the selection of optimal pumping operational management strategies (**Sub-objective 3.1**).

3. The third contribution of this research is the development of a method for modelling the important time-varying aspects of actual emissions factors associated with electricity used for pumping purposes. The resulting estimated 24-hour emissions factor curve represents the average diurnal variations of emissions intensity, enabling time-varying emissions factor data to be considered in situations where the use of actual emissions factor data is not feasible. Following from this, the effect of using the estimated 24-hour emissions factor curve is compared to using actual emissions factors. This research shows that solutions found using either the estimated 24-hour emissions factor curve or actual emissions factors are developed for the same fundamental reasons, suggesting that when the use of actual emissions factor data is not feasible, an estimated 24-hour emissions factor curve can be used to replicate the important time-dependent aspects of actual emissions factors (**Sub-objective 3.2**).

4. The fourth contribution of this research is the comparison of time-dependent emissions factors representing electricity generated with different amounts of wind generation. Wind generation is an intermittent source of generation that can cause time-dependent variations to the emissions intensity of electricity. The magnitude of these variations can be affected by the amount of wind generation supplying electricity to a grid. This research shows that when significant amounts of wind generation (near of above 15%) are present in an electricity grid supplying electricity for pumping purposes, it is important to consider the time-dependency of emissions factors. Conversely,

this research shows that when electricity is supplied without significant wind generation (near or below 3%) and the emissions intensity of the combination of other generation sources is not time-dependent, then accurate evaluation of pumping operational GHG emissions can be achieved by using an average emissions factor (**Sub-objective 3.3**). While these findings are likely to be case study dependent, this research shows that a certain threshold of the magnitude of wind generation can exist and where it becomes necessary to consider the time-variations of emissions intensity.

5. The fifth contribution of this research is the comparison of using different storage tank balancing volumes and their subsequent effect on the minimization of costs and GHG emissions (**Objective 4**). This research shows that the storage tank balancing volume can affect both the optimal design and pumping operational management strategies. Additionally, this research shows that by selecting a larger storage tank, it may be possible to further minimize GHG emissions associated with either a new or existing WDS, compared to when a smaller storage tank is considered (**Sub-objective 4.1**). However, this research also shows that these finding are affected by the choice to use either time-dependent emissions factors or an average emissions factor value (**Sub-objective 4.2**).

6.3 Publications

List of works contained within this thesis:

Paper 1 presented in Chapter 2: Stokes, C. S., A. R. Simpson, and H. R. Maier (2014d), *The cost-greenhouse gas emission nexus for water distribution systems including the consideration of energy generating infrastructure: An integrated optimization framework and review of literature*, Earth Perspectives, 1(1), 1-17.

Paper 2 presented in Chapter 3: Stokes, C. S., A. R. Simpson, and H. R. Maier (2014c), *A computational software tool for the minimization of costs and greenhouse gas emissions associated with water distribution systems*, Environmental Modelling & Software (submitted).

Paper 3 presented in Chapter 4: Stokes, C. S., H. R. Maier, and A. R. Simpson (2014a), *Water distribution system pumping operational greenhouse gas emissions reduction by considering time-dependent emissions factors*, Journal of Water Resources Planning and Management (accepted for publication).

Paper 4 presented in Chapter 5: Stokes, C. S., H. R. Maier, and A. R. Simpson (2014b), *Effect of storage tank size on the minimization of water distribution system cost and greenhouse gas emissions while considering time-dependent emissions factors*, Yet to be submitted.

List of works resulting from research associated with thesis but not contained within:

Stokes, C. S., H. R. Maier, and A. R. Simpson (2012a), *Water distribution system greenhouse gas emissions reduction by considering the use of time-dependent emissions factors*, in 14th

Water Distribution Systems Analysis Conference, Engineers Australia, Adelaide, Australia.

Stokes, C. S., A. R. Simpson, and H. R. Maier (2012b), *An improved framework for the modelling and optimization of greenhouse gas emissions associated with water distribution systems*, in 6th International Congress on Environmental Modelling and Software (iEMSs), Leipzig, Germany.

6.4 Research Limitations

The limitations of this research discussed below:

1. A fundamental limitation of this research is the use of time and region specific data, in particular emissions factor data, in order to demonstrate general characteristics associated with the issues covered in this research. An important example of this is the use of time-dependent emissions factors developed from electricity generation data from South Australia. The resulting outcomes from using this data demonstrate the importance of considering time-dependent emissions factors. However, as the time-variations of these emissions factors are specific to this region and time, they can only demonstrate what will occur when considering a similar mix of generation types. Similar examples can be found with the use of time-dependent water demand and electricity tariff data. Therefore, this research demonstrates why it is important to consider such issues by showing what can occur under certain circumstances. However, it does not show what will occur under every circumstance.
2. The use of case study WDSs can affect the research outcomes. For example, while pumping through a WDS with a relatively flat system curve (i.e. only small increases in frictional energy losses when increasing water flow through

the system) may result in minimal GHG emissions when restricting pumping to low emissions factor times, a similar outcome may not been seen when pumping through a WDS with a very steep system curve. Therefore, the specific results shown in this research can be case study WDS dependent.

3. A limitation of the WCEN computational framework is the time taken to run the optimization algorithm for a sufficient number of evaluations to achieve solution convergence when considering larger WDSs and/or using multiple pumping operational simulations. For example, as shown in Table 1.1 in Section 1.3, the larger D-town case study WDS considered in Chapter 5 requires significantly longer computational time to perform optimization than when the smaller case study WDS is considered. Additionally, when using a 365 day EPS in Chapter 4 or simulating multiple operational scenarios in Chapter 3, significantly longer computational time was required compared to using a single, shorter (e.g. 7 day or 48 hour long) EPS.
4. Another limitation of the WCEN computational framework is the ability to converge on optimal solutions when considering multiple pumping operational schedules for multiple operational conditions. As this requires a larger number of decision variables (i.e. for each pump schedule for each operational condition) than when considering only one pump schedule for a single operational condition, the number of evaluations before solution convergence is achieved can be significantly larger (i.e. due to the larger solution space). In addition to the longer computational time required to simulate the multiple operational conditions (discussed above), this can significantly extend the amount of computational time required to perform optimization to the point where it can be infeasible to consider all operational conditions during a single optimization run. For example, the

multiple operational conditions considered in Chapter 3 were required to be optimized separately, as testing showed that solution convergence was not possible within a feasible length of computational time.

5. Finally, a further limitation of the methodology used in this research is the consideration of only costs and GHG emissions. Other objectives, such as system robustness/reliability and water quality are important and should also be considered when optimizing a real world WDS. While considering only costs and GHG emissions is useful when investigating the trade-offs that occur when minimizing these objectives, application to WDSs in the real world will require the consideration of these other important objectives. With modern multi-objective optimization algorithms, such as AMALGIM and Borg [*Vrugt and Robinson*, 2007; *Hadka and Reed*, 2013], optimization while considering many objectives is possible. While this issue has been raised within recent literature [*Kang and Lansey*, 2012; *Wu et al.*, 2013; *Marchi et al.*, 2014], the trade-offs between costs, GHG emissions and these other objectives, and the implications these may have on the design and pumping operation of WDSs remains largely unknown.

6.5 Recommendations for Future Research

1. As discussed in *research limitations 1 and 2*, the outcomes from this research are data and case study WDS dependent. While this research has demonstrated the need to consider specific issues, such as the time-dependency of emissions factors, the results do not show what will occur for all situations. As such, future research should focus on demonstrating the outcomes of this research when it is applied to different data (e.g. emissions factor data from different regions) and different case study WDSs. By doing this, more generalized characteristics will be available to guide WDS developers and operators as to what specific circumstances require what approach in terms of modelling and evaluating costs and GHG emissions.
2. As discussed in *research limitations 3 and 4*, a limiting factor for using the WCEN computational framework is the computational time required for solution convergence when large case study WDSs and/or multiple operational simulations including multiple pumping operational schedules are considered. While it is likely that improving this will in part rely on the improved performance of optimization algorithms, future research should also focus on improving the way in which the simulation of large WDSs and multiple pumping operational scenarios are implemented. Additionally, while this research was conducted using single thread computing, implementing parallel computing could also help to improve computational times, such as using multiple threads to simulate multiple operational conditions in unison.
3. As discussed in *research limitation 5*, there remains a need to consider the trade-offs that can occur between costs, GHG emissions and other objectives, such as the improvement of

system reliability/robustness and water quality. With the advent of multi-objective optimization algorithms, such as AMALGIM and Borg [*Vrugt and Robinson*, 2007; *Hadka and Reed*, 2013], that can optimize many objectives, the tools required to consider these trade-offs are available. If optimization tools such as the WCEN computational software framework are going to be applicable to WDSs in the real world, they must allow for the consideration of the many objectives that are required to be considered when designing/operating a real-world WDS. Therefore, future research should focus on integrating other important objectives with the minimization of costs and GHG emissions.

References

Abadía Sánchez, R., C. Rocamora Osorio, A. Ruiz Canales, H. Puerto Molina, and A. Melián Navarro (2008), Energy efficiency in irrigation: calculation approach in water distribution system, paper presented at Agricultural and Biosystems Engineering for a Sustainable World. International Conference on Agricultural Engineering, European Society of Agricultural Engineers (AgEng), Hersonissos, Crete, Greece, 23-25 June.

Alandi, P. P., P. C. Pérez, J. F. O. Álvarez, M. Á. M. Hidalgo, and J. M. T. Martín-Benito (2005), Pumping selection and regulation for water-distribution networks, *Journal of Irrigation and Drainage Engineering*, *131*(3), 273-281, DOI: 10.1061/(ASCE)0733-9437(2005)131:3(273)

Alperovits, E., and U. Shamir (1977), Design of optimal water distribution systems, *Water Resources Research, 13*(6), 885-900,

Ambrose, M. D., G. D. Salomonsson, and S. Burn (2002), Piping systems embodied energy analysis, *Rep. CMIT Doc. 02/302*, CSIRO Manufacturing and Infrastructure Technology, Highett, Australia.

American Wind Energy Association (2013), U.S wind industry annual market report, *Rep.*, Washington DC, United States of America.

Asea Brown Boveri Ltd (2013), Denmark energy efficiency report, *Rep.*, Switzerland.

Australian Energy Market Operator (2011), South Australian supply and demand outlook, *Rep.*, Melbourne, Australia.

Australian Energy Market Operator (2013a), South Australia wind study report, *Rep.*, Melbourne, Australia.

Australian Energy Market Operator (2013b), Electricity NEM data, edited, Melbourne, Australia.

Australian Energy Regulator (2012), State of the energy market 2012, *Rep.*, Melbourne, Victoria.

Barán, B., Christian von Lücken, and Aldo Sotelo (2005), Multi-objective pump scheduling optimisation using evolutionary strategies, *Advances in Engineering Software*, *36*(1), 39-47,

Basupi, I., Z. Kapelan, and D. Butler (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., Z. Kapelan, and D. Butler (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 M. Fuamba (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.

Bennett, N. D., et al. (2013), Characterising performance of environmental models, *Environmental Modelling and Software*, *40*, 1-20, DOI: 10.1016/j.envsoft.2012.09.011.

Beven, K., and A. Binley (1992), The future of distributed models: model calibration and uncertainty prediction, *Hydrological Processes*, *6*(3), 279-298, Biehl, W. H., and J. A. Inman (2010), Energy optimization for water systems, *Journal of the American Water Works Association*, *102*(6), 50-55,

Bogdos, N., and E. S. Manolakos (2013), A tool for simulation and geo-animation of wildfires with fuel editing and hotspot monitoring capabilities, *Environmental Modelling & Software*, *46*(0), 182-195, http://dx.doi.org/10.1016/j.envsoft.2013.03.009.

Boulos, P. F., and C. M. Bros (2010), Assessing the carbon footprint of water supply and distribution systems, *Journal of the American Water Works Association*, *102*(11), 47-54,

Bunn, S, and C Hillebrand (2008), Operating pumps to maximize efficiency and to minimize your carbon footprint or save money, save the planet, in *American Water Works Association Annual Conference and Exposition*, edited, pp. 448-520, Atlanta, GA.

Cabrera, E., M. A. Pardo, R. Cobacho, and E. Cabrera Jr (2010), Energy audit of water networks, *Journal of Water Resources Planning and Management*, *136*(6), 669-677, DOI: 10.1061/(ASCE)WR.1943-5452.0000077

Castelletti, A., S. Galelli, M. Ratto, R. Soncini-Sessa, and P. C. Young (2012), A general framework for dynamic emulation modelling in environmental problems, *Environmental Modelling and Software*, *34*, 5-18, DOI: 10.1016/j.envsoft.2012.01.002.

Cutler, N. J., N. D. Boerema, I. F. MacGill, and H. R. Outhred (2011), High penetration wind generation impacts on spot prices in the Australian national electricity market, *Energy Policy*, *39*, 5939-5949, Dandy, G. C., A. R. Simpson, and L. J. Murphy (1996), An improved genetic algorithm for pipe network optimization, *Water Resources Research*, *32*(2), 449-458,

Dandy, G. C., and M. O. Engelhardt (2006), Multi-Objective Trade-Offs between Cost and Reliability in the Replacement of Water Mains, *Journal of Water Resources Planning and Management*, *132*(2), 79-88,

Dandy, G. C., A. Roberts, C. Hewitson, and P. Chrystie (2006), Sustainability objectives for the optimization of water distribution networks, paper presented at Proceedings of 8th Annual Water Distribution Systems Analysis Symposium, ASCE, Cincinnati, United States of America, August.

Dandy, G. C., A. Bogdanowicz, J. Craven, A. Maywald, and P. Liu (2008), Optimizing the sustainability of water distribution systems, paper presented at 10th Annual Symposium on Water Distribution Systems Analysis, American Society of Civil Engineers, Kruger National Park, South Africa, 17-20 August.

Deb, K., S. Agrawal, A. Pratap, and T. Meyarivan (2000), A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II, *Lecture notes in computer science*, *1917*, 849-858,

Deb, K., A. Pratap, S. Agarwal, and T. Meyarivan (2002), A fast and elitist multiobjective genetic algorithm: NSGA-II, *Evolutionary Computation, IEEE Transactions on*, *6*(2), 182-197,

Deb, K., M. Mohan, and S. Mishra (2003), Towards a quick computation of well-spread pareto-optimal solutions, paper presented at Evolutionary Multi-Criterion Optimization, Springer, Faro, Portugal.

Department of Climate Change and Energy Efficiency (2010), Australia's emissions projections 2010, *Rep.*, Canberra, Australia.

Department of Resources Energy and Tourism (2009), National energy policy - Framework 2030 strategic directions paper, *Rep.*, Australian Government, Canberra, Australia.

Devi Prasad, T., and N. S. Park (2004), Multiobjective genetic algorithms for design of water distribution networks, *Journal of Water Resources Planning and Management*, *130*(1), 73-82,

Devi Prasad, T. (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).

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

Ektesabi, M., A. H. Moradi-Motlagh, and A. H. Abdekhodaee (2009), Energy and sustainability through integrated water network management, *WIT Transactions on Ecology and the Environment*, *121*, 175-186,

eResearch South Australia (2014), High-performance computing services, edited, Adelaide, Australia.

Ertin, E., A. N. Dean, M. L. Moore, and K. L. Priddy (2001), Dynamic optimization for optimal control of water distribution systems., paper presented at Applications and Science of Computational Intelligence IV, Orlando, United States of America.

ETSA Utilities (2009), Notice of change to ETSA Utilities' distribution tariffs from 1 July 2009, *Rep.*, Adelaide, Australia.

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

Farmani, R., G. Walters, and D. Savic (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,

Filion, Y. R., H. L. MacLean, and B. W. Karney (2004), Life-cycle energy analysis of a water distribution system, *Journal of Infrastructure Systems*, *10*(3), 120-130, DOI: 10.1061/(ASCE)1076-0342(2004)10:3(119)

Filion, Y. R. (2007), Connections between population density, energy use, and GHG emissions in water networks, paper presented at CSCE 2007 Annual General Meeting and Conference, Yellowknife, United States of America, 6-9 June.

Filion, Y. R. (2008), Impact of urban form on energy use in water distribution systems, *Journal of Infrastructure Systems*, *14*(4), 337-346, DOI: 10.1061/(ASCE)1076-0342(2008)14:4(337)

Fu, G., Z. Kapelan, J. R. Kasprzyk, and P. Reed (2012), Optimal design of water distribution systems using many-objective visual analytics, *Journal of Water Resources Planning and Management*, *139*(6), 624-633,

Geoscience Australia, and Australian Bureau of Agriculture and Resource Economics (2010), Australian Energy Resource Assessment, *Rep.*, Canberra, Australia.

Ghimire, S. R., and B. D. Barkdoll (2008), Effect of demand on energy use in municipal water distribution systems, paper presented at World Environmental and Water Resources Congress, American Society of Civil Engineers, Honolulu, Hawai'i.

Ghimire, S. R., and B. D. Barkdoll (2009), Impact of storage tanks on energy consumption in municipal water distribution systems, paper presented at World Environmental and Water Resources Congress, American Society of Civil Engineers, Kansas City, Unites States of America.

Ghimire, S. R. (2010), Relationship between pump horsepower and energy usage in municipal water networks, paper presented at World Environmental and Water Resources Congress, American Society of Civil Engineers, Providence, United States of America.

Ghimire, S. R., and B. D. Barkdoll (2010), Sensitivity analysis of municipal drinking water distribution system energy use to system properties, *Urban Water Journal*, *7*(4), 217 - 232, DOI: 10.1080/1573062X.2010.484501.

Gibbs, M. S., G. C. Dandy, and H. R. Maier (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

Guzman, J. A., D. N. Moriasi, M. L. Chu, P. J. Starks, J. L. Steiner, and P. H. Gowda (2013), A tool for mapping and spatio-temporal analysis of hydrological data, *Environmental Modelling & Software*, *48*, 163-170,

Hadka, D., and P. Reed (2012), Diagnostic assessment of search controls and failure modes in many-objective evolutionary optimization, *Evolutionary Computation*, *20*(3), 423-452, DOI: 10.1162/EVCO_a_00053.

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

Halhal, D., G. A. Walters, D. Ouazar, and D. A. Savic (1997), Water network rehabilitation with structured messy genetic algorithm, *Journal of Water Resources Planning and Management*, *123*(3), 137-146,

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

Hernández, E., M. A. Pardo, E. Cabrera, and R. Cobacho (2010), Energy assessment of water networks, a case study, paper presented at Water Distribution System Analysis, American Society of Civil Engineers, Tuscon, Unites States of America.

Herstein, L. M., Y. R. Filion, and K. R. Hall (2009a), EIO-LCA based multi-objective design of water distribution systems with NSGA-II, paper presented at Computing and Control in the Water Industry 2009 'Integrating Water Systems', Taylor and Francis Group, London, United Kingdom, September 1-3.

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

Herstein, L. M., and Y. R. Filion (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., Y. R. Filion, and K. R. Hall (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,

Holguin-Gonzalez, J. E., G. Everaert, P. Boets, A. Galvis, and P. L. M. Goethals (2013), Development and application of an integrated ecological modelling framework to analyze the impact of wastewater discharges on the ecological water quality of rivers, *Environmental Modelling & Software*, *48*, 27-36,

Jakeman, A. J., R. A. Letcher, and J. P. Norton (2006), Ten iterative steps in development and evaluation of environmental models, *Environmental Modelling and Software*, *21*(5), 602-614,

Jayaram, N., and K. Srinivasan (2008), Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing, *Water Resources Research*, *44*(1), 1-15,

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

Kapelan, Z. S., D. A. Savic, and G. A. Walters (2005), Multiobjective design of water distribution systems under uncertainty, *Water Resources Research*, *41*(11), 1-15,

Kazantzis, M. D., A. R. Simpson, D. Kwong, and S. M. Tan (2002), A new methodology for optimizing the daily operations of a pumping plant, paper presented at Conference on Water Resources Planning and Management, American Society of Civil Engineers, Roanoke, United States of America.

Kelly, R. A., et al. (2013), Selecting among five common modelling approaches for integrated environmental assessment and management, *Environmental Modelling and Software*, *47*, 159-181, DOI: 10.1016/j.envsoft.2013.05.005.

Kollat, J. B., and P. M. Reed (2006), Comparing state-of-the-art evolutionary multi-objective algorithms for long-term groundwater monitoring design, *Advances in Water Resources*, *29*(6), 792-807,

Lansey, K. E., and L. W. Mays (1989), Optimization model for water distribution system design, *Journal of Hydraulic Engineering*, *115*(10), 1401-1418,

Lopez-Ibanez, M., T. Devi Prasad, and B. Paechter (2008), Ant colony optimization for optimal control of pumps in water distribution networks, *Journal of Water Resources Planning and Management*, *134*(4), 337-346,

Lundie, S., G. M. Peters, and P. C. Beavis (2004), Life cycle assessment for sustainable metropolitan water systems planning, *Environmental Science and Technology*, *38*(13), 3465-3473, DOI: 10.1021/es034206m.

Mackle, G., D. A. Savic, and G. A. Walters (1995), Application of genetic algorithms to pump scheduling for water supply, paper presented at Genetic Algorithms in Engineering Systems: Innovations and Applications, 1995., IET, Sheffield, United Kingdom.

MacLeod, S., E. Roshani, and Y. R. Filion (2010), Impact of pipe material selection on greenhouse gas mitigation in water networks under uncertain discount rates and carbon prices, paper presented at Water Distribution System Analysis, American Society of Civil Engineers, Tuscon, United States of America.

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

Maier, H. R., et al. (2014), Evolutionary algorithms and other metaheuristics in water resources: current status, research challenges and future directions, *Environmental Modelling and Software*,

Marchi, A., et al. (2014), The battle of the water networks II (BWN-II), *Journal of Water Resources Planning and Management*, 10.1061/(ASCE)WR.1943-5452.0000378.

McCormick, G., and R. S. Powell (2004), Derivation of near-optimal pump schedules for water distribution by simulated annealing, *Journal of the Operational Research Society*, *55*(7), 728-736,

Molly, J. P. (2011), Status der Windenenergienutzung in Deutschland (Status of wind energy use in Germany), *Rep.*, DEWI, Deutsches Windenergie Institut, Germany.

Moral, R. J., and G. S. Dulikravich (2008), Multi-objective hybrid evolutionary optimization with automatic switching among constituent algorithms, *AIAA journal*, *46*(3), 673-681, DOI: 10.2514/1.28926.

National Energy Board (2013), Canada's energy future 2013, *Rep.*, Canada.

National Round Table on the Environment and the Economy (2007), Getting to 2050: Canada's transition to a low-emission future, *Rep.*, Ontario, Canada.

Nicklow, J., et al. (2010), State of the art for genetic algorithms and beyond in water resources planning and management, *Journal of Water Resources Planning and Management*, *136*(4), 412-432, DOI: 10.1061/ASCEWR.1943-5452.0000053.

Ormsbee, L. E., and K. E. Lansey (1994), Optimal control of water supply pumping systems, *Journal of Water Resources Planning and Management*, *120*(2), 237-252,

Ostfeld, A., and A. Tubaltzev (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,

Ou, G., X. Chen, A. Kilic, S. Bartelt-Hunt, Y. Li, and A. Samal (2013), Development of a cross-section based streamflow routing package for MODFLOW, *Environmental Modelling & Software*, *50*, 132-143, DOI: 10.1016/j.envsoft.2013.09.012.

Purshouse, R. C., and P. J. Fleming (2003), Evolutionary many-objective optimisation: An exploratory analysis, paper presented at Evolutionary Computation, 2003. CEC'03. The 2003 Congress on, IEEE, Canberra, Australia.

Quindry, G. E., J. C. Liebman, and E. D. Brill (1981), Optimization of looped water distribution systems, *Journal of the Environmental Engineering Division*, *107*(4), 665-679,

Ramos, H. M., K. N. Kenov, and F. Vieira (2011), Environmentally friendly hybrid solutions to improve the energy and hydraulic efficiency in water supply systems, *Energy for Sustainable Development*, *15*(4), 436-442,

Razavi, S., B. A. Tolson, and D. H. Burn (2012), Review of surrogate modeling in water resources, *Water Resources Research*, *48*(7), DOI: 10.1029/2011WR011527.

Red Eléctrica de España (2013), The Spanish electricity system preliminary report, *Rep.*, Madrid, Spain.

Refsgaard, J. C., J. P. van der Sluijs, A. L. Højberg, and P. A. Vanrolleghem (2007), Uncertainty in the environmental modelling process–a framework and guidance, *Environmental Modelling and Software*, *22*(11), 1543-1556,

Richardson, S. J., and M. R. Hodkiewicz (2011), Modeling tool to support budgeting and planning decisions for pump overhauls, *Journal of Water Resources Planning and Management*, *137*(4), 327-334,

Robson, B. J. (2014), State of the art in modelling of phosphorus in aquatic systems: Review, criticisms and commentary, *Environmental Modelling and Software*, DOI: 10.1016/j.envsoft.2014.01.012.

Roshani, E., S. P. MacLeod, and Y. R. Filion (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,

Rossman, L. A. (2000), EPANET2 users manual, *Rep. EPA/600/R-00/057*, Water Supply and Water Resources Division, National Risk Management Research Laboratory, Office of research and Development, USEPA, Cincinnati, United States of America.

SA Water (2010), Metropolitan water treatment plant flow data (confidential), edited, SA Water, Adelaide, Australia.

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

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

Schaake, J., and D. Lai (1969), Linear programming and dynamic programming applications to water distribution network design, *Rep. Report 116*, Department of Civil Engineering, Massachusetts Institute of Technology., Cambridge, MA.

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

Simpson, Angus R. (2008), Selecting a discount rate for evaluating water distribution projects — the sustainability controversy, paper presented at Proceedings of Water Distribution Systems Analysis 2008, ASCE, Kruger National Park, South Africa, August 17-20.

Stern, Nicholas (2006), The economics of climate change, *Rep.*, Her Majesty's Treasury, London, UK.

Sterner, Thomas, and U. Martin Persson (2007), An even sterner review: Introducing relative prices into the discounting debate, *Rep. RFF Discussion Paper 07-37*, Resources for the Future.

Stokes, C. S., A. R. Simpson, and H. R. Maier (2012), An improved framework for the modelling and optimisation of greenhouse gas emissions associated with water distribution systems, in *6th International Congress on Environmental Modelling and Software (iEMSs)*, edited, Leipzig, Germany.

Stokes, C. S., H. R. Maier, and A. R. Simpson (2014a), Water distribution system pumping operational greenhouse gas emissions reduction by considering time-dependent emissions factors, *Journal of Water Resources Planning and Management (accepted for publication),*

Stokes, C. S., H. R. Maier, and A. R. Simpson (2014b), Effect of storage tank size on the minimization of water distribution system cost and greenhouse gas emissions while considering time-dependent emissions factors *not submitted*,

Stokes, C. S., A. R. Simpson, and H. R. Maier (2014c), 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,

Stokes, C. S., A. R. Simpson, and H. R. Maier (2014d), A computational software tool for the minimization of costs and greenhouse gas emissions associated with water distribution systems, *Environmental Modelling & Software (submitted)*,

Stokes, J., and A. Horvath (2006), Life cycle energy assessment of alternative water supply systems, *The International Journal of Life Cycle Assessment*, *11*(5), 335-343, DOI: 10.1065/lca2005.06.214.

Thorp, K. R., and K. F. Bronson (2013), A model-independent open-source geospatial tool for managing point-based environmental model simulations at multiple spatial locations, *Environmental Modelling & Software*, *50*, 25-36,

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

Tolson, B. A., H. R. Maier, A. R. Simpson, and B. J. Lence (2004), Genetic algorithms for reliability-based optimization of water distribution systems, *Journal of Water Resources Planning and Management*, *130*(1), 63-72,

Treloar, G. J. (1994), Energy analysis of the construction of office buildings, Master of Architecture Thesis thesis, Deakin University, Geelong, Australia.

Turner, A., M. Retamal, S. White, L. Palfreeman, and A. Panikkar (2010), Third party evaluation of wide bay water smart metering and sustainable water pricing initiative project, *Rep.*, Canberra, Australia.

US Energy Information Administration (2012), Electric power monthly February 2012, *Rep.*, Washington DC, United States of America.

Vamvakeridou-Lyroudia, L. S., D. A. Savic, and G. A. Walters (2007), Tank simulation for the optimization of water distribution networks, *Journal of Hydraulic Engineering*, *133*(6), 625-636,

Vamvakeridou-Lyroudia, LS, GA Walters, and DA Savic (2005), Fuzzy multiobjective optimization of water distribution networks, *Journal of Water Resources Planning and Management*, *131*(6), 467-476,

Vrugt, J. A., and B. A. Robinson (2007), Improved evolutionary optimization from genetically adaptive multimethod search, *Proceedings of the National Academy of Sciences*, *104*(3), 708-711,

Walski, T. M., et al. (1987), Battle of the network models: Epilogue, *Journal of Water Resources Planning and Management*, *113*(2), 191-203,

Walski, T. M. (2000), Hydraulic design of water distribution storage tanks, *Water distribution systems handbook*, *10*, 10.11-10.20, Walters, G. A., D. Halhal, D. Savic, and D. Ouazar (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, *Rep.*, Water Services Association of Australia.

Water Services Association of Australia (2010), Implications of population growth in Australia on urban water resources, *Rep.*, Water Services Association of Australia.

Wu, W., H. R. Maier, and A. R. Simpson (2008a), Genetic algorithm optimisation of water distribution systems accounting for greenhouse gas emissions, paper presented at 9th National Conference on Hydraulics in Water Engineering, Engineers Australia, Darwin Convention Centre, Australia, 23-26 September.

Wu, W., A. R. Simpson, and H. R. Maier (2008b), Water distribution system optimisation accounting for a range of future possible carbon prices, paper presented at 10th Annual Symposium on Water Distribution Systems Analysis, American Society of Civil Engineers, Kruger National Park, South Africa, 17-20 August.

Wu, W., A. R. Simpson, and H. R. Maier (2008c), Multi-objective genetic algorithm optimisation of water distribution systems accounting for sustainability, paper presented at Water Down Under 2008: Incorporating 31st Hydrology and Water Resources Symposium and the 4th International Conference on Water Resources and Environment Research (ICWRER), Adelaide, Australia.

Wu, W., H. R. Maier, and A. R. Simpson (2009a), Multi-objective water distribution system optimisation accounting for carbon emissions under different electricity tariffs, paper presented at Ozwater '09, Australian Water Association, Melbourne, Australia, March 16-18.

Wu, W., A. R. Simpson, and H. R. Maier (2009b), Trade-off analysis between cost and reliability of water distribution systems using genetic algorithms, paper presented at Computing and Control in the Water Industry 2009 'Integrating Water Systems', London, United Kingdom, September 1-3.

Wu, W., H. R. Maier, and A. R . Simpson (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), 1-11,

Wu, W., A. R . Simpson, and H. R. Maier (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., A. R. Simpson, and H. R. Maier (2010c), Accounting for carbon: Selecting the appropriate discount rate for multi-objective optimisation of water distribution systems, paper presented at Ozwater '10, Australia Water Association, Brisbane, Australia, March 08-10.

Wu, W., A. R. Simpson, and H. R. Maier (2010d), Reducing carbon footprint from water distribution systems by using a lower discount rate, paper presented at Practical Responses to Climate Change National Conference 2010, Engineers Australia, Melbourne, Australia, 29 September-1 October.

Wu, W. (2012), Multiobjective genetic algorithm optimization of water distribution systems accounting for economic cost, greenhouse gas emissions and reliability, University of Adelaide, Adelaide, Australia.

Wu, W., H. R. Maier, and A. R. Simpson (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., A. R. Simpson, H. R. Maier, and A. Marchi (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.

Wu, W., H. R. Maier, and A. R. Simpson (2013), Multiobjective optimization of water distribution systems accounting for economic cost, hydraulic reliability, and greenhouse gas emissions, *Water Resources Research*,

Wu, W., G. C. Dandy, and H. R. Maier (2014), Protocol for developing ANN models and its application to the assessment of the quality of the ANN model development process in drinking water quality modelling, *Environmental Modelling and Software*, *54*, 108-127, DOI: 10.1016/j.envsoft.2013.12.016.

Wu, Z. Y., and A. R. Simpson (2001), Competent genetic-evolutionary optimization of water distribution systems, *Journal of Computing in Civil Engineering*, *15*(2), 89-101,

Young, J. (2010), The'greening'of water: Taking aim at climate change through reducing greenhouse gas emissions, increasing efficiency, *Journal of the American Water Works Association*, *102*(6), 20-22,

Zambrano-Bigiarini, M., and R. Rojas (2013), A model-independent particle swarm optimisation software for model calibration, *Environmental Modelling & Software, 43*, 5-25, Zecchin, A. C., H. R. Maier, A. R. Simpson, M. Leonard, and J. B. Nixon (2007), Ant colony optimization applied to water distribution system design: Comparative study of five algorithms, *Journal of Water Resources Planning and Management*, *133*(1), 87-92,

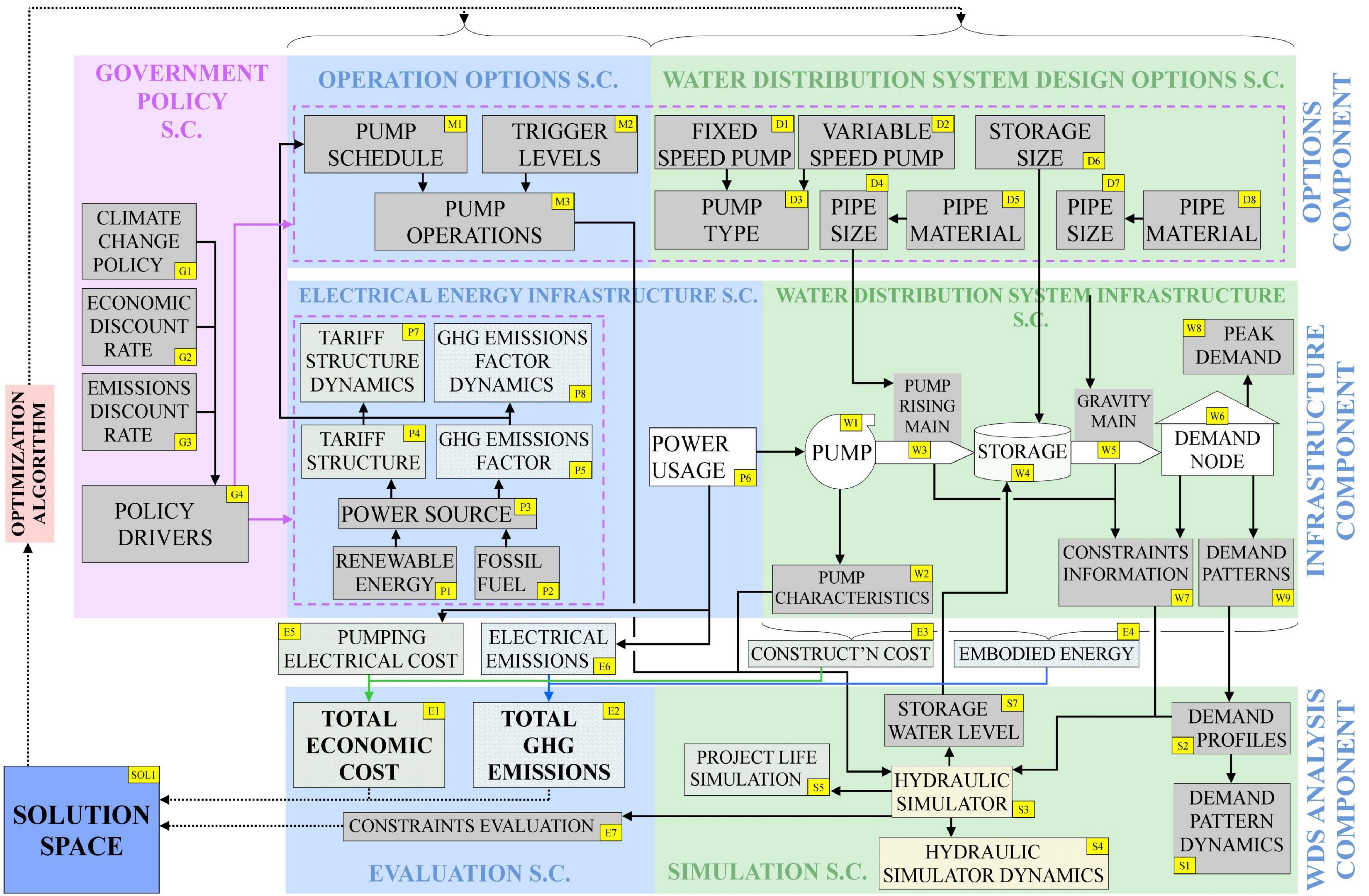
Zessler, U., and U. Shamir (1989), Optimal operation of water distribution systems, *Journal of Water Resources Planning and Management*, *115*(6), 735-752,

Zhang, H., W. Hu, K. Gu, Q. Li, D. Zheng, and S. Zhai (2013), An improved ecological model and software for short-term algal bloom forecasting, *Environmental Modelling & Software*, *48*, 152-162,

Zitzler, E., and L. Thiele (1999), Multiobjective evolutionary algorithms: a comparative case study and the strength Pareto approach, *Evolutionary Computation, IEEE Transactions on*, *3*(4), 257-271,

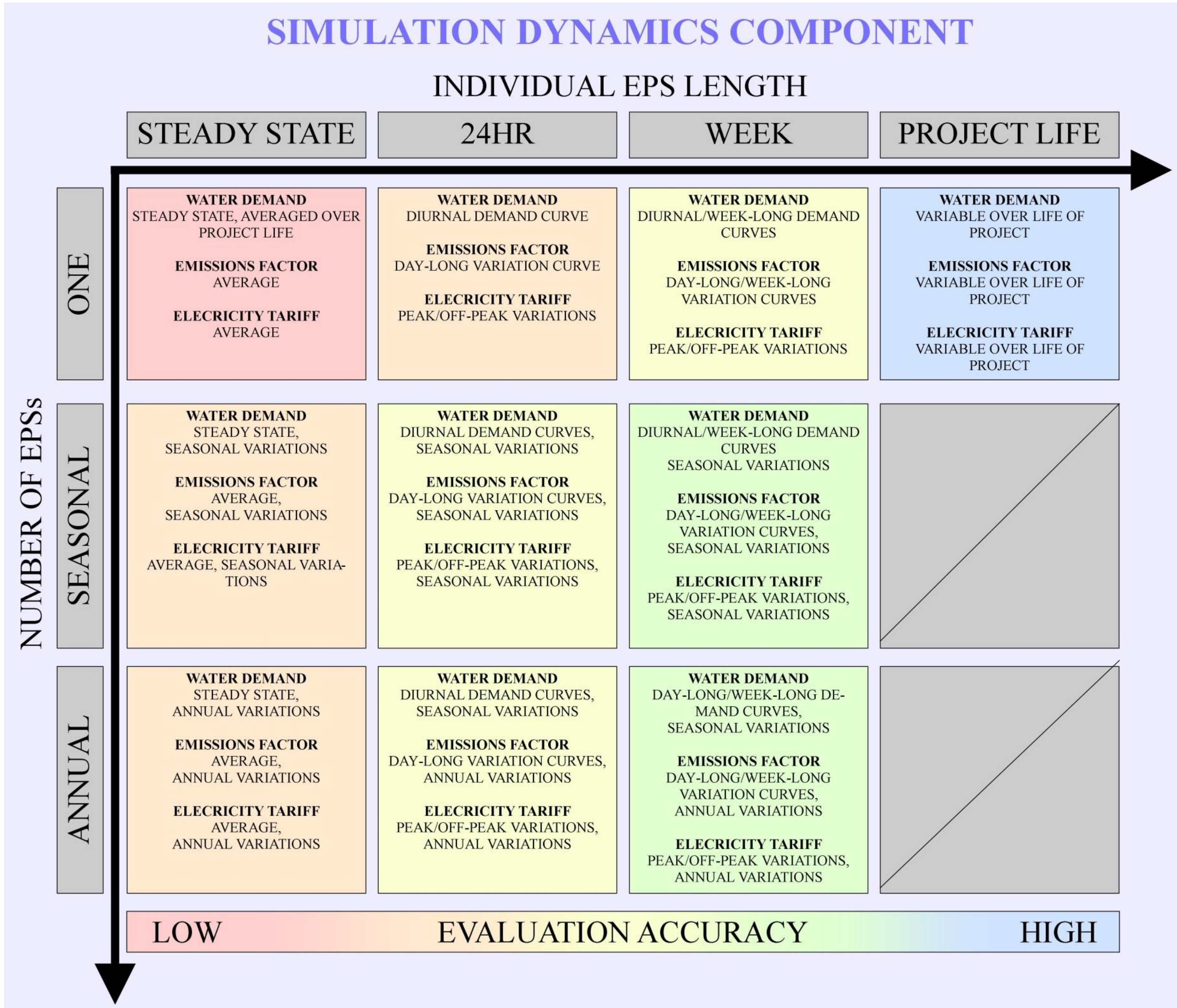
Zitzler, E., M. Laumanns, and L. Thiele (2001), SPEA2: Improving the strength Pareto evolutionary algorithm, *Rep.*, Swiss Federal Institute of Technology (ETH) Zurich ETH Zentrum, Zurich, Switzerland.

Appendix A: Enlarged image of the water distribution system cost-emissions nexus framework presented in Chapter 2



*S.C. = Sub-Component

Appendix B: Enlarged image of the simulation dynamics component presented in Chapter 2


SIMULATION DYNAMICS COMPONENT
INDIVIDUAL EPS LENGTH
STEADY STATE
24HR
WEEK
PROJECT LIFE
NUMBER OF EPSs
ONE
SEASONAL
ANNUAL
WATER DEMAND STEADY STATE, AVERAGED OVER PROJECT LIFE
EMISSIONS FACTOR AVERAGE
ELECRICITY TARIFF AVERAGE
WATER DEMAND DIURNAL DEMAND CURVE
EMISSIONS FACTOR DAY-LONG VARIATION CURVE
ELECRICITY TARIFF PEAK/OFF-PEAK VARIATIONS
WATER DEMAND DIURNAL/WEEK-LONG DEMAND CURVES
EMISSIONS FACTOR DAY-LONG/WEEK-LONG VARIATION CURVES
ELECRICITY TARIFF PEAK/OFF-PEAK VARIATIONS
WATER DEMAND VARIABLE OVER LIFE OF PROJECT
EMISSIONS FACTOR VARIABLE OVER LIFE OF PROJECT
ELECRICITY TARIFF VARIABLE OVER LIFE OF PROJECT
WATER DEMAND STEADY STATE, SEASONAL VARIATIONS
EMISSIONS FACTOR AVERAGE, SEASONAL VARIATIONS
ELECRICITY TARIFF AVERAGE, SEASONAL VARIA-TIONS
WATER DEMAND DIURNAL DEMAND CURVES, SEASONAL VARIATIONS
EMISSIONS FACTOR DAY-LONG VARIATION CURVES, SEASONAL VARIATIONS
ELECRICITY TARIFF PEAK/OFF-PEAK VARIATIONS, SEASONAL VARIATIONS
WATER DEMAND DIURNAL/WEEK-LONG DEMAND CURVES SEASONAL VARIATIONS
EMISSIONS FACTOR DAY-LONG/WEEK-LONG VARIATION CURVES, SEASONAL VARIATIONS
ELECRICITY TARIFF PEAK/OFF-PEAK VARIATIONS, SEASONAL VARIATIONS
WATER DEMAND STEADY STATE, ANNUAL VARIATIONS
EMISSIONS FACTOR AVERAGE, ANNUAL VARIATIONS
ELECRICITY TARIFF AVERAGE, ANNUAL VARIATIONS
WATER DEMAND DIURNAL DEMAND CURVES, SEASONAL VARIATIONS
EMISSIONS FACTOR DAY-LONG VARIATION CURVES, ANNUAL VARIATIONS
ELECRICITY TARIFF PEAK/OFF-PEAK VARIATIONS, ANNUAL VARIATIONS
WATER DEMAND DAY-LONG/WEEK-LONG DE-MAND CURVES, SEASONAL VARIATIONS
EMISSIONS FACTOR DAY-LONG/WEEK-LONG VARIATION CURVES, ANNUAL VARIATIONS
ELECRICITY TARIFF PEAK/OFF-PEAK VARIATIONS, ANNUAL VARIATIONS
LOW
EVALUATION ACCURACY
HIGH

Appendix C: Matrix representation of the reviewed literature presented in Chapter 2

Component					Options Component							Infrastructure Component										
Sub-Component (S.C.)					Operation		WDS Design Options S.C.					Electrical Energy Infrastructure S.C.							WDS Infrastructure S.C.			
		Rank												GHG Factors		Tariffs						
Paper Identifier	Paper	Optimization	Simulation	Analysis/review	Pump Scheduling	Trigger levels	Pump type selection	Variable speed pumps	Storage size/location selection	Pipe material selection	Pipe size selection	Renewable energy consideration	Power source consideration	Single, average GHG emissions factor value	Time-dependent GHG emissions factors	Single, average tariff value	Time-dependent tariff structure	Pump energy analysis	Simple system	Complex system	Demand pattern	Demand variations
					C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
Pr1	Abadia Sanchez, et al. (2008)			X														X	X			
Pr2	Alandi, et al. (2005)	X					X	X										X		X	X	X
Pr3	Ambrose, et al. (2002)		X	X						X	X											
Pr4	Basupi, et al. (2013)	X							X	X	X			X		X		X		X	X	
Pr5	Basupi, et al. (2014)	X			X				X	X	X			X		X		X		X		
Pr6	Biehl & Inman (2010)			X												X	X	X		X		
Pr7	Boulos & Bros (2010)			X										X				X		X		
Pr8	Bunn & Reynolds (2009)			X													X	X			X	
Pr9	Cabrera, et al. (2010)		X			X												X	X		X	
Pr10	Dandy, et al. (2006)	X					X			X	X			X				X		X		
Pr11	Dandy, et al. (2008)	X								X	X			X					X			
Pr12	Du, et al. (2013)	X		X						X	X			X		X		X		X		
Pr13	Ektesabi, et al. (2009)			X				X										X		X		
Pr14	Ertin, et al. (2001)	X			X	X												X	X		X	
Pr15	Filion (2007)		X							X	X			X				X	X			
Pr16	Filion (2008)		X							X	X							X	X			
Pr17	Filion et al. (2004)		X																X			X
Pr18	Ghimire & Barkdoll (2008)		X															X		X		
Pr19	Ghimire & Barkdoll (2009)		X						X									X		X	X	
Pr20	Ghimire & Barkdoll (2010)		X															X		X		
Pr21	Ghimire (2010)		X															X		X	X	
Pr22	Hernandez, et al. (2010)		X															X		X	X	
Pr23	Herstein & Filion (2011)	X							X	X	X			X		X		X		X	X	
Pr24	Herstein, et al. (2009)	X							X		X			X		X		X		X	X	
Pr25	Herstein, et al. (2009)	X						X			X		X	X		X		X	X		X	
Pr26	Herstein, et al. (2011)	X							X	X	X		X	X		X		X		X		
Pr27	Kang & Lansey (2012)	X					X			X	X			X		X		X		X		
Pr28	Kiselychnyk, et al. (2009)			X																		
Pr29	Kumar & Karney (2007)			X												X		X		X		
Pr30	Lundie, et al. (2004)			X								X	X					X		X		
Pr31	MacLeod & Filion (2011)	X				X					X			X		X		X	X		X	
Pr32	MacLeod, et al. (2010)	X								X	X			X		X		X		X	X	
Pr33	Marchi, et al. (2013)	X			X	X	X		X	X	X			X			X	X		X	X	
Pr34	Ramos, et al. (2011)	X			X	X						X	X				X	X	X		X	
Pr35	Richardson & Hodkiewicz (2011)	X												X		X		X	X			
Pr36	Roshani, et al. (2011)	X				X				X	X			X	X	X		X		X	X	
Pr37	Simpson (2008)			X																		
Pr38	Stokes & Horvath (2005)			X								X	X					X		X		
Pr39	Wu, et al. (2008)	X					X			X	X			X		X		X	X			
Pr40	Wu, et al. (2008)	X					X		X	X	X			X		X		X	X			
Pr41	Wu, et al. (2008)	X					X			X	X			X		X		X	X			
Pr42	Wu, et al. (2009)	X					X			X	X			X		X		X	X			
Pr43	Wu, et al. (2010)	X					X			X	X			X		X		X	X			
Pr44	Wu, et al. (2010)	X					X		X	X	X			X		X		X	X			
Pr45	Wu, et al. (2010)	X					X			X	X			X		X		X	X			
Pr46	Wu, et al. (2010)	X				X	X			X	X			X		X		X	X		X	
Pr47	Wu, et al. (2012)	X					X	X		X	X			X				X	X			X
Pr48	Wu, et al. (2012)	X					X			X	X	X	X	X	X		X	X	X			
Pr49	Wu, et al. (2013)	X					X			X	X			X	X	X		X		X	X	
Pr50	Young (2010)			X								X						X		X		

Component					Water Distribution System Analysis Component										
Sub-Component (S.C.)					Simulation S.C.				Evaluation S.C.				Government Policy S.C.		
		Rank							Objective function						
Paper Identifier	Paper	Optimization	Simulation	Analysis/review	Single hydraulic simulation	Hydraulic simulation resolution consideration	Hydraulic simulation length consideration	Number of hydraulic simulations consideration	Cost	GHG emissions	Energy	Other objective	Carbon cost (incl. Tariff increase)	Economic discount rate	Emissions discount rate
					C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29
Pr1	Abadia Sanchez, et al. (2008)			X							X				
Pr2	Alandi, et al. (2005)	X						X			X				
Pr3	Ambrose, et al. (2002)		X	X	X						X				
Pr4	Basupi, et al. (2013)	X			X				X	X		X			
Pr5	Basupi, et al. (2014)	X			X				X	X		X			
Pr6	Biehl & Inman (2010)			X					X		X				
Pr7	Boulos & Bros (2010)			X	X				X	X	X				
Pr8	Bunn & Reynolds (2009)			X					X		X				
Pr9	Cabrera, et al. (2010)		X		X		X				X				
Pr10	Dandy, et al. (2006)	X			X				X		X				
Pr11	Dandy, et al. (2008)	X			X				X		X				
Pr12	Du, et al. (2013)	X		X	X				X	X					
Pr13	Ektesabi, et al. (2009)			X							X				
Pr14	Ertin, et al. (2001)	X			X						X				
Pr15	Filion (2007)		X		X					X					
Pr16	Filion (2008)		X		X						X				
Pr17	Filion et al. (2004)		X					X			X				
Pr18	Ghimire & Barkdoll (2008)		X		X						X				
Pr19	Ghimire & Barkdoll (2009)		X		X						X				
Pr20	Ghimire & Barkdoll (2010)		X								X				
Pr21	Ghimire (2010)		X		X						X				
Pr22	Hernandez, et al. (2010)		X		X		X				X				
Pr23	Herstein & Filion (2011)	X			X				X	X		X			
Pr24	Herstein, et al. (2009)	X			X				X	X		X			
Pr25	Herstein, et al. (2009)	X			X				X	X		X			
Pr26	Herstein, et al. (2011)	X			X				X	X		X			
Pr27	Kang & Lansey (2012)	X			X				X	X		X			
Pr28	Kiselychnyk, et al. (2009)			X							X				
Pr29	Kumar & Karney (2007)			X							X				
Pr30	Lundie, et al. (2004)			X						X	X				
Pr31	MacLeod & Filion (2011)	X			X				X	X			X	X	
Pr32	MacLeod, et al. (2010)	X			X				X	X			X	X	
Pr33	Marchi, et al. (2013)	X			X				X	X		X			
Pr34	Ramos, et al. (2011)	X			X				X	X					
Pr35	Richardson & Hodkiewicz (2011)	X			X				X	X					
Pr36	Roshani, et al. (2011)	X			X				X	X			X	X	X
Pr37	Simpson (2008)			X										X	X
Pr38	Stokes & Horvath (2005)			X						X	X				
Pr39	Wu, et al. (2008)	X			X				X	X				X	X
Pr40	Wu, et al. (2008)	X			X				X	X				X	
Pr41	Wu, et al. (2008)	X			X				X	X			X	X	X
Pr42	Wu, et al. (2009)	X			X				X	X			X	X	X
Pr43	Wu, et al. (2010)	X			X				X	X				X	X
Pr44	Wu, et al. (2010)	X			X				X	X				X	X
Pr45	Wu, et al. (2010)	X			X				X	X				X	X
Pr46	Wu, et al. (2010)	X			X				X	X				X	X
Pr47	Wu, et al. (2012)	X						X	X	X					
Pr48	Wu, et al. (2012)	X			X				X	X			X		
Pr49	Wu, et al. (2013)	X			X				X	X		X			
Pr50	Young (2010)			X						X	X				

Appendix D: Supplemental Material from Paper 2 (Chapter 3)

1. WCEN input file for Average Simulation (AS) scenario (see Attachments to electronic copy of this thesis).

2. WCEN input file for Diurnal Simulation (DS) scenario (see Attachments to electronic copy of this thesis).

3. WCEN input files for Monthly, Diurnal Simulation (MDS) scenario (see Attachments to electronic copy of this thesis).

4. WCEN input files for Annual, Diurnal Simulation (ADS) scenario (see Attachments to electronic copy of this thesis).

5. Example EPANET 2.0 input file (see Attachments to electronic copy of this thesis).

6. Example user interface (command line) for Diurnal Simulation (DS) scenario (see Attachments to electronic copy of this thesis).

Appendix E: Supplemental Material from Paper 3 (Chapter 4)

1. Actual emissions factors data (see Attachments to electronic copy of this thesis).

2. Estimated 24-hour emissions factor curve (27% wind) data (see Attachments to electronic copy of this thesis).

3. Modified emissions factor curve (3% wind) (see Attachments to electronic copy of this thesis).

4. Modified emissions factor curve (15% wind) (see Attachments to electronic copy of this thesis).

5. Modified emissions factor curve (40% wind) (see Attachments to electronic copy of this thesis).

6. Example EPANET 2.0 input file (see Attachments to electronic copy of this thesis)

The Water Distribution Cost-Emissions Nexus computational software framework is available at:

http://www.ecms.adelaide.edu.au/civeng/research/water/software/wcen-framework/.

Appendix F: Copy of Paper 1 from Chapter 2 (as published)

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

Stokes et al. Earth Perspectives 2014, 1:9
http://www.earth-perspectives.com/content/1/1/9

Earth Perspectives
a SpringerOpen Journal

REVIEW Open Access

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

Christopher S Stokes*, Angus R Simpson and Holger R Maier

Abstract

The increased release of greenhouse-gas (GHG) emissions associated with human activities causing climate change is one of the most significant problems faced by human-kind. Water distribution systems (WDS), whilst providing an essential service to society, are responsible for the generation of significant amounts of GHGs. In response, the minimization of GHG emissions associated with WDSs has become a research focus. In this paper, a critical review of previous research is provided, summarizing research progress and highlighting research needs in this emergent and important area. This is done within the context of the water distribution system cost-emissions nexus (WCEN) conceptual framework, which is a novel conceptual framework that considers the interaction between all components required to accurately evaluate the costs and greenhouse gas (GHG) emissions associated with water distribution systems (WDSs) in an integrated fashion. Key findings from this review indicate that future research should (1) include the use of time-dependent emissions factors (EFs), which would allow the scheduling of pumps at times of lower emissions intense energy to be considered; (2) include the modeling of seasonally variable water demands; (3) include greater consideration of the hydraulic simulation process, such as using seasonal extended period simulations; (4) include greater consideration of the management of pumping operations at the design stage, instead of solely focusing on changes in infrastructure design to reduce costs and GHG emissions; (5) include consideration of the effects that external policies, such as carbon taxes and present value discounting, have on the trade-offs between costs and GHG emissions.

Keywords: Water distribution system; Greenhouse gas emissions; Multi-objective optimization; Sustainability; Hydraulic simulation; Water-energy nexus

Introduction

The increased release of greenhouse-gas (GHG) emissions associated with human activities causing climate change is one of the most significant problems faced by human-kind (Stokes et al. 2012). Greenhouse gas (GHG) releases through human-related activities have been identified as a major cause of human-induced climate change. The importance of mitigating climate change by reducing GHG emissions has been widely recognized by the scientific, commercial and political sectors. Water distribution systems (WDSs) provide an essential service to modern cities. However, they also contribute significantly to the release of GHG emissions through activities related to their construction and operation, especially when pumping operational energy is sourced from fossil fuel electricity generation sources. WDSs are also complex systems, with many different design and operational options being available to a decision maker. Thus, it is often impractical or even impossible for a decision maker to evaluate and consider the combination of all available options. As such, optimizing the design and operation of

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WDSs via the use of optimization algorithms has become a popular way of considering these many available options. In order to evaluate the performance of the many potential design and operation combinations during evolutionary algorithm based optimization processes, WDSs must be modeled (i.e. simulated). However, the modeling of WDSs can be computationally expensive. As such, simplifications are often made during the modeling process in order to reduce both the problem complexity and the computational time required to evaluate each solution in the optimization process (in the case where evolutionary algorithms or similar metaheuristics are used). This can include simplifications to the decision variables, such as limiting the types and number of options considered; simplifications to input data, such as replacing actually time-dependent input information with steady-state or approximate values; and simplifications to the simulation process, such as hydraulically simulating a limited number of water demand scenarios compared to what will be encountered during real-life operations (Stokes et al. 2012). The optimization of costs associated with water distribution systems has been covered extensively in the past three decades (Wu et al. 2010a). As such, simplifications made to the modeling of WDSs have been well established. Consideration of optimizing WDSs for the minimization of GHG emissions has only occurred more recently. Commonly, GHG emissions (both capital emissions and operational emissions from fossil fueled electricity sources) have been optimized along with costs by using multi-objective (MO) optimization algorithms. As such, modeling simplifications applied when evaluating costs are also applied when evaluating GHG emissions. These simplifications have the potential to affect the possible solutions and their corresponding evaluations. In addition, the primary focus of optimization has been on the selection of WDS infrastructure design options (e.g. pipe sizes and pump types). Only limited consideration has been given to the impact of pump operational management, interactions between water supply infrastructure and energy generating infrastructure and how policy drivers may affect the optimal trade-offs between cost and GHG emissions. Therefore, there remains a need to review the current literature considering the optimization of WDSs for the minimization of GHG emissions in order to establish what modeling simplifications have been made and to identify gaps in current modeling and evaluation processes. In order to achieve this, a conceptual framework is required to identify and show the nexus of modeling elements that can impact on the optimization of costs and GHG emissions associated with WDSs. Additionally, this conceptual framework should include consideration of energy generating infrastructure that affects pumping operational GHG emissions, as well as policy drivers that can impact the trade-offs between costs and GHG emissions associated with WDSs. Such a framework was first presented by Stokes et al. (2012). As such, the objectives of this paper are as follows:

1. To develop a conceptual framework, based on the framework presented by Stokes et al. (2012), that identifies and shows the interactions between the various modeling elements that have an impact on WDS cost and GHG emissions optimization, including those from energy generating infrastructure, in an integrated fashion.
2. To review existing literature considering the minimization of GHG emissions associated with WDSs in the context of the proposed conceptual framework in order to identify the research gaps with respect to the simplification of the modeling processes and future research required to address these gaps.

The water distribution system cost-emissions nexus (WCEN) conceptual framework (Objective 1), is presented in Water distribution cost-emissions nexus (WCEN) conceptual framework. The evaluation of existing literature in the context of the WCEN conceptual framework (Objective 2) is presented in Review of methods used for GHG emissions reduction associated with water distribution systems, leading to the identification of current research gaps and future research directions required to progress this field of research (Summary and conclusions and Recommendations for future research).

Water distribution cost-emissions nexus (WCEN) conceptual framework

The WCEN conceptual framework (Figures 1 and 2) is based on the similarly named framework presented by Stokes et al. (2012). While not an analytical tool itself, the WCEN conceptual framework represents the nexus of elements required to accurately model and evaluate costs and GHG emissions when optimizing the design and operation of a WDS. The conceptual framework is separated into four distinct components (Figure 1). These include an infrastructure component (WDS and electricity generation infrastructure), options component (design and operations of the WDS), analysis component (simulation and evaluation), and government policy sub-component, each of which consists of a number of related elements. The components are linked to one another to represent the flow of information through the system. A list of components and sub-components of the conceptual framework is given in Table 1. In addition, the framework also consists of a simulation dynamics component (Figure 2), as the most appropriate simulation duration and number of simulations performed can have a significant impact on accuracy and

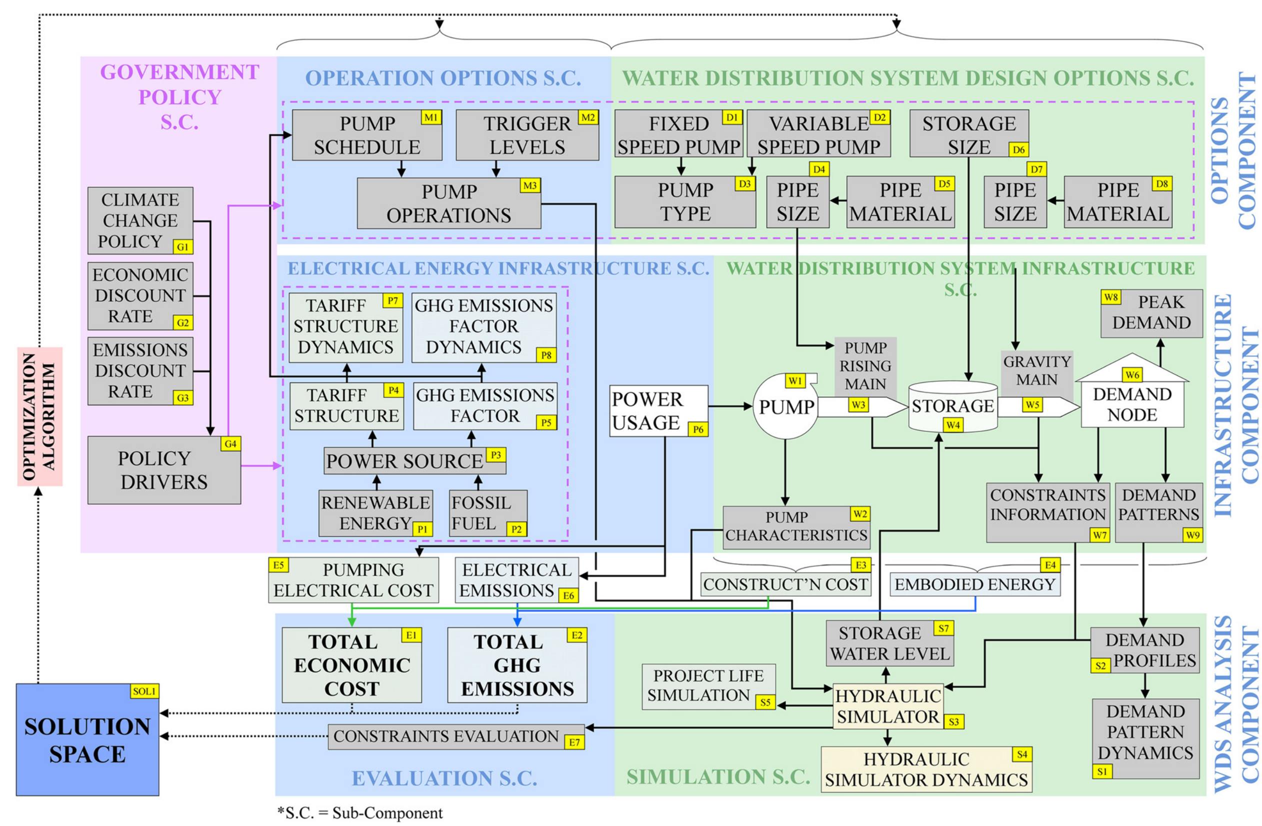

Figure 1 The water distribution system cost-emissions nexus framework (modified from *Stokes et al.* (2012)).

computational efficiency, and are likely to be different for the evaluation of costs and GHG emissions. The various sub-components of the WCEN conceptual framework are described in detail in the subsequent sections.

Infrastructure component

In order to obtain accurate estimations of the costs and GHG emissions when optimizing the design and operation of a WDS, it is important to consider the real-world infrastructure that is being modelled. The infrastructure component within the WCEN conceptual framework represents this real-world infrastructure. Two critical infrastructure types are important to consider. These include the WDS being modeled, as represented by the WDS infrastructure sub-component, and the sources of generation of electricity being used by pumps during the operation of WDSs, as represented by the electrical energy generating infrastructure sub-component. While simplifications to both systems are required, each system's critical aspects, as related to the conceptual framework's purpose, should be retained.

Modeling of the WDS infrastructure is used to represent the physical WDS elements that allow water to be supplied from sources to consumers. An accurate representation of the critical elements of the actual WDS is required if costs and GHG emissions are to be estimated accurately. These elements are represented within the WDS infrastructure sub-component, and include the pumps that supply water to the system [W1 – See Figure 1]; the pump rising mains [W3] that connect the pumps to the distribution pipe network; the water storage systems [W4], which can include either reservoirs or tanks; the gravity mains that distribute water from water storages to the demand nodes [W5]; and the demand nodes, which represent the consumer demands placed on the WDS [W6]. Water demand patterns [W9] of the WDS being modeled are used within the hydraulic simulation process to consider the real-world water demands. A water demand profile [S2] can represent multiple water demand patterns for different demand node requirements (e.g. residential, commercial and industrial). A combination of multiple water demand patterns can also be used to represent different water demand scenarios, such as different seasons in a year. While peak and average water demand flows are commonly used when simulating a WDS, it can be important to consider a range of operational conditions in order to obtain the most accurate estimate of operational costs and GHG emissions. Additionally, it can also be important to consider exceptional water demand circumstances, such

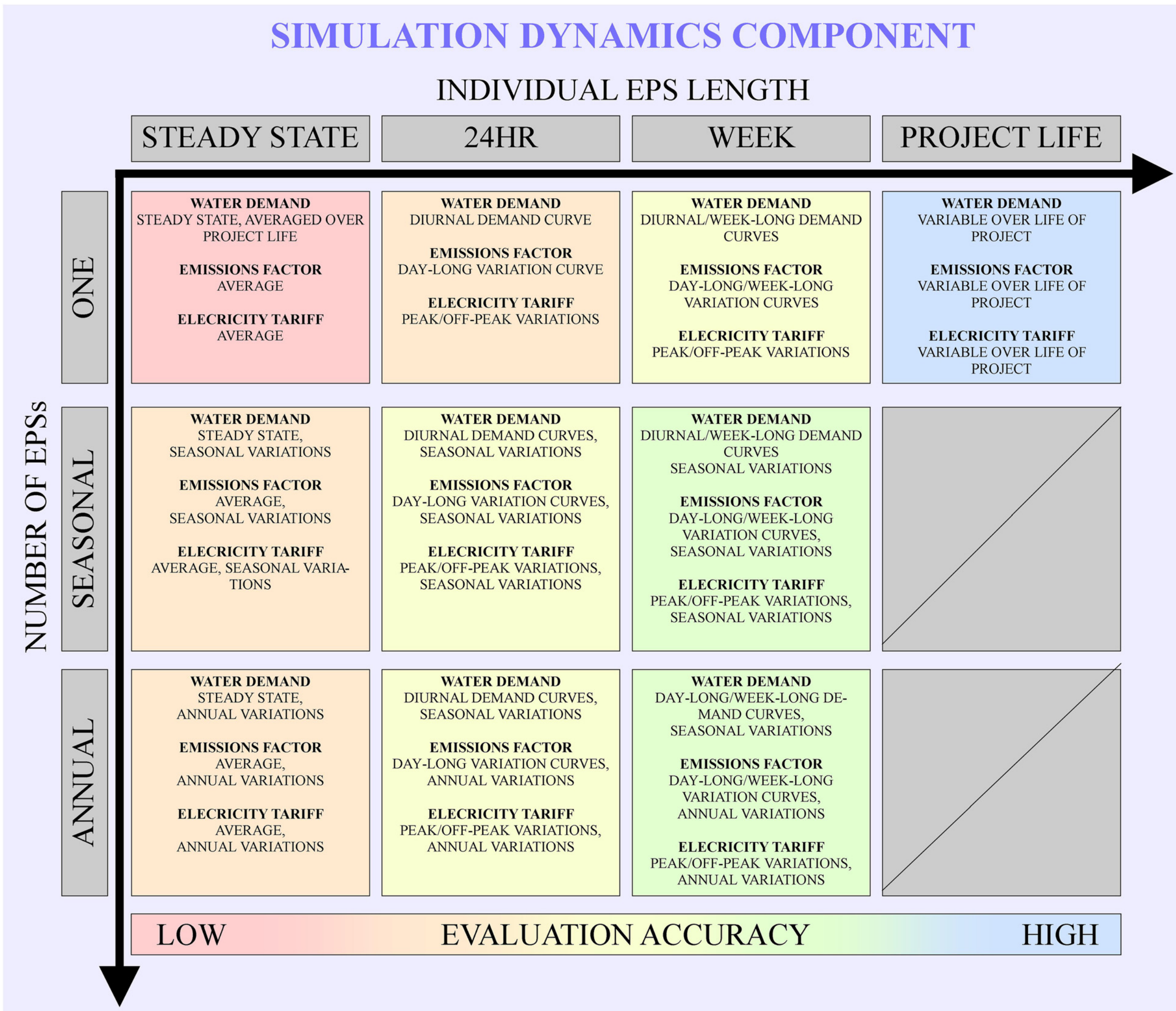

Figure 2 The simulation dynamics component.

Table 1 Components and sub-components, water distribution system cost-emissions nexus framework

Component	Sub-component (SC)
Options component	Operation options SC
	WDS Design options SC
	Government policy SC*
Infrastructure component	Electrical energy infrastructure SC
	WDS infrastructure SC
	Government policy SC*
WDS analysis component	Simulation SC
	Evaluation SC

*While the Government Policy sub-component is associated with both the Options and Infrastructure components, it is discussed separately from these components in the text.

as fire loadings and pipe breakages. As water demands drive the system hydraulics, an accurate representation of both water demands and the physical infrastructure can help to obtain an accurate estimation of the pumping operational energy required to meet the demands. Additionally, accurate representation of the physical infrastructure is important if design related costs and GHG emissions are to be accurately estimated. Other aspects of a WDS, such as infrastructure maintenance and replacement, miscellaneous running costs (e.g. electricity for lighting at pump stations) and labor costs are not usually able to be included as part of the hydraulic simulation and are therefore not represented by the WDS infrastructure sub-component of the conceptual framework presented in this paper.

The electrical energy infrastructure sub-component represents the elements of electricity generation and supply infrastructure that are required to accurately evaluate pumping operational costs and GHG emissions associated with a WDS. The cost of electricity for pumping is commonly calculated by using an electricity tariff, which is represented by a tariff structure [P4]. The tariff structure dynamics [P7] represent the different possible tariff structures, such as flat rate or peak/off-peak rates. In order to accurately estimate the cost of pumping operational energy consumption, it is important to consider the variability in electricity tariffs during each day and/or week, as well as possible seasonal and annual variability. Pumping operational GHG emissions can be calculated by considering the generation rate and emissions factors of individual generators feeding into the grid. As such, both renewable [P1] and fossil fuel (non-renewable) [P2] generation types are represented in the conceptual framework. In order to accurately estimate the overall emissions factor [P5] of the electricity supplied to the WDS, the amalgamation of all individual generators supplying into the grid, represented as the electrical source [P3], should be considered. The use of emissions factors is represented by the emissions factors dynamics [P8]. Emissions factors can range from the use of a single, average value, to the use of multiple emissions factors used to represent the change in emission intensities over the period of a day, between each month/season in a year, or between each year over the operational life-span of the WDS. As a WDS is just one of many users consuming electricity from a grid, careful consideration should be given to how emissions factors associated with the consumption of electricity by the WDS [P5] are calculated (e.g. whether emissions factors values consider all generated electricity, or only the generation of electricity used by the WDS). While the consideration of how emissions factor values are calculated is beyond the scope of this paper, the application of the emissions factor values must also be carefully considered. The way in which emissions factors are used can affect the evaluation of emissions.

Options components

In order to find solutions of minimized costs and GHG emissions when optimizing the design and operation of a WDS, it is important to consider the options available to decision makers. These options are represented within the options component by two sub-components; the water distribution system design options (WDS design options) sub-component and the operation options sub-component.

The WDS design options sub-component is used to represent the options related to the design of the hydraulic infrastructure. Design phase considerations commonly include the selection of sizes of pipes, storage tanks/reservoirs and pumps, and are generally assumed to be fixed after the construction (or redevelopment/rehabilitation) of the system. Chosen pump types [D3], both variable-speed pumps (VSPs) [D2] and fixed-speed pumps (FSPs) [D1], pipe sizes [D4, D7], material types [D5, D8] and water storage sizes [D6] can significantly affect design costs and GHG emissions associated with the products themselves and operational costs and GHG emissions, through their effect on system hydraulics. While design costs may be evaluated from pricing information gained from commercial sources, design GHG emissions must be calculated directly from the materials used. Embodied energy is commonly used to calculate these GHG emissions. A widely used definition of embodied energy has been given by *Treloar* (1994).

Options available for the operational management of WDSs are represented by the operation options sub-component. Pumping operations can be explicit (using pump scheduling) and/or implicit (using storage trigger levels). Pump scheduling [M1] can be used to control the timed status and speed of pumps, while trigger levels [M2] can be used to control storage levels. Chosen control options are represented as pump operation information [M3]. This information can be used to represent operational scenarios via the use of hydraulic simulation [S3], allowing pumping operational energy consumption to be calculated. While average conditions can be used to estimate pumping operational energy consumption, more accurate estimations can be achieved by considering multiple operational scenarios.

Water distribution system analysis components

In order to obtain more accurate trade-offs between costs and GHG emissions when optimizing the design and operation of a WDS, it is important to consider both the simulation and evaluation options available. To do this, the water distribution system analysis component of the conceptual framework uses two sub-components; the simulation sub-component, which represents the operational simulation of the WDS, and the evaluation sub-component, which represents the evaluation of costs and GHG emissions associated with the WDS. Evaluation of costs and GHG emissions can be achieved both directly from the design options, represented by the options component, and indirectly through operational simulation, represented by the simulation sub-component. The evaluation of objective functions using infrastructure design and hydraulic simulation information has been used extensively within the field of WDS optimization.

Hydraulic simulation [S3] is used to evaluate both design constraint satisfaction and objective function performance of each developed solution. Project life simulation [S5] represents the simulation of the WDS over the life of the project, including consideration of both construction and operation phases. Project life simulation can incorporate both infrastructure design information (from the options component) and information gained from the hydraulic simulation. Information outputted from an extended period simulation (EPS) can include the storage levels [S7], pipe flows and node pressure information at each time-step, which can be used for constraint evaluation [E7], and pump electrical energy consumption [P6] used for operational evaluation purposes. Hydraulic simulation requires water demand profiles [S2], pump characteristics (pump and efficiency curves) [W2] and pump operation information [M3]. Constraint information [W7], such as water balance and node pressure requirements, is used for the evaluation of constraints. Demand profiles can be used to simulate water demand changes over different seasons and years, as represented by the demand pattern dynamics [S1], to better represent the true nature of water demands. The hydraulic simulator requires a representation of the physical system; this information is commonly a simplified model of the real-life WDS, as represented by the WDS infrastructure sub-component, and includes design options information, as represented by the WDS design options sub-component. The total hydraulic simulation length can be controlled by modifying the EPS length and the number of different EPSs used (e.g. used for changes of input data values, such as emissions factors and water demands, over different months/seasons or years), which are represented by the hydraulic simulator dynamics [S4].

Evaluation of each objective function, namely total life cycle economic cost [E1] and total life cycle GHG emissions [E2], is represented by the evaluation sub-component. This sub-component is also used to represent constraint evaluation [E7], which is used to penalize designs that violate user-defined design constraints (such as node pressure and water balance violations). Design and operational information represented by both the water distribution system and electrical energy infrastructure sub-components is used to evaluate the fitness of each solution. Infrastructure construction costs [E3] and pumping electrical costs [E5] are used to evaluate total life cycle economic costs. GHG emissions from electrical energy consumption [E6] and from embodied energy (Treloar 1994) associated with infrastructure construction [E4] are used to evaluate total life cycle GHG emissions.

Simulation dynamics components

The simulation dynamics component (Figure 2) is used to represent the temporal dynamics of the hydraulic simulation. This includes representation of the number of EPSs (e.g. for different seasons) and the length of each EPS. The dynamics of the water demand model, the emissions factor model and the electricity tariff model are represented as variables used to adjust the level of accuracy achieved by the simulation process. The EPS dynamics are represented as a function of the other dynamic variables; the requirements for the number of EPSs and length of each EPS are dependent on how the water demands, emissions factors and tariffs are to be modeled. The EPS dynamics represent the transition of input data accuracy into hydraulic simulation and evaluation accuracy. In order to accurately estimate costs and GHG emissions, input data must be accurate, which in turn requires appropriate hydraulic simulations in order to account for this accuracy (e.g. using a 24 hour EPS to account for the use of diurnal water demands). In this way, each variable can be modeled to replicate the real-life operational environment as accurately as possible. However, this way of simulating the WDS requires a single EPS running over the length of the project life, which is computationally expensive and would usually be time prohibitive for use with optimization. This would also require future water demands, emissions factors and electricity tariffs to be known for the entire length of the project life, which would not be possible when modeling such complex systems.

In order to achieve accurate evaluation, particularly for electrical energy consumption, which is cumulative over the lifespan of the WDS as discussed earlier, while minimizing the time taken to perform the optimization, a compromise must be made. The most common way of increasing simulation accuracy whilst minimizing computational expense is to use a single EPS, where short term (daily) changes to the water demand and tariff are modeled. However, this does not consider longer term changes, such as seasonal and yearly variations. In order to accurately estimate operational costs and GHG emissions, it is important to consider both short and long term variations by considering different EPS lengths and numbers of EPSs used. While four different EPS lengths and three different numbers of EPSs are shown, other lengths and numbers of EPSs can also be used, depending on the requirements of the modeled demand, emissions factor and tariff data used.

Government policy sub-components

Policies and governance external to the control of a water utility can have a significant effect on both the design and operation of a WDS and the evaluation of its associated costs and GHG emissions. These policies are represented by the government policy sub-component. Three policy types are focused on, including climate change policy [G1], economic discount rate policy [G2] and emissions discount rate policy [G3]. These policies can significantly affect the operational costs and GHG emissions of a WDS when accumulated over longer time-periods. Therefore, it is important to consider the effects of policies over the entire life of a WDS, including both design and operational phases. This component has been included to highlight the importance of being able to consider the effects of policy on the optimal design and operation of a WDS.

Review of methods used for GHG emissions reduction associated with water distribution systems

In this section, papers that have focused on the minimization of GHG emissions associated with water distribution systems using formal optimization approaches are reviewed in the context of the WCEN conceptual framework introduced in the previous section, discussing the achievements that have been made within this field and the aspects that require further research. Additional papers that focus on the minimization of GHG emissions associated with WDSs from an analysis or simulation perspective are also included in the review. In total, thirty one journal papers, eighteen conference papers and one report have been included in the review (see Additional file 1: Table S1). While the WCEN conceptual framework focuses on the minimization of GHG emissions, papers considering energy reduction have also been included. It should be noted that while many papers that focus on the reduction of costs associated with WDSs exist, only those explicitly considering the reduction of either energy (within the context of reducing environmental impact) or GHG emissions are reviewed in this paper. The components of the WCEN conceptual framework considered in each paper are summarized in Additional file 1: Table S1 and discussed in detail in the subsequent sections.

Consideration of options

The papers that have considered aspects represented within the options component of the WCEN framework are presented in Additional file 1: Table S1. As can be seen, the most widely used options associated with the design of WDSs are pipe sizing [Additional file 1: Table S1, Column C7] (Pr3, Pr4, Pr5, Pr10, Pr11, Pr12, Pr15, Pr16, Pr23, Pr24, Pr25, Pr26, Pr27, Pr31, Pr32, Pr33, Pr34, Pr35, Pr36, Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45, Pr46, Pr47, Pr48, Pr49–See Additional file 1: Table S1) and the selection of pipe material type [C6] (Pr3, Pr5, Pr10, Pr11, Pr12, Pr15, Pr16, Pr23, Pr24, Pr25, Pr26, Pr27, Pr31, Pr32, Pr33, Pr34, Pr35, Pr36, Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45, Pr46, Pr47, Pr48, Pr49). Other options, such as storage tank size and location [C5] (Pr4, Pr5, Pr19, Pr23, Pr24, Pr26, Pr33, Pr40, Pr44) and pump type selection [C3] (Pr2, Pr10, Pr27, Pr33, Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45, Pr46, Pr47, Pr48, Pr49) were also used. Operational management options (pump scheduling [C1] and trigger levels [C2]) were not used as frequently (Pr5, Pr9, Pr14, Pr31, Pr33, Pr34, Pr36, Pr46).

Trade-offs can occur between the design and operational phases which can be affected by the options chosen for each phase. For example, a major trade-off can occur between the minimization of pipe sizes to minimize capital costs/GHG emissions and the minimization of pump energy consumption to minimize operational costs/GHG emissions. Similarly, trade-offs can occur between the objectives of minimizing costs and GHG emissions. For example, similar to electricity tariffs, the emissions intensity of electricity is time-dependent. Therefore changing the time-of-use of pumps can alter both the GHG emissions and costs associated with the electricity consumed, even if the amount of electricity consumed does not change. If the rise and fall of emissions factors and electricity tariffs do not coincide, trade-offs will be seen between operational costs and GHG emissions. While these examples are easy to grasp, other trade-offs may be more implicit, requiring more thorough analysis in order to understand their causes and effects.

Pipe size selection

As can be seen in Additional file 1: Table S1, pipe size selection [C7] is the most common option considered. Twenty eight of the reviewed papers considered the pipe sizes used in a WDS. Twenty five of these used the pipe size option as a decision variable for optimization, with twenty considering the reduction of GHG emissions. The majority of these showed a trade-off between construction and operational GHG emissions and while reduced pipe sizes also reduced GHG emissions associated with pipe construction, total GHG emissions (construction and operation) increased due to an increase in pumping energy required to overcome the higher friction losses of the smaller pipe sizes. However, some other interesting results were reported. *Herstein et al.* (2009a) (Pr25) showed that an increase in pipe size resulted in an increase in environmental impact (using the environmental index (EI) measurement). The use of larger pipes in this system allowed more water to be pumped to the storage tank instead of directly to the demand node. However, as the tank was located further away from the pump location, this resulted in greater energy losses, and thus an increase in energy usage, resulting in the reported increase in EI value. Results from *Wu et al.* (2010b) (Pr45) showed a trade-off between construction and operational GHG emissions that result in an optimal design that uses a relatively small pipe size (compared to the choices available). This is probably due to a low demand, with larger pipe sizes resulting in a relatively low pump energy usage reduction compared to the increase in construction emissions associated with the additional material required for larger pipes. *Dandy et al.* (2008) (Pr11) used multi-objective optimization to reduce the pipe costs and energy of a gravity fed system. As there was no operational energy expenditure, the lowest energy solution corresponded to the lowest pipe embodied energy solution.

From the reviewed literature, it is clear that a trade-off exists between construction and operational GHG emissions due to the sizes of pipes used in WDSs. A general trend of reducing pipe sizes (lower construction GHG emissions) resulting in increased pump energy requirements (higher operational GHG emissions) has been noted. However, other factors such as system layout, system hydraulic capacity and consumer water demands directly affect the point at which an optimal trade-off is found. While the area of WDS GHG emissions optimization is relatively new, the majority of research focused on the option of pipe size selection, with results showing a clear benefit of considering GHG emissions when sizing pipes for both WDS design and upgrade scenarios.

Pipe material selection

Twenty eight of the reviewed papers considered the type of material used for the construction of pipes. The majority of these used the concept of embodied energy to evaluate the environmental impact of pipe material type selection [C6]. *Ambrose et al.* (2002) (Pr3) considered the specific values for pipe embodied energy for different material types. While embodied energy values vary between each material type, it was noted that the quoted embodied energy value for a specific material type is also dependent on the level of detail used during the calculation of the embodied energy. While many pipe material types are available, the option of material type was commonly limited to either ductile iron cement mortar lined (DICL), polyvinyl chloride (PVC) or polyethylene (PE) pipes (Pr10, Pr11, Pr23, Pr32, Pr36), though *Du et al,* (2013) (Pr12) also compared these along with concrete, reinforced concrete and cast iron pipe materials. However, many papers considered the selection of only one material type (Pr4, Pr5, Pr24, Pr25, Pr26, Pr27, Pr31, Pr32, Pr33, Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45, Pr46, Pr47, Pr48, Pr49). *Wu et al.* (2008a) (Pr40) noted that while DICL has a relatively low embodied energy value when compared to that of PVC and PE based pipes, it also has a relatively high unit mass, which can also affect a pipe's associated GHG emissions and needs to be considered. *Ambrose et al.* (2002) (Pr3) showed that despite the apparent benefit of DICL, it contained an embodied energy up to five times that of PVC and PE based pipes when the unit mass and hydraulic performance of each pipe type was considered. *Du et al.* (2013) (Pr12) found that ductile iron had the greatest (worst) global warming potential (GWP, based on embodied energy analysis) for smaller pipe diameters, while PVC had the greatest GWP for larger pipe diameters due to the pipe wall thickness used for these larger diameters. Despite high production energy demands and carbon dioxide emissions, concrete pipes were found to have the lowest (best) GWP between pipe diameters of 102mm and 1219mm. Case study results by *MacLeod et al.* (2010) (Pr32) and *Roshani et al.* (2011) (Pr36) both showed little difference in GHG emissions of optimal designs using PVC or DICL pipes, although the construction costs of PVC pipes were considerably lower than those of DICL pipes. *Dandy et al.* (2006) (Pr10) considered both PVC and DICL pipe materials for the energy reduction optimization of a WDS and found that the optimal design used only PVC pipes. While *Roshani et al.* (2011) (Pr36) and *MacLeod et al.* (2010) (Pr32) only evaluated GHG emissions associated with operations, *Dandy et al.* (2006) (Pr10) evaluated energy associated with both capital (construction) and operations.

While only six of the reviewed papers focusing on optimization considered multiple material type choices for the construction of pipes, different studies showed different pipe materials to be beneficial for the reduction of GHG emissions. The work by *Ambrose et al.* (2002) (Pr3) showed a large difference in the embodied energy of DICL and PVC material types. PVC pipes have been shown to have a lower embodied energy value per unit length of pipe, which would suggest that they also have a lower environmental impact with respectively lower GHG emissions over DICL pipes. This finding was also shown by *Dandy et al.* (2006) (Pr10). However, the literature also suggested that pipe material type has little effect on the hydraulics of a WDS, resulting in little difference in operational GHG emissions. This suggests that while the difference in hydraulic performance (i.e. frictional losses) between material types may only be small, the differences in embodied energy values of the pipes can have a substantial effect on the overall GHG emissions associated with a particular design.

Pump type selection

Of the reviewed papers, fourteen considered the option of pump type selection during optimization. Pump type selection [C3] has been used in conjunction with pipe size selection by *Wu et al.* (2010a; 2010b; 2008a; 2008b; 2009; 2010c; 2012a; 2008c; 2010d; 2012b; 2013) (Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45, Pr46, Pr47, Pr48, Pr49), *Kang and Lansey* (2012) (Pr27) and *Marchi et al.* (2014) (Pr33), while using multi-objective optimization to find the optimal trade-off between construction and operational GHG emissions. Additionally, *Richardson and Hodkiewicz* (2011) (Pr35), while not considering pump type selection per se, considered the effect of pump overhaul scheduling, and hence the trade-offs between pump replacement capital and loss of efficiency due to wear, on the minimization of cost and GHG emissions. This study showed that similar trade-offs exist between costs and GHG emissions when considering pump overhaul scheduling as when considering other more often used options, such as selecting pipe sizes and pump types. *Wu et al.* (2010c) (Pr46) and used trigger levels to control the operation of a pump over a 48-hour EPS, while *Marchi et al.* (2014) (Pr33) considered the use of both pump scheduling and trigger levels to control pump operations. These studies highlighted the importance of considering both pump type selection and pump operational management together. The other studies stated above used steady-state analysis without the use of pump operational management, with the range of GHG emissions corresponding to optimal solutions being far smaller than those obtained while incorporating pump operational management. The ability to reduce GHG emissions by considering pump type selection and pump operational management options together has not been considered in depth in the reviewed literature. However, results showed that this consideration may lead to further reductions in GHG emissions, and it is therefore recommended that this be further explored.

Pump operational management

Eight of the reviewed papers considered the use of pump operational management. Of these, seven used storage trigger levels [C2] to implicitly control pumps, while four considered the use of pump scheduling [C1] to explicitly control the time of operation. *Ertin et al.* (2001) (Pr14) and *Ramos et al.* (2011) (Pr34) used both pump schedules and trigger levels, comparing the energy efficiency of each management type. *Ertin et al.* (2001) (Pr14) showed that a 12.5% energy saving can be made by using pump scheduling instead of storage tank trigger levels. Conversely, *Ramos et al.* (2011) (Pr34) reported that while no pump electrical energy savings were made by using pump scheduling instead of trigger levels, operational costs can be significantly reduced by pumping at off-peak electricity times and hence reducing the average unit cost of consumed electrical energy. Trigger level options were also used for the purpose of reducing GHG emissions (Pr31, Pr33, Pr34, Pr36, Pr46) and energy usage (Pr9, Pr14). While literature considering operational management options has suggested a benefit to the consideration of pump operational management for the reduction of GHG emissions, little work has been undertaken to consider the effects of time-dependent operational factors, such as time-dependent emissions factors, on the optimal operational management of WDSs. However, as considering the time-dependency of electricity tariffs has been shown to help select operational management choices that reduce operational costs (Pr34), by extension, consideration of the time-dependency of emissions factors could help to reduce operational GHG emissions. As pumps use the majority of consumed energy during WDS operation, careful consideration of pump control represents a possibility for further GHG emissions reduction and therefore warrants further research.

Infrastructure considerations

Water distribution system complexity

WDSs have been represented within the literature in different forms, from simple single pipe systems to complex, real-world networks. As can be seen from Additional file 1: Table S1, of the reviewed literature using multi-objective (MO) optimization and the objective of GHG emissions reduction, eleven examples used complex WDSs [C16], while fourteen of the reviewed papers used only simplified WDSs [C15] for case-studies. Simplified networks have been used for proof of concept and assessment of the impact of policy factors, such as discount rates. More complex networks were used for both initial design and system upgrade scenarios. Case-studies by *Abadia Sanchez et al.* (2008) (Pr1), *Cabrera et al.* (2010) (Pr9) and *Filion et al.* (2004) (Pr17) used simplified representations of WDSs for the purpose of system energy analysis. *Ertin et al.* (2001) (Pr14), *Filion* (2007; 2008) (Pr15, Pr16) and *MacLeod and Filion* (2011) (Pr31) used simplistic systems in order to analyze the effects of specific factors, such as pump scheduling, population density and urban form, on the energy usage and/or GHG emissions associated with a WDS. *Herstein et al.* (2009a) (Pr25) used a one pump, one tank and one demand node WDS in order to test the concept of the environmental impact index; used to rank a WDS based on several sustainability criteria, including the release of GHG emissions. This was later applied to an MO optimization problem using the Anytown WDS (Pr26), as described by *Walski et al.* (1987). *Biehl and Inman* (2010) (Pr5), *Boulos and Bros* (2010) (Pr7), *Ektesabi et al.* (2009) (Pr13) and *Young* (2010) (Pr50) discussed possible energy reduction and GHG emissions abatement strategies, and the considerations that need to be made when applying them to real-world systems. *Ghimire* (2010) (Pr21) and *Ghimire and Barkdoll* (2008; 2009; 2010) (Pr18, Pr19, Pr20) simulated a number of WDSs ranging in size and complexity, analyzing the effects of various factors on energy usage, such as pump power, storage tank parameters and water demands. *Wu et al.* (2013) (Pr49) optimized a South Australian WDS, among others, for the minimization of costs and GHG emissions and the maximization of hydraulic reliability. *MacLeod et al.* (2010) (Pr32) and *Roshani et al.* (2011) (Pr36) optimized the Amherstview, Canada, WDS as an upgrade problem, looking at the effect of pipe selection on GHG emissions, while *Dandy et al.* (2006) (Pr10) optimized the Anabranch rural WDS in Australia as a design problem, looking at the effect of pipe selection on capital and operational energy usage, with comparison to an original design, which focused on the reduction of capital and operational costs.

In summary, there has been limited consideration of complex WDSs. While they were used for the simulation and analysis of energy usage and the analysis of GHG emissions, only eleven of the reviewed papers used complex systems in case-studies for the optimization of GHG emissions (Pr4, Pr5, Pr12, Pr23, Pr24, Pr26, Pr27, Pr32, Pr33, Pr36, Pr49). While simple case-studies have shown the benefits of considering GHG emissions, only the use of more complex case study systems will be able to show the feasibility of considering GHG emissions associated with real-world WDSs outside of the research arena. Therefore, further research should be undertaken in order to understand the implications of considering GHG emissions on more complex systems.

Water demands

Daily water demand patterns [C17], also known as diurnal curves, were incorporated by nineteen of the reviewed papers into the simulation and optimization of energy usage and GHG emissions associated with WDSs (Pr2, Pr4, Pr5, Pr8, Pr9, Pr14, Pr19, Pr21, Pr22, Pr23, Pr24, Pr25, Pr31, Pr32, Pr33, Pr34, Pr36, Pr46, Pr49). Diurnal curves have become a popular way to increase the accuracy of modeling the time-dependency of water demands seen in the real world. This time dependency has become an important part of modeling the cost of operating WDSs, especially with the consideration of peak/off-peak electricity tariffs, where it is not only the total time of pump operation that is important, but also the time of use. *Ertin et al.* (2001) (Pr14) demonstrated a reduction in energy usage of 12.5% when considering pump time of use. This was done by careful consideration of storage tank levels, which required the use of diurnal curves to accurately simulate the change in tank levels over time. While the majority of literature considering GHG emissions opted for the use of steady-state water demands, *Herstein et al.* (2009a) (Pr24, Pr25), *MacLeod and Filion* (2011) (Pr31) and *Wu et al.* (2010c) (Pr46) included the use of diurnal curves while using extended period simulations (EPSs) when evaluating operational energy usage. While not commonly in use, demand variations [C18] over extended periods of time, such as monthly, seasonal and annual variations, have also been incorporated. *Alandi et al.* (2009b) (Pr2) used monthly demand variations in order to evaluate pump energy usage for each month in the year and *Filion et al.* (2004) (Pr17) used demands that were assumed to increase on a decade by decade basis. The demand variations were used to consider the difference in system requirements at each stage of pipe replacement during the life of the system. *Wu et al.* (2012b) (Pr47) incorporated seasonal demand variations as a way of assessing the benefits of using variable speed pumps. In this study, the benefit of being able to reduce the pump's speed was seen by a reduction in frictional energy loss, which in turn equated to a reduction in GHG emissions.

Nineteen of the reviewed papers used diurnal water demand patterns as a consideration of the time-dependency of consumer demands. This is important, as it allows the time-dependency of real-life water demands to be represented more accurately. The time-dependency of water demands over longer time periods is still rarely used, with only two optimization papers considering this (Pr17, Pr47). However, as shown by *Filion et al.* (2004) (Pr17) and *Wu et al.* (2012b) (Pr47), considering longer term water demand variations can affect the choice of optimal design options. Consideration of water demand variability is important for the accurate analysis of GHG emissions, as a WDS is a demand driven system and thus this consideration can directly affect the energy usage requirements of the system. Water demands may change over the operational life of a WDS (e.g. diurnal changes, seasonal changes and/or yearly changes) and these changes must be incorporated in order to more accurately reflect actual energy consumption. In order to achieve greater accuracy, future research will need to incorporate longer-term water demand changes along with the shorter-term changes that are presently used.

Electricity tariffs

Single, average tariff values [C12] have been predominantly considered when analyzing the operational costs associated with WDSs (Additional file 1: Table S1). Of the reviewed papers, only four considered peak/off-peak time-dependent tariffs [C13] (Pr6, Pr8, Pr33, Pr34). *Biehl and Inman* (2010) (Pr6) discussed the ways in which electricity is charged to the consumer, and suggested ways in which both energy usage and its associated costs can be reduced. Both time dependent charges, including peak and off peak tariffs, which charge for the actual amount of electricity used with a rate based on the time of usage, and time-independent charges, including demand charges, which charge for the highest demand reached over either the billing period, or a prescribed period of time, were considered. While a demand charge can account for 10-20% of a water utility's electricity costs, it is suggested that the majority of these costs can be attributed to tariff charges (Pr6). *Ramos et al.* (2011) (Pr34) showed that optimizing pump operations while considering peak/off-peak electricity tariffs can result in cost reductions by pumping during off-peak times. One study also looked at the effect of longer term changes to electricity costs. *Wu et al.* (2012a) (Pr48) used a fixed rate tariff, adjusted annually to model the effect of electricity price increases caused by the possible effects of carbon taxes and carbon trading schemes imposed on the electricity generation industry.

While literature using peak/off-peak electricity tariffs has shown that consideration of the time-dependency of electricity tariffs can be used to reduce operational costs (Pr34), there has been little research to assess the effects of time-dependent tariffs on the trade-offs between costs and GHG emissions. Although tariffs are only used to calculate costs associated with electricity usage, the trade-offs that often occur between costs and GHG emissions mean that the accurate analysis of operational costs is an important part of analyzing this trade-off. As with GHG emissions, operational costs are accumulated over the life of a WDS and as such, both the short-term and long-term time-dependencies of electricity tariffs must be considered if these costs are to be assessed accurately.

Greenhouse gas emissions factors

As can be seen from Additional file 1: Table S1, all of the reviewed papers which used emissions factors used single, average GHG emissions factors [C10] instead of considering short-term (e.g. diurnal) emissions factor variations. The only consideration of time-dependent emissions factors [C11] in the reviewed literature was by *Roshani et al.* (2011) (Pr36) and *Wu et al* (2012a; 2013) (Pr48, Pr49). In these studies, emissions factors were assumed to reduce annually, due to an increase in the proportion of renewable energy sources for electricity generation. However, short-term (e.g. daily) variations of emissions factors were not considered. Within the literature, there has been little discussion of the short-term variability of emissions factors, which considers the varying contribution of different generation types for different demand loads during the day. However, similar to electricity tariffs, emissions factors can vary over shorter (e.g. daily) time periods. Similar to the effect of electricity tariffs on costs (Pr34), these changes to emissions factors have the potential to affect the optimal operation of pumps when considering the minimization of GHG emissions. GHG emissions are accumulated over the lifetime of a WDS's operation. As such, the time of use of electricity generated from fossil fuel sources has the potential to considerably alter the GHG emissions associated with the operation of a WDS. For WDS optimization, there lies a potential to find reduced GHG emissions operational strategies by considering the impact of time-dependent GHG emissions factors. However, this has not been studied thus far.

Sources of electrical energy generation

While the analysis of pump energy usage was widely considered, only seven of the papers reviewed considered the source of electricity [C9] consumed by pumping activities (Pr25, Pr26, Pr30, Pr34, Pr36, Pr38, Pr48). These papers commonly accounted for the types of electricity generation by considering their associated emissions factors. This consideration allows the emissions factor for a specific electricity generation region to be evaluated, allowing for increased accuracy when evaluating GHG emissions. *Stokes and Horvath* (2005) (Pr38) used life cycle analysis (LCA) to evaluate the energy use and GHG emissions for two case-study WDSs in California. GHG emissions were evaluated for multiple activities throughout the life of the WDSs; including through the use of electricity for pumping, which was calculated considering the mix of electricity generation types for the state of California. *Lundie et al.* (2006) (Pr30) also used LCA to evaluate the environmental impacts of Sydney Water's activities, including the WDS used to supply the city. In this study, both conventional and alternative power sources, including the combustion of biosolid remains from wastewater treatment, were considered. *Ramos et al.* (2011) (Pr34) compared operational management optimization while considering different power sources, including from the electricity grid, a water turbine used to recover energy normally lost through a pressure reducing device and a wind turbine used to provide renewable energy generation. The results of this study concluded that using renewable energy (in the form of a wind turbine) can significantly reduce GHG emissions, as significantly less electricity is sourced from the electricity grid. *Herstein et al.* (2009a; Lundie et al. 2004) (Pr25, Pr26) included the consideration of electricity generation sources during the optimization of case-study WDSs, in which system cost and environmental impact were evaluated. The environmental impact objective used considers several factors, including air pollution and non-renewable resource depletion, associated with the use of electricity. The consideration of electricity generation source was used in the evaluation of these factors, where the type of generation impacts the amount of pollution and resource depletion.

Pump energy usage [C14] is often calculated as part of the analysis of a WDS. While the energy usage of a pump is generally considered, the consideration of where this energy has come from is often overlooked. This is important if the GHG emissions associated with the usage of electricity are to be calculated more accurately. However, only seven of the reviewed papers considered different sources of electricity generation (Pr25, Pr26, Pr30, Pr34, Pr36, Pr38, Pr48). While consideration was given to the location of electricity generation sources (generally on a regional basis), little research has been conducted into the influence of time on these sources. A WDS can operate over many decades, with GHG emissions associated with its operation being accumulated over this period. Because of this, accurate calculation of these GHG emissions will require consideration of the source of electricity generation in terms of both location and time. In order to accurately estimate GHG emissions, greater consideration needs to be given to the sources of electricity generation in order to increase the accuracy of GHG emissions analysis.

Water distribution system analysis considerations

Extended period simulations

Of the reviewed papers that used hydraulic simulation, thirty six used either single steady state or extended period simulation [C19], of no more than 96 hours in length, to evaluate energy use over the projected lifespan of the WDS. The majority of these have not considered variable lengths of EPS and the effect this can have on the accuracy of evaluation. However, two papers have discussed EPS length [C21]. *Cabrera et al.* (2010) (Pr10) used two EPS lengths during a WDS energy audit; one day and one year, with energy inputs and outputs being evaluated using both simulation lengths. The proportion of total input/output energy associated with each source/consumer was compared over the different EPS periods. *Hernandez et al.* (2010) (Pr22) also used various EPS lengths while conducting a WDS energy audit. In this case, short-term and long-term EPSs of one day and one month, respectively, were used.

The use of multiple hydraulic simulations [C22] can also help to improve the accuracy of evaluation. For example, the simulation of different demand patterns over multiple seasons within a year can be used to reflect the changing demands that occur in the real world; however, this requires a separate EPS for each demand pattern, which will increase the computational time required to run an optimization algorithm. Most of the reviewed literature has used a single hydraulic simulation in order to evaluate pump energy requirements. Exceptions to this include *Alandi et al.* (2009b) (Pr2), who simulated multiple demand scenarios for each month in the year; and *Wu et al.* (2012b) (Pr47), who simulated the use of both FSPs and VSPs over four demand scenarios to represent seasonal variation, using the demand variations to show the energy saving benefits of using VSPs over FSPs. *Filion et al.* (2004) (Pr18) also used multiple simulations for the purpose of analyzing multiple demand scenarios. Increases in demand were used at each system upgrade juncture, which require possible pipe size changes in order to fulfil hydraulic demands for the next maintenance period.

Few papers have considered the length and number of EPSs used to analyze the operation of a WDS. However, these constitute important considerations. As discussed in Simulation dynamics components, the use of water demand, electricity tariff and GHG emissions factor data that consider time-dependent variations will require simulations that encompass these time variations. Without considering these, the increased accuracy of the input data will not be translated into more accurate analysis. As such, research must consider the length and number of EPSs used, with consideration given to the requirements of the input data used.

Government policy considerations

Economic discounting

As can be seen from Additional file 1: Table S1, twelve papers considered the effects of economic discounting [C28], using discount rates ranging from 1.4% to 10%. Comparisons were also made between the results found by using different discount rates (Pr31, Pr32, Pr36, Pr39, Pr40, Pr41, Pr42, Pr43, Pr44, Pr45). Results commonly showed higher annual operating cost designs resulting from the use of higher discount rates. This result is expected, as a higher discount rate will place less value on future (operating) costs compared to present (construction) costs, resulting in a bias towards lower construction cost designs. This results in designs that require the use of more electrical energy for pumping requirements. The use of higher discount rates translates to greater pump energy requirements, with an associated increase in GHG emissions. The largest proportion of GHG emissions commonly results from electricity usage during operations. Reducing total GHG emissions can often be achieved by reducing operational GHG emissions, which has been seen with the use of lower discount rates. In practice, higher discount rates are applied to economic cost analyzes for water distribution systems (Pr43), however, the results shown within the reviewed literature would suggest that a lower discount rate should be applied to economic costs if importance is also to be placed on reducing GHG emissions.

Eleven of the sixteen papers which used optimization to reduce GHG emissions also considered the use of economic discount rates, which represents the majority of papers. Present value analysis (PVA), used to evaluate the present worth of future activities, is critical to the analysis of trade-offs between construction and operational costs, as the discount rate used can have a dramatic effect on the weighting given to operation. As such, sensitivity analyzes of economic discount rates will still be necessary in order to analyze these trade-offs in a robust fashion.

Greenhouse gas emissions discounting

While not as commonly considered as economic discounting, PVA was also applied directly to the evaluation of GHG emissions [C29] in nine of the reviewed papers. A discount rate of zero is often used for GHG emissions impact evaluation (Pr44), placing an equal weighting on present GHG emissions and those produced in the future. Use of positive discount rates was also suggested (reducing the value of future emissions), which reflects the belief that future technology will be able to better abate the impact of higher GHG emission concentrations in the atmosphere (Pr44). Of the reviewed papers that considered GHG emission discounting, the majority used a rate of zero. *Wu et al.* (2008c) (Pr41) used two discounting scenarios; economic costs and GHG emissions costs (using a carbon tax) were discounted at the same rate for the first scenario, while GHG emissions costs were given a zero discount rate in the second scenario. The results of this study show that the second scenario leads to results where a higher proportion of total costs are due to GHG emissions. Another study by *Wu et al.* (2010a) (Pr44) used the same scenarios as described above, while GHG emissions were discounted directly, however, a direct comparison between the two scenarios was not presented.

As with economic discount rates, the direct application of discount rates to GHG emissions is an important aspect of the analysis process. Trade-offs exist between construction and operational GHG emissions and also between costs and GHG emissions. As such, careful consideration needs to be given to the discount rates applied to GHG emissions. However, as discussed above, few studies have taken the effects of GHG emissions discounting into account. As with economic PVA, there remains a need to consider the effects of GHG emissions PVA with the use of sensitivity analyzes and the consideration of the effects different discount rates have on the trade-offs between the construction and operation phases, and the objectives of cost and GHG emission reduction.

Carbon costing

Carbon tax and carbon trading policies [C27] have been analyzed in six of the reviewed papers. This was done by applying a monetary cost to each unit of GHG emissions produced, including that from construction, calculated from embodied energy, and operation, calculated from electricity usage. *Roshani et al.* (2011) (Pr36) used three carbon tax scenarios as proposed by the Canadian National *Round Table on the Environment and the Economy* (2009), comparing optimization results for each. However, this study found little evidence that the use of a carbon tax will result in GHG emissions benefits, concluding that for the system upgrade problem considered, there was already adequate hydraulic capacity, suggesting that upgrading the system would do little to reduce pump energy requirements. *MacLeod and Filion* (2011) (Pr31) used the same carbon tax scenarios as *Roshani et al.* (2011) (Pr36), applied to a water transfer main design scenario. Results of this study showed that a larger pipe diameter was chosen for the two higher taxed scenarios when the lowest discount rate was used, resulting in fewer GHG emissions being produced during operation over the lifetime of the project. *Wu et al.* (2008c) (Pr41) applied five different carbon taxes to a WDS optimization problem. As with *MacLeod and Filion* (2011) (Pr31), a higher carbon tax showed some propensity to result in the selection of larger pipe diameters, thus reducing pump energy requirements. *Wu et al.* (2012a) (Pr48) used an increase in electricity costs to simulate the effect of a carbon trading scheme, with electricity tariffs increasing annually by a set percentage. Results from this study suggest that no significant GHG emissions reductions would be seen by considering higher electricity costs, as the use of higher electricity tariffs increased the operational cost of each design solution, however, it did not affect the order of the solutions.

The results from the above studies suggest that the use of carbon taxes and carbon trading schemes may help to reduce GHG emissions, however, there are other factors that need to be considered, which may also play a significant role in the choice of optimal solutions. These include the use of different discount rates, the emissions factors applied to the use of electricity and the impact of changing pipe sizes on a system's hydraulic capacity. While these studies have helped to recognise the benefits of carbon taxes and carbon trading schemes, more research is needed to understand what level of carbon tax and carbon costing is required to see optimal benefits in relation to the reduction of GHG emissions, and whether this can be applied to all cases or is case-study specific.

Summary and conclusions

The rising level of GHG emissions within the atmosphere of the Earth is a common problem faced by human-kind, with no easy solutions yet to be discovered. As such, it is the responsibility of each sector of industry to help reduce their contribution of GHG emissions released into the atmosphere. Water utilities are no exception. Research into the GHG emissions associated with WDSs is a new, yet important field. There remain many aspects of GHG emissions reduction that are yet to be properly researched. The importance of the field, coupled with the responsibility of water utilities to reduce their carbon footprint, means that these areas should become a priority for future research efforts.

Water distribution systems (WDSs), whilst providing an essential service to modern cities, contribute significantly to the release of GHG emissions. Optimization has been used as a way to more efficiently design and operate WDSs by reducing both costs and GHG emissions. This paper has presented the WCEN conceptual framework (Water distribution cost-emissions nexus (WCEN) conceptual framework), a conceptual tool used to analyze the components which affect the costs and GHG emissions associated with WDSs, and has reviewed current literature which considers the use of formal optimization methods for the reduction of GHG emissions (and energy usage, which is linked directly to GHG emissions in most cases) associated with WDSs (Review of methods used for GHG emissions reduction associated with water distribution systems). The review of the selected papers has outlined gaps in the current literature, which are summarized in Recommendations for future research.

While not an analytical tool itself, the WCEN conceptual framework provides a representation of all the components required to accurately evaluate the GHG emissions and costs associated with WDSs. This includes the integration of electricity generation infrastructure, used to more accurately represent the factors affecting GHG emissions associated with electricity usage; the introduction of more accurate, time-dependent input data, including water demands, electricity tariffs and GHG emissions factors; the ability to modify the hydraulic simulation process to fit the requirements made by the use of more accurate input data; the analysis of outside policies such as present value discounting policy and carbon trading policy; and the integration of these aspects into one complete framework.

Recommendations for future research

The literature reviewed in this paper has shown the benefits of reducing climate change effects that have come with the explicit consideration of GHG emissions in the optimization of WDSs. While trade-offs often exist between costs and emissions, it has been shown that the consideration of GHG emissions does not need to be at the detriment to cost savings. While the reviewed literature has introduced the concept of evaluating the GHG emissions associated with a WDS, there is scope for improvements to be made in the field of WDS simulation and optimization. Improvements need to be made so that GHG emissions are evaluated with the same degree of accuracy as costs. Greater accuracy will be found by both improving the input data used and careful consideration of the modeling process. An increase in accuracy will not only allow solutions to be viewed with greater confidence, but will also allow better solutions to be found.

Based on the review of the fifty papers on the reduction of energy usage and GHG emissions associated with the construction and operation of water distribution systems considered in this paper, the following recommendations for future research are made.

1) Costs, associated with both the design and operation of WDSs, have been well considered within the literature. Similarly, GHG emissions associated with the design of WDSs have been well considered, both in terms of factors affecting design GHG emissions (e.g. embodied energy analysis) and the choices available to control design GHG emissions (e.g. choosing pipe diameters). However, GHG emissions associated with the operation of WDSs have been given little consideration beyond simplistic evaluation. While considerations of material types and their respective production methods have been made in order to accurately evaluate design GHG emission, similar accuracy has not been afforded to operational GHG emissions. Considering the sources of electricity used for pumping purposes is critical, as they can have a significant impact on the emissions intensity of electricity being consumed. Future research should focus on the consideration of the sources of electricity, so that operational GHG emissions can be evaluated as accurately as costs and design GHG emissions.
2) Consideration should be given to the time-dependency of GHG emissions factors used for the evaluation of operational GHG emissions resulting from the operation of pumps. As discussed in Greenhouse gas emissions factors, current research predominantly treats emissions factors used to calculate GHG emissions as a single, average value. The sources of electricity (see recommendation 1) need to be considered if the time-dependency of emissions factors is also to be considered. However, as discussed in Sources of electrical energy generation, there is a lack of consideration of the source (s) of electricity used for pumping. Both of these gaps mean that the GHG emissions associated with electricity usage are not being accurately evaluated, with little consideration being given to both the time and place of electricity usage. In reality, emissions factors fluctuate with time and location according to the contribution of different generation types supplying to the electricity grid. As discussed previously, the time-variability of electricity tariffs has been successfully used to reduce the cost of WDS operations. Similar to this, the modeling of time-variability of emissions factors could not only increase the accuracy of operational GHG emissions evaluation, but could allow pump operational strategies to be explored, using potential times of low emissions energy as a way to reduce GHG emissions without the necessity of reduced energy consumption. While emissions factors may be difficult to accurately model due to the complex nature of the electricity generation industry, they may be modeled using similar ideas to those employed for water demands. These could include diurnal curves for hourly fluctuations through the day; multipliers used to adjust the peaks for different times of the year; and predictions for future

increases/decreases over the coming years and decades.

3) If the time-dependency of emissions factors is to be considered, then it is also necessary to consider the time-dependency of water demands. As water demands affect the timing and magnitude of water requirements placed on the WDS, they can directly affect the energy requirements of pumps and as such, affect the optimal use of pumps. Additionally, as the driver for the entire system, the accuracy of modeling a WDS is dependent on the modeling accuracy of water demands. As discussed in Water demands, while diurnal curves are now widely used to model the variation in water demands over the length of a day, other demand variations have not been widely considered within the reviewed literature. As GHG emissions are accumulated over the life of a WDS, longer term variations, such as seasonal and annual variations, should be modeled in order to accurately simulate the effect that changing water demands have on the amount of GHG emissions produced over the operational lifetime of a system.
4) In order to benefit from the additional accuracy afforded by considering time-dependent emissions factors and water demands, the time-of-use of pumps also needs to be considered. Pumps can be controlled to both reduce energy usage through unnecessary friction losses due to high pipe velocities and to use electricity during low emissions factor times to reduce operational GHG emissions. However, pumps also need to be controlled so that the ever-changing water demands placed on the WDS are met, without storage tanks running empty or below a minimum acceptable level. As such, the complex task of operating pumps to minimize costs and GHG emissions is ideally suited to formal optimization techniques. However, as discussed in Pump operational management, little consideration has been given to pump operational management options for the reduction of GHG emissions associated with WDSs. As the majority of GHG emissions (in a pumped system) are commonly associated with the use of pumps, there exists an opportunity to further reduce GHG emissions by considering optimal operational management of pumps within WDSs.
5) As discussed in Extended period simulations, little consideration has been given to the hydraulic simulation processes used for the evaluation of GHG emissions. Few improvements in the simulation processes applied to WDSs (including simulation length and the number of simulations used) have been considered in the reviewed papers. If the use of more accurate information, such as time-dependent GHG emissions factors and seasonal/annual water demand variations is to be considered, careful consideration of the simulation process is also required. The necessity to modify simulation practices when incorporating new input data has been highlighted in Figure 2, where the addition of input information complexity is matched against simulation requirements necessary to fully exploit the additional information. As such, if recommendations 1 to 4 are to be considered, it will also be necessary to further consider the requirements of the simulation processes used to evaluate operational costs and GHG emissions.
6) As discussed in Government policy considerations, government policies have been considered in the reviewed papers by including such factors as discount rates for both economic and GHG emissions discounting, and carbon pricing by considering carbon taxes and carbon trading schemes. While one or more of these factors have been included by thirteen of the sixteen papers that have used optimization to reduce GHG emissions, they have a significant effect on the evaluation of costs and GHG emissions. As such, it is important that policy factors are continually considered.

Additional file

Additional file 1: Table S1. Matrix representation of the reviewed literature (Basupi et al. 2013; Basupi et al. 2014; Bunn and Reynolds 2009; Herstein and Filion 2011; Kiselychnyk et al. 2009; Kumar and Karney 2007; Simpson 2008).

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

CSS carried out development of the WCEN conceptual framework, review of literature and drafted the manuscript. ARS participated in the development of the WCEN conceptual framework and helped to draft the manuscript. HRM participated in the development of the WCEN conceptual framework and helped to draft the manuscript.

Acknowledgements

The authors would like to thank the anonymous reviewers for their valuable contributions to this paper. The authors would also like to thank the University of Adelaide and the Goyder Institute for Water Research for their financial support of this research.

Responsible editor: Michael Piasecki.

Received: 12 October 2013 Accepted: 25 March 2014
Published: 23 May 2014

References

Abadía Sánchez R, Rocamora Osorio C, Ruiz Canales A, Puerto Molina H, Melián Navarro A: **Energy efficiency in irrigation: calculation approach in water distribution system.** In *Agricultural and Biosystems Engineering for a Sustainable World International Conference on Agricultural Engineering; 23-25 June.* Hersonissos, Crete, Greece: European Society of Agricultural Engineers (AgEng); 2008:OP-1380.

Alandi PP, Pérez PC, Álvarez JFO, Hidalgo MÁM, Martín-Benito JMT: **Pumping selection and regulation for water-distribution networks.** *J Irrig Drain Eng* 2005, **131:**273–281.

Ambrose MD, Salomonsson GD, Burn S: *Piping systems embodied energy analysis.* CSIRO Manufacturing and Infrastructure Technology: Highett, Australia; 2002.

Basupi I, Kapelan Z, Butler D: **Reducing life-cycle carbon footprints in the redesign of water distribution systems.** *J Water Climate Change* 2013, **4:**176–192.

Basupi I, Kapelan Z, Butler D: **Reducing life-cycle carbon footprint in the (re) design of water distribution systems using water demand management interventions.** *Urban Water J* 2014, **11:**91–107.

Biehl WH, Inman JA: **Energy optimization for water systems.** *J Am Water Works Assoc* 2010, **102:**50–55.

Boulos PF, Bros CM: **Assessing the carbon footprint of water supply and distribution systems.** *J Am Water Works Assoc* 2010, **102:**47–54.

Bunn S, Reynolds L: **The energy-efficiency benefits of pump-scheduling optimization for potable water supplies.** *IBM J Res Dev* 2009, **53:**5.1–5.13.

Cabrera E, Pardo MA, Cobacho R, Cabrera E Jr: **Energy audit of water networks.** *J Water Resour Plan Manag* 2010, **136:**669–677.

Dandy GC, Roberts A, Hewitson C, Chrystie P: **Sustainability objectives for the optimization of water distribution networks.** In *Proceedings of 8th Annual Water Distribution Systems Analysis Symposium; August.* Cincinnati, USA: American Society of Civil Engineers; 2006.

Dandy GC, Bogdanowicz A, Craven J, Maywald A, Liu P: **Optimizing the sustainability of water distribution systems.** In *10th Annual Symposium on Water Distribution Systems Analysis; 17-20 August.* Kruger National Park, South Africa: American Society of Civil Engineers; 2008.

Du F, Woods GJ, Kang D, Lansey KE, Arnold RG: **Life cycle analysis for water and wastewater pipe materials.** *J Environ Eng* 2013, 139:703–711.

Ektesabi M, Moradi-Motlagh A, Abdekhodaee A: **Energy and sustainability through integrated water network management.** *WIT Trans Ecol Environ* 2009, **121:**175–186.

Ertin E, Dean AN, Moore ML, Priddy KL: **Dynamic optimization for optimal control of water distribution systems.** In *Applications and Science of Computational Intelligence IV*; 2001:142–149.

Filion YR: **Connections between population density, energy use, and GHG emissions in water networks.** In *CSCE 2007 Annual General Meeting and Conference; 6-9 June.* Yellowknife: NWT; 2007:151–160.

Filion YR: **Impact of urban form on energy use in water distribution systems.** *J Infrastruct Syst* 2008, **14:**337–346.

Filion YR, MacLean HL, Am A, Karney BW, Asce M: **Life-cycle energy analysis of a water distribution system.** *J Infrastruct Syst* 2004, **10:**120–130.

Ghimire SR: **Relationship between pump horsepower and energy usage in municipal water networks.** In *World Environmental and Water Resources Congress.* Providence, Rhode Island, USA: American Society of Civil Engineers; 2010:4180–4184.

Ghimire SR, Barkdoll BD: **Effect of demand on energy use in municipal water distribution systems.** In *World Environmental and Water Resources Congress.* Honolulu, Hawai'i: American Society of Civil Engineers; 2008.

Ghimire SR, Barkdoll BD: **Impact of storage tanks on energy consumption in municipal water distribution systems.** In *World Environmental and Water Resources Congress.* Kansas City, Missouri, USA: American Society of Civil Engineers; 2009:158–164.

Ghimire SR, Barkdoll BD: **Sensitivity analysis of municipal drinking water distribution system energy use to system properties.** *Urban Water J* 2010, **7:**217–232.

Hernández E, Pardo M, Cabrera E, Cobacho R: **Energy assessment of water networks, a case study**. In *Water Distribution System Analysis.* Tuscon, AZ: American Society of Civil Engineers; 2010:1168–1179.

Herstein LM, Filion YR: **Life-cycle assessment of common water main materials in water distribution networks.** *J Hydroinf* 2011, **13:**(3)346–357.

Herstein LM, Filion YR, Hall KR: **Evaluating environmental impact in water distribution system design.** *J Infrastruct Syst* 2009a, **15:**241–250.

Herstein LM, Filion YR, Hall KR: **EIO-LCA based multi-objective design of water distribution systems with NSGA-II.** In *Computing and Control in the Water Industry 2009 'Integrating Water Systems'; September 1-3.* London, U.K: Taylor and Francis Group; 2009b:225–231.

Herstein LM, Filion YR, Hall KR: **Evaluating the environmental impacts of water distribution systems by using EIO-LCA-based multiobjective optimization.** *J Water Resour Plan Manag* 2011, **137:**162–172.

Kang D, Lansey K: **Dual water distribution network design under triple-bottom-line objectives.** *J Water Resour Plan Manag* 2012, **138:**162–175.

Kiselychnyk O, Bodson M, Werner H: *Overview of energy efficient control solutions for water supply systems.* Kremenchuk, Ukraine: Transactions of Kremenchuk State Polytechnic University; 2009:40–46.

Kumar G, Karney B: **Electricity usage in water distribution networks.** In *Electrical Power Conference.* Montreal, Quebec, Canada: IEEE; 2007:97–102.

Lundie S, Peters GM, Beavis PC: **Life cycle assessment for sustainable metropolitan water systems planning.** *Environ Sci Technol* 2004, **38:**3465–3473.

MacLeod SP, Filion YR: **Issues and implications of carbon-abatement discounting and pricing for drinking water system design in Canada.** *Water Resour Manag* 2011, **26:**44–61.

MacLeod S, Roshani E, Filion YR: **Impact of pipe material selection on greenhouse gas mitigation in water networks under uncertain discount rates and carbon prices.** In *Water Distribution System Analysis.* Tuscon, AZ: American Society of Civil Engineers; 2010:1014–1027.

Marchi A, Salomons E, Ostfeld A, Kapelan Z, Simpson AR, Zecchin AC, Maier HR, Wu ZY, Elsayed SM, Song Y: **The battle of the water networks II (BWN-II).** *J Water Resour Plan Manag* 2014.

National Round Table on the Environment and the Economy: Achieving 2050: *A carbon pricing policy for Canada.* Ottawa: Library and Archives Canada Cataloguing in Publication; 2009.

Ramos HM, Kenov KN, Vieira F: **Environmentally friendly hybrid solutions to improve the energy and hydraulic efficiency in water supply systems.** *Energy Sustain Dev* 2011, **15:**436–442.

Richardson SJ, Hodkiewicz MR: **Modeling tool to support budgeting and planning decisions for pump overhauls.** *J Water Resour Plan Manag* 2011, **137:**327–334.

Roshani E, MacLeod SP, Filion YR: **Evaluating the impact of climate change mitigation strategies on the optimal design and expansion of the Amherstview, Ontario water network: a Canadian case study.** *J Water Resour Plan Manag* 2011, 138:100–110.

Simpson AR: **Selecting a discount rate for evaluating water distribution projects — The sustainability controversy**. In *Water Distribution System Analysis; August 17-20.* Edited by Van Zyl K. American Society of Civil Engineers; 2008.

Stokes J, Horvath A: **Life cycle energy assessment of alternative water supply systems.** *Int J Life Cycle Assess* 2006, **11:**335–343.

Stokes CS, Simpson AR, Maier HR: **An improved framework for the modelling and optimisation of greenhouse gas emissions associated with water distribution systems**. In *6th International Congress on Environmental Modelling and Software (iEMSs).* Leipzig, Germany: International Environmental Modelling and Software Society; 2012.

Treloar GJ: *Energy analysis of the construction of office buildings: Master of Architecture Thesis.* Melbourne, Australia: Deakin University; 1994.

Walski TM, Brill JED, Gessler J, Goulter IC, Jeppson RM, Lansey K, Lee HL, Liebman JC, Mays L, Morgan DR, Ormsbee L: **Battle of the network models: epilogue.** *J Water Resour Plan Manag* 1987, **113:**191–203.

Wu W, Simpson AR, Maier HR: **Multi-objective genetic algorithm optimisation of water distribution systems accounting for sustainability.** In *Water Down Under 2008.* Adelaide, Australia: Incorporating 31st Hydrology and Water Resources Symposium and the 4th International Conference on Water Resources and Environment Research (ICWRER); 2008a.

Wu W, Maier HR, Simpson AR: **Genetic algorithm optimisation of water distribution systems accounting for greenhouse gas emissions.** In *9th National Conference on Hydraulics in Water Engineering; 23-26 September.* Darwin Convention Centre, Australia: Engineers Australia; 2008b.

Wu W, Simpson AR, Maier HR: **Water distribution system optimisation accounting for a range of future possible carbon prices.** In *10th Annual Symposium on Water Distribution Systems Analysis; 17-20 August.* Kruger National Park, South Africa: American Society of Civil Engineers; 2008c.

Wu W, Maier HR, Simpson AR: **Multi-objective water distribution system optimisation accounting for carbon emissions under different electricity tariffs.** In *Ozwater '09; March 16-18.* Melbourne, Australia: Australian Water Association; 2009.

Wu W, Simpson AR, Maier HR: **Accounting for greenhouse gas emissions in multiobjective genetic algorithm optimization of water distribution systems.** *J Water Resour Plan Manag* 2010a, **136:**146–155.

Wu W, Simpson AR, Maier HR: **Reducing carbon footprint from water distribution systems by using a lower discount rate.** In *Practical Responses to Climate Change National Conference 2010; 29 September-1 October.* Melbourne, Australia: Engineers Australia; 2010b.

Wu W, Maier HR, Simpson AR: **Single-objective versus multiobjective optimization of water distribution systems accounting for greenhouse gas emissions by carbon pricing.** *J Water Resour Plan Manag* 2010c, **136:**1–11.

Wu W, Simpson AR, Maier HR: **Accounting for carbon: Selecting the appropriate discount rate for multi-objective optimisation of water distribution systems.** In *Ozwater '10; March 08-10.* Brisbane, Australia: Australia Water Association; 2010d.

Wu W, Maier HR, Simpson AR: **Sensitivity of optimal tradeoffs between cost and greenhouse gas emissions for water distribution systems to electricity tariff and generation.** *J Water Resour Plan Manag* 2012a, **138:**182–186.

Wu W, Simpson AR, Maier HR, Marchi A: **Incorporation of variable-speed pumping in multiobjective genetic algorithm optimization of the design of water transmission systems.** *J Water Resour Plan Manag* 2012b, **138:**543–552.

Wu W, Maier HR, Simpson AR: **Multiobjective optimization of water distribution systems accounting for economic cost, hydraulic reliability, and greenhouse gas emissions.** *Water Resour Res* 2013, **49:**1211–1225.

Young J: **The 'greening' of water: taking aim at climate change through reducing greenhouse gas emissions, increasing efficiency.** *J Am Water Works Assoc* 2010, **102:**20–22.

doi:10.1186/2194-6434-1-9
Cite this article as: Stokes *et al.*: 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* 2014 1:9.