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An Improved Framework for the Modelling and Optimisation of Greenhouse Gas Emissions Associated with Water Distribution Systems

Christopher S. Stokes, Angus R. Simpson, Holger R. Maier.
School of Civil, Environmental and Mining Engineering
University of Adelaide

Abstract: Human-induced climate change and its associated effects have become one of the most significant problems faced by human-kind. The importance of climate change mitigation has been widely recognised by the scientific, commercial and political sectors. Greenhouse gas (GHG) releases have been identified as a major cause of human-induced climate change. Water distribution systems (WDSs), whilst providing an essential service to modern cities, significantly contribute to the release of GHG emissions. While recent literature has considered the reduction of GHG emissions associated with WDSs, there has been limited consideration of the impact of operational strategies, the interaction between water supply infrastructure and energy generating infrastructure and the effect of policy drivers on the optimal trade-offs between cost and GHG. In order to maximise GHG emission reductions from the design and operation of a WDS, an integrated framework is required. Such a framework is presented in this paper. In order to identify best design options, the framework can be used in conjunction with optimisation approaches. By considering the interconnections between the various components in the framework, the effect of each component on the whole system can be investigated. This enables the most effective strategies for the reduction of GHG emissions associated with WDSs to be developed.

Keywords: Water distribution; optimisation; greenhouse gas emissions.

1 INTRODUCTION

Human-induced climate change and its associated effects have become one of the most significant problems faced by human-kind. The importance of climate change mitigation has been widely recognised by the scientific, commercial and political sectors. Greenhouse gas (GHG) releases have been identified as a major cause of human-induced climate change. Water distribution systems (WDSs), whilst providing an essential service to modern cities, significantly contribute to the release of GHG emissions. WDSs are also complex systems, with many different options being available during both their design and operational management. Thus, it is often impractical or even impossible to evaluate the combination of all options available to the designer/operator. As such, optimisation algorithms have become a popular way to evaluate WDSs while reducing the computational time required to find optimal solutions. In order to evaluate the WDS during optimisation, it must be modelled. Simplifications are often made during this modelling process in order to reduce the computational time required to evaluate each solution in the optimisation process. This can include simplifications to the options made available, such as reducing the number and types of options; simplifications to input data, such as the use of static values for input data that are actually time-dependent; and simplifications to the simulation process, such as reducing the number of water demand scenarios that are hydraulically simulated.

The optimisation of costs associated with water distribution systems has been extensively covered in the past three decades [Wu, et al., 2010b]. However, consideration of GHG emissions has only occurred recently. Commonly, GHG emissions have been optimised along with costs by using multi-objective (MO) optimisation algorithms. While literature considering the optimisation of GHG emissions associated with WDSs has been limited, sufficient research has been conducted to show its usefulness. However, the processes within the WDS modelling phase have been directly translated from cost optimisation literature. As such, there has been no real analysis of the simplifications that have been made to these processes, the effect these have on the ability to find optimal solutions when GHG minimisation is considered along with cost minimisation and the accuracy of solutions that are found. In addition, the primary focus has been on the optimisation of water supply infrastructure, with limited consideration of the impact of operational strategies, the interaction between water supply infrastructure and energy generating infrastructure and the effect of policy drivers on the optimal trade-offs between cost and GHG emissions for WDSs. Consequently, a framework is required that shows the interactions between the various factors that have an impact on WDS cost and GHG emissions optimisation in an integrated fashion. Such a framework, the water distribution system cost-emissions nexus (WCEN) framework, is presented in this paper.

2 WATER DISTRIBUTION COST-EMISSIONS NEXUS (WCEN) FRAMEWORK

The WCEN framework is a tool that can be used to address the problem of reducing GHG emissions and costs associated with the design and operation of a WDS. This is achieved by investigating the effect that each component within the framework has upon the whole system. The WCEN framework (Figure 1) is separated into four distinct models. These are the infrastructure model, options model, analysis model and government policy model. Each model is used to represent a system of related components within the modelling of a WDS. The components are linked to one another to represent the flow of information throughout the system. In order to investigate the effects that each component has on the performance of solutions (i.e. solutions of reduced GHG emissions and cost), a method of improving the solutions is required. Multi-objective (MO) optimisation algorithms, such as evolutionary algorithms, provide an efficient means of searching a solution space (the set of all possible solutions) in order to find a set of optimal or near-optimal solutions; and are therefore used in the WCEN framework to investigate the effect each component within the framework has on the ability to obtain optimal solutions.

A MO evolutionary optimisation algorithm obtains a set of optimal solutions by creating an initial set of solutions (known as the population) and improving the performance of the population through multiple generations. The optimisation algorithm is used in conjunction with the WCEN framework, which is used to represent, simulate and evaluate the WDS described by each solution created by the optimisation algorithm. Firstly, an initial population is required for evaluation. Each individual in the population represents an entire solution. Within the WCEN framework, each individual solution describes a WDS with a chosen set of options (e.g. pipe sizes and pump types). The options chosen for each solution are selected from the available options within each component of the options model.

The WDS is represented within the infrastructure model. Along with the WDS itself, the infrastructure model also represents the source of electricity being used by the WDS. This is done using the electrical energy sub-model, which considers the different types of generation used to supply electricity, along with the GHG emissions produced by each type. Information from the infrastructure model, along with information about chosen options from the options model are then used by the analysis model to evaluate the performance of the solution. Once each solution has been evaluated, the performance information for each solution is passed back to the optimisation algorithm. Each solution is assigned a rank according to its performance, with better performing solutions having a higher rank. The evaluated solutions are then compared by the optimisation algorithm, with lower ranked solutions being eliminated. The higher ranked solutions (known as parent solutions) are then used to create a new set of (child) solutions, with each child solution sharing the characteristics of two or more parent solutions. The information for each child solution is then passed back into the options model, and the same process of evaluation, ranking and evolution is performed to obtain the next generation.

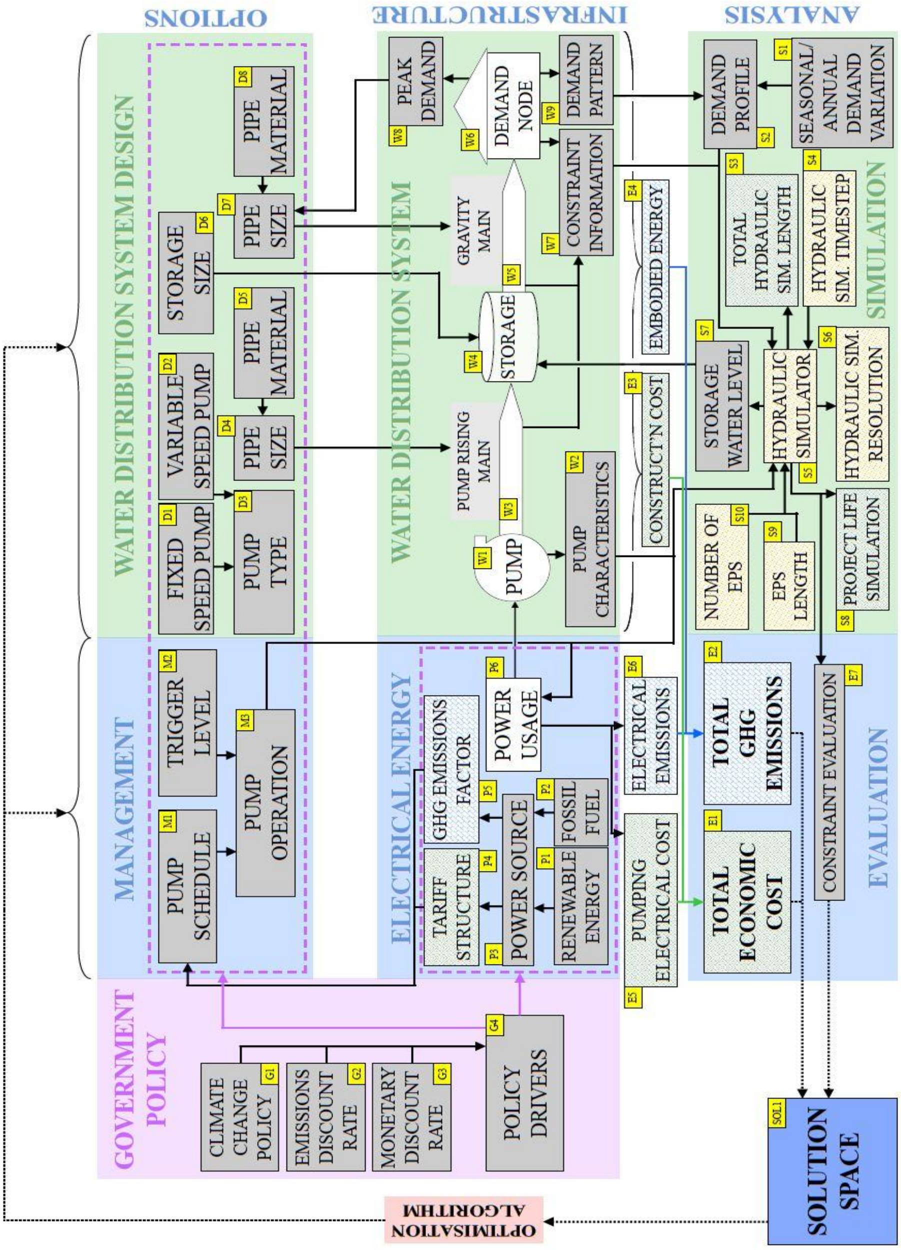

Figure 1. The water distribution system cost-emissions nexus framework

The WCEN framework introduces the consideration of GHG emissions in addition to costs, associated with both the design and operation of a WDS. In order to accurately evaluate GHG emissions, specific parts of the WCEN framework are included; above what is needed for the evaluation of costs alone. These additions affect the options, infrastructure, analysis and government policy models, as described below.

First, the amount of emissions produced for a given amount of electricity generation (emissions intensity) changes according to the source of generation, whereas emissions intensity is represented by the emissions factor. Traditional means of electricity generation (fossil fuel derived) and renewable generation have different associated emissions factors. As such, the emissions factor of electricity is time–dependent. The different emissions factors associated with each type of generation, along with their changing contributions through time, are considered by the electrical energy sub-model (Figure 1). Therefore, the inclusion of the electrical energy sub-model allows the time-dependency of emissions to be considered.

Second, the changes seen in electricity emissions factors over the life of a WDS mean that the chosen operational management strategies must be flexible in order to result in the greatest reduction in GHG emissions. Therefore, there is a requirement to use multiple operational management strategies through the life of the WDS. This is considered by the operational management sub-model. Pump operation options allow for multiple strategies that can be implemented at different times throughout the operational life of the WDS.

Finally, operational GHG emissions are compounded over the life of a WDS. Coupled with the need to use multiple operational management strategies, the analysis of a WDS must consider the need for multiple hydraulic simulations to accurately evaluate the GHG emissions associated with the operation of the WDS. In order to evaluate operational GHG emissions accurately, the analysis model also allows the hydraulic simulation to be modified to achieve the required accuracy.

Policy factors outside of the control of a water utility can also affect the performance of solutions. Such factors, including the use of monetary and emissions discount rates, climate change policies and the effect these have on electricity tariff regimes and emissions intensities, can change the operational performance of a WDS, potentially affecting the trade-offs that occur between design and operations. Such policy factors are considered by the government policy model. The effects of policy are particularly important for long term planning, where changes can have large-scale effects, and can be considered by the use of sensitivity analysis. The various components that make up each model are discussed in further detail in subsequent sections.

2.1 Infrastructure Model

The purpose of the infrastructure model within the WCEN framework is to represent the real-world infrastructure. Two critical infrastructure systems are represented; the WDS sub-model, representing the WDS being modelled; and the electrical energy sub-model, being used to represent the sources of electricity being consumed by the WDS during operation. While both systems are simplified, the critical aspects of each system (relating to the framework's purpose) are retained.

The WDS sub-model is comprised of the critical components that allow the WDS to function. These include the pumps within the system [W1]; the pump rising mains [W3]; the storage systems [W4], which can be both reservoirs and tanks; the gravity mains fed from storage [W5]; and the demand nodes, which represent the consumer end of the WDS [W6]. The peak hour demand flow [W8] is used to calculate pipe size requirements for demand node connections. Peak flows through pump rising mains are not controlled by the peak demand flow, but by the requirement to fill storage systems. Pump rising mains should therefore be sized using an extended period simulation (EPS), in which a demand pattern is employed. The demand pattern component [W9] links to the demand profile [S2], which represents the demand used within the hydraulic simulation process. The demand pattern and profile have been represented separately, as more than one demand pattern can be used for each node. This can be used to represent different demand scenarios, such as different seasons in a year. The combination of demand patterns makes up the profile used for each node. As hydraulic simulators, such as EPANET [Rossman, 2000], are commonly used to assess the hydraulic suitability of a WDS, the representation of the WDS is influenced by the requirements of the hydraulic simulator.

The electrical energy sub-model includes the elements of electrical generation and supply infrastructure that are required to evaluate the WDS's overall performance. This sub-model is used to represent both the cost and GHG emissions associated with electricity used for pumping. The cost of electricity is represented by the tariff structure [P4], which can be used to represent both flat rate and variable rate tariff charges. Tariff charges which treat the use of electricity as a quantity charge have been commonly used within WDS cost optimisation literature, as they aim to reflect the pay-per-use nature of electricity supply. The emissions associated with the generation of the consumed electricity are represented by considering the generation rate and emissions factors of individual generators feeding into the grid. Both renewable [P1] and fossil fuel (non-renewable) [P2] generation types are considered. The emissions factor of the electricity supply is calculated by the amalgamation of each individual generator supplying into the grid, which is represented as the electrical source [P3]. This representation assumes that the electrical grid is homogeneous, meaning that the electricity being consumed by one user cannot be discerned as coming from any particular generator connected to the grid. As a WDS is just one of many users consuming electricity, the time-dependent emissions factor associated with the electricity being consumed by the WDS [P5] is assumed to be an average of the emissions factors of each individual generator supplying the grid, weighted by its contribution. Here, the emissions factor is used as a measurement of the emissions intensity associated with the generation of electricity. The actual consumption of electricity by the WDS [P6] considers only the electricity used for pumping.

2.2 Options Model

The options model is used to represent the options available to decision makers during both construction and operation, specific to the design of the WDS. Two sub-models are used, the water distribution design (WDS design) sub-model and the management sub-model.

The WDS design sub-model is used to represent the options available during the design of the physical system. These options consist of pipes, storages and pumps, and are assumed to be fixed after the construction (or redevelopment) phase. Both variable-speed pumps (VSPs) [D2] and fixed-speed pumps (FSPs) [D1] are considered within the pump type selection [D3]. Pipe sizes [D4, D7] and material types [D5, D8] are considered as discrete options, with pipe costs and diameters being available from commercial sources. Storage sizes [D6] are considered as continuous options. Information from the WDS design sub-model is passed to the WDS sub-model, thus the properties of each component in the WDS can be inputted for the purposes of hydraulic simulation and objective function evaluation.

The management sub-model represents the options available for the operational management of the system. Pumping operations are managed by changing the status/speed of each pump, with decisions based on time (scheduling) and/or storage (trigger levels). Other management devices, such as flow control and pressure control valves, are not explicitly considered, however could be easily incorporated. Pump scheduling [M1] is used to control the timed status and speed of pumps, while trigger levels [M2] are used to control storage levels. Chosen control options are inputted as pump operation information [M3], which is passed to the hydraulic simulator [S5] for use during hydraulic simulation.

While both the WDS design and management sub-models consider options controlled through different stages of a WDS's project life, trade-offs can occur within the objective function fitness between each stage. Most decisions made during the option selection phase will have trade-off effects. A major trade-off is that between construction of pipes and pumping energy requirements. While decreasing pipe sizes decreases the associated construction costs/emissions, increased pumping energy is required if the same flows are to be met, due to increased friction losses. Other trade-offs have been introduced with the consideration of GHG emissions. Like electricity tariffs, the emissions efficiency of electricity is time-dependent. Therefore changing the time of pumping can alter both the emissions and costs associated with the electricity consumed, even if the actual consumption quantity does not change. If the rise and fall of emissions factors and tariffs do not coincide, trade-offs will be seen between the two objectives. 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 Analysis Model

The analysis model is used to represent the simulation and evaluation processes. By using the evaluation and simulation sub-models, information passed from the options and infrastructure models is used to assess design and operational performance. This is done via the use of simulation, with each objective function being evaluated using a combination of information gained directly from the options model (design) and indirectly through the simulation sub-model (operation). This use of design and simulation information for the evaluation of an objective function has been used extensively within the field of WDS optimisation.

The simulation sub-model is used to represent the hydraulic simulator [S5], which is used to conduct the hydraulic simulations for both constraint evaluation and operational performance evaluation purposes. The project life simulation [S8], used for the design life evaluation, includes both construction and operation phases, and incorporates the information gained from the hydraulic simulation. The purpose of the hydraulic simulation is to balance the system hydraulics over an extended period simulation (EPS), outputting the storage levels [S7] at each time-step, as well as flow and pressure information for constraint evaluation [E7], and the power required for pumping purposes [P6]. The hydraulic simulator uses the demand profile [S2], pump characteristics (pump and efficiency curves) [W2], pump operation information [M3] and constraint information [W7]. The demand profile can also be used to simulate water demand changes over different seasons and years [S1], better representing the true nature of water demands. The hydraulic simulator requires a representation of the physical system; this information is taken from the WDS sub-model, which includes options information from the WDS design sub-model. The total hydraulic simulation length [S3] can be controlled by modifying the EPS length [S9] and the number of EPSs used [S10]. The hydraulic simulation's resolution can also be adjusted [S4], which changes the time-step used in the EPSs.

The main benefit of the simulation sub-model is to provide the ability to alter simulation processes, such as the length and number of hydraulic simulations that are to be performed for each solution. The hydraulic simulation is used to calculate the amount of energy used for pumping; information which is critical when evaluating both GHG emission and cost associated with WDS operation. As operational GHG emissions are compounded over the life of a WDS, it is important to accurately evaluate the use of energy throughout the entire operational life-span. However, emissions intensities (associated with electricity generation) change over both the short- and long-term. Therefore, it is necessary to consider these changes in order to accurately evaluate GHG emissions over the entire life-span. This means that it is necessary to perform multiple EPSs, reflecting the changes in emissions intensities. At the same time, computational complexity must be kept to a minimum, as an increase in complexity can greatly increase the time required to perform the optimisation process. The increased run-time for hydraulic simulations will increase the computational complexity required for the simulation process. The simulation sub-model allows this complexity to be controlled and analysed by considering the number and length of EPSs and the hydraulic time-step. Thus, the desired accuracy can be achieved with minimal increases to the optimisation run-time.

The ability to modify the use of EPSs will also be important as other long-term factors are introduced for consideration. Factors such as policies (explained in the government policy model section below) and water demand changes will affect the optimal operation of a WDS over the long term. Therefore, it is desirable to simulate these changes so that policies and other long-term effects can be considered when evaluating operational management options. This type of evaluation can only be achieved by the use of multiple EPSs that reflect the changes in operational management over the life of the WDS.

The evaluation sub-model is used to evaluate the fitness of each objective function, namely economic cost [E1] and GHG emissions [E2]. This sub-model is also used for constraint evaluation [E7]; used for the purpose of penalising designs that violate certain constraints (such as pressure violations at demand nodes). Information used in the evaluation of each objective function comes from both the water distribution system and electrical energy sub-models. Pumping electrical costs [E5] and construction costs [E3] are used to evaluate economic costs, with electrical emissions [E6] and embodied energy from construction [E4] being used to evaluate GHG emissions.

2.4 Government Policy Model

The government policy model is used to represent policies and governance external to the control of a water utility. Three policy types are focussed on in the model; climate change policy [G1], emissions discount rate policy [G2] and monetary discount rate policy [G3]. The effects of these policies will be increasingly seen over the long-term. Therefore, it is important to consider such policies over the operational life-span of a WDS, which can often be many decades in length. This model has been included so that the effects of policy on the optimal design and operation of a WDS can be analysed.

Climate change policies are being increasingly used as a way of mitigating the amount of GHG emissions released. This can be achieved by introducing carbon taxes and carbon trading schemes, which aim to charge a GHG emitter for the amount of emissions they create. This type of policy will have a substantial effect on the electricity generation sector, as this sector is currently a major contributor of GHG emissions. As climate change policy makes it increasingly expensive to produce fossil-fuel generated electricity, renewable generation, which generally produces no operational GHG emissions, will become more popular. As explained previously, this change in generation type will have an effect on the emissions intensity of electricity, which will in turn affect optimal WDS operational strategies.

Discount rates affect the way in which we view future costs and emissions. Increasing the discount rate reduces the importance of the long-term for evaluation. For this reason, it is important to carefully consider the discount rates that will be used, both for operational costs and GHG emissions discounting. A change in discount rates will ultimately affect the trade-offs between design and operations. Recent discussions have promoted the use of lower discount rates to increase the consideration of future costs where GHG emissions are associated with the project [Stern, 2006, Sterner and Persson, 2007]. The discount rate used for GHG emissions evaluation will also affect the consideration of long-term GHG emissions production.

3 CONCLUSION

The WCEN framework has been presented as a tool for reducing GHG emissions and costs associated with water distribution systems. The use of optimisation for the purpose of reducing GHG emissions associated with WDSs is a new field of research, with little literature being available. While previous research has shown the benefits of the specific consideration of GHG emissions, 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 increasing the accuracy of input data and modifying the modelling process with specific consideration of the objectives being evaluated. An increase in accuracy will not only allow solutions to be viewed with greater confidence, but will also allow better solutions to be found. The WCEN framework has been developed with the explicit consideration of GHG emissions evaluation and provides the ability to use more accurate GHG emissions input data, and to specifically tailor the modelling process to the objectives being evaluated. The WCEN framework highlights the complexity of WDS modelling; it considers all aspects of the problem, as it forms a nexus of the components required to accurately model a WDS.

The WCEN framework has been presented here as a conceptual framework. Currently, the framework is being applied as a practical simulation and multi-objective optimisation package. Results from the research being undertaken with the WCEN framework will be used to develop guidelines for GHG emissions reduction strategies. Ultimately, this research aims to provide practical advice that can be applied by water utilities, allowing the currently research based field of WDS GHG emissions reduction to find a useful basis in the water supply industry.

REFERENCES

Rossman, L. A. EPANET2 users manual. Water Supply and Water Resources Division, National Risk Management Research Laboratory, Office of research and Development, USEPA, Cincinnati, Ohio, USA. 2000.

Stern, N. The economics of climate change. UK: Her Majesty's Treasury, London. 2006.

Sterner, T., and Persson, U. M. An even sterner review: Introducing relative prices into the discounting debate. Resources For the Future. 2007.

Wu, W., Simpson, A. R., and Maier, H. R. 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, 2010.