Wu, Wenyan; Simpson, Angus Ross; Maier, Holger R.
Water distribution system optimisation accounting for a range of future possible carbon prices
WDSA 2008: Proceedings of the 10th Annual Water Distribution Systems Analysis Conference, August 17-20, 2008, Kruger National Park, South Africa / K. Van Zyl (ed.) 12 p.

WATER DISTRIBUTION SYSTEM OPTIMISATION ACCOUNTING FOR A RANGE OF FUTURE POSSIBLE CARBON PRICES

Wenyan Wu, Angus R. Simpson and Holger R. Maier

School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, Australia
email: wwu@civeng.adelaide.edu.au, asimpson@civeng.adelaide.edu.au, hmaier@civeng.adelaide.edu.au

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

WATER DISTRIBUTION SYSTEM OPTIMISATION ACCOUNTING FOR A RANGE OF FUTURE POSSIBLE CARBON PRICES

Wenyan Wu, Angus R. Simpson and Holger R. Maier

School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, Australia
email: wwu@civeng.adelaide.edu.au, asimpson@civeng.adelaide.edu.au, hmaier@civeng.adelaide.edu.au

Abstract

Climate change, especially global warming caused by human activities presents serious global risks. Mitigating global warming by reducing greenhouse gas (GHG) emissions is a unique challenge facing our generation. In order to tackle this challenge, many measures are being developed, among which carbon trading is a popular one. In this paper, a new paradigm for the design of water distribution systems (WDSs) is being developed under a possible emission trading scheme. In this paradigm, minimisation of the costs of GHG emissions is incorporated into the optimisation of WDSs either as one part of the objective or as a second objective. A multi-objective genetic algorithm (MOGA) called WSMGA (water system multi-objective genetic algorithm) has been developed to solve this problem. The time value of both the system costs and the costs from GHG emissions has been taken into account by using present value analysis. Following the Stern Review Report there is controversy as to what discount rate should be used in present value analysis for mitigation of climate change, consequently two different discount rates have been used in this study. The impacts that the carbon prices used in the emission trading scheme have on the optimisation of WDSs have been explored for two hypothetical case studies. The optimisation results show that the different carbon prices used lead to different solutions in the single-objective optimisation formulation. In general, a network with larger pipes is chosen when a higher carbon price is used. In contrast, the carbon price used has no impact on the multi-objective optimisation results. However, different carbon prices lead to different amounts of savings in greenhouse gas costs resulting from the same amount of increase in system costs for the same ordered set of Pareto-optimal solutions.

1. INTRODUCTION

Climate change, especially global warming caused by human activities, presents serious global risks. Mitigating global warming by reducing greenhouse gas (GHG) emissions is a unique challenge facing our generation. In order to tackle this challenge, many measures are being developed including emission trading schemes. Under an emission or carbon trading scheme, some businesses may need to buy permits to cover the GHGs they emit while others may be able to sell excess permits they own on the carbon market, if they can reduce their emissions by employing advanced technology. As a result, many industries, including the water industry, will be affected by the price of carbon. To meet this challenge, a new paradigm for the design of water distribution systems (WDSs) under an emission trading scheme is proposed in this paper. In this paradigm, the minimisation of the costs of GHG emissions is incorporated into the optimisation of WDSs either as one part of the objective or as a second objective. A multi-objective genetic algorithm (MOGA) called WSMGA (water system multi-objective genetic algorithm) has been developed to solve this problem. The impacts that different carbon prices have on the optimisation of WDSs have been explored for two hypothetical case studies. In addition, the time value of both the system costs and the costs from GHG emissions has been taken into account by using present value analysis in the objective function evaluation process. Following the Stern Review Report on the Economics of Climate Change (2006) there is controversy as to which discount rate should be used in present value analysis for mitigation of climate change. Thus two different discount rates have been used in this study.

The remainder of the paper is organised as follows. The genetic algorithm optimisation is presented in Section 2. In Sections 3 and 4, the pricing of carbon for the analysis and methodology for present value analysis are introduced. Section 5 describes how the objective functions are formulated. Section 6 presents the two hypothetical case studies and corresponding optimisation results while Section 7 draws conclusions from the paper.

2. GENETIC ALGORITHM OPTIMISATION

Due to the large scale of WDSs and the complexity of the design and operation of these systems, optimisation techniques are often required in order to identify near global optimal solutions. In this study, a genetic algorithm (GA) is used, as GAs have been shown to be effective for WDS optimisation problems (Simpson, et al., 1994).

GAs are a global optimization method that belongs to the class of evolutionary algorithms, which are inspired by natural phenomena (Goldberg, 1989). GAs differs from traditional optimization techniques in that the concept of GAs are inspired by natural phenomena of heredity. GAs use the “principle of survival of the fittest” to select more suitable trial solutions. In applying this principle, GAs deal with a population of solutions simultaneously. Each solution is represented by a binary, integer or real valued string called a chromosome. By applying three genetic operators: selection, crossover and mutation to the chromosomes, GAs maintain good solutions in the current population and explore the search space for better solutions. The search process will terminate when the stopping criteria are met.

Traditionally, GAs only deal with optimisation problems that have one objective. However, most problems in the real world have more than one objective that needs to be satisfied. Therefore, a multi-objective GA is required to solve these multi-objective problems. In this study, a multi-objective genetic algorithm called WSMGA has been developed to solve both the single and two-objective problems presented in this paper. WSMGA is based on the state-of-the-art multi-objective generic algorithm NSGA-II (Deb, et al., 2002). The details of WSMGA can be found in Wu, et al. (2008).

3. CARBON PRICING

Emission trading is one of the most popular schemes for controlling GHG emissions. It is also the approach that will be adopted by the Australian government to ensure a flexible and smooth transaction into a carbon constrained future. Currently, a national emissions trading scheme (NETS) is being developed by the National Emissions Trading Taskforce (NETT). This emissions trading scheme will start no later than 2010. In most emissions trading schemes a cap and trade approach is used. Under the cap and trade approach, emission permits will be issued by the government. Business must have enough permits to cover the GHG emissions they produce each year. These permits can be sold or purchased and the price will be determined by the market (The Task Group on Emissions Trading, 2007). The average market price of a tonne of CO_2-e (carbon dioxide equivalent) in 2005-06 was around $US20 - $US25 (Mitchell, et al., 2007). In order to achieve long-term abatement, the carbon price is expected to rise over time (The Task Group on Emissions Trading, 2007). In the literature, there are many estimates of possible future carbon prices based on different scenarios. The Australian Bureau of Agricultural and Resource Economics (ABARE) estimates carbon prices to vary from $A28 to 46 per tonne of CO2-e for international action scenarios and from $A15 to 31 per tonne of CO2-e for Australian abatement scenarios in 2030 (The Task Group on Emissions Trading, 2007). However, the actual social cost of carbon could be higher. Sterner and Persson (2007) quote a marginal social cost of carbon reaching over $US400 per tonne of carbon by 2050, which is equivalent to about $US110 or $A120 per tonne of CO_2-e. Therefore, in this study, a range of carbon prices from $A10 to $A120 per tonne of CO_2-e are used.

4. PRESENT VALUE ANALYSIS AND SOCIAL DISCOUNT RATES

Present value analysis (PVA) is essential in any economic or financial analysis. With an appropriate discount rate, PVA translates values from the future to the present, enabling effects occurring at different times to be compared (Kaen, 1995). In conventional exponential discounting, the present value (PV) of a future payment can be calculated using the following equation:

$$PV_t = \frac{C}{(1+i)^t} \tag{1}$$

where, C is the payment on a given future date; t is the number of periods; i is the discount rate. Therefore, PV_t is the present value of a future payment at the end of the t-th period. In this equation, the term $\frac{1}{(1+i)^t}$ is the discount factor (DF), which represents the extent of the reduction that occurs when a future payment to be received at time t is translated into its current present value. It can be seen from the equation that the selection of the value of discount rate i is important, as it has a significant impact on the results of present value analysis.

The selection of appropriate discount rates, especially for social projects with a long design life or those having environmental effects which will potentially be spread out over hundreds of years, remains a controversial issue in economics. In the literature, the selection of social discount rates can be divided into three categories: a zero discount rate, constant discount rates and time declining discount rates (Rambaud and Torrecillas, 2005). A zero discount rate places equal weighting on the costs and benefits at present and those in the future (Azar and Sterner, 1996, Dasgupta, et al., 1999). Constant discount rates ranging from 2% to 10% are the most commonly used values by current government agencies and organisations (Rambaud and Torrecillas, 2005). In addition, a constant discount rate of 1.4% has been suggested for a 100-year time horizon in the *Stern Review* released in 2006. The 1.4% discount rate is calculated according to the feasibility and costs of stabilising GHG concentrations in the atmosphere in a specific range in order to prevent dramatic gross domestic product (GDP) loss due to climate change (Weitzman, 2007). Time declining discount rates have recently been proposed by a number of economists (Heal, 1997, Henderson and Langford, 1998, Weitzman, 2001, Gollier, 2002, Rambaud and Torrecillas, 2005). However, they are not widely used in practice. To the authors' knowledge, the UK government was the first government that has adopted a time declining discount rate. In The Green Book (Her Majesty's Treasury, 2003), a long term discount rate is suggested as 3.5% for periods up to 30 years and then declining linearly to 1.0% for periods starting from year of 301. In this study, two constant discount rates of 1.4%, 8% have been used.

Traditionally, a specific discount rate is used for a specific project or industry. However, some researchers have argued that the discount rate used for economic considerations should be different from that used for carbon (Fearnside, 2002). The International Panel on Climate Change (IPCC) is currently using a 100-year time horizon without discounting (i.e. zero discount rate) for the calculation of GHG emission impacts (Fearnside, 2002). Therefore, in this study, two discount scenarios are considered. In the first discount scenario, both the system and emission costs are discounted at the same rate. In the second scenario, the system cost is discounted at various rates while the GHG emission costs are not discounted.

5. PROBLEM FORMULATION

In this paper, the minimisation of GHG emission cost is incorporated into the optimal design of WDSs either as one component of a single objective or as a second objective. The objective function evaluation process is illustrated in Figure 1. In the single-objective optimisation, WDSs are optimised in order to minimise the total cost of the system, which is the sum of the system cost and the GHG emission cost. In the multi-objective optimisation, the system cost and GHG cost are considered as two different objective functions and minimised separately. It should be noted that in the single-objective optimisation scenario, perfect substitutability, in which one dollar worth of damage caused by GHG emissions can be compensated by a dollar worth of economic growth, is assumed (Sterner and Persson, 2007). However, whether or not the use of perfect substitutability is appropriate is still a controversial issue.

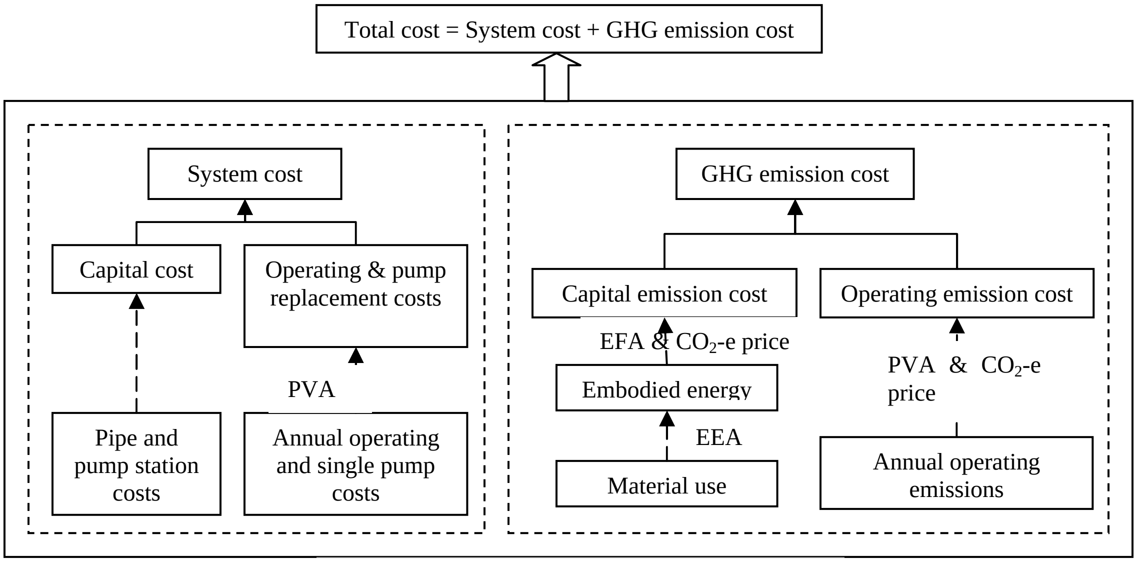


Figure 1 Objective function evaluation

Figure 1 shows that the system cost considered in this study consists of capital costs, pump replacement costs and operating costs. The capital cost is the initial investment, which mainly comes from the purchase and installation of network components, in this case, the purchase of pipes and the construction of pump stations. The capital cost occurs at the beginning of a project. As the service life of pumps is much shorter than the design life of a WDS, pumps need to be replaced periodically in order to ensure the performance of the system is maintained. In this study, a pump service life of 20 years has been used. The operating costs mainly arise from the energy consumption related to the operation activities of a system, such as pumping. In this study, a typical electricity price of $A0.135 per kWh is used, which is an approximate average electricity tariff in South Australia. Both pump replacement costs and operating costs occur during the whole life of the network. Consequently, the evaluation of these two costs requires present value analysis.

The GHG emission cost can be calculated by multiplying the carbon price by the amount of GHG emissions in tonnes. It can be seen from Figure 1 that the GHG emissions considered in this study consist of capital emissions and operating emissions. Capital emissions are due to the manufacture and installation of network components, mainly pipes. In this study, the capital emissions account for the emissions from pipe manufacture, which can be computed using embodied energy analysis (EEA) (Treloar, 1994) and emission factor analysis (EFA). The GHG emissions from the installation and transportation of pipes are highly project dependent and are therefore not included in this study. Similarly to operating costs, operating emissions mainly arise from the energy consumption related to the operation (mainly pumping) of a WDS. Operating emissions occur during the design life of a system. Therefore, the evaluation of operating emissions also requires present value analysis. The details of EEA and EFA used in GHG emission evaluation of WDSs can be found in Wu et al. (2008). In the current study, a typical emission factor of 1.042 kg CO_2-e per kWh is used, which is a full fuel cycle emission factor in South Australia (Australian Greenhouse Office, 2006). The embodied energy of ductile iron cement mortar lined (DICL) pipes used is 40.2 MJ/kg, which is obtained from Ambrose et al. (2002).

6. CASE STUDIES

Case Study One

This case study was first considered in Wu et al. (2008). The network configuration is shown in Figure 2 and the design conditions are summarised in Table 1. The aim of the design is to select the best combination of the pump size and the pipe size that can deliver the minimum average peak-day flow and also minimise both the total cost and GHG emissions of the network during its design life. Thirty different fixed speed pumps and twenty-six ductile iron cement mortar lined (DICL) pipes of different diameters are considered as options in this study. The pumps were selected using Thompson Kelly & Lewis' pump selection program EPSILON. It should be noted that the prices of the pumps are different from those in Wu, et al. (2008), as the pump costs in this paper are divided into station costs and pump costs. The station cost is part of the capital cost and the pump cost will be used to compute pump replacement cost. The prices of the pumps and corresponding pump stations have been calculated according to the sizes of the pumps. The mass per unit length of the pipes is calculated according to DICL pipe data obtained from Tyco Water. Details of the pumps and pipes are given in Tables 2 and 3, respectively.

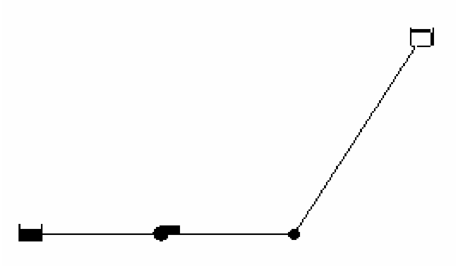


Figure 2 Network configuration of case 1

Table 1 Design conditions of case 1

Annual demand (m^3)	1,500,000
Average peak-day flow (L/s)	120
Static head (m)	95
Pipe length (m)	1,500
Design life (years)	100

As mentioned in Section 4, two discount scenarios are considered in this study. In the first discount scenario, both the system and emission costs are discounted at the same rate. In the second discount scenario, the system cost is discounted at two different rates and a zero discount rate is used for the GHG emission cost calculation. The total search space for the first case study has only 780 solutions and there are only 690 feasible solutions. Therefore, instead of genetic algorithm optimisation, a full enumeration is used to optimise the system. As a result, the optimisation results are true optimal solutions. The single-objective optimisation results of case study 1 are presented in Table 4.

Table 2 Pump information

No.	Pump Type	Speed (rmp)	Dia (mm)	BEP[*] (%)	Q at BEP (L/s)	H at BEP (m)	Rated Power (kW)	Station cost ($)	Pump cost ($)
1	EC/8*17A_ECS	1475	410	83.1	126	107	159	989,720	644,343
2	EC/8*17A_ECS	1475	432	83.3	130	120	183	1,085,898	722,801
3	EC/8*17B	1475	393	81.7	112	118	158	987,827	642,827
4	EC/8*17B	1475	445	84	130	154	233	1,263,020	875,000
5	EC/8*17B_ECS	1475	445	84	130	104	158	984,598	640,243
6	HN/8HN124A	2950	293	78.5	175	95.9	209	1,180,861	803,121
7	HN/8HN124A	2950	318	81	189	119	272	1,384,445	985,413
8	LR/6LG13/A	2900	311	80.4	109	117	155	975,259	632,787
9	LR/6LG13/A	2900	321	80.8	113	125	171	1,038,859	684,075
10	VDP/430DMH	1480	251	84	142	99.2	164	1,011,253	661,664
11	VDP/430DMH	1480	275	84	157	94.6	173	1,046,509	690,326
12	VDP/430DMH	1480	312	85	180	121	251	1,319,762	925,971
13	VDP/430DMH	1480	312	85	180	151	313	1,502,301	1,097,337
14	VDP/430DML	1480	272	81.3	123	107	158	988,302	643,207
15	VDP/430DML	1480	290	81.6	131	101	159	989,347	644,044
16	VDP/430DML	1480	313	81.9	140	118	197	1,138,432	766,875
17	VDP/430DML	1480	313	81.9	140	142	238	1,277,211	887,646
18	VDP/460CDKH	1480	280	81.3	183	93.5	206	1,169,306	793,192
19	VDP/460CDKH	1480	336	83	220	134	348	1,593,265	1,186,731
20	VDP/460DKL	1480	295	84.2	162	90.7	171	1,037,675	683,109
21	VDP/460DKL	1480	334	85.1	182	87	182	1,081,395	719,064
22	VDP/460DKL	1480	336	85.2	185	116	247	1,306,186	913,676
23	VDP/510DML	1480	332	79.5	220	83.4	226	1,238,333	853,164
24	VDP/510DML	1480	369	81.2	240	104	301	1,468,830	1,065,086
25	VDP/510DMH	980	339	83.3	197	88.3	204	1,163,588	788,294
26	VDP/510DMH	980	368	83.2	215	103	261	1,350,157	953,725
27	ST[**]/200*300-630	1480	537	81.3	192	97.1	224	1,233,435	848,856
28	ST/200*300-630	1480	635	82.8	230	135	367	1,641,363	1,234,938
29	ST/250*300-500B	1480	553	84.2	273	93.9	298	1,460,743	1,057,348
30	ST/250*300-500B	1480	562	84.3	275	97.3	311	1,495,998	1,091,236

[*] BEP: Best efficiency point; [**] ST: Super-Titan

Table 3 Pipe information

No	Dia. (mm)	Price ($/m)[*]	Unit weight (kg/m)	No	Dia. (mm)	Price ($/m)	Unit weight (kg/m)
1	100	228	17.70	14	900	2012	310.06
2	150	307	30.02	15	960	2040	337.26
3	225	433	50.91	16	1000	2142	355.69
4	300	568	74.07	17	1050	2270	379.04
5	375	813	99.07	18	1085	2360	395.59
6	450	1033	125.64	19	1220	2655	460.91
7	525	1252	153.60	20	1290	2860	495.67
8	600	1415	182.79	21	1350	2996	525.93
9	675	1658	213.12	22	1500	3337	603.33
10	700	1739	223.46	23	1650	3678	683.12
11	750	1900	244.49	24	1800	4020	765.15
12	800	1950	265.94	25	1950	4361	849.27
13	825	1976	276.82	26	2100	4696	935.38

[*] All costs in this study are in Australian dollars.

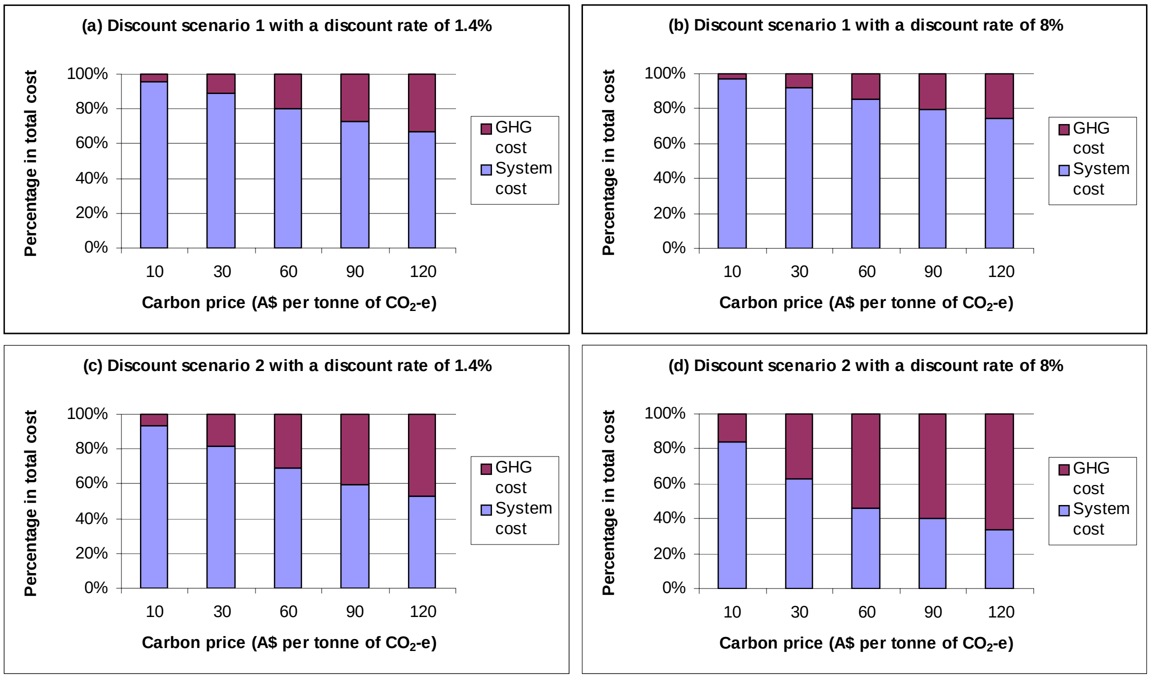
Table 4 Single-objective optimisation results of case study 1

DS[*]	DR[**]	CP[***]	Pump ID	Pipe dia.(mm)	System cost (M$)	GHG cost (M$)	Total cost (M$)
1	1.4%	10	5	**300**	7.07	0.31	7.38
		30	5	375	7.10	0.88	7.98
		60	5	375	7.10	1.75	8.85
		90	5	375	7.10	2.63	9.73
		120	5	375	7.10	3.50	10.60
	8.0%	10	5	300	2.92	0.08	3.00
		30	5	300	2.92	0.25	3.17
		60	5	300	2.92	0.50	3.41
		90	5	300	2.92	0.75	3.66
		120	5	300	2.92	0.99	3.91
2	1.4%	10	5	375	7.10	0.53	7.63
		30	5	375	7.10	1.59	8.69
		60	5	375	7.10	3.17	10.28
		90	5	375	7.10	4.76	11.86
		120	5	375	7.10	6.35	13.45
	8.0%	10	5	300	2.92	0.57	3.49
		30	5	300	2.92	1.72	4.63
		60	5	300	2.92	3.44	6.35
		90	5	**375**	3.21	4.76	7.97
		120	5	**375**	3.21	6.35	9.56

[*]DS = Discount scenario; [**]DR = Discount rate; [***]CP = Carbon Price in $A per tonne of CO_2-e

As can be seen in Table 4, different carbon prices lead to different single-objective optimisation solutions. In discount scenario 1 (both the system and GHG costs are discounted), when a discount rate of 1.4% is used, the carbon price of $A10 per tonne of CO2-e results in a final solution with a pipe of 300 mm in diameter; while the higher carbon prices (from $A30 to $A120 per tonne of CO2-e) all lead to a network with a larger pipe size of 375 mm. In discount scenario 2 (GHG costs are not discounted), when a discount rate of 8% is used, the carbon prices of $A10, 30 and 60 per tonne of CO2-e result in the same network (with a diameter of 300 mm) as was found by using a carbon price of $A10 per tonne of CO2-e in discount scenario 1 with a discount rate of 1.4%; while the higher carbon prices lead to the network with a larger pipe size. However, in discount scenario 1 when a discount rate of 8% is used, and in scenario 2 when a discount rate of 1.4% is used, the carbon price has no impact on the final optimisation results. Therefore, the impact of carbon price on the single-objective optimisation is influenced by the discount rate used in the objective function evaluation process.

The impact of carbon price on the single-objective optimisation can be explained by comparing the different total cost components (system and GHG costs) of the solutions obtained by using different carbon prices. Figure 3 shows the percentage of both system and GHG costs in the total cost of the single-objective optimisation solutions in the four different optimisation situations (four combinations of two discount scenarios and two discount rates for system cost evaluation) considered in this study. It is evident that as the carbon price increases, the impact of GHG cost on the total cost increases. It can be seen in Figure 3 (a) that if the cost of CO_2-e is $A10 per tonne, the GHG cost only accounts for about 5% of the total cost; while when the carbon price is increased to $A120 per tonne of CO_2-e, GHG cost accounts for about 35% of the total cost. In discount scenario 2, the GHG cost has greater impact on the total cost than in discount scenario 1. Figure 3 (d) shows that in discount scenario 2, when the carbon price is increased to $A60 per tonne of CO_2-e and higher, the GHG cost has more impact on the total cost than the system cost. This greater impact of GHG costs on the total cost is due to the impact of discount rate on objective function evaluation.


(a) Discount scenario 1 with a discount rate of 1.4%

(b) Discount scenario 1 with a discount rate of 8%

(c) Discount scenario 2 with a discount rate of 1.4%

(d) Discount scenario 2 with a discount rate of 8%

Figure 3 Different total cost components of optimal solutions in different situations ((a) Discount scenario 1 with a discount rate of 1.4%; (b) Discount scenario 1 with a discount rate of 8%; (c) discount scenario 2 with a discount rate of 1.4%; (d) Discount scenario 2 with a discount rate of (8%))

In contrast to the single objective optimisation results, it has been found that the carbon price used has no impact on the relative ranking of the multi-objective optimisation results. For example, all of the five different carbon prices result in the same ordered set Pareto-optimal solutions (six in total) for case study 1 in discount scenario 2 when a discount rate of 1.4% is used. Table 5 shows the network configurations of these solutions, in which design 1 is the solution with the lowest system cost and design 6 is the solution with the lowest GHG cost. Table 6 shows the system costs, different components of system cost and the total costs obtained by using different carbon prices of these 6 solutions. The GHG costs and different components of GHG costs obtained using different carbon prices are summarised in Table 7.

These Pareto-optimal solutions show significant tradeoffs between the system cost and GHG cost. It can be seen from Tables 6 and 7 that from design 1 to design 6, as the system cost increases the GHG cost decreases. There is a $0.7 M increase in the system cost from design 1 to design 6. This increase is caused by the increase in capital system cost and pump replacement cost due to the larger pump and pipe sizes selected in design 6 (Table 5). Whereas, the corresponding reduction in the GHG cost is dependent on the carbon price used. When a carbon price of $A10 per tonne of CO2-e is used, the GHG cost of design 6 is only $0.05 M lower than that of design 1; while when a carbon price of $A120 per tonne of CO2-e is used, the corresponding reduction in GHG cost is increased to $0.68 M (Table 7).

In addition, the increase in capital system cost and associated capital GHG cost leads to a reduction in the operating system cost and corresponding operating GHG cost. Table 6 shows that from design 1 to design 6, the operating system cost is reduced by $0.49 M; while the corresponding reduction in the operating GHG cost is $0.07 M when a carbon price of $A10 per tonne of CO2-e is used, and $0.84 M when a carbon price of $A120 per tonne of CO2-e is used. This reduction in both operating system costs and operating GHG costs is mainly due to the decline in the system friction loss, which is 14.43 m for design 1, which includes a pipe with a diameter of 300mm, and 1.30 m for design 6, which includes a pipe with a diameter of 525mm (Table 5).

Table 5 Network configurations and characteristics of multi-objective optimisation solutions of case 1 obtained in discount scenario 2 with a discount rate of 1.4%

Design No.	Pump No.	Pump Efficiency (%)	Pump Rated Power (kW)	Pipe Dia. (mm)	Flow (L/s)	Annual Pumping hours	Friction loss hf (m)
1	5	83.1%	**158**	**300**	120	3467	**14.43**
2	5	83.6%	158	375	135	3092	5.71
3	5	83.2%	158	450	139	2992	2.39
4	11	83.5%	173	450	149	2787	2.74
5	20	83.5%	171	525	151	2757	1.27
6	11	83.7%	**173**	**525**	152	2734	**1.30**

Table 6 System and total costs of multi-objective optimisation solutions of case 1 obtained in discount scenario 2 with a discount rate of 1.4%

Design No	System Cost (M$)	Capital System Cost (M$)	Pipe Cost (M$)	Pump Station Cost (M$)	Pump Replac. Cost (M$)	Operating System Cost (M$)	Total Cost (M$)				
							10*	30*	60*	90*	120*
1	**7.07**	**1.84**	0.85	0.98	**1.34**	**3.89**	7.64	8.78	10.50	12.22	13.94
2	7.10	2.20	1.22	0.98	1.34	3.56	7.63	8.69	10.28	11.86	13.45
3	7.33	2.53	1.55	0.98	1.34	3.46	7.85	8.89	10.45	12.01	13.57
4	7.50	2.60	1.55	1.05	1.45	3.46	8.02	9.06	10.62	12.18	13.73
5	7.75	2.92	1.88	1.04	1.43	3.40	8.27	9.30	10.85	12.40	13.95
6	**7.77**	**2.92**	1.88	1.05	**1.45**	**3.40**	8.29	9.32	10.87	12.41	13.96

*Carbon prices of $A10, 30, 60, 90 and 120 per tonne of CO2-e

Table 7 GHG emission costs of multi-objective optimisation solutions of case 1 obtained in discount scenario 2 with a discount rate of 1.4%

Design No	GHG Cost (M$)					Capital GHG Cost (M$)					Operating GHG Cost (M$)				
	10*	30*	60*	90*	120*	10	30	60	90	120	10	30	60	90	120
1	**0.57**	1.72	3.44	5.15	**6.87**	0.01	0.04	0.08	0.12	0.16	**0.56**	1.68	3.36	5.04	**6.71**
2	0.53	1.59	3.17	4.76	6.35	0.02	0.05	0.10	0.16	0.21	0.51	1.54	3.07	4.61	6.14
3	0.52	1.56	3.12	4.68	6.24	0.02	0.07	0.13	0.20	0.26	0.50	1.49	2.99	4.48	5.97
4	0.52	1.56	3.12	4.68	6.23	0.02	0.07	0.13	0.20	0.26	0.50	1.49	2.99	4.48	5.97
5	0.52	1.55	3.10	4.65	6.20	0.03	0.08	0.16	0.24	0.32	0.49	1.47	2.94	4.41	5.88
6	**0.52**	1.55	3.10	4.64	**6.19**	0.03	0.08	0.16	0.24	0.32	**0.49**	1.47	2.94	4.40	**5.87**

*Carbon prices of $A10, 30, 60, 90 and 120 per tonne of CO2-e

Case Study Two

The network configuration of the second case study is shown in Figure 4. The network consists of a water source, a pump, eight pipes and three tanks, each with the same elevation. The aim of this study is to minimise both the cost of and GHG emissions from the network, while being able to deliver at least 50 L/s of water to all three tanks. The design conditions are summarised in Table 8. The options for the pump are the same as those presented in Table 2. The sizes of the pipes can only be selected from the first 16 choices presented in Table 3, as the larger pipes were identified as being too big and were removed to reduce the size of the search space. As was the case in the first case study, two discount rate scenarios are considered. The single-objective optimisation results obtained are summarised in Table 9.

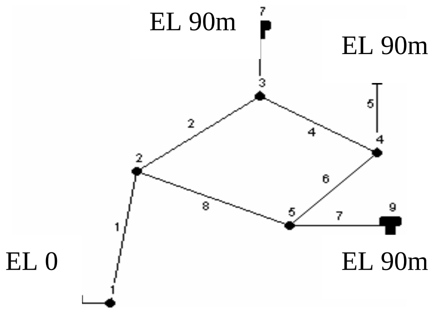


Figure 4 Network configuration of case 2

Table 8 Design conditions of case 2

Total annual demand (m^3)	1,875,000
Average peak-day flow for each tank (L/s)	50
Pipe 1 length (m)	1,000
Pipe 2 length (m)	1,200
Pipe 3 length (m)	500
Pipe 4 length (m)	1,000
Pipe 5 length (m)	500
Pipe 6 length (m)	1,000
Pipe 7 length (m)	500
Pipe 8 length (m)	1,500

Table 9 Single-objective optimisation results of case study 2

DS	DR (%)	CP	Pump ID	Dia.1 (mm)	Dia.2 (mm)	Dia.3 (mm)	Dia.4 (mm)	Dia.5 (mm)	Dia.6 (mm)	Dia.7 (mm)	Dia.8 (mm)	System Cost (M$)	GHG Cost (M$)	Total Cost (M$)
1	1.4	10	21	450	375	300	375	375	100	300	300	11.71	0.40	12.11
		30	21	450	375	300	375	375	100	300	300	11.71	1.19	12.90
		60	21	450	375	300	375	375	100	300	300	11.71	2.38	14.09
		90	**20**	**525**	375	300	375	375	100	300	300	11.73	3.55	15.28
		120	**20**	**525**	375	300	375	375	100	300	300	11.73	4.73	16.46
	8.0	10	22	300	300	225	300	225	100	225	225	6.18	0.15	6.32
		30	22	300	300	225	300	225	100	225	225	6.18	0.44	6.62
		60	22	300	300	225	300	225	100	225	225	6.18	0.88	7.05
		90	22	300	300	225	300	225	100	225	225	6.18	1.31	7.49
		120	22	300	300	225	300	225	100	225	225	6.18	1.75	7.93
2	1.4	10	11	600	375	300	375	375	100	375	300	12.01	0.67	12.69
		30	11	**600**	**375**	300	**375**	375	100	**375**	300	12.01	2.02	14.03
		60	11	**600**	**375**	300	**375**	375	100	**375**	300	12.01	4.04	16.05
		90	11	600	375	300	375	375	100	375	300	12.01	6.06	18.07
		120	11	**600**	**375**	300	**375**	375	100	**375**	300	12.01	8.08	20.09
	8.0	10	22	300	300	300	375	375	100	225	300	6.83	0.82	7.65
		30	22	300	300	300	375	375	100	225	300	6.83	2.45	9.28
		60	**20**	**525**	**375**	300	375	375	100	300	300	7.29	4.03	11.32
		90	**20**	**525**	**375**	300	375	375	100	300	300	7.29	6.05	13.34
		120	**20**	**525**	**375**	300	375	375	100	300	300	7.29	8.07	15.36

The results presented in Table 9 confirm the finding of case study 1 that different carbon prices lead to different optimal solutions when a single-objective optimisation approach is used. In discount scenario 1 when a discount rate of 1.4% is used, carbon prices from $A10 to $A60 per tonne of CO2-e result in the same lowest cost network in terms of total cost; while carbon prices of $A90 and $A120 per tonne of CO2-e lead to a network with a slightly larger pipe 1. In discount scenario 2 with a discount rate of 8%, the carbon prices of $A10 and $A30 per tonne of CO2-e lead to a network with a 300mm pipe for both pipe 1 and 2; while the other higher carbon prices result in a solution with a 525mm diameter pipe 1 and 375mm diameter pipe 2, which lead to a $0.46 M increase in system cost. However, in discount scenario 1 with a discount rate of 8%, and in discount scenario 2 with a discount rate of 1.4% all carbon prices result in the same optimal solutions. This provides further evidence to the finding in the previous case study that the impact of carbon price on the single-objective optimisation is influenced by the discount rate used.

In the multi-objective optimisation, similar results have been found in this case study as in case study 1, in which different carbon prices lead to the same ordered set of Pareto-optimal solutions in each of the four optimisation situations (four combinations of two discount scenarios and two discount rates for system cost evaluation). Therefore, this provides further evidence that the carbon price used has no impact on the multi-objective optimisation solutions in this study.

7. CONCLUSIONS

In the present study, the impacts that different carbon prices, which could be used in future emission trading systems, have on the optimal design of WDSs have been investigated. Both single-objective and multi-objective approaches are used. In the single-objective approach, the minimisation of the total cost, which is the sum of the system and GHG costs, is considered to be the objective; while in the multi-objective approach, the system and GHG costs are considered as two different objective functions and minimised separately.

In the objective function evaluation process, the time value of both the system and GHG costs is taken into account by using present value analysis. As there is controversy as to what discount rate should be used in present value analysis for mitigation of climate change following the Stern Review Report on the Economics of Climate Change (2006), two discount scenarios are considered in this study. In the first discount rate scenario, both the system and emission costs are discounted at the same rate (either 1.4% or 8%). In the second discount scenario, the system cost is discounted at two different rates and a zero discount rate is used for the GHG emission cost calculation.

In order to investigate the impacts that carbon prices have on the optimal design of WDSs, five carbon prices ($A10, 30, 60, 90 and 120 per tonne of CO_2-e) are used in this study. These carbon prices are selected from the predicted carbon price range in the current literature. The single-objective optimisation results show that the carbon price used has a significant impact on the optimisation results obtained. In general, higher carbon prices lead to solutions with larger pipes. This is because higher carbon prices increase the impact of GHG cost on the total cost, and therefore lead to solutions with relatively high system cost but low GHG cost. It has also been found that the impact of carbon price on the optimal design of WDSs accounting for the total cost is influenced by the discount rate used.

The multi-objective optimisation results show that the carbon price has no impact on the multi-objective optimisation solutions. This is because different carbon prices only change the scale of the objective space, but the relative ranking of different solution points in the objective space remain the same. However, when different carbon prices are used, the same amount of increase in the system cost results in different amounts of reduction in the GHG cost. In general, higher carbon prices lead to larger reduction in GHG cost.

In the current study, a new paradigm for the design of WDSs under a possible future carbon trading scheme has been proposed. A range of future possible carbon prices are investigated. However, as the carbon price is expected to rise over time, further studies, which incorporate a carbon price prediction model in the objective function evaluation process, may be required to investigate the impact that the increasing carbon price will have on the optimal design of WDSs. In addition, investigating how the discount rate influences the impact of carbon price on the optimal design of WDSs remains an area of further research.

8. ACKNOWELEDGEMENTS

This research was supported by resources supplied by the South Australian Partnership for Advanced Computing (SAPAC).

9. REFERENCES

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

Australian Greenhouse Office (2006), *AGO Factors and Methods Workbook*, Canberra.

Azar, C. and Sterner, T. (1996), "Discounting and distributional considerations in the context of global warming", *Ecological Economics*, Vol.**19**(2)**,** pp. 169-184.

Dasgupta, P., Mäler, K.-G. and Barrett, S. (1999) *Discounting and Intergenerational Equity*, (Eds, Portney, P. R. and Weyant, J. P.) Resources for the Future, Washington, DC, pp. 51-77.

Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T. (2002), *A Fast and Elitist Multi-Objective Genetic Algorithm: NSGA-II*, KanGAL, India Institute of Technology Kanpur, Kanpur, India.

Fearnside, P. M. (2002), "Time preference in global warming calculations: a proposal for a unified index", *Ecological Economics*, Vol.**41**(1)**,** pp. 21-31.

Goldberg, D. E. (1989), *Genetic Algorithm in Search Optimization, and Machine Learning,* Addison-Wesley Publishing Company, Inc., Canada.

Gollier, C. (2002), "Time Horizon and the Discount Rate", *Journal of Economic Theory,* Vol.**107**(2)**,** pp. 463-473.

Heal, G. (1997), "Discounting and Climate Change; An Editorial Comment", *Climatic Change,* Vol.**37**(2)**,** pp. 335-343.

Henderson, N. and Langford, I. (1998), "Cross-Disciplinary Evidence for Hyperbolic Social Discount Rates", *Management Science,* Vol.**44**(11, Part 1 of 2)**,** pp. 1493-1500.

Kaen, F. R. (1995), *Corporate Finance: Concepts and Policies,* Blackwell Business, USA.

Mitchell, C., Fane, S., Willetts, J., Plant, R. and Kazaglis, A. (2007), *Costing for Sustainable Outcomes in Urban Water Systems: A Guidebook*, The Cooperative Research Centre for Water Quality and Treatment, Salisbury SA, Australia.

Rambaud, S. C. and Torrecillas, M. J. M. (2005), "Some considerations on the social discount rate", *Environmental Science & Policy,* Vol.**8**(4)**,** pp. 343-355.

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

Sterner, T. and Persson, U. M. (2007), *An Even Sterner Review: Introducing Relative Prices into the Discounting Debate,* Resources For the Future.

The Task Group on Emissions Trading (2007), *Report of the Tasks Group on Emissions Trading,* Australian Government.

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

Weitzman, M. L. (2001), "Gamma Discounting", *The American Economic Review,* Vol.**91**(1)**,** pp. 260-271.

Weitzman, M. L. (2007), "A review of the Stern Review on the Economics of Climate Change", *Journal of Economic Literature,* Vol.**45**(3)**,** pp. 703-724.

Wu, W., Simpson, A. R. and Maier, H. R. (2008), "Multi-objective Genetic Algorithm Optimisation of Water Distribution systems Accounting for Sustainability", *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