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Issues and Implications of Carbon-Abatement Discounting and Pricing for Drinking Water System Design in Canada

Stephanie P. MacLeod · Yves R. Filion

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Abstract Water utilities generate greenhouse gas (GHG) emissions when they construct, retrofit, and operate their water distribution systems. The prospect of introducing carbon-abatement strategies such as carbon pricing and using low discount rates for project planning could potentially change the manner in which water utilities plan and design their drinking water systems. The objectives of this paper are to: (i) Review the current issues and controversies surrounding the choice of discounting rate and carbon prices in Canada to reduce the GHG emissions linked to operating water systems in Canada; (ii) Review previous research that has examined the impact of discounting and carbon pricing on design decisions in water supply and distribution systems, and; (iii) Illustrate the possible implications of carbon-abatement strategies (discounting and carbon pricing) on the design of Canadian water systems by way of a real-world case study. The implications of discount rate and carbon price uncertainty on water distribution system design are illustrated with the Amherstview-Odessa water transmission system in Ontario, Canada. The results of the Amherstview study indicated that lowering discount rate led to significant increases in electricity costs. The study results also suggested that for a sufficiently low discount rate of 1.4%, increasing carbon price led to a larger pipe size and pipe cost to offset carbon costs levied on fossil-fuel based electricity to operated the pumps for the life of the system. Additional studies are needed on large-scale water systems to inform decisions on system upgrades taken by water utility managers.

Keywords Uncertainty · Climate change · Greenhouse gas · Discount rate · Carbon tax · Water distribution system design

S. P. MacLeod
Utilities Kingston, Kingston, ON, Canada

Y. R. Filion (✉)
Department of Civil Engineering, Queen's University, Kingston, ON, Canada K7L 3N6
e-mail: yves.filion@civil.queensu.ca

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC)—arguably the world's foremost scientific authority on climate change—has concluded with very high confidence that the primary source of the increased atmospheric concentration of carbon dioxide (CO_2) since the pre-industrial period is from anthropogenic fossil fuel use (IPCC 2007a). While there is significant scientific evidence to support the argument that global climate change is occurring and that it is being induced by anthropogenic emissions of CO_2, methane and other greenhouse gases (GHGs), gaps in available climate change data have created disagreement among researchers over the scale and timing of GHG abatement (IPCC 2007a). Balancing environmental and economic considerations, the Government of Canada has committed itself to medium-term and long-term GHG emission reduction targets of 20% below 2006 levels by 2020, and 65% below 2006 levels by 2050 (Environment Canada 2007). While the Canadian *Regulatory Framework for Air Emissions* identifies specific carbon prices required for short-term GHG reductions, there is a great deal of uncertainty regarding emission prices for long-term mitigation (Environment Canada 2007).

The water industry in Canada will likely experience a carbon cost levy (e.g., a carbon tax is already in place in Quebec and British Columbia) on fossil fuel-derived electricity (such as coal and natural gas) used during the manufacture of pipes and other components and operation of water distribution systems, as well as on liquid fuels like diesel and gasoline which are needed to operate machinery in transport, installation, maintenance and disposal activities. The magnitude and long-term uncertainty of a carbon pricing policy in Canada could have significant implications on water distribution system capital planning decisions that are made today. A carbon cost levied on fossil fuel-derived electricity and liquid fuels will create an incentive for water utilities to design systems that satisfy sustainability criteria such as minimizing carbon emissions, in addition to satisfying traditional cost and hydraulic performance criteria.

Determining the appropriate discount rate for public infrastructure projects like water distribution systems with GHG implications has been a source of contention among economists for nearly two decades. According to the IPCC, the arguments for a higher or lower discount rate often turn around questions of ethics and efficiency: how to discount the welfare of future generations? How to discount future pollution? Weitzman (2007) argues that "*the higher the interest rate the stronger the desire to move toward getting more pleasure now at the expense of postponing more pain until later*." While economists like Schneider (2007) suggest that near-zero discounting artificially magnifies how much we would be willing to spend today in order to avoid losses in the future. These two opposing views reflect the current quandary of water utilities in reaching capital rehabilitation and replacement decisions in a manner that balances the financial exigencies and constraints of today with energy use, GHG emission, and climate change risks and potential losses in the future.

The objectives of this paper are threefold: (i) To review the current issues and controversies surrounding the choice of discounting rate and carbon pricing to reduce GHGs linked to public water infrastructure projects in Canada; (ii) To review previous research that has examined the impact of discounting and carbon pricing on design decisions in water systems, and; (iii) To illustrate the possible implications of carbon-abatement strategies (discounting and carbon pricing) on the design of Canadian water systems by way of a real-world Canadian case study. The paper is organized as follows. First, a review of the issues and controversies surrounding lower discount rates and carbon pricing as carbon-abatement tools will then be presented. Second, previous research that has examined the impact of discounting and carbon pricing on water system design and the generation of greenhouse gas emissions in the construction and operation of water systems will be reviewed. The paper will conclude with a design example that illustrates the potential impact of discount rates and carbon prices on capital improvement decisions and GHG emissions in the Amherstview-Odessa water transmission pipeline in Amherstview in Eastern Ontario, Canada.

2 Present Value Analysis and Discount Rates in Infrastructure Projects with GHG Implications

There is ongoing debate among researchers over how fast we should react to the threat of global warming and the extent of policy impacts to reduce GHG emissions. Central to this debate in public infrastructure projects, such as water supply and distribution systems, is the choice of discount rate in present value analysis (PVA) and cost-benefit analysis. The discount rate has significant implications on the economic analysis of public infrastructure projects. As such, choosing an appropriate discount rate and discounting procedure to reduce GHG emissions and mitigate climate change effects has been one of the most contentious and controversial issues surrounding PVA. According to Weitzman (2007) "*it is not an exaggeration to say that the biggest uncertainty of all in the economics of climate change is the uncertainty about which interest rate to use for discounting*."

The higher the discount rate the more weight is placed on the costs and benefits at present in comparison to the costs and benefits in the future (Lee et al. 2000). With high discount rates, the climate-related environmental impacts and costs that take place in the distant future have little or no influence on the net PV of a project. Conversely, low discount rates place more weight on costs and benefits in the distant future in comparison to the costs and benefits at present. If the discount rate is too low it could lead to too much investment in the control of potential climate change impacts at the expense of possibly more efficient or better uses of resources today (Rao 2000). According to Sterner and Persson (2008) the debate over a suitable discount rate "*cuts to the core of many fundamental questions regarding global environmental change: how much weight should we put on the welfare of future versus current generations? Will growth continue so that future generations are all richer than we are today? How important is the distribution of impacts (i.e., how should we value costs that disproportionately fall upon the poor or the rich)?*" Specific arguments put forward by researchers for low discount rates versus BAU discount rates will be explored in detail below.

There is general agreement among researchers that public projects should be discounted at the social discount rate. The social discount rate is defined as the minimum real rate of return that a public investment must earn if it is to be worthwhile undertaking (Boardman et al. 2008). The typical method used by governments and organizations for valuing future costs and benefits is by means of a constant discount rate, generally in the order of 2 to 10% (Rambaud and Torrecilla 2005). Selecting an appropriate discount rate has been a policy issue in Canada for many years (Jenkins and Kuo 2007). Until recently, the social discount rate that federal agencies were required to use was an annual real value of 10% (Treasury Board of Canada Secretariat 1998). Based on work by economists Jenkins and Kuo (2007), the discount rate for Canada was re-estimated and the Treasury Board of Canada Secretariat (2007) interim report is now recommending a real rate of approximately 8%, with the acknowledgement that discount rates as low as 3% may be appropriate for projects with intergenerational circumstances.

According to Boardman et al. (2008) Canada's reduction in social discount rate is at least a partial reflection of research and policy trends in other countries. For instance, in 2003, the United Kingdom became the first government to recommend a declining discount rate for evaluating intergenerational projects (Her Majesty's Treasure 2003). Her Majesty's Treasure (2003) recommends a discount rate of 3.5% for 1 to 30 years, a 3% rate for 31 to 75 years, a 2.5% rate for 76 to 125 years, a 2% rate for 125 to 200 years, 1.5% for 201 to 300 years, and 1% for longer periods. Similarly, in 2004, France replaced its constant discount rate of 8% with a 4% discount rate that decreases to 2% for longer maturities (IPCC 2007b).

To illustrate the dramatic effect of various discount rates on PVA, consider a project with a series of $100,000 per annum carbon tax payments over a period of 100 years. From the results presented in Table 1, it is evident that for conventional discount rates in the range of 5% to 10%, future environmental costs are significantly discounted and given little weight in the PVA calculations. The conflict between long-term environmental policy and standard discounting is described by Lind (1990) as "*regardless of how small the cost today of preventing an environmental catastrophe that will eventually wipe out the entire economy, it would not be worth this cost to the present generation if the benefits in the future are sufficiently distant.*" To put this in perspective, when environmental costs in the example above are discounted at 10%, the resulting total PV is less than one-tenth of the total PV of costs discounted at 0%. In contrast, near-zero discount rates give significantly more weight to environmental costs occurring in the distant future.

Table 1 Impact of discounting a $100,000 annual carbon tax payment over 100 years

Discount Rate			Present Value ($)			
(%)	Year 1	Year 25	Year 50	Year 75	Year 100	Total PV ($)
0.0	100,000	100,000	100,000	100,000	100,000	10,000,000
0.5	99,502	88,277	77,929	68,793	60,729	7,854,264
1.0	99,010	77,977	60,804	47,413	36,971	6,302,888
1.5	98,522	68,921	47,500	32,738	22,563	5,162,470
2.0	98,039	60,953	37,153	22,646	13,803	4,309,835
2.5	97,561	53,939	29,094	15,693	8,465	3,661,411
3.0	97,087	47,761	22,811	10,895	5,203	3,159,891
3.5	96,618	42,315	17,905	7,577	3,206	2,765,543
4.0	96,154	37,512	14,071	5,278	1,980	2,450,500
4.5	95,694	33,273	11,071	3,684	1,226	2,194,985
5.0	95,238	29,530	8,720	2,575	760	1,984,791
5.5	94,787	26,223	6,877	1,803	473	1,809,584
6.0	94,340	23,300	5,429	1,265	295	1,661,755
6.5	93,897	20,714	4,291	889	184	1,535,629
7.0	93,458	18,425	3,395	625	115	1,426,925
7.5	93,023	16,398	2,689	441	72	1,332,369
8.0	92,593	14,602	2,132	311	45	1,249,432
8.5	92,166	13,009	1,692	220	29	1,176,134
9.0	91,743	11,597	1,345	156	18	1,110,910
9.5	91,324	10,343	1,070	111	11	1,052,511
10.0	90,909	9,230	852	79	7	999,927

2.1 The Case for a Lower Discount Rate

The issue of discounting climate change impacts has effectively divided economists into two camps: those who are in support of lower discount rates and those who are in support of BAU discounting. Within the two camps, there is further divide over the appropriate discount rate and discounting mechanism. One of the earliest pioneers in the discount rate dispute, William R. Cline, argued in the 1992 publication *The Economics of Global Warming* that discount rates in the range of 5 to 10%, often used in public investment project analysis, are inappropriate for analysis of very long-term environmental effects, despite their frequent use (Cline 1992). Cline and authors including Stern et al. (2006) and Sterner and Persson (2008) contend that issues of risk, uncertainty and ethics provide a foundation for low and declining discount rates. According to Dietz and Stern (2008) we must understand the risks of action compared to the risks of inaction when discounting climate change impacts. When a low discount rate is used, we risk an irreversible commitment to capital that reduces GHG emissions. If it is later discovered that climate change poses a lesser threat than anticipated, we will have needlessly invested in GHG-efficient capital and processes. However, Dietz and Stern (2008) contend that if a high discount rate is used, we risk an irreversible (i.e. locked-in) investment in energy- and carbon-intensive capital that produces GHG emissions. If it is later discovered that climate change poses a greater threat than anticipated, meeting stabilization targets will become more costly as much more rapid GHG reductions will have to be made. Dietz and Stern (2008) argue that when the risks of climate change are evaluated appropriately and in light of an explicit ethical discussion, it becomes much more important to avoid an irreversible commitment to energy- and carbon- intensive capital in the next decade or two, than to avoid an irreversible commitment to mitigation capital.

The risks of climate change also mean that we cannot assume that economic growth will continue on its present trajectory if emissions continue to follow BAU (Dietz and Stern 2008). Gollier et al. (2008) claim that climate change will introduce costs that will eventually depress the growth rate resulting in discount rates that decreases with time. According to Gollier et al. (2008) declining discount rates are also theoretically justified by uncertainty about future economic conditions. That is to say, if economic uncertainty increases with the time period under consideration, the precautionary saving motive increases the incentive to save and as a result the required rate of return on investment is lowered (Pearce et al. 2003). In addition to economic uncertainty, Weitzman (2007) suggests that uncertainty surrounding extreme climate events can lead to the use of lower discount rates as investors are disproportionately afraid of rare disasters. As Weitzman (2007) explains, "*people are willing to pay high premiums for relatively safe stores of value that might represent "catastrophe insurance" against out-of-sample or newly evolved rare disasters*."

Ethical considerations of intergenerational and intragenerational equity also come into play when justifying lower discount rates. Intergenerational equity requires that future generations be treated equally with the present generations through near-zero discount rates. To Arrow (1995) the fact that an individual will be alive at some future time instead of today does not seem like a morally relevant distinction. Intragenerational equity requires that communities and nations within one generation be treated equally. According to Conceição et al. (2007), a low discount rate implies that affluent populations are adverse to intragenerational inequity. As indicated in the *Stern Review*, the impacts of climate change are expected to fall disproportionately on developing regions as developing regions are, on average, warmer than developed regions. They also typically experience high rainfall variability and rely heavily on agriculture—the most climate-sensitive of all economic sectors (Stern et al. 2006). The *Stern Review* therefore concludes that there is a double inequality in climate change that must be accounted for in the discount rate: historically developed countries have produced the majority of GHG emissions, and therefore have a special responsibility for the state of the world, whereas the consequences of GHG emissions will fall particularly hard on developing countries (Stern et al. 2006).

On the basis of the aforementioned arguments, the *Stern Review* advocates the use of a constant near-zero discount rate of 1.4%. To Weitzman (2007), the use of a constant near-zero discount rate is akin to "*declaring immediate all-out war on greenhouse gas emissions*." Instead, Weitzman suggests that we would do better to steadily but surely ramp up GHG cuts over the next decade or two with a discount rate that decreases systematically with time.

2.2 The Case for Business-as-Usual Discounting

Opponents of the argument for low discount rates cite substantial uncertainty about the extent of global climate change costs and the likelihood that these costs will occur in the far distant future as justification for BAU CO_2-e emissions. Carter et al. (2006) are highly critical of the science behind the *Stern Review* and the "*over-confident*" conclusions that are drawn about the prospective course of GHG concentrations and global warming. The authors claim that if a comparison is made with the global average temperature statistic since 1860, then the late twentieth-century warming is similar in both amount and rate to an earlier (natural) warming between 1905 and 1940. Thus, Carter et al. (2006) conclude that the *Stern Review*'s claim that "*An overwhelming body of scientific evidence indicates that the Earth's climate is rapidly changing, predominantly as a result of increases in greenhouse gases caused by human activities,*" is "*without foundation*." Dasgupta (2006) also reach the conclusion that "*the strong, immediate action on climate change advocated by the authors [Stern] is an implication of their views on intergenerational equity; it isn't driven so much by the new climatic facts the authors have stressed*."

Those in favour of BAU discounting also cite issues of ethics in support of their argument. However, unlike the argument for the ethical treatment of future generations made by authors like Arrow (1995) and Stern et al. (2006), Gollier et al. (2008) argue that high discount rates should be used for the ethical treatment of current generations. Gollier et al. (2008) reason that economic growth will make future generations richer or much richer than we are, therefore, it is unfair to devote current resources from the poor to increase the well-being of the future rich. Byatt et al. (2006) argue that because our knowledge of future events becomes more uncertain as the time horizon is extended, discount rates should if anything increase rather than diminish with time. According to Nordhaus (2007), the idea is not that climate change should not be taken seriously, but that it would be more equitable and efficient to invest in physical and human capital now, so as to build up the productive base of economies, and divert funds to meet the problems of climate change at a later year. With global per capita consumption currently around $10,000 (2007 dollars), and estimated by the *Stern Review* to grow to around $130,000 (2007 dollars) in two centuries, the ethical stance that we have a duty to reduce current consumption by a substantial amount to improve the welfare of the rich future generations is not very persuasive to economists like Nordhaus. Nordhaus (2007) concludes that, "*despite the serious threats to the global economy posed by climate change, little should be done to reduce carbon emissions in the near future; that controls on carbon should be put into effect in an increasing, but gradual manner, starting several decades from now.*"

3 Carbon Pricing in Infrastructure Projects with GHG Implications

The social cost of carbon (SCC) measures the full cost today of an incremental unit of carbon (or equivalent amount of other GHGs) by summing the full cost of the damage it imposes over the whole of its time in the atmosphere (Downing et al. 2005). Estimates of the SCC are particularly sensitive to assumptions about future economic development, the range and likelihood of economic and social damage arising from climate change at future dates and the discount rate to apply to that damage. As a result, the valuation of emission reduction costs can be controversial, and requires a level of sophisticated analysis that IPCC (2007b) finds is still mostly lacking in a climate change context. According to Downing et al. (2005), since discount rates are derived from ethical considerations and value judgements, the SCC cannot be considered an objective, definitive number, but rather the result of subjective, negotiated, societal decisions. Tol (2005) assessed SCC uncertainty by combining estimates of the marginal damage costs of CO_2-e emissions from 28 publications to form a probability density function (PDF). When the results from the 28 studies were combined, the PDF was found to have a mode of US$2 per tonne CO_2-e, a median of US$14 per tonne CO_2-e, a mean of US$93 per tonne CO_2-e, and a 95th percentile of US$350 per tonne CO_2-e. Stern et al. (2006) suggests that the SCC today, if we remain on a BAU trajectory, and incorporate recent evidence of risk, is of the order of US$85 per tonne CO_2-e.

Policy makers in Canada are beginning to develop climate change mitigation strategies that incorporate carbon pricing schemes with the aim of achieving substantial emission reductions by 2020 and beyond. In October of 2007, the province of Quebec became the first province in Canada, and the first jurisdiction in North America, to impose a carbon tax (Government of Quebec 2008). The carbon tax is one mechanism that the Quebec government is using to cut its output of GHGs by 6% from 1990 levels to meet Canada's Kyoto obligations. Quebec's origin-based carbon tax amounts to $0.008 on every litre of gasoline sold in Quebec, $0.009 on each litre of diesel fuel, $0.0096 on every litre of light heating oil and $8.00 per metric ton for coal. The tax applies to approximately 50 large emitters, which operate primarily in the gasoline, heating oil, electricity and natural gas sectors. The tax is expected to generate approximately $200 million a year in revenue, with electricity distributor Hydro-Québec expected to contribute $4.5 million annually (Séguin 2007). While electricity purchasers and end-users of fossil fuels are not targeted directly by the carbon tax, it is likely that the petroleum industry and Quebec's electricity and natural gas utilities will roll their tax costs in with other costs when they seek rate increases (Dougherty 2006).

In 2008, the province of British Columbia (B.C.) enacted the *Carbon Tax Act* to become the second province in Canada to implement a carbon tax (British Columbia B.C. Government 2008). B.C.'s revenue-neutral destination-based (consumer-based) carbon tax applies to virtually all fossil fuels, including: gasoline, diesel, natural gas, coal, propane, and home heating fuel. Biofuels and renewable energy, such as biodiesel, ethanol and biomass are not subject to the carbon tax. Under the B.C. carbon tax regime, emission prices start at $10 per tonne CO_2-e for 2008, and increase to $15 per tonne CO_2-e in 2009, $20 per tonne CO_2-e in 2010, $25 per tonne CO_2-e in 2011 and $30 per tonne CO_2-e in 2012. Beyond the year 2012 the tax rate increase is to be determined by the government of the day. The specific tax rates will vary for each type of fuel depending on the amount of CO_2-e released as a result of its combustion. For example, the carbon tax rate for Canadian bituminous coal after July 1, 2009 will be $31.18 per tonne CO_2-e, while the carbon tax rate for sub-bituminous coal will be $26.58 per tonne CO_2-e. The carbon tax is expected to represent just over 8% of the effort required to reach B.C.'s goal of reducing GHG emissions 33% below 2007 levels by 2020 (with carbon prices beyond 2012 assumed to stay at $30 per tonne CO_2-e).

In November 2006, the Government of Canada made a request to the NRTEE to provide advice on how Canada could achieve significant long-term reductions in GHG emissions and air pollutants by 2050. In particular the NRTEE was asked to examine the implications of long-term GHG emission reductions of 45% to 65% from current levels by 2050. In response, in 2007, the NRTEE released their advisory report entitled *Getting to 2050: Canada's Transition to a Low-emission Future*. The most central recommendation made in the advisory report is for the Government of Canada to establish an economy-wide price on carbon as soon as possible in order to create the long-term predictability required for investment decisions made today. NRTEE (2007) found that an economy-wide emission price policy will need to be the main GHG-reduction policy lever, as emission prices are the most cost-effective mechanism for encouraging investment in higher efficiency and lower emission technologies and processes.

To generate alternative GHG emissions price trajectories, NRTEE (2007) evaluated four GHG emission reduction scenarios for two different targets ("shallow" 45%, and "deep" 65%), and two different GHG price path scenarios ("slow" and "fast"). A "slow" start sought a pathway to meet the 2050 target by stabilizing emissions to 2005 levels in 2020. While a "fast" start also met the 2050 target, but aimed to reduce emissions in 2020 in the order of 20% below 2005 levels (NRTEE 2007). The four price trajectories are shown below in Fig. 1.

NRTEE (2007) modelling suggests that for the 45% and the 65% targets, the "slow" start requires a significantly higher emission price in the latter years to compensate for low prices in the former years. Conversely, the "fast" start requires a higher emission price in the medium-term (2020), which results in lower emission prices over the long-term and results in greater emission reductions in the earlier period. The federal government's emission reduction commitments made in the *Framework* match those of the NRTEE's "fast and deep" scenario. NRTEE (2007) modelling suggests that GHG prices in the range of $10 to $270 (in 2003 Canadian dollars) per tonne of CO_2-e are required to attain a reduction of 20% from 2005 levels by 2020, and 65% below 2005 levels by 2050 if Canada were to meet the targets using domestic actions only. NRTEE (2007) found these prices to similar to global GHG emissions prices suggested by the IPCC (2007b). IPCC (2007b) suggests that GHG prices in the range of US$15 to $130 per tonne CO_2-e are required to attain a global

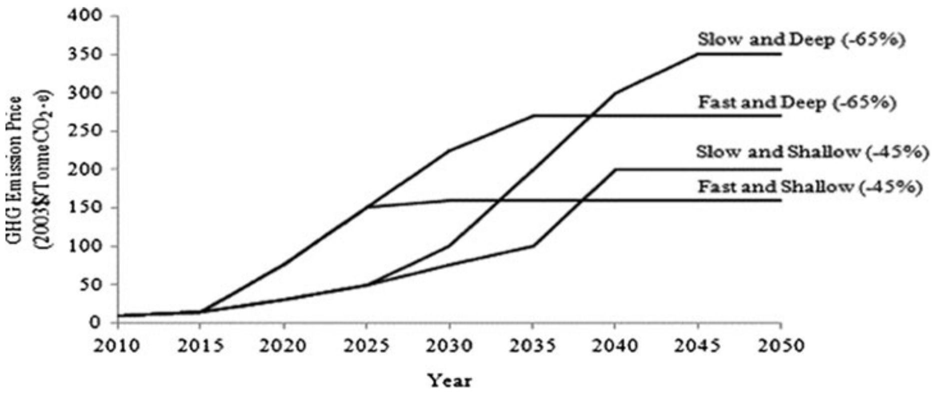

Fig. 1 GHG emission price trajectories for each NRTEE policy scenario (NRTEE 2007)

reduction of approximately 20% from 2005 levels by 2050. It is important to note however, that a great deal of uncertainty exists regarding the price of GHG mitigation. At higher carbon prices, there is no way to accurately predict how the markets will react or how innovation will accelerate in response (NRTEE 2007). As a result, all emission prices predicted beyond the year 2025 are speculative (NRTEE 2007). According to recent research by NRTEE (2007) and Rivers (2010), with the introduction of a carbon price—even a very steep one—Canada's economy is projected to continue growing rapidly. Under BAU scenarios, Canada's economy is expected to grow to a GDP of $1.79 trillion (in 2003 dollars) in 2020. Modelling by Rivers (2010) predicts that the application of a $100 per tonne CO_2-e emissions price would likely lower GDP by 0.5 to 1.3% in 2020. The economic cost of a $200 per tonne CO_2-e price is likely to be greater, with modelling suggesting losses of economic output of 1.0 to 2.4% in this case (Rivers 2010). However, Rivers (2010) also found that if the revenue that the Canadian Government collects from the carbon pricing is properly reintroduced into the Canadian economy, the projected decline in the rate of economic growth can be reduced by half.

4 Research in Water System Design and Optimization that Includes Carbon Pricing and Climate Change

Recently, a number of researchers have begun to examine the impact of discount rates and carbon pricing on the design of water networks and the mass of GHGs they generate. Wu et al. (2008, 2010a) were the first to develop optimization schemes that include greenhouse gas emissions (GHG) generated by water distribution networks. Wu et al. (2008, 2010a) used their multi-objective optimization scheme to examine the impact of discount rate and carbon pricing on the design and the GHGs generated by two hypothetical networks. The results indicated that discount rate selection has a significant impact on pipe costs and operational costs and thus on decision-making. The results also indicated that increasing carbon prices generally led to larger pipe sizes to offset energy costs and greenhouse gases in the future.

Wu et al. (2010b) followed up on their initial research by examining the question of whether multi-objective optimization would remain a useful decision-making tool under a carbon emissions trading scheme. This question was explored with two hypothetical networks. Both single-objective and multi-objective optimization schemes were used in the analysis. The results indicated that the single-objective approach results in a loss of trade-off information between the two objectives and that the multi-objective approach provides decision makers with more insight into the trade-offs between the two objectives.

MacLeod et al. (2010) and Roshani et al. (2011) examined the impact of discounting and carbon pricing on cost, energy use and greenhouse gas (GHG) emissions in the single-objective design/expansion optimization of the real-world Amherstview water distribution system in Amherstview, Ontario, Canada. A parametric analysis was conducted to examine the impact of discounting and carbon pricing on GHG reductions for cement-mortar ductile iron and polyvinyl chloride pipe materials. The results indicated that the discount rate and carbon prices investigated did not significantly reduce energy use and GHG mass in the Amherstview system and did not meet the emission-reduction targets set by the Canadian Government. This result was attributed to a number of factors including, adequate installed hydraulic capacity in the Amherstview system, the use of a time-declining GHG emission intensity factor, and the scope of the expansion problem.

Other research has begun to focus on the impact of changes in air temperature and related water demand on the management and future infrastructure needs of water systems. Ruth et al. (2007) investigated possible changes in water use and future needs in infrastructure based on climate and population forecasts in the City of Hamilton, New Zealand. The authors found that population rather than climate change will drive an overall increase in water demand, but that climate change might increase per capita consumption. Moreover, the authors found that long-term capacity expansion or demand-side management would be needed to avoid possible water supply shortages as early as 2030 in the Hamilton system. In another study, O'Hara and Georgakakos (2008) presented a framework to assess the ability of existing storage to meet present and future urban water demand and to evaluate the effectiveness of storage upgrades in the San Diego system. The authors found that upgrade costs were higher when climate change was considered in the planning scenarios of the San Diego system. Subak (2000) surveyed a number of UK water utilities about the perceived impact of climate change on the resilience of their water systems. The survey revealed that many utilities were building additional storage in their water supply systems to deal with dryer summer periods and shorter and more intense rainfall events. The survey also revealed that few water utilities were considering climate change in their capital and infrastructure planning even though new requirements had been placed on these water utilities to incorporate climate change into their long-term water supply planning.

While the research outlined above has helped to clarify the link between discount rates/carbon prices and water network design and the greenhouse gas emissions generated by these networks, two important research gaps remain. First, more research should be devoted to examining the links between discounting/carbon pricing on design and GHGs in large, real-world networks with complex topology, operating rules, diurnal patterns, time-of-day energy pricing and other real-world complexities. Increasing carbon prices might effectively reduce GHGs in small undersized networks, but it is not yet clear whether they are as effective at reducing GHGs in adequately-sized water distribution networks. Also, it is not yet clear if discounting and carbon pricing have a significant impact on pipe-sizing, pump-replacement, and tank siting/sizing decisions in large, real-world networks. Information at the "real-world" scale is critical if water utility engineers and managers are to make informed decisions about their networks to reduce energy costs and reduce GHGs in the future.

The second major research gap rests with the uncertainty in discount rates and carbon prices that will be in effect in the near- and long-term. Currently, carbon cap-and-trade and tax schemes are in current state of evolution in North America and in Europe and in other parts of the world. The use of discounting as a tool to encourage carbon-abatement in the planning of public infrastructure projects is still an idea being discussed and debated in academic and policy circles (Stern et al. 2006). Therefore, there is still a great deal of uncertainty surrounding what discounting rates and carbon pricing that water utility managers will face in the future as they make key decisions concerning the upgrading and renewal of their drinking water systems. The research thus far has dealt with this uncertainty through scenario analysis, but if this research is to inform the real-world decisions that water utility managers make, more clarity and certainty surrounding discounting rates and carbon pricing is needed soon.

The present paper builds upon the research outlined above and makes an important research contribution by examining the impact of discounting and carbon pricing on the real-world Amherstview-Odessa transmission pipeline. The paper also includes proposed policy on time-varying carbon pricing.

5 Discounting/Carbon Pricing Scenario Analysis on Amherstview-Odessa Water Transmission System

5.1 General Description of Amherstview-Odessa Transmission Pipeline

An overview of the Amherstview-Odessa water system is shown in Fig. 2 and a schematic of the idealized Amherstview-Odessa transmission pipeline is shown in Fig. 3a. In this last figure, water supplied by the Fairfield network is represented by a storage reservoir (R1) with a static head of 65 m. Figure 3a indicates the booster pumping station north of the Fairfield distribution network which consists of three pumps: one emergency diesel Armstrong Series 4030 pump (not shown in Fig. 3a) and two Armstrong Series 4300 Split Coupled Vertical In-Line 3600 RPM pumps (P1 and P2). Figure 3a also indicates the Amherstview-Odessa transmission pipeline of length 6,300 m (6.3 km) with a Hazen-Williams ‘C’ factor of 140 (T1), the Odessa tank (S1), and the Odessa water demand (N1) with an average day level of 25 L/s. Average day demand was modelled as a dynamic extended period simulation using a diurnal curve. The diurnal curve in Fig. 3b was derived by CH2M Hill (2007) from SCADA data obtained for a time period of two weeks (one week in April 2006 and one week in August 2005) during which water production at the FWTP was close to normal production.

Pump operation in the Amherstview-Odessa transmission system is controlled by standpipe (S1) water levels. The standpipe (S1) is cylindrical in shape with a storage capacity of 0.9 ML. The standpipe diameter is 10.36 m and the standpipe height is 10 m. The bottom elevation of the standpipe is approximately 36 m. The minimum normal-day operating water level is 7.5 m. At a water level of 7.5 m, both pumps (P1 and P2) turn on. When the water level reaches the maximum normal-day operating level of 9.8 m, both pumps are shut off. In the event that the water level falls to 4 m, the stand-by emergency pump will turn on.

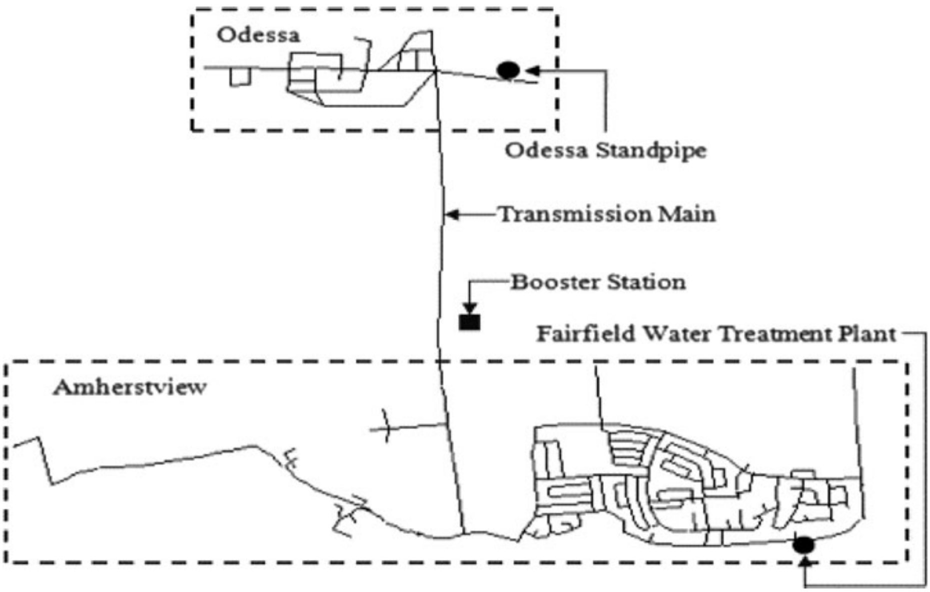

Fig. 2 Overview of the Amherstview-Odessa water transmission system

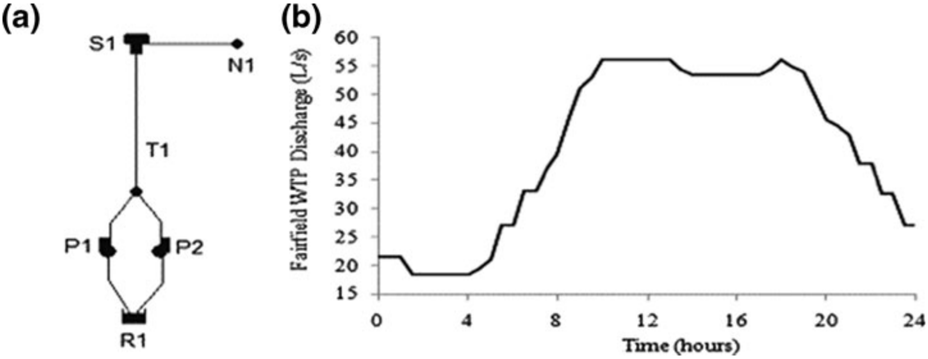

Fig. 3 **a** Schematic of Amherstview-Odessa water transmission system; **b** Normal-day Fairfield WTP diurnal curve (CH2M Hill 2007)

5.2 General Description of Scenario Analysis

The implications of discount rate and carbon price uncertainty on the evaluation of a public-sector infrastructure project like a water distribution system are illustrated though a scenario analysis of the Amherstview-Odessa water transmission system. The objective of the scenario analysis is to evaluate how discount rate and carbon price influence water main infrastructure decisions in the Amherstview-Odessa transmission system and the PV of long-term pumping energy and carbon tax costs over a 100-year design life. A sensitivity analysis of discount rate has been carried out at 8%, 3% and 1.4%. For each discount rate, the effect of no carbon price is compared to the NRTEE carbon price trajectories "Slow and Shallow" and "Fast and Deep" presented in Table 2. In each discount rate/carbon price scenario, the transmission main diameter of the Amherstview-Odessa system is optimized to meet the minimum hydraulic requirements and to minimize the present value sum of pipe and pump replacement costs, pump electrical costs and carbon costs. The Amherstview-Odessa design/optimization formulation is formally presented next.

5.3 Optimization Formulation of the Amherstview-Odessa Transmission System with Carbon Pricing

For a given level of discount rate and carbon price set in the scenario analysis, the optimization of the Amherstview-Odessa system consists of choosing the transmission main diameter (decision variable) that minimizes total cost in the objective function (1). It was determined that the Amherstview-Odessa transmission system has adequate tank and pump capacity, and so the location and sizing of new elevated tanks and pump stations were not included as decision variables in the optimization problem. It was further assumed that the two service pumps (P1 and P2 in Fig. 3a) are replaced every 20 years. Therefore the decision consists of selecting a transmission main diameter that minimizes the sum of prevent value pipe cost, pump cost, electricity cost, and the cost of a carbon tax levied on electricity to operate the pumps over the 100-year planning horizon.

Minimize:

$$Total\ Cost = C_{Pipe} + C_{Pump} + C_{Operating} + C_{GHG} \tag{1}$$

Table 2 Carbon price trajectories: "No tax", "Slow and shallow" and "Fast and deep"

Year	Carbon Price Trajectories ($/tonne CO_2-e)		
	No Tax	Slow and Shallow	Fast and Deep
2010	0	10	10
2015	0	15	15
2020	0	30	75
2025	0	50	150
2030	0	75	225
2035	0	100	270
2040 +	0	200	270

where C_{pipe} = present value cost of the new transmission main ($); C_{pump} = present value cost of the pump replacements (on a 20-year cycle) ($); $C_{Operating}$ = present value cost of electricity for pumping ($); and C_{GHG} = present value cost of a carbon tax levied on electricity production for pumping ($). Capital cost ($C_{Capital}$) is calculated as:

$$C_{Pipe} = C_p(d, L) \tag{2}$$

$$C_{Pump} = \sum_{p=1}^{2} \sum_{r=1}^{R} PV\left(PUMP_{p,r}\right) \tag{3}$$

where $C_p(d, L)$ = cost of transmission main with diameter d and length L ($); p = number of pumps; r = 20-year replacement cycle index; R = number of 20-year replacement cycles in the 100-year planning period; $PV(PUMP_{p,r})$ = present value cost of replacing pump p in replacement cycle r ($). The replacement cost for each of the two Armstrong Series 4300 pumps (P1 and P2 in Fig. 3a) is $3,482.

Operating costs ($C_{Operating}$) and GHG costs (C_{GHG}) occur annually throughout the design life of the project and are calculated with net present value (NPV) analysis. Operating costs are calculated with

$$C_{Operating} = \sum_{p=1}^{2} \sum_{t=1}^{T} PV\left(PE_{p,t} \cdot EC\right) \tag{4}$$

where t = time; T = number of years in the design life of the project; $PE_{p,t}$ = annual electricity consumption of pump p in year$t$ (kWh); and EC = price of electricity ($/kWh). The cost of electricity is assumed to be 6.6 cents per kWh, which is the average Regulated Price Plan (RPP) electricity consumption price set by the Ontario Energy Board (OEB) for November 2008 (OEB 2008).

The mass of GHGs emitted over the design life of a water network can be calculated as follows

$$GHG_e = \sum_{p=1}^{2} \sum_{t=1}^{T} PV\left(PE_{p,t} \cdot EIF_t\right) \tag{5}$$

where GHG_e = total GHG mass generated in network operation (tonne CO_2-e); and EIF_t = GHG emission intensity factor for year t (tonne CO_2-e/kWh). In the most recent *National*

Inventory Report, Environment Canada reported the 2006 GHG emission intensity value for Ontario to be 0.218 kg CO_2-e/kWh (Environment Canada 2008). GHG costs are calculated using (6)

$$C_{GHG} = \sum_{p=1}^{2} \sum_{t=1}^{T} PV\left(PE_{p,t} \cdot EIF_t \cdot CP_t\right) \tag{6}$$

where CP_t = the cost of carbon in year t (\$/tonne CO_2-e). Both electricity and carbon costs were discounted with a single discount rate selected in the scenario analysis.

Subject To:

a) Conservation of mass at nodes and energy conservation around pseudo-loops:

$$\sum Q_{in} - \sum Q_{out} = Q_e \tag{7}$$

$$\sum_{loop} h_f - \sum_{loop} E_p = 0 \tag{8}$$

b) Minimum pressure requirement (245 kPa):

$$h_i \geq h_{i,\min} \text{ for } i = 1, 2, \ldots, N \tag{9}$$

c) Commercially-available pipe diameter constraints:

$$D \in \mathbf{D} \tag{10}$$

where Q_{in} = the flow of water into the junction (l/s); Q_{out} = the flow of water out of the junction (l/s); and Q_e = the demand at the junction node (l/s); h_f = headloss in each pipe (m); E_p = pumping head (m); h_i = pressure head at node i (m); $h_{i,min}$ = minimum pressure head required at node i (m); N = number of network nodes; D = transmission main diameter (mm); $\mathbf{D}$ = set of discrete commercially-available pipe diameters. The transmission main diameter was selected from six commercially-available IPEX DR25 Blue Brute PVC diameters in Table 3. The unit cost of IPEX DR25 Blue Brute PVC for the 6 commercially-available PVC diameters in Table 3 was obtained from a local PVC pipe manufacturer.

Design solutions were generated with enumeration and the EPANET2 hydraulic solver (Rossman 2000) was used to evaluate constraints (7)–(10) and the hydraulic performance of the network (minimum pressure) under average day demands.

5.4 Results and Discussion

Table 4 presents the chosen transmission main diameter and cost break-down for different discount rate and carbon tax scenarios. The system cost includes the initial cost of the transmission main and the booster pump, as well as the PV cost of pump replacements every 20 years. Operating costs were calculated using the normal-day diurnal curve (Fig. 3b), booster pump energy consumption rates reported by EPANET2 (Rossman 2000) and the most recent RPP electricity price for Ontario. The cost of GHG emissions were calculated using booster pump energy consumption rates, the GHG emission intensity for electricity use in Ontario and three different carbon price regimes. The results show that a transmission main with a 250 mm diameter had the least PV cost for discount rates of 3% and 8%. When the discount rate was lowered to 1.4% and a carbon price was introduced, a

Table 3 Nominal diameter and unit cost of commercially-available PVC pipe diameters

Design Solution	Nominal Diameter (mm)	Unit Cost ($/m)
D1	250	63
D2	300	75
D3	350	103
D4	400	134
D5	450	170
D6	500	210

transmission main with a 300 mm diameter produced the least PV cost. Similar results have been presented in Wu et al. (2008).

The design example results are presented in Fig. 4. The following can be noted from Table 4 and Fig. 4: (1) The rate at which long-term energy and GHG costs are discounted significantly affects the total cost of a design solution; (2) The more aggressive the carbon price trajectory (higher carbon price), the greater the impact of GHG costs on the total cost of a design solution; (3) The greater the investment in capital costs the greater the savings in operating and GHG costs. This can be seen in Table 4 as the 300 mm diameter design solution reduces the mass of GHGs that are emitted over the design life of the project when compared to the 250 mm diameter solution. Larger diameter systems have lower long-term operational energy requirements as a result of reduced friction losses in the system; (4) The higher the carbon price the greater the savings in GHG costs when selecting a large diameter design solution; and (5) The advantages of larger diameter design alternatives (i.e., lower pumping and GHG costs) are virtually eliminated when Canada's recommended discount rate of 8% is used.

Within the context of the current debate over appropriate discounting rates, the Amherstview results can be viewed in support of both low and high discount rates. Lowering discount rates to 1.4% does lead to marginally higher pipe diameter (from 250 mm to 300 mm) and thus a bigger up-front investment of capital. However, in the Amherstview-Odessa system specifically, the marginal increase in diameter hardly constitutes an irreversible commitment to capital to reduce GHG emissions. In addition

Table 4 Design example results for discount rate and carbon price trajectories

Carbon Regime	Discount Rate (%)	Pipe Diameter (mm)	System Cost ($)	Operating Cost ($)	Carbon Tax ($)	Total Cost ($)	Mass GHG (t/100 years)
No Tax	8	250	405,762	76,476	0	482,238	2,068
	3	250	411,691	184,458	0	596,149	2,068
	1.4	250	418,445	308,273	0	726,718	2,068
Slow and Shallow	8	250	405,762	76,476	11,969	494,207	2,068
	3	250	411,691	184,458	65,391	661,540	2,068
	1.4	300	494,045	256,435	118,046	868,526	1,720
Fast and Deep	8	250	405,762	76,476	22,788	505,026	2,068
	3	250	411,691	184,458	107,484	703,633	2,068
	1.4	300	494,045	256,435	182,211	932,691	1,720

to GHG-reducing benefits, the larger pipe diameter offers better fire protection and a hedge against uncertain future demand in the Odessa system. The case for retaining the *status quo* discount rate of 8% is also tenable here considering that this *status quo* discount rate leads to considerable up-front savings in capital pipe stock in the Amherstview-Odessa system. In theory, these savings could be invested and applied to climate-mitigation initiatives in the future.

6 Summary

The paper reviewed the current issues and controversies surrounding the choice of discounting rate and carbon prices in Canada to reduce the greenhouse gas emissions linked to public water systems in Canada. The arguments for and against low discount rates and

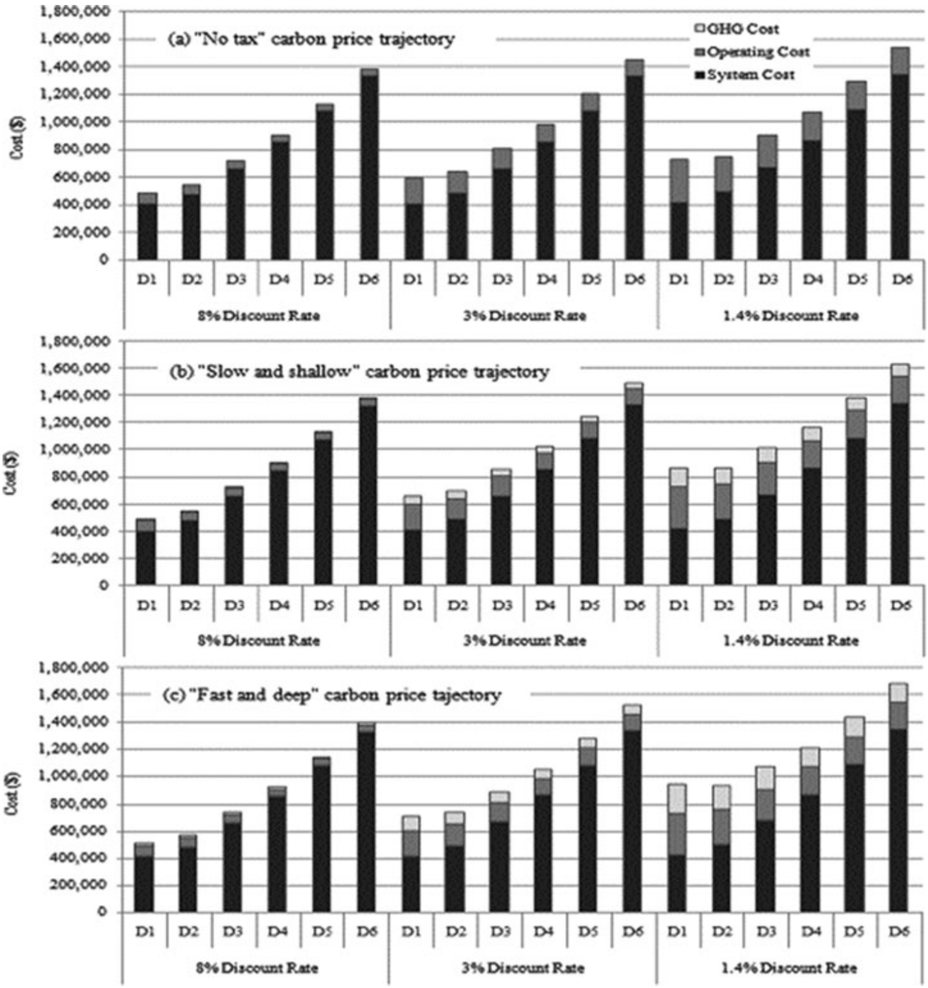

Fig. 4 Chosen transmission main diameter and cost break-down for different discount rate and three carbon price scenarios: (a) "No Tax"; (b) NRTEE "Slow and Shallow", (c) NRTEE "Fast and Deep"

carbon pricing were reviewed and mostly turned around issues of ethics and efficiency. These two opposing views reflect the current quandary of water utilities in reaching capital rehabilitation and replacement decisions in a manner that balances the financial exigencies and constraints of today with energy use, GHG emission, and climate change risks and potential losses in the future. The paper also reviewed previous research that has examined the impact of discounting and carbon pricing on design decisions in water systems.

The paper also served to illustrate the implications of discount rate and carbon price uncertainty on water network design by way of the Amherstview-Odessa water transmission system. The objective of the design example was to choose a transmission main diameter that met minimum hydraulic requirements and minimized PV cost under plausible discount rate and carbon price scenarios. The carbon price trajectories selected for evaluation included “No Tax”, the NRTEE recommended “Fast and Deep” and the NRTEE “Slow and Shallow”. The “Slow and Shallow” and “Fast and Deep” trajectories were found to increase the impact of GHG costs on total cost. When a discount rate of 1.4% was selected both carbon price trajectories led to solutions with a larger diameter pipe. This is because larger diameter pipes have lower long-term operating and carbon costs, and decreasing the discount rate increases the impact of these long-term costs on total cost.

The Amherstview results can be viewed in support of both low and high discount rates. Lowering discount rates to 1.4% does lead to marginally higher pipe diameter (from 250 mm to 300 mm) and thus a bigger up-front investment of capital. However, in the Amherstview-Odessa system specifically, the marginal increase in diameter hardly constitutes an irreversible commitment to capital to reduce GHG emissions. The larger pipe diameter offers other public benefits such as enhanced fire protection and a hedge against uncertain future demand in the Odessa system. The case for retaining the *status quo* discount rate of 8% is also tenable here considering that this *status quo* discount rate leads to considerable up-front savings which could in theory be invested and applied to climate-mitigation initiatives in the future.

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References

Arrow KJ (1995) Intergenerational equity and the rate of discount in long-term social investment. IEA World Congress, Tunis

Boardman AE, Moore MA, Vining AR (2008) Social Discount Rates for Canada.” John Deutsch Institute Conference: Discount Rates for the Evaluation of Public Private Partnerships. Kingston, Ontario

British Columbia (B.C.) Government. (2008). *Carbon Tax Act [B.C. Reg. 125/2008]*. Queen’s Printer, Victoria.

Byatt I, Castles I, Goklany IM, Henderson D, Lawson N, McKitrick R, Morris J, Peacock J, Robinson C, Skidelsky R (2006) The stern review: a dual critique, Part II: economic aspects. World Econ 7(4):199–232

Carter RM, de Freitas CR, Goklany IM, Holland D, Lindzen RS (2006) The stern review: a dual critique, part I: the science. World Econ 7(4):165–198

CH2M Hill (2007) Fairfield water storage project final report prepared for loyalist township. Ottawa, Canada

Cline WR (1992) The economics of global warming. Institute for International Economics, Washington

Conceição P, Zhang Y, Bandura R (2007) Brief on discounting in the context of climate change economics. In: Human Development Report 2007/2008: Fighting climate change: human solidarity in a divided world. Human Development Report Office, United Nations Development Programme, New York, New York

Dasgupta P (2006) Comments on the Stern Review's Economics of Climate Change. Prepared for a seminar on the Stern Review's Economics of Climate Change, organised by the *Foundation for Science and Technology* at the Royal Society, London

Dietz S, Stern N (2008) Why economic analysis supports strong action on climate change: a response to the *Stern Review*'s critics. Rev Environ Econ Pol 2(1):94–113

Dougherty K (2006) Driving in Quebec likely to cost more. National Post, June 16

Downing TE, Anthoff D, Butterfield B, Ceronsky M, Grubb M, Guo J, Hepburn C (2005) Scoping uncertainty in the social cost of carbon. DEFRA, London

Environment Canada (2007) Regulatory Framework for Air Emissions. Library and Archives Cataloguing in Publication, ISBN 978-0-662-69717-6, Ottawa

Environment Canada (2008) Canada's National Greenhouse Gas Inventory (1990–2006). Library and Archives Cataloguing in Publication, ISBN: 978-1-100-11176-6, Ottawa

Gollier C, Koundouri P, Pantelides T (2008) Declining discount rates: Economic justifications and implications for long-run policy. Economic Policy, October 2008, 757–795

Government of Quebec (2008) Quebec and climate change a challenge for the future: 2006–2012 action plan. Government of Quebec, Quebec City

Her Majesty's Treasury (HMT) (2003) Appraisal and Evaluation in Central Government (The Green Book). Her Majesty's Stationary Office, London

IPCC (2007a) Climate change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

IPCC (2007b) Climate change 2007: mitigation of climate change. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L (eds) Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Jenkins GP, Kuo CY (2007) The Economic Opportunity Cost of Capital for Canada – An Empirical Update. Queen's Economics Department Working Paper No. 1133, July

Lee CF, Lee JC, Lee AC (2000) Statistics for business and economics. World Scientific Publishing Company, New Jersey

Lind RC (1990) Reassessing the Government's discount rate policy in light of new theory and data in a world economy with a high degree of capital mobility. J Environ Econ Manag 18:S-8–S-28

MacLeod S, Roshani E, Filion Y (2010) Impact of Pipe Material Selection on Greenhouse Gas Mitigation in the Optimal Design of Water Networks Under Uncertain Discount Rates and Carbon Prices. Water Distribution System Analysis Symposium. Tucson, Arizona

National Round Table on the Environment and the Economy (NRTEE) (2007) Getting to 2050: Canada's transition to a low-emission future. Library and Archives Canada Cataloguing in Publication, Ottawa

Nordhaus WD (2007) A review of the stern review on the economics of climate change. J Econ Lit, XLV, pp 682–702

O'Hara JK, Georgakakos KP (2008) Quantifying the urban water supply impacts of climate change. Water Resour Manag 22(10):1477–1497

Ontario Energy Board (OEB) (2008) Regulated price plan price report. Queens Printer for Ontario, Toronto

Pearce D, Groom B, Hepburn C, Koundouri P (2003) Valuing the future: recent advances in social discounting. World Econ 4(2):121–141

Rambaud C, Torrecilla MJM (2005) Some considerations on the social discount rate. Environ Sci Pol 8:343–355

Rao PK (2000) The economics of global climate change. M. E. Sharpe, Armonk

Rivers N (2010) "Impacts of climate policy on the competitiveness of Canadian industry: how big and how to mitigate?" Energ Econ 32(5):1092–1104

Roshani E, MacLeod S, Filion Y (2011) Evaluating climate change mitigation strategies on the optimal design and expansion of the Amherstview Ontario Water Network: A Canadian Case Study. J Wat Resrc Plann Mangmt (Advanced Publication)

Rossman LA (2000) Epanet2 user's manual. US EPA, Washington

Ruth M, Bernier C, Jollands N, Golubiewski N (2007) Adaptation of urban water supply infrastructure to impacts from climate and socioeconomic changes: The case of Hamilton, New Zealand. Water Resour Manag 21(6):1031–1045

Schneider N (2007) Economists respond to the *Stern Review* on the economics of climate change. Fraser Forum, February, 20–23

Séguin R (2007) Quebec pulls trigger on carbon tax. Globe and Mail, July 6

Stern N, Peters S, Bakhshi V, Bowen A, Cameron C, Catovsky S, Crane D, Cruickshank S, Dietz S, Edmonson N, Garbett S-L, Hamid L, Hoffman G, Ingram D, Jones B, Patmore N, Radcliffe H, Sathiyarajah R, Stock M, Taylor C, Vernon T, Wanjie H, Zenghelis D (2006) Stern review: the economics of climate change. HM Treasury, London

Sterner T, Persson MU (2008) An even sterner review: introducing relative prices into the discounting debate. Rev Environ Econ Pol 2(1):61–76

Subak S (2000) Climate change adaptation in the U.K. Water industry: managers' perceptions of past variability and future scenarios. Water Resour Manag 14(2):137–156

Tol RSJ (2005) The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. Energ Pol 33:2064–2074

Treasury Board of Canada Secretariat (TBS) (1998) Benefit-Cost Analysis Guide. Treasury Board of Canada Secretariat, Ottawa

Treasury Board of Canada Secretariat (TBS) (2007) Benefit-cost analysis guide—interim report. Treasury Board of Canada Secretariat, Ottawa

Weitzman M (2007) A review of the stern review on the economics of climate change. J Econ Lit 45(3):703–724

Wu W, Simpson AR, Maier HR (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

Wu W, Simpson AR, Maier HR (2010a) Accounting for greenhouse gas emissions in multi-objective genetic algorithm optimization of water distribution systems. J Water Resour Plann Manage 136(2):146–155

Wu W, Maier HR, Simpson AR (2010b) Single-objective versus multiobjective optimization of water distribution systems accounting for greenhouse gas emissions by carbon pricing. J Wat Resrc Plann Mangmt 136(5):555–565