Life Cycle Analysis for Water and Wastewater Pipe Materials

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Abstract: A life cycle analysis (LCA) was performed for six commonly used types of water and wastewater pipe materials: polyvinyl chloride (PVC), ductile iron, cast iron, high density polyethylene (HDPE), concrete, and reinforced concrete. The objectives were to (1) compare the six pipe materials in terms of global warming potential (GWP) through four LCA phases: pipe production, transport, installation, and use; (2) determine the primary source(s) of differences in LCA results; and (3) examine the effectiveness of currently used pipe size selection criteria when LCA GWP is considered. The results for unit lengths of discrete pipe sizes were used to generate functions relating GWP per kilometer of pipe to diameter and material selections. The LCA results were monetized using an emission penalty of \$25/equivalent ton of CO_2. For pipe diameters ≤61 cm (24 in.), GWP due to pipe manufacture, transport, and installation of ductile iron pipe was the largest among the six materials. At diameters ≥76 cm (30 in.), the GWP of PVC was highest. Concrete pipe resulted in the lowest GWP across the entire range of pipe sizes investigated. The GWP for pipe production, transport, and installation in a high-growth planning area in southeast Tucson, Arizona, was approximately one-tenth of the GWP derived from pipe network operation. The lifetime GWP from production, transport, and installation increased monotonically with pipe diameter for all materials analyzed, whereas, for a given flow, GWP from energy loss due to friction in flow simulations was inversely related to pipe diameter. The tradeoff suggests that there is an optimum diameter that minimizes lifetime GWP. However, optimum pipe sizes based on GWP were similar to pipe diameters selected based on economic cost alone, suggesting that LCA of water distribution and wastewater collection systems will not yield major changes in criteria for selection of pipe size. **DOI: 10.1061/(ASCE)EE.1943-7870.0000638.** *© 2013 American Society of Civil Engineers.*

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Introduction

The analysis of environmental impacts arising from water distribution and wastewater collection systems has grown increasingly relevant due to refinement of life cycle analysis (LCA) methods. The potential environmental effects of pipe material selection for water distribution systems have previously been studied. Dennison et al. (1999), for example, compared the fractional contributions of manufacturing, materials, and energy to material-dependent global warming potential (GWP) without holistically comparing the two materials. Piratla et al. (2012) ranked overall CO_2 emissions from the manufacture and use of a hypothetical, 20.3 cm (8 in.), 500 ft pipe over a 50-year lifetime for four different pipe materials. Molecular oriented polyvinyl chloride (PVCO) provided the lowest equivalent CO_2 emissions over the lifetime of the pipe. Herstein et al. (2009) and Herstein and Filion (2011) introduced a multiobjective optimization technique and a unique environmental index to extend water distribution system planning beyond the consideration of economic objectives alone. Because their environmental index tended to be dominated by pumping energies, environmental and economic objectives were jointly satisfied for the most part (Herstein et al. 2011). Recio et al. (2005) investigated the life cycle energy consumption and related greenhouse gas (GHG) emissions attributable to polyvinyl chloride (PVC), high density polyethylene (HDPE), polypropylene, ductile iron, and concrete pipes. That study indicated that externalized costs such as GHG emissions contribute significantly to the overall cost of water distribution system construction and use.

This study analyzed the LCA damages of six commonly used pipe materials. Material-dependent GWPs were organized as functions of pipe diameter for use in (1) designing real pipe networks and (2) reevaluating criteria used to select optimal pipe sizes. LCA estimates of GWP were monetized to strengthen economic comparisons of pipe system alternatives in a high growth planning area in southeast Tucson, Arizona.

Methods

LCA Methodology

Standard LCA methodology (ISO 14040) (2006) consists of the following four steps:

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1. Goal and scope definition to identify the objectives and boundaries of the system analyzed.
2. Life cycle inventory (LCI) analysis to quantify collected data (LCA inputs, e.g., material and energy use) and calculate LCA outputs (LCI results, e.g., emissions and waste).
3. Life cycle assessment to convert LCI results into environmental impacts. During this step, environmental effects are assigned to different impact categories to obtain category-specific indicator values.
4. Interpretation, to evaluate and summarize results obtained from the previous steps and move toward a comprehensive conclusion.

The primary objectives of this study were to determine material-specific LCA damages for water and wastewater transmission—specifically, GWP and other categories of environmental impact for six commonly used pipeline materials. In the final analysis, however, the primary LCA result considered was GWP. Four phases were modeled in terms of their contributions to GWP: pipe production, transport, installation, and use. The functional unit to present and compare LCA results was unit pipeline length (km), as opposed to more commonly used functional units based on the volume of water produced or delivered. Simplifications were necessary (Table 1) to make the problem manageable. It was not possible, for example, to generalize on the GWP arising from energy demand for water pressurization and delivery because results are sensitive to system topography (static lift). Those damages were considered, however, when LCA was applied to the design of a water distribution system in a high-growth Tucson area in which topography is known.

Table 1. Summary of Elective Constraints and Simplifications for LCA of Water/Wastewater Pipeline Systems

LCA phase	Included in the analysis	Excluded
Production	Material-specific and size-specific energy consumption during raw material acquisition, pipe production	Production and maintenance of machinery required in the production phase
Transport	Transport distance, fuel consumption, vehicle types	Production and maintenance of transportation vehicles
Installation	Fuel consumption for trench excavation	Production and maintenance of excavator, embodied energy of bedding and backfill materials
Use	Friction losses during water transmission	Static lift, delivery pressure
Recovery/ disposal	None—the elective method for pipe disposal was abandonment in place	All—no recovery expense or salvage value was taken

Data Collection

The discrete pipe sizes selected for inclusion in the study ranged from 10.2 to 122 cm (4–48 in.) in diameter for six distinct types of pipelines: PVC, ductile iron, cast iron, HDPE, concrete, and reinforced concrete. LCA requires certain information at each stage of the analysis (i.e., production or transport; Fig. 1, Table 2). Data for the pipeline LCA were collected from all available sources, primarily from environmental reports, archival scientific literature, and personal communication with private companies. LCI calculations were conducted using the commercial software GaBi 4 (Goedkoop et al. 2008).

For the production phase, material-dependent energy demands for discrete sizes of pipe were calculated as the embodied energies. Embodied energy includes the energy expended for raw material acquisition and all processes necessary for material production; that is, all energy consumed up to the point at which materials (in this case, finished pipes) leave the factory. References supporting the estimation of material-dependent and size-dependent embodied energies are summarized in Tables 3–4. In summary, raw material inputs for 1-km pipe lengths were calculated from published pipe dimensions and consequent material volume requirements. Ductile iron pipe calculations are used to illustrate the nonlinearity in relationships between pipe diameter and material requirements

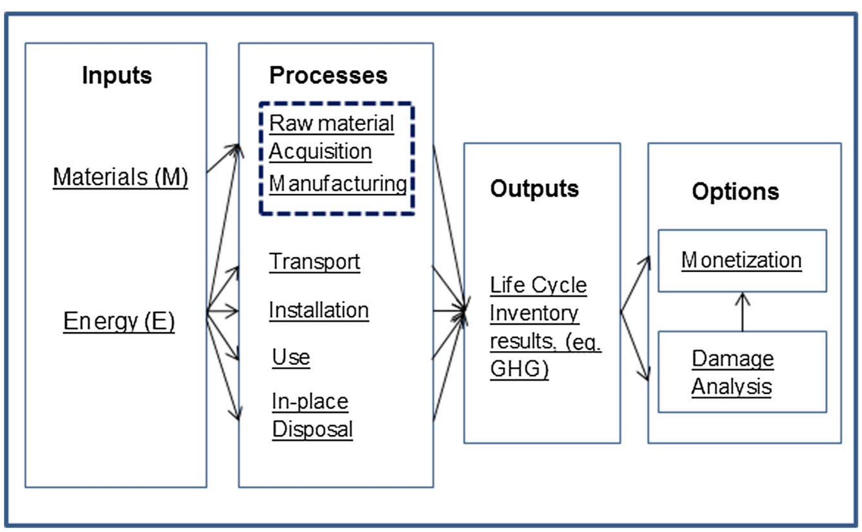

Fig. 1. Detailed flowchart for LCA: the solid line surrounding the figure shows the system boundary; inputs include materials and energy use for various processes, and the dashed line encloses processes that contribute to the embodied energy for material production; outputs (LCI results) can either be directly monetized or further analyzed by an LCA damage model and then monetized based on estmated damages to environmental and human health (further described in Supplementary Data, including Fig. S1 and Table S1), (Althaus et al. 2009; Frischknecht and Jungbluth 2007)

Table 2. Detailed Summary of Input Data for the LCA Software

Production	Process inputs per km of pipe
Materials	
PVC	PVC granulate (kg), electricity (MJ), industrial water (kg)
Ductile iron	Iron ore (kg), electricity (MJ), industrial water (kg)
Concrete	Sand (kg), rock (kg), portland cement (kg), electricity (MJ), industrial water (kg)
HDPE	HDPE granulate (kg), electricity (MJ), industrial water (kg)
Reinforced concrete	Sand (kg), rock (kg), portland cement (kg), steel (kg), electricity (MJ), industrial water (kg)
Cast iron	Iron ore (kg), electricity (MJ), industrial water (kg)
Transport	Distance[a] (km), cargo weight (kg)
Installation	Diesel (kg)

[a]Total delivery distance plus return (km).

Table 3. Representative Calculations: Weight per Unit Length of Ductile Iron Pipe

Size (cm)	Size (in.)	OD (in.)	Thickness (in.)	Weight (kg/km)
10.2	4	4.8	0.24	1.68E+04
20.3	8	9.05	0.27	3.28E+04
30.5	12	13.2	0.31	5.42E+04
40.6	16	17.4	0.34	8.27E+04
50.8	20	21.6	0.39	1.16E + 05
61.0	24	25.8	0.41	1.53E+05
76.2	30	32	0.43	2.14E+05
91.4	36	38.3	0.48	2.76E+05
106.7	42	44.5	0.53	3.41E+05
121.9	48	50.8	0.58	4.22E+05

Note: Parallel calculations for other pipe materials are provided in Supplemental Data (data from AWWA/ANSI C150/A21.50-91 Standards, Ductile Iron Design, 2004), OD = outer diameter.

Table 4. Material-Specific Embodied Energies for the Pipe Materials Investigated

Material category	Embodied energy (MJ/kg)	Source
Ductile iron	34.4	Piratla et al. (2012)
Cast iron	25.5	Energy Conservation in Iron Casting Industry (1998)
PVC	75.2	Piratla et al. (2012)
HDPE	74.9	Piratla et al. (2012)
Reinforced concrete	3.5	Struble and Godfrey (2004); Marceau and Nisbet (2007)
Concrete	1.34	Marceau and Nisbet (2007)

Note: The values shown are from the indicated references.

(and ultimately GWP) per kilometer of pipe (Table 3). The conversion of material demands to embodied energy requirements was based on literature values (Table 4). GWP was estimated from energy requirements using default conversions in the LCA software. Because these were derived to represent fuel blends in Europe, calculations were repeated using a blend of fuels that is more representative of southwestern (United States) municipalities. GWP estimates obtained using the two blends differed by <1%. The overall emissions factor for each blend was in the range 0.90–0.91 kg CO_2 equivalent/kWh.

Transport between points of production and installation was based on a 322-km (200-mi) round trip between Phoenix and Tucson. Diesel-fueled, 13-ton road trucks were the assumed transport vehicles for all pipe materials.

The installation phase primarily accounted for fuel consumed during trench excavation, which was calculated based on the volume of soil removed and consequent trenching velocity (described in the following). The calculation of trench volume differed for each pipe material based on trenching and installation standards [Bonds 2000, 2001; United States Pipe and Foundry Company 2004; Ductile Iron Pipe Research Association 2000, 2006; American Water Works Association (AWWA) 1996; American Concrete Pipe Association 2007]. The basis of concrete pipe trench volume estimates illustrates the procedure used for all pipeline materials (Fig. 2).

Trench volume is a nonlinear function of pipe diameter. When the volume per unit length was known, the trenching velocity was determined from

$$U = C \times V^{-0.7} \tag{1}$$

where V = excavation volume per unit length of pipe (m^3/m); U = average trenching velocity (m/day); and C = fitted constant.

The estimated trenching velocity for the installation of 10.2-cm (4-in.) pipe was 100 m/8-h working day, leading to $C = 4{,}100\ m^{2.4}/\text{day}$. Then:

$$T_e = 1{,}000/U \tag{2}$$

where T_e = time to excavate a 1-km trench (days, assuming an 8 h working day); and

$$C_f = T_e \times D_f \tag{3}$$

where C_f = fuel (gal.) consumed per km of trench; and D_f = daily fuel demand (gal./day).

It was also assumed that the hydraulic excavator used consumes 363 L (96 gal.) of diesel fuel per 8-h working day (Caterpillar, Inc. 2007). In-place disposal was presumed at the end of pipeline service life based on guidance from the City of Tucson; that is, no recycling or reuse benefits were taken, and there was no excavation or transportation cost for recovery.

LCI outputs consisting of emissions and wastes can be organized into a few environmental impact categories (Guinée 2001) such as GWP, human toxicity potential, and acidification potential (Fig. 3). In this study, however, GWP was the primary impact category. The use and potential importance of LCA end points other than GWP are illustrated in the Supplemental Data.

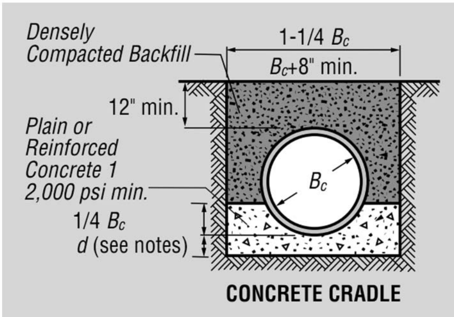

Fig. 2. Concrete pipe trench configuration and dimensions that were used to estimate pipe trench volume per unit length as a function of pipe diameter: B_c = inside diameter of the concrete pipe, d = depth of bedding material below pipe (permission from American Concrete Pipe Association 2007)

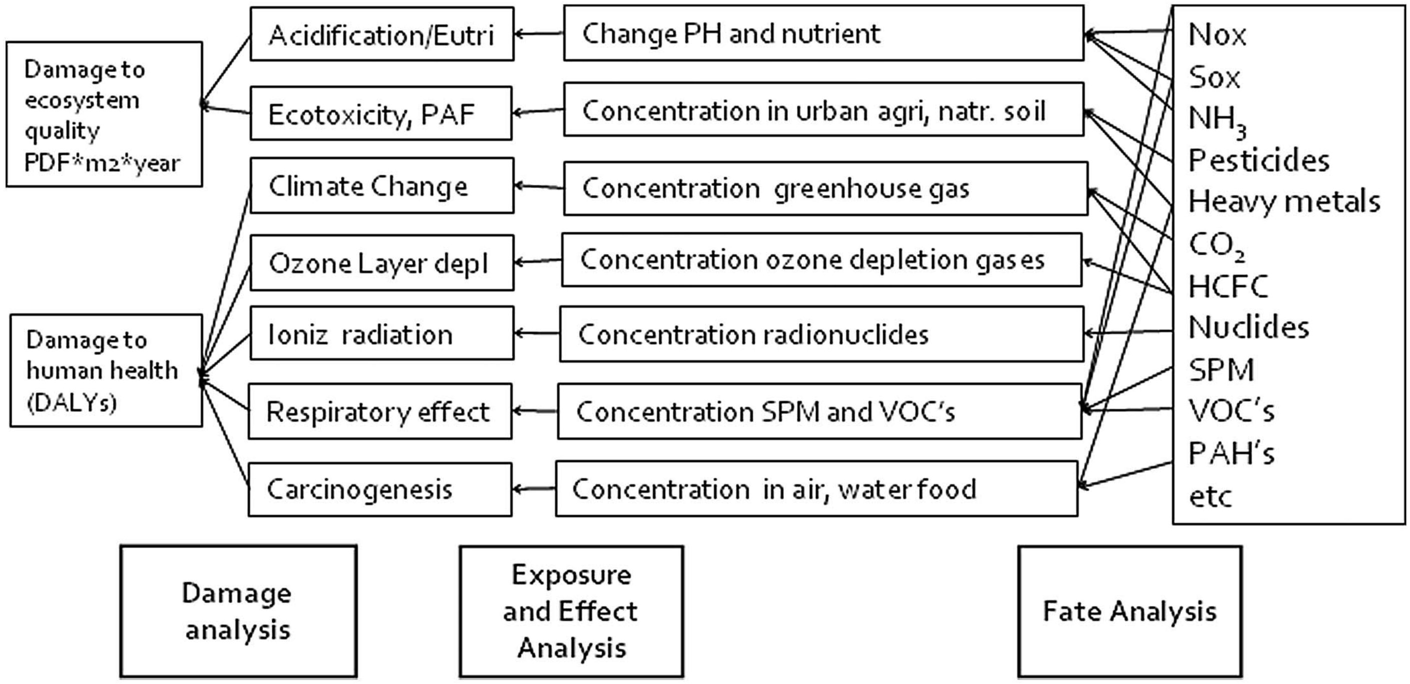

Fig. 3. LCA computational method schematic: from right to left, user must specify energy and material requirements, which are converted to specific emissions using conversions embedded in the LCA software; fate analysis links emissions to environmental concentrations, exposure and effect analysis links concentration changes to corresponding environmental effects, and damage analysis links environmental effects to ecosystem and human health damages; the LCA software utilizes embedded transmission and exposure factors to estimate damages to ecosystems and human health (Goedkoop and Heijungs 2009, with permission from PRé North America Inc.)

Results of LCA: Global Warming Potential

Single Pipe Application

GWP values in units of equivalent CO_2 mass per km of pipeline were compared for the six pipeline types investigated [Table 5; 30.5 cm (12 in.) diameter only]. For the 12-in. diameter example, iron pipes contributed the greatest increment to GWP among the six kinds of pipe materials compared. Concrete pipe had the lowest GWP, despite the energy demand associated with cement production (Marceau and Nisbet 2007; Martin et al. 1999). Nevertheless, concrete pipe was selected to illustrate the dependence of GWP on pipe diameter and to separate GWP components attributable to production, transport, and installation phases (Fig. 4). Pipe production (embodied energy) was the dominant source of GWP for all six pipe materials (Table 5). GWP per km of pipe was then expressed as a continuous function of pipe diameter for each material investigated (Fig. 5, Table 6). Because GWP from pipe use is a function of flow and topography, the use phase was temporarily omitted from the analysis.

For the monetization of GWP in Table 3, a value of \$25 per ton was selected. Although there are a few different methods to pay for carbon emissions or to estimate their value, there is a fairly similar range of values for all of these methods. In the European Union, where emissions credits are exchanged as part of a cap-and-trade scheme to meet Kyoto Protocol targets, the going rate is roughly \$22 per ton of CO_2 equivalent (\$20/ton; Serchuk 2009). The recently enacted carbon trading framework in Australia prices a ton of CO_2 equivalent at \$23, to rise to \$25.40 by 2015 (Cubby 2012). A carbon tax suggested by American legislator John B. Larson would start at \$16.50/metric ton (MT) (\$15/ton) and increase by \$11/MT per year (GovTrack.us 2009; Komanoff 2009). A review in the U.K. of valuations of the social cost of carbon emissions found estimates ranging (in dollars from the year 2000) from approximately \$3 to \$264 per ton (Clarkson and Deyes 2002). The purchase price for carbon offsets generally ranges from \$3 to \$100 per ton, with most offsets in the \$10–30 range (EcoBusinessLinks 2012). Given this range of available carbon valuations, it was felt that \$25 per ton represents a reasonable value to use in this analysis.

Table 5. Summary of Phase-Dependent and Total GWP per km of 30.5 cm (12 in.) Diameter Pipes for Different Materials

Pipe materials (12-in. pipe)	Total GWP (10^3 kg CO_2/km)	Production phase (10^3 kg CO_2/km)	Installation phase (10^3 kg CO_2/km)	Transportation phase (10^3 kg CO_2/km)	Equivalent cost for total GWP at \$25/MT
PVC	318	315	2.81	0.26	\$7,950
Ductile iron	472	468	3.28	0.88	\$11,800
Concrete	68.3	63.1	2.91	2.26	\$1,706
HDPE	218	215	2.81	0.17	\$5,450
Reinforced concrete	152	146	2.91	2.47	\$3,791
Cast iron	353	349	3.28	0.84	\$8,820

Note: Equivalent costs were calculated using a penalty cost of \$25/MT of CO_2 equivalent.

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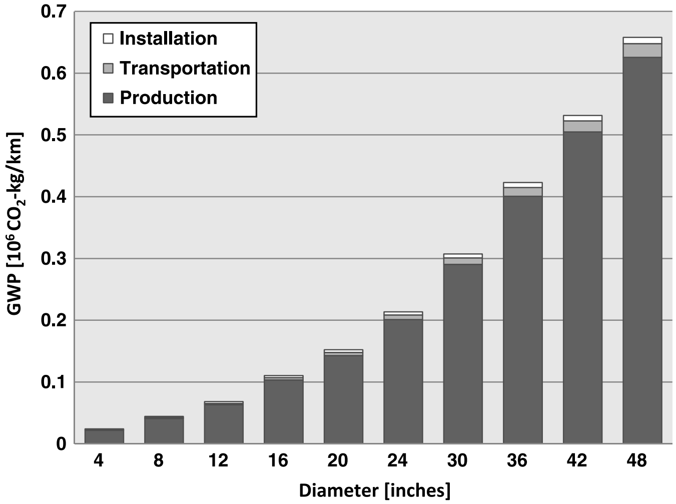

Fig. 4. GWP in kg CO_2 per km length as a function of pipe diameter for concrete pipe; contributions of production, transport, and installation to GWP are represented (Table 5 provides detailed results)

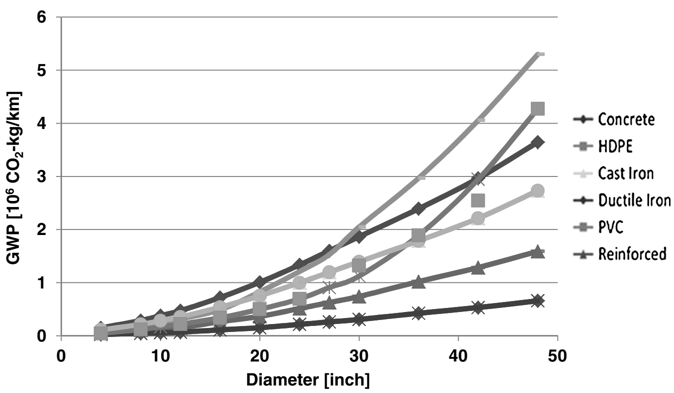

Fig. 5. GWP for pipe materials as a function of pipe diameter (in.), equivalent CO_2 emissions in kg per km of pipe; continuous curves are lines of best fit from nonlinear regression using a second-order polynomial fit that was constrained to pass through the origin

This assumption was examined via a sensitivity analysis (described in the following).

When the relationship between pipe type and GWP was generalized to include pipe diameters from 10.2–121.9 cm (4–48 in.), it became apparent that iron pipe is responsible for the highest GWP at diameters ≤61.0 cm (24 in.; Fig. 5). At diameters ≥76.2 cm (30 in.), PVC yields the greatest GWP per unit pipe length. This seeming anomaly arises from the material-dependent schedule of pipe thicknesses, which increase dramatically for plastic water pipes of diameter greater than 61.0 cm (24 in.) (Supplementary Data, Tables S2–S7). Thickness requirements for iron pipes increase monotonically with diameter, but at a much more measured rate.

The results are insensitive to transport distance and fuel efficiency assumptions because transport and installation contribute relatively little (from 1–8%) to GWP, even when the use phase is omitted from the analysis. For this reason, several potential weaknesses of the analysis can be overlooked. For example, the insensitivity of results to assumptions regarding travel distance and fuel efficiency during transport is evident. Furthermore, the LCA impacts of obtaining and emplacing trench bedding material were ignored. Sand and gravel bedding material were assumed to be locally available and easy to obtain, and their contribution to GWP was held to be negligible. As expected, GWP is a nonlinear function of pipe diameter, primarily because of material requirements (increased pipe thickness) for larger pipe sizes. Diameter-dependent and material-dependent GWP per km were fitted with second-order polynomials that were constrained to pass through the origin, such that

$$Y_i = A_i x^2 + B_i x \tag{4}$$

where Y_i = total GWP per km of pipe material i; x = pipe diameter (cm); and A_i and B_i = constants derived from nonlinear regression analysis (Table 6).

Table 6. Summary of Material-Dependent Coefficients from Nonlinear Regression Analysis Using LCA Estimates of Diameter-Dependent GWP

Pipe material	A	B
PVC	3.9E02	−4.1E03
Ductile iron	1.4E02	1.3E04
Concrete	0.3E02	1.5E03
HDPE	3.2E03	−7.4E03
Cast iron	1.1E02	9.6E03
Reinforced concrete	0.8E02	3.5E03

Note: See Eq. (4).

Pipe Size Selection to Minimize GWP, Including Use Phase

The LCA exercise to this point excluded environmental costs derived from pipe use. It is probable, however, that energy requirements for water pressurization and transmission contribute significantly to both (1) total economic cost and (2) damages to human and environmental health derived from the manufacture, transport, installation, and use of network distribution systems. For a given rate of water delivery, small pipe sizes lower material requirements and energy use during production, but increase energy losses during water transport. Both energy use for pipe production and energy required to satisfy delivery objectives are nonlinear functions of pipe size. It follows that pipe size can be selected to minimize total GWP production over the design life of a pipe. Furthermore, the optimal size of water transmission system elements may be affected by GWP and other external costs that are not paid by utilities and are not normally considered in pipe size selection.

The following exercise was conducted to determine the material-dependent pipe sizes that minimize overall GWP from construction and use of a 1-km length of pipe for water transmission at an average rate of 43.8 L/s (1.0 mgd) that is capable of transmitting a fireflow of 190 L/s (3,000 gal./m). Two pipe materials, PVC and reinforced concrete, were selected because they represent near extremes in terms of LCA costs. The service life of a pipe was initially assumed to be 30 years. Future GWP due to pressure requirements over the life of the pipe were discounted in the same way as economic costs (discount operator, 0.06 year^{-1}), so that the Fig. 6 comparisons represent the present value GWP. The use of a discount operator, although unconventional in this sense, is appropriate because (1) there will someday be a penalty or tax for GHG emissions, as in Europe today (a price of \$25/MT is used here to monetize GWP); and (2) the environmental damage due to GHG emissions is cumulative. That is, current emissions are more damaging than future emissions because at any point in time, GHGs emitted earlier have a longer residence time in

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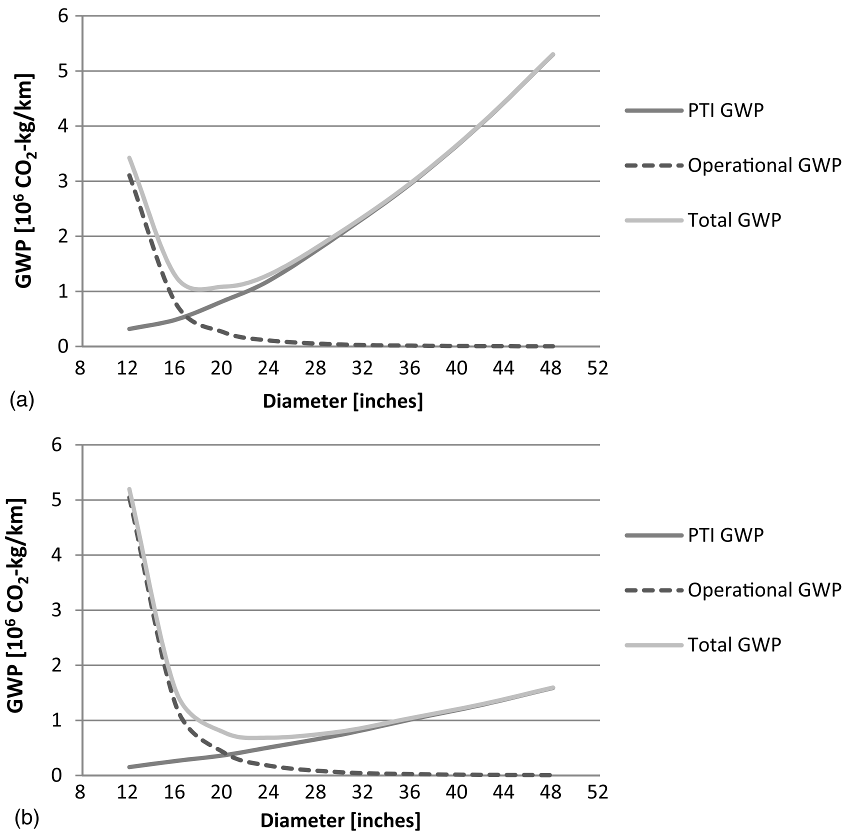

Fig. 6. GWP as a function of pipe diameter over an assumed 30-year design life: (a) PVC; (b) reinforced concrete pipe; PTI GWP includes GWP generated from pipe material production, transport, and installation phases

the atmosphere. Roshani et al. (2012) and Wu et al. (2010) provide insight on the use of discounting related to GWP in water systems. Elevation changes over the 1-km length of pipe were ignored in the analysis because they do not affect the relative, size-dependent GWP; that is, static lift requirements are identical for all pipe sizes. The Hazen-Williams equation ($C = 130$ for PVC, 120 for ductile iron, 100 for reinforced concrete, and 140 for HDPE) was utilized to calculate friction losses and relative energy requirements during pipe use (Mays 2010). GWP during pipe production, delivery, and installation was estimated as described previously.

At a flow rate of 43.8 L/s (1.0 mgd), results indicate that the optimal pipe size to minimize GWP is weakly related to selection of pipe materials: from 50.8–60.9 cm (18–22 in.) diameter for PVC pipe to 56–66 cm (22–26 in.) diameter for reinforced concrete [Figs. 6(a and b), respectively]. The results for all pipe types are summarized in Table 7. The 1 mgd flow was representative of a single transmission main designed to transport potable water to a housing development. At a per capita demand of 606 L per day (160 gal/d, a reasonable estimate for southwestern municipalities), the pipeline would be the primary potable water source for a hypothetical development of 6,250 people.

Pipe size selection based on economic criteria alone leads to much the same result The previously provided energy assumptions and capital/installation costs were utilized for a 1-km pipe from Clark et al. (2002) within a decision support system (DSS) described by Woods et al. (2013). The least costly PVC pipe (without considering GWP) is 40.6–50.8 cm (16–20 in.) in diameter (Fig. 7). It is also apparent that for near-optimal pipe diameters, the GWP from energy consumed during pipe use (i.e., energy to convey water, ignoring static lift and pressure requirements) is approximately equal to that resulting from pipe manufacture, transport, and installation combined.

Table 7. Material-Dependent, Optimal Pipe Diameter Range to Minimize Economic Cost, LCA-GWP, or Total Cost, Including the monetized LCA-GWP

Pipe materials	Size (cm / in.) to minimize economic cost	Size (cm / in.) to minimize GWP	Size (cm / in.) to minimize total cost
PVC	41–51 / 16–20	46–56 / 18–22	41–51 / 16–20
Ductile iron	46–51 / 18–20	46–56 / 18–22	46–51 / 18–20
HDPE	41–46 / 16–18	51–56 / 20–22	41–46 / 16–18
Reinforced concrete	51–61 / 20–24	56–66 / 22–26	51–61 / 20–24
Concrete	51–61 / 20–24	71–76 / 28–30	51–61 / 20–24
Cast iron	46–56 / 18–22	56–61 / 22–24	46–56 / 18–22

Sensitivity Analysis

The sensitivity of pipe diameter for minimum lifetime GWP to service life and discount operator was explored by varying each parameter and recalculating the optimal pipe diameter, described previously, for PVC pipe. At higher discount rates, smaller pipe sizes are preferred, reflecting the diminished present value of future emissions [Fig. 8(a)]. Longer service life favors larger pipe sizes because size-dependent GWP arising from pipe manufacture and installation can be amortized over a longer period. As expected, the effect of service life on optimal diameter is minimal at the highest discount rate used in the analysis (0.08 year^{-1}).

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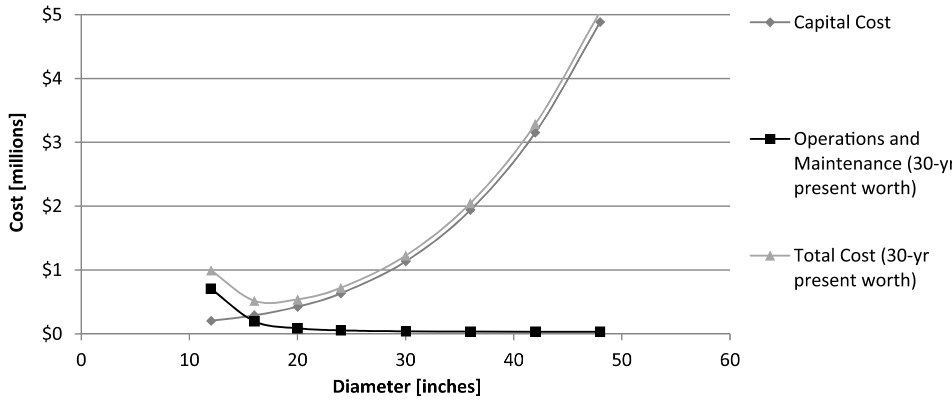

Fig. 7. Diameter-dependent economic costs (30-year present worth) for a 1-km PVC pipe carrying 43.8 L/s (1 mgd), and capable of transmitting a fireflow of 190 L/s (3,000 gal./m); capital and operation/maintenance costs are included, and the analysis does not include externalized costs such as the monetized cost of LCA-GWP

Pipe design to minimize economic cost responds similarly to assumptions regarding service life and discount operator, although the analysis recommends modestly smaller diameter pipes than optimization based on GWP [Fig. 8(b)]. The difference in sizes is ≤4 in., or at most one commercial pipe size, again suggesting that consideration of LCA-GWP would not result in major shifts in pipe size selection for water conveyance.

The sensitivity of optimum pipe diameter to GWP penalty cost was also examined (Fig. 9). The optimization was based on total cost, or the sum of total present worth (capital plus operations and maintenance over 30 years at a 6% discount rate) and the total present worth of GWP contributions. The diameter to minimize economic cost was close to that minimizing GWP. Consequently, pipe diameter for minimum total cost is remarkably insensitive to carbon price, varying less than 2.54 cm (1 in.) over a range of $0 to $300 per ton of CO_2 equivalent.

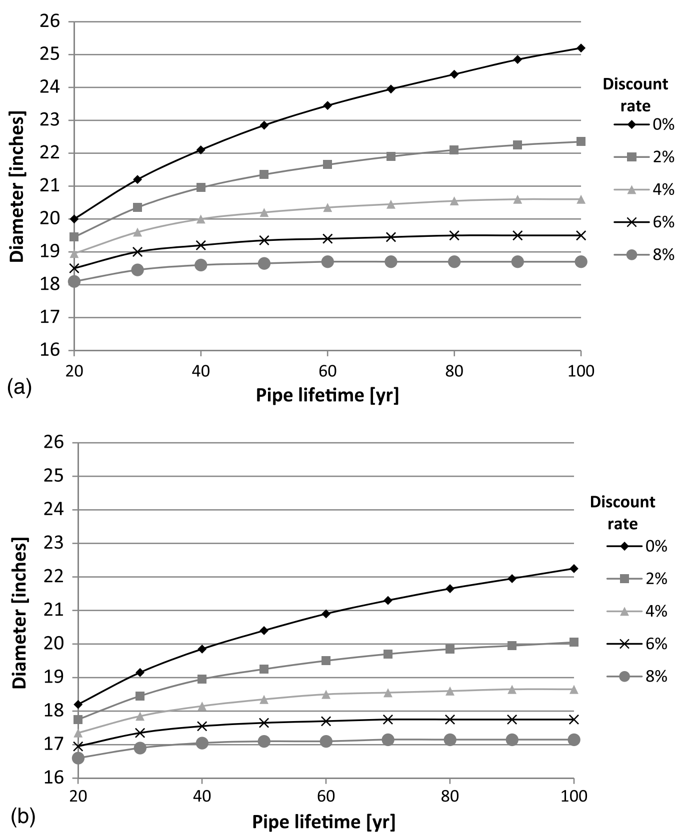

Fig. 8. Optimal pipe diameter for a 1-km PVC pipe as a function of assumed pipe service life (horizontal axis) and discount rate (legend) based on: (a) minimum estimated GWP over pipe lifetime; (b) minimum total present value (economic) cost

Pipe Network Application

The network application that follows is designed to overcome limitations of the previous single-pipe analysis, i.e., the inability to account for site-specific topography at points of delivery. However, it necessarily involves a site-specific application. The primary problem is related to the external nature of human and environmental health costs. Because costs attributable to GWP are paid by the public at large, as opposed to the GWP generator, they are frequently omitted from economic comparisons of engineering alternatives. To account for GWP, environmental costs were monetized based on a unit cost of \$25/equivalent MT of CO_2 emitted (described previously).

The illustration builds on the results of a related study (Woods et al. 2013) in which a DSS was used to compare the economic

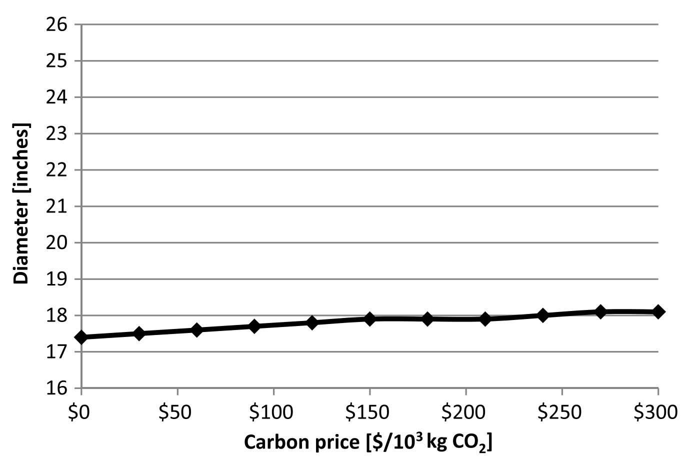

Fig. 9. Optimal pipe diameter for a 1-km PVC pipe as a function of carbon price; optimization is based on the sum of economic cost and monetized GWP

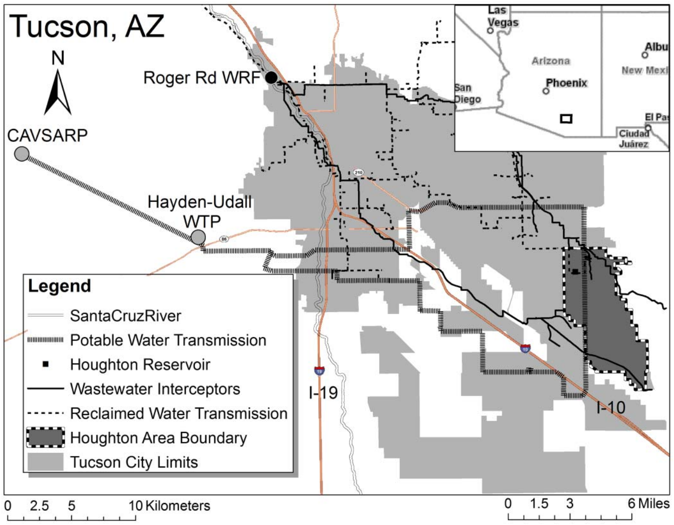

Fig. 10. City of Tucson/Houghton Area, including major infrastructure elements: the city is lightly shaded, and the Houghton Area is enclosed by the dark broken line at lower right; water originates at Central Avra Valley Storage and Recovery Project (CAVSARP), and wastewater is collected and treated at the Roger Road Wastewater Reclamation Facility

costs of centralized versus distributed water reclamation facilities in a high-growth area of Tucson, Arizona, hereafter referred to as the Houghton area. The Houghton area consists of 45 km^2 in southeast Tucson (Fig. 10). Water from a central distribution system must be pumped ~40 km with a vertical lift of ~270 m to reach the Houghton area. Reclaimed water can be provided for landscape irrigation from either (1) a central wastewater treatment facility, the Roger Road Wastewater Reclamation Facility, which requires transport over a similar distance and elevation change; or (2) construction of a local reclamation facility in the Houghton area to reclaim water for landscape irrigation at a much reduced transport cost. The DSS considered the cost of energy for water distribution and the capital cost of distribution system elements, but noneconomic LCA damages of the distribution system (i.e., GWP calculated here for pipeline production, transport, installation, and use) were originally omitted.

To illustrate the potential importance of GWP emissions, a scenario was developed by Woods et al. (2013), in which 26,460 m^3/day (7.0 mgd) of reclaimed water are used in the Houghton area for landscape irrigation and aquifer replenishment. The water is reclaimed at a facility located directly adjacent to the Houghton area, and wastewater in excess of the plant's 26,460 m^3/day (7.0 mgd) capacity is conveyed to a downstream regional facility. The DSS located and sized a total of 80 km of water distribution pipes in the Houghton area based on projected regional water demands. At \$0.08/kWh, the present value cost of energy to pump water through those pipes over a period of 30 years was ~\$46 million (discount rate = 6%), and the CO_2 emissions for energy required to distribute water were estimated at 3.3×10^4 MT/year. Because all pipe diameters, lengths, and types were part of the DSS output, it was possible to calculate the GWP from pipe production, transport, and installation (3.7×10^4 MT of CO_2) to build the eventual water distribution system using the tools described here. Based on a penalty cost of \$25/MT of CO_2, the incremental GWP from pipe production, transport, and installation represents a one-time externalized cost of \$0.93 million. This is approximately 2% of the present value cost of energy purchase (~\$46 million) for water transmission. When all delivery system GWPs were considered for potable and non-potable water in the Houghton area, the total monetized GWP for pipe production, transport, installation, and system use phases was ~\$12.4 million, of which approximately \$11.5 million arose from use. This is approximately one-quarter of the \$46 million cost of energy for water distribution estimated for the Houghton area in the analyzed scenario.

Summary and Conclusions

The following observations are based on the previous analyses.

1. For pipes ≤60.9 cm (24 in.) in diameter, ductile iron resulted in the greatest LCA-GWP among the six pipe types compared. At diameters ≥76.2 cm (30 in.), PVC pipe produced the greatest GWP per kilometer of pipe. The seeming anomaly results from the pipe thickness schedule. Plastic pipe thickness increases more rapidly as a function of diameter than ductile iron pipe. The GWP of concrete pipe was the lowest at $10.2\ \text{cm} \leq \text{diameter} \leq 121.9\ \text{cm}$ $(4 \leq \text{diameter} \leq 48\ \text{in.})$ despite high energy demand and carbon dioxide emissions associated with cement production.
2. When GWP was calculated for pipe production, transport to site and installation (ignoring the use phase, where GWP is site specific), the production phase or embodied energy accounted for 92–99% of total GWP for the range of pipe materials considered. Because of the relatively small contributions of transport and installation to overall GWP, results are insensitive to assumptions related to transport distance and installation.
3. For the same reasons, there are material-dependent pipe diameters that minimize lifetime economic costs [capital plus operation and maintenance (O&M)] and lifetime GWP. Because the pipe diameters that minimize economic costs are similar to those that minimize LCA-GWP, the inclusion of GWP in analyses leading to pipe diameter selection is unlikely to change optimal size selection.
4. Even when static lift and pressure requirements are ignored, the energy required to overcome friction losses is of the same magnitude as the embodied pipe energy. When the energies to satisfy static lift and delivery pressure objectives are considered, however, the use phase GWP is likely to be much larger than GWP arising from manufacture, transport, and installation.
5. When both GWP and economic costs are considered, longer pipe service life leads to the selection of larger optimal pipe diameters, as does the selection of lower discount rates. The selection of pipe diameter to minimize total cost (economic cost plus monetized GWP) was insensitive to the assumed GWP penalty cost.
6. GWP is an external cost that is paid by the public in general; therefore, it is ignored in comparisons of alternative water production and delivery scenarios. Externalized costs represent a small portion of overall water transmission costs, as illustrated by an exercise in which the water distribution system costs (economic plus monetized GHG emissions) were projected for the Houghton area in Tucson, Arizona.

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Supplemental Data

Fig. S1 and Tables S1–S7, which contain estimated damage costs, a comparison of GWP penalty costs with damage, and data for pipe dimensions used in calculations, are available online in the ASCE Library (www.ascelibrary.org).

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