Abstract

There are more than 150,000 municipal water distribution systems (WDS) in the United States. These systems were built and upgraded at various times in their history using a wide range of pipe materials. The American Water Works Association estimates that 26% of these pipes are currently in need of repair and that the rest are expected to reach their end of life within the next 30 years. Thus, the water distribution industry is reaching a time where it will need to replace a significant number of pipes in its systems. The purpose of this analysis is two-fold. First a comparison of the environmental impact and cost of two of the most popular and currently-available pipe materials, ductile iron with a concrete lining (DICL) and polyvinyl chloride (PVC), was conducted. Second, a sensitivity analysis of pumping energy reduction related to the location of pipe upgrade with a one-size-larger was run for seven different WDS. The pipe comparison analyses determined that the cumulative energy demand and global warming potential of an 8” diameter, 20’ length DICL pipe is 72% greater than a PVC pipe of the same size. Pipes of larger nominal diameters followed a similar trend. On a pipe-only basis PVC is also cheaper than DICL, however, additional excavation costs may be associated with PVC that raise the cost significantly. The sensitivity analysis concluded that a single pipe upgrade during standard scheduled replacement in WMDSs can result in energy savings up to 11%. In addition, the single-pipe upgrades resulting in the most energy and greenhouse gas emission reduction tend to be located directly between tanks and reservoirs and/or are bottle necks.

Introduction

There are over 150,000 municipal water distribution systems in the United States. About 26% of the pipes in these systems are currently in need of repair and the entire network is expected to need replacement within the next 30 years (AWWA, 2001; AWWSC, 2002; NRC 2006). Those in charge of upgrading these systems will be able to choose from several different pipe materials to replace the old, deteriorated pipes. The most common pipe materials currently found in water distribution systems (WDS) are asbestos cement, cast iron (both concrete-lined and unlined), ductile iron with a concrete lining (DICL) and PVC (Fig. 1). Of these materials, only DICL and PVC are still available in the United States and seem to be the most likely options for WDS managers seeking to upgrade their systems.
Pipe materials in existing WDS. Cast iron (both lined and unlined) and asbestos cement pipes are common, but due to the market unavailability they were not chosen for this analysis. DICL and PVC pipes are both common in existing WDS and currently available. Source: USEPA 2009, AWWA 2004

In order to help WDS managers make the best decisions when upgrading their systems, the environmental and economic impacts of the two materials should be determined. A life-cycle analysis was conducted to assess the environmental impact, including the cumulative energy demand and global warming potential, associated with each material. The analysis considered the entire life-cycle of the pipe from material extraction through disposal (Fig 2). SimaPro7.1, a life-cycle impact assessment software (see PRé Consultants 2006), was used to run the analysis and the Franklin USA life cycle inventories within SimaPro were used wherever possible (see Franklin Assoc. 1998). Although SimaPro is largely based on European data, the Franklin USA profiles are based on average U.S. data from the late 1990s.

When upgrading a WDS system, the managers may also have the option to increase the pipe diameter and potentially reduce pumping costs as a result. It is important, however, that the environmental impacts related to pipe enlargement be evaluated to determine if this is a wise choice to make. The SimaPro analysis was expanded to compare the environmental impact of manufacturing, transportation and pumping of 8”, 10”, 12”, 14” and 16” diameter pipes.

The environmental impact assessment is for an idealized, single-pipe scenario. Real-world WDS systems, however, can be quite complex and include hundreds or thousands of pipes Thus, in order to understand how pipe replacement will affect
pumping costs in an actual WDS, a sensitivity analysis of pumping energy reduction related to the location of pipe replacement was run for seven different WDS using EPANET and MATLAB.

**Objectives**

The objective of the environmental impact assessment comparison of the two pipe materials portion of this project is to determine which pipe material, DICL or PVC, has the lowest environmental impact, in terms of energy demand and GWP, over its lifetime. This addresses the environmental sustainability of the product, but a cost analysis is also done to address the economic sustainability. If the amount of energy demand and GWP reduction from pumping through a larger diameter pipe outweighs the increased levels required for manufacturing and transporting a larger pipe, then replacing an existing pipe with a larger diameter pipe could be seen as environmentally and economically favorable. The social aspect is also important, as there must be adequate and appropriate logic for WDS managers to be convinced that using the methodology presented here will benefit them and their systems.

The energy demand and GWP reduction analyses are ideal situations, and, therefore, an analysis that approaches more realistic conditions to support the SimaPro findings is described later. This analysis on realistic WDSs using complete enumeration to determine if there exists a general trend to the location of pipe upgrades (enlarging pipe diameter) in a system that are both environmentally and financially beneficial when compared to the status quo.

**METHODS**

**LCA Methods:**

A life-cycle assessment should include all aspects of the product's lifetime. For this analysis, the manufacturing, transportation, pumping and disposal scenarios were included (Fig 2). Due to popularity in WDS and market availability, one pipe of 20' length and 8" nominal diameter was chosen as the functional unit for the initial comparison. Several assumptions were made for the analysis. Since actual transportation distances were not known, an estimate of 1000 miles from manufacture to installation to disposal was assumed. This value reflects the fact that most pipe manufacturing operations are located some distance from the water district where they will be used, so pipes will have to be transported some distance, likely by truck. WDS managers looking to utilize this methodology could alter this value to reflect the actual distance from the pipe manufacture they use.
While the roughness of DICL pipes does change over time due to calcium buildup, average roughness coefficients were assumed over the lifetime of the pipe. This assumes the best-case scenario and is a common approach in the literature. The pumping energy was determined using the Hazen-Williams equation for a circular pipe flowing full and with a roughness coefficient of 120 for DICL and 142.5 for PVC (Table 1, Eqn 1).

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Based on this information, two analyses were performed, one assuming a 50-year lifetime for both pipes and one assuming a 100-year lifetime for DICL and a 50-year lifetime for PVC. The second analysis included two PVC pipes, two transportation periods of 1000 miles and the excavation required to install a new pipe after 50 years. The excavation volume was determined based on a 6' deep trench and 20' length pipe and information

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**Figure 2:** Life-cycle diagram and LCA boundaries for (a) Analysis 1, 50-year lifetime and (b) Analysis 2, 100-year lifetime adding excavation for PVC after 50 years.
for municipal PVC pipe installation (REHAU 1998). The DICL manufacturing was assumed to be done in a Cupola furnace melting operation since approximately 75% of DICL foundry operations in the U.S. use this process (Shipley 1997). This operation consumes 1200-1300 kWh/ton of metal so an average value of 1250 kWh/ton was used (Shipley 1997). The manufacturing energy for molding a PVC pipe was found to be 585 MJ (Ambrose 2002). The weights of cast iron and cement came from the American Cast Iron Pipe Company (Appendix A). The weights of PVC pipes came from an industry representative, Jesse Madden of North American Pipe (Appendix B). Based on these assumptions and the available information, the materials inventory for the SimaPro7.1 analysis was developed (Table 2).

Table 2: Inventory for SimaPro7.1 analysis assuming (a) a 50-year lifetime for both DICL and PVC and (b) a 100-year lifetime for DICL and a 50-year lifetime for PVC. The energy for DICL was based on the average energy required for casting ductile iron pipes in a Cupola furnace. Pumping energy was based on the Hazen-Williams equation using average roughness coefficients over the entire lifetime of the pipe. FAL indicates Franklin USA.
The study was then expanded to include pipes with 10”, 12”, 14”, and 16” nominal diameters, which are also common in WDS. The inventory was expanded to include values for the larger pipes. In this part of the study a 50-year lifetime was assumed for both PVC and DICL to be conservative.

**WDS Analysis Methods**

A simulation was created using MATLAB to determine the effects of increasing the pipe diameter and material during replacement in a WDS. The effects were quantified by calculating the percent change in energy consumption from pumping requirements, time for return of investment, and savings of greenhouse gas emissions from reduced pumping. Seven WDSs were analyzed with the effects quantified for each pipe in the system. The EPANET network solver was used for quantification of pumping energy requirements in the WDS. The time of return of investment (ROI) and the savings of greenhouse gas emissions were derived from the change in required pumping energy.

The MATLAB simulation utilizes input files (*.inp) from EPANET to load the system data into MATLAB matrices. The simulation uses complete enumeration in which it iterates through each pipe in the system and determines the reduction of pumping energy caused by changing the pipes’ diameter and material (DICL or PVC) through the use of the EPANET model. Safe guards within the MATLAB simulation prevent inclusion of data of pipe changes that cause the pressure in the WDS to be outside of the acceptable range of 30-100 psia. If the original pressure of the pipe lies outside the acceptable range, changes of 10% or less outside the acceptable range where deemed acceptable. EPANET returns the energy cost of the system per day for use in comparison to the original conditions.

The savings of kg of CO₂ equivalent from reduced pumping requirements was determined from the following equation:
After removing acidification and water intake from the chart, it is found that DICL also has a larger contribution to ecotoxicity, smog and resource depletion.

Using Simapro and the IPCC 2007 GWP method, the life cycle kg CO\textsubscript{2} equivalent emissions for various pipe sizes were estimated. As the pipe diameter increased, so did the amount of material and energy necessary for production. The analysis shows that this increases the amount of kg CO\textsubscript{2} emitted from manufacturing (Fig 7a). The larger pipes also had a greater weight, adding to larger energy needs for transportation and greater levels of CO\textsubscript{2} eq emissions (Fig 7b). As suggested by the Hazen-Williams equation, the headloss decreases through a pipe of larger diameter and thus less energy should ideally be needed for pumping. The manufacturing, transportation and pumping aspects were all put into the life-cycle assessment and analyzed side-by-side. Pumping once again dominated the life-cycle GWP and energy demand and greatly outweighed the manufacturing and transportation aspects. Thus, the reduction in pumping energy associated with larger diameter pipes generates an overall reduction in energy demand and GWP as pipe diameter is increased (Fig 8).

Figure 7: Global Warming Potential (GWP) in kg CO\textsubscript{2} equivalents for (a) manufacturing and (b) transportation.
Figure 8: Global warming potential in kg CO\textsubscript{2} equivalents for the life-cycle of 8” through 16” PVC and DICL pipes. Pumping dominates the life-cycle and thus the reduced pumping energy for larger diameter pipes leads to an overall reduction in energy demand and GWP as pipe diameter increases.

To determine the time frame for when the benefits of reduced pumping demand outweighs the additional impacts of manufacturing, a return of investment on CO\textsubscript{2} emissions was evaluated. The additional kg CO\textsubscript{2} emitted for the manufacture and transport of larger diameter pipes was compared with the kg CO\textsubscript{2} saved from reduced pumping. The return of investment (ROI) in terms of kg CO\textsubscript{2} equivalents was calculated using the equation \( \text{x days} \times (-\Delta P/\text{day}) = \Delta M + \Delta T \). To increase an 8” PVC pipe to a 10”, the ROI is 1.7 days. To increase an 8” DICL pipe to a 10”, the ROI is 4.1 days. With larger pipes, increasing the diameter by one size has a longer ROI (Fig. 7).

![Figure 7: CO\textsubscript{2} equivalent Return of Investment (days) for PVC and DICL pipes, based on single pipe assessment](image)

The kg CO\textsubscript{2} equivalent emitted over pipe life cycles was based on a typical mix of energy sources in the United States called Franklin USA Electricity avg. kWh USA. To see what percentage of the energy mix needed to be renewable energy to make the emissions of DICL equal to PVC, the energy mix was split into two sources, coal and photovoltaic (PV). It was found that an energy mix of 44% coal and 56% PV resulted in life cycle CO\textsubscript{2} emissions of an 8” DICL pipe (about 1.44*10\textsuperscript{6} kg CO\textsubscript{2} over 50 years) matching the emissions of an 8” PVC pipe with the normal energy mix.

In order to understand the economics of decision making, a cost analysis was performed comparing the two pipes in both the 50-year and 100-year scenarios. In the 50-year analysis the cost included the market price (Madden pers. comm.) for one 20’
length 8” nominal diameter PVC or DICL pipe and the cost of pumping energy over the functional lifetime of the pipe. In the 100-year analysis an additional PVC pipe was added and installation costs were included for replacing the PVC pipe after 50 years. The energy cost was based on the average retail price for electricity in Michigan, which the Department of Energy estimates is $0.12/kWh (EIA 2011). The installation cost includes demolition, excavation, refill and pavement replacement costs, calculated using average US values of approximately $66.40 per foot of pipe (Waier at all 2009, Appendix 1). The cost of one DICL pipe from United States Pipe and Foundry, LLC is $13.56, while the cost of one PVC pipe is only $4.84 (Madden pers. comm.). The electricity for pumping cost turned out to be the most expensive component of the total costs in all scenarios, completely overshadowing the other components (Fig 8).

![Figure 8: Cost analysis for DICL vs PVC including pipe, energy and installation costs.](image)

**WDS Results**

Seven different WDSs were used in the simulation (Figs. 9-15). Systems that contain “V2” in their names are modified systems. The original input files contained several nodes at elevations of zero feet. These erroneous elevations where changed to elevations similar to the elevation of nearby nodes.
**Figure 9:** A 3D graphical representation of System 2 that depicts the different components of the WDS proportionally.

**Figure 10:** A 3D graphical representation of System 3-V2 that depicts the different components of the WDS proportionally.

**Figure 11:** A 3D graphical representation of System 4 that depicts the different components of the WDS proportionally.
Figure 12: A 3D graphical representation of System 4-Original that depicts the different components of the WDS proportionally.

Figure 13: A 3D graphical representation of System 5-V2 that depicts the different components of the WDS proportionally.

Figure 14: A 3D graphical representation of System 6-V2 that depicts the different components of the WDS proportionally.
Figure 15: A 3D graphical representation of System C-Town-Original-File Converted English Units that depicts the different components of the WDS proportionally

Due to the simplicity and constant elevation of System 2, results pertaining to System 2 will be used for the primary investigation. See appendix C for the other WDS results. This will introduce some bias to the analysis as System 2 operates near ideal conditions. The bias will be discussed further in the discussion.

Top Energy Saving Upgrades

The top ten energy saving pipe upgrades (replaced with next size larger pipe) for PVC and DICL pipes in each system were determined and plotted (Fig 16)

Figure 16: The percent energy savings of the top ten PVC and top ten DICL energy saving upgrades in System 2. The head loss and original pipe diameters are included to help categorize upgrades as well as to visual determine trends.
The graphs depict 20 upgrades in each system that have potential to save energy used for pumping, but there also exists upgrades that will cause the energy requirements of the WDS to increase and will be discussed later.

It can be seen that the percent of energy savings increases with high headloss pipes with little variation for pipe size.

The results of the other systems are located in Appendix C.

**CO₂ Emission Reduction Of Top Energy Saving Upgrades**

The CO₂ emission savings from reduced pumping over a 50 year period for the top energy saving upgrades was plotted on a kg equivalent CO₂ per foot basis. These values can be proportionally scaled to analyze CO₂ emission reduction for any given length of time:

**Figure 17:** The potential CO₂ emissions savings from reduced pumping requirements of WDS caused by the top ten PVC and top ten DICL energy saving upgrades in System 2. The head loss and original pipe diameters are included to help categorize upgrades as well as to visually determine trends.

In general, it can be seen that higher CO₂ savings are achieved through the upgrading of higher headloss pipes and that pipe size has little effect.

The results of the other systems are located in Appendix D.

**Placement Of Top Energy Saving Upgrades Within Systems**

The placements of the top energy saving upgrades with energy savings greater than 0.1% within each system were plotted on system maps with thick red lines (Fig 18)
Figure 18: The location of energy saving upgrades greater than 0.1% (depicted as thick red lines) within System 2.

It can be seen that upgrading of mainline pipes connecting the system source and tanks results in the greatest CO2 emission reduction. The results of the other systems are located in Appendix E.

Scenario 1 ROI

ROI of Top Energy Saving Upgrades

The Return on Investment in years (ROI) is the time it takes to recover either initial cost expenditures or CO2 emissions. ROI of the top ten energy-saving upgrades of PVC and DICL pipes assuming scenario 1 conditions were calculated and plotted on a log$_{50}$ scale. The log$_{50}$ scale was chosen as log$_{50}$(ROI) values below 1 are financially profitable for the WDS and values above 1 are unprofitable:

Figure 19: The ROI of the top ten PVC and top ten DICL energy saving upgrades
in System 2 under scenario 1 conditions. The head loss and original pipe diameters are included to help categorize upgrades as well as to visualize trends. Log base 50 is used on the z-axis as z values below one are financially profitable under scenario 1 conditions since the ROI is less than the design life of the pipe.

It can be seen that a faster ROI is achieved at high headloss pipes, for smaller pipes, and for PVC pipe. In addition, there are several DICL and PVC pipe upgrades that have ROI under the lifetime of the pipes, but there are also pipe upgrades with ROI over the lifetime of the pipes.

The results of the other systems are located in Appendix F.

Fastest ROI upgrades

ROI values for PVC and DICL replacement pipe upgrades in each system were calculated under scenario 1 assumptions and the top ten fastest ROI PVC and DICL upgrades were graphed in Fig. 20:

![Fastest ROI Upgrades for System 2](image)

**Figure 20:** The ROI of the top ten PVC and top ten DICL fastest ROI upgrades in System 2 under scenario 1 conditions. The head loss and original pipe diameters are included to help categorize upgrades as well as to visualize trends. Log base 50 is used on the z-axis as z values below one are financially profitable under scenario 1 conditions.

It can be seen that a faster ROI is achieved at high headloss pipes, for smaller pipes, and for PVC pipe. In addition, the fastest ROI graphs contain many of the same pipe upgrades as the top energy saving upgrades, however, there are several more pipe upgrades with profitable ROI that are not included in the top energy saving upgrades.

The results of the other systems are located in Appendix G.

CO₂ emission reduction of fastest ROI pipe upgrades

The CO₂ emission reduction from reduced pumping needs for the fastest ROI pipe
upgrades under scenario 1 assumptions were plotted in Fig. 21:

**Figure 21:** The potential CO₂ emissions savings from reduced pumping requirements of WDS caused by the top ten PVC and top ten DICL fastest ROI upgrades in System 2 under scenario 1 conditions. The head loss and original pipe diameters are included to help categorize upgrades as well as to visually determine trends.

It can be seen that the highest CO₂ savings results from upgrading to PVC of the highest headloss pipes.

The results of the other systems are located in Appendix H.

**Fastest ROI pipe upgrades locations-PVC**

The following graphs show the locations within the systems of the fastest ROI upgrades using PVC piping under scenario 1 assumptions:

**Figure 22:** The location of PVC pipe upgrades (depicted as thick red lines) within System 2 with ROI under the lifetime conditions set by scenario 1.

It can be seen that upgrading mainline pipes and shorter high headloss per foot pipes from the source and tanks result in the fastest ROI.

The results of the other systems are located in Appendix I.
Fastest ROI pipe upgrades locations-DICL

The following graphs show the locations within the systems of the fastest ROI upgrades using DICL piping under scenario 1 assumptions:

**Figure 23:** The location of DICL pipe upgrades (depicted as thick red lines) within System 2 with ROI under the lifetime conditions set by scenario 1.

The results of the other systems are located in Appendix J.

Scenario 2 ROI

**ROI of Top Energy Saving Upgrades**

The ROI of the top ten energy-saving upgrades of PVC and DICL pipes assuming scenario 2 were calculated and plotted on a log_{100} scale. The log_{100} scale was chosen as log_{100}(ROI) values below 1 are financially profitable for the WDS and values above 1 are unprofitable:
Figure 24: The ROI of the top ten PVC and top ten DICL energy saving upgrades in System 2 under scenario 2 conditions. The head loss and original pipe diameters are included to help categorize upgrades as well as to visually determine trends. Log base 100 is used on the z-axis as z values below one are financially profitable.

Under scenario 2 conditions, the top energy saving PVC pipe upgrades are unprofitable in most situations (see appendix for exceptions in other systems) while the top ten energy saving DICL pipe upgrades are more profitable than under scenario 1 conditions.

The results of the other systems are located in Appendix K.

Fastest ROI upgrades
ROI values for PVC and DICL replacement pipes upgrades in each system where calculated under scenario 2 assumptions and the top ten fastest ROI PVC and DICL upgrades were graphed in Fig. 25:
Figure 25: The ROI of the top ten PVC and top ten DICL fastest ROI upgrades in System 2 under scenario 2 conditions. The head loss and original pipe diameters are included to help categorize upgrades as well as to visually determine trends. Log base 100 is used on the z-axis as z values below one are financially profitable under scenario 2 conditions.

Under scenario 2 conditions, use of PVC pipe upgrades is unprofitable in most situations (see appendix for exceptions in other systems) while DICL pipe upgrades can be more profitable than under scenario 1 conditions.

The results of the other systems are located in Appendix L.

**CO₂ Emission Reduction of Fastest ROI Pipe Upgrades**

The CO₂ emission reduction from reduced pumping needs for the fastest ROI pipe upgrades under scenario 2 assumptions were plotted:
Figure 26: The potential CO\textsubscript{2} emissions savings from reduced pumping requirements of WDS. The results of the other systems are located in Appendix G.

It can be seen that higher CO\textsubscript{2} savings are realized at high headloss PVC pipes. The results of the other systems are located in Appendix M.

**Fastest ROI pipe upgrades locations-PVC**

The following graphs show the locations within the systems of the fastest ROI upgrades using PVC piping under scenario 2 assumptions:

Figure 27: The location of PVC pipe upgrades (depicted as thick red lines) within System 2 with ROI under the lifetime conditions set by scenario 2.

There are no PVC pipe upgrades in System 2 under scenario 2 conditions that result in profitable returns. This general trend hold across the other WDS analyzed. The results of the other systems are located in Appendix N.
Fastest ROI pipe upgrades locations-DICL

The following graph (Fig. 28) shows the locations within the systems of the fastest ROI upgrades using DICL piping under scenario 2 assumptions:

Figure 28: The location of DICL pipe upgrades (depicted as thick red lines) within System 2 with ROI under the lifetime conditions set by scenario 2.

It can be seen that the main lines to the source and tank result in the fastest ROI.
The results of the other systems are located in Appendix O.

Discussion

The pumping energy savings from PVC pipe upgrades are larger than DICL upgrades due to the higher roughness coefficient of PVC piping. System 2 top energy saving upgrades also depicts the expected ideal result that pipes with higher headloss provide more energy savings when upgraded. However, other factors affect this ideality such as the location of the pipe in the system and the direction of the flow within the pipe with reference to demand needs. This deviation from ideality can be seen in System 4, System 4 – Original, and C-Town Original File-Converted English Units. From the locations of the top energy saving pipe upgrades within the systems it seems the top energy saving upgrades tend to be located on the most direct path between the reservoir and the tank or are pipes that are bottle necks to another part of the system. During the analysis, it was found that pipe upgrades that lead away from the demand locations actually increase the required pumping energy of the WDS. This is logical as the flow will increase away from the demand, therefore causing water to be pumped a further distance, increasing the losses in the WDS.

The GWP savings from PVC and DICL upgrades analyzed based on energy savings, ROI, and the different scenarios show that in all cases the GWP increase caused by the production of the larger diameter piping is easily overcome through reduction in GWP from reduced pumping times through the larger diameter pipe installed. The environmental impact analysis revealed that PVC piping has significantly less GWP than
DICL, and therefore use of PVC pipe upgrades under both scenarios is more environmentally beneficial than DICL upgrades.

The ROI analysis under scenario 1 conditions revealed that PVC pipe upgrades are the most profitable. Also, additional profitable ROI pipe upgrades were found when compared to the top energy saving analysis. These additional pipe upgrades tend to be shorter, small diameter pipes with relatively small to medium head losses that enhance flow towards the high-demand regions of the WDS. This makes logical sense as these pipes will not have as large of energy savings as longer, higher head loss pipes, but the lower cost of shorter and small diameter pipes is more easily recuperated from reduced pumping costs.

The ROI analysis under scenario 2 conditions revealed that PVC pipe upgrades are unprofitable under most conditions and that DICL pipe upgrades are more profitable than under scenario 1 conditions. This follows logic as additional costs were included in the PVC ROI calculation and not into the DICL ROI calculation. DICL ROI under scenario 2 showed better returns than scenario 1 because of the increased amount of time allowed for the recuperation of money while the cost of the DOI upgrade did not increase.

**Conclusions**

This analysis determined that PVC is a better option, both environmentally and economically, and should be chosen over DICL when upgrading a WDS. The PVC has lower cumulative energy demand as well as global warming, acidification, and smog potential even if its lifetime is assumed to be half as long as DICL. The PVC is also more economical both in the short and long term. Even if PVC has a shorter lifetime than DICL and needs to be replaced sooner, the savings in pumping energy still outweigh the additional expense of installation. The pumping phase of both PVC and DICL was revealed as the biggest contributor to environmental damages with the DICL performing worse. This conclusion is reasonable since pumping over a 50 or 100-year period would be expected to consume a significant amount of energy and the conveyance coefficient, Hazen-Williams C, is smaller for DICL, creating more resistance to flow.

Since the electricity in the Franklin USA datafile (based on average U.S. Data from the late 1990s) is largely generated using fossil fuels, it releases significant greenhouse gases and contributes to other environmental dilemmas. The manufacturing stage also contributes to the environmental impact and the impact for DICL is greater due to the high amount of energy required to cast the metal pipe. Thus, the high energy cost, sometimes called the embodied energy, of DICL pipes make it a less environmentally-friendly option for WDS piping. It is important to note, however, that DICL is stronger than PVC and this additional strength may be necessary in some situations (NRC, 2006). But due to the 72% reduction in cumulative energy demand and global warming potential and the corresponding cost benefits of 20-60%, PVC should be chosen over DICL during pipe replacement.

In spite of the result for a single pipe that PVC is always more beneficial, when installed in a WDS and replaced after 50 years, PVC is not always the preferred pipe material. If, however, the PVC lasts for 100 years, then it is always preferred. It is in the interest of WDSs to analyze the potential financial and environmental benefit of increase...
the pipe diameter of replacement pipes. A general trend of beneficial pipe upgrades in WDSs is to upgrade pipes located directly between reservoirs and tanks and pipes that are bottle necks in the system. For faster ROI, pipes that follow the general trend but that are smaller in diameter and length should be upgraded. Before any upgrades are installed into a WDS, it is strongly advised that the WDS manager use EPANET to determine if the pipe upgrade will provide a significant reduction in pumping cost. In general, it was found that any pipe upgrades that are financially beneficial to the WDSs are also environmentally beneficial.

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**Appendix A:**
Weights of Cast Iron for DICL Pipes
Weights of Cement for Lining of DICL Pipes

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<tr>
<td>72</td>
<td>20</td>
<td>22.89</td>
<td>459</td>
<td>1/4</td>
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<tr>
<td>100</td>
<td>20</td>
<td>24.71</td>
<td>484</td>
<td>1/4</td>
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http://www.acipco.com/adip/linings/linings.cfm
http://www.acipco.com/adip/pipes/flanged/specs.cfm
Appendix B:

<table>
<thead>
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<th>PVC Pipe Diameter (in)</th>
<th>Weight (lb/ft)</th>
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<tr>
<td>8</td>
<td>5.39</td>
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<tr>
<td>10</td>
<td>7.55</td>
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<td>12</td>
<td>10.01</td>
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<td>14</td>
<td>11.8</td>
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<td>15.43</td>
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Cost Table for 8” diameter pipe

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<th>Pipe</th>
<th>Pipe ($)</th>
<th>Electricity ($)</th>
<th>Excavation ($)</th>
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</thead>
<tbody>
<tr>
<td>PVC 50 Yr</td>
<td>4.84</td>
<td>232183.2</td>
<td>1328</td>
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<tr>
<td>DICL 50 Yr</td>
<td>13.56</td>
<td>319082.5</td>
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<tr>
<td>PVC 100 Yr</td>
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<tr>
<td>DICL 100 Yr</td>
<td>13.56</td>
<td>638164.9</td>
<td>1328</td>
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</table>

Appendix C:

**Top Energy Saving Upgrades**

The top ten energy saving pipe upgrades for PVC and DICL pipes in each system where determined and plotted:
Appendix D:

**CO₂ emission reduction of top energy saving upgrades**

The CO₂ emission reduction from reduced pumping over a 50 year period for the top energy saving upgrades was plotted on a kg equivalent CO₂ per foot basis. These values can be proportionally scaled to analyze CO₂ emission reduction for any given length of time:
Appendix E:

Placement of top energy saving upgrades within systems

The placements of the top ten energy saving upgrades with energy savings greater than 0.1% within each system were plotted on system maps with thick red lines:
Appendix F:

**Top Energy Saving Upgrades ROI - Scenario 1**

The ROI of the top ten energy-saving upgrades of PVC and DICL pipes assuming scenario 1 were calculated and plotted on a log$_{50}$ scale. The log$_{50}$ scale was chosen as log$_{50}$(ROI) values below 1 are financially profitable for the WDS and values above 1 are unprofitable:
Top Positive Energy Saving Upgrades for SYSTEM3-V2

Top Positive Energy Saving Upgrades for SYSTEM4
Appendix G:

Fastest ROI upgrades – Scenario 1

ROI values for PVC and DICL replacement pipes upgrades in each system where calculated under scenario 2 assumptions and the top ten fastest ROI PVC and DICL upgrades were graphed:
Appendix H:

**CO₂ emission reduction of fastest ROI pipe upgrades- Scenario 1**

The CO₂ emission reduction from reduced pumping needs for the fastest ROI pipe upgrades under scenario 1 assumptions were plotted:
Appendix I:

**Fastest ROI pipe upgrades locations-PVC –Scenario 1**

The following graphs show the locations within the systems of the fastest ROI upgrades using PVC piping under scenario 1 assumptions:
Barkdoll et al., 2011
Appendix J:

**Fastest ROI pipe upgrades locations-DICL – Scenario 1**

The following graphs show the locations within the systems of the fastest ROI upgrades using DICL piping under scenario 1 assumptions:
Appendix K:

**Top Energy Saving Upgrades ROI – Scenario 2**

The ROI of the top ten energy-saving upgrades of PVC and DICL pipes assuming scenario 2 were calculated and plotted on a log\(_{100}\) scale. The log\(_{100}\) scale was chosen as log\(_{100}\)(ROI) values below 1 are financially profitable for the WDS and values above 1 are unprofitable:
Top Positive Energy Saving Upgrades for SYSTEM3-V2
PVC ROI includes cost of additional replacement

Original Pipe Diameter [in]  Original Headloss

Top Positive Energy Saving Upgrades for SYSTEM4
PVC ROI includes cost of additional replacement

Original Pipe Diameter [in]  Original Headloss
Top Positive Energy Saving Upgrades for SYSTEM6-V2
PVC ROI includes cost of additional replacement

Top Positive Energy Saving Upgrades for C-TOWN
PVC ROI includes cost of additional replacement
Appendix L:

Fastest ROI upgrades – Scenario 2

ROI values for PVC and DICL replacement pipes upgrades in each system where calculated under scenario 2 assumptions and the top ten fastest ROI PVC and DICL upgrades were graphed:

![Diagram showing Fastest ROI Upgrades for SYSTEM2. PVC ROI includes cost of additional replacement.](image)
Fastest ROI Upgrades for SYSTEM3-V2
PVC ROI includes cost of additional replacement

Fastest ROI Upgrades for SYSTEM4
PVC ROI includes cost of additional replacement
Appendix M:

**CO\textsubscript{2} emission reduction of fastest ROI pipe upgrades – Scenario 2**

The CO\textsubscript{2} emission reduction from reduced pumping needs for the fastest ROI pipe upgrades under scenario 2 assumptions were plotted:

*Fastest ROI Upgrades for SYSTEM2*

PVC ROI includes cost of additional replacement

![Graph showing CO\textsubscript{2} emissions reduction](image)
Fastest ROI Upgrades for SYSTEM4-ORIGINAL
PVC ROI includes cost of additional replacement

Fastest ROI Upgrades for SYSTEM5-V2
PVC ROI includes cost of additional replacement
Appendix N:

**Fastest ROI pipe upgrades locations-PVC – Scenario 2**

The following graphs show the locations within the systems of the fastest ROI upgrades using PVC piping under scenario 2 assumptions: