PRIORITIZATION OF POTABLE WATER INFRASTRUCTURE INVESTMENTS ON THE NAVAJO NATION

by

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DEDICATION

This dissertation is in memoriam of my mother Katherine J. Chee. I just want to say thank-you for being the best mother that anyone could ask for. Thank you for imparting faith, wisdom, and perseverance in me and pushing me to continue my education. All your efforts have paid off. Thank you for raising me to be a good man. This is also your accomplishment. I love you.

TABLE OF CONTENTS

APPENDICIES

LIST OF FIGURES

ABSTRACT

Notorious for its high poverty levels and low socio-economic status, the Navajo Nation's socio-economic well-being is hindered greatly in part by the lack of an adequate potable water infrastructure which has resulted in health disparities and has attributed to stunted economic growth within the Nation. Large candidate regional water transmission pipelines projects aimed to meet these needs have been identified. With capital costs exceeding their fiscal capability, decision-makers must choose projects that generate the most bang for the buck. To address these challenges, three (3) interconnected planning tools have been developed: (1) a water pipe installation construction cost estimation model (WaterCOSTE) to improve the accuracy of capital cost estimates; (2) a hydraulic optimization model (WaterTRANS) that improves design efficiency for branched water transmission systems; and (3) a decision support system (DSS) that allows candidate water transmission projects to be ranked while considering economic development, health improvement and environmental protection objectives. Estimates derived from WaterCOSTE are used as input into WaterTRANS to find least-cost system designs. The system costs along with other project data are then input into the DSS to determine project rankings. To demonstrate how the DSS can be used and applied, two candidate projects on the Navajo Nation are evaluated. The tools developed will enable decision-makers to improve planning processes and make wiser investment decisions that will lead to expanding the water infrastructure coverage and living conditions on the Navajo Nation.

1. INTRODUCTION AND BACKGROUND

1.1 Overview and Problem Statement

There is no other region within the United States in which approximately 30% of a population lacks basic sanitation facilities in their homes (i.e., potable water, sewer and solid waste facilities) than on the Navajo Nation (NDWR 2011). The Navajo Nation (Nation) is a large jurisdiction/political boundary that spans across three states (Arizona, New Mexico and Utah) covering an area of approximately 27,000 sq. miles (see Figure 1). This land base is home to roughly 180,000 Navajos. The 30% of the population lacking basic sanitation facilities live in rural areas beyond the extents of the water distribution and wastewater systems. Residents not connected to water distribution systems obtain their water by manually hauling water from local water sources to their homes. It is not uncommon for residents living in very remote locations to use local water sources that may be contaminated with uranium or are intended for livestock use.

The activity of water haulage costs an average of $43,000 per acre-foot (ac-ft) compared with $600 per ac-ft for typical suburban water users in the region (NDWR 2011). Additionally, the average daily per capita usage of water ranges between 10 and 100 gallons per day (gpd), compared to neighboring non-Indian communities in the southwest which range around 165 gpd to 190 gpd (NDWR 2011). This high cost of water and below-average water consumption rates are characteristic of areas with high poverty levels and low socioeconomic status. The lack of access to clean potable water also strains the health care and social support systems and limits economic activity and growth. The lack of potable water infrastructure on the Nation can be attributed to:

- A lack of available capital to invest in water infrastructure projects. Most funds are appropriated elsewhere other socioeconomic improvement programs.

- A rural and sparsely distributed population density. With an area average population density of approximately 7 persons per square mile the Navajo Nation is unable to take advantage of economies of scale for large capital infrastructure investments.

- A stifled economy as the result of minimal businesses development and slow economic growth. A lack of large businesses and industrial centers are not able to help in subsidizing utility costs.

The Nation currently does not have capital to invest in water infrastructure. The Nation operates on internal revenues generated within the Navajo Nation and Federal Funding. The funds generated and received by the Nation are designated to cover the Nation's operating expenses. It is rare that surplus funding is available to invest in water infrastructure. It has been argued that the lack of capital surplus is the result of depressed socioeconomic conditions and lack of economic development on the reservation. It will cost the Nation billions of dollars in investments to bring its water infrastructure up to par with the rest of the United States. Currently, about 1% of all U.S. homes lack safe water in the home while about 25% of the world's population lack basic sanitation facilities (Hutton 2012). About 12% of American Indian and Alaskan Native homes on reservations lack safe water in the home (Hennessy et al. 2008).

Another challenge to developing water infrastructure on the Nation is the distribution of residences. The majority of the people live in towns and communities that have potable water and sewer services, however, a significant number of individuals live in remote areas. The sparse residential density outside of the population centers creates additional challenges as most projects are infeasible because operation, maintenance and repair (OMR) costs alone greatly exceed potential revenues that could be generated by water customers on those systems. The sporadic nature of residences is tied to the culture and history of the Navajo people. Most residence locations are passed down from previous generations. This sense of history is integral to the identity and culture of Navajo people. Thus, relocation of residences into communities and towns to take advantage of economies of scale is not a simple solution. Figure 1 shows the known location of approximately 4,100 homes that lack basic in home potable water facilities on the Navajo Nation (D. McDonnell, Indian Health Service, personal communication; July 21, 2015). The number of residencies lacking adequate sewer facilities is even higher but are not shown. Figure 1 also shows the existing water distribution system and the proposed large regional water transmission systems (WTSs), some of which are currently under construction.

The lack of a stable sustainable economy can also be attributed to the water infrastructure deficiencies that face the Nation. As a sustainable economy is dependent on a reliable potable water infrastructure to support it, so is a sustainable water infrastructure is dependent on a sustainable economy. This relationship between economic development and a reliable water supply is supported by studies conducted by the Stockholm International Water Institute and the World Health Organization (SIWI-WHO 2005) and the American Society of Civil Engineers (EDRG 2011). Business development on the Nation is hindered because the existing water infrastructure is operating at or near capacity and cannot support growth. For example, many business opportunities on the Nation are hindered because insurance companies are requiring higher premiums because fire suppression systems cannot meet the regulatory pressure requirements (A. Perry, Navajo Division of Economic Development [NDED], personal communication; July 20, 2015). Similarly, tax dollars, and utility revenues generated from a thriving economy is necessary to offset the OMR costs associated with water infrastructure.

The lack of businesses, commercial and industrial users on the Nation has put strains on the Navajo Tribal Utility Authority (NTUA), the utility provider for the Navajo Nation (R. Kontz, NTUA, personal communication, October 7, 2013). NTUA has many miles of pipeline but has few connections per mile. This results in OMR costs for many of the existing water systems exceeding the revenues generated by water users. Thus, NTUA must rely on grants and other types of aid to cover costs (R. Kontz, NTUA, personal communication, October 7, 2013). In effort to keep rates affordable for a population with below average incomes, NTUA cannot raise utility rates to keep up with increasing OMR costs. As the infrastructure ages, OMR costs will continue to increase and the gap between revenues and costs will widen.

The lack of a sustainable economy and lack of jobs and basic services has resulted in population decreases over parts of the Navajo Nation (NDED 2010). Residents are leaving outlying areas and moving to nearby towns and cities, which have the economic base to support jobs. Between 1980 and 1990 the off-reservation Navajo population in New Mexico, Arizona and Utah grew by 125% whereas the on-reservation Navajo population grew by 22% (NDWR 2011). In addition, vital tax dollars, currency circulation and revenues are leaving the reservation, due to the lack of basic wholesale and retail outlets.

Approximately $0.64 of every dollar earned on the Navajo Nation is spent off the reservation (NDED 2010).

Overcoming capital investment challenges, engineering challenges and socioeconomic challenges are the keys to developing water infrastructure on the Navajo Nation. Developing a sustainable economy along with a sustainable water infrastructure is crucial to the Navajo Nation's future. This dissertation aims at providing new and innovative solutions for planning and the development of water infrastructure for the Navajo Nation.

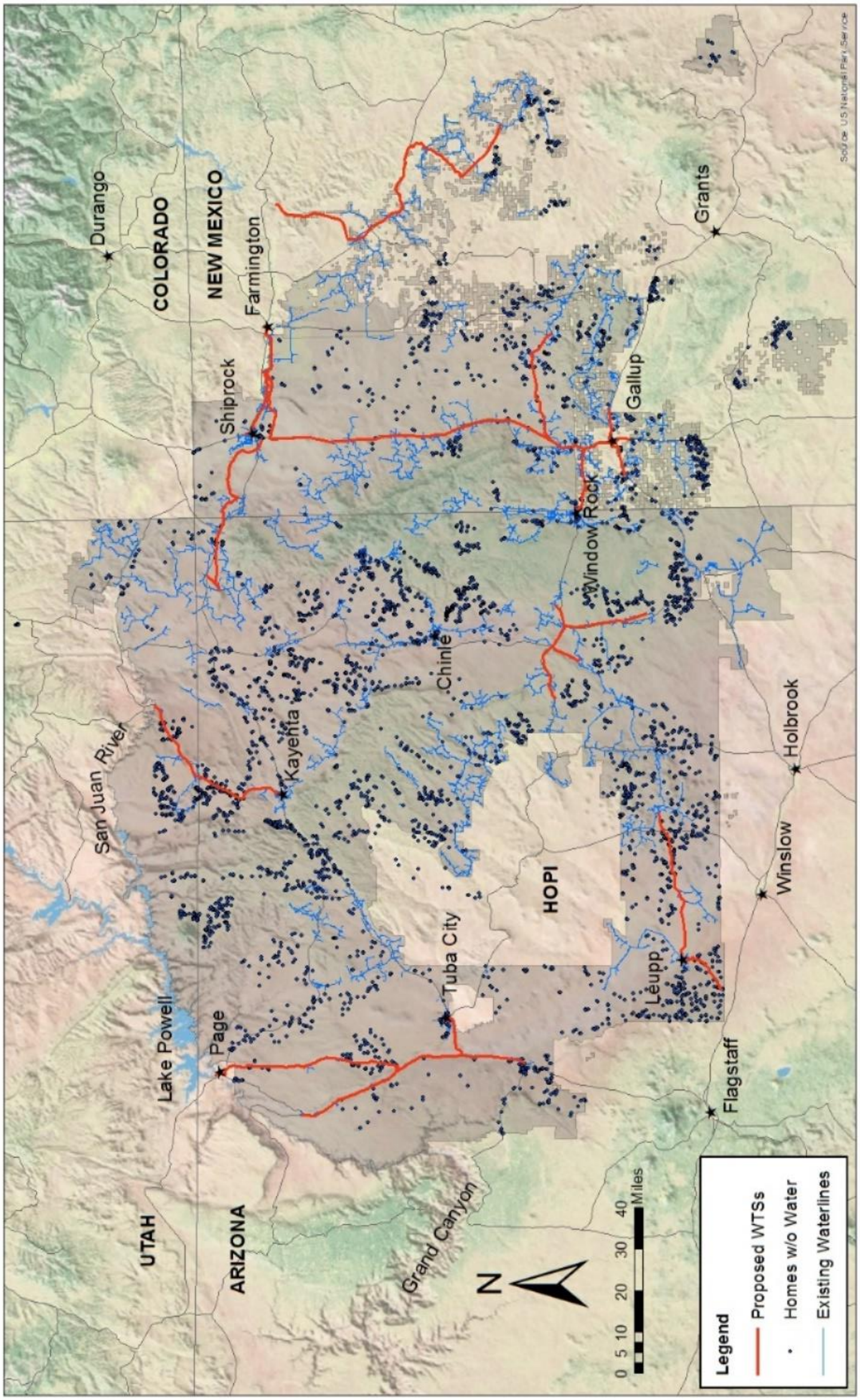

Figure 1. Homes lacking potable water connections on the Navajo Nation

1.2 Current Water Infrastructure Planning

The Nation has realized its deficiency and need for new and improved potable water infrastructure. The Nation has plans to invest in its water infrastructure, approximately 11 large regional water supply projects are in planning stages to be implemented in the next 40 years (NDWR 2011). The total estimated capital cost of these projects exceeds a few billion dollars. To deliver water to individuals, regional transmission supply lines will be constructed and tied to local water distribution systems. However, the costs associated with developing and constructing large scale projects lie beyond the Navajo Nation's financial and resource capabilities. The U.S. Government has also acknowledged this major deficiency in water infrastructure; as a result various federal agencies are leading planning efforts for these large regional supply projects.

Current planning efforts and the development of water infrastructure on the Navajo Nation is a combined effort of several agencies consisting of Navajo Nation agencies and U.S. government agencies. Navajo Nation agencies include the Navajo Nation Department of Water Resources (NDWR) and the Navajo Tribal Utility Authority (NTUA). U.S. government agencies include but are not limited to the Bureau of Reclamation (Reclamation) and the Indian Health Service (IHS). Project planning and funding is not limited to these agencies.

Figure 2 conceptualizes the current planning process, agency involvement, agency interaction and funding avenues for the development of water infrastructure on the Navajo Nation. This schematic shows a simplified version of the process and levels of involvement for a typical water infrastructure project. At the project planning (engineering) process, Navajo and Federal agencies are involved. Each agency contributes to a particular project using its own federally funded budget. Navajo agencies are funded by their internally generated revenues and federal aid. After the planning process is completed for a project, construction commences. Construction funding is normally achieved through a variety of avenues such as collective pooling, congressional funding, or water right settlements (NDWR 2011). Due to the high expense for construction, this phase is where most projects are postponed or canceled. Completed projects are operated by the NTUA. Operation is sustained by a combination of: utility revenues, Navajo Nation funding and external funding from federal or private sources. Revenues are rarely recycled back into the project lifecycle. A description of current major key stakeholders and agencies involved in the water infrastructure planning process is provided here.

Navajo Nation Department of Water Resources (NDWR)

The NDWR is responsible for the protection, management and development of water resources of the Navajo Nation. The NDWR is responsible for the long-term stewardship of the Nation’s water resources and also serves as the main communication hub for the Nation in terms of water resource planning and development. They also provide technical support to the Navajo Nation government in water rights litigation and negotiations (NDWR 2011). The NDWR also ensures that the interests of the Navajo Nation are communicated and accurately accounted for in large regional planning studies headed by U.S. government agencies. For example, in large scale water supply projects lead by the Bureau of Reclamation, the NDWR will provide demand projections, growth rates, express tribal concerns, coordinate and integrate with existing and future projects (Jason John, NDWR, personal communication, September 3, 2013). NDWR is normally involved throughout the project planning and construction phases.

With a limited annual operating budget NDWR does not have the resources to fully plan and design water infrastructure, nor does it have the capital for construction funding. Thus, NDWR project involvement is limited to administering and coordinating with other agencies that have the resources and capabilities to plan and design infrastructure projects. This is unfortunate as the NDWR possesses the significant knowledge and insight, and is culturally adept and cognizant of the internal challenges that hinder water infrastructure development on the Navajo Nation.

Navajo Tribal Utility Authority (NTUA)

The NTUA provides electricity, natural gas, water, wastewater, renewable energy and telecommunications across the Navajo Nation. NTUA has approximately 56,258 electric customers, 39,172 water customers, 13,956 waste water customers, 7,900 natural gas customers, and 200 photovoltaic customers (NTUA 2017). NTUA is an enterprise of the Navajo Nation and operates under a tariff rate that is set by a management board that is overseen by the Navajo Nation Economic Development Committee. Nearly all water infrastructure constructed on the Navajo Nation is eventually turned over to NTUA to operate and maintain. NTUA is involved in almost nearly every project beginning in the planning phase to ensure that it is able to operate, maintain and cover the costs associated with a new infrastructure. However, NTUA is often obligated to take over projects in which OMR costs exceed revenues. As water and wastewater infrastructure projects get constructed, NTUA takes on the full responsibility of operation and maintenance.

Bureau of Reclamation

In general, the Bureau of Reclamations role is *"…to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public* (USBR 2017)". More specifically, Reclamations' Rural Water Supply Program aims at developing water infrastructure on Tribal Nations. The Rural Water Supply program is the result of the Rural Water Supply Act of 2006, Public Law 109-451. This Act *"…authorized Reclamation to establish a program to work with rural communities, including tribes, throughout the 17 western states to assess potable water supply needs and to identify options to address those needs through appraisal investigations and feasibility studies* (USBR 2017)". The Bureau of Reclamation's efforts in developing water infrastructure on the Navajo Nation are generally funded as part of the Bureau of Reclamation's Rural Water Supply Program.

Reclamation has the resources and funding necessary to conduct large scale regional water supply studies. Currently, Reclamation is leading roughly 11 major regional supply studies within the Navajo Nation. These projects are in the pre-planning and appraisal stages. Reclamation works in conjunction with the NDWR and IHS in identifying needs and planning projects (K. Black, personnel communication, October 22, 2013).

Indian Health Service (IHS)

In general, the Indian Health Service is responsible for providing federal health service to American Indians and Alaska Natives throughout the United States. Recognizing the correlation between providing health services and in-home sanitation facilities, IHS's role has extended to improving in-home sanitation facilities in Indian communities as part of

Public Law 94-437. Sanitation facility improvements include the design and construction of potable water, sewer, and solid waste facilities.

Sanitation facility improvement efforts are identified, designed, prioritized and constructed by IHS's Sanitation Deficiency System (SDS). Sanitation deficiencies are identified for individual homes lacking facilities; these homes are then grouped into SDS projects. Each SDS project may consist of a design and cost estimate that will provide potable water and sewer services to a group or cluster of homes. SDS project construction is prioritized based on the following factors (listed in descending order of its prioritization weight): health impact, existing deficiency, adequate previous service, capital cost, local tribal priority, O&M capability, tribal contributions, and local conditions factor (IHS 2003).

Each year the SDS prioritization list is updated to account for changes in conditions, price adjustments for inflation, etc. Currently, IHS has identified 570 sanitation deficient facility projects with an estimated cost of $589 million dollars (D. McDonnell, IHS, personal communication, March 21, 2017). About $257 million dollars of the total are considered economically feasible (a project is considered economically feasible if the unit cost per home of the entire project is below the set allowable unit cost, based on State). Based on the current funding situation, the current set of feasible projects will require nearly 20 years to construct (D. McDonnell, IHS, personal communication, March 21, 2017). This still leaves a large number of homes without water.

Currently, the IHS SDS program scope and funding is limited to residential improvement and development as defined in Public Law 94-437. In some cases, it may be difficult to plan and construct IHS distribution systems in conjunction with regional transmission systems that may aim to support planned commercial development and growth. Exhaustive efforts are required to overcome these administrative constraints and often results in missed opportunities. For example, projects that are low priority on the SDS list may become more feasible (and move up in priority) when planned in conjunction with a regional transmission system as there may be cost savings in tying the local system into the transmission main versus having to develop infrastructure associated with the source (i.e., wells and treatment). In addition, a regional transmission system may have high priority for the Tribe in terms of economic development and growth opportunities whereas IHS SDS projects in the same area may rank low on the prioritization list. This discrepancy in prioritization objectives amongst the Navajo Nation and other agencies can also result in missed opportunities and cost savings. With the water infrastructure deficiencies that impair the Navajo Nation and limited funding, a highly coordinated and collaborative effort amongst agencies is needed to best utilize limited available funds.

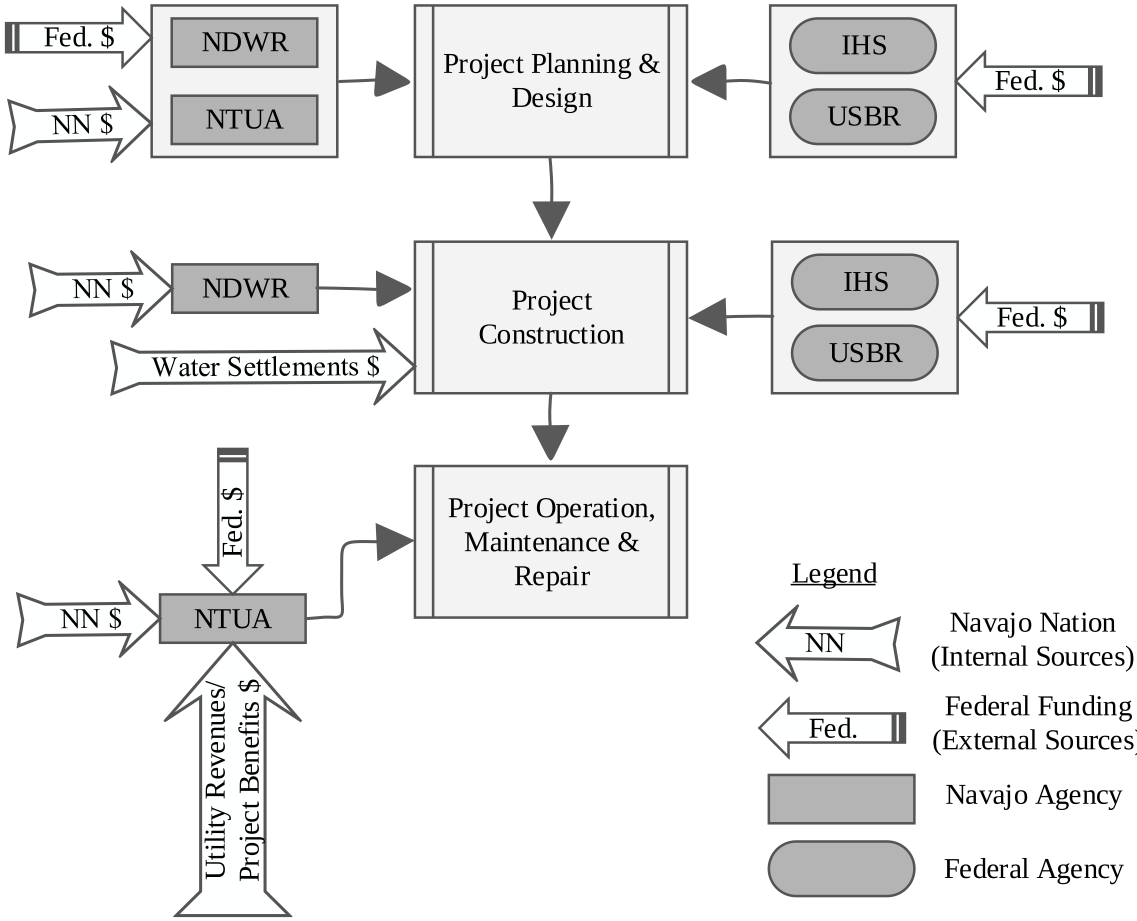

Figure 2. Current Project Planning Processes, Agency Involvement, and Funding Avenues

1.3 Project Planning Deficiencies and Needs

1.3.1. Increased Inter-Agency Collaboration for Project Planning

Current water infrastructure planning is strongly influenced by external perspectives rather than from the Navajo Nation view point. Generally, studies conducted by non-Navajo agencies fail to recognize the unique and underlying challenges facing water infrastructure development on the Navajo Nation. Current planning of water infrastructure does not consider a holistic view of issues that plague the Navajo Nation. This is an inherent problem as the Navajo Nation seeks aid from outside sources and can result in planning and design that is biased toward the agency providing the funding while failing to recognize the tribe's best interests. Economic and engineering factors are not the only concerns that may affect the feasibility or selection of a water infrastructure project in areas such as the Navajo Nation. Benefits and costs linked to the culture and way of life may go unrecognized and unaccounted for. In addition, the connectedness of economic needs, environmental considerations, health and social impacts should be considered during project planning.

Project planning from the Navajo Nation's perspective would account for costs, benefits and savings that may not normally be considered. The Navajo Nation understands the connectedness of these social, environmental and economic systems and should play a larger role in project planning and selection to ensure that a project will have significant impacts (get the biggest "bang for the buck"). The Nation is best suited to distinguish these differences and modify or adapt project objectives accordingly. Finally, the Navajo Nation should be able to discern which projects and objectives are most important to its nationwide needs and livelihood.

1.3.2. Need for Multi-Criteria Planning

To date, most engineering efforts for planning water resource infrastructure are single-criteria in nature with designs driven by cost or economic feasibility. Projects are deemed feasible or infeasible based on the willingness to pay of the users that will be served by the system. Most projects in urban areas are deemed feasible as they are able to take advantage of economies of scale and relatively low costs. In these instances, sufficient household income and commercial development cover the economic value of the infrastructure and provide funds for loan repayment and OMR costs. Current and past Navajo Nation water infrastructure project evaluations are primarily economically driven.

The Nation has begun to recognize the challenges in continuing to apply conventional single criteria project planning to new projects that aim at serving rural areas. Current water infrastructure systems on the Nation demonstrate this difficulty. Existing water systems are limited to communities and towns and have reached their economically sustainable limits as well as physical capacity; any further extensions of the current systems are not economically infeasible (R. Kontz, NTUA, personal communication, October 7, 2013). Thus, the task of getting water to the remaining 30% of the population (who primarily live in rural areas) is difficult.

Conventional economic driven approaches to plan and design systems to serve the remaining residents without water utilities deem many of the proposed major water delivery projects on the Navajo Nation to be infeasible. The ‘willingness to pay’ factor based on conventional methods results in an inability to pay due to the high unemployment rates and low socio-economic conditions. In an appraisal level study conducted by the Bureau of Reclamation for the Southwestern Navajo Rural Water Supply Project; a regional water supply system with an estimated capital cost of $300 million dollars; Reclamation concluded that by using current U.S. Environmental Protection Agency standards for estimating ‘willingness to pay’ the project was infeasible, but when evaluating the current rates paid for water haulage activities in the area the project was deemed feasible (USBR 2013). This calls a re-evaluation of current planning processes and objectives on the Nation. New planning methods are needed to assess the need for new water infrastructure projects and innovative strategies to implement those projects.

An example of the shortcoming of the single criteria planning is seen in the IHS’s SDS program. The SDS is specifically geared to improving health and providing in-home sanitation facilities. Under their administrative guidelines, potential future demands associated with commercial development into a water system design are not incorporated into the planning process. IHS assumes a 50 gpcd demand for delivery system designs (IHS 2005). A benefit of this criterion is that it avoids over-design and decreases construction costs resulting in design that serve in more residents. However, the low demand can result in an under-designed system that does not permit future growth. Failure to account for economic development and growth can result in costly upgrades or retrofitting in the future. In some instances, upgrading or retrofitting costs can be more expensive than initially installing a larger system. This condition hinders vital economic development needed to sustain OMR costs.

Continuing to plan with a single objective agenda can result poor decisions where low cost solutions are implemented initially but may result in costly impacts in the future to upgrade the system or by becoming too expense to expand. This planning approach has resulted in water infrastructure deficiencies to many tribal members and demonstrates the conflict between Tribal priorities and other agency objectives. Health and social objectives should be considered in conjunction with economic costs to ensure water infrastructure sustainability. In addition, the Tribal priority of economic development is not captured in a single objective planning and results in in wasted capital and resources. The economic development concern is further impacted by isolated project analysis, rather than taking a regional planning perspective.

A multi-criteria planning effort and inter-agency collaboration can result in a design that meets present demands for the current population while allowing for future growth. However, such a multi-dimensional planning framework with multi-criteria objectives is lacking to evaluate Navajo Nation water projects. Substantial project factors including social, economic, and health impacts are not addressed. Social factors would include improved standards of living as the result new water utilities in the home and water-haulage time and cost savings. Economic factors would include the potential economic impacts from business and commercial development as the result of a new reliable water system. Health care costs savings related to in-home sanitation deficiencies can be a positive health impact of a new water system.

1.3.3. System-wide Prioritization for Project Selection

The Navajo Nation has not completed a global prioritization effort regarding development of water infrastructure. Current efforts and prioritization are based on the project with the most potential for federal funding (with the exception of IHS); planning efforts are often a response and reaction versus a thoroughly master planned approach. Piece-wise segmented planning processes are common throughout the U.S. and the World and not specific to the Navajo Nation. Federal funding and specific government initiatives are often the result of this type of planning. It is not unusual for projects to be pushed through the planning and design phases and having funding withdrawn upon reaching the construction phase.

It is argued that piece-wise planning is not the most feasible or economical approach to infrastructure planning, particularly in areas, such as the Navajo Nation, where resources and funding are already stretched thin. This non-prioritized approach for water planning and management can result in wasted efforts at the planning and engineering levels and can lead to regret costs over time. Rather a systematic approach is needed to prioritize projects and planning efforts. This approach should bring all stakeholders together during the decision-making process including and most importantly the Navajo Nation.

1.3.4. Hypothetical Example

Many times projects are selected for construction based on their potential for federal funding. However, the selected project may not be consistent with the Nation's long term development and strategic plans. However, as the funding potential presents itself, the Nation cannot miss out on the opportunity and will act on it resulting in reactive planning and the inefficient use of financial resources.

Let's take an example scenario; assume that the Nation's economic development plans call for development in a particular area to generate tourist attractions and retail outlets to serve a small number of residents in a particular area. This area may coincide with water shortages and in-home infrastructure deficiencies, thus, a water system can be initially designed to satisfy multiple objectives at a feasible cost. Additionally, let's say this particular area is located within a Chapter (political jurisdictional boundary) who may be in full support of the project and has worked to overcome zoning and land acquisition/right-of-ways barriers. These conditions would be ideal for an infrastructure investment as economic and social benefits could be reaped quickly. Investment returns from utility revenues, business taxes, job creation and tourism revenues can be quickly collected. More importantly, residents in the area without water can be served.

Let's take another project scenario; assume an area has a large dispersed rural population who has a long history of in-home deficiencies and high water haulage costs. The area is remote and access to the area limits business, commercial development and tourism opportunities. Residents of the local Chapter have been persistent in advocating for water utilities which has gained much attention. The preliminary water system design calls for an expensive water system in which OMR costs will exceed utility revenues.

Navajo decision-makers are then faced with the decision of which project to invest in first. The Nation is often faced with this conundrum and is difficult to assess without the aid of a systematic procedure which can compare and evaluate these projects. A systematic procedure can aid in evaluating which objectives are the most important and will assist in project selection. Various scenarios that place emphasis on particular objectives can be simulated to explore possibilities and aid in project selection. The systematic procedure along with collaborative efforts from all agencies will select the highest priority project and can focus resources and capital to execute the chosen project. Poor project selection without a thorough analysis and evaluation can result in significant delays in reaping project benefits and/or returns on the investment. This can tie up precious capital that can otherwise be reinvested into other projects. When capital becomes available to fund water infrastructure projects, unique, extensive and rigorous cost-benefit analysis tools that account for multiple goals are needed to help prioritize and aid in selecting projects which will provide the most benefit to an area. Additionally, engineering planning models and methods for large scale water distribution systems in sparsely populated areas like the Navajo Nation are limited.

2. DISSERTATION OUTLINE

2.1 Overall Goals

The development of a DSS to aid in prioritizing water infrastructure investments is the primary objective for the dissertation. The DSS can be used to assist Navajo planners and decision-makers to make economically sound and objective decisions when selecting water infrastructure projects. Development and successful implementation of the model will help:

- Provide a clear global project selection and execution plan to all involved parties including: tribal and federal agencies, the tribal council, governing bodies and constituents;
- Focus resources and planning efforts (e.g., engineering and environmental) on specific projects;
- Provide a clear plan and objectives to allow various agencies with different sources of capital to pool money to contribute toward a common goal;
- Increase interagency coordination within the Navajo Nation and with federal agencies;
- Agencies and decision makers justify their decisions (project selection) by having a robust method that can stand up against scrutiny.

Appropriate project selection is crucial when capital is limited and when attempting to develop in economically challenged areas like the Navajo Nation. Planning for a simple water infrastructure project can easily turn into a complex problem as social, health and economic factors come into play and may strongly influence a decision. Current planning methods do not account for these factors and is the premise for this dissertation. Accordingly, the DSS developed attempts to capture and account for multiple objectives (health, economy and environment) when planning and selecting water infrastructure projects.

With the Navajo Nation recognized and operating as a sovereign nation, opportunities for the Nation exist to have direct input/control into how funding is appropriated and prioritized throughout the project lifecycle. For purposes of this study and to demonstrate the need for a fully integrated planning effort (from all agencies involved), a proposed alternative organizational and funding structure is presented in Figure 3. This proposed structure is attainable with a global planning tools such as the DSS developed to help guide decisions and organize collaboration amongst agencies. Under this proposed structure, it is assumed that all funding available for the development of water infrastructure (whether internally generated or federal aid), will enter at the project planning phase and be administered through the Navajo Nation. Project planning efforts, project selection and construction will be a collective effort of all involved agencies and additional agency involvement may be required depending on the project. For example, the NDED could play a larger role in project planning and selection by introducing information on planned growth and economic centers, potential revenues, workforce projections, and estimating economic impacts. With the implementation of a more systematic and master planned approach in project planning, positive returns on investment and revenues can be realized. Increased revenues can result in more economically sustainable water systems, and may generate revenue for reinvestment in new or improving aging infrastructure.

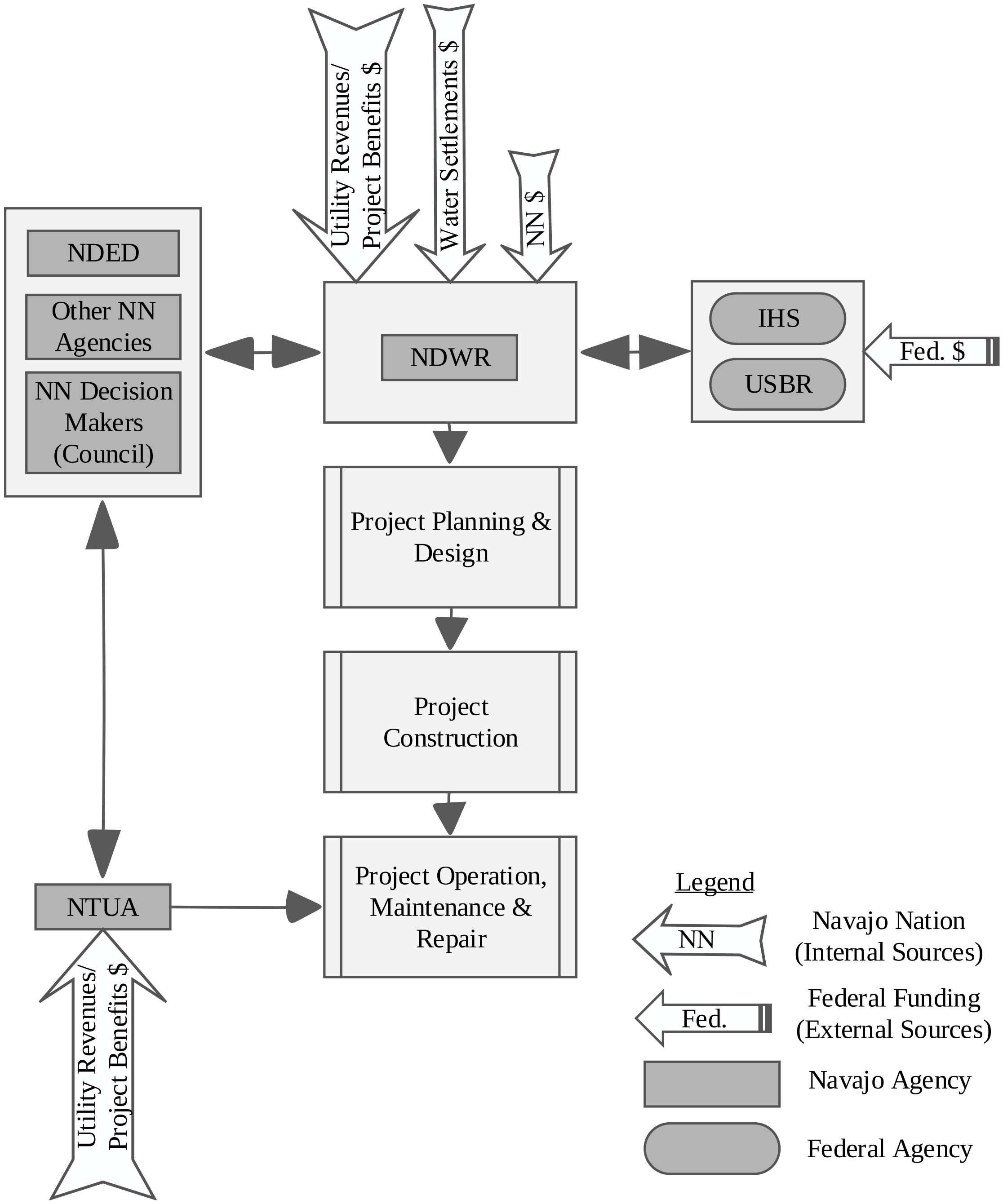

Figure 3. Proposed Project Planning Processes, Agency Involvement, and Funding Avenues

With a systematic project planning and selection system in place that is guided by the DSS, the intent is for the Navajo Nation to invest more wisely. Wiser investments should result in water systems that are economically sustainable and provide health benefits while minimizing impacts to the environment. Investments that account for the potential economic growth that will accompany the water infrastructure will allow benefits to be reaped more quickly. Quicker benefits then translate into more capital that is available to reinvest back into infrastructure. Through this process, it is expected that the water infrastructure coverage on the Nation will increase, eventually reaching the 30% of the residents without water.

2.2 Subtopics and Sequence of Study

The main dissertation goal of developing a DSS for the Navajo Nation was achieved through three focused studies (or subtopics); when combined together, they constitute the overall dissertation. The three subtopics were selected and developed so that they could be standalone studies as well as contribute to the overall dissertation goals. Accordingly, each subtopic builds upon findings and results from the previous (with the exception of the first) as illustrated in Figure 4.

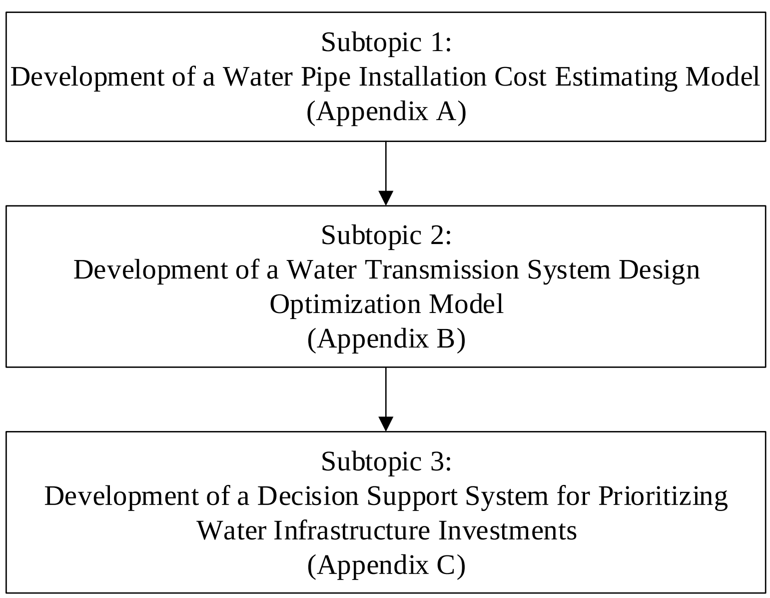

Figure 4. Dissertation Subtopics and Sequence of Study

A summary of each subtopic and how it contributes to the overall dissertation goal is provided in the following sections.

2.2.1. Subtopic 1 – Pipe Installation Cost Estimating

Before projects can be prioritized in the DSS, project costs need to be estimated using a consistent estimating methodology to ensure fair evaluations. An inconsistent cost estimating methodology among projects can lead to unreliable project rankings determined by the DSS. Due to the size of the water transmission systems under consideration, pipe installation costs are the single largest capital cost item, ranging between 50%-60% of the total capital cost. Pipe installation cost estimates are known to have a wide range of variability, which can lead to significant over- and under-estimates of a system's actual cost. Because pipe installation makes up the majority of the total system cost, and because of the complexities of developing accurate pipe installation cost estimates; the focus of the first study (subtopic) was to develop a pipe installation costing methodology that can be used to estimate project costs and perform system cost optimizations.

Accordingly, a **Water** pipe installation **CO**nstruction Co**ST** **E**stimation model (**WaterCOSTE**) was developed to provide reliable pipe installation cost estimates (see Appendix A). WaterCOSTE is novel in that it can provide estimates for the installed pricing for various pipe materials and diameters under a wide range of bury and embedment conditions. WaterCOSTE employs a bottom-up pricing approach commonly used by contractors to estimate installed pricing for high density polyethylene (HDPE), polyvinyl chloride (PVC), ductile iron and steel water pipe. This bottom-up approach is advantageous over conventional methods that employ cost data from previously installed projects. This conventional method can lead to inaccurate estimates as specifications, regional location, market conditions and other site-specific factors may differ greatly from the proposed project. WaterCOSTE is based on U.S. industry standards for pipe installation and is designed so that it can be applied throughout the U.S. However, its application is not limited to the U.S., as simple changes to input costs and parameters allow WaterCOSTE to be applied worldwide.

WaterCOSTE was developed in an Excel spreadsheet format in a user-friendly manner and contains dropdown menus that allows users to select as well as input their own parameters to develop estimates for site-specific conditions. The output results from WaterCOSTE are ultimately provided in dollars per foot (installed). WaterCOSTE allows engineers and planners to efficiently develop a wider range of estimates for evaluating more options early in the planning and design stages. To date, there are no widely accepted peer-reviewed standardized methodologies like WaterCOSTE in the civil engineering and/or construction fields. The derivation of bottom-up pricing for pipe installation is a task that that is typically left to the contractor. With the contractor often excluded from planning and design phases so are their accurate cost estimates. This leaves a large gap in the planning and design process as accurate estimates are needed early on to evaluate tradeoffs in design (e.g., various pipe diameters, pressure class considerations, on-site embedment material vs import, etc.). WaterCOSTE bridges this gap as it brings the contractor's detailed estimating methodology into the planning and engineering phases.

In this dissertation, WaterCOSTE was used to develop site-specific cost estimates for two potential water projects on the Nation. These estimates were then compared against other estimating models which use regression curves that were derived from construction cost databases. These cost estimates (in $/ft installed) were the then used as input into a water transmission main optimization model, which is the second study (subtopic) of this dissertation as discussed in the following section.

2.2.2. Subtopic 2 – Water Transmission Main Optimization

In addition to implementing a consistent cost estimating methodology for pipe installation, a unified design methodology was also adopted. This ensures that pipe materials and demand conditions used to design and size the system are consistent among the candidate projects. It is difficult to make a fair comparison when two projects are designed with different materials or have different sizing criteria (e.g., peak factors). Take for instance, if two similar sized systems (with the same benefits) are being considered, and one is made with ductile iron and the other PVC, the DSS will most likely select the cheaper design (PVC) because it will bring the same benefits at a cheaper cost. In order to get a fair comparison, both projects should be designed using the same material and re-evaluated.

These large systems, such as those proposed for the Nation, can require multiple booster pumps and pressure regulators which can complicate the design and estimating process. Locating these booster pumps and pressure regulators while considering pipe pressure classes is an iterative and time consuming process and results in countless design alternatives with varying costs. Locating booster pumps and pressure regulators is crucial as their placement and operational settings can have significant capital and operational cost implications, especially for long-distance pipelines. Locating pumps and regulators using conventional hydraulic models is time consuming and not easily accomplished, especially for these long-distance branched systems. Conventional models require a trial and error process to locate pumps and regulators and requires the system network model to be altered multiple times (e.g., computational nodes and pipe segments must be broken and reconstructed to simply relocate a pump). This alteration of the network geometry hinders through optimization and alternative analyses (especially when pairing hydraulic models with optimization algorithms).

To overcome these difficulties with conventional hydraulic models, WaterTRANS was developed (see Appendix B). WaterTRANS improves design efficiency (reduces design time) by automatically creating a hydraulic model by transposing the topographic profiles created from a pipeline alignment that samples elevation and stationing data off a digital terrain model. System hydraulics are then computed by observing the calculated hydraulic gradeline in relation to the terrain profile. This unique approach allows WaterTRANS to automatically locate pumps and pressure regulators in branched water transmission systems as well as assign pipe pressure classes to specific sections of pipeline using American Water Works Association design criteria. Currently, there is no hydraulic modeling software capable of performing such tasks. By incorporating WaterCOSTE results into WaterTRANS, the cost savings of allowing pipe pressure classes to change along the pipeline can be realized and quantified.

The strength of WaterTRANS is further exhibited by pairing it with a Genetic Algorithm (WaterTRANS-GA) to determine least-cost water transmission designs for four (4) different material types (HDPE, PVC, ductile iron and steel pipe) for two (2) alternative alignment options for the North Central Arizona Water Supply Project (NCAZ; USBR 2006). Steel pipe proved to be the ideal pipe material for that system. Lastly, WaterTRANS-GA was also used to design and optimize the Mexican Hat to Kayenta Regional Water Supply Project (MHK; USBR 2011); another potential investment the Nation is considering that is similar in size and scale to the NCAZ. The capital and OMR cost estimates generated by WaterTRANS-GA for these two systems were then input into the DSS as discussed in the following section.

2.2.3. Subtopic 3 – Decision Support System

The DSS is perhaps is the most important tool that has been developed to address the challenges of water infrastructure development on the Nation. The DSS allows water transmission projects to be ranked while considering economic development, health and environmental objectives. The DSS consists of a cost benefit analysis integrated into a MCDA framework that allows projects to be ranked based on a non-monetized benefit cost ratio (BCR). The DSS is structured as a hierarchy that descends from an overall goal (project selection), to objectives to various criteria and sub-criteria. Objectives consist of health improvement, economic development and environmental protection. Criteria and sub-criteria consist of the major factors affecting decision-making such as the usage of water and wastewater generation, system costs, health and economic benefits gained by off-grid users, utility revenues, economic development potential, and the reduced usage of contaminated water sources.

Pairwise comparisons (or the determination of weights for the various criteria) can then be ultimately performed by Navajo decision-makers to transcribe their judgments into the DSS's internal mathematical model. A BCR is then calculated for each project using the weighted priorities and numerical scores for the various criteria. The projects are then ranked according to their BCR with the highest BCR being the most preferred project. This approach is unique in that the cost benefit analysis within the MCDA framework method has not been specifically applied to rank (or prioritize) potential potable water infrastructure projects (see Appendix C for more detail regarding the DSS).

To demonstrate the DSS's effectiveness in planning and decision-making, it is applied to rank the two candidate NCAZ and MHK projects. Because of the deterministic nature of the DSS, five (5) highly probably alternative future scenarios were applied to evaluate how the rankings of the candidate projects would be affected. These alternative scenarios were also evaluated to take into account the uncertainty with model predictions as well as to demonstrate the robust decision making capability of the DSS. In addition to the scenarios, the candidate projects were also evaluated using hypothetical criteria weights of three decision-makers with health, environmental and economic development agendas. The analysis demonstrated that the MHK project ranked higher under the health and environmental agendas with the NCAZ project ranking higher under the economic development agenda. This dichotomy in the results demonstrates how critical the role of the decision-maker is when evaluating projects with the DSS.

3. UNIQUENESS AND CONTRIBUTION OF RESEARCH

This work is novel and provides a contribution of knowledge through aspects of the research described in the three appendices. Important results and the uniqueness of each subtopic in the appendices are summarized below.

Subtopic 1 – Pipe Installation Cost Estimating (WaterCOSTE)

- WaterCOSTE is based on a unique bottom-up methodology to cost estimating that mimics a contractor's approach.
- Provides an expanded range of alternative installed piping costs relative to previously published efforts that are based on construction cost data including:
    - Pipe material (PVC, HDPE, DI and steel).

  - Pipe diameter (4 inch through 72 inch).
  - Pipe pressure class (all commercially available pressure classes up to 500 psi).
  - Pipe embedment specifications (AWWA embedment Types 1 - 5).
  - Excavation soil type (OSHA based trench excavation for soil types A, B and C).
  - Labor and equipment rates.
- Unlike other estimation models, the cost estimates here can be adapted to site specific conditions by adjusting the individual cost items mentioned above.

Subtopic 2 – Water Transmission Main Optimization (WaterTRANS)

- Provided a digital terrain model, the hydraulic model is easily created by sampling topographic data along the specified pipe alignment.
- Has an embedded automatic process for siting pump stations and pressure regulator locations.
- Ability to efficiently incorporate pipe material, pipe diameter, pump head and pressure regulator setting decisions.
- Ability to assign pressure classes (as well as hydraulically account for the changing inside diameter) to specific portions of pipeline based on AWWA working and surge pressure design criteria.

- Determine efficacy of turbines/PRVs in downhill segments.

Subtopic 3 – Decision Support System

- Novel application of AHP in a BCR/MCDA framework .
- Development of set of indicators for economic, environmental and health using available data.
- Demonstration of impact of decision maker preferences on final decision.
- Incorporation of scenarios in DSS to test alternative robustness.

4. CONCLUSION AND FUTURE WORK

In closing, three important tools were developed as a result of this study:

- A cost estimating methodology for the installation of water pipe;
- An improved hydraulic model to design branched water transmission systems; and
- A multicriteria decision support system to prioritize water infrastructure investments on the Navajo Nation.

These tools do not only benefit the Navajo Nation but also help to advance the field of civil engineering in general. These tools can be applied throughout the world to: help improve cost estimates for installed water pipe; significantly reduce the time it takes to design branched water transmission systems; and providing a template for improving the decision making regarding water infrastructure investments.

Implementation of these tools and the DSS on the Nation would force the various agencies and decision makers to come together to work toward a common goal. Through this collaborative process, it is more likely that the water infrastructure coverage will increase on the Navajo Nation. The improved potable water infrastructure can then provide the foundation that is needed for a sustainable economy which will then lead to improved socio-economic conditions on the Nation.

Lastly, the work presented in this dissertation has has laid the foundation for future studies which may include:

- Extension of WaterCOSTE to consider other pipe materials, diameters larger than 72 inches, and excavation through rock.
- Extension of WaterCOSTE to consider stochastic processes to provide a range of values as opposed to a single value.
- Extension of WaterCOSTE and WaterTRANS into a more user-friendly computer program with a graphical user interface (GUI).
- Extension of WaterTRANS to consider multiperiod simulation and allow for pump stations to incorporate user specified pump curves.
- Extension of the DSS to include uncertainty analysis to quantify the range of error expected with the models use; as well as the inclusion or refinement of criteria as guided by Navajo decision-makers.

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APPENDIX A

Estimation of Water Pipe Installation Construction Cost

Estimation of Water Pipe Installation Construction Costs

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Abstract

With the Nation currently experiencing record droughts and water shortages in the western and southwestern states, the importation of water via large diameter pipe transmission systems from distant more reliable sources are becoming viable options. As drought conditions worsen, engineers and water planners will need efficient cost models to plan and design these large water transmission systems. To address these challenges, a **Water** pipe installation **CO**nstruction Co**ST** **E**stimation model (**WaterCOSTE**) has been developed to estimate the installed pricing for various pipe materials and diameters under a wide range of bury and embedment conditions. The WaterCOSTE model employs a bottom-up pricing approach commonly used by contractors to estimate installed pricing for high density polyethylene (HDPE), polyvinyl chloride (PVC), ductile iron and steel water pipe. WaterCOSTE is used to estimate installed pricing for a potential large scale real-world water transmission project in northeastern Arizona. Pipe material cost and pressure class are found to be significant cost factors, followed by embedment type, soil type and bury depth. A cost comparison based on pressure class was performed for the candidate materials.

Keywords: Pipeline Construction Cost; Cost Estimation; Cost Model; Water Supply Cost Estimation; Pipelines; Water Transmission System, Bottom-up Cost Estimation. Pipe Material Selection.

INTRODUCTION

Background

Importation of potable water to water-scarce regions via transmission pipelines from distant more reliable sources is common throughout the world and is expected to increase with population shifts to urban areas and drought and climate change conditions further stress available water supplies. These conditions are particularly true for the southwestern and western United States (U.S.) where record droughts are the primary cause for depleting local water sources. Municipalities and government agencies have begun exploring the importation of water via large-scale transmission pipelines as a feasible alternative to meet future water demands and to preserve more local sources (USBR 2006). Additionally, existing water transmission pipelines are nearing the end of their design lives and will be in need of replacement in the near future (ASCE 2013). As large water transmission pipeline projects are quickly emerging as feasible alternatives, engineers and water planners will need effective cost model planning tools to form the basis of meaningful high level planning and engineering. For long transmission projects that may span tens to hundreds of miles, the pipe installation is the largest single capital cost item thus accurate estimation of pipe installation cost is crucial. Accurate and readily available cost estimating tools are needed to assist engineers to quickly and thoroughly evaluate various project alternatives and perform studies such as cost-benefit analyses.

Generally, engineers prepare cost estimates for water pipelines using installed unit pricing derived from previously constructed projects that may be similar in diameter, material, bury depth and location, etc. (i.e., use of project bid tabulations). Several researchers expanded this approach by implementing regression techniques using construction databases (e.g., Clark et al. 2002 and Marchionni et al. 2016). These methods are valid for high level planning, but are limited in that not all pipe diameters for various material types are covered. Clark et al. (2002) developed regression curves for polyvinyl chloride (PVC), ductile iron (DI) and steel water pipe for a limited range of diameters. Further, high-density polyethylene (HDPE) was not considered. Marchionni et al. (2016) developed regression curves for various materials (with diameter range); PVC (<400 mm [16 inches]), DI (<700 mm [28 inches]), steel (600-1200 mm [24-48 inches]), and HDPE (<300 mm [12 inches]). Like Clark et al. (2002), these pipe sizes do not cover the range of available pipe sizes that can be acceptably used in pressurized systems. As manufacturing processes improve, consideration should be given to alternative material types at the planning levels.

In addition, pressure class considerations were either limited or not considered in the noted papers. Regression equations developed by Clark et al. (2002) allowed only two pressure classes (150 psi and 200 psi for PVC; Class 50 and Class 52 for DI and Steel) to be specified while Marchionni et al. (2016) did not allow the pressure class to be specified (data used was collected from 10 – 16 bar [145 - 232 psi] systems). Additionally, both papers did not consider any regional cost adjustment factors. Regression equations based on only pipe diameter can be misleading as costs will vary by pressure class. Further, not all pipe sizes are available in all pressure classes.

Another problem frequently encountered when using cost data (i.e., bid tabulations or regression curves) from previously installed projects is when the proposed project specifications differ greatly from all previously constructed projects. When this problem arises, the engineer may develop unit prices that significantly underestimate or overestimate a project’s cost. Overestimates may price a project out of an agency’s fiscal reach and delay project implementation. Underestimates can mislead decision makers into pursing an infeasible project.

Project planning funding may also be very limited and restrict engineers from evaluating a full range of options such as evaluating different pipe materials and embedment conditions. If equipped with accurate and efficient cost estimation tools, engineers can make more informed decisions and explore a larger range of design alternatives in less time while having increased confidence in their cost estimates.

Lindsay and Walski (1982) and Walski (1980) approached this challenge by developing the Methodology for Area-wide Planning Studies (MAPS) computer program that implemented bottom up costing methods to develop and design cost estimates for water infrastructure projects such as force mains, gravity mains, pipelines and pump stations. Flow, length and elevation difference were the required inputs in order to calculate construction costs. The Engineering Manual (Walski 1980) has been rescinded by the Corps of Engineers and it is no longer in use.

To improve the water transmission pipelines cost estimate accuracy for planning and design, **Water** Pipe Installation **CO**nstruction Co**ST E**stimation (WaterCOSTE) has been developed. WaterCOSTE is a cost model that estimates the installed price of water pipelines using a “bottom-up” cost building approach that is often employed by contractors and construction estimators when appraising or bidding a project. The bottom-up pricing approach attempts to account for all the construction processes and costs necessary for the installation of a water pipe including: construction material procurement (pipe, embedment material, construction water, and material delivery costs), heavy equipment machinery costs, labor costs and the time required to perform the job.

Advantages of Bottom-up Pricing

The primary advantage of a bottom-up pricing approach is that it allows engineers and estimators to derive costs specific to a project using current market prices and site-specific conditions. In addition, it allows for the estimation of installed pricing of virtually any size pipe or material under a multitude of embedment and bury conditions and is not limited to certain pipe diameters and/or material types. Thus, fair comparisons among candidate pipe materials can be made using the same embedment and bury conditions. Further, factors such as regional location, proximity to suppliers, regional equipment and labor rates that can significantly influence construction costs can be accounted for using a bottom-up pricing approach. Du et al. (2013) demonstrated the effectiveness of a bottom-up approach to estimate the global warming potential for six different pipe materials. Life cycle analysis (LCA) was performed for various pipe materials and were compared according to their calculated CO_2 emission potential. Four (4) phases were considered in the LCA: pipe production, transport, installation, and use.

By comparison, historical project cost data can be misleading as it may be difficult to take into account the current market conditions and their effect on the various pipe material prices. Use of current pipe prices (i.e., current market conditions) provided by pipe manufacturers can help guide pipe material selection, as it may favor or eliminate candidate pipe materials based solely on cost. In some instances, taking advantage of current market rates may even help advance a project or allow materials to be procured well before construction.

A bottom-up pricing model is reasonable because installation methods, equipment, and crews are relatively consistent across the industry and among contractors. Pipe materials specifications, excavation and installation procedures have been standardized through agencies such as the American Water Work Association (AWWA), the American National Standards Institute (ANSI) and the Occupational Safety and Health Administration (OHSA). These standards limit the variation in construction materials and procedures and help eliminate "shortcuts" that a contractor may take. The WaterCOSTE model is based on standardized installation methods that have been adopted by most water districts and municipalities in the U.S.

Lastly, it is argued that the WaterCOSTE model allows engineers to make complete and reliable cost estimates with limited initial knowledge incorporating project site conditions, material specifications and installation specifications. The WaterCOSTE model is intended to be used through all cost estimation tiers defined by the American Association of Cost Engineers (AACE): concept screening (Class 5); study or feasibility (Class 4); budget authorization or control (Class 3); control or bid/tender (Class 2); and check estimate or bid/tender (Class 1) (AACE 2016). As a project progresses through the tiers and more site information is collected, the engineer will adjust and refine assumptions within a consistent cost estimating methodology. Thus, project cost estimates are less likely to have drastic fluctuations as project planning progresses.

MODEL THEORY AND DEVELOPMENT

Overview

WaterCOSTE is designed to estimate construction costs from a contractor's point of view in a manner similar to a competitive bid to install water pipe correctly, safely and efficiently. The machine selection methods, trenching rates and installation rates are based on decisions and thought processes following contractor bid practices. The installation rates embedded in WaterCOSTE were developed with the intent that they can be achieved by competent construction firms with experience in pipe installation. Default installation rates (and consequently unit price estimates) were conservatively selected to fall in the average contractor performance range. In reality, it is expected that some contractors will be able to perform the work faster and cheaper than those estimated by WaterCOSTE while other will be more expensive.

WaterCOSTE is based on typical buried water pipe installation construction methodologies that are transformed into programmable decisions given assumed (or known) project field conditions. These programmable decisions are ‘rule-based’ in nature and designed to mimic decisions that an experienced contractor would make when bidding to install buried water pipe. In general, WaterCOSTE calculates installed unit pricing as follows (see Figure 1):

- The bury depth, native soil type, pipe data (i.e., pipe diameter, pipe material, pressure class, total length), embedment type, are specified by the engineer and provided as input into the WaterCOSTE model.

- Based on the input above, the equipment, labor, and materials required to perform the work are calculated using embedded trenching and machine decision processes. The embedded decision processes then reference material and equipment databases that lookup machine performance and costs; pipe and embedment material costs; and labor rates. From this, equipment and crew daily costs are calculated.

- The rate at which the work can be performed (i.e., length of pipe installed per day) is determined using typical installation rates of experienced pipe installation contractors. Installation rates were developed for a range of diameters and embedment conditions. The installation rate is used to calculate a hypothetical job duration that is used to determine the equipment and crew costs.

- The equipment, labor and material costs are divided by the total length of the job to determine the installed unit pricing in dollars ($) per foot (ft).

These processes are discussed in more detail in the following sections.

Applicable Pipe Material and Installation Standards

WaterCOSTE calculates the installed pricing for HDPE, PVC, Steel, and DI pipe with diameter and pressure class ranges listed in Table 1. HDPE, PVC, and DI pipe include the full range of standard diameters currently manufactured. Steel is limited to 72 inches (1800 mm; although pipe it can be made to any size) because the weight of steel pipe larger than 72 inches (1800 mm) begins to approach the lifting limits of the largest excavator embedded in WaterCOSTE. Pipes larger than 72 inches (1800 mm) may require a crane to lift into place; this significantly changes to construction methods and equipment that are not included in WaterCOSTE. Pipe material and installation methods embedded within WaterCOSTE adhere to AWWA and ANSI standards (Table 2). Pipe material pricing obtained from suppliers adhere to the specifications in these standards.

Assumptions and Limitations

Installation methods and cost estimates in WaterCOSTE are for newly installed pipe in open country with relatively flat terrain that has minimal disturbances (e.g., existing utility interference, road crossings, groundwater) and has wide right-of-way's that do not limit heavy equipment mobility or material placement and staging. Trench boxes for protection are not considered as they may slow production and are used primarily in areas where the trench width is restricted such as road crossings and in areas with existing development adjacent to the trench.

WaterCOSTE is only valid for pipe installation in ripable material that can be excavated by a hydraulic excavator. Trenching through solid rock is not addressed. Trenching through rock may require a rock trencher, blasting, or an excavator with rammer attachment, which can significantly affect installation rates and costs.

Pipe runs are assumed to be primarily straight and have minimal grade breaks, fittings and valves. The embedded installation rates and number of laborers also assume that 10% of joints are restrained (i.e., mechanical joint restraints for DI and PVC; and outside lap welded joints for steel pipe). As HDPE is fusion welded, it does not require mechanical joint restraints (only at fittings and valve locations). Embedded installation rates also account for a limited number of installed valves and fittings. It is assumed that a valve and/or fitting can placed approximately every 1,000 feet along the pipeline.

Right-of-way acquisition, appurtenant fittings and valves (e.g., ARVs, PRVs, bends, isolation valves, check valves, etc.), clearing and grubbing, cathodic protection systems, SCADA systems, material testing, construction oversight, engineering services, taxes, and surveying should be estimated separately.

Construction Crew and Equipment

WaterCOSTE's minimum crew size and equipment needed to perform a pipe installation job safely and efficiently include but are not limited:

- A hydraulic excavator (and operator) to dig the trench;
- A front-end wheel loader (and operator) that collects, screens and processes trench spoils; places pipe bedding and embedment material into the trench; places the final native

backfill material into the trench; and unloads pipe from delivery truck and strings out pipe along the trench.

- A water truck (and operator) to add water as needed to trench spoils and embedment material for processing and to control dust created from the excavation.
- Four (4) laborers and one (1) foreman who prepare the pipe bedding; lower and assemble pipe in the trench; place and compact embedment material around pipe; and compact backfill in lifts as needed.
- A crew truck with all necessary tools to install pipe.

This base pipe installation crew and equipment is conceptually illustrated on Figure 2. This crew is typical across the industry and is sustainable for longer duration projects. It should be noted that the number of crew members may vary slightly among contractors (less skilled crews may require more laborers). Additional crew members and equipment may be added to the base crew depending on model inputs such as pipe data (e.g. type of pipe, diameter, weight) and trench depth. Additional crew members and equipment are added to the base crew in WaterCOSTE as follows:

- Up to three (3) additional laborers (to 7 total) can be added to the crew depending on the pipe material and diameter. These laborers assist with pipe assembly and improve safety and efficiency. For DI and PVC pipe, four laborers are required, an additional laborer (5 total) is added for diameters exceeding 10 inches (250 mm) or when the trench depth exceeds 8 feet (2.4 m). Six (6) laborers are required for HDPE in all conditions. Seven (7) laborers and a minimum of 2 welders (9 minimum total) are required for steel pipe in all conditions. The total number of welders required is based on the welding time and the diameter of the steel pipe.

- A second hydraulic excavator is added for trenches deeper than 10 feet (3 m) and pipes exceeding 300 lbs (136 kg). A second excavator of the same size is required to: help place embedment material and assist with compacting final backfill. The additional excavator increases production and lowers unit pricing because it allows the first excavator to dig and push pipe joints together without interruption.
- Additional water trucks (and operators) may be required depending on the water content deficiency of the spoils and embedment materials to achieve compaction; as well as the distance to the nearest water source. WaterCOSTE calculates the required number of water trucks when the distance to the water source and water content deficiency of the soil is provided.

WaterCOSTE assumes the excavation, pipe laying and backfilling processes all stay within close proximity to one another. This organization avoids long open trenches that may pose safety hazards (AWWA 2002). Additionally, WaterCOSTE uses the rate at which the labor crew can install and embed pipe as the overall governing installation rate as this task is the most labor intensive. All other processes (i.e., excavation, backfilling, pipe fusion/welding) are adjusted to match the installation rate so that the crew is not limited. Thus, if excavation, backfilling or pipe fusion/welding is slower than the pipe installation rate, it is assumed that the excavator, loader and laborers fusing/welding the pipe must work additional hours to keep up with the laborers installing pipe.

Trench Excavation

Trench Cross Sectional Area

The trench excavation process is driven by four factors: native soil type; pipe bury depth, pipe outside diameter, and the pipe embedment type. These four inputs are used to determine the trench cross sectional area that, in turn, is used to estimate trenching rates.

The trench depth is calculated as:

$$D_t = \frac{\left(D_p + D_b + D_c\right)}{12} \tag{1}$$

where D_t = the trench depth (ft); D_p = the outside diameter of the pipe (in); D_b = the bedding thickness below the pipe (in); and D_c = the bury depth over the pipe (in). D_p, D_b, and D_c are inputs specified by the user (Figure 3).

The trench base width is the narrowest portion of the trench where the pipe sits (Figure 3) and guides selection of the excavator's bucket width. Trench base widths that are cut larger than necessary increase embedment material costs. Thus, the objective is to match the excavator's bucket width as closely as possible to the required trench base width. The required trench base width is dependent on the pipe's outside diameter and the embedment type (E_t) as follows:

When E_t = Type 1, Type 2 or Type 3

$$W_{tr} = \max\left[\left(D_p + 12\right), 18\right] \tag{2}$$

When E_t = Type 4 or Type 5

$$W_{tr} = \begin{cases} D_p + 24, & D_p < 48 \\ D_p + 48, & D_p \geq 48 \end{cases} \tag{3}$$

where W_{tr} = the required trench base width (in). Type 1, Type 2, and Type 3 embedment conditions (discussed later) do not require compaction on the sides of the pipe so the trench bottom width can be minimized. Type 4 and Type 5 embedment conditions require compaction between the pipe and trench sidewalls, therefore the trench is wider to accommodate compaction equipment.

The soil type also determines the cross sectional area of the trench and whether benches are needed or whether trench side walls need to be sloped. In the U.S., trench excavations are regulated by OSHA and are geared to protecting the safety of the workers in the trench. OSHA's trenching criteria are driven by the hardness of native soil and its caving potential. The soil types (i.e., Type A, Type B or Type C) and corresponding excavation configurations embedded in WaterCOSTE follow 29 C.F.R § 1926 Subpart P App B (rock excavations are not considered; see Figure 4). The trench cross sectional area (A_t) is calculated according to Figure 4, where W_t = the final trench base width (in) and is discussed in the following section.

The total trench volume to be excavated is calculated as:

$$V_{exc} = \frac{A_t}{27} L_{tot} \tag{4}$$

where V_{exc} = the volume of excavated material (BCY) and L_{tot} = the total length of pipe/trench (ft). The total trench volume to be excavated can also be expressed as a daily rate:

$$V_{exc\_d} = \frac{A_t}{27} R_{pipe} \tag{5}$$

where V_{exc_d} = the daily volume of excavated material (BCY); and R_{pipe} = the pipe installation rate (ft/day) and is discussed in the following sections.

Hydraulic Excavator Selection

Eighteen different Caterpillar (CAT®) hydraulic excavators with 12 different bucket sizes are embedded in WaterCOSTE. Embedded CAT® hydraulic excavator sizes range from the CAT® 311 to the CAT® 390. Bucket widths for the CAT® 311 range from 18 - 30 inches (457 – 762 mm) while bucket widths for the CAT® 390 range from 42 - 79 inches (1067 – 2007 mm). It should be noted that not all buckets widths are available for all excavator sizes. A full range of excavator sizes was considered to account for the differences in excavation production from various equipment size and the cost differences in equipment size. Larger equipment is more expensive to mobilize and operate than smaller equipment.

In WaterCOSTE, excavator size (m) and bucket width (w) are required to simulate the excavation process as each combination equates to a unique production rate. The excavator size is determined by two criteria:

1) The depth of the trench (D_t) must not exceed 30% of the excavator's maximum reach depth (D_{exc}), or

$$D_t \leq 0.30 D_{exc} \quad (6)$$

This criterion allows the machine to operate near its rated cycle time without overextending its reach; maintains adequate break-out forces at the bucket's teeth for digging and pushing pipe joints together.

2) Pipe weights (W_p) greater than 300 lbs (136 kg) must not exceed 30% of the excavator's rated side-lift capacity with the boom and stick extended to 25 feet (7.62 m). This criterion provides the machine with sufficient flexibility to maneuver and lower pipe into the trench without tipping or exceeding the machine's hydraulic limits.

The above criteria were developed based on contractor experience and were corroborated with field observations of various pipe installations.

Selection of the excavator's bucket width (W_b) is determined by selecting the bucket width closest to the required trench base width given by:

$$W_b = 6\left\lfloor \frac{W_{tr}}{6} \right\rceil \ (inches), \qquad 18'' \le W_b \le 78'' \tag{7}$$

The excavator's bucket widths that are available at six-inch increments will either be smaller or larger than the required minimum trench width by no more than 3 inches (76 mm). The final trench base width (W_t) is determined by the larger of the excavator's bucket width or the required trench base width.

Trenching Rate

The trenching rate (R_{exc} in ft/day) is the linear feet of trench that can be excavated in a day and is dependent on the trench cross sectional area and the excavation production rate of the excavator and bucket selection. The trenching rate is calculated from:

$$R_{exc} = \frac{P_{exc}}{\frac{A_t}{27}} \times 24 \tag{8}$$

where P_{exc} = the excavation production rate of the selected excavator and bucket combination (cy/hr) is determined from:

$$P_{exc} = f_i \frac{v_{(m,w)}}{t_{i(m,w)}} T_{hr} \times 60 \tag{9}$$

where i = A, B and C for Type A, B and C soils respectively; f_A, f_B and f_C = bucket fill factors for Type A, Type B and Type C soils respectively; v = the rated bucket capacity (cy) from the manufacturer's listed bucket capacities in which rows m are the machine sizes and columns w are the bucket widths; t_A, t_B, and t_C = predetermined machine cycle times (sec) for excavator performance in Type A, Type B and Type C soils respectively; and T_{hr} = the number of production minutes in an hour (min/hr).

Excavator cycle times, bucket capacities and bucket widths were determined from machine performance data published in CAT (2016) and adjusted based on field observations and contractor experience with each machine. Embedded cycle times in WaterCOSTE vary with machine size, bucket size, and material type. Select machine performance data is provided in the Supplementary Data.

Pipe Assembly and Installation

Pipe installation rates are critical for estimating installed pipe costs as the job duration is based on this rate. Pipe installation rates were developed from field observations, project productivity reports and contractor experience with installing various pipe materials and diameters in the various embedment conditions accounting for the tasks:

- Grading the pipe bedding material;
- Lowering the pipe into the trench;
- Joining the pipe together;
- Haunching to the pipe's springline;
- Placing and compacting the initial backfill up to the point where the front-end loader can backfill the remaining trench with screened and processed native material.

PVC, DI, and Steel pipe assume that bell and spigot joint assembly is performed in the trench while HDPE pipe is electro-fused above the trench and lowered into the trench in longer segments. Steel pipe installation rates assume that all joints are cement mortar-lined and that

10% of the pipe joints are welded. For larger diameter HDPE and Steel pipe, the time to fuse/weld each joint can limit the installation rate. Thus, additional hours and costs are incurred to account for the additional fusing/welding time that is required to keep up with installation production.

Installation rates (R_{pipe}) in feet per day (ft/day) were computed for each pipe material for each diameter and embedment type for each pipe type and are stored in installation rate matrices $\boldsymbol{R_{pvc}}$, $\boldsymbol{R_{di}}$, $\boldsymbol{R_{s}}$, $\boldsymbol{R_{h}}$ where rows e are the embedment types and columns d are the commercially available diameters for PVC, DI, Steel, and HDPE pipe, respectively. Select installation rates are provided in the Supplementary Data.

Pipe Embedment

Embedment Types

Pipe embedment limits pipe deflection and protects the pipe from rock in the native material that may damage it during backfill (AWWA 2004). The five (5) predetermined embedment types (1-5) as defined by the AWWA (2013) are modeled in WaterCOSTE (see Figure 3 and Table 3). Although these embedment types are specific to PVC, they are also applied to HDPE, Steel and DI pipe (that have similar embedment configurations). The embedment types are further defined by the soil material class and the degree of compaction.

Soil classifications that meet AWWA pipe embedment types include: Class I, II, III, IV, and V as defined per ASTM D2487 and ASTM D2488 (AWWA 2013). Embedment types within WaterCOSTE are summarized as follows:

- Pipe installed in a Type 1 embedment is placed directly on a smooth trench bottom with no bedding. The trench bottom is assumed to be competent material and free of sharp or protruding rocks that can damage the pipe. The WaterCOSTE assumes that the material used for a Type 1 embedment can be generated (i.e., screened and processed on-site) from native material and screened of particles exceeding 0.75 inches (19 mm) for angular rock and 1.5 inches (38 mm) for rounded rock.

- A Type 2 embedment is similar to Type 1, however, embedment material must meet Class II, III or IV specifications. WaterCOSTE assumes that the embedment material is lightly compacted with hand tools. The user specifies whether the Class II, III or IV native material can be generated from native material or can be purchased (and delivered) from nearby borrow sources. If native material can be generated from the site, there is no additional cost.
- A Type 3 embedment is similar to Type 2, but a 4-inch (102 mm) minimum bedding that meets Class II, III, or IV specifications must be provided. Similarly, the bedding material can either be generated from site or purchased.
- A Type 4 embedment requires a 4-inch (102 mm) minimum bedding that meets Class I or II specifications and Class II, III or IV material that is compacted to greater than 80% standard proctor density (SPD) to the top of the pipe.
- A Type 5 embedment is similar to Type 4, however, embedment material up to the top of the pipe must be compacted to greater than 90% SPD.

For all embedment types, the user may specify the cover material and depth (i.e., the material directly over the top of the pipe, Figure 3). The cover can either be an extension of the same embedment material around the pipe (i.e., Class II, III or IV material) or can be native material free of particles exceeding 0.75 inches (19 mm) for angular rock and 1.5 inches (38 mm) for rounded rock.

Embedment Volumes

Embedment material volumes are ultimately quantified by weight as embedment material is purchased based on weight. The total embedment material weight, W_{emb} (tons) is:

$$W_{emb} = \frac{V_{emb}}{D_i S_f} \frac{1}{2000} L_{tot} \tag{10}$$

where D_i = the density of the embedment material Class i (i = I, II, III, IV or V in accordance with AWWA 2013); S_f = the shrink factor of the embedment material; and V_{emb} = the unit embedment material volume (BCY). The unit embedment material volume, V_{emb}, is:

$$V_{emb} = (V_{bed} + V_h + V_{ib} + V_c)/27 \tag{11}$$

where V_{bed} = the bedding material volume (ft^3/ft); V_h = the haunching material volume (ft^3/ft); V_{ib} = the initial backfill material volume (ft^3/ft); and V_c = the cover material volume (ft^3/ft). V_{bed}, V_h, V_{ib}, and V_c are calculated according to Equations (S1) - (S11) in Table S1 in the Supplemental Data. The bedding material volume can also be expressed as a daily rate (V_{emb_d}):

$$V_{emb\_d} = V_{emb} R_{pipe} \tag{12}$$

Embedment Material Delivery

If embedment material importation is required, WaterCOSTE calculates the total delivered cost to the site provided the distance to the borrow source and a raw material unit cost. The daily production rate of embedment material delivered to the site by a single truck and trailer, R_{emb_prod} (tons/day), is:

$$R_{emb\_prod} = \frac{W_{emb\_tr}}{T_{cemb}} T_{hr} T_{day} \quad (13)$$

where W_{emb_tr} = the total weight of embedment material delivered in a single load (tons); T_{cemb} = the cycle time for a single truck and trailer to deliver one load from the borrow source to the project site (minutes); and T_{day} = the number of hours in a workday (hours). W_{emb_tr} is dependent on the truck/trailer's capacity and the unit weight of embedment material to be transported. T_c is dependent on the distance from the source of the borrow material to the project location; and the average speed of the truck. It is assumed that embedment material is delivered dry to the site (to maximize delivered volume), water is added at the site via water trucks.

Trench Backfill

A percentage of the final backfill material is assumed to be screened of rocks larger than 8 inches (203 mm) and compacted to densities similar to the native soil. Compaction is assumed to be achieved in minimal lifts via the secondary excavator with a sheep's foot roller attachment; wheel rolling with the front-end loader; and/or use of small compaction equipment. As WaterCOSTE and its embedded installation rates are geared toward pipelines in open areas, the final backfill material does not need to meet high densities such as those required when installing pipe below roads. Achieving higher densities may require more time, machinery and laborers; resulting in increased installation costs.

Front-End Loader Selection

Ten (10) CAT® front-end loaders are embedded in WaterCOSTE. The embedded sizes range from the CAT® 926 to the CAT® 986. Corresponding bucket capacities range from 3 - 9 cy (2.3 – 6.9 m^3) The loader size is determined to ensure that it is able to perform all the required duties in a single day. The duties of the front-end loader include:

- Collecting and placing trench spoils in piles alongside the trench in preparation for screening and processing; as well as placing the final native backfill material (from the trench spoils pile). The number of (N_{sp}) and the distance (D_{sp} in ft) between trench spoils piles are calculated by:

$$N_{sp} = \left\lceil \frac{V_{exc\_d}}{V_{sp}} \right\rceil \tag{14}$$

$$D_{sp} = \frac{N_{sp}}{R_{pipe}} \tag{15}$$

respectively, where V_{sp} = the average volume of a spoil pile (cy) in a conic pile of a maximum height of 10 feet (3 m) with 1.5H:1V side slopes. With D_{sp}, loader speeds, loader load and dump times for the various loader sizes, the cycle times for the various embedded loader sizes are calculated. The spoils pile collection rate (P_{sp} in cy/hr) and final backfill placement rate (P_{back} in cy/hr) are calculated by:

$$P_{sp}(i) = P_{back}(i) = \frac{C_{lb(i)}}{t_{ls(i)} + t_{es(i)} + t_{l(i)} + t_{d(i)}} 60T_{hr} \tag{16}$$

where C_{lb} = the bucket capacity of loader size i; t_{ls} = the travel time of loaded loader i from the trench to the spoils pile location (sec); t_{es} = the travel time of empty loader i from the spoils pile location back to the trench; t_l = the time it takes to load loader i bucket (sec); t_d = the time it takes to dump a loaded bucket for loader i (sec). Travel times are calculated by:

$$t = \frac{\left(\frac{D_{sp}}{2}\right)}{V_{l(i)}} \tag{17}$$

where V_l = the travel speed of loader i; $D_{sp}/2$ is the average distance the loader has to travel from the spoils pile to the trench.

- Screening and processing native embedment material (if needed) to be free of particles exceeding 0.75 inches (19 mm) for angular rock and 1.5 inches (38 mm) for rounded rock; and screening native backfill material to be free of particles larger than 8 inches (203 mm). The screening rate (P_{sc} in cy/hr) and processing rate (P_{pro} in cy/hr) of loader i at the spoil pile locations is calculated as:

$$P_{pro}(i) = P_{sc}(i) = \frac{C_{lb(i)}}{t_{l(i)} + t_{d(i)}} 60T_{hr} \tag{18}$$

- If imported embedment material is specified, the production rate for placement of embedment (P_{emb}) is calculated as:

$$P_{emb}(i) = \frac{C_{lb(i)}}{t_{li(i)} + t_{ei(i)} + t_{l(i)} + t_{de(i)}} 60T_{hr} \tag{19}$$

where t_{li} = the travel time of loaded machine i from the imported pile to the trench (sec); t_{ei} = the travel time of empty machine i from the trench to the imported pile; t_{de} = the time it takes to dump embedment material in the trench (sec). Travel times are calculated using Equation (17) where D_{sp} is substituted by D_{ip} (distance to the imported embedment pile). The distance to the imported embedment pile is calculated assuming that trucks importing embedment material evenly place imported piles along the trench by:

$$N_{ip} = \left\lceil \frac{V_{emb\_d}}{V_{ip}} \right\rceil \tag{20}$$

$$D_{ip} = \frac{N_{ip}}{R_{pipe}} \tag{21}$$

respectively, where N_{ip} = the number of import piles; and V_{ip} = the volume of an imported pile. If native material is specified, the production rate for placement of native embedment is calculated according to Equation (19) as the distance to the pile is the same.

Using Equations 14 – 21 the total time required for a loader to accomplish all tasks (T_{load}) must be less than the number of hours in a work day (T_{day}):

$$T_{load} = \frac{V_{exc\_d}}{P_{sp}} + \frac{V_{emb\_d}}{P_{emb}} + \frac{V_{exc\_d}}{P_{sc}} S + \frac{V_{exc\_d}}{P_{pro}} P + \frac{V_{exc\_d}}{P_{back}} \tag{22}$$

where S = the percentage of trench spoils that requires screening; and P = the percentage of trench spoils that require processing. These are estimated from site specific conditions (e.g., rockier soils will require more screening and drier soils will require more processing).

Water Volume

Construction water is generally needed to control dust and for adding to the final backfill and embedment material to achieve compaction. The volume of water that is required (V_{wat} in ft^3) is based on the calculated volume of bedding and backfill material and an assumed water content deficit for that material:

$$V_{wat} = (V_{exc} + V_{emb}) w_d \tag{23}$$

where w_d = the water content deficit of the backfill and embedment material (% volume).

Water Trucks

WaterCOSTE assumes that the delivery and application of construction water to the trench backfill and bedding material is performed by 3,400-gallon (12.9 m^3) capacity water trucks. The number of water trucks required for job (N_{wt}) is based on the daily production rate of the water truck and the volume of trench backfill and bedding material that is moved on a daily basis and is calculated as:

$$N_{wt} = \begin{cases} 1, & \frac{P_{wat}}{V_{wat\_d}} \leq 1 \\ 2, & 1 < \frac{P_{wat}}{V_{wat\_d}} \leq 2 \\ 3, & 2 < \frac{P_{wat}}{V_{wat\_d}} \leq 3 \end{cases} \quad (24)$$

The daily production rate of one water truck (P_{wat} in gal/day) and the daily amount of construction water required (V_{wat_d} in gal/day) are calculated by:

$$P_{wat} = \frac{V_{wt}}{T_{wt}} 60 T_{day} \quad (25)$$

$$V_{wat\_d} = \frac{V_{wat}}{T_{job}} \times 7.48 \quad (26)$$

Respectively, where V_{wt} = the water truck capacity (gallons) and T_{wt} = the total cycle time of the water truck (min) is:

$$T_{wt} = T_l + T_t + T_d + T_e \quad (27)$$

where T_l = the time to load water at the source (min); T_t = the time to travel to job site water loaded with water from the source (min); T_d = the time it takes for the truck to dump a load at the site (min); and T_e = the time it takes for the truck to travel back to the source empty (min). T_t and T_e are calculated as:

$$T_t = T_e = \frac{D_w}{S_{wt}} \times 60 \quad (28)$$

where D_w = the average distance to the water source from the job site (mi); and S_{wt} = the average travel speed of the water truck (mph).

MODEL COST FORMULATION

Based on physical parameters described in the previous section, costs for material and installation processes are computed. The total installed cost of the project, C_{tot}, (\$) is the sum of the component costs:

$$C_{tot} = C_{pipe} + C_{emb} + C_{wat} + C_{lab} + C_{equip} \quad (29)$$

where C_{pipe} = the pipe material cost ($); C_{emb} = the embedment material cost ($); C_{wat} = the cost of construction water ($); C_{lab} = the labor cost ($); and C_{equip} = the equipment cost ($). C_{tot} can be divided by the total length of pipe (L_{tot}) to obtain the total installed unit price of pipe in $/ft.

Pipe Cost

Pipe cost (C_{pipe}) in dollars ($) consists of the cost of the pipe, its delivery, and all the gaskets and fittings necessary for assembly. These values can be obtained directly from suppliers and are primarily dependent on the quantity of pipe and project location. A thirty percent (30%) markup was added to push-on joint pipe costs to account for restrained joint costs for PVC and DI. This markup was then applied to 10% of the pipe joints (assuming 10% of pipe joints are restrained). Ten percent (10%) of steel pipe joints were also assumed to be restrained (i.e., bell and spigot lap welded joints). However, the added cost of welding is included in the welding labor time rather than the pipe cost.

Embedment Material Cost

When necessary for pipe installation, embedment material cost (C_{emb}) in dollars ($) includes material and delivery and is calculated by:

$$C_{emb} = C_{emb\_u} \times W_{emb} \quad (30)$$

where C_{emb_u} = unit cost of embedment material delivered to the site ($/ton). If embedment material can be processed on site from native material, C_{emb_u} = 0, else if the embedment material is imported:

$$C_{emb\_u} = (R_{emb\_prod} \times C_{emb\_r} + C_{emb\_tr})/R_{emb\_prod} \quad (31)$$

where C_{emb_tr} = daily truck cost based on the truck and trailer daily rate plus fuel and the operator's wages; C_{emb_r} = raw (undelivered) cost of embedment material at the source location. The unit material cost can be obtained from local gravel and sand suppliers.

Water Cost

The cost of water (C_{wat}) in dollars ($) for dust control dust and bringing embedment and backfill material to the required moisture content to achieve adequate compaction is calculated as:

$$C_{wat} = 201.96 V_{wat} C_{wat\_u} \tag{32}$$

where C_{wat_u} = unit cost of water ($/gal).

Labor Cost

The cost of labor (C_{lab}) in dollars ($) is the cost of laborers, the foreman and welders, but does not include heavy equipment operators.

$$C_{lab} = T_{job} T_{day} (N_{lab} C_l + C_f) + C_w T_{hw} \tag{33}$$

where C_l = hourly rate of laborer i ($/hr); C_f = the hourly rate for the foreman ($/hr); N_{lab} = number of laborers required to perform the work (unitless); T_{job} = duration of the pipe installation job (days); C_w = the hourly rate of a welder and his helper (for steel pipe only) and T_{hw} = number of welding time required (hrs). T_{job} is defined as:

$$T_{job} = L_{tot} / R_{pipe} \tag{34}$$

Equipment Cost

Equipment costs (C_{equip}) include all the necessary equipment and heavy machinery to install the pipe. Equipment costs are calculated as:

$$C_{equip} = C_{exc} + C_{load} + C_{wt} + C_{mob} + C_{misc} \tag{35}$$

where C_{exc} = excavation equipment cost ($); C_{load} = front-end loader cost ($); C_{wt} = water truck cost ($); C_{mob} = cost to mobilize all heavy equipment machinery ($); and C_{misc} = cost of additional miscellaneous equipment needed to install pipe ($).

Daily Costs

Equipment costs for excavators (C_{exc}), front-end wheel loaders (C_{load}), and water trucks (C_{wt}) are estimated using the general equation:

$$C_k = N_k C_{dr} T_{job} \tag{36}$$

Where k = *exc*, *load*, and *wt* for excavators, loaders and water trucks respectively; N_k = the calculated number of excavators, loaders and water trucks required; and C_{dr} = the equipment daily rate ($/day). C_{dr} includes fuel costs, lubrication costs, maintenance costs, equipment markup and the operator's wages.

Mobilization Costs

Mobilization costs (C_{mob}) for heavy equipment including the front-end loader, hydraulic excavators are calculated from:

$$C_{mob} = N_{exc} C_{mob\_exc} + C_{mob\_load} + C_{mob\_wt} \tag{37}$$

where C_{mob_exc}, C_{mob_load}, C_{mob_wt} = the mobilization cost for excavators, loaders and water trucks respectively. Mobilization costs vary with the size of the equipment; the larger the machinery the higher the mobilization cost (e.g., higher transport costs and permits)

Miscellaneous

Miscellaneous costs (C_{misc}) includes cost items other than those specifically addressed above and may include but are not limited to: rock screens, compaction equipment (e.g., plate rammers, vibratory plates, small wheel rollers, excavator compaction wheel attachments), pipe cutting saws, generators, compressors, pipe soap (lubrication), hand tools, hydraulic excavator attachments, porta-pottys, equipment repairs, replacement parts, etc. Miscellaneous cost items are calculated as:

$$C_{misc} = C_{misc\_d} T_{job} \quad (38)$$

where C_{misc_d} = daily unit cost ($/day). The miscellaneous costs items can vary among contractors.

MODEL APPLICATION

Case Study

To demonstrate how WaterCOSTE can guide pipe size, material and pressure class selection from a cost perspective, it is applied to the North Central Arizona Regional Water Supply Project (NCAZ; USBR 2006); a transmission pipeline intended to deliver renewable water supplies from Lake Powell to northeastern Arizona communities (Figure 5). The preliminary project alignment is primarily through open country with minimal utility interference and disturbances. Cost estimates were developed for a range of pipe diameters (4 - 72 inches [100 – 1800 mm]) and materials. We examine how pressure class (i.e., thickness), embedment type, bury depth, and soil type affect costs for each pipe material (HDPE, PVC, DI, Steel). Finally, a focused comparison is made of different pressure classes for the same field conditions and materials.

Design Criteria and Model Inputs

As WaterCOSTE is able to account for numerous site-specific parameters, as a basis for comparison in this paper the design criteria and site conditions for the NCAZ project are summarized in Table 4 from known or assumed site conditions. Some WaterCOSTE parameters are fixed to default values that are not expected to change significantly with project location.

These include those relating to equipment performance (e.g., machine speeds, machine cycle times) and performance of the crew (e.g., pipe installation rates).

Other parameters are project/site specific and may have a significant impact on costs. Site specific parameters include equipment and material costs (e.g., embedment material volumes; the distance to construction water supply; the proximity to borrow sources and the raw material cost of borrow material for embedment; equipment and labor rates). Table S2 (Supplementary Data) summarizes the fixed and site specific parameters for the NCAZ project.

Pipe manufacturers and suppliers provided preliminary budgetary prices for a full range of pipe diameters and thicknesses (i.e., pressure classes) based on applicable AWWA standards. Pipe pricing included the freight cost to deliver pipe from the manufacturing plant to the project site. The distance from the pipe manufacturing plant to the project site can have significant cost implications. Therefore, prices were obtained from at least two pipe manufacturers for each pipe material (except for steel). Depending on the pipe size, it is not uncommon for a pipe manufacturer to produce and supply pipe from two different plants. In all, pipe prices varied significantly for the same pipe size and material. To provide a best estimate under these variations, the average of the budgetary prices obtained was applied. Lastly, steel pipe is assumed to follow industry standards: spiral welded; cement mortar lined interior with polyurethane coating; and ASTM A139 grade C steel with an assumed 36,000 psi (248 MPa) minimum yield strength. However, steel pipe is manufactured in many other ways and available in a variety of grade and strength options.

Validation

WaterCOSTE results for the NCAZ baseline condition were compared to previous pipe estimation models (Clark et al. 2002 and Marchionni et al. 2016). Figure 6 compares installed pricing for the various pipe materials at various pressure classes using the assumed baseline conditions (Table 4). Parameters used in the Clark et al. (2002) equations were selected to match the baseline conditions as closely as possible, and are provided in Table S14 in the Supplementary Data. The plotted results from Clark et al. (2002) assume 150 psi and 200 psi pressure classes for PVC pipe; and Class 50 and Class 52 for DI pipe (which are the only pressure class options available). The plotted results for Clark et al. (2002) and Marchionni et al. (2016) steel pipe equations are even more generic as pressure class cannot be specified. Equations by Marchionni et al. (2016) for PVC, HDPE and DI pipe do not allow pressure class to be specified, however the study collected data from systems with pressures between 10 bar (145 psi) and 16 bar (230 psi). Values from Clark et al. (2002) were not adjusted according to Producer Price Index as current market rates for PVC and HDPE pipe are very low. Values from Marchionni et al. (2016) were converted to U.S. dollars.

Unit costs for all three models had similar trends over the ranges of diameters appropriate for the earlier equations. For larger pipe diameters, actual cost information is lacking to adequately evaluate results generated by WaterCOSTE. Although trends are consistent, the differences in the two published relationships can be significant (e.g., 75% differences for some diameters of PVC pipe). WaterCOSTE predictions fall between those results with significant variation with pressure class. One reason for the large differences in the two previous studies may be their inability to adjust for cost factors such as: the total length of pipe; market conditions; pressure class; and location. Rather, these factors are lumped into the regression equations, which leaves the engineer uncertain of the project's cost components.

An advantage of WaterCOSTE is its ability to breakdown the cost components as demonstrated in Figure 7. Results for PVC pipe are provided in Figures 7(a) and 7(b); component cost plots for DI, HDPE, and Steel are provided in the Supplementary Data. In general, for plastic, pipe cost is the largest component of the total cost for pipe larger than 10 inches (250 mm). For metal, pipe material is the single largest component of the total cost for all diameters. The cost of imported embedment material is the second largest contributor, followed by equipment and labor costs. Figure 7(c) shows a comparison of equipment and labor costs for all pipe materials at the 125 psi pressure class. As expected, equipment costs for metal pipe are more expensive than plastic pipe and the labor cost to install steel pipe is the most expensive followed by HDPE, DI and PVC.

Sensitivity of Pressure Class, Specifications and Installation Conditions

A sensitivity analysis was performed to determine which input factors have the greatest influence on cost. Using the baseline condition (as summarized in Table 4), the sensitivity analysis was performed by changing the following parameters for each pipe material: pipe pressure class, soil type (S_t), embedment type (E_t) and bury depth (D_c). As results for each pipe material were consistent, only select sensitivity results are plotted in Figure 8 (the remaining plots for each pipe material can be found in the Supplementary Data).

The sensitivity of input factors affecting costs showed that for a given pipe material, the pipe's pressure class is most significant cost differentiation factor followed by native soil type, embedment type and bury depth. This conclusion was consistent for all pipe materials (Figures 8 and S2-S5). Another noteworthy factor is the embedment material source. Baseline conditions assumed that embedment material is imported, however, significant cost savings (up to 30%) may be possible if embedment material is generated on site (Figure 8c).

Pressure Class Cost Comparisons

Since the pipe material and its pressure class is the main driver in overall costs, a comparison of pipe materials with pressure class as the common denominator, was performed to demonstrate how WaterCOSTE is effective when considering various candidate pipe materials. It should be noted that for HDPE, PVC and DI, pipe is classified according to standard pressure classes. Steel however, is an engineered product that is designed and manufactured to meet specific project needs, and is normally specified by a wall thickness rather than assigned into predetermined pressure classes. Thus, to compare the price of steel to the other pipe materials, hypothetical pressure classes similar to those of HDPE, PVC and DI were created. Based on this hypothetical pressure class, the thickness was calculated and was used to estimate pipe pricing.

Figure 9 compares installed pricing for PVC, HDPE, DI and steel pipe in various pressure classes (125 psi, 150 psi, 200 psi, 250 psi, 300 psi and 350 psi; dashed lines represent the baseline condition). In Figure 9, smaller diameters are not made for lower pressure classes, thus the lowest pressure class available is shown to provide a full cost curve. We recognize that comparing pipe material according to pressure classes is a simplified approach and does not take into account other design considerations like surge pressures, water hammer, and external load factors. More detailed design should consider these factors.

Figure 9(a) compares all pipe materials at the 125 psi pressure class. This is the highest pressure class that all pipe materials (up to 60 inches [1500 mm]) are available. At the 125 pressure class, DI is the most expensive for all diameters. For diameters less than 24 inches (600 mm), steel is more expensive than PVC and HDPE; for diameters larger than 42 inches (1050 mm), steel becomes the least expensive material. Between 36 inches and 48 inches (900 - 1200 mm) steel and PVC have similar costs. For diameters less than 54 inches (1350 mm), PVC is slightly less expensive than HDPE, but becomes slightly more expensive at 54 inches (1350 mm) and above.

Figure 9(b) compares pipe materials at the 150 psi pressure class. At this pressure class HDPE is available only up to 42 inches (1050 mm) and is only slightly more expensive than PVC. After 24 inches (600 mm), steel becomes more economical than HDPE and PVC. Again, DI is more expensive for all diameters. At 60 inches (1500 mm) PVC becomes comparable to DI.

Figure 9(c) compares pipe materials at the 200 psi pressure class. At this pressure class HDPE and PVC begin to show their limitations as they are only available up to 36 inches (900 mm). Again, HDPE is slightly more expensive than PVC. Steel becomes more economical than HDPE and PVC for diameters greater than 24 inches (600 mm). Again, DI is the most expensive for all diameters.

At the 250 psi pressure class, HDPE is limited to 36 inches (900 mm) and PVC to 18 inches (450 mm). Again, HDPE is slightly more expensive than PVC. Steel becomes more economical than HDPE and PVC after 14 inches (350 mm). DI is always more expensive for pressures greater than 250 psi. At the 300 psi pressure class, HDPE is limited to 24 inches (600 mm) and PVC to 18 inches (450 mm), with HDPE being more expensive. Steel becomes more economical than HDPE and PVC after 14 inches (350 mm). At the 350 psi pressure class, DI and steel are the only material types available to meet the required pressures with steel being the more economical option.

To summarize, the primary conclusions from the pressure class comparison are:

- When considering various pipe materials, pressure class has a great influence of pipe material selection.
- Not all diameters are available in each pressure class. As pressure class increases, HDPE and PVC become less and less available. For pressures greater than 350 psi, steel and DI are the only materials that can currently meet requirements.
- The plastic materials are less expensive for smaller diameters (less than 30 inches [750 mm]) and lower pressure applications. As the pressure increases the cost of plastic materials rise and steel becomes economical. HDPE and PVC have similar costs but generally HDPE is slightly more expensive.
- DI pipe is the most expensive type of pipe for all diameters and all pressure classes considered. However, if considering other aspects such as cathodic protection or increasing the number of restrained (welded) joints, the total cost of ownership of steel will increase and may potentially approach the cost of DI.

SUMMARY AND CONCLUSIONS

A cost model to estimate the installation of water pipe based on bottom-up pricing methods has been developed. WaterCOSTE allows engineers to evaluate costs for a wide range of pipe materials and diameters for typical embedment specifications and bury depths in various material types and can be used in real world applications throughout the design and planning process. WaterCOSTE has demonstrated to be an effective tool in that it also allows engineers to analyze how pressure classes, soil types, bury depths and embedment types affect installation costs of a system. Lastly, WaterCOSTE demonstrated valid results when compared to previous cost estimation studies that derived installed costs from previously constructed projects.

ACKNOWLEDGEMENTS

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SUPPLEMENTAL DATA

Supplementary data provides additional results generated by WaterCOSTE as well as provides select model input data, and is available online in the ASCE Library (www.ascelibrary.org).

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Figure 1. WaterCOSTE Flow Chart

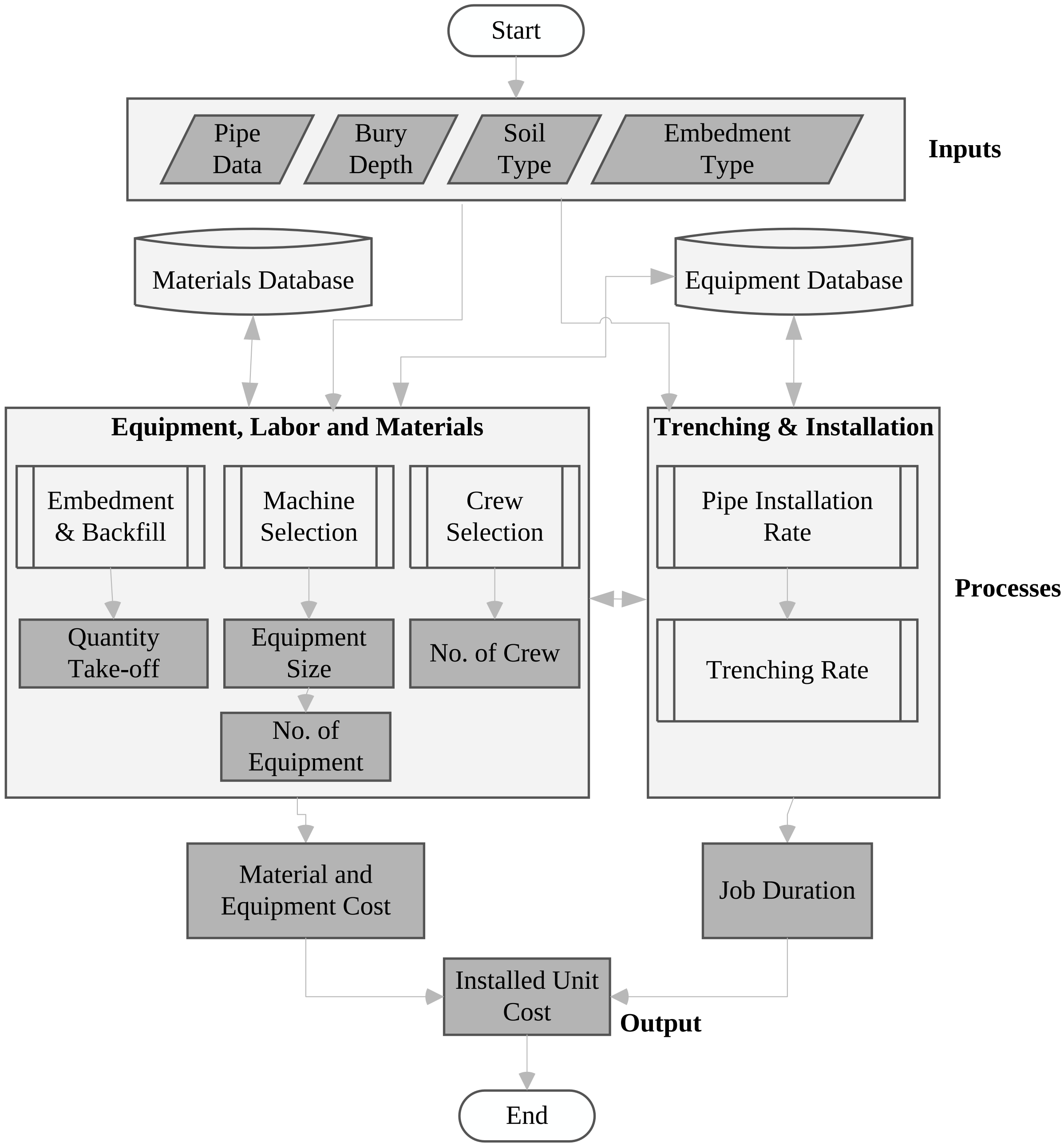


Figure 2. Typical Pipe Installation Base Crew Schematic

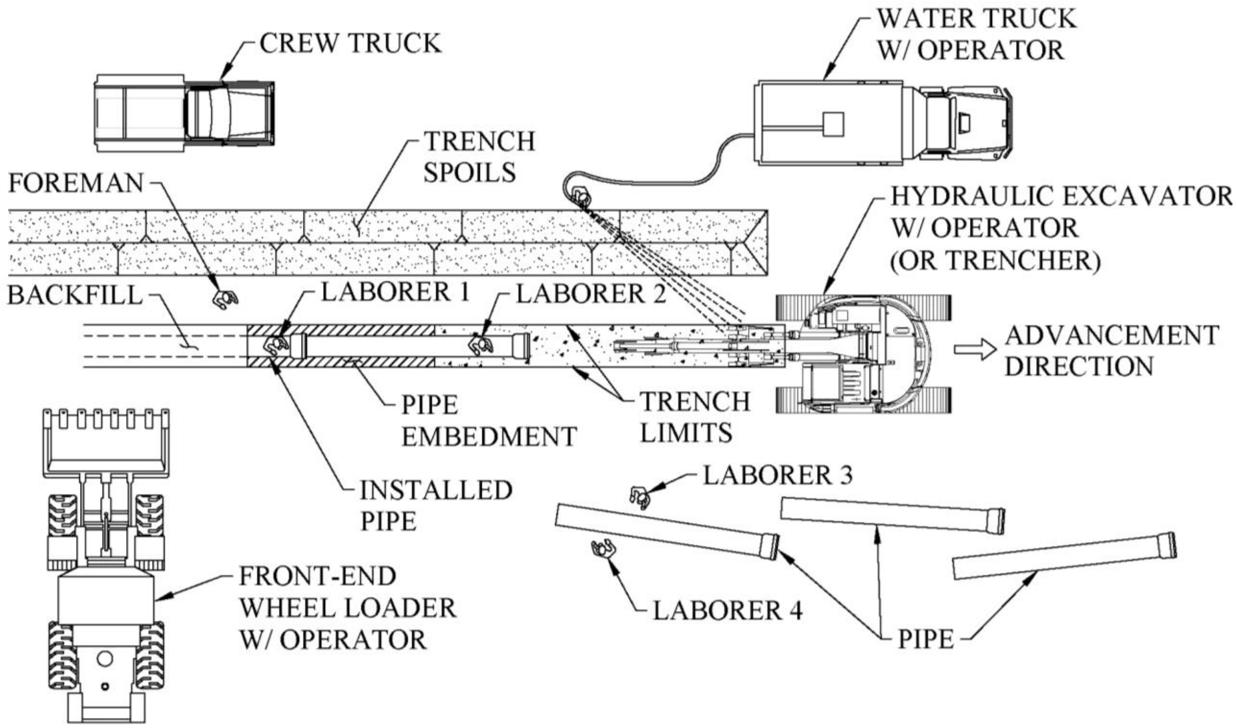


Figure 3. Typical Trench Cross Section and Terminology

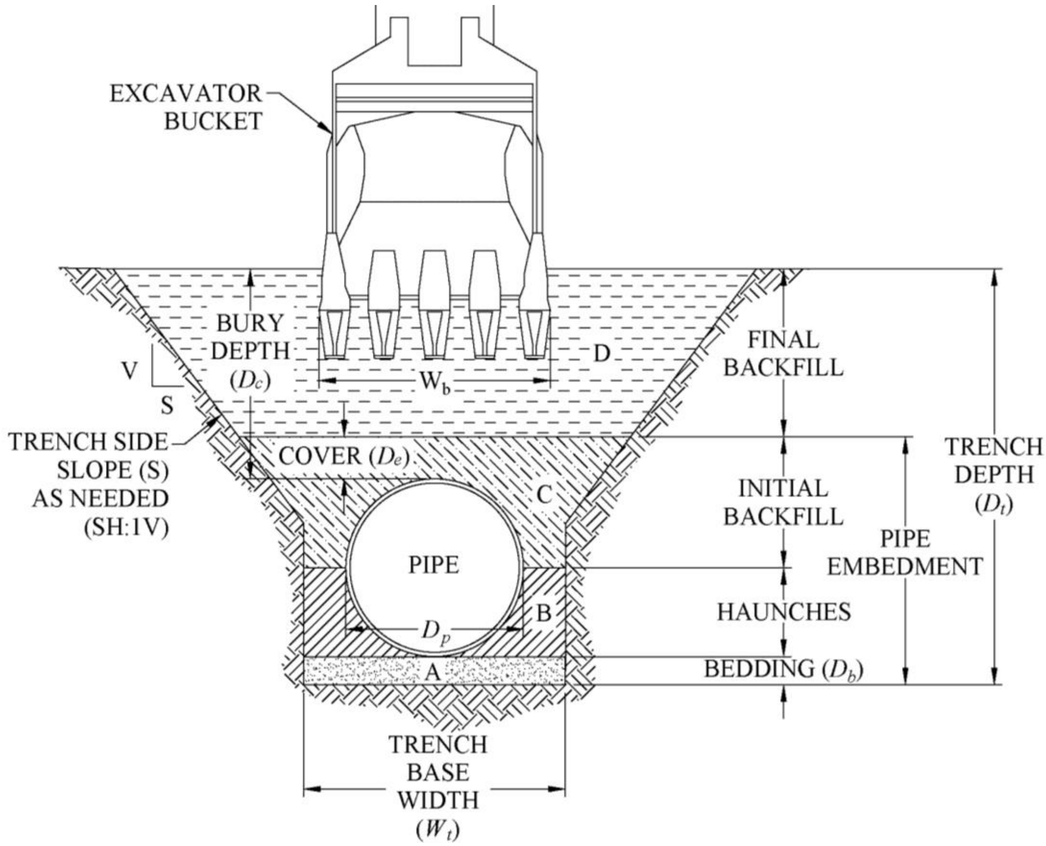


Figure 4. Embedded Trench Configurations (adapted from 29 C.F.R § 1926 Subpart P App B)

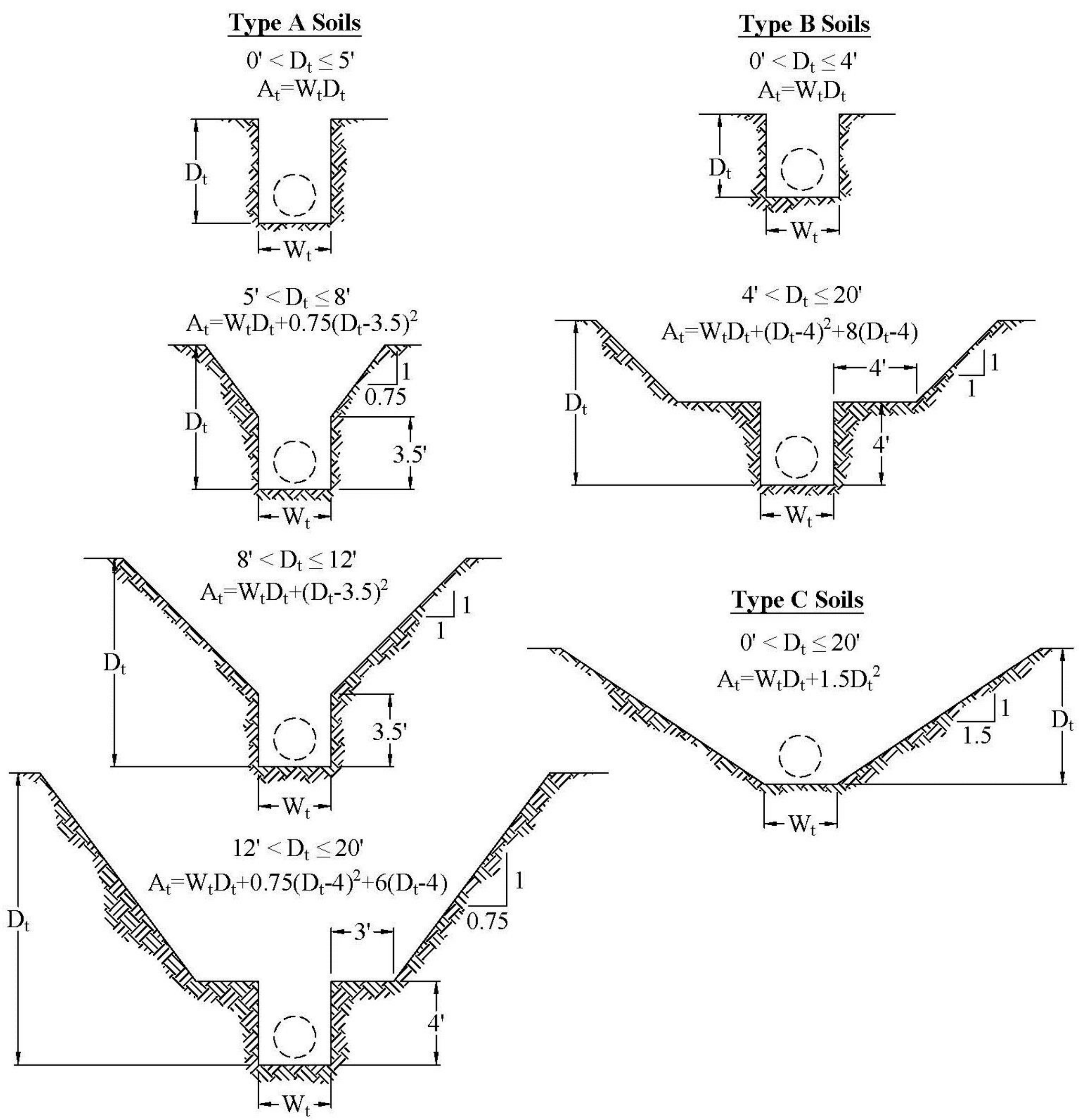


Figure 5. North Central Arizona Regional Water Supply Project Preliminary Alignment

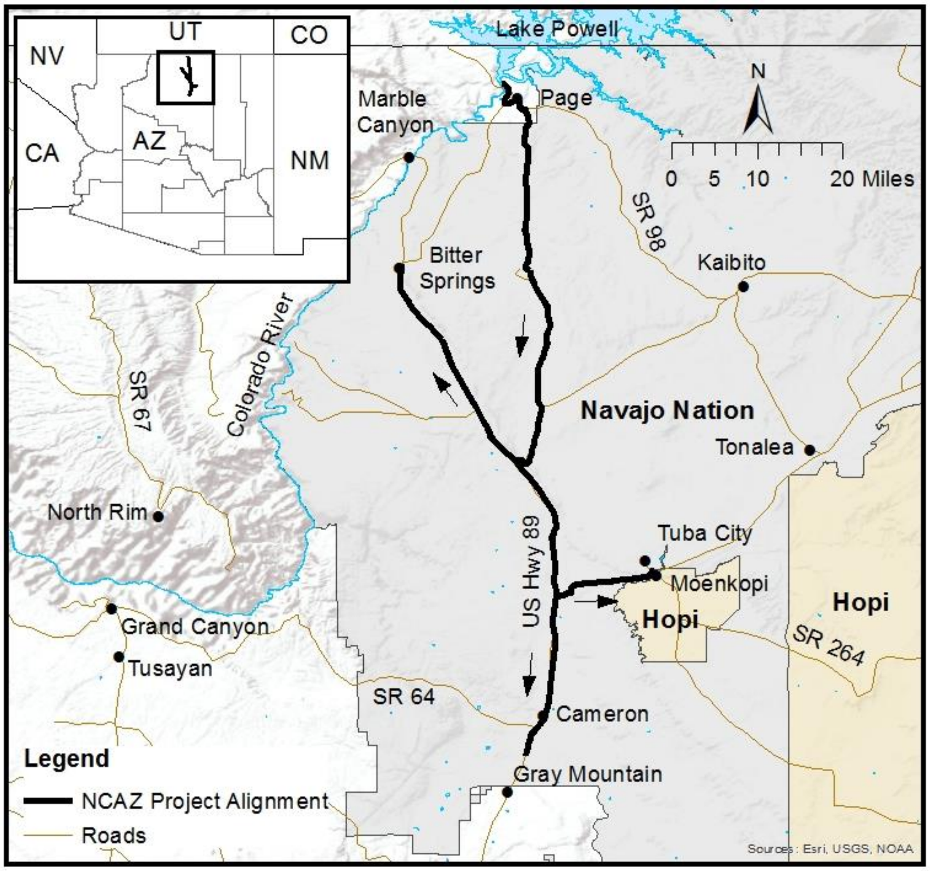


Figure 6. Model Validation Results

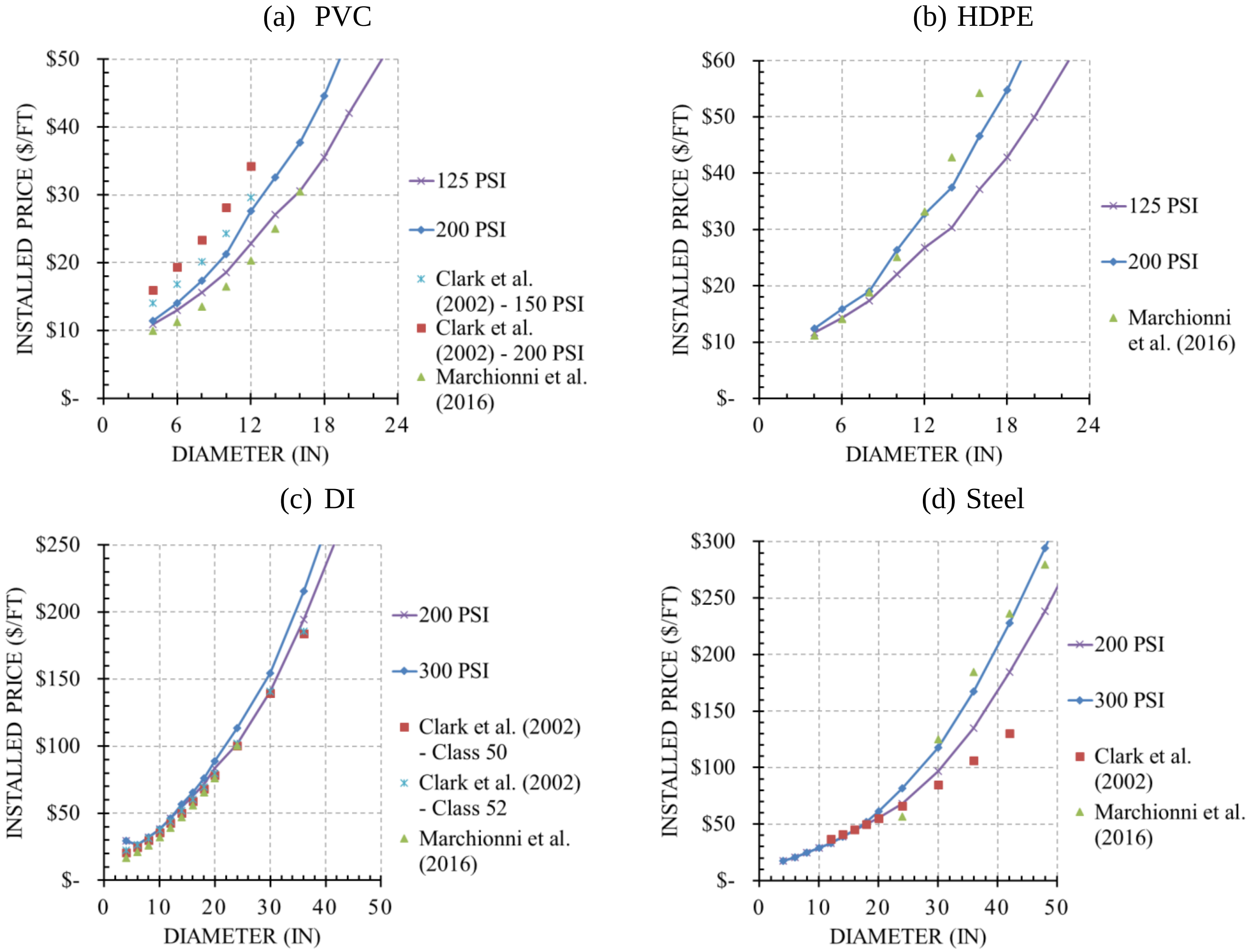
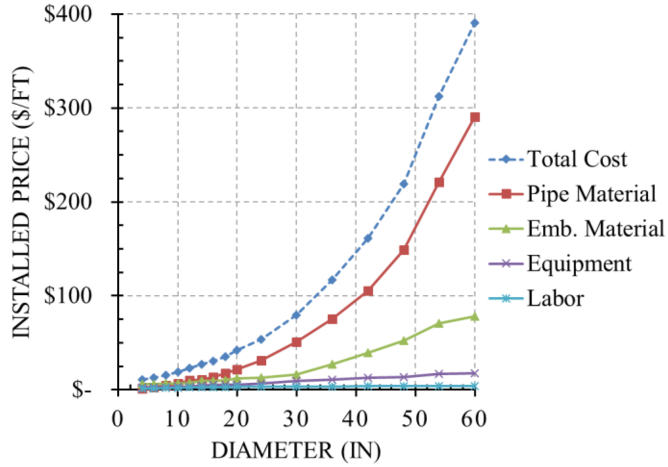
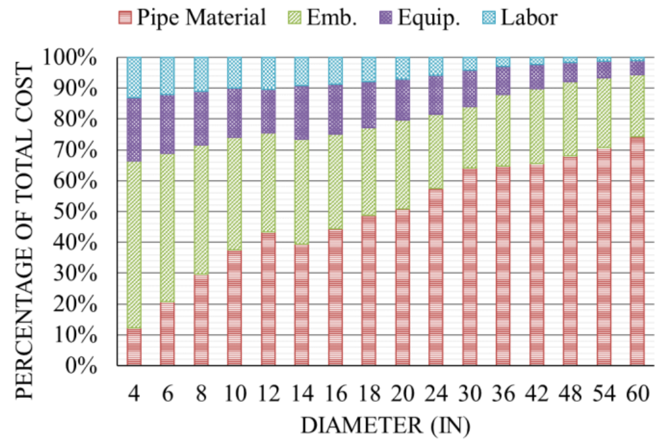


Figure 7. Component Cost

(a) PVC



(b) PVC Component Costs by %



(c) Equipment and Labor (125 PSI)

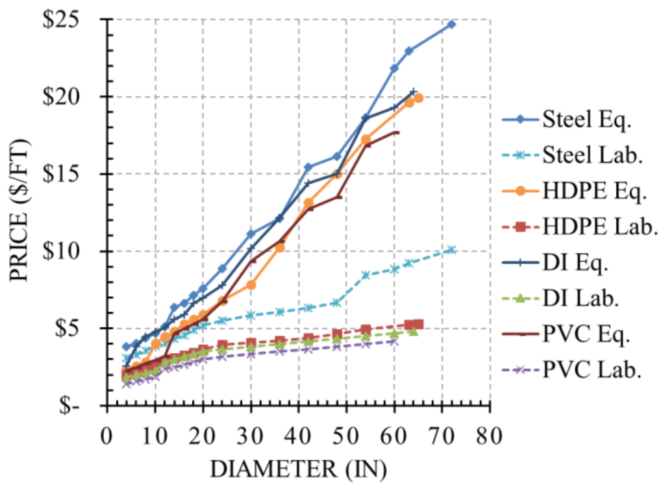


Figure 8. Sensitivity Results

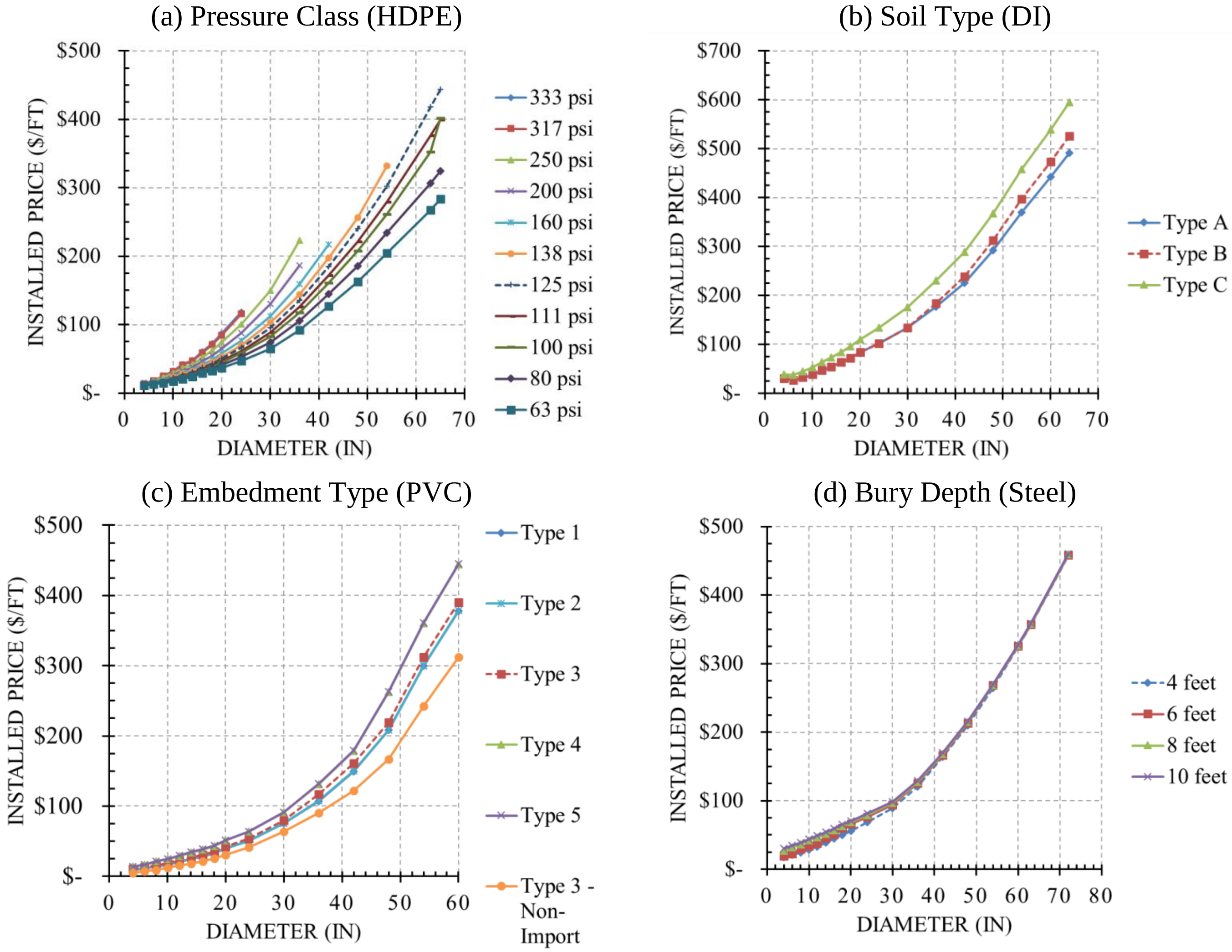


Figure 9. Pressure Class Cost Comparison

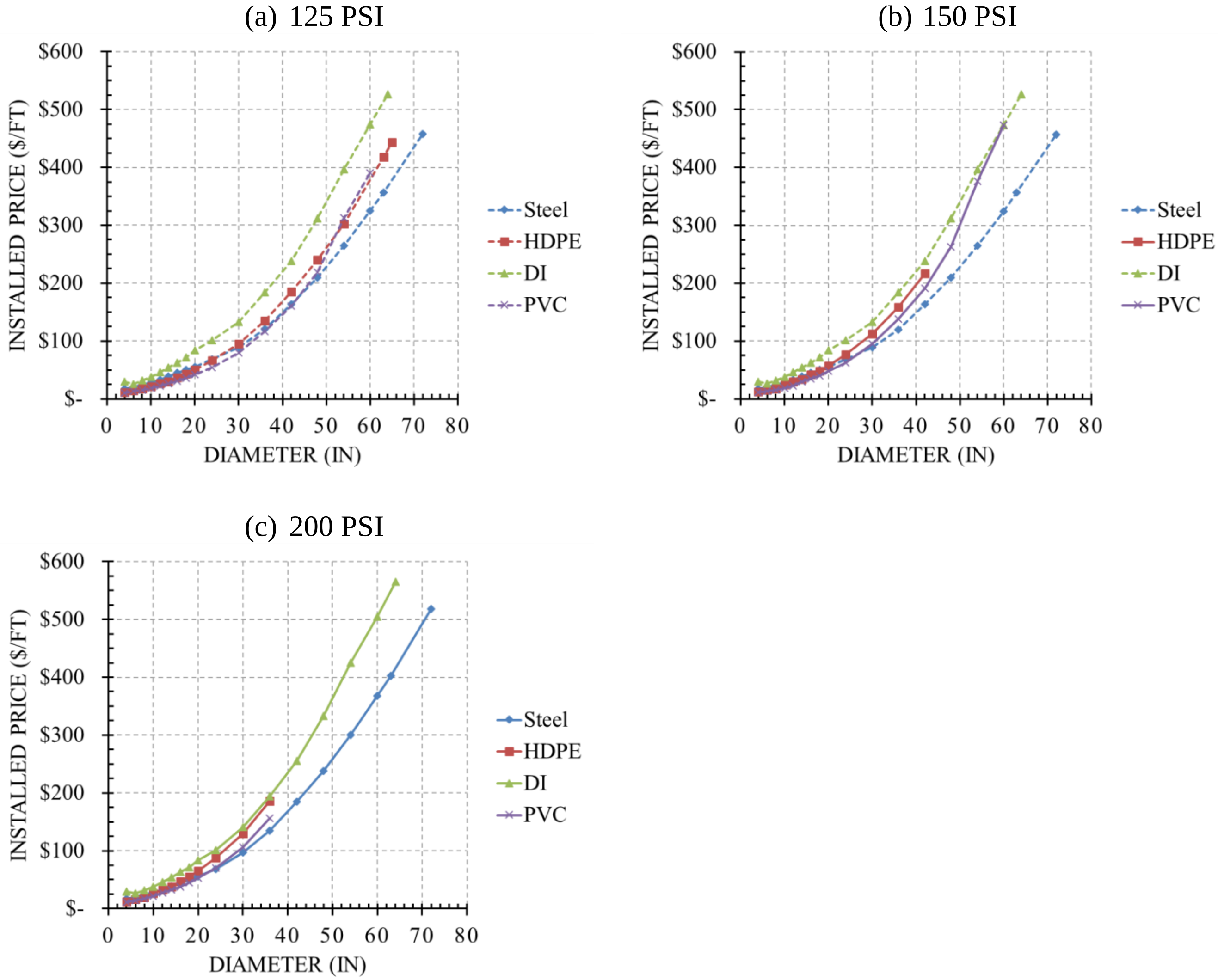


Table 1. Pipe Material Size Thickness Class Range

Material Type	Nominal Pipe Size Range (in)	Thickness/ Pressure Class Range	Pipe Sizing System	Joint Type
HDPE	4 – 63	DR 14 – DR 51 (80 psi – 305 psi)	IPS	Fusion Welded
PVC	4 – 60	DR 7 – DR 32.5 (32.5 psi – 333 psi)	DIOD	Bell and Spigot
Steel	4 – 72	0.1345” – 1.0” (150 psi – 500 psi)	IPS	Bell and Spigot
DI	4 – 64	0.25” – 0.87” (150 psi – 350 psi)	DIOD	Bell and Spigot

Note: The full range of pipe thickness/pressure class are not available for all diameters.

Table 2. Pipe Material and Installation Standards

Pipe Material	Material Standard	Installation Standard	Design Manual
HDPE	ANSI/AWWA C906-15 (AWWA 2015)	*N/A	AWWA M55 (AWWA 2006)
PVC	ANSI/AWWA C900-16 (AWWA 2016)	ANSI/AWWA C605-13 (AWWA 2013)	AWWA M23 (AWWA 2002)
Steel	ANSI/AWWA C200-12 (AWWA 2012)	ANSI/AWWA C604-11 (AWWA 2011)	AWWA M11 (AWWA 2004)
Ductile Iron	ANSI/AWWA C150/A21.50-14 (AWWA 2014) ANSI/AWWA C151/A21.51-09 (AWWA 2009b)	ANSI/AWWA C600-10 (AWWA 2010a)	AWWA M41 (AWWA 2009a)

*Installation standards for HDPE pipe are not available from AWWA.

Table 3. Embedment Configurations

Embedment Zone	Embedment Type				
	1	2	3	4	5
A	None	None	CL	CL-1	CL-1
B	L	CL-LC	CL-LC	CL-80	CL-90
C	N-4	N-4 or CL	N-4 or CL	N-4 or CL	N-4 or CL
D	N	N	N	N	N

CL=Class II, III, or IV Material (not compacted)
CL-LC=Class II, III or IV Material (lightly compacted)
CL-1=Class I or II Material (not compacted)
CL-80=Class II, III or IV Material (compacted to >80% SPD)
CL-90=Class II, III or IV Material (compacted to >90% SPD)
L=Loose Material (4” Minus)
N=Native Material
N-4=Native Material (4” Minus)

Table 4. NCAZ Design Criteria – Baseline Condition

Parameter/Model Input	Value
Total length of pipe (L_{tot})	100,000 feet
Embedment type (E_t)	Type 3
Soil type (S_t)	Type B
Embedment material imported?	Yes
Embedment cover depth over pipe (D_e)	12 inches
Bury depth (D_c)	4 feet
Water content deficit (w_d)	10%
Design pressure/pressure class	125 psi
Percentage of restrained joints	10%

Note: A design criteria of 100,000 feet was provided to provide an equal comparison of pipe pricing. The actual NCAZ project is over 100,000 feet in length. A design pressure of 125 psi was chosen so that all pipe materials could be represented for the full range of pipe diameters,

Estimation of Water Pipe Installation Construction Costs

Ronson Chee, Kevin Lansey and Erickson Chee

SUPPLEMENTAL DATA

This supplementary data provides additional results generated by WaterCOSTE as well as provides select model inputs and embedded information.

Figure S1 provides the breakdown of component costs for HDPE, DI and Steel. Figures S2 through S5 provide additional sensitivity results for PVC, HDPE, DI and Steel pipe.

Table S1 provides equations for estimating embedment material volumes for the various trench configurations. Table S2 provides a summary of a WaterCOSTE model parameter inputs. Tables S3 through S13 provide select model input data. Table S14 summarizes the cost coefficients used for Clark et al. (2002).

Figure S1. Component Costs

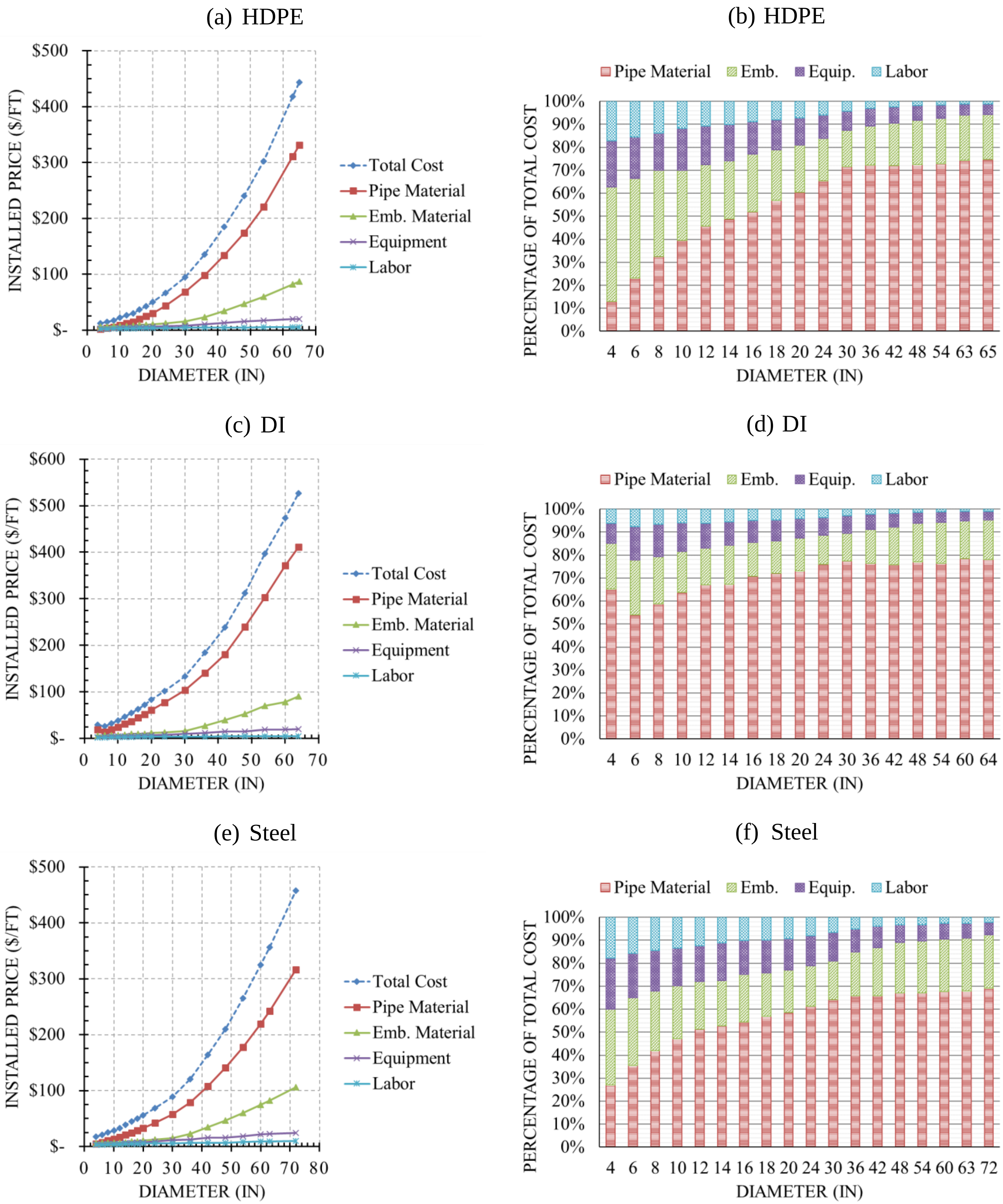
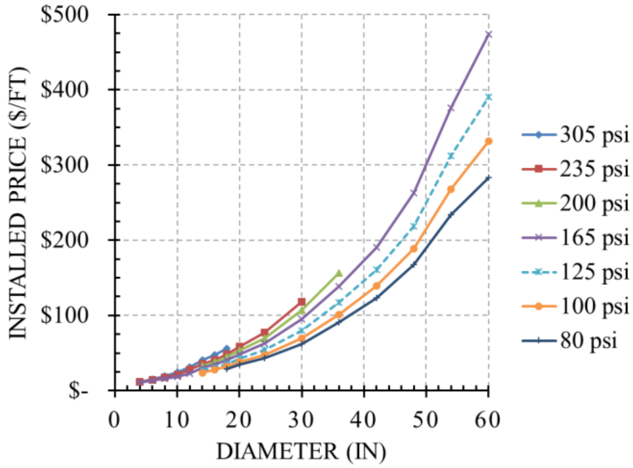
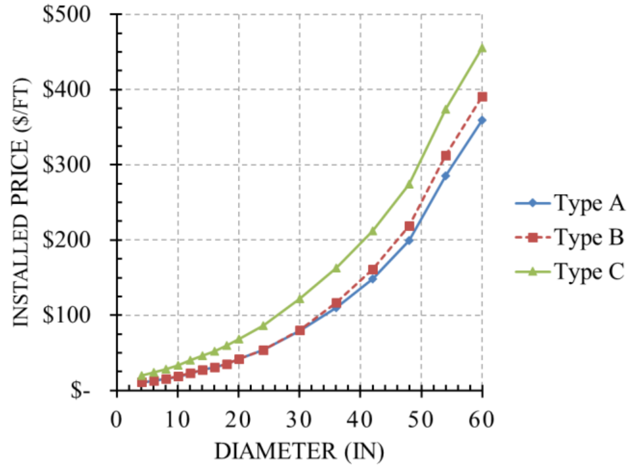


Figure S2. Sensitivity Results – PVC

(a) Pressure Class



(b) Soil Type



(c) Bury Depth

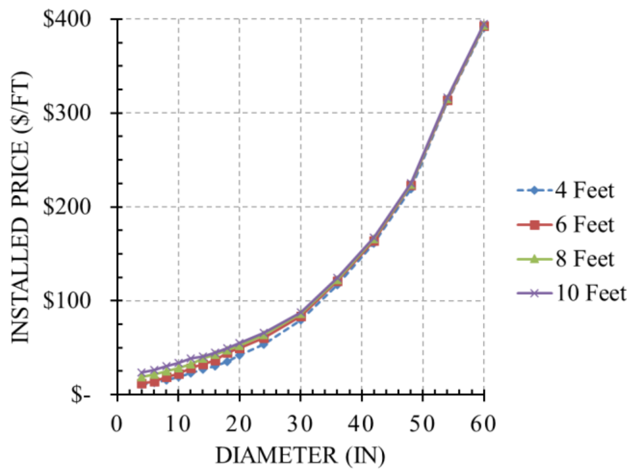
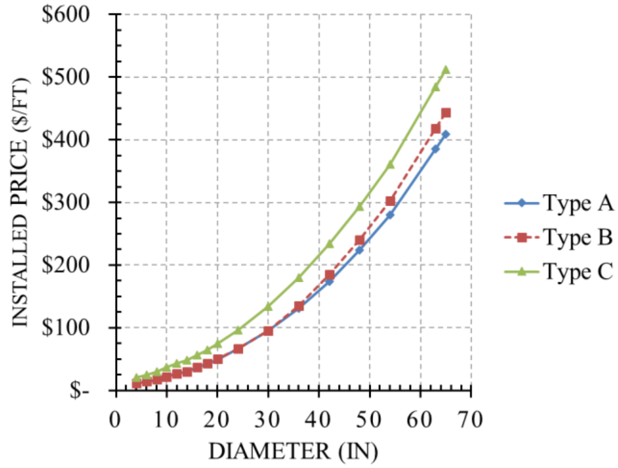
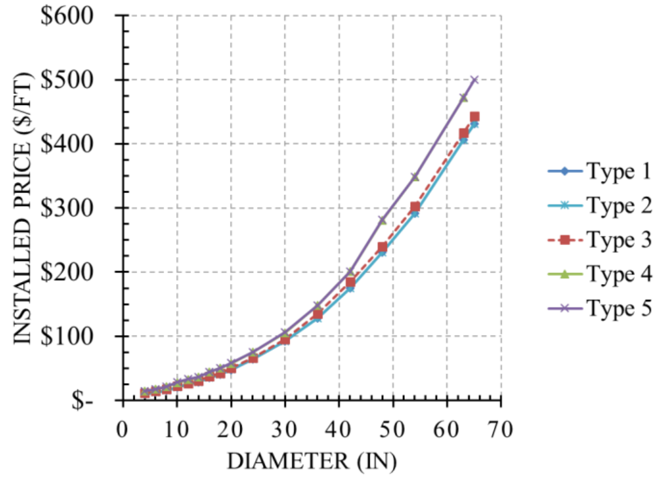


Figure S3. Sensitivity Results – HDPE

(a) Soil Type



(b) Embedment Type



(c) Bury Depth

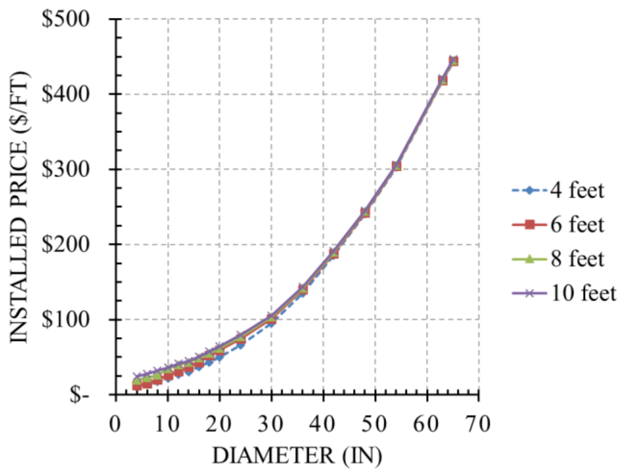
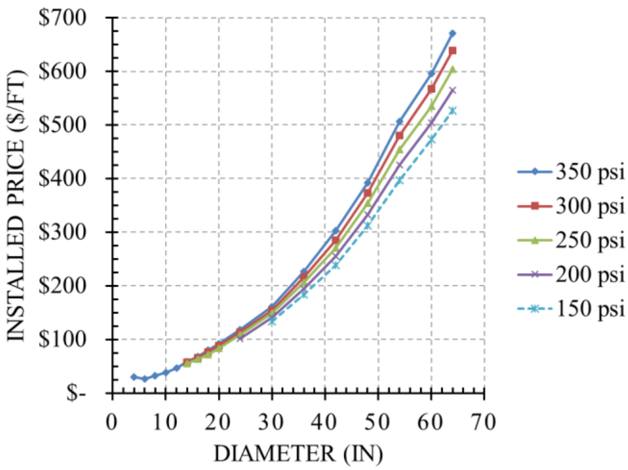
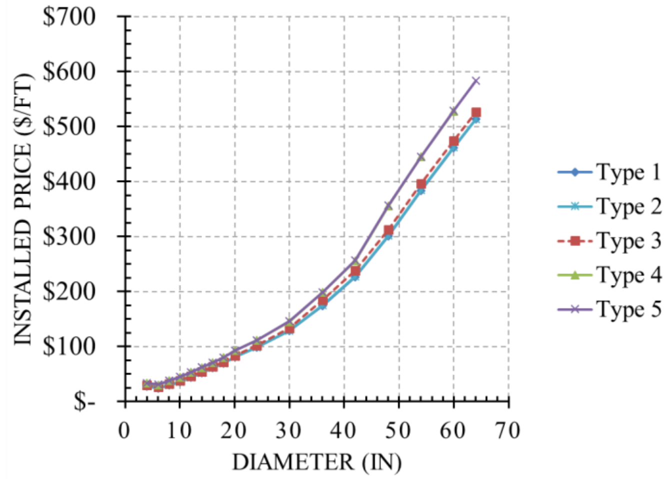


Figure S4. Sensitivity Results – DI

(a) Pressure Class



(b) Embedment Type



(c) Bury Depth

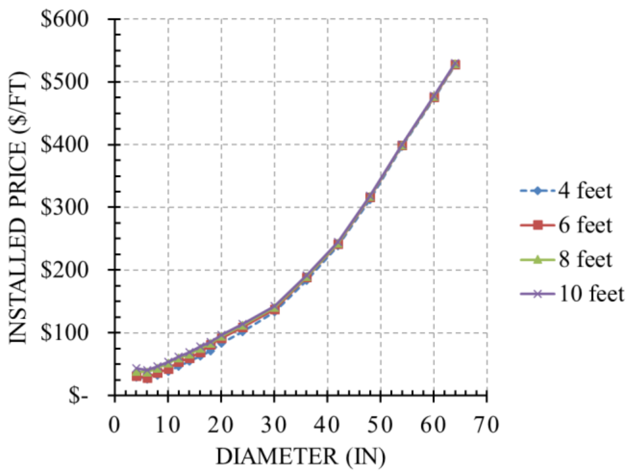
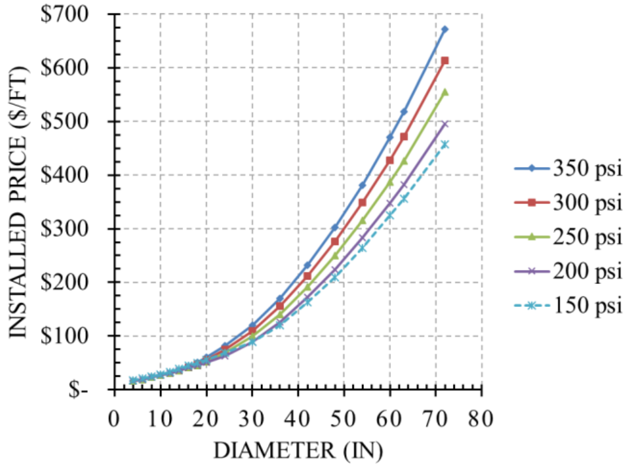
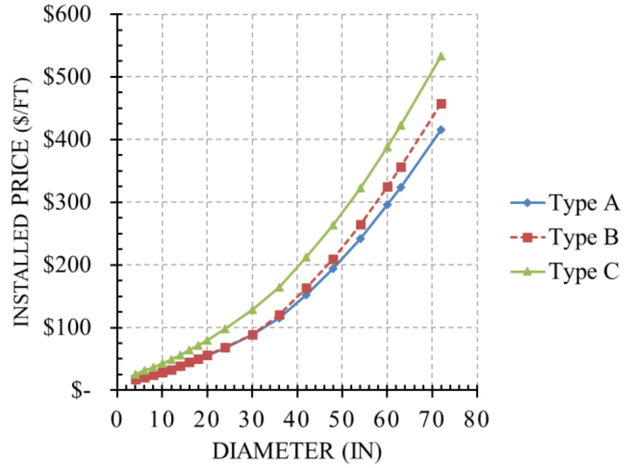


Figure S5. Sensitivity Results – Steel

(a) Pressure Class



(b) Soil Type



(c) Embedment Type

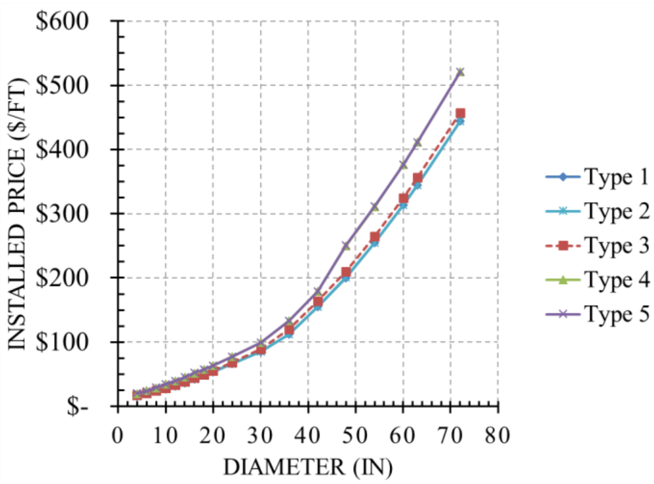


Table S1. Embedment Material Volume Equations

Equation	**Eq.**	**Embed. Type (E_t)**	**Depth Range (D_t)**
$V_{bed} = D_t \times \frac{W_t}{12}$	(S1)	Type A Type B	$D_t \leq 20$
$V_{bed} = \frac{D_b}{12} \times \frac{W_t}{12} + \left(\frac{D_b}{12}\right)^2 \times 1.5$	(S2)	Type C	$D_t \leq 20$
$V_h = \left(\frac{D_p}{2} \times W_t - \frac{\pi D_p{}^2}{8}\right) \times \frac{1}{144}$	(S3)	Type A Type B	$D_t \leq 20$
$V_h = \left[\left(\frac{D_p}{2} \times W_t - \frac{\pi D_p{}^2}{8}\right) + 1.5\left(\left(\frac{D_p}{2} + D_b\right)^2 - D_b{}^2\right)\right] \times \frac{1}{144}$	(S4)	Type C	$D_t \leq 20$
$V_{ib} = \left(\frac{D_p}{2} \times W_t - \frac{\pi D_p{}^2}{8}\right) \times \frac{1}{144}$	(S5)	Type A Type B	$D_t \leq 5$ $D_t \leq 4$
$V_{ib} = \begin{cases} \left(\frac{D_p}{2} \times W_t - \frac{\pi D_p{}^2}{8}\right) \times \frac{1}{144}, & \frac{(D_p + D_b)}{12} \leq 3.5 \\ \left(\frac{D_p}{2} \times W_t - \frac{\pi D_p{}^2}{8}\right) \times \frac{1}{144} + S\left(\left(\frac{D_b + D_p}{12}\right) - 3.5\right)^2, & \frac{(D_p + D_b)}{12} > 3.5 \end{cases}$	(S6)	Type A	$5 < D_t \leq 8$ ($S = 0.75$) $8 < D_t \leq 12$ ($S = 1.0$)

$$V_{ib}=\begin{cases}\left(\frac{D_p}{2}\times W_t-\frac{\pi {D_p}^2}{8}\right)\times\frac{1}{144}, & \frac{\left(D_p+D_b\right)}{12}\le 4.0\\ \left(\frac{D_p}{2}\times W_t-\frac{\pi {D_p}^2}{8}\right)\times\frac{1}{144}+2B\left(\frac{D_b}{12}+\frac{D_p}{12}-4\right)+S\left(\left(\frac{D_b+D_p}{12}\right)-4\right)^2, & \frac{\left(D_p+D_b\right)}{12}>4\end{cases}$$	(S7)	Type A Type B	$12 < D_t \le 20$ (S = 0.75, B = 3.0) $4 < D_t \le 20$ (S = 1.0, B = 4.0)
$$V_c=\begin{cases}\frac{W_t\times D_{ec}}{144}, & D_b+D_p+D_e\le H\\ \frac{D_{ec}\times W_t}{12}+S\left(\frac{D_p}{12}+\frac{D_e}{12}+\frac{D_b}{12}-H\right)^2, & D_b+D_p+D_e>H\ and\ D_b+D_p<H\\ \frac{(W1+W2)}{2}\times\frac{D_e}{12}, & D_b+D_p+D_e>H\ and\ D_b+D_p>H\end{cases}$$ $$W1=\frac{W_t}{12}+2S\left(\frac{D_b}{12}+\frac{D_p}{12}-H\right)$$ $$W2=\frac{W_t}{12}+2S\left(\frac{D_b}{12}+\frac{D_p}{12}+\frac{D_e}{12}-H\right)$$	(S8)	Type A	$5 < D_t \le 8$ (S = 0.75, H = 3.5) $8 < D_t \le 12$ (S = 1.0, H = 3.5)

$$V_c = \begin{cases} \dfrac{W_t \times D_e}{144}, & D_b + D_p + D_e \le H \\ \dfrac{D_e \times W_t}{12} + 2B\left(\dfrac{D_p}{12} + \dfrac{D_e}{12} + \dfrac{D_b}{12} - H\right) + S\left(\dfrac{D_p}{12} + \dfrac{D_e}{12} + \dfrac{D_b}{12} - H\right)^2, & D_b + D_p + D_e > H \text{ and } D_b + D_p < H \\ \dfrac{(W1 + W2)}{2} \times \dfrac{D_e}{12}, & D_b + D_p + D_e > H \text{ and } D_b + D_p > H \end{cases}$$ $$W1 = \frac{W_t}{12} + 2B + 2S\left(\frac{D_b}{12} + \frac{D_p}{12} - H\right)$$ $$W2 = \frac{W_t}{12} + 2B + 2S\left(\frac{D_b}{12} + \frac{D_p}{12} + \frac{D_e}{12} - H\right)$$	(S9)	Type A Type B	$12 < D_t \le 20$ (S = 0.75, H = 4, B = 3) $4 < D_t \le 20$ (S = 1.0, H = 4, B = 4)
$$V_c = \frac{W_t \times D_e}{144}$$	(S10)	Type A Type B	$D_t < 5$ $D_t \le 4$
$$V_c = \frac{(W1 + W2)}{2} \times \frac{D_e}{12}$$ $$W1 = \frac{W_t}{12} + 2S\left(\frac{D_b}{12} + \frac{D_p}{12}\right)$$ $$W2 = \frac{W_t}{12} + 2S\left(\frac{D_b}{12} + \frac{D_p}{12} + \frac{D_e}{12}\right)$$	(S11)	Type C	$D_t \le 20$ (S = 1.5)

Where D_e = the embedment cover depth (in); S = trench side slope (SV:1H ratio); H = the vertical trench sidewall height (ft); B = bench width (ft); Table can be used in conjunction with Figure 4.

Table S2. Summary of Model Parameters

Category/ Process	Site-specific (Variable) Parameters	Embedded (Fixed) Parameters	Internally Calculated Parameters (vary)	Output Values
Pipe	L_{tot} = 100,000 ft. C_{pipe} (M)	D_p & W_p (AWWA)	-	C_{pipe}
Trench Excavation	S_t = Type B(BC) D_c = 4 ft.(BC)	V_{sp} = 87 CY	A_t , D_t , V_{exc}, V_{exc_d}, W_t , W_{tr} , W_{emb}, N_{sp}, D_{sp} ,	-
Embedment	D_b = 4 in.(BC) E_t = Type 3 (BC) C_{emb_r} (Table S10)	D_i & S_f (Table S10) V_{ip} = 87 CY	V_{emb} , V_{emb_d} , V_{bed} , V_h , V_{ib} , V_c *(Eq. S1-S11)* W_{emb_tr} , D_{ip} , N_{ip} , D_{ip} , C_{emb_u} ,	C_{emb}
Backfill	S=10%, P=10% D_w=20 mi., T_l =3.4 min., T_d=68 min., w_d =10%, S_f (Table S7&S9) C_{wat_u}=0.005 $/gal	V_{wt} = 3,400 gal S_{wt}=50 mph	V_{wat} , V_{wat_d} ,P_{wat} , T_{load} , T_{wt} , T_t , T_e	C_{wat}
Equipment	*Cex* & C_{mob_exc} (Table S6) *Cld* & C_{mob_load} (Table S4) *Cwt* & C_{mob_wt} (Table S5) C_{emb_tr} (Table S5) C_{misc_d}=$200/day	D_{exc} , C_{lb} , t_{ls} , t_{es} , t_l, t_d , t_{li} , t_{ei} , t_{de}, & V_l (Table S7&S9)	W_b , N_{exc} , N_{wt} , C_{exc} , C_{load} C_{wt} , C_{mob} , C_{misc}	C_{equip}
Labor	C_l , C_f & C_w (Table S3)	-	N_{lab} , T_{hw}	C_{lab}
Production	f_A , f_B & f_C =1.1	t_a , t_b , t_c , T_a, T_b, T_c (Table S12) v & V_{bc} (Table S11) R_{pipe} , R_{pvc}, R_{di}, R_s, R_h (Table S13) T_{hr} = 50 min/hr T_{day}= 8hr/day	T_{cemb} , R_{exc} , P_{exc} , R_{emb_prod} , P_{sp} , P_{sc} , P_{emb} , P_{ro} , P_{back} , T_{job}	C_{tot}

M=from Manufacturer.

AWWA = from AWWA manuals.

BC=Baseline Condition (other conditions were also evaluated).

Table S3. Labor Rates

Labor Code	Labor rate ($/hr)
Foreman	$50.00
Excavator Operator	$40.00
Loader Operator	$40.00
Laborer	$30.00
Truck Driver	$30.00
Welder	$80.00
Welder Helper	$40.00

Table S4. Loader Equipment Costs

Loader Model	Total Daily Cost ($)	Mobilization ($)
926	$625	$2,000
930	$637	$2,000
938	$727	$2,000
950	$845	$2,000
962	$899	$2,000
966	$975	$5,000
972	$1,101	$5,000
980	$1,288	$5,000
982	$1,414	$5,000
986	$1,624	$5,000

Table S5. Truck Equipment Costs

Truck Type	Total Daily Cost ($)	Mobilization
2000gal Water Truck	$509	$400
3400gal Water Truck	$590	$400
3700gal Water Truck	$650	$400
Crew Truck	$117	N/A
Semi + Belly Dump	$669	N/A

Note: Total Daily Cost includes the operator.

Table S6. Excavator Equipment Costs

Excavator Model	Total Daily Cost ($)	Mobilization
311	$694	$2,000
313	$701	$2,000
315	$676	$2,000
316	$762	$2,000
318	$761	$2,000
319	$768	$2,000
320	$866	$2,000
323	$866	$2,000
326	$976	$2,000
329	$1,048	$2,000
330	$1,075	$5,000
336	$1,148	$5,000
349	$1,383	$5,000
352	$1,574	$5,000
365	$1,912	$5,000
374	$2,174	$5,000
385	$2,402	$5,000
390	$2,589	$5,000

Note: Total Daily Cost includes the operator.

Table S7. Loader Bucket and Performance Data

	[1]Avg. Bucket Capacity (CY)	Bucket Width (ft)	Avg. Loaded Speed (mph)	Avg. Empty Speed (mph)	[2]Load Time (sec)	[2]Dump Time (sec)	Dump Time Emb. (sec)
926	3	8.333	10	11	9	5	20
930	3.3	8.333	10	11	9	5	20
938	3.8	9	10	11	9	5	20
950	4.05	9.75	10	11	9	5	20
962	4.45	9.75	10	11	9	5	20
966	5.25	10.67	10	11	9	5	20
972	6.25	10.67	10	11	9	5	20
980	7.06	11.25	10	11	9	5	20
982	7.98	11.75	10	11	9	5	20
986	9	12	10	11	9	5	20

[1]Avg. bucket based on General Purpose bucket rated capacity.

[2]Dump and load time estimated includes turnaround and maneuver time.

Table S8. Excavation Soil Type Properties

		Unit Weight (lbs/ft^3)	Swell Factor (%)	Shrink Factor (%)
Native	Rock	130	60%	-
	Type A	130	32%	-
	Type B	130	20%	-
	Type C	130	12%	-
Native	I	100	-	1
	II	135	-	0.9
	III	125	-	0.85
	IV	120	-	0.8
	V	100	-	0.8

Table S9. Excavator Performance Data

Excavator Model	Full Reach (No Bucket - ft)	Side Lift Capacity at 25' (lbs)	30% of side lift capacity at 25' (lbs)	Max Cut Depth for 8' Level Bottom (ft)	30% of Max Depth (ft)
311	22.5	3700	1110	16.3	4.90
313	23.6	3850	1155	18.5	5.55
315	24.4	4450	1335	18.6	5.57
316	24.9	4600	1380	20.3	6.08
318	25.7	5000	1500	20.8	6.25
319	26.4	4450	1335	20.3	6.08
320	27.5	7050	2115	21.5	6.45
323	27.5	7800	2340	21.5	6.45
326	27.6	9750	2925	21.8	6.53
329	29.5	11700	3510	23.3	6.98
330	29.5	11950	3585	23.3	6.98
336	30.3	14800	4440	22.5	6.75
349	32.5	20850	6255	24.7	7.40
352	33.3	22800	6840	26.0	7.80
365	35.6	29250	8775	28.9	8.68
374	39.1	35950	10785	30.3	9.10
385	41.5	41150	12345	34.8	10.45
390	43.5	45400	13620	34.9	10.48

Table S10. Import Embedment Material Data

Material Class	Unit Weight (lbs/ft^3)	Shrink Factor	Raw Material Cost ($/ton)	Import Total Cost ($/ton)
I	100	1	$23	$33.90
II	135	0.9	$26	$34.08
III	125	0.85	$19	$27.72
IV	120	0.8	$14	$23.09

Table S11. Excavator Bucket Capacities

Exc. Model	Heaped Bucket Capacity (CY) Bucket Width (in)											
	18	24	30	36	42	48	54	60	66	72	75	79
311	0.27	0.4	0.54	NA	NA	NA	NA	NA	NA	NA	NA	NA
313	0.27	0.4	0.54	0.69	NA	NA	NA	NA	NA	NA	NA	NA
315	0.27	0.4	0.54	0.69	NA	NA	NA	NA	NA	NA	NA	NA
316	NA	0.46	0.64	0.81	1	NA	NA	NA	NA	NA	NA	NA
318	NA	0.46	0.64	0.81	1	NA	NA	NA	NA	NA	NA	NA
319	NA	0.59	0.76	1.01	1.2	NA	NA	NA	NA	NA	NA	NA
320	NA	0.72	0.98	1.24	1.52	NA	NA	NA	NA	NA	NA	NA
323	NA	0.72	0.98	1.24	1.52	1.8	NA	NA	NA	NA	NA	NA
326	NA	0.83	1.13	1.43	1.75	2.07	NA	NA	NA	NA	NA	NA
329	NA	0.83	1.13	1.43	1.75	2.07	NA	NA	NA	NA	NA	NA
330	NA	0.83	1.13	1.43	1.75	2.07	2.4	NA	NA	NA	NA	NA
336	NA	NA	1.23	1.56	1.91	2.26	2.62	2.98	NA	NA	NA	NA
349	NA	NA	1.24	1.6	1.98	2.36	2.74	3.13	NA	NA	NA	NA
352	NA	NA	NA	1.6	1.98	2.36	2.74	3.13	3.64	NA	NA	NA
365	NA	NA	NA	NA	2.12	2.42	3.01	3.61	3.68	NA	NA	NA
374	NA	NA	NA	NA	2.5	2.9	3.4	3.9	4.3	4.8	NA	NA
385	NA	NA	NA	NA	2.75	3.3	3.88	4.44	5	5.25	5.5	NA
390	NA	NA	NA	NA	3	3.5	4	4.55	5.1	5.5	6	6

Table S12. Excavator Cycle Times (sec)

Type B Soil – Avg. Excavator Cycle Times (sec)												
Exc. Model	**Bucket Width (in)**											
	18	24	30	36	42	48	54	60	66	72	75	79
311	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5
313	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5
315	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5
316	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5
318	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5
319	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5
320	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5
323	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5
326	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5
329	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5
330	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5
336	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5
349	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5
352	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23	23.5
365	20	20.5	21	21.5	22	22.5	23	23.5	24	24.5	25	25.5
374	22	22.5	23	23.5	24	24.5	25	25.5	26	26.5	27	27.5
385	24	24.5	25	25.5	26	26.5	27	27.5	28	28.5	29	29.5
390	26	26.5	27	27.5	28	28.5	29	29.5	30	30.5	31	31.5

Table S13. PVC Pipe Installation Rates

Nom. Pipe Diameter (in.)	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**24**	**30**	**36**	**42**	**48**	**54**	**60**
Pipe Stick Length (ft)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Type 1																
Install Time (min. per pipe)	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Install Time (pipe per hour)	7.5	6.7	6.0	5.5	5.0	4.6	4.3	4.0	3.8	3.5	3.3	3.2	3.0	2.9	2.7	2.6
Feet of Pipe per hour	150	133	120	109	100	92	86	80	75	71	67	63	60	57	55	52
Feet of Pipe per day	1200	1067	960	873	800	738	686	640	600	565	533	505	480	457	436	417
Type 2																
Install Time (min. per pipe)	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Install Time (pipe per hour)	6.7	6.0	5.5	5.0	4.6	4.3	4.0	3.8	3.5	3.3	3.2	3.0	2.9	2.7	2.6	2.5
Feet of Pipe per hour	133	120	109	100	92	86	80	75	71	67	63	60	57	55	52	50
Feet of Pipe per day	1067	960	873	800	738	686	640	600	565	533	505	480	457	436	417	400
Type 3																
Install Time (min. per pipe)	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Install Time (pipe per hour)	6.0	5.5	5.0	4.6	4.3	4.0	3.8	3.5	3.3	3.2	3.0	2.9	2.7	2.6	2.5	2.4
Feet of Pipe per hour	120	109	100	92	86	80	75	71	67	63	60	57	55	52	50	48
Feet of Pipe per day	960	873	800	738	686	640	600	565	533	505	480	457	436	417	400	384
Type 4																
Install Time (min. per pipe)	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Install Time (pipe per hour)	5.5	5.0	4.6	4.3	4.0	3.8	3.5	3.3	3.2	3.0	2.9	2.7	2.6	2.5	2.4	2.3
Feet of Pipe per hour	109	100	92	86	80	75	71	67	63	60	57	55	52	50	48	46
Feet of Pipe per day	873	800	738	686	640	600	565	533	505	480	457	436	417	400	384	369
Type 5																
Install Time (min. per pipe)	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Install Time (pipe per hour)	5.0	4.6	4.3	4.0	3.8	3.5	3.3	3.2	3.0	2.9	2.7	2.6	2.5	2.4	2.3	2.2
Feet of Pipe per hour	100	92	86	80	75	71	67	63	60	57	55	52	50	48	46	44
Feet of Pipe per day	800	738	686	640	600	565	533	505	480	457	436	417	400	384	369	356

Table S14. Cost Coefficients for Clark et al. (2002)

Pipe Material	Cost Component	Indicator Variable	Parameter Values					
			a	b	c	d	e	f
Ductile Iron	Base Installed	[a]50 & 52	-44	0.33	1.72	2.87	0.74	0
	Trenching and Exc.	4	2.9	0.0018	1.9	0.13	1.77	0
	Embedment	1	1.6	0.0062	1.83	-0.2	1	0.07
	Backfill and Compaction	4	-0.0904	-0.062	0.73	0.18	2.03	0.02
	Valve Fitting and Hydrant	0	4.4	0.48	0.62	0	0	0
PVC	Base Installed	150 & 200	-1	0.0008	3.59	0.011	1	0.0067
	Trenching and Exc.	4	2.9	0.0018	1.9	0.13	1.77	0
	Embedment	1	1.6	0.0062	1.83	-0.2	1	0.07
	Backfill and Compaction	4	-0.0904	-0.062	0.73	0.18	2.03	0.02
	Valve Fitting and Hydrant	0	4.4	0.48	0.62	0	0	0
Steel	Base Installed	N/A	14.2	0.19	1.66	0	0	0
	Trenching and Exc.	4	2.9	0.0018	1.9	0.13	1.77	0
	Embedment	1	1.6	0.0062	1.83	-0.2	1	0.07
	Backfill and Compaction	4	-0.0904	-0.062	0.73	0.18	2.03	0.02
	Valve Fitting and Hydrant	0	4.4	0.48	0.62	0	0	0

[a]Indicates Class 50 and 52 DI pipe which is an older identification system (prior to 1991) for specifying DI pipe. Class 50 pipe is now a special thickness class of DI pipe. Rated working pressures for Class 50 range from 350psi (up through 16 inch) to 190psi (for 54 inch).
Note: HDPE cost function are not available in Clark et al. (2002).

APPENDIX B
Optimal Design of Water Transmission Systems

Optimal Design of Water Transmission Systems

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Abstract

The need for long-distance water transmission systems that deliver fresh water from more reliable sources is expected to increase as water shortages are projected throughout the world and as existing systems age. When these transmission systems branch out and reach tens to hundreds of miles and traverse undulating terrain, the hydraulic design can get very complex and time consuming using current hydraulic models. WaterTRANS was developed to reduce design time and improve design efficiency. WaterTRANS automatically creates a hydraulic model by transposing the topographic profiles created from a pipeline alignment that samples elevation and stationing data off a digital terrain model. This approach allows WaterTRANS to locate pumps and pressure regulators (e.g., valves or turbines) and assign pipe pressure classes to specific sections of pipeline. WaterTRANS currently designs in accordance with and provides cost estimates for the following standards/pipe materials: AWWA C900 (PVC), AWWA C906 (HDPE), AWWA C151 (ductile iron), and AWWA C200 (steel). WaterTRANS is paired with a Genetic Algorithm to determine least-cost designs for two alternate routes using the various material types, for a potential large scale real-world water transmission project in northeastern Arizona.

Keywords: Pipelines; Water Transmission System Design, Pipe Network Optimization, Pipe Pressure Class, Surge Pressure, Branched Water Systems

INTRODUCTION

Background

As current drought conditions and water shortages persist throughout the world, importation of water via large transmission systems from more reliable sources will become more common. In the United States, municipalities and government agencies have increased water importation via large-scale transmission pipelines to meet future water demands and to preserve more local sources (e.g., Charles and Kriss 2006; Gibson et al. 2013; Cottingham et al. 2010; Maughn et al. 2014; Shivakumar et al. 2011; Blackwelder et al. 2016; Robertson 2016; USBR 2006, 2009). As large long-distance water transmission systems (WTSs) are emerging as feasible alternatives to meet projected water shortages, engineers will need more efficient and advanced tools to design and perform accurate cost estimates for these critical and expensive infrastructures.

As reliable and renewable water sources become scarcer, the distance to those sources will also increase. Further, accessing them may require water transmission pipelines to cross undulating terrain that significantly increases design complexity. Multiple booster pumps and pressure regulation (through valves or turbines) may be required when traversing terrain with large elevation changes. For these types of systems, selecting a pipe material (and pressure classes) combined with locating pumps and pressure regulators can become overwhelming; as the number of potential pipe/pump/turbine combinations mushrooms. Placement and sizing of pumps and pressure regulators can have significant capital and operational cost implications; especially for long distance pipelines where pumping energy costs can be the largest cost item.

Hydraulic models and design tools that can consider various pipe materials and pipe pressure classes while locating pumps and pressure regulators in WTSs are not available. Most recent literature pertaining to WTSs focuses on: evaluation and assessment of existing pipelines (e.g., Al-Barqawi and Zayed 2006; Villalobos and Perry 2006; Kong and Mergelas 2009); cleaning and re-lining of existing pipelines (e.g., Keenan 2006; McReynolds et al. 2013), rehabilitation and replacement (e.g., Donnally 2013; Matthews et al. 2013; Heisler and Turner 2006); or pipeline construction (e.g., Charles and Kriss 2006; Cottingham et al. 2010; Shivakumar et al. 2011; Gibson et al. 2013; Maughn et al. 2014).

Design of most WTSs is completed using spreadsheets or commercial hydraulic models (e.g., Shivakumar et al. 2011; and Charles and Kriss 2006). Optimization (if completed) is typically performed on a trial and error basis with analyses that only evaluate limited variations of a base design. Most often hydraulic design criteria is determined by rules of thumb a (e.g., a maximum flow velocity of 1.5 m/s [5 fps]; pipe friction losses limited to 25% of the pump head). These rules of thumb may work for certain systems but can lead to sub-optimal designs for more complex systems. Life-cycle cost optimization approaches using numerical and stochastic methods have been applied to water distribution networks (e.g. Chiplunkar and Khanna 1983; Young 1994; Jung et al. 2013; Zhang et al. 2013; Kang and Lansey 2013, 2014). However, application of these studies are limited to: small scale systems; simplistic hypothetical systems; systems that contain a single fixed pump station; and networks with minimal elevation changes that do not require pressure regulation in between nodes.

Here, we bridge the gap that exists for hydraulic optimization of real world long-distance branched WTSs. A reason for this gap is that the design of real world WTSs are primarily performed by practicing engineers who will use readily available commercial hydraulic modeling software, while the research community develops complex optimization methods that are rarely integrated into commercial hydraulic modeling software. Thus, practicing engineers are usually limited by their hydraulic modeling software's optimization capabilities. This is unfortunate, as the inability to optimize while designing expensive WTSs can overlook crucial aspects such as optimal pipe material selection and optimal placement of pumps and pressure regulators. All of which can lead to significant unnecessary capital and operational expenses.

Limitations of using Current Hydraulic Models for WTS Design

The standard WTS design process using current commercial hydraulic modeling software (e.g., EPANET, WaterCAD, HydrauliCAD, InfoWater) that is implemented by most engineers follows the steps below:

- The physical network geometry of the WTS is defined by first identifying computational nodes (or demand locations) that are linked together by pipes, pumps and/or valves. Reservoirs and/or tanks (i.e., water sources) provide the boundary condition for the hydraulic model. Elevations are assigned to reservoirs, tanks and nodes; distances, diameters and roughness coefficients are assigned to pipes; pump curves are assigned to pumps; and loss settings are applied to valves. The location of pumps and valves and their settings (e.g., pump curves, loss coefficients, valve settings) are pre-defined (i.e., pumps and valves are placed between computational nodes in the hydraulic model).
- With the network geometry defined, a hydraulic simulation is performed and model results are checked. Checking typically consists of ensuring that nodal pressures are positive throughout the system but do not exceed pipe pressure ratings.
- Adjustments are then made to pipe diameters, pump curves, valve settings, etc., and the model is re-simulated until all nodal pressures are within a desired range. This process often requires relocating pumps (especially those in series) and pressure regulators

(valves/turbines). Relocating entails rearranging the network by: deleting a pipe in between nodes; inserting the relocated pump/valve; and re-inserting a pipe where the original pump/valve was located. In some instances, depending on the node spacing, additional nodes may be created. This process is repeated until a working system is obtained.

- When the working pressures are within reasonable bounds, a pressure transient analysis may be performed to check that velocities are within reason bounds and surge pressures do not exceed pipe pressure ratings. Pipe pressure classes can then be re-assigned to pipeline segments to reduce cost. However, the hydraulic impacts of changing the pipe pressure classes and the inside pipe diameters must be examined. Other modifications are made based on engineering judgement. Final adjustments are made to the system and a total WTS cost is estimated.

For shorter WTSs in flat terrain with few pumps, nodes, pipes and valves, this process can be performed manually and in a short amount of time. However, when transmission systems cover tens to hundreds of miles, and cross undulating terrain that generates high-pressures, the process is labor intensive and time consuming. Long distance WTSs that traverse uneven terrain, typically require many computational nodes to capture changes in the terrain so pressures are adequately monitored throughout the system. More computational nodes equate to more pipe segments that increases model complexity and solution time.

Designing WTSs using current hydraulic models exposes some modeling/design limitations. The most fundamental and significant limitation is manual relocation of pumps and valves in the WTS hydraulic model. This time-consuming task hinders engineers from performing thorough optimization and alternative analyses. Manually moving pumps is especially problematic when engineers pair hydraulic models, like the EPANET Toolkit (Rossman 2000), with optimization algorithms. The toolkit allows programmers to change network settings such as demands, and pipe diameters; but cannot facilitate physical network alterations (i.e., movement of pumps, pipes, valves, nodes, etc.). Thus, most optimal pump operation studies focus on pump operations at fixed locations (e.g., Jowitt and Germanopoulos 1992; van Zyl et al. 2004; Lopez-Ibanez et al. 2008; Wu et al. 2012; Marchi et al. 2016), and optimization of valve settings at fixed locations (e.g., Jowitt and Xu 1990; Nicolini and Zovatto 2009; Ali 2014), rather than pump and valve location and operation.

Proposed Model and Benefits

Tools to rapidly move pumps are necessary for WTS optimization and are a key piece of this effort. To that end, WaterTRANS was developed, to overcome restrictions limitations in current hydraulic modeling software. WaterTRANS is a hydraulic model that locates pumps and pressure regulators (valves or turbines) in branched WTSs. WaterTRANS is further extended to integrate other important design aspects such as surge pressure and changes to pipe pressure classes along the pipeline. In this paper, WaterTRANS is integrated with a genetic algorithm (GA) optimization tool to find optimal designs that minimize life-cycle costs. GA was selected as an appropriate search method due to its ability to search complex solution spaces and solve non-linear problems. It is a heuristic and stochastic optimization search method based on natural selection and mechanisms of natural population genetics first developed by Holland (1975). These mechanisms are inspired by evolution processes such as crossover, elitism, and mutation; and have been applied to solve a variety of systems and engineering problems. The application of GA to optimize water distribution system (WDS) problems was pioneered by Goldberg and Kuo (1987). Since then, GAs have been successfully applied to optimize a range of WDS/WTS problems including: Murphy and Simpson 1992; Murphy et al. 1993; Walters and Cembrowicz 1993; Walters and Lohbeck 1993; Simpson et al. 1994; Savic and Walters 1997; Gupta 1999; Lippai et al. 1999; and Ostfeld 2005. Since then, GAs have been modified and customized to solve a variety of WDSs problems.

Detailed hydraulic modeling may not always be considered at the route selection level in effort to save engineering costs. Without assessing alternatives, life-cycle costs estimates can be premature, leading to selection of sub-optimal alternatives; especially for long-distance WTSs where pumping costs are significant. Given the new capability for rapid analysis, WaterTRANS coupled with a GA (WaterTRANS-GA) can more efficiently design and evaluate multiple pipe routes, evaluate various candidate materials, and conduct more accurate hydraulic analyses and life-cycle cost estimates; early in the planning process.

WaterTRANS MODEL DEVELOPMENT

Network Geometry

The internal network geometry used by WaterTRANS is automatically created from topographic profiles along the pipeline alignment with station (*STA*) and elevation (*Z*) data. These topographic profiles can either be generated manually or through the use of a terrain modeling software that is able to sample data off a digital terrain model (e.g., ArcGIS or AutoCAD). The sampled data pairs (*STA* and *Z*) become computational nodes in the model and the line connecting the points become individual pipe segments with lengths (L_p) and slopes (*S*) (see Figure 1). The interval (*Ds*) at which the elevation data is sampled, defines the hydraulic model resolution. For the application in this paper, *Ds* was selected so that pipe segments were approximately 610 m (2,000 feet) long. Branches and/or demands are then assigned to specified nodes.

Hydraulics

The hydraulic solver in WaterTRANS performs calculations in a stepwise manner beginning at the source and progressing downstream one node at a time (see Figure 1) while ensuring that the conservation of mass is maintained at each node:

$$\sum Q_{in} - \sum Q_{out} = Q_d \tag{1}$$

and the conservation of energy is maintained between any two nodes A and B, or:

$$H_A - H_B = h_L - H_P + H_T \tag{2}$$

where Q_{in} = flow into the node; Q_{out} = flow out of the node; and Q_d = external demand at a node. H_A and H_B = the total energy at nodes A and B; H_P = the pump head; H_T = the head reduction from the pressure regulator; and h_L = the headloss in the pipe from node A to B and is calculated using the Hazen-Williams friction loss equation:

$$h_L = \frac{10.66 L Q^{1.85}}{C^{1.85} ID^{4.87}} \tag{3}$$

where L = the pipe length (m); C = the pipe roughness coefficient (unitless; 130 for all materials); Q = the flow rate in the pipe (m^3/s); and ID = the inside diameter of the pipe (m).

Accordingly, WaterTRANS calculates system pressures, locates pumps and pressure regulators based on the relationship between the hydraulic grade line (HGL) and the *STA* and *Z* points (from the topographic profile). As the calculation proceeds downstream, the h_L in each pipe segment is calculated to determine the head at the next node. If the calculated elevation of the

HGL is above the elevation at the next node, the head at that node is stored and added to the HGL, the calculation continues to proceed downstream until one of the following conditions is encountered: (1) where the HGL intersects the topographic profile, a pump (with head H_P) is automatically inserted in between two nodes and $H_T = 0$ in Eq. 2; (2) where the difference between the HGL and the topographic profile exceeds a specified head (H_T) a pressure regulator (with head H_T) is inserted in between two nodes and $H_P = 0$ in Eq. 2. Through this process, the HGL is calculated for the entire pipeline. At branches, the computed head at that node (on the main line) becomes the starting condition for the branched line and the process is repeated for the branch.

This pump and turbine placement feature embedded into the hydraulic solver eliminates negative pressures and controls pressures throughout the system which cannot be accomplished with current hydraulic models. This logic ensures that a sound hydraulic solution is identified for every simulation and reduces the number of explicit constraints. As will be seen below, this result is important if WaterTRANS is paired with an optimization search algorithm, as it is able to more freely explore the solution space.

Pipe Pressure Class Assignment

WaterTRANS's capability is further extended by allowing various pipe pressure classes to be placed along the pipeline (which can result in significant cost savings). This feature requires an iterative process to converge on a solution due to the pipe's changing inside diameter affecting system hydraulics as discussed here (also refer to the Hydraulic Design Module on Figure 2):

- Initial inside diameters (ID_o) are specified; then the HGL, the number of pumps (N_P) and number of turbines (N_T) for the system are computed.

- Potential surge pressures are added to the HGL and a pipe pressure class (*PC*) is assigned to each pipe segment using the appropriate American Water Works Association (AWWA) pipe design criteria (discussed later). Pipe data corresponding to each pressure class such as inside diameter (*ID*), dimension ratio (*DR*) and installed unit cost (*UC*) are stored in a pipe database.

- After the appropriate pipe pressure class has been determined for each pipe segment, the corresponding *ID* is re-assigned to the appropriate pipe segment and another simulation is performed. The HGL and surge pressures are recomputed and *PC*s and corresponding *ID*s are reassigned.

- This process is repeated until the *PC* for each pipe segment converges to a single value (i.e., the HGL no longer changes). In order for the model to converge H_P and H_T remain constant throughout the iterations.

The convergence of the HGL constitutes a single hydraulic simulation. From this simulation, a total system cost is computed. The installed unit cost (*UC*) corresponding with the assigned pipe diameter and pressure class (*PC*) is then multiplied by the pipe segment length to compute capital pipe cost. Pump, turbine and other costs are also computed and added to pipe costs.

Pipe Design Criteria

WaterTRANS has design and cost information for four standard pipe materials per the American Water Works Association (AWWA): AWWA C900 Polyvinyl Chloride (PVC); AWWA C906 High-Density Polyethylene (PE); AWWA C151 Ductile Iron (DI) and AWWA C200 steel. Pipes are selected from the database and assigned to the hydraulic model based on the appropriate AWWA standards.

The required pipe pressure class is determined by checking working pressure (P_w) and surge pressure (P_s). Working pressure is determined from the HGL and the surge pressure is determined using Joukowsky's equation as defined per AWWA (2002):

$$P_s = \frac{a}{g} V \tag{4}$$

where V = the maximum velocity change (m/s); g = acceleration due to gravity (9.81 m/s^2); and a = the wave velocity of water (m/s) generically defined as:

$$a = \sqrt{\frac{k/\rho}{1 + kDR/E}} \tag{5}$$

where k = fluid bulk modulus for water (2,068 MPa [300,000 psi]); DR = the pipe dimension ratio; E = Modulus of Elasticity of the pipe material (2,575 MPa [400,000 psi] for PVC; 1,034 MPa [150,000] for HDPE; 206,842 MPa [30,000,000 psi] for Steel and 165,474 MPa [24,000,000 psi] for DI). It is assumed that flow stoppage is instantaneous in a pipe segment (i.e., V = the flow velocity in the pipe in Eq. 4) which is a conservative assumption that is practical for higher level designs. Due to the relatively high pressures in WTSs, it was determined that internal pressures (and not external loading) controls pipe thickness (and pressure class). The internal pressure design standards for each material type are discussed in the following sections.

PVC and HDPE Pipe Design

PVC and HDPE pipe are manufactured in standard pressure classes (or dimension ratios) according to criteria established in AWWA (2016) and AWWA (2015), respectively. The appropriate pressure class is selected according to two criteria:

1) The working pressure (P_w) must never exceed the pipe's pressure class (PC) rating times the temperature-compensating multiplier coefficient (F_t) defined as

$$P_w < PC \times F_t \tag{6}$$

2) The working pressure plus surge pressure must not exceed the occasional surge pressure capacity (P_w + P_s) defined as

$$P_w + P_s < \mathrm{SF} \times PC \times F_t \tag{7}$$

where SF is the 'safety factor' coefficient (1.6 for PVC pipe and 2.0 for HDPE); and F_t = 1.0.

The model selects from all diameters and pressure classes specified in AWWA (2015, 2016).

DI Pipe Design

DI pipe is also manufactured in standard pressure classes per AWWA (2009). However, selection of the pipe's pressure class is based on a thickness design requirement. The required thickness for DI pipe (t_{DI}) is calculated per AWWA (2014), which can be defined as:

$$t_{DI} = \frac{2.0(P_w + P_s)\mathrm{D}}{2S} + 2.0 + t_{ca} \tag{8}$$

Where D = the outside diameter of the pipe (mm [in.]); S = the minimum yield strength in tension (289,590 kPa [42,000 psi]); t_{ca} = the casting allowance which varies by pipe diameter per AWWA (2014); and *2.0* = the service allowance (mm; or 0.08 in.). The selected standard thickness (pressure class) must be greater than this required thickness (t_{DI}). All diameters and pressure classes up to 2,413 kPa (350 psi) as specified in AWWA (2009) are permitted here.

Steel Pipe Design

Unlike PVC, HDPE and DI, steel pipe is manufactured to a specified thickness and is not available in standard pressure classes or dimension ratios. Steel water pipe is made in accordance with AWWA (2012). The required thickness for steel pipe (t_S) is calculated per AWWA (2004) as:

$$t_S = \frac{(P_w + P_s)\mathrm{D}}{2s} \tag{9}$$

Where s = allowable design stress (kPa [psi]). When working pressure governs (i.e., $P_s < 0.5P_w$), s = 124,105 kPa (18,000 psi) or 50% of the minimum-yield strength (248,211 kPa [36,000 psi]) and $P_s = 0$. When surge pressure governs (i.e., $P_s > 0.5P_w$), s = 186,158 kPa (27,000 psi) or 75% of the minimum-yield strength (AWWA 2004). For costing and modeling purposes, steel was assumed to be available in 50 mm (2 in.) increments from 100 to 1,800 mm (4 to 72 in.) and a maximum pressure of 3,447 (500 psi).

WaterTRANS-GA SYSTEM OPTIMIZATION

As WaterTRANS is a standalone hydraulic model, system designs and costs can be obtained by manually selecting H_P, H_T and ID. Due to the long distances and large elevation changes of the system under consideration, there were countless possible design configurations. Accordingly, WaterTRANS was paired with a GA optimization scheme to help find the least cost system designs as discussed in the following.

Formulation

The objective of the optimization model is to minimize the overall life-cycle cost of the WTS while meeting system demands and pressure requirements. The total cost is the capital (construction) cost plus the operation and maintenance (O&M) over the life of the system or:

$$Minimize\ f\left(D_{n_1}, \dots, D_{n_{npipe}}, H_{P_1}, \dots H_{P_{npump}}, H_{T_1}, \dots H_{T_{nturb}}\right)$$
$$= \sum_{i=1}^{npipe} C_{pipe}(Dn_i, L_i, PC_i) + \sum_{j=1}^{npump} C_{pump}(H_{P_j}, Q_{P_j})$$
$$+ \sum_{k=1}^{nturb} C_{turb}(H_{T_k}, Q_{T_k}) + \sum_{n=1}^{nnode} C_{pen}(P_n) + C_{misc} \tag{10}$$

Where $C_{pipe}(D_i, L_i, PC_i)$ = the construction cost of pipe segment i with nominal diameter D_n, length L, and pressure class PC; $C_{pump}(H_j, Q_j)$ = the construction and operational cost of pump j with head H_P and flow Q; $C_{turb}(H_k, Q_k)$ = the construction and operational cost plus the energy credits of turbine k with head H_T and flow Q; $C_{pen}(P_n)$ = the penalty cost of node n with pressure (P_n) in exceedance of the pipe design criteria; C_{misc} = miscellaneous system costs; *npipe* = number of pipe segments; *npump* = the calculated number of pumps; *nturb* = the calculated number of turbines; and *nnode* = the number of nodes in the WTS. The objective function (Eq. 10) is subject to the hydraulic constraints defined in Eqs. 1 - 3.

Within WaterTRANS-GA, the decision variables that pass from WaterTRANS to the GA are the nominal pipe diameters (D_n), pump heads (H_P) and pressure regulator heads (H_T). Turbines are selected as the pressure regulator; thus, H_T refers to the total head removed by the turbine. A process diagram of the optimization model is provided in Figure 2 and can be summarized as follows:

- A population of nominal diameters and pump heads (either random or user specified) are generated to initiate the GA. Similarly, an initial pipe pressure class (with a constant inside diameter or *ID*) is assigned to all pipes. Based on experience with algorithm convergence and practicality, nominal pipe diameters are fixed between demand centers while individual segments may change in pressure class.

- Given that data, WaterTRANS performs a hydraulic simulation as discussed previously.
- When a simulation is completed, the objective function is computed.
- Because H_P and H_T can be allowed to exceed the pressure class of a pipe, a penalty cost is implemented. The penalty is applied if the working or surge pressures fail to meet the pipe design criteria as specified in Eqs. 6 - 9.
- The objective function cost and fitness scores for the decision variables are then passed back to the GA. This process is repeated until a GA stopping criteria is met.

Cost Functions

The cost functions used to find the least-cost system designs are provided here. These functions are specific to the project under consideration as discussed in the Case Study section.

Pipe Cost

The pipe cost (C_{pipe}; from Eq. 10) is the sum of the capital cost (C_{pipe_cap}) plus the net present value (NPV) of the operation and maintenance cost (C_{pipe_om}) for the system life-cycle defined as:

$$C_{pipe} = C_{pipe\_cap} + C_{pipe\_om} NPVc \tag{11}$$

where $C_{pipe\_om} = 0.005 C_{pipe\_cap}$ (or an annual maintenance cost of 0.5% of the initial pipe cost; USBR 2006, 2009) and $NPVc$ = the net present value coefficient for an annual discount rate of 5% and 50-year project life. C_{pipe_cap} is:

$$C_{pipe\_cap} = \sum_{i=1}^{npipe} UC_i \times L_i \tag{12}$$

where UC = the installed unit cost of pipe segment i ($/m[ft]). Installed unit costs were estimated using the WaterCOSTE program developed by Chee (2017). WaterCOSTE estimates installed unit pricing for various pipe materials, diameters and pressure classes; and considers site-specific conditions including excavation material, bedding/backfill, labor and equipment costs necessary to install the pipe. The installed unit costs for all the pipe materials considered are provided in Tables S1-S4 in the Supplementary Data.

Pump and Turbine Costs

As a turbine is essentially a pump in the reversed direction, pump and turbine capital costs were assumed to be the same based on their capacities. The total pump (C_{pump}) and turbine cost (C_{turb}) from Eq. 10, is the sum of the pump/turbine capital cost (C_{cap}) plus the NPV of operational costs (C_{oper}) and maintenance costs (C_{maint}) for the system life-cycle:

$$C_{pump} = C_{turb} = C_{cap} + (C_{oper} + C_{maint})NPVc \qquad (13)$$

A review of cost estimates developed for WTS pump stations reveals that WTS pump stations (and consequently turbines) benefit from economies of scale, i.e., the unit cost per horsepower ($/HP) reduces with larger capacity pumps. This is supported by the fact that the pump/turbine station infrastructure (i.e., pump housing, electrical wiring, controls, concrete, tanks, valves, etc.) will have a fixed initial cost regardless of the size of the pump/turbine. Watson Engineering, Inc. (2002) developed a relationship for estimating pump station costs for rural WTSs. This relationship was also assumed valid for turbine stations and was modified to reflect current costs:

$$C_{cap} = (500{,}000 + 695.303H - 0.06701H^2) \qquad (14)$$

where $H = H_P$ or H_T (the pump/turbine horsepower) which is calculated as:

$$H = \left(\frac{\gamma Q H}{\eta}\right) \tag{15}$$

where γ = specific weight of water; η = the efficiency (75% for pumps; and 90% for turbines); Q = the flow rate through the pump/turbine (m^3/s). C_{oper} is the annual energy costs/credits for the pump/turbine:

$$C_{oper} = \underbrace{8760 C_E \frac{P_{pd}}{PF}}_{cost\ of\ power} + \underbrace{12 P_{pd} C_D}_{demand\ charge} \tag{16}$$

where C_E = either the electricity cost for pump operation ($0.0425/kWh) or the electricity credits generated by the turbine (-$0.02/kWh); P_{pd} = either the peak power demand for pumps or the peak power generation for turbines (*0.746Hp*; kW); C_D = either the monthly demand charge for pumps ($16.50/kW) or equals zero for turbines; and *PF* = the peak factor (2).

C_{maint} is the annual pump/turbine maintenance cost which is estimated according to Eyer (1965):

$$C_{maint} = \underbrace{0.96 Q^{0.11} H^{0.41} V^{0.43} W_o}_{Labor\ Costs} + \underbrace{2.0 Q^{0.11} H^{0.41} V^{0.43} I}_{Other\ Costs\ (Supplies,\ etc.)} \tag{17}$$

where V = the annual volume of water pumped (ac-ft); *Wo* = mechanic's hourly wage rate ($/hr); Q = flowrate in pump/turbine (cfs); I = the ratio of current price level to 1965 level (using RS Means historical cost indices = 22.7/207.2).

Miscellaneous Costs

C_{misc} consists of SCADA equipment installation costs (3% of the total capital cost), corrosion and cathodic protection of steel and DI pipe (1% of C_{pipe}), unlisted items such as gate valves, air relief valves, and fittings (10% of the C_{pipe}). Storage tanks were not considered. Water treatment plant was also not included as this was assumed to be the same cost for all alternatives.

Penalty Costs

Penalty costs (C_{pen} in Eq. 10) for HDPE, PVC and steel pipe are based on the sum of exceedances for two conditions:

$$C_{pen} = C_{pen\_pw} + C_{pen\_tp} \tag{18}$$

where C_{pen_pw} = the working pressure penalty (\$), and C_{pen_tp} = the total pressure penalty (\$). When the working pressure (P_w) exceeds the standard pressure class (PC), C_{pen_pw} for PVC and HDPE is calculated as:

$$C_{pen\_pw} = \sum_{i=1}^{npipe} \left| PC_i - P_{w_i} \right| Cp \tag{19}$$

where Cp = the penalty coefficient (\$10M). When the total pressure (P_w+P_s) exceeds SF×PC, C_{pen_tp} for PVC and HDPE is calculated as:

$$C_{pen\_tp} = \sum_{i=1}^{npipe} \left| SF \times PC_i - P_{w_i} \right| Cp \tag{20}$$

When the working pressure condition governs (i.e. P_s<0.5P_w) the working pressure penalty (which substituted into Eq. 18) for steel is:

$$C_{pen\_pw} = \sum_{i=1}^{npipe} \left| \frac{(2t_{S_i} \times 18{,}000)S}{D_i} - (P_{w_i}) \right| Cp \tag{21}$$

When the surge pressure condition governs (i.e. P_s >0.5P_w) the total pressure penalty for steel is

$$C_{pen\_tp} = \sum_{i=1}^{npipe} \left| \frac{(2t_{S_i} \times 27{,}000)S}{D_i} - (P_{w_i} + P_{s_i}) \right| Cp \tag{22}$$

The penalty cost for DI pipe is based on the exceedance of the total pressure corresponding to required thickness. When the total pressure (P_w+P_s) exceeds the pressure rating corresponding to the selected standard thickness, the penalty is calculated as:

$$C_{pen} = \sum_{i=1}^{npipe} \left| \frac{(t_{DI_i} - 0.08 - t_{ca})S}{D_i} - (P_{w_i} + P_{s_i}) \right| Cp \tag{23}$$

MODEL APPLICATION

Case Study

WaterTRANS-GA was applied to design two route options for the North Central Arizona Regional Water Supply Project (NCAZ Project) that is intended to deliver renewable water supplies from Lake Powell to northeastern Arizona communities (USBR 2006; see Figure 3). Four pipe materials (PVC, HDPE, DI and steel) were considered for each alignment (a total of 8 different design alternatives). The lower portions of the two routes (i.e., below Gap) share the same alignment. Route 1 is the USBR (2006) proposed alignment in which the northern portion of the pipeline crosses open rural terrain then follows a local highway. Route 2, on the other hand, parallels a major recreational traffic corridor that provides to access Lake Powell. In addition, the higher-capacity portion of the pipeline is in closer proximity to scenic areas near the Grand Canyon. Route 2 was considered for its potential to spur economic development in the region and its shorter total length (174 km vs. 190 km [108 miles vs. 118 miles]). However, the total elevation change for Route 2 is slightly larger (735 m vs. 728 m [2,413 feet vs. 2,390 feet]). A peak factor of 2 was used to size and cost the WTSs (demands are shown on Figure 3).

Application of the model demonstrates how it can be used to: evaluate route alternatives; provide accurate cost estimates; and help guide pipe material selection by analyzing costs and hydraulic performance. However, as both routes deliver water to a number of unserved reservation residents and have different long term economic impacts, it is clear that cost is only one component of the route selection process.

Model Performance

Because of the heuristic (random) nature of GAs, multiple model simulations (runs) were performed in order to find optimal solutions. The least-cost and most practical design of the multiple runs was selected as the optimal design. Model runs were performed using various initial population sets consisting of: (1) starting diameters corresponding to velocities ranging between 1.2 and 1.8 m/s (4 and 6 fps), similar to the approach taken by Kang and Lansey (2012); and (2) starting initial pump and turbine head ranges that were close to the maximum static head rating for each type of pipe material. The least-cost and most practical of the multiple runs was further improved upon by using that solution set as the starting population for subsequent runs until the cost could no longer be improved.

GA parameters (elite count, crossover rate and mutation function) were held constant in all runs. Multiple trail runs and sensitivity analyses yielded a cross over fraction of 0.5, an elite count of 0.3 and a uniformly distributed mutation function were found to be the best parameters. These parameters paired well with the initial populations; adequately searched the solution space (i.e., did not converge to quickly); and had the best performance for converging to similar solutions every run. Random initial populations yielded non-optimal solutions, and were not used for simulation runs.

In general, the WaterTRANS-GA generated relatively consistent solutions in terms of costs and pipe sizes from the multiple runs that were performed for each design alternative. However, differences emerged in pump/turbine locations and consequently pipe pressure classes. An important tradeoff that was observed is that the primary tension in this system is between pipe class and pumping head. The model either: (1) chose lower pump/turbine heads (or more pump/turbine stations) and lower pressure class pipe; or (2) selected larger pump/turbine heads (or fewer pump/turbine stations) resulting in slightly higher pressure class pipe. Both had similar total costs. From an operational perspective, the more practical solution is to reduce the number of pump/turbine stations and a slightly higher pipe cost. Here, the design that exhibited the best combination of practicality and cost was selected.

Results

Cost Overview

Route 2 was generally more expensive than Route 1 for all materials (Figure 4) due to the higher pumping O&M cost required for Route 2 (Table 1). The main O&M cost differentiator was not the total pipe length or total elevation change, but rather the profile of the terrain of the main trunk line (larger diameter portion of pipeline). The main trunk line for Route 2 traversed two large hills that require additional pumps as opposed to one hill for Route 1 (see Figures 5 and 6). Terrain profiles and HGLs for spurs off the main trunk line are provided in Figures S1 – S4 in the Supplementary Data. With the exception of the DI design for Route 2, the largest cost was for pumping O&M (ranging between 36% and 61% of the total cost) followed by pipe capital costs (ranging between 21% and 46%).

Although pumping O&M costs were the largest cost component, the differences in total cost amongst design alternatives were driven by pipe capital cost and the differences in material costs (Figure 4 and Table 1). Pump capital was the next most significant cost factor (ranging between 6% and 11%) of the total cost. The remaining cost factors (Pipe O&M, SCADA controls, turbine capital, turbine O&M, cathodic protection and miscellaneous) did not significantly influence total costs.

With respect to pipe material, PVC was the least expensive while DI pipe was the most expensive for both routes. Steel was cheaper than HDPE by about 2% for Route 1 and 8% for Route 2; and came close to the cost of PVC (Table 1). The performance of the various materials on specific sections of terrain also affected total costs.

With the exception of the HDPE pipe alternative for Route 2, turbines incorporated into the designs did not justify their capital expense. They do not generate sufficient energy (revenues) to cover their O&M costs. In these cases, turbines should be replaced by pressure reducing valves with equivalent heads.

PVC and HDPE Pipe System Designs

PVC pipe required both systems to operate at relatively lower pressures (compared to DI and steel). The average pipe pressure class was about 1,082 kPa and 1,041 kPa (157 and 151 psi) for Routes 1 and 2, respectively. The selection of lower pressure class pipe is due primarily to its lower material strength and pressure limitations. The maximum PVC pressure class is 2,102 kPa (305 psi) for pipes up to 450 mm (18 in.). It then gradually decreases with larger pipe sizes; down to 1,138 kPa (165 psi) for a 1,500 mm (60 in.) pipe.

Because of the lower available pressure classes, PVC designs required more pump stations than DI and steel (Table 2). Six (6) pump stations each were required for the long uphill slopes for both options (Figures 5 and 6), while DI and steel only required five. On the long gradual downhill slopes, the hydraulic grade line (HGL) ran parallel to the terrain reducing the need for turbines/PRVs. Relatively small PVC diameter pipes were selected to control pressures though pipe energy headlosses that also resulted in fairly high flow velocities compared to DI and steel. The average flow velocities in pipes P3 – P5 for Route 1 ranged from 1.98 – 2.07 m/s (6.5 – 6.8 fps) for PVC, compared to 1.19 – 1.31 m/s (3.9 – 4.3 fps) for DI, and 1.68 – 1.92 m/s (5.5 – 6.3 fps) for steel (see Table S5 in the Supplementary Data). Turbine/PRV's are avoided in PVC pipe in flatter downhill sections due to its lower modulus of elasticity that reduces the magnitude of potential surge pressures. On steep slopes turbines were needed as pipe friction losses were insufficient to lower pressure levels (Route 2 on Figure 6).

HDPE designs had lower pressure class pipe and fewer turbines with hydraulic performance similar to PVC pipe. Because of the generally lower available pressure classes, HDPE required the same number of pump stations as PVC (Table 2). Because of its even lower modulus of elasticity, HDPE controlled pressures slightly better than PVC through pipe headlosses/sizing. HDPE required one less turbine than PVC for Route 2 (Table 5 and Figure 6) and had the highest average velocities on the downhill slopes (pipes P3-P5 for Route 1 and pipes P5-P6 for Route 2; Tables S5 and S6).

DI and Steel Pipe System Designs

DI performed differently than the plastic materials. Due to its higher strength, the average pipe pressure class was about 1,813 kPa (263 psi) for Route 1 and 1,731 kPa (251 psi) for Route 2. DI available pipe pressure classes range to 2,413 kPa (350 psi) for diameters up to 1,600 mm (64-

in.; special thickness classes that allow higher pressures are available but were not considered). The commercial pressure class designations for DI include an additional 689 kPa (100 psi) surge pressure allowance (AWWA 2014) that increases the actual pressure rating of the pipe (i.e., a 2,413 kPa [350 psi] pressure class pipe would actually be rated for 3,103 kPa [450 psi]).

As a result of DI's higher pressure rating, its designs required fewer pump stations compared with HDPE and PVC pipe systems. DI's high strength also makes it susceptible for higher surge pressure potential. As a result, the DI design resulted in the slowest total average flow velocities for both routes (1.13 m/s [3.7 fps] for Route 1 and 1.07 m/s [3.5 fps] for Route 2). The slower flow velocities resulted in lower pipe head losses (characterized by a flatter HGL) and smallest pumping O&M costs (Table 1). Lastly, because of the low headlosses, DI was not able to self-regulate pressures (through pipe headlosses) on the downhill slopes like PVC and HDPE. This resulted in DI systems having the most turbines (Table 2).

Because of its strength, steel operated at pressures similar to DI. The average pressure class was 2,648 kPa (384 psi) for Route 1 and 2,234 kPa (324 psi) for Route 2. Steel required the same number of pump stations as DI and required one less turbine station than DI. Although surge pressure potential is the highest in steel, it still was able to self-regulate pressures through pipe headlosses on downhill slopes (Figures 5 and 6) because the thickness design criteria for steel is less conservative than DI pipe (Eq. 10). When surge conditions govern (i.e., surge pressures are more than 50% of the normal working pressure), stresses in the pipe are allowed to reach up to 75% of the yield strength, whereas DI pipe only allows surge plus operating pressures to reach up to 50% of the yield strength. As a result, higher velocities could be achieved to self-regulate pressures on the downhill runs and demonstrates steel pipe's versatility.

Discussion

The performance of each pipe material and its influence on system cost in this application can help guide pipe material selection in regard to WTS design. Key points are summarized here:

- PVC and HDPE perform very similarly. Their application can be limited due to their pressure ratings that requires more pump stations when elevation changes quickly.
- PVC and HDPE are more appropriate and cost-effective for smaller diameter applications and flatter terrains. In gradual downhill conditions, PVC/HDPE pipes can accommodate higher velocities to increase head losses and the resulting potential surge pressures since the materials are more flexible. These velocities may eliminate the need for turbines (or PRVs); reducing costs and simplifying operations.
- While DI pipe is the most expensive material, it’s advantage is in its strength and ability to withstand high operating pressures. Withstanding high pressures, allows the distance between pump stations to be increased on long uphill slopes, and to handle higher pressure differentials caused by changes in the terrain (e.g., valley crossings). However, this strength is also a weakness in downhill conditions as the pipe stiffness increases surge pressure potential. Here, this resulted in lower velocities compared to the other materials examined. The net result was more pressure regulation (through turbines) in steep pipe segments since pipe friction could not be used to regulate pressure.
- Steel demonstrated its versatility for use in WTSs that cross undulating terrain. Although more expensive on a unit basis, steel was competitive with HDPE and PVC in overall cost. Because of its high strength and its ability to accommodate higher pressures, the distance between pump stations was similar to DI pipe (requiring significantly less pump

stations than HDPE and PVC). In addition, since steel is less rigid, it was better at handling surge pressures than DI pipe so it can self-regulate pressures on the long gradual downhill slopes with high velocity/friction loss flow.

For the project and pipe materials considered here, steel provided a good balance between strength and rigidity. From an operational standpoint, it required the least number of pump and turbine stations. It is clear that installing different material types specific to pipe segment conditions can provide additional cost savings. For example, steel is most appropriate for long uphill runs and in valleys to minimize the number of pump stations/turbines and PVC or HDPE is most effective for long gradual downhill runs to minimize pressure regulators.

Lastly, it should be noted that the design criteria for surge pressure assumed instantaneous stoppage of flow for all materials, in reality, controls can be put into place such as non-slam valves, surge vessels, air release valves, etc., that could help reduce the surge pressures. This would require more detailed design analysis. However, the results of such an analysis would most likely not affect the cost results presented here.

SUMMARY AND CONCLUSION

A novel hydraulic modelling software - WaterTRANS - has been developed that provides WTS design using PVC, HDPE, DI and steel pipe materials. WaterTRANS designs branched WTSs and is able to automatically locate pump stations and pressure regulators. The hydraulic network used in WaterTRANS is created by drawing an alignment over a digital terrain model and sampling terrain data to generate profiles. WaterTRANS is also able to assign pipe pressure classes to sections of the pipeline based on the modeled working and surge pressures in accordance with AWWA standards. This capability improves hydraulic modeling accuracy as it accounts for the actual inside pipe diameter associated with different pressure classes and for a more accurate pipe cost estimates.

WaterTRANS was then linked with a GA to find least-cost designs for the NCAZ project, a proposed long WTS in northern Arizona. A total of eight designs were optimized; four (4) candidate pipe materials for two (2) alternate routes. PVC was found to be the least expensive design followed by steel, HDPE and DI. Although it was not the lowest cost, steel was the ideal candidate material for the project as it was the most cost effective. Its strength allowed for design and, likely, operational flexibility. The model results also provide insights into how the various materials performed on the various sections of the terrain as described in the Discussion section.

ACKNOWLEDGEMENTS

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SUPPLEMENTAL DATA

The supplemental data provides: terrain profiles and hydraulic gradelines figures for the pipeline spurs of the main trunk line; pipe data and unit pricing for the WaterTRANS-GA model; and model output pipe hydraulic data. It is available online in the ASCE Library (www.ascelibrary.org).

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Figure 1. Hydraulic Model Creation

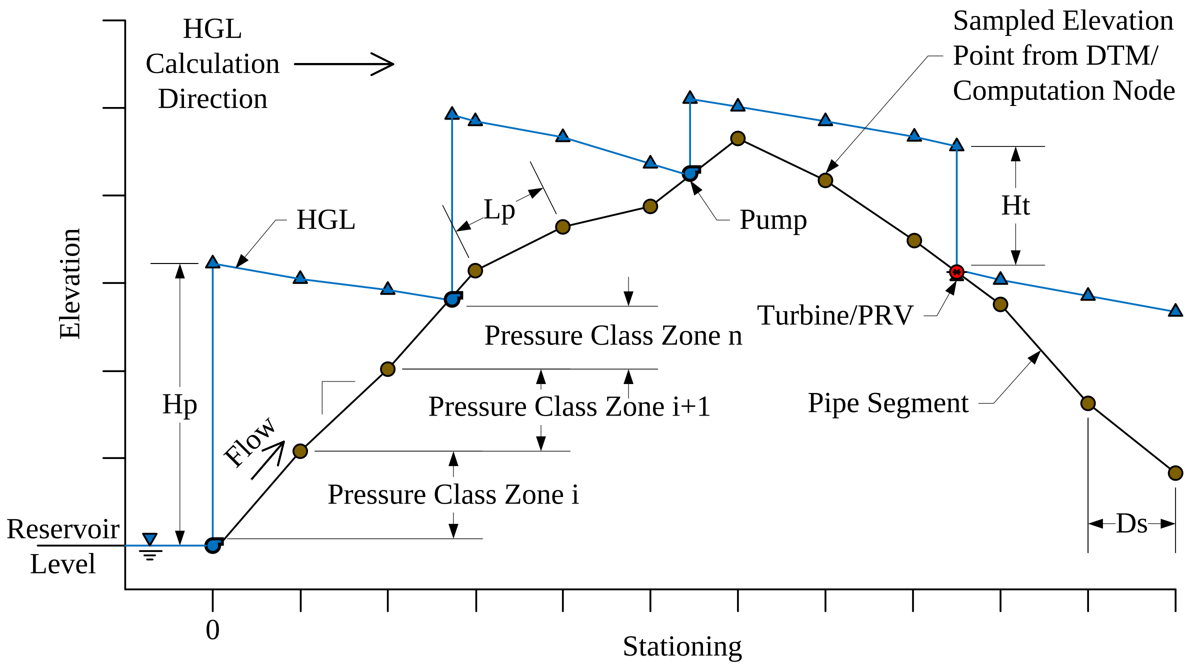


Figure 2. WaterTRANS-GA Flow Chart

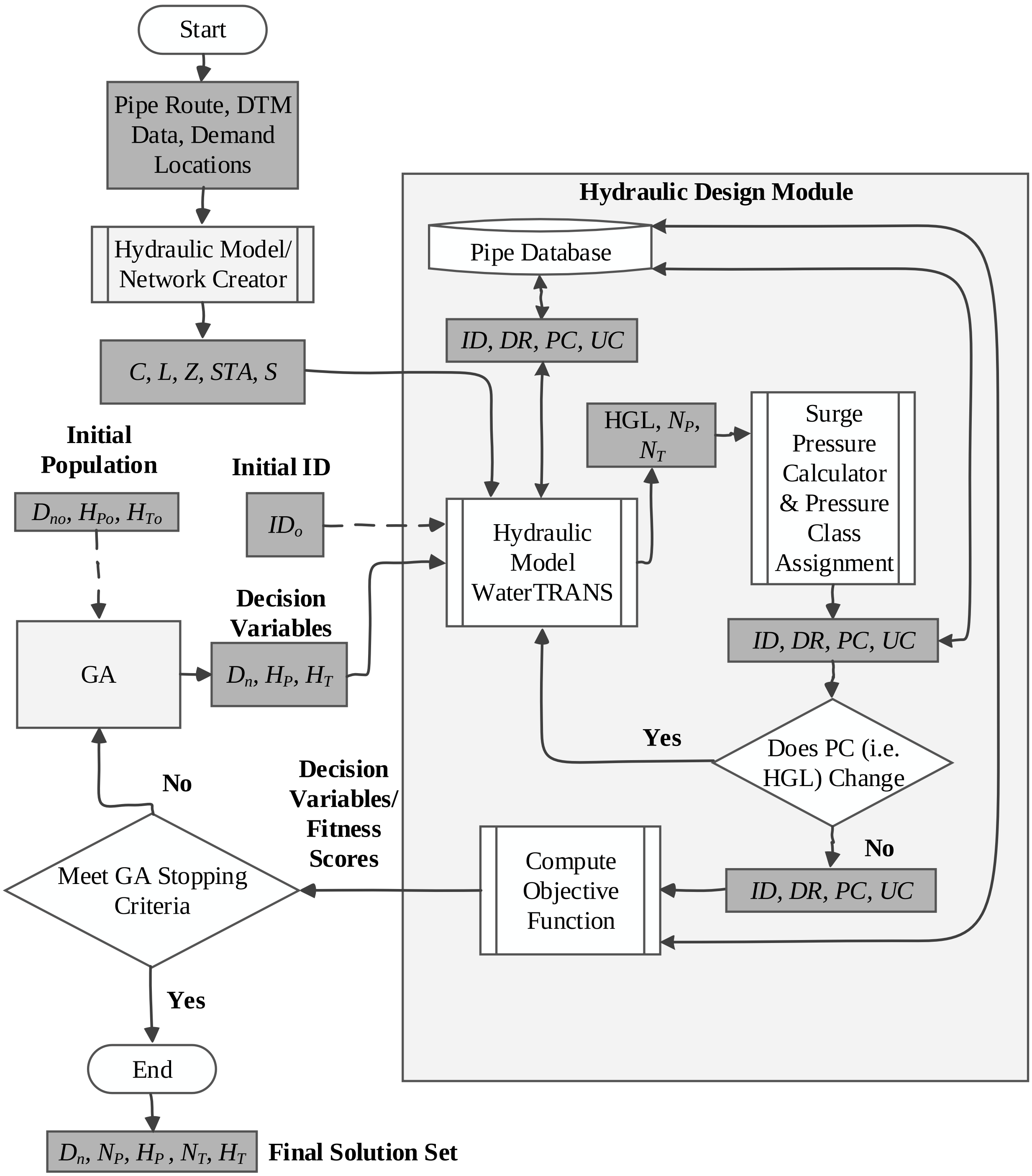
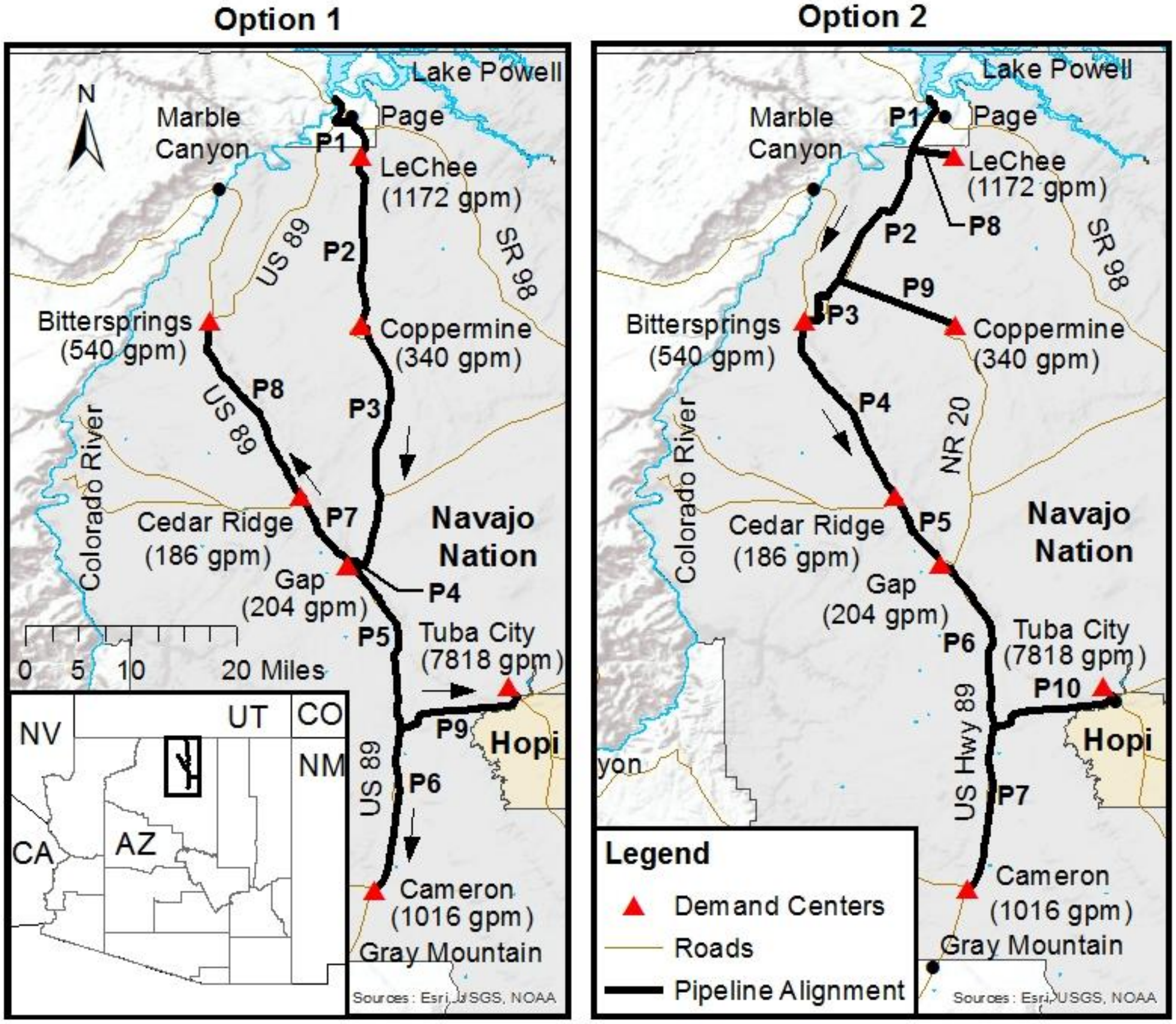


Figure 3. North Central Arizona Regional Water Supply Project Alignment Alternatives



Note: Multiply demands by 0.06309 to convert to L/s; multiply distance by 1.609 to convert to km.

Figure 4. Cost Comparison Results

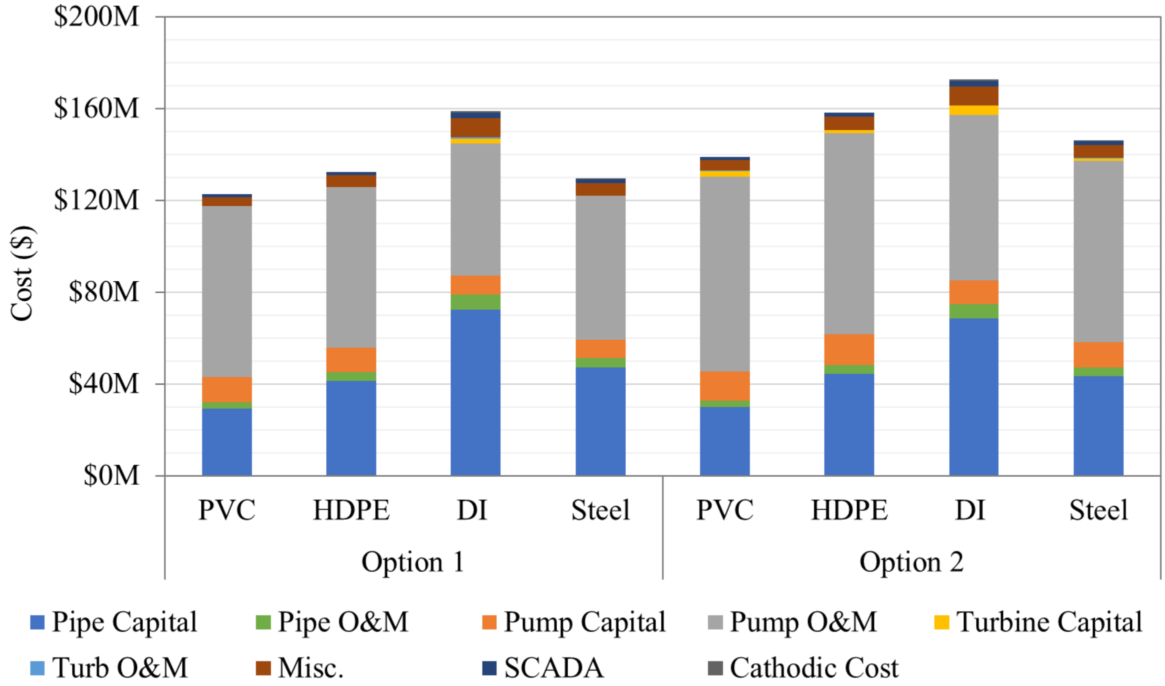
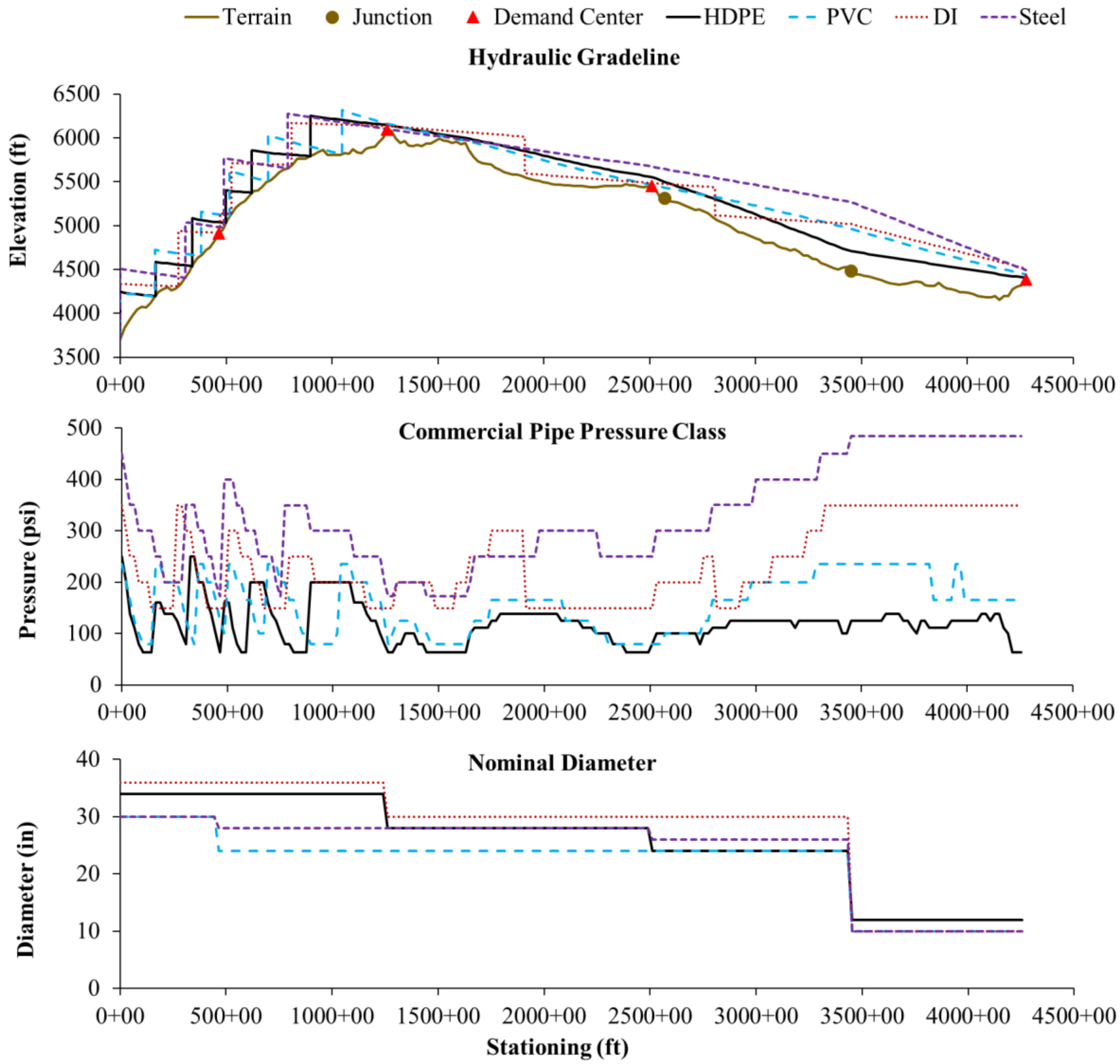
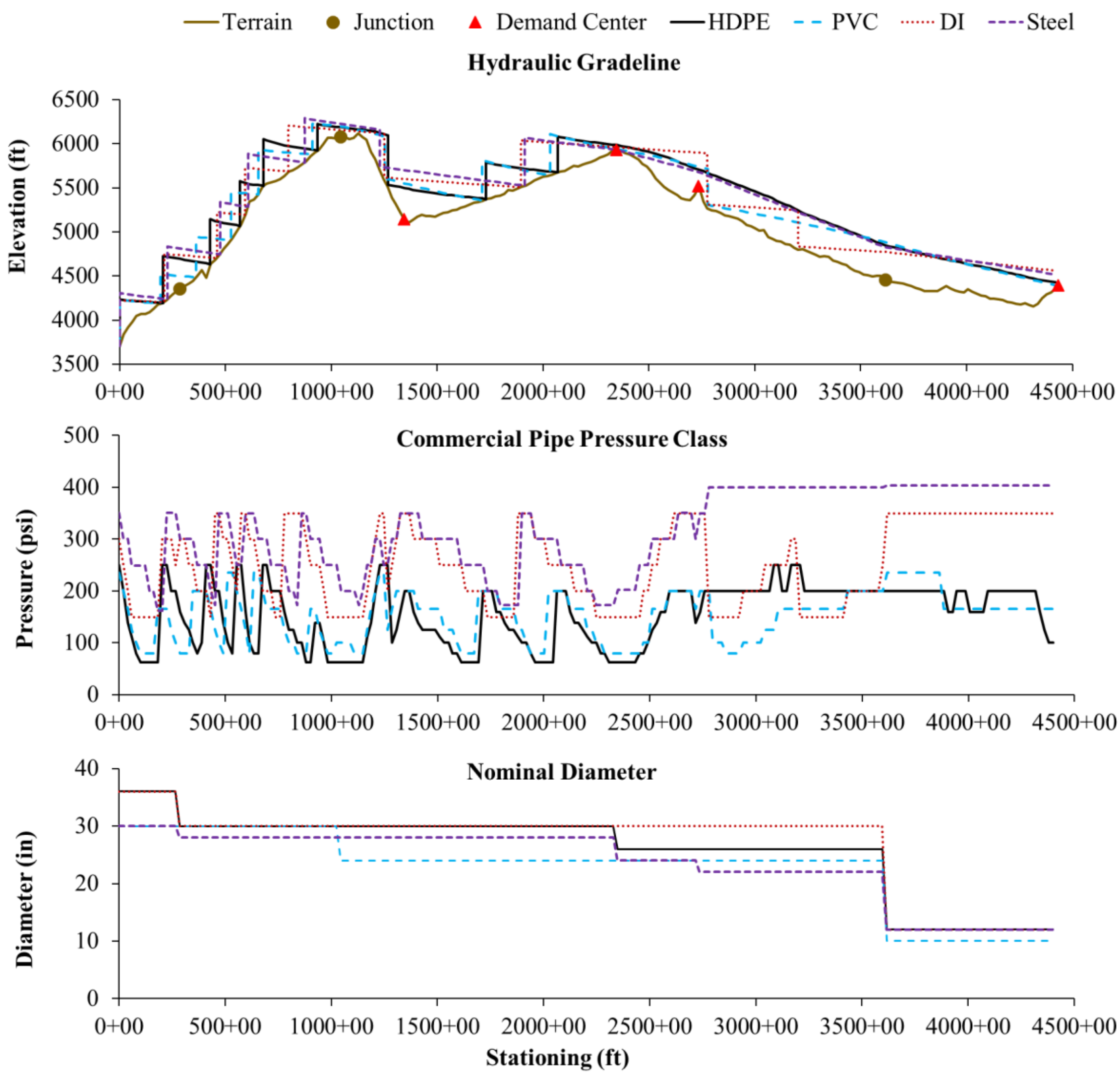


Figure 5. Hydraulic Design Comparison – Route 1 – Page to Cameron



Note: Multiply elevation and stationing by 0.3048 to convert to m; multiply pressure by 6.894 to convert to kPa; mulitply diameter by 25.4 to convert to mm.

Figure 6. Hydraulic Design Comparison – Route 2 – Page to Cameron Route



Note: Multiply elevation and stationing by 0.3048 to convert to m; multiply pressure by 6.894 to convert to kPa; mulitply diameter by 25.4 to convert to mm.

Table 1. Route 1 – Cost Results (in $M)

	Material Type	Pipe Capital	Pipe O&M	Pump Capital	Pump O&M	Turbine Capital	Turbine O&M	SCADA	Misc.	Cathodic Protection	Total
Route 1	PVC	29.4	2.7	10.9	74.4	-	-	1.2	4.0	-	122.6
	HDPE	41.3	3.8	10.5	70.1	-	-	1.6	5.2	-	132.5
	DI	72.4	6.6	8.2	57.6	2.2	0.5	2.5	8.3	0.7	159.0
	Steel	47.1	4.3	7.9	62.8	-	-	1.7	5.5	0.5	129.8
Route 2	PVC	29.8	2.7	12.9	84.8	2.4	0.3	1.4	4.5	-	138.8
	HDPE	44.3	4.0	13.2	87.7	1.4	(0.1)	1.8	5.9	-	158.2
	DI	68.5	6.3	10.2	72.4	3.8	0.1	2.5	8.3	0.7	172.8
	Steel	43.3	4.0	10.7	79.1	1.2	0.1	1.7	5.5	0.4	146.0

Table 2. Pump and Turbine Results

	Material Type	No. Pumps	Avg. Pump Head (m[ft])	No. Turbines	Avg. Turbine Head (m[ft])
Route 1	PVC	8	147.5 (484)	-	-
	HDPE	8	141.7 (465)	-	-
	DI	6	160.9 (528)	2	112.8 (370)
	Steel	5	213.4 (700)	-	-
Route 2	PVC	10	130.8 (429)	2	134.1 (440)
	HDPE	10	131.4 (431)	1	170.7 (560)
	DI	7	148.1 (486)	3	151.5 (497)
	Steel	7	163.4 (536)	1	128.0 (420)

Optimal Design of Water Transmission Systems

Ronson Chee and Kevin Lansey

SUPPLEMENTAL DATA

This supplementary data provides: terrain profiles and hydraulic gradelines figures for the pipeline spurs of the main trunk line (Figures S1-S4); pipe data and unit pricing for the WaterTRANS-GA model (Table S1-S4); and model output pipe hydraulic data (Tables S5-S6).

Figure S1. Hydraulic Design Comparison – Route 1 – Bittersprings Spur

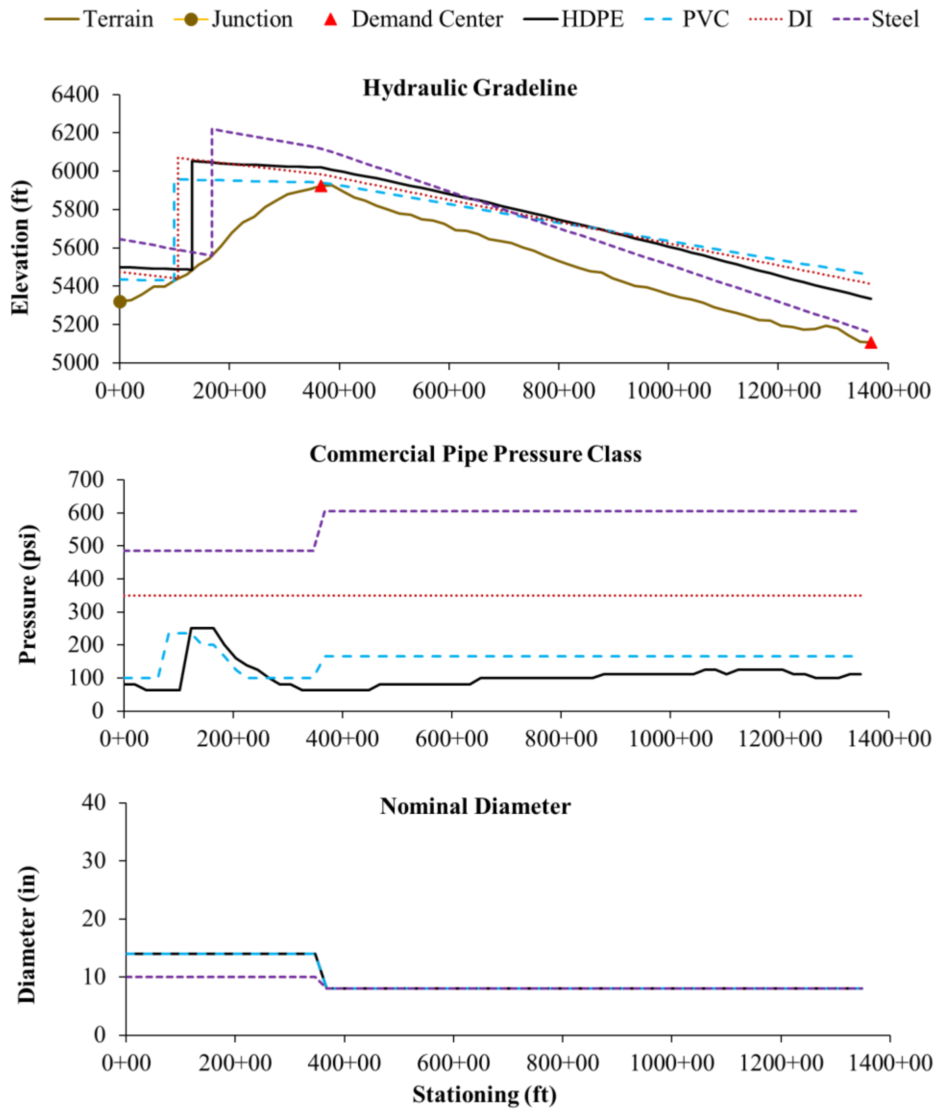


Figure S2. Hydraulic Design Comparison – Route 1 – Tuba City Spur

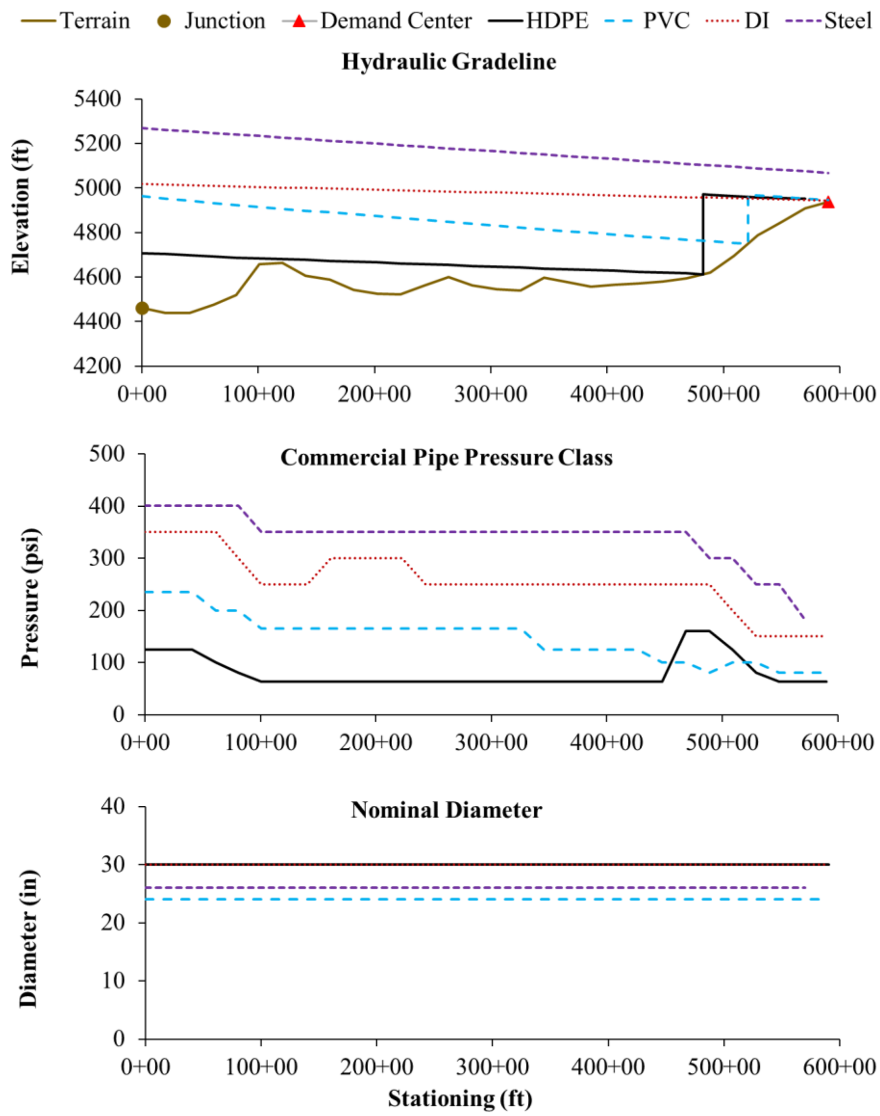


Figure S3. Hydraulic Design Comparison – Route 2 – LeChee & Coppermine Spurs

(a) LeChee Spur (b) Coppermine Spur

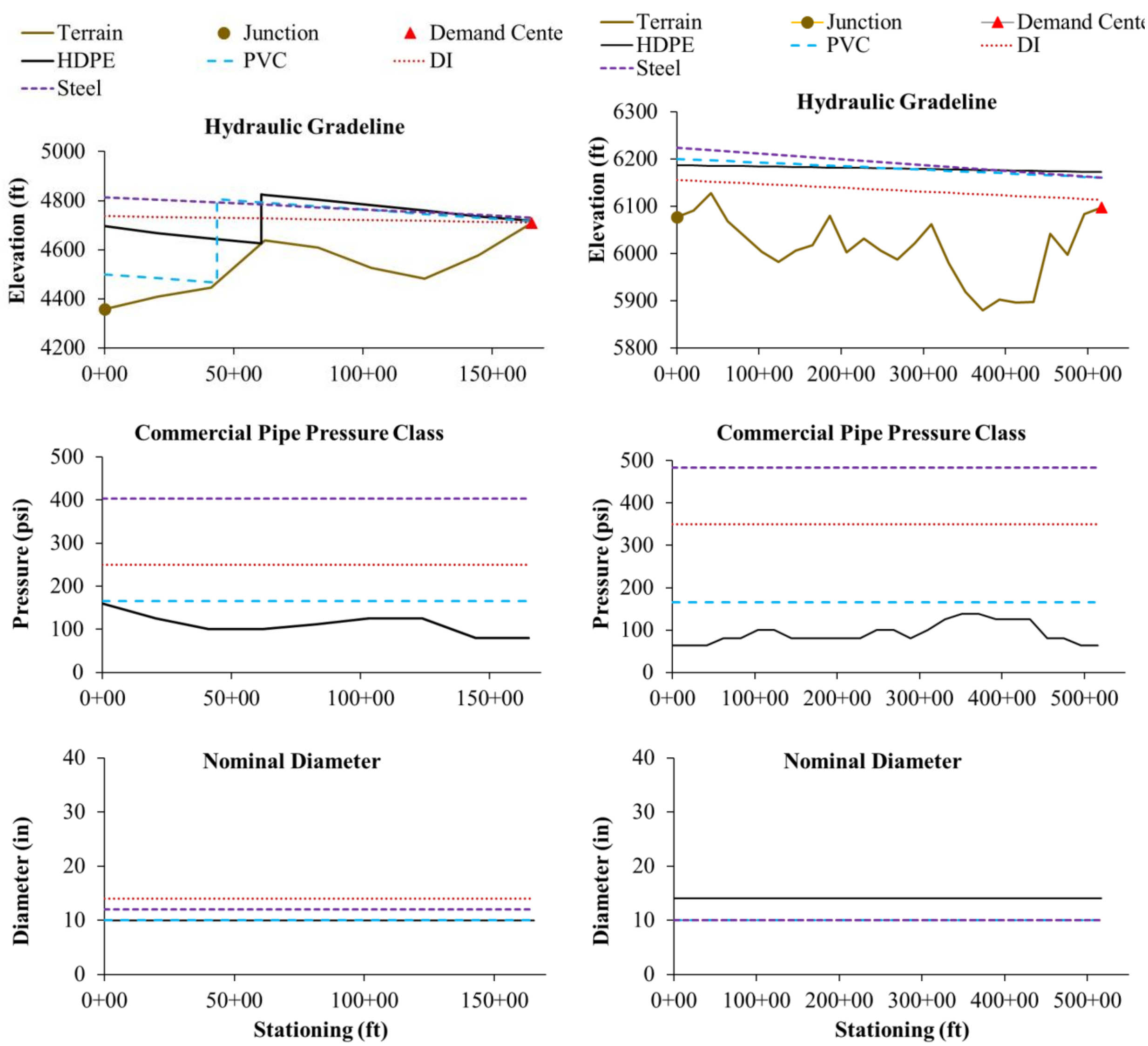


Figure S4. Hydraulic Design Comparison – Route 2 – Tuba City Spur

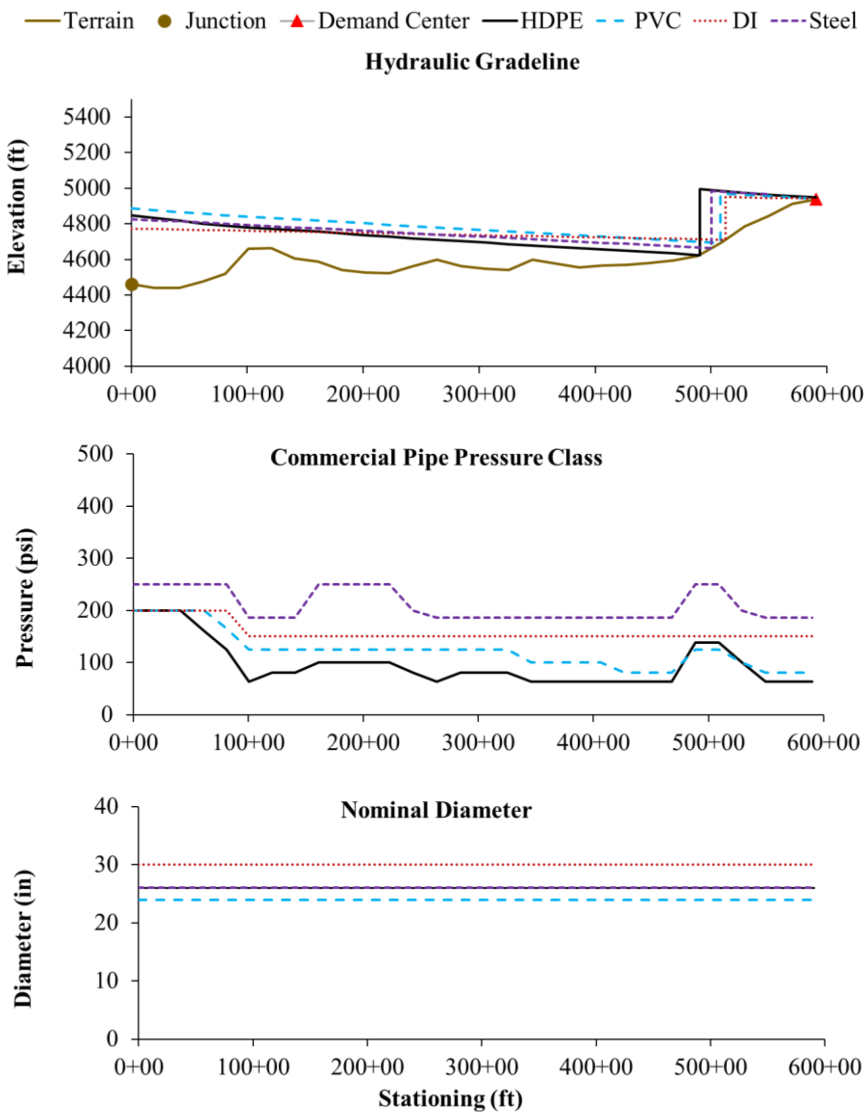


Table S1. PVC Data

Nominal Size	OD	DR	Thickness	ID	Pressure Class	Installed Cost ($/ft)
4	4.8	14	0.343	4.114	305	$ 11.85
4	4.8	18	0.267	4.266	235	$ 11.38
4	4.8	25	0.192	4.416	165	$ 10.89
6	6.9	14	0.493	5.914	305	$ 14.96
6	6.9	18	0.383	6.134	235	$ 13.99
6	6.9	25	0.276	6.348	165	$ 13.01
8	9.05	14	0.646	7.758	305	$ 19.02
8	9.05	18	0.503	8.044	235	$ 17.35
8	9.05	25	0.362	8.326	165	$ 15.64
10	11.1	14	0.793	9.514	305	$ 24.75
10	11.1	18	0.617	9.866	235	$ 21.23
10	11.1	25	0.444	10.212	165	$ 18.60
12	13.2	14	0.943	11.314	305	$ 31.26
12	13.2	18	0.733	11.734	235	$ 27.59
12	13.2	25	0.528	12.144	165	$ 22.86
14	15.3	14	1.093	13.114	305	$ 40.27
14	15.3	18	0.85	13.600	235	$ 35.25
14	15.3	21	0.729	13.842	200	$ 32.59
14	15.3	25	0.612	14.076	165	$ 30.15
14	15.3	32.5	0.417	14.466	125	$ 27.05
14	15.3	41	0.373	14.554	100	$ 23.65
16	17.4	14	1.243	14.914	305	$ 47.52
16	17.4	18	0.967	15.466	235	$ 40.88
16	17.4	21	0.829	15.742	200	$ 37.74
16	17.4	25	0.696	16.008	165	$ 34.49
16	17.4	32.5	0.535	16.330	125	$ 30.59
16	17.4	41	0.424	16.552	100	$ 27.81
18	19.5	14	1.393	16.714	305	$ 55.98
18	19.5	18	1.083	17.334	235	$ 48.67
18	19.5	21	0.929	17.642	200	$ 44.56
18	19.5	25	0.78	17.940	165	$ 40.46
18	19.5	32.5	0.6	18.300	125	$ 35.49
18	19.5	41	0.476	18.548	100	$ 31.93
18	19.5	51	0.382	18.736	80	$ 29.08
20	21.6	18	1.2	19.200	235	$ 58.46
20	21.6	21	1.029	19.542	200	$ 53.24
20	21.6	25	0.864	19.872	165	$ 48.27

20	21.6	32.5	0.665	20.270	125	$ 42.05
20	21.6	41	0.527	20.546	100	$ 37.68
20	21.6	51	0.424	20.752	80	$ 34.52
24	25.8	18	1.433	22.934	235	$ 77.59
24	25.8	21	1.229	23.342	200	$ 69.95
24	25.8	25	1.032	23.736	165	$ 62.89
24	25.8	32.5	0.794	24.212	125	$ 53.88
24	25.8	41	0.629	24.542	100	$ 47.81
24	25.8	51	0.506	24.788	80	$ 42.85
30	32	18	1.778	28.444	235	$ 117.92
30	32	21	1.524	28.952	200	$ 106.65
30	32	25	1.28	29.440	165	$ 95.09
30	32	32.5	0.985	30.030	125	$ 79.78
30	32	41	0.78	30.440	100	$ 69.78
30	32	51	0.627	30.746	80	$ 61.85
36	38.3	21	1.824	34.652	200	$ 156.32
36	38.3	25	1.532	35.236	165	$ 138.31
36	38.3	32.5	1.178	35.944	125	$ 116.85
36	38.3	41	0.934	36.432	100	$ 101.33
36	38.3	51	0.751	36.798	80	$ 90.63
42	44.5	25	1.78	40.940	165	$ 190.77
42	44.5	32.5	1.369	41.762	125	$ 160.99
42	44.5	41	1.085	42.330	100	$ 139.71
42	44.5	51	0.872	42.756	80	$ 123.45
48	50.8	25	2.032	46.736	165	$ 263.07
48	50.8	32.5	1.563	47.674	125	$ 218.93
48	50.8	41	1.239	48.322	100	$ 188.78
48	50.8	51	0.996	48.808	80	$ 167.13
54	57.56	25	2.303	52.954	165	$ 375.96
54	57.56	32.5	1.771	54.018	125	$ 312.52
54	57.56	41	1.404	54.752	100	$ 267.80
54	57.56	51	1.129	55.302	80	$ 233.65
60	61.61	25	2.465	56.680	165	$ 473.59
60	61.61	32.5	1.896	57.818	125	$ 390.64
60	61.61	41	1.503	58.604	100	$ 331.85
60	61.61	51	1.208	59.194	80	$ 283.00

Table S2. HDPE Data

Nominal Size (in)	OD (in)	DR (in)	Thickness (in)	ID (in)	Pressure Class (psi)	Installed Cost ($/ft)
4	4.5	7	0.643	3.137	333	$ 13.54
4	4.5	7.3	0.616	3.29	317	$ 13.42
4	4.5	9	0.5	2.751	250	$ 12.89
4	4.5	11	0.409	3.633	200	$ 12.46
4	4.5	13.5	0.333	3.793	160	$ 12.08
4	4.5	15.5	0.29	3.885	138	$ 11.85
4	4.5	17	0.265	3.939	125	$ 11.71
4	4.5	19	0.237	3.998	111	$ 11.55
4	4.5	21	0.214	4.046	100	$ 11.44
4	4.5	26	0.173	4.133	80	$ 11.25
4	4.5	32.5	0.138	4.206	63	$ 11.04
6	6.625	7	0.946	4.619	333	$ 18.26
6	6.625	7.3	0.908	4.701	317	$ 18.02
6	6.625	9	0.736	5.064	250	$ 16.87
6	6.625	11	0.602	5.348	200	$ 15.92
6	6.625	13.5	0.491	5.585	160	$ 15.09
6	6.625	15.5	0.427	5.719	138	$ 14.60
6	6.625	17	0.39	5.799	125	$ 14.31
6	6.625	19	0.349	5.886	111	$ 13.96
6	6.625	21	0.315	5.956	100	$ 13.71
6	6.625	26	0.255	6.085	80	$ 13.30
6	6.625	32.5	0.204	6.193	63	$ 12.85
8	8.625	7	1.232	6.013	333	$ 24.96
8	8.625	7.3	1.182	6.12	317	$ 24.54
8	8.625	9	0.958	6.593	250	$ 22.61
8	8.625	11	0.784	6.963	200	$ 18.99
8	8.625	13.5	0.639	7.271	160	$ 16.99
8	8.625	15.5	0.556	7.445	138	$ 16.43
8	8.625	17	0.507	7.549	125	$ 17.32
8	8.625	19	0.454	7.663	111	$ 16.74
8	8.625	21	0.411	7.754	100	$ 16.31
8	8.625	26	0.332	7.922	80	$ 15.61
8	8.625	32.5	0.265	8.062	63	$ 14.86
10	10.75	7	1.536	7.494	333	$ 32.51
10	10.75	7.3	1.473	7.628	317	$ 31.85
10	10.75	9	1.194	8.218	250	$ 28.85
10	10.75	11	0.977	8.678	200	$ 26.34

10	10.75	13.5	0.796	9.062	160	$	24.15
10	10.75	15.5	0.694	9.28	138	$	22.86
10	10.75	17	0.632	9.409	125	$	22.08
10	10.75	19	0.566	9.551	111	$	21.18
10	10.75	21	0.512	9.665	100	$	19.51
10	10.75	26	0.413	9.873	80	$	18.43
10	10.75	32.5	0.331	10.049	63	$	17.26
12	12.75	7	1.821	8.889	333	$	41.42
12	12.75	7.3	1.747	9.047	317	$	40.50
12	12.75	9	1.417	9.747	250	$	36.27
12	12.75	11	1.159	10.293	200	$	32.75
12	12.75	13.5	0.944	10.748	160	$	29.67
12	12.75	15.5	0.823	11.006	138	$	27.84
12	12.75	17	0.75	11.16	125	$	26.76
12	12.75	19	0.671	11.327	111	$	25.49
12	12.75	21	0.607	11.463	100	$	24.55
12	12.75	26	0.49	11.71	80	$	23.04
12	12.75	32.5	0.392	11.918	63	$	20.28
14	14	7	2	9.76	333	$	47.89
14	14	7.3	1.918	9.934	317	$	46.78
14	14	9	1.556	10.702	250	$	41.76
14	14	11	1.273	11.302	200	$	37.52
14	14	13.5	1.037	11.801	160	$	33.80
14	14	15.5	0.903	12.085	138	$	31.60
14	14	17	0.824	12.254	125	$	30.29
14	14	19	0.737	12.438	111	$	28.76
14	14	21	0.667	12.587	100	$	27.63
14	14	26	0.538	12.858	80	$	25.81
14	14	32.5	0.431	13.087	63	$	23.83
16	16	7	2.286	11.154	333	$	60.56
16	16	7.3	2.192	11.353	317	$	59.13
16	16	9	1.778	12.231	250	$	52.08
16	16	11	1.455	12.916	200	$	46.54
16	16	13.5	1.185	13.487	160	$	41.69
16	16	15.5	1.032	13.812	138	$	38.81
16	16	17	0.941	14.005	125	$	37.11
16	16	19	0.842	14.215	111	$	35.11
16	16	21	0.762	14.385	100	$	33.63
16	16	26	0.615	14.695	80	$	31.25
16	16	32.5	0.492	14.956	63	$	28.65
18	18	7	2.571	12.549	333	$	72.43

18	18	7.3	2.466	12.773	317	$ 70.60
18	18	9	2	13.76	250	$ 62.17
18	18	11	1.636	14.531	200	$ 54.75
18	18	13.5	1.333	15.173	160	$ 48.61
18	18	15.5	1.161	15.538	138	$ 44.96
18	18	17	1.059	15.755	125	$ 42.82
18	18	19	0.947	15.992	111	$ 40.28
18	18	21	0.857	16.183	100	$ 38.42
18	18	26	0.692	16.532	80	$ 35.40
18	18	32.5	0.554	16.826	63	$ 32.12
20	20	7	2.857	13.943	333	$ 86.84
20	20	7.3	2.74	14.192	317	$ 84.58
20	20	9	2.222	15.289	250	$ 73.74
20	20	11	1.818	16.145	200	$ 65.07
20	20	13.5	1.481	16.859	160	$ 57.49
20	20	15.5	1.29	17.265	138	$ 52.58
20	20	17	1.176	17.506	125	$ 49.92
20	20	19	1.053	17.768	111	$ 46.80
20	20	21	0.952	17.981	100	$ 44.50
20	20	26	0.769	18.369	80	$ 40.77
20	20	32.5	0.615	18.695	63	$ 36.72
22	22	7	3.143	15.337	333	$ 103.06
22	22	7.3	3.014	15.611	317	$ 101.05
22	22	9	2.444	16.818	250	$ 88.15
22	22	11	2	17.76	200	$ 77.21
22	22	13.5	1.63	18.545	160	$ 68.03
22	22	15.5	1.419	18.991	138	$ 62.05
22	22	17	1.294	19.256	125	$ 58.94
22	22	19	1.158	19.545	111	$ 55.16
22	22	21	1.048	19.779	100	$ 52.37
22	22	26	0.846	20.206	80	$ 47.86
22	22	32.5	0.677	20.565	63	$ 42.96
24	24	7	3.429	16.731	333	$ 118.57
24	24	7.3	3.288	17.03	317	$ 116.17
24	24	9	2.667	18.347	250	$ 100.68
24	24	11	2.182	19.375	200	$ 87.90
24	24	13.5	1.778	20.231	160	$ 76.51
24	24	15.5	1.548	20.717	138	$ 70.04
24	24	17	1.412	21.007	125	$ 66.21
24	24	19	1.263	21.322	111	$ 61.71
24	24	21	1.143	21.577	100	$ 58.39

24	24	26	0.923	22.043	80	$ 53.12
24	24	32.5	0.738	22.434	63	$ 47.19
26	26	7.3	3.562	18.449	317	$ 135.61
26	26	9	2.889	19.876	250	$ 117.65
26	26	11	2.364	20.989	200	$ 101.78
26	26	13.5	1.926	21.917	160	$ 88.31
26	26	15.5	1.677	22.444	138	$ 80.39
26	26	17	1.529	22.758	125	$ 75.78
26	26	19	1.368	23.099	111	$ 70.71
26	26	21	1.238	23.375	100	$ 66.56
26	26	26	1	23.88	80	$ 60.14
26	26	32.5	0.8	24.304	63	$ 53.35
28	28	9	3.111	21.404	250	$ 135.02
28	28	11	2.545	22.604	200	$ 117.76
28	28	13.5	2.074	23.603	160	$ 101.70
28	28	15.5	1.806	24.17	138	$ 92.38
28	28	17	1.647	24.508	125	$ 87.06
28	28	19	1.474	24.876	111	$ 81.18
28	28	21	1.333	25.173	100	$ 76.33
28	28	26	1.077	25.717	80	$ 69.00
28	28	32.5	0.862	26.174	63	$ 61.04
30	30	9	3.333	22.933	250	$ 149.79
30	30	11	2.727	24.218	200	$ 129.99
30	30	13.5	2.222	25.289	160	$ 112.72
30	30	15.5	1.935	25.897	138	$ 102.59
30	30	17	1.765	26.259	125	$ 94.95
30	30	19	1.579	26.653	111	$ 88.18
30	30	21	1.429	26.971	100	$ 82.65
30	30	26	1.154	27.554	80	$ 74.20
30	30	32.5	0.923	28.043	63	$ 65.04
32	32	9	3.556	24.462	250	$ 171.20
32	32	11	2.909	25.833	200	$ 146.28
32	32	13.5	2.37	26.975	160	$ 126.61
32	32	15.5	2.065	27.623	138	$ 115.14
32	32	17	1.882	28.009	125	$ 108.13
32	32	19	1.684	28.429	111	$ 100.44
32	32	21	1.524	28.77	100	$ 94.15
32	32	26	1.231	29.391	80	$ 84.56
32	32	32.5	0.985	29.913	63	$ 74.15
34	34	9	3.778	25.991	250	$ 172.85
34	34	11	3.091	27.447	200	$ 167.56

34	34	13.5	2.519	28.661	160	$ 144.53
34	34	15.5	2.194	29.35	138	$ 131.53
34	34	17	2	29.76	125	$ 123.64
34	34	19	1.789	30.3206	111	$ 114.94
34	34	21	1.619	30.568	100	$ 107.84
34	34	26	1.308	31.228	80	$ 97.01
34	34	32.5	1.046	31.782	63	$ 85.24
36	36	9	4	27.52	250	$ 222.90
36	36	11	3.273	29.062	200	$ 186.09
36	36	13.5	2.667	30.347	160	$ 158.80
36	36	15.5	2.323	31.076	138	$ 144.24
36	36	17	2.118	31.511	125	$ 135.41
36	36	19	1.895	31.983	111	$ 125.67
36	36	21	1.714	32.366	100	$ 117.66
36	36	26	1.385	33.065	80	$ 105.55
36	36	32.5	1.1085	33.652	63	$ 92.36
42	42	13.5	3.111	35.404	160	$ 216.92
42	42	15.5	2.71	36.255	138	$ 197.12
42	42	17	2.471	36.762	125	$ 185.10
42	42	19	2.211	37.314	111	$ 171.86
42	42	21	2	37.76	100	$ 160.97
42	42	26	1.615	38.575	80	$ 144.41
42	42	32.5	1.292	39.26	63	$ 126.48
48	48	15.5	3.097	41.435	138	$ 256.03
48	48	17	2.824	42.014	125	$ 240.31
48	48	19	2.526	42.644	111	$ 221.67
48	48	21	2.286	43.154	100	$ 207.52
48	48	26	1.846	44.086	80	$ 185.90
48	48	32.5	1.477	44.869	63	$ 162.48
54	54	15.5	3.484	46.614	138	$ 332.11
54	54	17	3.176	47.266	125	$ 302.45
54	54	19	2.842	47.975	111	$ 279.39
54	54	21	2.571	48.549	100	$ 261.42
54	54	26	2.077	49.597	80	$ 234.11
54	54	32.5	1.662	50.478	63	$ 204.48
63	63	17	3.706	55.143	125	$ 417.81
63	63	19	3.315	55.97	111	$ 376.08
63	63	21	3	56.631	100	$ 352.65
63	63	26	2.423	57.854	80	$ 306.39
63	63	32.5	1.938	58.881	63	$ 267.63
65	65	17	3.824	56.894	125	$ 443.44

65	65	19	3.421	57.747	111	$ 399.03
65	65	21	3.095	58.438	100	$ 402.05
65	65	26	2.5	59.7	80	$ 324.16
65	65	32.5	2	60.76	63	$ 283.05

Table S3. DI Pipe Data

Nominal Size (in)	OD (in)	DR (in)	Thickness (in)	ID (in)	Pressure Class (psi)	Installed Cost ($/ft)	CML Thickness (in)	Casting Allowance (in)
4	4.8	19	0.25	3.800	350	$ 29.63	0.25	0.05
6	6.9	28	0.25	5.900	350	$ 26.20	0.25	0.05
8	9.05	36	0.25	8.050	350	$ 32.01	0.25	0.05
10	11.1	43	0.26	10.080	350	$ 38.06	0.25	0.06
12	13.2	47	0.28	11.997	350	$ 46.34	0.3215	0.06
14	15.3	55	0.28	14.097	250	$ 54.41	0.3215	0.07
14	15.3	51	0.3	14.057	300	$ 56.89	0.3215	0.07
14	15.3	49	0.31	14.037	350	$ 58.09	0.3215	0.07
16	17.4	58	0.3	16.157	250	$ 62.97	0.3215	0.07
16	17.4	54	0.32	16.117	300	$ 65.71	0.3215	0.07
16	17.4	51	0.34	16.077	350	$ 68.53	0.3215	0.07
18	19.5	63	0.31	18.237	250	$ 71.59	0.3215	0.07
18	19.5	57	0.34	18.177	300	$ 76.21	0.3215	0.07
18	19.5	54	0.36	18.137	350	$ 79.30	0.3215	0.07
20	21.6	65	0.33	20.297	250	$ 83.55	0.3215	0.07
20	21.6	60	0.36	20.237	300	$ 88.69	0.3215	0.07
20	21.6	57	0.38	20.197	350	$ 92.12	0.3215	0.07
24	25.8	78	0.33	24.390	200	$ 101.50	0.375	0.07
24	25.8	70	0.37	24.310	250	$ 108.38	0.375	0.07
24	25.8	65	0.4	24.250	300	$ 113.48	0.375	0.07
24	25.8	60	0.43	24.190	350	$ 118.58	0.375	0.07
30	32	94	0.34	30.570	150	$ 133.23	0.375	0.07
30	32	84	0.38	30.490	200	$ 140.87	0.375	0.07
30	32	76	0.42	30.410	250	$ 148.57	0.375	0.07
30	32	71	0.45	30.350	300	$ 154.25	0.375	0.07
30	32	65	0.49	30.270	350	$ 160.93	0.375	0.07
36	38.3	101	0.38	36.790	150	$ 183.95	0.375	0.07
36	38.3	91	0.42	36.710	200	$ 194.20	0.375	0.07
36	38.3	81	0.47	36.610	250	$ 205.75	0.375	0.07
36	38.3	75	0.51	36.530	300	$ 215.39	0.375	0.07
36	38.3	68	0.56	36.430	350	$ 226.24	0.375	0.07
42	44.5	109	0.41	42.680	150	$ 238.25	0.5	0.07
42	44.5	95	0.47	42.560	200	$ 255.41	0.5	0.07
42	44.5	86	0.52	42.460	250	$ 271.05	0.5	0.07
42	44.5	78	0.57	42.360	300	$ 285.34	0.5	0.07
42	44.5	71	0.63	42.240	350	$ 303.08	0.5	0.07
48	50.8	110	0.46	48.880	150	$ 311.99	0.5	0.08

48	50.8	98	0.52	48.760	200	$	333.10	0.5	0.08
48	50.8	88	0.58	48.640	250	$	354.17	0.5	0.08
48	50.8	79	0.64	48.520	300	$	373.31	0.5	0.08
48	50.8	73	0.7	48.400	350	$	392.50	0.5	0.08
54	57.56	113	0.51	55.540	150	$	396.68	0.5	0.09
54	57.56	99	0.58	55.400	200	$	425.33	0.5	0.09
54	57.56	89	0.65	55.260	250	$	454.01	0.5	0.09
54	57.56	80	0.72	55.120	300	$	480.01	0.5	0.09
54	57.56	73	0.79	54.980	350	$	505.99	0.5	0.09
60	61.61	114	0.54	59.530	150	$	473.66	0.5	0.09
60	61.61	101	0.61	59.390	200	$	504.50	0.5	0.09
60	61.61	91	0.68	59.250	250	$	535.58	0.5	0.09
60	61.61	81	0.76	59.090	300	$	566.98	0.5	0.09
60	61.61	74	0.83	58.950	350	$	596.01	0.5	0.09
64	65.67	117	0.56	63.550	150	$	526.34	0.5	0.09
64	65.67	103	0.64	63.390	200	$	565.49	0.5	0.09
64	65.67	91	0.72	63.230	250	$	604.41	0.5	0.09
64	65.67	82	0.8	63.070	300	$	639.35	0.5	0.09
64	65.67	75	0.87	62.930	350	$	670.63	0.5	0.09

Table S3. Steel Pipe Data

Nominal Size (in)	OD (in)	DR	Thickness (in)	ID (in)	Pressure Class (psi)	Installed Cost ($/ft)	CML Thickness (in)
4	4	30	0.1345	3.231	1211	$ 17.27	0.25
6	6	45	0.1345	5.231	807	$ 20.82	0.25
8	8	59	0.1345	7.231	605	$ 24.72	0.25
10	10	74	0.1345	9.231	484	$ 28.75	0.25
10	10	72	0.139	9.222	500	$ 29.10	0.25
12	12	89	0.1345	11.106	404	$ 32.95	0.3125
12	12	80	0.1499	11.0752	450	$ 34.42	0.3125
12	12	72	0.1668	11.0414	500	$ 36.42	0.3125
14	14	104	0.1345	13.106	346	$ 38.91	0.3125
14	14	103	0.136	13.103	350	$ 39.07	0.3125
14	14	90	0.1555	13.064	400	$ 41.25	0.3125
14	14	80	0.175	13.025	450	$ 43.42	0.3125
14	14	72	0.1943	12.9864	500	$ 45.57	0.3125
16	16	119	0.1345	15.106	303	$ 44.81	0.3125
16	16	103	0.1555	15.064	350	$ 47.50	0.3125
16	16	90	0.1776	15.0198	400	$ 50.32	0.3125
16	16	80	0.2	14.975	450	$ 53.63	0.3125
16	16	72	0.222	14.931	500	$ 56.82	0.3125
18	18	134	0.1345	17.106	269	$ 49.84	0.3125
18	18	120	0.15	17.075	300	$ 52.08	0.3125
18	18	103	0.175	17.025	350	$ 56.17	0.3125
18	18	90	0.2	16.975	400	$ 59.76	0.3125
18	18	80	0.225	16.925	450	$ 64.12	0.3125
18	18	72	0.25	16.875	500	$ 67.69	0.3125
20	20	149	0.1345	19.106	242	$ 55.66	0.3125
20	20	144	0.139	19.097	250	$ 56.90	0.3125
20	20	120	0.1668	19.0414	300	$ 61.37	0.3125
20	20	103	0.1947	18.9856	350	$ 66.17	0.3125
20	20	90	0.2222	18.9306	400	$ 70.07	0.3125
20	20	80	0.25	18.875	450	$ 75.68	0.3125
20	20	72	0.278	18.819	500	$ 80.47	0.3125
22	22	164	0.1345	21.106	220	$ 62.85	0.3125
22	22	144	0.153	21.069	250	$ 66.12	0.3125
22	22	120	0.1835	21.008	300	$ 71.86	0.3125
22	22	103	0.214	20.947	350	$ 77.78	0.3125
22	22	90	0.2445	20.886	400	$ 83.69	0.3125
22	22	80	0.275	20.825	450	$ 89.03	0.3125

22	22	72	0.3055	20.764	500	$	96.33	0.3125
24	24	178	0.1345	22.981	202	$	68.28	0.375
24	24	144	0.1665	22.917	250	$	74.46	0.375
24	24	120	0.2	22.85	300	$	81.47	0.375
24	24	103	0.2335	22.783	350	$	88.51	0.375
24	24	90	0.2665	22.717	400	$	96.01	0.375
24	24	80	0.3	22.65	450	$	102.41	0.375
24	24	72	0.333	22.584	500	$	109.59	0.375
26	26	193	0.1345	24.981	186	$	74.40	0.375
26	26	180	0.1445	24.961	200	$	76.49	0.375
26	26	144	0.1805	24.889	250	$	84.60	0.375
26	26	120	0.217	24.816	300	$	92.87	0.375
26	26	103	0.253	24.744	350	$	101.55	0.375
26	26	90	0.289	24.672	400	$	109.02	0.375
26	26	80	0.325	24.6	450	$	117.45	0.375
26	26	72	0.361	24.528	500	$	125.85	0.375
28	28	208	0.1345	26.981	173	$	82.02	0.375
28	28	180	0.1555	26.939	200	$	87.14	0.375
28	28	144	0.1945	26.861	250	$	95.93	0.375
28	28	120	0.2335	26.783	300	$	106.61	0.375
28	28	103	0.2722	26.7055556	350	$	115.29	0.375
28	28	90	0.311	26.628	400	$	125.01	0.375
28	28	80	0.35	26.55	450	$	134.69	0.375
28	28	72	0.389	26.472	500	$	145.10	0.375
30	30	223	0.1345	28.981	161	$	89.17	0.375
30	30	180	0.1667	28.9166667	200	$	96.96	0.375
30	30	144	0.208	28.834	250	$	107.69	0.375
30	30	120	0.25	28.75	300	$	117.80	0.375
30	30	103	0.292	28.666	350	$	128.89	0.375
30	30	90	0.333	28.584	400	$	141.61	0.375
30	30	80	0.375	28.5	450	$	151.64	0.375
30	30	72	0.4165	28.417	500	$	162.65	0.375
32	32	241	0.133	30.984	150	$	95.57	0.375
32	32	180	0.178	30.894	200	$	107.19	0.375
32	32	144	0.222	30.806	250	$	119.33	0.375
32	32	120	0.2669	30.7162	300	$	131.87	0.375
32	32	103	0.311	30.628	350	$	146.17	0.375
32	32	90	0.3554	30.5392	400	$	157.51	0.375
32	32	80	0.4	30.45	450	$	168.86	0.375
32	32	72	0.444	30.362	500	$	182.63	0.375
32	32	65	0.489	30.272	550	$	194.03	0.375

34	34	239	0.142	32.966	150	$	108.59	0.375
34	34	180	0.189	32.872	200	$	121.49	0.375
34	34	144	0.236	32.778	250	$	135.20	0.375
34	34	120	0.283	32.684	300	$	150.86	0.375
34	34	103	0.331	32.588	350	$	165.21	0.375
34	34	90	0.378	32.494	400	$	177.96	0.375
34	34	80	0.425	32.4	450	$	193.36	0.375
34	34	72	0.472	32.306	500	$	206.04	0.375
36	36	240	0.15	34.95	150	$	120.20	0.375
36	36	180	0.2	34.85	200	$	134.73	0.375
36	36	144	0.25	34.75	250	$	151.16	0.375
36	36	120	0.3	34.65	300	$	167.44	0.375
36	36	103	0.35	34.55	350	$	183.20	0.375
36	36	90	0.4	34.45	400	$	198.98	0.375
36	36	80	0.45	34.35	450	$	214.66	0.375
36	36	72	0.5	34.25	500	$	230.18	0.375
38	38	241	0.158	36.684	150	$	134.02	0.5
38	38	180	0.211	36.578	200	$	153.08	0.5
38	38	144	0.264	36.472	250	$	169.29	0.5
38	38	120	0.317	36.366	300	$	188.32	0.5
38	38	103	0.369	36.262	350	$	204.14	0.5
38	38	90	0.422	36.156	400	$	222.89	0.5
38	38	80	0.475	36.05	450	$	238.92	0.5
38	38	72	0.528	35.944	500	$	257.35	0.5
40	40	240	0.167	38.666	150	$	149.05	0.5
40	40	180	0.222	38.556	200	$	169.68	0.5
40	40	144	0.278	38.444	250	$	189.16	0.5
40	40	120	0.333	38.334	300	$	208.32	0.5
40	40	103	0.389	38.222	350	$	227.51	0.5
40	40	90	0.444	38.112	400	$	247.61	0.5
40	40	80	0.5	38	450	$	265.43	0.5
40	40	72	0.555	37.89	500	$	284.40	0.5
42	42	240	0.175	40.65	150	$	163.57	0.5
42	42	180	0.2339	40.5322	200	$	184.60	0.5
42	42	144	0.292	40.416	250	$	205.70	0.5
42	42	120	0.35	40.3	300	$	228.10	0.5
42	42	103	0.408	40.184	350	$	249.18	0.5
42	42	90	0.467	40.066	400	$	270.00	0.5
42	42	80	0.525	39.95	450	$	290.97	0.5
42	42	72	0.583	39.834	500	$	310.30	0.5
45	45	241	0.187	43.626	150	$	185.85	0.5

45	45	180	0.25	43.5	200	$	211.35	0.5
45	45	144	0.3125	43.375	250	$	236.99	0.5
45	45	120	0.375	43.25	300	$	259.56	0.5
45	45	103	0.4375	43.125	350	$	284.83	0.5
45	45	90	0.5	43	400	$	307.28	0.5
45	45	80	0.5625	42.875	450	$	331.36	0.5
45	45	72	0.625	42.75	500	$	355.37	0.5
48	48	240	0.2	46.6	150	$	209.84	0.5
48	48	180	0.267	46.466	200	$	238.53	0.5
48	48	144	0.333	46.334	250	$	267.17	0.5
48	48	120	0.4	46.2	300	$	294.07	0.5
48	48	103	0.466	46.068	350	$	321.24	0.5
48	48	90	0.533	45.934	400	$	348.71	0.5
48	48	80	0.6	45.8	450	$	374.30	0.5
48	48	72	0.666	45.668	500	$	401.25	0.5
51	51	239	0.213	49.574	150	$	238.24	0.5
51	51	180	0.284	49.432	200	$	268.83	0.5
51	51	144	0.354	49.292	250	$	300.61	0.5
51	51	120	0.425	49.15	300	$	331.59	0.5
51	51	103	0.496	49.008	350	$	360.57	0.5
51	51	90	0.567	48.866	400	$	391.39	0.5
51	51	80	0.638	48.724	450	$	422.13	0.5
51	51	72	0.708	48.584	500	$	452.38	0.5
54	54	240	0.225	52.55	150	$	264.85	0.5
54	54	180	0.3	52.4	200	$	300.10	0.5
54	54	144	0.375	52.25	250	$	334.73	0.5
54	54	120	0.45	52.1	300	$	369.27	0.5
54	54	103	0.525	51.95	350	$	403.72	0.5
54	54	90	0.6	51.8	400	$	436.04	0.5
54	54	80	0.675	51.65	450	$	470.31	0.5
54	54	72	0.75	51.5	500	$	504.48	0.5
57	57	239	0.238	55.524	150	$	294.39	0.5
57	57	180	0.316	55.368	200	$	333.59	0.5
57	57	144	0.396	55.208	250	$	370.29	0.5
57	57	120	0.475	55.05	300	$	408.58	0.5
57	57	103	0.554	54.892	350	$	446.77	0.5
57	57	90	0.634	54.732	400	$	485.31	0.5
57	57	80	0.713	54.574	450	$	523.29	0.5
57	57	72	0.791	54.418	500	$	558.57	0.5
60	60	240	0.25	58.5	150	$	324.57	0.5
60	60	180	0.334	58.332	200	$	367.51	0.5

60	60	144	0.416	58.168	250	$	409.37	0.5
60	60	120	0.5	58	300	$	449.82	0.5
60	60	103	0.584	57.832	350	$	492.42	0.5
60	60	90	0.666	57.668	400	$	533.94	0.5
60	60	80	0.75	57.5	450	$	576.31	0.5
60	60	72	0.834	57.332	500	$	618.57	0.5
63	63	240	0.263	61.474	150	$	356.47	0.5
63	63	180	0.35	61.3	200	$	403.08	0.5
63	63	144	0.4375	61.125	250	$	449.82	0.5
63	63	120	0.525	60.95	300	$	496.44	0.5
63	63	103	0.613	60.774	350	$	543.18	0.5
63	63	90	0.7	60.6	400	$	586.93	0.5
63	63	80	0.788	60.424	450	$	633.42	0.5
63	63	72	0.875	60.25	500	$	679.28	0.5
66	66	240	0.275	64.45	150	$	389.93	0.5
66	66	180	0.367	64.266	200	$	441.42	0.5
66	66	144	0.458	64.084	250	$	492.25	0.5
66	66	120	0.55	63.9	300	$	543.47	0.5
66	66	103	0.641	63.718	350	$	594.03	0.5
66	66	90	0.733	63.534	400	$	644.97	0.5
66	66	80	0.825	63.35	450	$	695.78	0.5
66	66	72	0.917	63.166	500	$	746.45	0.5
72	72	240	0.3	70.4	150	$	457.34	0.5
72	72	180	0.4	70.2	200	$	518.17	0.5
72	72	144	0.5	70	250	$	578.83	0.5
72	72	120	0.6	69.8	300	$	639.33	0.5
72	72	103	0.7	69.6	350	$	699.67	0.5
72	72	90	0.8	69.4	400	$	759.84	0.5
72	72	80	0.9	69.2	450	$	819.85	0.5
72	72	72	1	69	500	$	879.70	0.5

Table S5. Route 1 – Pipe Results Summary

		Pipe No.									
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**Avg. of all pipes**
PVC	Dn	30	24	24	24	24	10	14	8	24	-
	Avg. ID	29.4	23.8	24.3	24.8	23.6	10.0	14.3	9.9	23.9	19.5
	Avg.Vel.	5.3	7.3	6.8	6.4	6.5	4.1	1.5	2.7	5.6	5.3
	Avg. PC	166.9	159.4	118.2	80.0	174.8	201.8	138.7	148.8	149.9	157.4
HDPE	Dn	34	34	28	24	24	12	14	8	30	-
	Avg. ID	29.2	29.3	25.2	21.7	21.2	11.2	12.3	9.1	27.5	20.3
	Avg.Vel.	5.5	4.9	6.3	8.3	8.0	3.3	2.0	3.2	4.2	5.0
	Avg. PC	143.5	140.6	99.7	93.3	115.4	119.3	120.5	92.1	80.6	112.3
DI	Dn	36	36	30	30	30	10	10	8	30	36
	Avg. ID	36.7	36.7	30.5	30.5	30.4	10.1	10.1	8.6	30.4	24.3
	Avg.Vel.	3.4	3.1	4.3	4.2	3.9	4.1	2.9	3.3	3.5	3.7
	Avg. PC	219.5	202.7	187.8	183.1	236.2	350.0	350.0	350.0	260.2	262.6
Steel	Dn	30	28	28	26	26	10	10	8	26	-
	Avg. ID	28.8	26.8	26.9	24.8	24.7	9.2	9.2	7.7	24.8	20.0
	Avg.Vel.	5.6	5.7	5.5	6.3	5.9	4.9	3.5	4.0	5.2	5.2
	Avg. PC	286.7	292.5	240.0	283.4	371.2	484.2	484.2	575.0	342.8	384.0

Table S6. Route 2 – Pipe Results Summary

		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Avg. of all pipes
		Pipe No.										
PVC	Dn	30	30	24	24	24	24	10	10	10	24	-
	Avg. ID	29.9	29.8	24.0	24.0	24.0	23.9	10.1	10.2	10.2	24.2	21.5
	Avg.Vel.	5.1	4.7	6.9	6.6	6.4	6.3	4.1	4.6	1.3	5.4	5.2
	Avg. PC	132.9	142.1	145.6	144.2	142.5	152.0	188.3	165.0	165.0	124.5	151.2
HDPE	Dn	36	30	30	30	26	26	12	10	14	26	-
	Avg. ID	31.0	25.8	26.2	26.5	22.6	20.9	10.5	9.5	12.7	23.5	21.2
	Avg.Vel.	4.9	6.3	5.9	5.4	7.3	8.3	3.8	5.3	0.9	5.8	5.5
	Avg. PC	142.2	141.7	129.7	117.5	131.5	204.8	185.8	115.7	93.1	97.6	142.4
DI	Dn	36	30	30	30	30	30	12	14	10	30	-
	Avg. ID	36.7	30.4	30.4	30.4	30.4	30.5	12.0	14.1	10.1	30.6	25.9
	Avg.Vel.	3.4	4.5	4.3	4.1	4.0	3.9	2.9	2.4	1.4	3.4	3.5
	Avg. PC	210.6	256.7	229.4	236.8	252.8	197.6	350.0	250.0	350.0	158.5	251.1
Steel	Dn	30	28	28	28	24	22	12	12	10	26	-
	Avg. ID	28.8	26.8	26.9	26.8	22.9	20.9	11.1	11.1	9.2	24.9	21.3
	Avg.Vel.	5.6	5.7	5.5	5.2	7.1	8.3	3.4	3.9	1.6	5.1	5.3
	Avg. PC	265.6	278.3	248.1	259.0	276.8	397.7	403.5	403.5	484.2	211.2	323.7

APPENDIX C

Multicriteria DSS for Water Infrastructure Project Selection on the Navajo Nation

Multicriteria DSS for Water Infrastructure Project Selection on the Navajo Nation

Ronson Chee[1] and Kevin Lansey[2]

Abstract

Notorious for its high poverty levels and low socio-economic status, the Navajo Nation's socio-economic well-being is hindered greatly in part by the lack of an adequate potable water infrastructure which has resulted in health disparities and has attributed to stunted economic growth within the Nation. Large candidate regional water transmission pipelines projects aimed to meet these needs have been identified. With capital costs exceeding their fiscal capability, decision-makers must choose the project that will bring the most benefits. Accordingly, a decision support system (DSS) has been developed that allows projects to be compared considering the competing interests of: economic development, health improvement and environmental protection. The DSS consist of a cost-benefit analysis integrated into a multiple criteria decision analysis framework that allows projects to be ranked based on a non-monetized benefit cost ratio. Due to the high uncertainty with development on the Navajo Nation, future scenarios were developed for robust decision-making. Two candidate projects are evaluated through three hypothetical decision-makers with different agendas. The methods developed herein can be applied to developing nations with similar socio-economic conditions.

Keywords: Project Selection, Project Prioritization, Analytic Hierarchy Process, Multiple Criteria Decision Analysis, Robust Decision-making, Scenario Analysis, Drinking Water Infrastructure, Developing Countries

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INTRODUCTION

Background and Problem

The Navajo Nation (Nation) is the largest sovereign American Indian Nation in the United States with its land base spanning into 3 states (Arizona, New Mexico and Utah; see Figure 1) and is notorious for its high poverty levels and low socio-economic status. The Navajo Nation's socio-economic well-being is hindered greatly in part by the lack of a sustainable economy, the lack of capital surplus, and by the lack of adequate potable water infrastructure. The lack of adequate potable water infrastructure has resulted in health disparities and has attributed to stunted economic growth within the Nation. Approximately 30% still do not have in-home potable water connections and must rely on water hauling to meet daily needs (NNDWR 2011). Because of the time-consuming duty of water hauling it is not uncommon for some water-haulers to resort to using more local wells that are intended for livestock use and may be contaminated with uranium. The deep depths to reliable and quality groundwater sources and the long overland distances to reliable surface water sources in the region make the delivery of water very costly. This high cost to develop reliable water infrastructure hinders the economic development and growth that is vital for the creation of jobs and addressing health concerns.

In addition to the current infrastructure shortages, local groundwater sources (which are the primary water sources) are becoming scarce and future water shortages have been identified throughout the Nation. In response to these infrastructure deficiencies and projected water shortages, the Nation has begun allocating resources for future investments. Currently, two large-scale regional transmission pipelines that will deliver more reliable supplies into the Nation have been identified as potential projects for the Nation to invest in (see Figure 1). With combined preliminary capital costs estimates exceeding $450M, the Nation does not have the fiscal capability to construct both simultaneously. Thus, with limited resources, Navajo decision-makers must strategically select the water infrastructure project that will generate the most "bang-for-the-buck" while considering multiple criteria such as health, economics and the environment.

Need for Multi-Criteria Decision Analysis Methods

Current efforts to address the Nation's infrastructure deficiencies and projected water shortages are a combined effort between tribal and federal agencies. Past water infrastructure planning efforts among the multiple agencies have been very compartmentalized; with each agency pushing its own (single) objective and has resulted in non-optimal planning and slow project implementation. For instance, the Indian Health Service (IHS; in accordance with Public Law 94-437) designs and provides construction funding to provide/improve in-home sanitation facilities (i.e., potable water and sewer facilities for residential use only) with a primarily health driven (single) objective. Administrative constraints can make it difficult to plan and construct IHS water distribution systems in conjunction with large transmission systems aimed to support commercial growth. This strict health objective may then conflict with the Nation's objectives, which may be geared more toward economic development. This lack of a unified vision for infrastructure development can result in missed opportunities. This compartmentalized planning has also lead to strains on the Navajo Tribal Utility Authority's (NTUA; the Nation's utility provider) operations. Due to the current lack of commercial and industrial (C&I) users, long-term operation, maintenance and repair (OMR) costs lie primarily on residents, which has led to instances where OMR costs exceed utility revenues (R. Kontz, NTUA, personnel communication, October 7, 2013). Thus, an integrated planning framework for water infrastructure implementation that can balance economic development and health objectives is needed.

Until recently, more collaborative efforts amongst agencies have been initiated to find commonality between projects and find common goals for project implementation, but a standardized multi-dimensional planning framework with multi-criteria objectives has not been adopted. To fill this need, a decision support system (DSS) has been developed that accounts for these multiple objectives while integrating objective data to aid in evaluating and selecting candidate water projects on the Navajo Nation.

The DSS allows water transmission projects to be compared and ranked based on available quantitative data and considers economic development, health, and environmental objectives. The DSS is composed of a cost-benefit analysis (CBA) integrated into a multiple criteria decision analysis (MCDA) framework. The DSS will help to: (1) quantify the range of impacts of a project; (2) guide alternative evaluation; (3) promote interagency coordination; (4) focus resources and planning efforts (e.g. engineering and pooling capital); (5) support final project selection; (6) give tribal leaders the transparency needed to justify their investment decisions; and lastly but most importantly, (7) it will provide a unified vision for the comprehensive planning that is needed to integrate water infrastructure with economic development.

METHODOLOGY

CBA and MCDA Overview

CBA is perhaps the most widely used and accepted methodology for evaluating and appraising large infrastructure projects throughout the world. Countless guidelines and manuals have been developed for project appraisal and have been applied to nearly every type of application. CBA itself may be used to guide project selection when faced with multiple alternatives. When evaluating multiple projects, a CBA could be performed for each, and the alternative with the highest benefit cost ratio (BCR) could be selected as the most favorable as long as monetary evaluations are consistent among candidate projects (Pearce and Nash 1981). One of the weaknesses with this approach is that CBA relies almost entirely on the conversion of costs and benefits into a monetary valuation. Often important costs and benefits that may influence decisions (such as health, social and environmental impacts) are not easily assigned a monetary value and are often excluded. In cases like the Navajo Nation, this can lead to vital projects having BCRs being less than one (i.e., costs outweigh benefits), which may mislead decision-makers by implying that a project is not feasible or is not needed. There are currently no widely accepted or universal methods for transforming impacts such as health, social and environmental into monetary values for project appraisals. The lack of inclusion of non-monetary values is one of the major shortcomings of using conventional CBA when used to select projects.

MCDA methods offer a viable alternative and complement to conventional CBA. When MCDA is paired with CBA, MCDA supplements the weaknesses of CBA, e.g., not being able to account for non-monetary values (van Wee 2011; Gühnemann et al. 2012). MCDA paired with CBA is a widely-accepted approach that allows monetary and non-monetary values to be combined for ranking or scoring the overall performance of decision options against multiple objectives (Hajkowicz 2007). MCDA is a broad sub-discipline of operations research developed in the 1960s and 1970s that explicitly considers multiple criteria in decision making environments (Figueira et al. 2005). The purpose of MCDA is to structure a decision-making problem involving multiple criteria and providing a systematical solution by combining quantitative data with human judgment. MCDA techniques provide a method to deal with human difficulties in handling large amounts of complex information in a consistent way (DCLG 2009). MCDA methods have proven effective when used in applications where: a single most preferred option must be identified, options must be ranked, options must be short listed, or options must be distinguished as acceptable or unacceptable from a number of possibilities (DCLG 2009). MCDA methods have been successfully applied to various fields such as: energy planning (see Pohekar and Ramachandran 2004); agriculture (see Hayashi 2000; Raju and Kumar 1999); natural resource management (see Romero and Rehman 1987), financial decision making (see Steuer and Na 2003); water policy evaluation (see Hajkowicz and Collins 2007; Hajkowicz and Higgins 2008; Rahm et al. 2013) and water resources management (see Gershon and Duckstein 1983; Hipel 1992; Ozelkan and Duckstein 1996; Eder et al. 1997; Hajkowicz 2007; Herath 2010).

Combining CBA along with MCDA is long established (Manheim et al. 1975) and has since been applied to many fields to support decision making and project selection/prioritization problems. In civil engineering type applications CBA and MCDA has been mostly applied to transportation project selection/prioritization type problems (see Lootsma 1992; Bristown and Nelthorp 2000; Leleur 2000; Grant-Muller et al. 2001; Salling et al. 2007; Gühnemann et al. 2012). Combining CBA with MCDA has many framework variations, most framework variations fall into two main approaches: 1) the CBA results are incorporated into the MCA framework; or 2) the MCA framework is incorporated into a CBA framework. The DSS developed for the Navajo Nation is based on the former approach. More specifically, the analytic hierarchy process (AHP; Saaty 1980), which is part of the MCDA family; is built into the DSS as discussed in the following section.

Analytic Hierarchy Process

The AHP, developed by Saaty (1977, 1980) is one of the most commonly used MCDA methods for decision making problems and breaks down large unstructured decision problems into manageable and measurable components. The AHP embodies a sound and mature theoretical basis taken from mathematics and psychology and consists of three main parts: a hierarchy structure, a pairwise comparison matrix, and a method for calculating the priorities (Mafakheri 2007). In AHP, the elements involved in a decision problem are structured into a hierarchy descending from an overall goal, to objectives, to various criteria and sub-criteria with the alternatives (or projects) at the lowest level.

Once the hierarchy is constructed, the decision-maker performs a pairwise comparison of all elements at each level. The pairwise comparison is a process comparing entities in pairs to judge which entity is more preferred over the other by using a quantitative scale. The pairwise comparison ultimately provides a quantifiable measurement (or weight) of the relative importance of each objective/criteria/sub-criteria in the overall hierarchy (or decision-making process).

A pairwise comparison is performed by first creating a pairwise comparison matrix ***A*** as follows:

$$[A] = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{1}$$

where ***A*** is a $n \times n$ real matrix and n is the number of evaluation criteria considered, with a_{ij} denoting the entry in the ith row and jth column. Each entry a_{ij} of matrix ***A*** represents the importance of the ith criterion relative to the jth criterion. If $a_{ij} > 1$, then the ith criterion is more important than the jth criterion. If $a_{ij} < 1$, then the ith criterion is less important than the jth criterion. When the two criterion have equal importance, $a_{ij} = 1$. The entries in matrix ***A*** must also satisfy the following constraints:

$$a_{ij} \cdot a_{ji} = 1, \qquad \forall i, j = 1,2, \dots, n \tag{2}$$

$$a_{ii} = 1, \qquad \forall i = 1,2, \dots, n \tag{3}$$

The relative importance between the two criteria is measured according to a Saaty's (1980) fundamental scale of pairwise comparisons which is a numerical scale from 1 to 9 as shown on Table 1. After matrix $\boldsymbol{A}$ is constructed, it corresponds to the calculation of a normalized vector of weights for each nest in the hierarchy. The dimension of the normalized vector of weights is $n \times 1$, and each entry, which corresponds to the objective/criteria weights w_i, are calculated as:

$$w_i = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}}, \qquad \forall i = 1,2, \ldots, n \tag{4}$$

The reliability of the judgments made in the pairwise comparisons is then measured by a consistency ratio (*C.R.*; Saaty 1980), which is calculated as:

$$C.R. = C.I./R.I. \tag{5}$$

where *R.I.* is the random index (which is a consistency index of a randomly generated reciprocal matrix from the scale 1 to 9 with reciprocals forced; Saaty 1980) and is selected according to Table 2. *C.I.* is the consistency index and is calculated as:

$$C.I. = (\lambda_{max} - n)/(n - 1) \tag{6}$$

where λ_{max} = the maximum eigenvalue of the comparison matrix $\boldsymbol{A}$. *C.R.* is acceptable if it does not exceed 0.10. The pairwise judgements should be repeated and reviewed if *C.R.* is greater than 0.10.

Calculating the Benefit Cost Ratio

As the DSS incorporates CBA into the AHP framework, this requires the most important tradeoff (costs and benefits) to be at the top of the hierarchy (see Figure 2). Putting costs and benefits at the top of the hierarchy allows output results from the DSS to be shown in a non-monetized benefit cost ratio (BCR_{nm}) form so that projects can be ranked (with the highest BCR_{nm} being the most favorable). Using the weights determined from the pairwise comparisons, the BCR_{nm} for a project is calculated as:

$$BCR_{nm} = \frac{W_{EI}(W_{WW}S_{WW} + W_W S_W) + W_{EC}(W_C S_C + W_{OM}S_{OM})}{W_{EB}\left(W_D S_D + W_R S_R + W_{ED}\left(S_J + S_{TR} + S_T\right)\right) + W_{HI}(W_H S_H + W_U S_U + W_{IA}S_{IA})} \tag{7}$$

where W denotes the weights derived for each objective and criteria and S is the score for each criterion. The weights and scores for the objectives and criteria are discussed later.

Growth Model

A growth model was also developed to be used in conjunction with the DSS to help envision the future and help quantify potential future impacts/benefits that a project may provide. Population growth rates and demands are critical for quantifying impacts, as most of the criteria in the hierarchy is ultimately scored based off the projected population and their water demands (e.g., costs are directly impacted by the size of the system which is determined by demands that are based on gallons per capita per day). In order to quantify the potential future impacts from the project, two future realities must be envisioned, (1) a future scenario "without" the project, and (2) a future "with" the project. The actual benefits and impacts from a future with the project are then compared to the future without a project. This ensures that project impacts do not overestimate benefits to a region that may occur regardless if the project is constructed.

Particular attention was paid to the connectivity of residences that are currently or will be connected to the water utility grid. Not all residences will be impacted equally from the project as the majority of off-grid users still will not be connected to the water grid (but may have increased access to it). Because of this reality, individual residences, growth rates and demands were divided into on-grid and off-grid users to prevent over-representation of benefits from a project.

Additionally, growth rates and demands for on- and off-grid users will also differ significantly. For instance, current and future on-grid users: use more water; generate more wastewater going to centralized systems; and consequently, pay higher utilities. Whereas off-grid users will likely: use less water; generate less wastewater going to centralized systems (i.e., more septic systems); and pay lower utilities. Off-grid users should also see more health and economic benefits than on grid users. These differences in on- and off-grid users then ultimately affect calculated benefits and costs. Accordingly, the total projected population growth is a summation of on-grid and off-grid residents and is defined as:

$$P_T = P_{off} + P_{on} \tag{8}$$

where P_T = the total population; P_{off} = the off-grid population and P_{on} = the on-grid population. P_{off} and P_{on} are estimated using the following population growth formula:

$$P_{off} = P_{0\_off} e^{r\_off \cdot t} \tag{9}$$

$$P_{on} = P_{0\_on} e^{r\_on \cdot t} \tag{10}$$

where t is the number of years; P_{0_off} = the initial population of off-grid residents with growth rate *r_off;* and P_{0_on} = the initial population of the on-grid residents with growth rate *r_on*. P_{0_off} and P_{0_on} were estimated based on the number of homes assuming 3.7 persons per household. The number and locations of homes without water was obtained from IHS (D. McDonnell, IHS, personal communication; July 21, 2015).

The total demand (D_T) was also estimated according to on- and off-grid users and their indirect C&I uses as follows:

$$D_T = D_{R\_off} P_{off} + D_{R\_on} P_{on} + D_{CI} \left(\frac{P_{off}}{P_T} \right) + D_{CI} \left(\frac{P_{on}}{P_T} \right) \tag{11}$$

Where D_{R_off} = the estimated water demand for off-grid users (gpcd); D_{R_on} = the average water demand for on-grid users (gpcd); D_{CI} = the commercial and industrial water usage. D_{CI} is assumed to also include all other uses such as: public/government facilities, agriculture, power generation, mining, etc. Population growth rates and demands are summarized in Table 3.

Future "Without" Project (Baseline) Scenario

Without the project is the baseline scenario and assumes that socioeconomic conditions will essentially remain the same without intervention. The future without the project is more predictable than the future with the project and can be envisioned by observing the current demographic trends taking place on the Nation and projecting them forward. Without the project, it is assumed that the majority of the residential growth will occur primarily on-grid until the capacity of the existing water infrastructure system is reached, then growth will be forced to occur off-grid or off the Nation. Off-grid growth will also eventually be limited by the access to water as public watering points (local wells or distribution points off the grid) would not be able to keep up with demands. Thus, it is projected that off-grid growth will be slightly higher than on-grid growth (see Table 3). Currently off-grid users only use an estimated 10 gpcd, while on-grid users use about 33 gpcd in the home; and consume a combined additional 11 gpcd indirectly through commercial and industrial (C&I) demands (R. Kontz, NTUA, personal communication, May 29 2015). Without the project, it is assumed that these same demands for residential and C&I uses can be projected forward.

Future "With" Project

Projecting conditions for a future with the project is more complex as it opens the door to many possible outcomes with high uncertainty. This high uncertainty requires robust decision-making strategies. Accordingly, alternative future scenarios (or possible outcomes) that may result as a consequence of the project were developed. These alternative future scenarios were then compared against the baseline (future without the project) and the project that ranked the highest through all the alternative scenarios would be selected. The use of scenarios to aid in the planning and design of water infrastructure where there is high uncertainty has demonstrated to be a successful approach (Kang and Lansey 2014). A total of five (5) different with-project scenarios, were analyzed to see how the costs and benefits were affected by each scenario and are discussed in the following sections.

Ideal Scenario

It is expected that the majority of growth will occur on-grid (at a rate of 2.5%) as the infrastructure will more easily facilitate additional residential and C&I growth. Because of the on-grid growth, it is expected that off-grid growth will be less (at a rate of 0.7%) as residents would more likely want to live where they are connected to the grid (see Table 3). With increased on-grid capacity, residential water usage is also expected to increase (up to 70 gpcd). It is also expected that off-grid water usage will increase, as water haulers should have increased access. C&I uses are expected to have the largest gains. A developmental goal of 50 gpcd for C&I uses was implemented (see Table 3). This C&I demand is characteristic of more economically developed cities in the region.

Outmigration

Even with construction of the project, a possible outcome is the outmigration of residents to neighboring cities in towns. Outmigration can be caused by factors such as: better economic opportunities off the Nation (e.g. higher education, higher paying jobs, land ownership opportunities); government distrust (e.g., political corruption, disagreement with the future direction of the Nation); and preference for modern conveniences and amenities offered by neighboring cities and town (e.g., retail and entertainment). The outmigration scenario assumes that the population growth rates and demands remain the same as the baseline scenario, and C&I demands (i.e., economic development) only reach 50% of its goal.

Slow Economic Growth

Another possible outcome may be if the economic growth does not go according to plan. Stunted economic growth (even after project implementation) may still be a possibility on the Nation due to factors as: administrative/political barriers that hinder business development (e.g., lengthy or complex administrative processes, high startup costs/fees); public or political opposition to the establishment of outside businesses; public or political opposition to large commercial, industrial, or agricultural development projects; or public preference for use of off-Nation services or businesses. This slow economic growth scenario would most likely result in a modest population growth rate that is less than the ideal (1.5% for on-grid and 0.7% off-grid) and economic development only reaching 50% of its goal. This scenario was implemented to show how reduced utility revenues from projected C&I users will affect the ability to sustain OMR costs.

Non-Willingness to Pay

Another highly likely possibility is when residents are not willing to pay for the cost of the delivered potable water and pertains mostly to off-grid residents. This is a possibility as off-grid residents may not be willing to use or pay for the potable water that is delivered from watering points along the pipeline. This can happen because the watering point is not any closer than their current watering point, thus they will continue using the closer source which is free and may be unregulated. Or else, they may not have the fiscal ability to pay for the water and would resort to continue using the free source. This would result in unrecognized health benefits and unrecognized utility revenues. This scenario assumes that the ideal on- and off-grid growth rates are reached, but the off-grid demand remains the same as current conditions.

Drought

Due to climate change and its geographic location, the Nation has recently experienced periods of drought (USBR 2013) and is especially susceptible to future drought conditions (Roy et al. 2010; Seager et al. 2007). Drought can increase the demand for water, which creates stresses on the water distribution system. Accordingly, it is expected that in the event of prolonged drought conditions, water usage will increase considerably. It is expected that water usage will increase slightly for on-grid users and will significantly increase for off-grid users (see Table 3). Off-grid users are expected to pull more water from watering points for their own domestic uses and for livestock uses (assuming that livestock wells cannot keep up water demands). C&I demands are also expected to see demand increases. This scenario assumes that growth rates and economic development go according to plan. Development of this scenario was intended to see how system operational costs will vary under stressed conditions.

DSS HIERARCHY AND FRAMEWORK

Directly below the costs and benefits hierarchy are the main competing objectives that influence decision-making. In regards to water infrastructure development, these main competing objectives are:

- Improving the overall health of the people (Health Impacts);
- Contributing to a sustainable economy (Economic Impacts), and
- Protecting the natural environment (Environmental Impacts).

Accordingly, health impacts were placed under the benefits hierarchy; economic impacts were placed in both the cost and benefit hierarchy; and environmental impacts were placed under the cost hierarchy (see Figure 2).

The health objective measures the potential health benefits that may be brought to the region as a result of the project. Health benefits are measured according to the number of off-grid residents (i.e., water-haulers) that will have increased access to potable water; as well as the total number of residents already connected to the grid.

The economic objective is accounted for in both the cost and benefit hierarchy. Under the benefit hierarchy, the economic objective is measured by the potential economic growth that may be brought to the region as a result of the water infrastructure. These economic benefits include: job creation from planned C&I development that will accompany the water infrastructure and the new utility revenues generated through them; the water haulage time savings gained by off-grid residents; and the potential for unplanned future growth from tourism and general traffic in the region. Under the cost hierarchy, the economic costs include capital and OMR costs of the new water system. This economic objective introduces the economic sustainability component which is missing from current infrastructure planning efforts on the Nation.

The environmental objective is concerned primarily with minimizing impacts to the environment, particularly, the conservation and protection of water resources, and the minimization of wastewater. Excessive water consumption and the release of wastewater into sacred locations are significant cultural concerns and can have great influence on decisions regarding Tribal development projects. The environmental objective introduces the environmental sustainability component into the decision-making process, but more importantly, also brings in a cultural component. The environmental, economic and health objectives are further broken down into criteria and sub-criteria that are scored to ultimately derive BCR_{nm}'s for each project (see Figure 2).

Criteria and Scoring

In order to bring in an objective perspective into the DSS, each criteria and sub-criteria in the hierarchy was carefully selected using criteria that could either be estimated or quantifiable using readily available data. In many instances, certain criteria had to be eliminated because data was not available or could not easily be obtained. This is a challenge that is typically encountered when engineering economy analyses are conducted in developing countries or with conditions similar to the Navajo Nation (Khademi et al. 2014). The criteria and scoring functions are described here.

Water Usage and Wastewater Generation

Water usage and wastewater generation are criteria in the cost hierarchy that indirectly account for the environmental and cultural impacts that may result from too much water being used and the larger amounts of wastewater that must be managed and discharged into culturally appropriate areas. The water usage and wastewater criterion/scoring system is based on the premise that higher water usage equates to greater environmental and cultural impacts. Accordingly, the scores for water usage (S_W) and wastewater generation (S_{WW}) are based on the anticipated annual volumes of water used and wastewater generated at full project buildout measured in acre-feet per year (AFY), and are calculated as:

$$S_W = S_{WW} = \frac{V_{w/P} - V_{w/oP}}{7000} \tag{12}$$

where $V_{w/p}$ = the annual volume of water consumed or volume of wastewater generated with the project (afy); $V_{w/oP}$ = the annual volume of water consumed and volume of wastewater without the project (afy). Water usage and wastewater generation volumes are estimated according to the growth model. Wastewater from off-grid residents is assumed to be managed locally through septic systems while on-grid residents discharge to central systems (either lagoons or wastewater treatment plants).

Capital and OMR Costs

The capital and OMR cost criteria are estimates based on preliminary engineering designs of each project. The estimated capital costs for each project correspond with the demand conditions at full buildout for the ideal scenario while OMR costs match the anticipated operational conditions for each scenario at full buildout. Capital cost only includes the cost of the water transmission system and all appurtenances (i.e., valves, tanks, pumps, controls) the electrical infrastructure, and water treatment plant. The cost of upgrades to the existing distribution systems or wastewater systems were not included. OMR costs includes the electricity costs to operate pumps, and the costs to maintain the system (e.g., pumps, replace pipes, valves, repairs). The score for the total capital cost of the project (S_C) in dollars ($) is calculated as:

$$S_C = \frac{CC_P}{2.0\times10^8} \tag{13}$$

where CC_P = the total capital cost of the project designed for the ideal scenario. The score for the OMR costs is calculated as:

$$S_{OM} = \frac{OMRC_P}{2.0\times10^7} \tag{14}$$

where $OMRC_P$ is the anticipated annual OMR costs at full buildout of the project for each scenario.

Water Haulage Distance Savings

It is expected that off-grid users should also see substantial economic benefits through the reduced time it takes to haul water as the distance to quality regulated sources should decrease. This translates to time savings that residents can apply toward other duties or economic opportunities. The score for the time saved by water-haulers (S_D) is measured according to distance saved (in mi.) and is calculated as:

$$S_D = \frac{D_{w/P} - D_{w/oP}}{2000} \tag{15}$$

where $D_{w/oP}$ = the summation of the distances from each off-grid home to the nearest regulated water source in the future without the project. $D_{w/P}$ = the summation of the distances from each off-grid home to the nearest regulated water source in the future with the project. The future number of homes is based off the population growth model, and the location of the future homes are randomly distributed throughout the region associated with the project. Future regulated water sources without the project are assumed to be the same as current locations. Future regulated water sources include current sources and new watering points spaced at 10 mile increments along the transmission system (see Figure 1).

Utility Revenues

Utility revenues from new users that will be connected to the new infrastructure is critical for the long term economic sustainability of the project. This criterion is incorporated to demonstrate the importance for residential and C&I development to be planned in conjunction with the water infrastructure. Utility revenues are estimated according to the expected residential and C&I usage rates estimated by the growth model and the scenarios. The score for the additional revenues (S_R) that are expected from the new users connected to the system at full buildout is calculated as:

$$S_R = \frac{R_{w/P} - R_{w/oP}}{20.0 \times 10^6} \quad (16)$$

where $R_{w/P}$ = the estimated annual revenues at full project buildout ($); $R_{w/oP}$ = the estimated annual revenues without the project ($). Utility revenues are estimated using NTUA standard rates converted into $/ac for residential users and C&I users. C&I users were estimated to generate an average of $2,402 ac/ft in all scenarios while residents were estimated to generate between $2,188 - 2,393 ac/ft depending on the scenario.

Economic Development

The economic development criterion consists of three sub-criteria that were deemed significant contributors to spur economic development in each project's respective region: (1) the number of permanent jobs that will be created through planned development in the region to accompany the water infrastructure (Permanent Jobs); (2) the potential for unplanned development to spring up in areas adjacent to the project based on traffic in the area (Traffic); and (3) the potential to further develop the tourism industry (Tourism).

The permanent job sub-criterion accounts for the planned short term developmental goals for the Nation and is scored according to the estimated number of new jobs that will be created. It is assumed that these jobs will directly equate to economic benefits from increased spending in the region. The estimated number of jobs is based on the Nation's short term development goals which includes a mixture of retail, commercial, recreational, tourist amenities and small industrial establishments (Navajo Division of Economic Development, personal communication, July 20, 2015).

The traffic sub-criterion considers the potential for unplanned development (such as retail and services) to spring up as a result of the planned growth and general population growth in the region.

This criterion is scored based on traffic counts along major roadways adjacent to the project. It is assumed that higher traffic in the region will result in higher growth potential.

With three major tribal parks in the vicinity of the two candidate projects, tourism has shown to be a substantial contributor to the greater economy by pulling in outside dollars and has potential to further spur development. In 2011, out-of-region visitors generated an estimated total economic impact of $144M for tourism on the Nation (NAU 2012). The Monument Valley Navajo Tribal Park is located the near the MHK project. The Antelope Canyon Navajo Tribal Park and the Little Colorado River Navajo Tribal Park are located near the NCAZ project (see Figure 1). Additionally, the NCAZ project runs along a major recreational traffic corridor connecting southern Arizona to Lake Powell. During the summer months, this traffic consists of the more affluent Arizona residents such as recreational boaters.

The scores for each economic development sub-criteria can be calculated according to:

$$S_i = \frac{N_i}{C_i} \tag{17}$$

Where i = J, TR and T representing the permanent jobs, traffic and tourism sub-criteria respectively. N_J = the estimated no. of jobs, and C_J = 200. N_{TR} = the average annual daily traffic (in both directions) along major roadways adjacent to the project; and C_{TR} = 6000. N_T = the number of visitors that visited one of the aforementioned tribal parks in 2016; and C_T =20.0×10^6.

Existing Homes Served

This criterion accounts for the number of existing homes that are currently connected to the water grid. A criterion for the on-grid residents is required to ensure that the health of the current population is maintained. Without project intervention, the on-grid users water needs will eventually be unmet; resulting in the health deterioration of a larger population. This criterion is scored according to:

$$S_H = \frac{N_{Hon}}{15000} \tag{18}$$

where N_{Hon} = the number of on-grid homes.

Reduced Exposure to AUM Contaminated Sources

A large number of groundwater sources on the Nation are currently contaminated with uranium. Uranium in groundwater sources can either be naturally occurring or can be caused by man-made disturbances to the natural environment such as mining (TerraSpectra Geomatics 2007). Historical uranium mining on the Nation has resulted in hundreds of open mine shafts and exposed tailings and waste piles. The water that then comes into contact with the unnatural state of the uranium (exposed ore or waste) can then carry and alter the contaminates that may leach back into the groundwater, exacerbating conditions (TerraSpectra Geomatics 2007). With regulated drinking water sources few and sparsely distributed, residents in the very remote areas often resort to using these contaminated sources. Accordingly, this criterion accounts for the number of off-grid residents who live within 15 miles of an abandoned uranium mine who should have improved access to a cleaner water source. This criterion is based on the premise that homes in close proximity to the AUMs have a higher likelihood of using contaminated sources (assuming that sources near AUMs are more likely to be contaminated). This criterion is one that can be further refined in future studies by taking into consideration other contaminant transport factors such as the depth to groundwater, the direction of groundwater and surface gradients and wind direction, etc. This criterion is scored as:

$$S_U = \frac{N_{HAUM}}{15000} \quad (19)$$

where N_{HAUM} = the number of off-grid homes within a 15-mile radius of an AUM. The location of AUMs were determined by TerraSpectra Geomatics (2007).

Improved Access to Potable Water

This criterion accounts for the number of off-grid homes that have improved access to a potable water supply as a result off the project. It is expected that the project will have positive health impacts, particularly for residents that haul water as they will have improved access to potable water. This also results reduces health care costs associated with enteric diseases caused by the lack of access to potable water (Schliessmann 1958). This criterion assumes that off-grid users will be inclined to use and pay for the new regulated watering points created from the project and discontinue the use of free and unregulated sources. This criterion is scored according to:

$$S_{IA} = \frac{N_{Hoff}}{600} \quad (20)$$

where N_{Hoff} = the current number of off-grid homes near the project area.

DSS APPLICATION

Two candidate projects were evaluated by the DSS: (1) the North Central Arizona Water Supply (NCAZ; USBR 2006) and (2) the Mexican Hat to Kayenta Regional Water Supply (MHK; USBR 2011) as show on Figure 1. The NCAZ project withdraws water from Lake Powell and distributes water to 7 different communities on the western side of the Nation. The MHK project withdraws water from the San Juan river (a tributary to the Colorado river) and distributes water to three main communities. Both projects would provide improved access to potable water for off-grid residents and have the potential to provide water for C&I use to spur economic development. Both projects also server regions that have the potential for increased tourism. Selected demographic and project data comparing the two projects are summarized in Table 4.

Criteria Weights

In order to mimic the differences in priorities amongst the various decision-makers and how they may influence project selection, three sets of predetermined (preset) criteria weights were developed for the DSS. The preset weights, which are derived through the pairwise comparisons, were made through the lens of decision makers with the following views on water infrastructure development:

- Environmental protection focus – a decision-maker who puts the highest priority on protecting the environment and conserving water resources; and is indifferent on economic and health objectives. The weights derived by this decision-maker should favor the selection of projects that use less water and generate less wastewater.
- Economic development focus – a decision-maker who views economic development (i.e., increased C&I users) in conjunction with planned water infrastructure as critical for the long-term economic sustainability of a water infrastructure project. This decision-maker is assumed to be indifferent on environmental and health objectives. The weights derived by this decision-maker should favor the selection of projects that are accompanied by C&I users which: generates higher utility revenues, provides jobs, and have the potential for increased tourism.
- Health improvement focus – a decision maker who views the improvement of the health of the people (through the increased access to potable water) as the top priority. This decision-maker is assumed to be indifferent on environmental and economic development

objectives. The weights derived by this decision-maker should favor the selection of projects which serve a region where there are large numbers of off-grid users and off-grid users who are near AUMs.

The preset objective and criteria weights and the corresponding priority matrices from pairwise comparisons are provided in Tables 5 and 6.

RESULTS

DSS Performance

DSS results for the 5 different scenarios using three different sets of criteria weights are provided on Figure 3. For all the scenarios and preset criteria weights, both projects had very similar BCR_{nm}s. This provided some indication that both projects were very competitive and would bring similar benefits to each respective region. The BCR_{nm}s among the various focus objectives varied in magnitude, this was expected, due to the changing weights and emphasis on the various criteria.

Under the health focus, the outmigration and slow economic development scenarios had higher BCR_{nm}s. The reason for this is because the number of off-grid residents remain the same regardless of the scenario. With the weight and priority on the number of off-grid residents being served, the benefits remain high while the costs essentially remain the same. Similarly, with an environmental focus, the outmigration scenario and slow economic development scenarios had higher BCR_{nm}s. The reason for this is because these two scenarios use the least amount of water and consequently generate the least amount of waste, resulting in lower costs (or less impacts to the environment). With an economic development focus all BCR_{nm}s were very similar. It is important to recognize that the magnitude of the BCR_{nm}s is not as important as the difference between the BCR_{nm}s within the same scenario.

Project Comparisons

Under the health focus, the MHK project ranked higher than the NCAZ project in 4 out of the 5 scenarios (ideal, outmigration, slow economic development and drought). The MHK project ranked higher under those scenarios because the MHK project had a higher percentage of residents living off-grid and a larger number of residents living within 15 miles of an AUM. Under the non-willingness to pay scenario, the NCAZ was the slightly better project. This is because the health benefits of the off-grid residents are not recognized because it is assumed that they continue to use unregulated water sources.

Under the economic development focus, the NCAZ project ranked higher than the MHK project in 3 out of the 5 scenarios (ideal, non-willingness to pay and drought). The NCAZ project scored higher than the MHK project in these scenarios because: the population is greater; the planned growth will create more jobs; the region generates more tourist activity; and higher utility revenues are expected. As expected, the MHK project is a better choice under the outmigration and slow economic development scenarios.

Under the environmental focus, the MHK project ranked higher than NCAZ in all scenarios. This is due to the expected lower water usage and lower wastewater generated for the project. Accordingly, the following general conclusions can be made regarding the projects analyzed in the DSS:

- Under a health and environmental focus, the MHK project was the best candidate.
- Under an economic development focus, the NCAZ project was the best candidate.

These results demonstrate how important the decision-makers' priorities influence project selection and how vital their participation is in using this DSS. The closeness of the BCR_{nm}s for these particular projects shows how vital the accuracy of the collected/input data is.

A few inferences can also be drawn from the results of the hypothetical decision-makers:

- Decision makers with health and environmental agendas should be able to agree on selection of the MHK project.
- Although the NCAZ project demonstrated to be better investment than the MHK project for decision makers with economic agendas, they should have some assurance that under the outmigration and slow economic development scenarios they can count on the MHK project to be a better investment. This may sway economic decision makers to be in support of the MHK project, bringing unity to the decision-making group.

The working DSS shows the connection between health, economic development and the environment. The link between economic development goals and revenues will promote collaboration between agencies like the economic development teams and water infrastructure teams to ensure accurate demands and projections are made. The DSS and its framework helps to identify all the necessary teams that need to be involved in the planning process.

Future Work

The focus of this paper was to demonstrate the methodology used to develop a DSS that can be used by Navajo decision-makers. With a working DSS, actual decision-makers can be invited to participate by developing their own objective and criteria weights. Other candidate projects can also be added to the project list. Because of the closeness of the BCR_{nm}s, a case can be made to justify future investments in data collection such as on- and off-grid home counts and census data.

The model has potential for improvement, each of the scoring formulas can be upgraded to more detailed models. For instance, individual economic impact models can be developed for tourism impacts, traffic count impacts, and job creation. Creation of certain job types (C&I vs. retail and service) may equate to more permanent and larger economic impacts to the region. Other improvements can be made such as the development of a more sophisticated growth model that can model the spatial growth of on- and off-grid users. Additional studies can also be made to more accurately assess the current capacity of the existing systems, as well as the inclusion of other costs such as upgrading the existing water distribution system and/or wastewater infrastructure. As project designs evolve and as more data is collected, and costs are refined, the inputs can be continually updated to see how project rankings change.

SUMMARY AND CONCLUSION

A DSS that allows water transmission projects to be compared considering economic development, health and environmental objectives has been developed for the Navajo Nation. The DSS consist of a CBA integrated into a MCDA framework that allows projects to be ranked based on a non-monetized benefit cost ratio (BCR_{nm}). BCR_{nm}s are calculated according to weights (or priorities) determined through pairwise comparisons that are assigned to objectives and criteria. Each project is then scored through each criterion using quantitative data that compares a baseline future (without the project) to a future with the project. Because of the future high uncertainties in growth conditions on the Nation, various alternative scenarios were simulated in the DSS for robust decision making. Two candidate projects were used to demonstrate how the DSS is used to rank projects through the lens of three hypothetical decision-makers with different agendas. The methodologies used to develop the DSS and can be applied to assist with decision making regarding water infrastructure for developing regions with similar socioeconomic conditions as the Navajo Nation.

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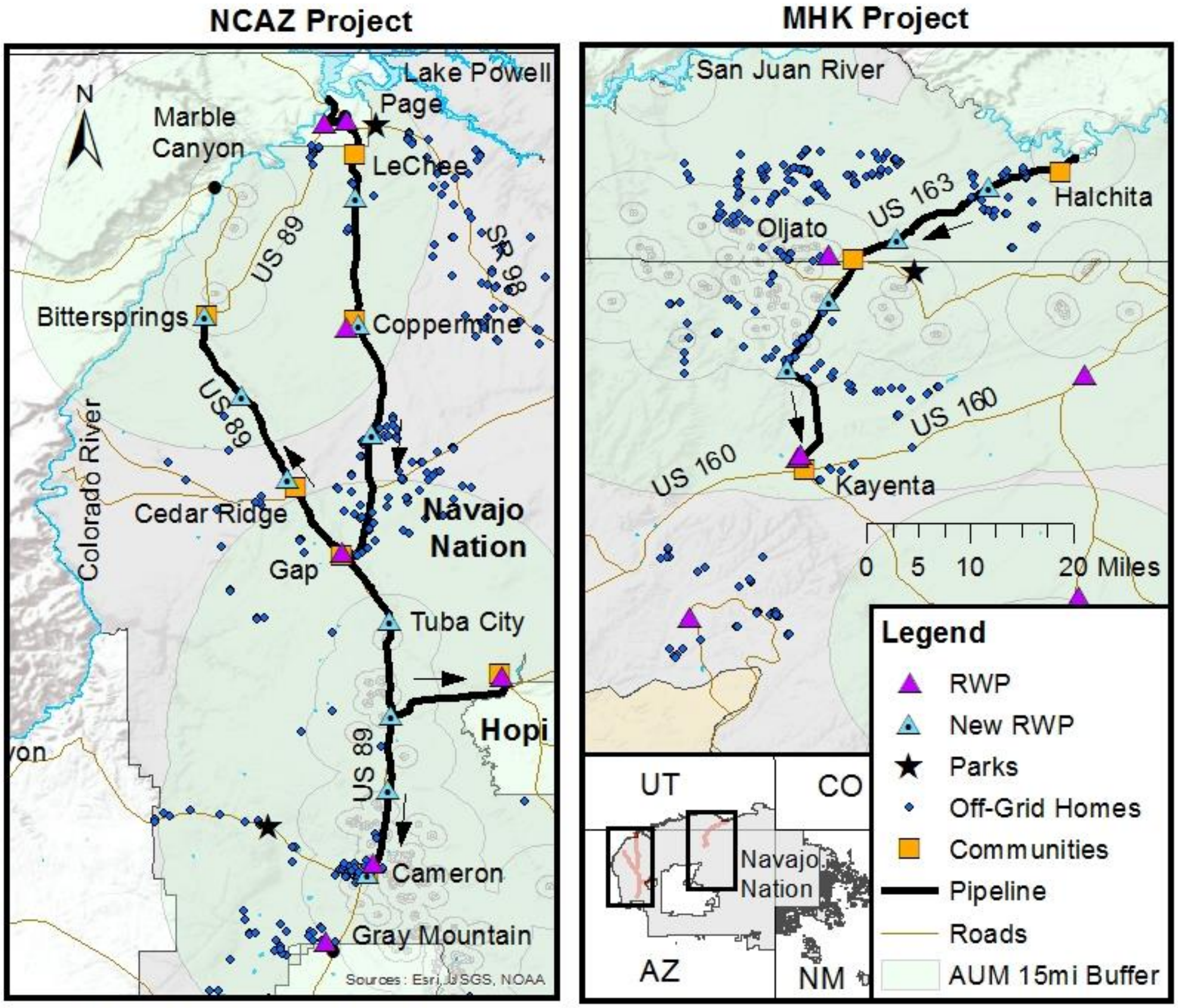
Figure 1. Alternative Projects Map



RWP = Regulated Watering Point

Figure 2. DSS Hierarchy Framework

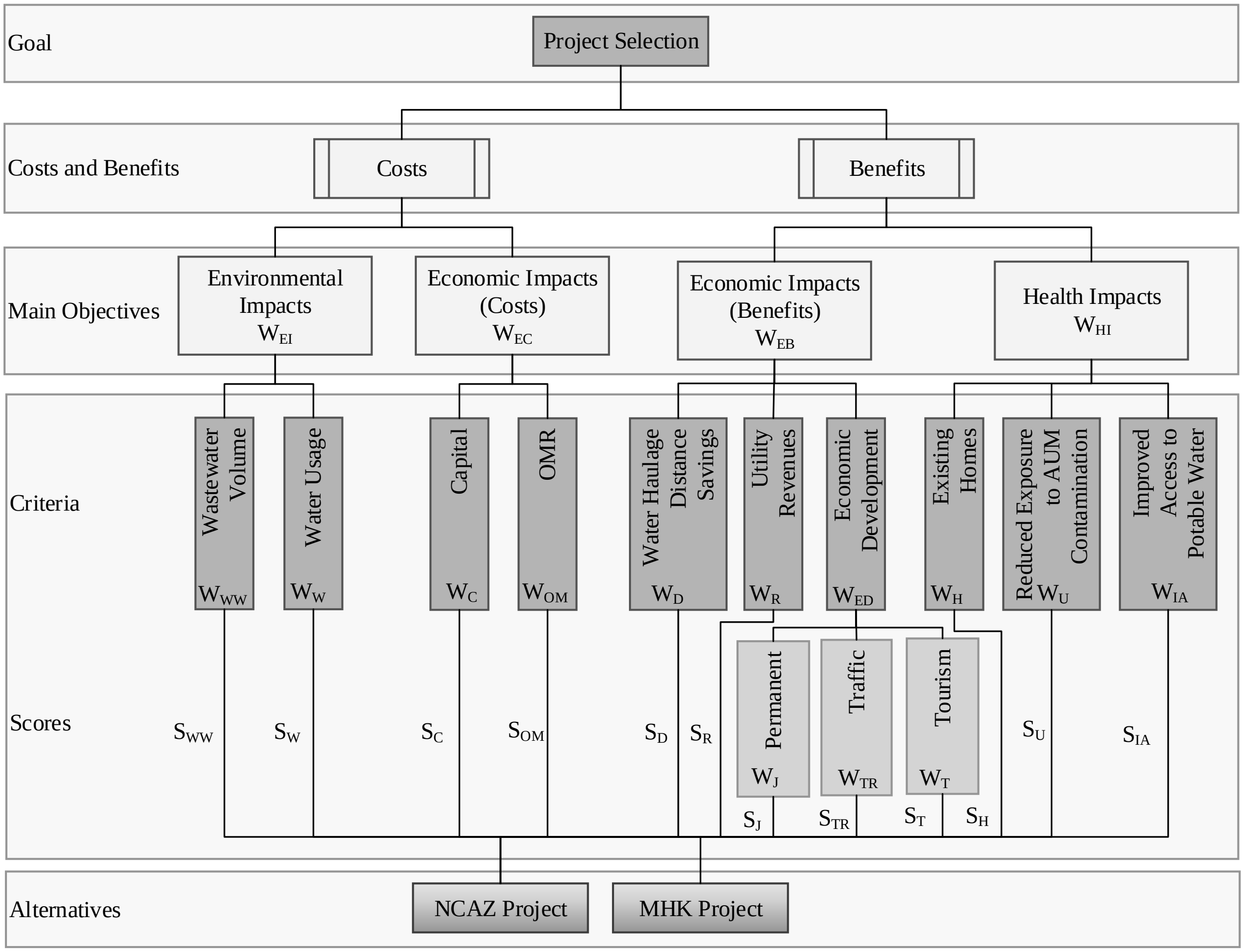
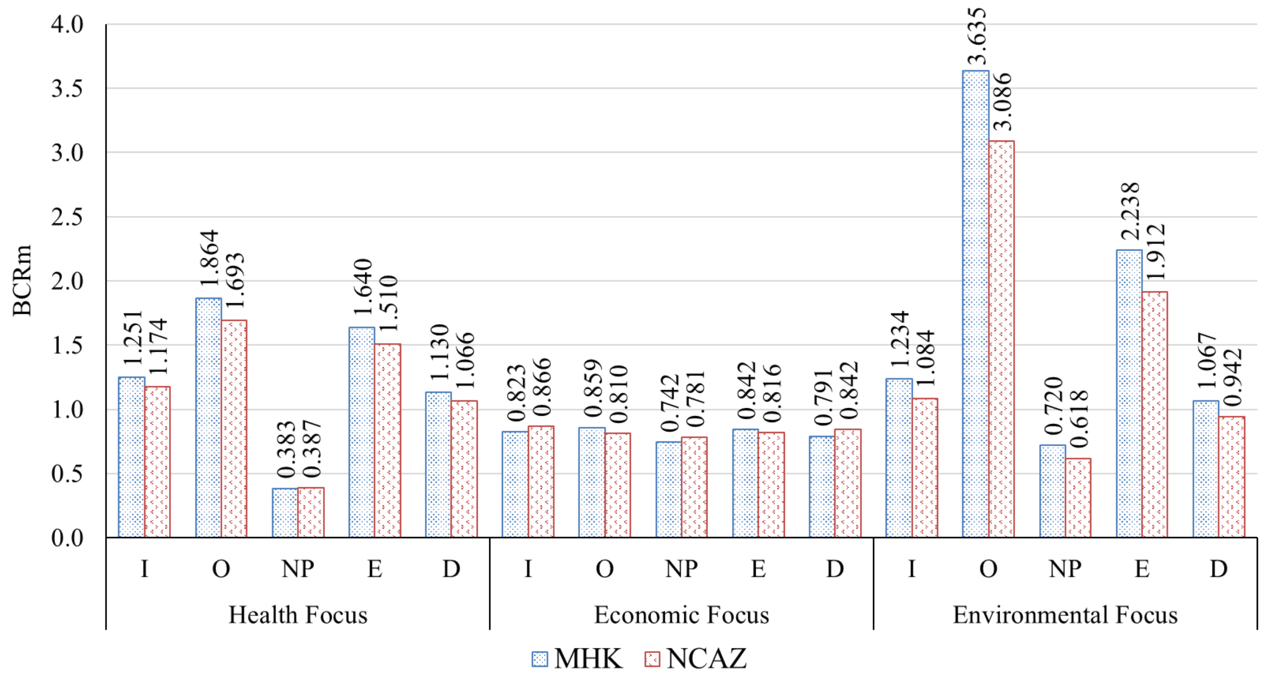


Figure 3. DSS Model Results



I = Ideal future scenario
O = Outmigration scenario
NP = Non-willingness to pay scenario
E = Slow economic development scenario
D = Drought scenario

Table 1. Fundamental Scale for Pairwise Comparisons (Saaty 1980)

Intensity of Importance (a_{ij})	Definition	Explanation
1	Equal Importance	Two elements contribute equally to the objective
3	Moderate Importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very Strong Importance	One element is favored very strongly over another, its dominance is demonstrated in practice
9	Extreme Importance	The evidence favoring one element over another is of the highest possible order of affirmation

Note: Even values can also be used for fine tuning.

Table 2. Random Index (R.I.) of a Randomly Generated Reciprocal Matrix (Saaty 1980)

Size of Matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 3. Growth and Demand

		Current	Scenarios: Without Project (Baseline)	Ideal	Outmigration	Non-willingness to Pay	Slow Econ Development	Drought
Off Grid (10% of Pop.)	Population Growth	-	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%
	Residential Demand (gpcd)	10	10	30	30	10	30	50
On Grid (90% of Pop.)	Population Growth	-	0.5%	2.5%	0.5%	2.5%	1.5%	2.5%
	Residential Demand (gpcd)	33	33	70	70	70	70	90
Total C&I Demand		11	11	50	25	50	25	60
Avg. Total Demand (avg)		42	42	118	90	117	92	148

Note: Growth and usage rates were assumed to be the same for the whole Nation, in reality there will be differences in the various regions.

Table 4. Project Data Comparison (Current Data)

		NCAZ	MHK
Population	On-grid	11,348	8,321
	Off-grid	1,325	1,092
Current Off-grid Population within 15 mi. of AUM		829	884
Current Total Distance Traveled by Water Haulers (mi)		2,846	2,588
Ideal Scenario – Total Projected Demands (afy)		4,515	3,308

Table 5. Cost Hierarchy Pairwise Comparisons

Main Objectives

Health Focus

	W_{EI}	W_{EC}	Wt.
W_{EI}	1	1	0.50
W_{EC}	1	1	0.50

Economic Development Focus

	W_{EI}	W_{EC}	Wt.
W_{EI}	1	1/9	0.10
W_{EC}	9	1	0.90

Environmental Focus

	W_{EI}	W_{EC}	Wt.
W_{EI}	1	9	0.90
W_{EC}	1/9	1	0.10

Criteria

Health Focus

	W_{WW}	W_{W}	Wt.
W_{WW}	1	1	0.50
W_{W}	1	1	0.50

	W_{C}	W_{OM}	Wt.
W_{C}	1	1	0.50
W_{OM}	1	1	0.50

Economic Development Focus

	W_{WW}	W_{W}	Wt.
W_{WW}	1	1	0.50
W_{W}	1	1	0.50

	W_{C}	W_{OM}	Wt.
W_{C}	1	1/2	0.33
W_{OM}	2	1	0.67

Environmental Focus

	W_{WW}	W_{W}	Wt.
W_{WW}	1	1/2	0.33
W_{W}	2	1	0.67

	W_{C}	W_{OM}	Wt.
W_{C}	1	1	0.50
W_{OM}	1	1	0.50

Note: C.R.s were all less than 0.10.

Table 6. Benefit Hierarchy Pairwise Comparisons

Main Objectives

Health Focus

	W_{EB}	W_{HI}	Wt.
W_{EB}	1	1/9	0.10
W_{HI}	9	1	0.90

Economic Development Focus

	W_{EB}	W_{HI}	Wt.
W_{EB}	1	9	0.90
W_{HI}	1/9	1	0.10

Environmental Focus

	W_{EB}	W_{HI}	Wt.
W_{EB}	1	1	0.50
W_{HI}	1	1	0.50

Criteria

Health Focus

	W_H	W_U	W_{IA}	Wt.
W_H	1	3	1/3	0.32
W_U	1/3	1	1	0.24
W_{IA}	3	1	1	0.44

	W_D	W_{ED}	W_R	Wt.
W_D	1	1	1	0.33
W_{ED}	1	1	1	0.33
W_R	1	1	1	0.33

Economic Development Focus

	W_H	W_U	W_{IA}	Wt.
W_H	1	1	1	0.33
W_U	1	1	1	0.33
W_{IA}	1	1	1	0.33

	W_D	W_{ED}	W_R	Wt.
W_D	1	1/2	1/2	0.20
W_{ED}	2	1	2	0.49
W_R	2	1/2	1	0.31

Environmental Focus

	W_H	W_U	W_{IA}	Wt.
W_H	1	1	1	0.33
W_U	1	1	1	0.33
W_{IA}	1	1	1	0.33

	W_D	W_{ED}	W_R	Wt.
W_D	1	1	1	0.33
W_{ED}	1	1	1	0.33
W_R	1	1	1	0.33

Sub-criteria

Health Focus

	W_J	W_{TR}	W_T	Wt.
W_J	1	1	1	0.33
W_{TR}	1	1	1	0.33
W_T	1	1	1	0.33

Economic Development Focus

	W_J	W_{TR}	W_T	Wt.
W_J	1	2	1/2	0.31
W_{TR}	1/2	1	1/2	0.20
W_T	2	2	1	0.49

Environmental Focus

	W_J	W_{TR}	W_T	Wt.
W_J	1	1	1	0.33
W_{TR}	1	1	1	0.33
W_T	1	1	1	0.33

Note: C.R.s were all less than 0.10.

Table 7. DSS Input Data

		NCAZ					MHK				
		I	O	NP	E	D	I	O	NP	E	D
Environmental Costs	Water Usage (afy)	4,515	848	4,473	1,852	5,855	3,308	624	3,273	1,360	4,292
	Wastewater Generation (afy)	3,355	605	3,355	1,358	3,609	2,455	442	2,455	994	2,641
Economic Costs	Capital ($M)	198.7	198.7	198.7	198.7	198.7	198.7	198.7	198.7	198.7	198.7
	OMR ($M)	50.0	40.0	50.0	40.0	60.0	40.0	30.0	40.0	30.0	50.0
Economic Impacts	WH Distance Savings (mi)	1,012	1,012	1,012	1,012	1,012	915	915	915	915	915
	Utility Revenues ($M)	10.3	1.8	10.2	4.1	13.2	7.5	1.3	7.5	3.0	9.7
	Perm Jobs	109	55	109	55	109	40	20	40	20	40
	Traffic Count	3,773	3,773	3,773	3,773	3,773	4,572	4,572	4,572	4,572	4,572
	Tourism	816,097	816,097	816,097	816,097	816,097	448,205	448,205	448,205	448,205	448,205
Health Benefits	On-Grid Homes	10,598	3,938	10,598	6,493	10,598	7,772	2,888	7,772	4,761	7,772
	Off-grid homes near AUM	559	559	0	559	559	343	343	0	343	343
	Off-grid homes w/ impr. access	508	508	508	508	508	419	419	419	419	419

I = Ideal future scenario; O = Outmigration scenario; NP = Non-willingness to pay scenario; E = Slow economic development scenario; D = Drought scenario.