RESILIENT, SUSTAINABLE WATER AND WASTEWATER INFRASTRUCTURE PLANNING

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ABSTRACT

An ongoing project funded by the U.S. National Science Foundation is examining the opportunities and triple bottom line costs of integrating water and wastewater planning to take advantage of water reuse. The goal of the project is to examine decentralized treatment and dual water supply systems as a means to extend scarce water supplies and develop tools that allow decision makers to formulate sustainability, resilient, and robust long term community infrastructure plans. This talk will provide a summary of the project and important progress to date including indicators for water resource sustainability and resilience for water supplies and users, assessment of public perception and institutional context, models for triple bottom line costs for wastewater systems that extend WateReuse Foundation tools, optimization models and results for regional water and wastewater infrastructure design, and optimal design tools for dual water distribution systems on regional and local scales.

KEYWORDS: Water resources planning, sustainability, infrastructure

INTRODUCTION

An ongoing U.S. National Science Foundation project has focused on development of management tool and approaches that will expose the costs and benefits of water and wastewater resource decisions in the presence of complex, competing objectives. The tool are transferable, so that it can be applied in any region where water is of great value and the implications of water/wastewater-related decisions and/or institutional constraints fall within a complex geopolitical and social landscape. A focus of the effort is to quantify the benefits of consolidating water and wastewater systems and the influence of geographic conditions. The project team has been working closely with practitioners to ensure that the integrated approaches are transferable to users and decision makers. With the ability to fully plan for integrated water and wastewater infrastructures, a new planning paradigm that is particularly critical in water scarce regions and areas susceptible to droughts or short term water shortages is emerging. This paper provides an overview of the project and significant outputs that can serve to support general planning processes.

Critical Infrastructures

A water supply system typically includes multiple sources and demand centers (agricultural, domestic, industrial and commercial users). System components are designed to treat relatively good quality source waters from an aquifer or various surface supplies and deliver it to users in a water distribution system that is sized to provide fire flows. Water system design represents a tradeoff between treatment plant size (economy of scale) and the number of plants, pipe and pump sizes and energy consumption, and component sizes, travel time and water quality. All of these decisions are made subject to uncertainties introduced by future growth rates and locations, water resource availability, and changing social and institutional conditions.

In a typical wastewater (WW) system, the collection system brings municipal sewage, possibly with pumping, to one or more wastewater treatment plants (WWTP). These waters are highly treated in a sequence of unit operations and either returned to the environment or to a reuse system for distribution among outdoor consumptive uses (Figure 1a). The age of most WW systems is such that few envisioned the benefits or need to distribute treatment capacity throughout a community; instead treatment at a single centralized treatment facility is the norm. An extensive reclaimed water distribution system is a more recent and rare development. If reclaimed water is introduced to the system it often is provided to large irrigation users (parks, schools, or agriculture) through long pipelines to locations near where the wastewater was generated.

In many water scarce regions the balance of water supply and demand is already tenuous and tensions among competing users will grow. New freshwater sources are essentially unavailable, and the largest underutilized water resource is treated wastewater. More comprehensive planning that includes reuse could suggest a new infrastructure system. As shown in Figure 1b, shifting from a single centralized facility to multiple decentralized wastewater treatment plants reduces the distance and corresponding energy costs for delivering reclaimed water to users. Further, it can provide flow for additional users even to the household level. The introduction of this “new” supply can be critical in water scarce regions in terms of water supply sustainability, resilience and robustness. Further, secondary benefits of changing the water supply paradigm to an integrated water and wastewater infrastructure system are lower energy consumption and cost, a reduced carbon footprint, and better overall water quality.

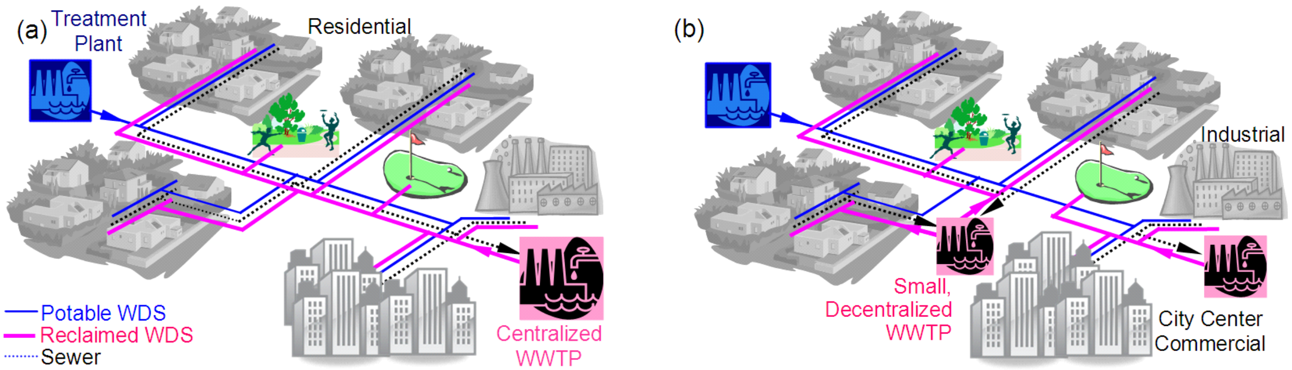

Figure 1: Schematics of communities representing (a) Centralized wastewater treatment and distribution and (b) decentralized treatment and water reclamation

METHODS

Sustainability/Robustness/Resilience

A fundamental step is system’s planning is to define the planning objectives. Clearly, water resources and water supply are multiple objective problems. An encompassing objective is defined as system sustainability. We define sustainability is described to consider from two perspectives: the availability of water in the long term and the costs of providing acceptable quality water. The former is defined as resource sustainability and the latter infrastructure sustainability.

Resource sustainability is defined as ability to provide resource of desired quantity and quality for a defined long period of time. Two widely accepted concepts of resource sustainability are as follows;

…*sustainable water management is achieved when only as much water is abstracted from the locally available water resources*… (Carlowitz 1713)

…*sustainability is achieved when the needs of the present are met without compromising the ability of future generations to meet their own needs*… (WDEC 1983)

Resource sustainability examines a comprehensive system and can be quantified with respect to the sustainability of the water supply or the water user to have adequate water under a given distribution policy (Huizar et al 2011).

Infrastructure sustainability is assessed using a triple-bottom-line (TBL) framework to consider the tradeoffs between economic, environmental, and societal benefits and objectives. The economic component of TBL is well developed and historically the metric applied for comparing designs. Environmental and societal benefits and objectives are more difficult to assess and incorporate in quantitative modeling studies. Thus, TBL tradeoffs are often opaque. We have used the global environmental metric of greenhouse gas production (GHG) as an indicator of environmental impact and are furthering our analysis to assess a more complete life-cycle costs (described below). Localized social and environmental benefits/values, such as the value of riparian zones that are supported by wastewater effluent or the acceptability of water reuse, must be addressed on a local scale. To formally incorporate these factors in a water supply planning process, the project team with our partner utilities is completing a scenario planning exercise (discussed below).

Robustness

Water utilities are by nature conservative organizations, particularly regarding the significant infrastructure investments necessary to provide water to a large community. Thus, they attempt of balance investments to provide system robustness. Robustness is defined as flexibility to meet range of future uncertain conditions. Hashimoto et al (1982a) defined robustness as "adaptation to a wide range of possible conditions at little additional cost under uncertainty". Here we determine decision points and system design while minimizing TBL costs through multi-stage development, especially for regional scale infrastructure. It is also often defined as Bayesian cost - TBL expected costs given uncertainty of future demand conditions, Cost(P|F). The goal of flexibility requires that the system design/operation be capable of providing service under a range of conditions and that it can evolve with changes in external forces. For example, the system shown in Figure 1a with a large WWTP that is constructed to handle an entire community is likely not robust. As growth rate is uncertain, a slower than expected level of development occurs, the large WWTP may remain overzsized for a long period of time and the distribution system may be unable to readily adapt an unanticipated spatial growth pattern. Here, the scenario planning process that is adaptive over time provides flexibility and reduces the regret costs over or under building infrastructure.

Resilience

For a water supply/wastewater system, the system disturbances will be caused by drought and climate related changes. For regional scale system, water supply interruptions (for quantity and quality) result from treatment plant failures. For local distribution system, withstanding pipe/pump/tank failure through alternative pump/tank operation to maintain adequate pressure will be quantified. Other major disruptions may include earthquake, power outage, pollutant injections, and earth fissures. A resilient system is capable of withstanding this type of short term disturbance through system (over) design or adaptation (changing operation) process. Hashimoto et al. (1982b) defined the capability of a system to recover or bounce back from failure once failure has occurred as resilience.

Trade-offs between Sustainability-Robustness-Resilience (SRR)

When designing a system, possible trade-offs between each measures must be considered. For example, distributed (or decentralized) water supply systems are more robust in terms of economic flexibility compared to the centralized large systems. However, since distributed systems are generally smaller in size, they are more likely to fail thus less reliable and resilient. On the other hand, once failure occur the intensity of the failure for centralized systems are greater than distributed systems. Understanding tradeoffs between these indicators is necessary during a design process to maintain robustness without losing resilience and sustainability described as TBL costs must be overlaid on top of robustness and resilience. Huizar et al (2011) discusses SRR tradeoffs for a regional water supply system while Kang and Lansey (2011) present an approach to consider the tradeoffs between economic costs and robustness (below) that is being extended to consider multiple SRR facets.

FINDINGS AND DISCUSSION

Economic and Environmental Water Supply Costs

An overriding objective with respect to regional water infrastructure is system cost. Appropriate costing is the first step to determining the appropriate degree of decentralization. The development and application of a decision support system (DSS) with which to inform integrated water and wastewater management decisions in urban settings has been developed in collaboration with our research partner Malcolm Pirnie/Arcadis. MP/A, under contract with the Water Reuse Foundation, developed a spreadsheet based cost model for decentralized system (Davis and Osgood 2008, Davis and USBOR 2009). We have continued their effort and extended the program. The DSS is designed to support facilities planning by comparing centralized collection/treatment/redistribution alternatives leading to reuse of municipal wastewater with physical alternatives that stress decentralized treatment and localized reuse of reclaimed water based on triple bottom line objectives including GHG production during operations.

Modifications to the DSS include (i) branched rather than radial transmission systems carrying reclaimed water to application sites; (ii) staged facilities construction; (iii) existing downstream infrastructure including collection system elements, treatment facilities, and reclaimed water distribution system; (iv) existing potable water infrastructure, (v) possibilities for multiple satellite treatment locations, and (vi) the necessity for peripheral underground storage and recovery facilities to satisfy inter-seasonal variation in demand for reclaimed water. Costs that are now considered within the DSS algorithm include:

- *Wastewater Reclamation (*Central reclamation plant, Satellite reclamation plant(s), Satellite influent intake/ solids return, recharge)
- *Water Source* (source purchase, surface intake, wells, recharge, treatment)

- *Potable Water Transmission (*pipes, pumps, tanks)
- *Reclaimed Water Transmission* (regional pipes, pumps, and tanks and local pipes, pumps, and tanks)
- *Wastewater Collection* (pipes and lift stations)

The improved model was applied, using input data and development plans from Tucson Water and the Pima County Regional Wastewater Reclamation Department, for consolidated water/wastewater planning in the so-called Houghton Area Master Plan (HAMP) area (Figure 2). The HAMP is largely a greenfield area on the periphery of the existing Tucson urban area that has been earmarked for development by the City of Tucson and Pima County. Alternative regional water and wastewater infrastructure configurations were compared based on relative economic cost and greenhouse gas generation. The seven options proposed and evaluated ranged from no reuse to indirect potable reuse (IPR).

The scenarios developed for the application of the DSS to the Houghton Area (Figure 3) included a no reclamation option; centralized reclamation, with and without a completely new pipeline to return reclaimed water for reuse in the Houghton Area (due to capacity concerns in the existing reclaimed water distribution system); and satellite reclamation with either a 7 million gallon per day (MGD) facility and long-term groundwater banking or a 3 MGD facility and seasonal underground storage. Another satellite reclamation scenario was added, whereby seasonal storage for a 3 MGD reclamation facility would be provided at the regional facility and a portion of summertime peak demand would be supplied to the Houghton Area from the regional facility obviating the need for a satellite infiltration and recovery facility. A final scenario involved IPR from a 7 MGD satellite reclamation facility: reclaimed water would be infiltrated in basins, mixed with native groundwater and eventually withdrawn for use as a fully potable source. For obvious reasons, the IPR scenario did not require a dual water supply system. Table 1 summarizes the results of scenario-dependent economic costs and GHG emissions. In some cases, a monetary benefit ($140/AF) was taken for the use of reclaimed water, representing the cost savings of preserving freshwater supplies for other uses. Greenhouse gas production from the production and installation of the pipes (developed as part of a life-cycle analysis) was equivalent to only one or two years of emissions from pump operation.

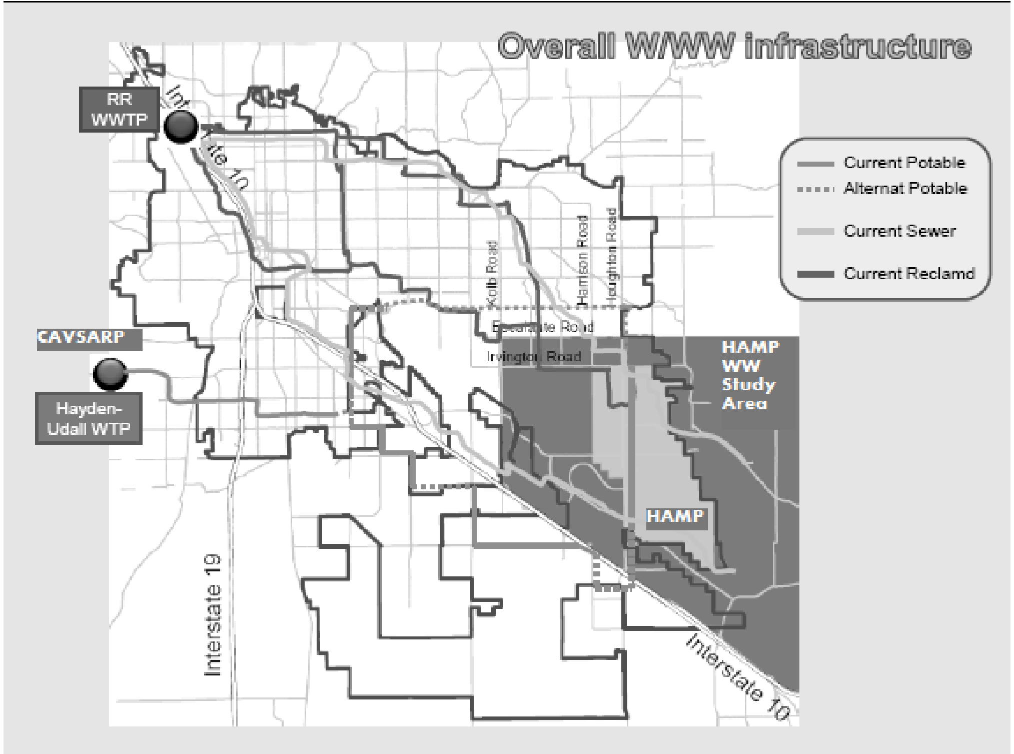

Figure 2. Regional layout of existing Tucson wastewater, potable water, and reclaimed water infrastructure. The Houghton area is the lightly shaded region to the southeast, and the wastewater study area is shown as the darker shaded area. Total distance from the Roger Road Wastewater Treatment Plant (WWTP) to the Houghton area is approximately 26 miles. Total distance from the Central Avra Valley Storage and Recovery Project (CAVSARP) through the Hayden Udall Water Treatment Plant (WTP) to the Houghton area is also about 26 miles.

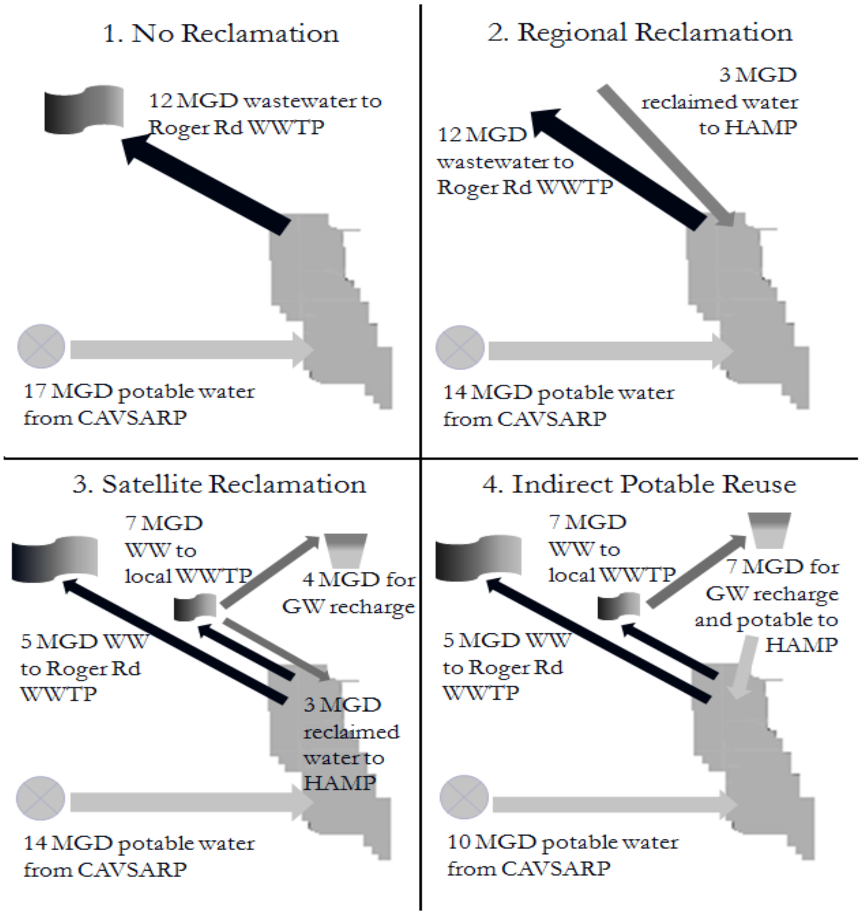

Figure 3. Schematic representations of the four main reclamation system configurations evaluated: 1) no reclamation, 2) regional reclamation, 3) satellite reclamation, and 4) indirect potable reuse (with satellite reclamation). CAVSARP is recharge recovery facility that provides potable water originally delivered though the Central Arizona Project Canal.

Table 1. Cost of greenhouse gas production and benefits of offsets to potable water use. GHG production was valued at a cost of $20/ton (Serchuk 2009), and offsets to potable water were valued at $140/acre-foot (in line with costs for Central Arizona Project water).

Scenario	**1**	**2**	**2a**	**3**	**3a**	**3b**	**4**
Brief Description	**No Reclamation**	**Regional Reclamation**	**Regional Reclamation New Line**	**Satellite Reclamation 7 MGD with Recharge**	**Satellite Reclamation 3 MGD with Recharge**	**Satellite Reclamation 3 MGD no Recharge**	**Satellite Reclamation 7 MGD with Indirect Potable Reuse**
Scenario Costs *	$320.59	$319.62	$345.77	$324.82	$328.84	$328.40	$316.94
Cost of GHG emissions **	$14.88	$13.37	$13.65	$13.54	$13.03	$13.02	$11.35
Benefit of Recharge**	$0.00	-$5.40	-$5.40	-$12.59	-$5.40	-$5.40	-$12.59
Total	$335.47	$327.59	$354.03	$325.77	$336.47	$336.02	$315.71

*baseline economic costs only, **20-yr present worth

When GHG costs and recharge benefits are taken into account, scenario 4 is clearly the preferred option, indicating that the energy and water savings of IPR make it a valuable component of urban water portfolios. This analysis only considers economic and environmental objectives. Selection of scenario 4 would be based public sensitivity to IPR that has not yet been considered here.

Life Cycle Infrastructure Costs

A second limitation of the DSS cost function is that environmental impacts of GHG are only included for the energy consumed during system operation for pumping and treatment. We have been to extend those costs to consider a full Life Cycle Analysis (LCA) for various types of water distribution and wastewater collection system pipes. Five commonly used pipe materials were chosen: Polyvinyl chloride pipe, ductile Iron pipe, HDPE pipe, concrete pipe and reinforced concrete pipe. The objective was to compare the life cycle environmental impacts of these five pipe materials. Also, LCA was used to identify the life cycle phase(s) that contribute most heavily to total environmental impact. Equations generated from the Life Cycle Analysis will be used to generate LCA cost estimates for construction and installation of the water distribution and wastewater collection system elements in the Houghton Area.

LCA is used to evaluate the total environmental impact of engineered systems over their entire service life—including raw materials acquisition, production, transportation to point of use, installation, operation, recovery and disposal. The life cycle of pipeline systems was arbitrarily divided into four phases: Production, transportation, installation, and disposal. Unit costs were estimated for pipeline systems that were one kilometer in length. Material and energy requirements for production were then calculated for discrete pipe sizes, generally from 4 inches to 20 inches in diameter. The transportation distance is arbitrarily based on a 100 mile trip from factory to site of installation using 13-ton road trucks. In the installation phase, the excavation fuel consumption was calculated based on the volume of excavation work, which was a function of pipe diameter. Different trench configurations were adopted for each kind of pipeline system based on specific trench standards. In-place disposal was presumed at the end of pipeline service life—no recycling or reuse benefits were taken.

Life Cycle Analysis was completed using the commercial LCA software GABI (PE International 2011). It is the state-of-the-art LCA software in industrial applications, enabling users to create specific system configurations by defining scenario-specific combinations of processes. Conversions from input information (e.g. electricity use, raw material requirements and fuel consumption) to life cycle costs in various environmental categories are embedded in the GABI software. System or scenario-specific environmental costs are organized into a few environmental impact categories such as global warming potential and human toxicity potential, acidification potential, etc. Numerical values in each environmental category are then provided and can be weighted and combined in order to yield a single numerical indication of LCA costs. Here, we present the global warming potential of the five alternative pipeline materials. The unit of the Global Warming Potential (GWP) is CO_2-kg equivalent, or carbon dioxide equivalents in kilograms.

Figure 4 shows the results of global warming potential estimates per kilometer of pipe of PVC pipe. The figure illustrates the fractional contributions of different LCA phases to the overall global warming potential. As expected, the production phase contributes most to the global warming potential. The pipe production phase generally requires large energy inputs that release greenhouse gases. The transportation phase contributed little to the total global warming potential. Material- and size-dependent LCA pipe costs are summarized for five pipe types and fitted with second order polynomial functions (Figure 5). Ductile Iron pipe has the highest global warming potential. The main reason is the tremendous energy requirement for iron processing activities such as iron ore extraction and smelting processes leading to steel production. Concrete pipeline has the lowest global warming potential, since its principal inputs are sand, rock and Portland cement, and mixing those ingredients does not require a very large energy input. Although the production of cement is energy-intensive, the relatively low proportion of cement in concrete results in a low global warming potential.

Scenario Planning

We now have tools available to perform analyses on economic and environmental costs and address sustainability of infrastructure systems in those terms. However, we also desire to develop robust designs. Traditional planning processes begin with the selection of a future condition that is perceived to most likely occur and planning is completed under that assumption; a single-scenario approach (Figure 6a). This process, however, results in a design that lacks robustness to satisfy needs under alternative futures. For example, designs based on a worst case scenario (that leads to the most conservative design) may be preferred by the utility because they reduce the risk of system failure at the expense of higher cost. The result is oversized system components and poor water quality due to excessive residence times. Alternatively, the use of a most likely scenario will have a lower cost. However, when a more severe condition than expected actually occurs, a significant system failure is concern and system adaptation costs can be substantial. Hobbs and Hepenstal (1989) demonstrated this effect by showing that an optimal solution for a defined condition will always be optimistically biased in an uncertain future.

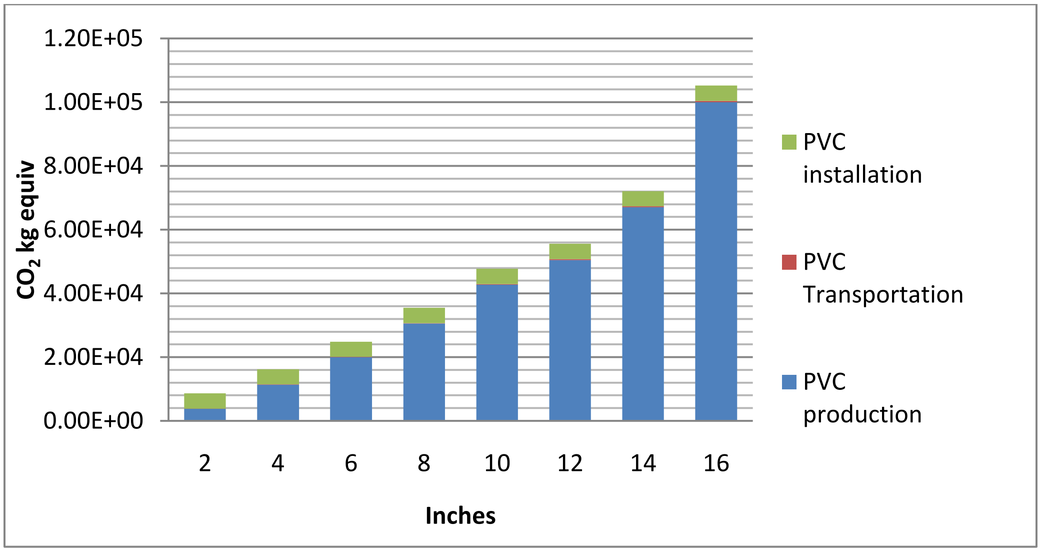

Figure 4. Life-cycle, size-specific GWP per km of PVC pipe.

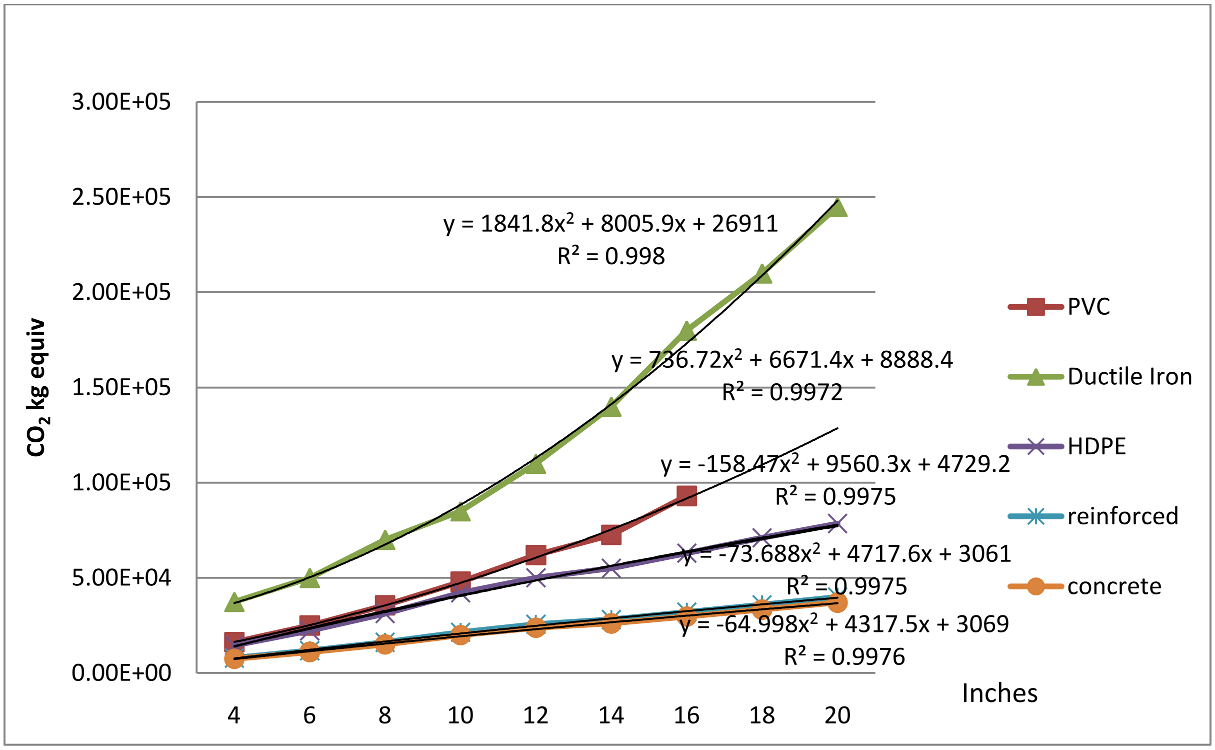

Figure 5. Total GWP as a function of pipe material and diameter.

An alternative process, described as (multiple) scenario planning, considers a range of “endpoint” scenarios (Figure 6b) and is gaining widespread popularity in the water planning community (City of Tucson Water Department 2004; USBR 2011). Scenarios are alternative views of how the future might unfold. Scenarios are not predictions or forecasts of future; rather a set of representative ranges of plausible futures. The scenario planning process considers multiple scenarios simultaneously in the planning exercise thus it provides robust solutions that are intended to be flexible and satisfy various future conditions.

Development of scenarios is time-consuming stakeholder driven process that involves the eight steps shown in Figure 7. In Step 1 the problem formally defined to ensure that all parties are in agreement with the goals for the process. Steps 2 and 3 are related to identifying and ranking critical external forces that will influence the planning process. Similarly, step 4 shifts the discussion to understand the uncertainties and degree of uncertainty that influence the process. The result of these steps is a set of conditions that are plausible and define the range of possible futures. Steps 5 and 6 formally outline how these futures may play out and provide stakeholder friendly names. A significant benefit of this approach is that non-quantifiable impacts and uncertainties can be introduced with the scenarios. In particular, social and environmental constraints can be included which partially overcomes the weaknesses of the framework described above.

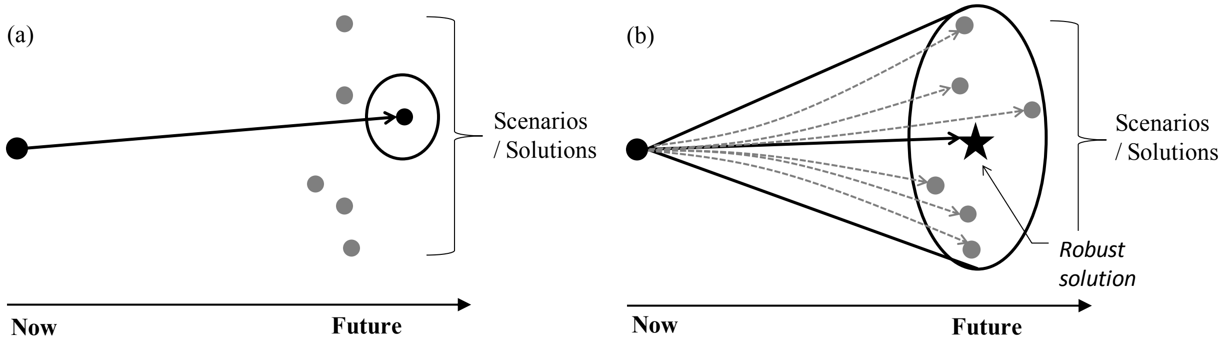

Figure 6. Scenario planning: (a) one- and (b) multi-dimensional approaches

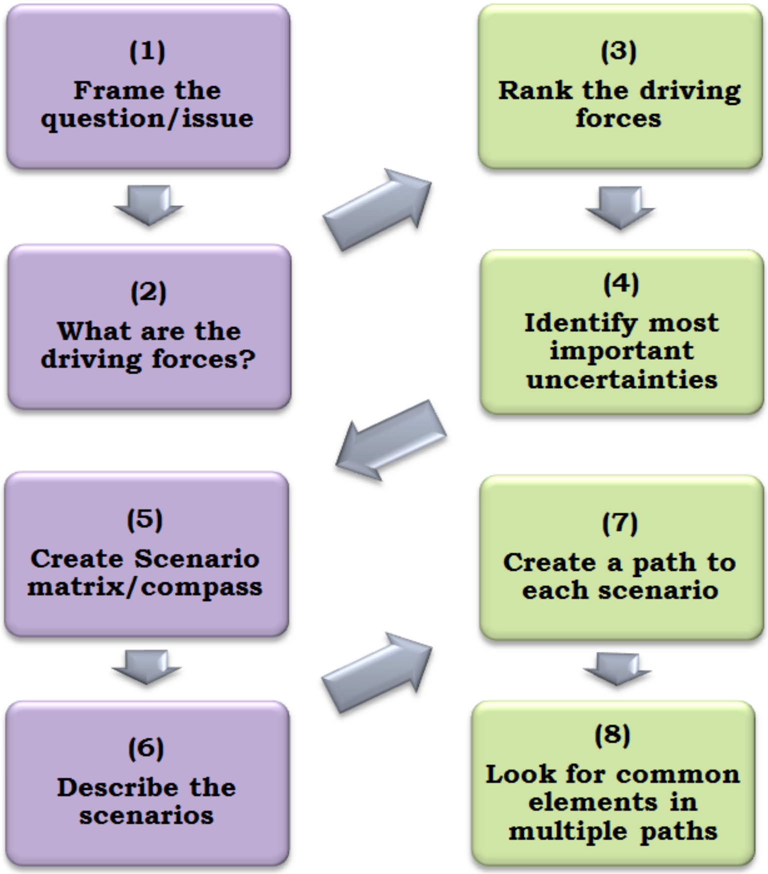

Figure 7: Scenario planning process

Determining a set of infrastructure elements to meet those scenarios and an implementation timeline are completed in step 7 for each independent scenario (Figure 8). Note that, like Figure 6, Figure 8 has an implied time axis.

The final question for the present time is what steps to implement given that each scenario may have different requirements over time (Step 8). Figure 9 shows a decision tree type structure of element implementation. Each branching point becomes a decision epoch. Depending how the future has played out, the decision makers must select the next element to construct. The goal is to implement a project that meets the short term needs and is common to all scenarios. This approach avoids overcommiting to a single scenario and allows flexibility (robustness) in the long term.

Adaptation provides further robustness. Here, we present a plan for all scenarios for the entire planning period. Clearly, as knowledge is a gained, some scenario may not be feasible and new driving forces and uncertainties may be identified. Thus, the scenario planning process should be periodically re-visited.

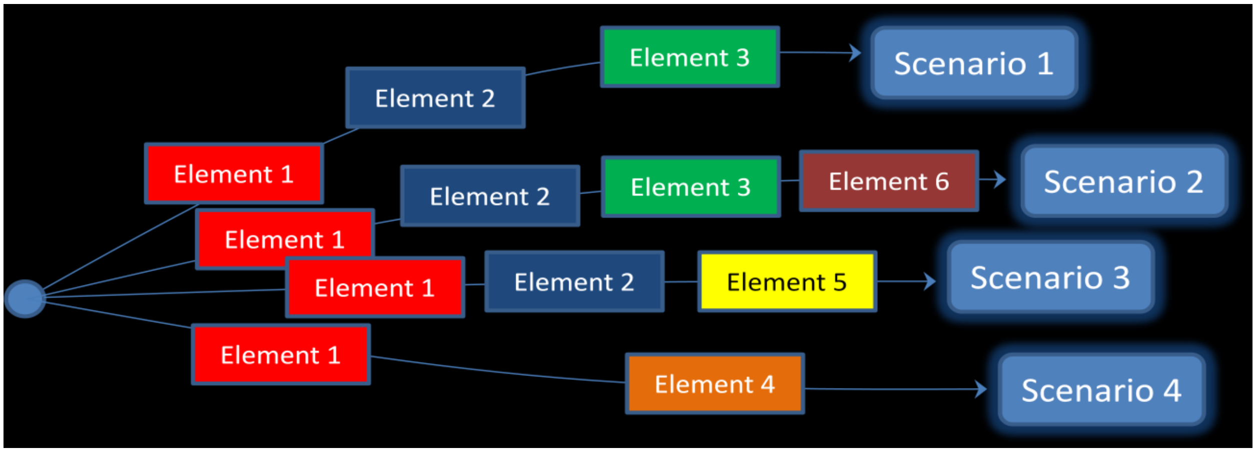

Figure 8: Set of plans for meeting alternative scenario conditions; results of step 7.

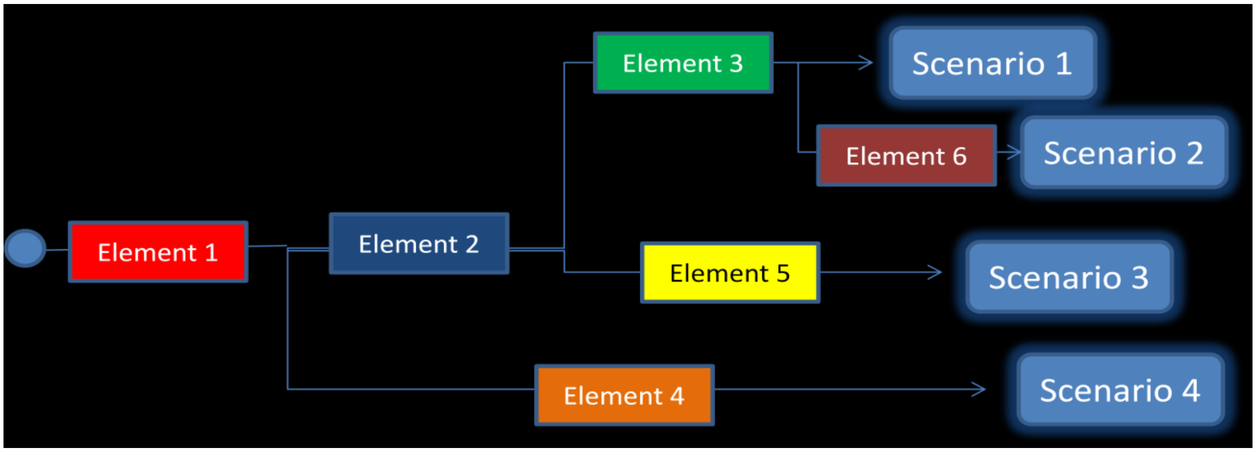

Figure 9: Integrated plan to adapting to scenarios over time; result of step 8.

Scenario-Based Multiple Objective Robust Optimization

To determine an integrated plan across scenarios, a scenario-based multiple objective robust optimization (SMORO) approach has been developed (Kang and Lansey 2011). At present, it does not consider adaptability and temporal changes. Rather, it is intended to identify the best compromise solution for a static condition in which all infrastructure is intended be constructed in one period. The HAMP site with multiple potential WWTP locations shown in Figure 10 is considered for demonstration purposes.

As shown in the scenario-planning process, SMORO begins by determining the optimal plan for each of five scenarios. The five results are similar to plans shown in Figure 8. With five separate solutions, consider the design based on scenario 3 (i.e., design 3) which has an optimal cost of nearly $400M is scenario 3 occurs (Figure 11). This scenario is conservative condition. If scenario 2 occurs which is a low estimate, the net cost for design three would be about $380M and require a small amount of new construction denoted by the supplementary cost but a significant amount of overpayment cost would be incurred. The total of these costs is the regret cost for designing under scenario 3 and scenario 2 being the reality. Other similar costs are seen for the other scenarios.

SMORO formulates a two objective problem to determine the best compromise solution. The first objective is to minimize the total cost and the second is to minimize the variance between the costs of the different scenarios. As the expected cost increases, the variability as measured by the standard deviation decreases (Figure 12). This curve provides decision makers a robustness relationship between the risk of higher cost and the expected expenditure. This approach will be extended to consider multiple TBL objectives, multiple planning periods and more scenarios. However, it serves as an initial approach to optimally determining robust systems.

CONCLUSION

A framework for assessing the viability of decentralized treatment is described that begins with indicators for sustainability, robustness and resilience. To implement these measures, cost tools for economic and environmental costs are developed and will be refined. To account for social objective and constraints, a scenario based planning process is described and being applied with partnering practitioners. Finally, an optimization model for integrating designs across scenarios is developed for static designs. These approaches are seen as baseline methodologies that require substantial research to fully develop for practice.

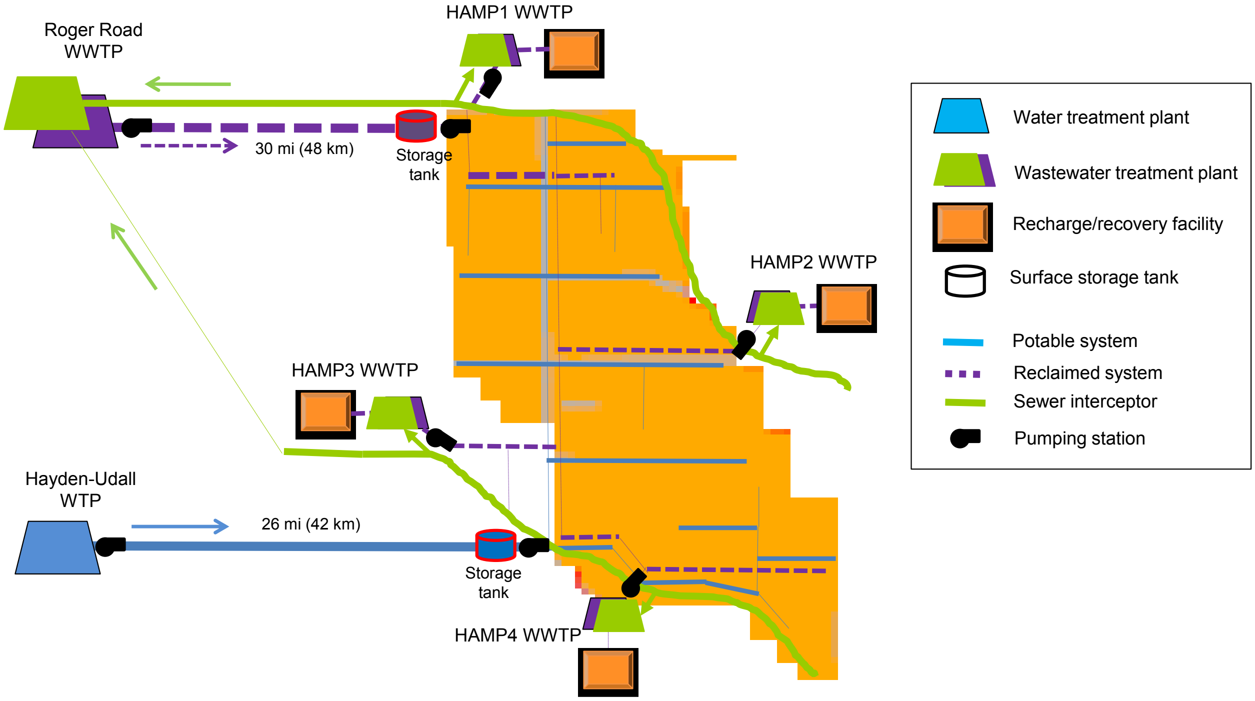

Figure 10: Application system (HAMP) layout

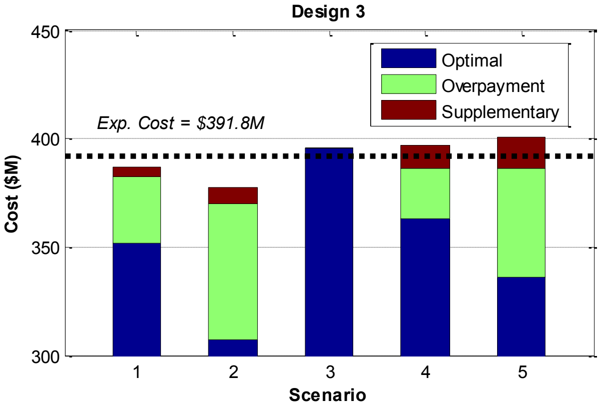

Figure 11: Cost tradeoff between scenario 3 design and costs under alternative scenarios.

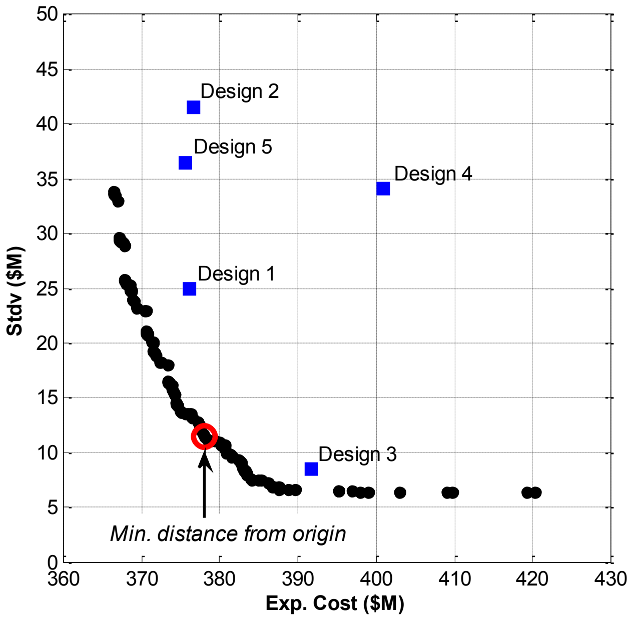

Figure 12: Tradeoff curve between expected cost and its standard deviation

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