A Tool for Integrated Planning of Water Infrastructure

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Importance and potential benefits of this study

With resource scarcity comes a need for careful management of that resource. Thus, in Arizona and other arid and semi-arid areas, managing water resources is of critical importance. There are, however, several factors that make such management, particularly the planning of future water and wastewater infrastructure, challenging. Systems for potable water, nonpotable water, and wastewater may all be planned separately, but significant amounts of water actually move from one system to the next within an urban area. Uncertainty in data and forecasts about such things as population and available river water can render detailed planning efforts difficult or inaccurate. Economy of scale for wastewater reclamation (treatment) facilities may conflict with the energy cost of pumping reclaimed water over long distances that may be associated with centralized reclamation. Yet the need to plan for new water and wastewater infrastructure remains. In the *Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment*, Theobald et al. (2013) report:

Most analysts expect the West, and especially the Southwest, to continue growing in population faster than the nation as a whole for the foreseeable future (Travis 2007). . . . The Census Bureau’s population projections to 2030. . . reflect this scenario. Arizona and Utah likely will grow by about 50% of their 2010 populations, and Colorado and New Mexico are expected to add another third to their populations . . . Most states extend their projections even further in time; linear extrapolation to each state’s extended population projection suggests a [Southwest] regional population in 2050 of around 94.8 million, a 69% (1.37% annualized) increase over the 2010 census.

Even if per-capita use rates are dropping, significant investments in infrastructure will be required to supply water and wastewater services to newly developed areas as populations continue to climb. And while it is clear that population is likely to grow, the exact location, timing, and water use preferences of this growth are far from certain. While gathering data and consulting experts may help gain a better understanding of likely future conditions, as Vano et al. (2014) note,

However, the evidence indicates there is no single magic bullet that will “reduce uncertainties,” nor will uncertainty ever be reduced to zero. Therefore, it is critical that both researchers and water managers redouble efforts and research to incorporate uncertainty and reconcile differences in future projections when possible.

Vano et al. (2014) were referring specifically to climate science and climate change uncertainty, but there are many areas in which uncertainty cannot be eliminated. This study aims to create a software tool that addresses these challenges by allowing planners and engineers to use computer power to design near-optimal infrastructure systems. This tool will facilitate integrated planning of potable and nonpotable water systems as well as sewerage, allow modeling of decentralized reclamation of wastewater at smaller plants, and examine the effect of uncertainty on system design. The tool will be generally applicable in areas where certain base data are available, thus greatly reducing the time and effort needed to begin water infrastructure planning processes. While not yet complete, the study has made significant progress toward development of this tool.
Methods

The main methods for this study were a scenario planning process and a genetic algorithm, both of which are described below.

Scenario planning

Scenario planning is an approach to considering uncertainty in planning for the future. Traditional planning methods design for one scenario that is the most probable single solution or future. In contrast, scenario planning defines a range of possible futures (scenarios) and identifies project components common to multiple scenarios within that range. Decisions made by individuals or organizations can be calculated for success under multiple futures. Scenario planning, its steps, and its uses are explained in detail in Schwartz (1996). Figure 1 summarizes the steps in the process. The potential for applying this approach to infrastructure decisions is summarized in Marra and Thomure (2009). Dembo (1991) proposed a model for scenario optimization that involves defining scenarios, solving a problem for each scenario, and then using a coordinating equation or model to come up with a single solution that is reasonable for all scenarios. Kang and Lansey (2013) extended this approach by developing an approach to minimize expected cost across a set of possible scenarios by optimizing (via genetic algorithm) infrastructure for single scenarios, reducing the search space by identifying common or similar elements between scenarios, and conducting a final optimization considering regret costs incurred for various designs under all potential futures. Here, the approach used by Kang and Lansey (2013) was started from a stakeholder-driven scenario planning process and is being applied to a larger, more complex case study area. In this study, geographic information system (GIS) data was utilized heavily in the description and visualization of scenarios and in creating the hydraulic model evaluated by the genetic algorithm.

Genetic Algorithm

To solve for the network design for each scenario (step 7, see Figure 1), a genetic algorithm (GA) was employed. The genetic algorithm is a heuristic search method, which means that it is distinct from “pure” optimization methods which guarantee that if a solution is found, it has the best objective function value (e.g. the lowest cost). Heuristic search methods provide no guarantee of obtaining the absolute optimal solution, but, as Simpson et al. (1994) noted, even though GAs are slower than nonlinear (NLP) optimization approaches, they avoid the rounding issues caused by modeling a discrete variable, such as pipe diameter, with continuous variables and also generate a number of near-optimal solutions that can be individually evaluated for other qualities that are not easily quantifiable.

A brief description of GAs follows. Holland (1975) and Goldberg (1989) give more detailed descriptions of GAs’ theoretical underpinnings and implementation details. GAs are based on principles of natural selection and include such evolutionary processes as mutation and crossover. A GA initially generates a population, which is a set of possible solutions. In this case, each individual in the population was a list of a diameter for each pipe, a design head for the pump curve at each pump station, a design flow for the pump curve at each pump station, a number of pumps (from 0 to 4) on at each pump station during peak conditions, a number of pumps (from 0 to the number on during peak conditions), and a capacity for each wastewater reclamation facility. The GA then computes the fitness or objective function (in this case, total present worth cost of the system over 40 years) for each individual in the population. The
objective function in this study made use of cost curves and functions developed as part of a previous study reported in Woods et al. (2013). A penalty cost is assigned to systems that do not meet requirements such as adequate pressure at demand points. Those solutions with the highest fitness have the greatest chance of being selected into the next generation of solutions. Solutions selected to “reproduce” then cross with other selected solutions (some decision variable values from one solution are traded with the values for the same decision variables from another solution). A mutation operation can also be conducted, which changes values at random for a certain fraction of decision variables, thus maintaining the population diversity. By repeating these operations through many generations, near-optimal solutions can be obtained.

The GA used in this study was developed by Donghwi Jung and is coded in C. Hydraulic evaluations of the network designs were done in EPANET (Rossman 2000) with the use of the EPANET Toolkit, which allows program functions to be called from C. One of the unique features of this GA is its frequent introduction of new random individuals. After every 500 crossover and mutation operations (each on a pair of individuals from the population), only the best solution is kept. That solution is repeated in 20% of the population, and the other 80% of the individuals are randomly generated, with each parameter restricted to being within a certain range. The crossover and mutation frequencies used in this work were 85% and 5%, respectively. Previous use of other GA formulations was not as successful. MATLAB’s embedded GA frequently failed to find viable solutions and took longer to perform computations. It is theorized that the Jung GA’s introduction of many new random individuals may help to find a few feasible solutions amongst many infeasible ones.

Key Findings

The preliminary steps (1-6, see Figure 1) of scenario planning were completed prior to this year, but a brief summary follows.

The first step of the process was to frame the question or issue. Stakeholders, in this case Tucson Water and the Pima County Regional Wastewater Reclamation Department, identified a timeframe for consideration as the 40 years from 2010 to 2050 and delineated the study area, sometimes referred to as the RESIN study area (Figure 2). The study area encompasses some 260 square miles of land and was inhabited by about 50,000 people in 2010, according to Census data.

The second step was to identify the driving forces for the problem, anything that could affect the outcome of the planning process. A list of dozens of factors was generated in the planning group, and this list was classified into several categories such as “supply based forces” and “macro forces in the larger environment.”

Next, driving forces were ranked in the third step. Forces were evaluated collectively on the basis of both uncertainty and importance to the planning process. In the fourth step, the three most critical uncertainties were found to be supply, demand, and the public acceptability of indirect potable reuse (IPR).

Once the most critical uncertainties were established, a scenario matrix (Figure 3) could be generated in step 5. The matrix establishes high and low bounds for each of the critical uncertainties and uses them to create a number of scenarios from the combination of bounds for
different critical uncertainties or drivers. In this case, the high supply was considered to be the current Central Arizona Project (CAP) allocation to Tucson, and low supply was set as a 10% reduction in CAP flows. The demand driver was bounded by a population of 460,000 people in the study area by 2050 (Figure 4), each using 121.5 gallons per capita per day of water (total, including commercial and outdoor use; this represents a 10% reduction from the current design demand), and by a population of 740,000 people by 2050 (Figure 5), each using 148.5 gallons per capita per day (a 10% increase from the current design demand). The IPR driver’s endpoints were public rejection of indirect potable reuse and total acceptance of IPR throughout the study area.

In the sixth step, descriptions for each scenario were developed. These descriptions can be useful in communicating the scenarios to others, including the public.

Essentially all of recent efforts on this project have been focused on step 7, which consists of identifying or creating a path to each scenario. In this case study, such a path consists of a near-optimal network design; this solution is obtained via a genetic algorithm.

To obtain a proposed network layout for each scenario, general features of the network first needed to be determined. The population distribution was developed with a one square mile grid (see Figure 4 and Figure 5), and a proposed water transmission network was also laid out with a one square mile grid, offset a half mile in each direction from the population grid. Thus, each demand node on the transmission network would serve the surrounding square mile of population. The network was then divided into pressure zones (Figure 6), and potential pump station locations were identified to connect the pressure zones. Connections to existing Tucson Water transmission lines were added, as well as potential input locations of potable (IPR scenarios) or non-potable (no IPR scenarios) water from wastewater reclamation facilities located in or adjacent to the study area. The resulting network is shown in Figure 7. The sizes of components in this network were then determined with the GA as described in the Methods section.

The resulting near-optimal layouts for Scenario A (high supply, high demand, IPR; see Figure 3), and Scenario B (high supply, high demand, no IPR) are shown in Figure 8 through Figure 11. It can be observed that the two potable transmission systems are quite similar in many respects. As expected, larger pipes are found near major points of entry for water to the system, particularly at the northwest corner of the study area but also at the Houghton Road connection point and near other wastewater reclamation facilities in Scenario A. For example, scenario A places more large-diameter pipes in the potable system in the immediate vicinity of the WWTP2 reclamation location, whereas in Scenario B, these larger pipes are absent in the potable system, but there is a small amount of added capacity in the pipelines near this plant location in the non-potable system design. One interesting similarity to note is that both scenarios placed the majority of wastewater reclamation capacity at the WWTP5 location. This location has a high degree of wastewater available to reclaim and also is not quite as far downhill as WWTP1.

These similarities and differences between scenarios can be examined and mitigated in step 8 of the scenario planning process. The solution space for each variable can be reduced by looking at the results for each individual scenario and finding the range for each decision variable. For instance, a particular pipe might turn out to be 24”, 30”, or 36” in each of the eight scenarios. The solution space for that pipe could then be reduced from 12 to 72 inches to 24 to 36 inches.
Once the solution space has been narrowed, an overall solution can be obtained by evaluating possible solutions under all 8 possible future conditions and determining which one has the lowest overall expected cost given an equal probability of all future scenarios. This overall solution may not be the best solution under any one scenario, but it stands the best chance of performing reasonably well under all foreseeable conditions. The idea behind this approach is to minimize regret costs that come from either overbuilding or underbuilding infrastructure. This part of the work is ongoing, along with improvements to the network model for the RESIN area to better model the way Tucson Water typically designs and operates their transmission and distribution system.

In all, this study has gone from having defined scenarios but not having solutions to identifying a viable solution methodology and generalizing much of the code associated with the solutions so that it can be applied to many different areas.

References


Figure 1. Steps in the scenario planning process. Steps on the left are carried out by a small working group, whereas steps on the right are carried out by a larger group of stakeholders.

Figure 2. Study area relative to Tucson. City limits are shown in orange, and RESIN study area is the outlined and shaded purple area on the southeast edge of existing Tucson development. Potential wastewater reclamation locations are the green rectangles marked with “WTP”. Other Tucson water infrastructure elements appear on the map. CAVSARP and SAVSARP are the major locations of infiltration of CAP water for quality improvement and for storage. Hayden Udall is the location of chlorination, Roger Rd and Ina Rd wastewater reclamation facilities are the main treatment locations for wastewater from the city. Both the CAVSARP/SAVSARP facilities and Roger/Ina Rd facilities are at least 25 miles from the study area.
Figure 3. Scenario compass with the 8 scenarios determined through the scenario planning process.

Figure 4. Low population bound. 460,000 people by 2050.
Figure 5. High population bound. 740,000 people by 2050.

Figure 6. Pressure zones in the study area (C is the lowest zone). Only zones C through I were modeled, due to limited development in higher zones. Zone G was modeled as a single zone with a connection between northeast and southwest portions, but zone F was divided into two separate zones.
Figure 7. Network layout, showing locations of demand nodes (dots), pipes (lines), pump stations (roundish symbols, up to 4 pumps at each station, potential wastewater reclamation facilities (WWTP series), and connections to the existing Tucson Water infrastructure.

Figure 8. Results for the Scenario A (single, potable) water transmission system. Link (line) width is proportional to diameter for the pipe, with red indicating no pipe (or the smallest allowable). Nodes (dots) are proportional to demand, and wastewater reclamation facility capacities (in MGD) are labeled.
Figure 9. Results for the potable (a) and non-potable (b) layouts for Scenario B.
Figure 10. Pump station results for the single system of Scenario A. Pump station icon size is proportional to the amount of flow passing through it; the smallest light gray pumps actually represent places where a pump was proposed but was not chosen to be built. Pipe thickness is also proportional to flow through the pipe.
Figure 11. Flow/pump results for Scenario B for the potable (a) and non-potable (b) systems.