Scenario Planning to Address Critical Uncertainties for Resilient Water-Wastewater Infrastructures under Conditions of Water Scarcity and Rapid Development

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1. Introduction

Multiple interrelated processes affect water use and reuse planning. Of the many factors involved, each in its own right exerts influence on water supply and demand. However, in combination they represent a formidable mix of uncertain impacts that operate over varying spatial and temporal scales. For instance, how might climate-driven water scarcity at the river basin level affect infrastructure operations and thereby local costs and rates for service delivery? How would water rates, in turn, influence demand? Decision-makers – that is, water managers, planners, political leaders, citizens’ groups, researchers, and others – often find such complexity overwhelming and may even avoid or reject the need to account for the many potential factors in planning. Tools are thus needed that address uncertainty in a process that makes use of available and potential new sources of information while incorporating multiple perspectives of the many types of stakeholders.

This paper presents ongoing experience with the applied technique known as Scenario Planning (Schwartz 1996). “Scenario Planning is a systematic method for thinking creatively about possible complex and uncertain futures. The central idea of Scenario Planning is to consider a variety of possible futures that include many of the important uncertainties in the system rather than to focus on the accurate prediction of a single outcome” (Peterson et al. 2003 p. 359). Aiming to be robust to the important uncertainties by including qualitative and quantitative understandings, scenario planning begins with a specific management issue and creates a structured account of a range of possible futures. Based on unique combinations of possible futures, the process provides flexibility in planning by providing a range of options with various degrees of similarities and overlapping common elements.

The Scenario Planning exercise described and assessed in this paper is supported by the National Science Foundation’s Emerging Frontiers in Research Innovation program area, specifically in its Resilient and Sustainable Infrastructures (RESIN) program. The approach taken responds to broader questions on resilience, sustainability, and decision-making. We document the Scenario Planning process used to address three critical uncertainties associated with water and wastewater infrastructure over the 2010-2050 period. First, future water-supply reliability may become less certain based on climate change drivers that can impact surface water and ground water availability. This uncertainty can be either exacerbated or mitigated when it is coupled with regional water sharing agreements among multiple competing uses. Second, within the Tucson-Pima planning area, the spatial patterns and aggregate future demand for water are uncertain due to unpredictable densities of development and per-user consumption that in turn is influenced by water conservation behavior, pricing, development pressure, regional economic conditions, and so on. Third, although water reuse is essential to ensuring future supply reliability and sustainability, an important but often overlooked uncertainty is public acceptance of reclaimed water for indirect potable use (via aquifer storage and recovery). The decision to use Scenario Planning in this study was primarily driven by an intention to investigate its
application in a situation where it appears to be suitable but there is little prior scholarly research (Marra and Thomure 2009).

Figure 1. Tucson and Pima County, Arizona, in the southwestern USA

2. Scenario Planning in Tucson, Pima County, Arizona

Water supply, reuse, and development in Tucson and Pima County, Arizona (Figure 1) present many of the challenges that are illustrative for other water-scarce regions experiencing rapid development. The greater Tucson area has access to three sources of water supply: local groundwater, Colorado River water conveyed via the Central Arizona Project (CAP), and locally-generated municipal effluent. Until recently, water users in the region relied solely on local groundwater mined from aquifer storage, and this historical practice has resulted in significant groundwater-level declines and measurable land subsidence in some areas. Of these, the State of Arizona only recognizes imported Colorado River water (i.e. CAP water) and locally-generated municipal effluent as renewable supplies.

Tucson Water has the largest annual CAP water allocation in the State of Arizona—currently 177.8 million cubic meters (MCM) (144,172 acre-feet) per year. CAP water is an imported supply conveyed to the area via an aqueduct and pipeline system, which delivers a portion of Arizona’s annual Colorado River water allocation over 530 km (330 miles) and which terminates in the Tucson area. Once Tucson Water and other local water utilities began utilizing CAP water, the local region’s water outlook was forced to broaden. From a water-resources perspective, this change means that the amount of annual precipitation that occurs in the Rocky Mountains is more important than the local annual precipitation in the Tucson area. This also means that water-resource decisions made in Phoenix, Los Angeles, San Diego, Las Vegas, Denver, and Washington D.C. are potentially much more important than local water decisions made in either the City of Tucson or Pima County. When it comes to water resource planning, the Tucson region is no longer local. Drought in the near- to mid-terms (Coles and Scott 2009)
and longer-term climate change in the Colorado River watershed will increase the resource vulnerability of Colorado River water users and hence the supply reliability of many large urban centers. The uncertain outcomes of future high-stakes negotiations among the seven basin states and Mexico will have a bearing on how the City of Tucson will utilize its rights to withdraw local groundwater and use its effluent entitlement as well as its interest in further promoting conservation and in acquiring additional supplies.

In the mid-1980s, Tucson Water began recycling a portion of its effluent entitlement by constructing a non-potable reclaimed water system which currently delivers tertiary treated effluent to large turf users such as local golf courses, school yards, parks, and so on. The reclaimed water system has expanded over time and in 2010, about 14.8 MCM (12,000 acre-feet) of the City’s entitlement was delivered to reclaimed water customers. However, only a portion of the City’s effluent entitlement is used in the City’s reclaimed water system with the balance being discharged into the local Santa Cruz River. The unused portion of its effluent entitlement, less a small amount for riparian restoration, will likely be used to secure its water-resources portfolio in times of Colorado River water shortage—shortages which are expected to increase in frequency and possibly in magnitude partly in response to longer-term climate change. The ability to implement supply strategies that rely on the indirect potable reuse of effluent, however, depends on sufficient public acceptance. Such acceptance is at this time uncertain and Tucson Water is developing its Recycled Water Master Plan to assess what needs to be done in order to prepare for that possible eventuality.

### 2.1 Initiating Scenario Planning

The Scenario Planning process can be very time and labor intensive. As a result, the research team established ongoing and alternating meetings between a “small group” of very active participants, comprising University of Arizona researchers, City of Tucson Water Department (Tucson Water), and Pima County Regional Wastewater Reclamation Department (RWRD) staff, including project managers, planners, engineers, and hydrologists, and a “large group” of participants who attended only a subset of meetings but provided oversight and ratified (or modified) key decisions made by the small group. The large group meetings included members of the small group and added director and senior level staff to assist at critical decision points including ranking the driving forces and identifying the most important uncertainties that influence the scenario matrix design.

The initial question that framed the Scenario Planning process was outlined by the University of Arizona project team as finding the optimal use of integrated water and wastewater in the RESIN planning area, as established in the EFRI-RESIN project goals. In essence, however, Scenario Planning strives to achieve a strategic position that is flexible enough to adapt to a credible range of possible uncertain futures. As a result, the optimization was focused on cost-reduction objectives instead of attempting to identify one or a limited set of scenarios as “optimal” outcomes.

After framing the focal issue, the small group collectively considered the key factors influencing optimal use of integrated water and wastewater. The exhaustive list of forces included nearly sixty items covering a wide range of factors including: demand based forces (e.g., land-use, per capita residential consumption), supply based forces (e.g., potable water budget), cost based
forces (e.g., price per gallon to produce reclaimed water), perception based forces (e.g., publically acceptable water quality), physical-engineering based forces (e.g., the ability to recharge surface/future water supplies), institutional-political based forces (e.g., regional planning uncertainties regarding jurisdiction), as well as the key driving forces in the macro-environment (e.g., external forces that affect rate of economic and population growth).

2.2 Ranking Driving Forces

The next step of the Scenario Planning process involved ranking the driving forces noted above in terms of their importance and uncertainty. Both the large and small groups participated in collectively plotting the relevant forces on axes of uncertainty and importance, which conveys the evolution of the priority-setting process. The most uncertain and most important forces included: a) demand based forces of population density and per capita residential demand; b) supply based forces including all potentially available future water supplies; c) macro based forces including the regional supply uncertainty (both in terms of quantity and quality) due to extended droughts, Colorado River shortage sharing agreements, and the potential effects of climate change; and d) perception based forces of public adoption of indirect potable reuse of effluent (including willingness to pay).

The most important step in the Scenario Planning process is to identify, among the critically ranked factors, the two or three with the highest impact and uncertainty for integrated water and wastewater planning in the study area. After multiple meetings and rounds of debate, consensus was achieved on the following three most important and uncertain scenario drivers and their “end members” (maximum and minimum values): a) water and reuse demand ranging from high to low population density following different urban form projections; b) currently available water supply ranging from sufficient to insufficient existing supply; and c) public perception of water reuse ranging from blended potable supplies to non-potable reuse. These three drivers combine to form eight unique scenarios, or end-member futures, as shown in Figure 2.

2.3 Supply-Based Drivers

The supply-based driver is the most complex force with the widest geographical influences and greatest inter-regional effects; hence, it needs some additional explanation. The selected end members were sufficient existing supply and insufficient existing supply. The sufficient supply is defined as the currently available groundwater, Colorado River water delivered via CAP, and effluent water resources (e.g., the total of all existing and legally available water supplies). Insufficient existing supply is defined for our purposes as the case where large-scale local aquifer/groundwater mining is resumed or increasing reliance on additional water supplies imported from outside the local region, which could include desalinated seawater or saline groundwater, groundwater mined from outlying basins, or Colorado River water currently being used by agricultural interests along the Colorado River. Importantly, the future availability of many of these potential supply options for the City of Tucson, Pima County, or other local water users are uncertain since they require agreement on the part of other parties. Continued reliance on local groundwater mining (i.e. overdraft) to support future municipal growth is currently constrained in the greater Tucson area under the State’s Assured Water Supply rules as outlined in Arizona’s Groundwater Management Act (Colby and Jacobs 2007). In essence, the Scenario
Planning team assumes additional water supplies will become available – even if there is currently ‘insufficient’ supply – but importantly it will come at a higher price.

Figure 2. Scenario matrix showing unique combinations of drivers

2.3 Demand-Based Drivers

Urban planning at the city and county level presently directs much of the growth in the Tucson region toward the southeast, where the land is relatively flat and owned in the most part by the Arizona State Land Trust. Local government master plans such as the *Houghton Area Master Plan* (City of Tucson Department of Urban Planning and Design 2005), covering the northeastern portion of the study area, have been designed to create higher densities of development than have previously been developed in the area.

The white paper entitled *Location of Growth, Urban Form and Cost of Infrastructure* (City of Tucson and Pima County 2009) analyzed the effect of a conservation land preservation system and potential high-density development on predicted build-out densities across the Tucson metropolitan area, expected in the coming 50 years or longer. For the RESIN study, these were analyzed again at a coarser scale to facilitate future computer modeling of infrastructure. The model was run with various input populations to provide the stakeholder group with a selection of potential end members ranging from 460,000 to 740,000 inhabitants in the study area. Figure
5 shows the current population distribution and three possible future distribution types modeled for this paper using the low population of 460,000. The small group indicated a preference to use only the Infrastructure Efficient model, stating that the newest developments in the study area already demonstrate higher densities than are present in the Habitat Protection and Status Quo models.

![Population distribution maps](image)

**Figure 5. Population densities per square mile in the present and in possible futures (based on City of Tucson and Pima County, 2009). Top left: Current population densities. Top Right: Future Status Quo. Lower Left: Future Habitat Protection. Lower Right: Future Infrastructure Efficient**

The Scenario Planning team uses a genetic algorithm for infrastructure in each scenario considering a square grid modeled on Tucson’s existing street layout. All links of the grid represent possible potable or reclaimed water transmission pipes. Each intersection (node) on the grid represents a demand point for water. Using a genetic algorithm, the model chooses which pipes on the possible grid should actually be installed and at what diameters. Costs for the pipe are based on a function that is nonlinear with respect to diameter and the depth of excavation and linear with respect to length, given in Clark et al. (2002). Pipes 12 inches and lower in diameter are modeled as PVC; those of larger diameters, as ductile iron. Costs for pumps are modeled as a nonlinear function of design pressure and flow. Additionally, life-cycle costs of pipes, pumps and decentralized treatment facilities are estimated.

### 2.3 Perception Based Drivers

The crucial perception-based uncertainty identified is whether the public will accept reclaimed water as part of their drinking water supplies through indirect potable reuse (IPR). Tucson Water
has long valued the potential of reclaimed resources and most heavy irrigators (golf courses, public parks, and schools) are already connected to the reclaimed water system with highly visible public signage where it is being reused. Although reclaimed water use in the Tucson area is currently largely limited to outdoor irrigation, a number of additional reclaimed water applications are possible in the future, including the practice known as indirect potable reuse (IPR). IPR projects blend highly treated reclaimed water with conventional drinking water supplies via aquifer recharge before recovering it via wells and delivering it through the municipal potable supply system to customers’ taps. IPR represents a shift from the largely accepted supply-substitution strategy (substituting reclaimed water for potable water and using it for non-potable purposes) to an augmentation strategy which aims to expand potable supply by blending highly treated reclaimed water with an existing natural water source before delivery to municipal customers’ taps (Browning-Aiken et al. 2011).

A number of IPR projects are in practice or are being considered in high-growth urban areas throughout the southwestern U.S. (Rodriguez et al. 2009). An alternative of expanding the reclaimed water system to the household level to serve more non-potable uses (e.g., for residential outdoor uses or toilet flushing) is an option with high levels of public acceptance (Campbell and Scott 2011). However, this option would require a dual pipe system to keep reclaimed supply separate from potable supply and may not be cost effective. When planning IPR projects, public perception is considered the greatest obstacle to successful implementation (Po et al. 2003). It has been clearly demonstrated (Dishman et al. 1989) that public perception of IPR can be changed through the actions of the water utility and community leaders. As part of its Recycled Water Master Plan, Tucson Water has already begun revising its signage posted at reclaimed water use sites to emphasize the importance of recycling this vital resource and de-emphasizing negative messaging that focused on potential hazards associated with drinking it.

Given that population growth will increase demand for water, attitudes toward regional growth and development are crucial to understanding opinions about risks and reclaimed water (Asano 2005; Scott et al. 2011). In addition to political resistance to urban sprawl, Tucson is also recognized for its rancorous water politics (Logan 1995). For example, in 2007 a citizen-led ballot initiative, entitled Tucson Water Users Bill of Rights, sought to ban any possibility of potable water reuse and limit future water connections. Although the 2007 ban failed, the threat of citizen intervention is considered a likely possibility where IPR is concerned. Thus, it is uncertain whether consumers will eventually come to accept IPR in the Tucson area.

3. Conclusions

Planning for the future requires flexibility to adapt to changing future conditions. Even local initiatives with relatively good access to information and future projections – such as the Tucson and Pima County, Arizona case presented here – are confronted with major uncertainties. When considered in a broader global context, uncertainties can lead to poor outcomes from investments of financial, human, and natural resources by public and private and decision-makers. Scenario Planning provides a robust tool to consider multiple potential outcomes over the long term. This paper has demonstrated that rigorously ranking planning forces by the level of uncertainty and degree of importance can build consensus among decision-makers on ways forward.
The exploration through a scenario building process of possible futures created by stakeholder decisions may provide valuable insight into the indirect results of such decisions as how much investment is made in changing public perceptions of IPR. Loucks (1994) describes a process of considering futures based on choices between short-term efficiency and long-term sustainability and survivability. While Loucks does not refer to scenarios, he does talk of multiple future uncertainties and their connections to present decision making, such as whether the preservation of non-renewable groundwater in the present will be valuable to future generations, or whether it is better to “mine” groundwater now to maintain growth until alternatives are found. We cannot predict future opinions or technological states with any certainty, but we can identify possible scenarios and plan accordingly.

The evolving, iterative process of Scenario Planning described in this paper reflects the importance of new information, both on changing current conditions but also on enhanced understanding of future trends. As a result, the process must be seen as continuous, entailing reconsideration – even redefinition – of uncertainties. In this sense, Scenario Planning is a robust tool to accommodate broad regional and global forces such as climate change or urban development.

The collaboration of researchers and planners described in this paper, which is a particular instance of science-policy dialogue to address global change in the broadest sense, has led to some notable innovations. Chief among these is the enhanced identification of drivers and uncertainties, the application of new analytical tools, the improved uptake of information in scientific/engineering and planning models, the relevance of these models to real-world conditions and to political and institutional contexts in which decision-making occurs, and finally the inclusion of policy questions and challenges in research at the fundamental level of framing questions and not simply in the more conventional mode of science providing answers (without regard to stakeholders’ needs and priorities).

The approach described in this paper has addressed numerous uncertainties that confront water, reuse, and urban growth planning in the context of water scarcity, climate variability, uncertain development processes, and evolving public perception. The implications of the specific Arizona case assessed here have broader generic relevance. First, the sustainable development objectives of urban growth conforming to natural resource constraints can be pursued through Scenario Planning aided by modeling. Second, a more open and iterative science-policy process greatly enhances the interface between the scenario modeling and policy-making. Finally, emerging approaches to scenario analysis must account for uncertainties, not only through attempts to reduce uncertainty (though modeling may enhance this ability) but, as demonstrated here, to rank uncertainty and consider its impact in complex biophysical, social, and political-institutional contexts.
References


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