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System Dynamics Modeling in Local Water Management: Assessing Strategies for the City of Boerne, Texas

by
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Abstract

As more pressure is exerted onto water sources, hydrologic systems may be altered in ways that are difficult to predict. In Texas, water deficits can become widespread as sources are strained beyond capacity. For smaller communities, such as Boerne, Texas, water management and planning is a way to prepare. The supply-demand water balance in Boerne is conceptualized through causal loop diagrams and system dynamics modeling. Through stakeholder engagement, xeriscaping, rainwater harvesting, and smart meters were chosen as interventions, each varied in adoption levels. The resulting 125 combinations were analyzed under three scenarios: a base case assuming maximum supply of water is firm, and two responses to a meteorological drought. Results show that the city can effectively forestall a deficit. Different combinations of adoptions can achieve the same goal, giving the city optionality in choosing strategies that are best suited for its needs and constraints. Rainwater harvesting was found to be the dominant intervention influencing demand, but its influence is reduced in the two drought scenarios. Xeriscaping was the second most influential intervention and smart meters for irrigation had no effect on demand. The approach used in this study highlights the interdependency between community adoption of conservation strategies and the importance of considering these relationships using systems modeling.

Keywords: system dynamics (/search?q=system+dynamics); water management (/search?q=water+management); Boerne (/search?q=Boerne); Texas (/search?q=Texas); stakeholder engagement (/search?q=stakeholder+engagement); sustainability and resilience (/search?q=sustainability+and+resilience)

1. Introduction

Future accessibility, quality, and quantity of water resources are threatened from the growing pressure of population, economic development, and climate change [1]. Once relatively balanced, hydrologic systems have been and will continue to be altered by competing stresses, generating changes that are difficult to predict and quantify, especially at local scales. Scale-appropriate analyses can reveal solutions feasible for a given city by understanding their relationship with water and how these may vary given local circumstances. While national- or state-scale water management and planning approaches can prove too abstract, vis-à-vis system components and stakeholders, the municipal/district level facilitates identification of relevant stakeholders and system boundaries. This scale of analysis is also naturally bounded by service areas and jurisdictional boundaries.

Sustainable and resilient water management and planning will prepare Boerne, Texas for water shortages that are likely to occur in the future. In 2015, the city contracted with HDR Engineering Inc. [2] to guide a water planning process to account for rapid population growth. The plan projects water shortages based on two sources of data, population estimates from the city itself and population estimates from the Texas Water Development Board (TWDB) in the 2016 Region L Water Plan [3]. This study highlights the importance of projected population growth, changes in per capita consumption, and the use of treated wastewater. With city data, shortages were estimated by 2070, while TWDB data estimated shortages by 2050 and worsening through 2070. While population estimates from the TWDB are smaller than those of the City of Boerne, estimated consumption by the TWDB is greater at 0.73 m^3 (192 gallons) per capita per day (PCD) in 2020 to 0.71 m^3 (187 gallons) PCD in 2070. Furthermore, the city estimates reclaimed water use to increase to almost 2.5×10^6 m^3 (2000 AF) by 2070, while the TWDB found this to be a constant 8.6×10^3 m^3 (7 AF).

With a population of 17,250 as of 2020, Boerne, Texas typifies a relatively small community adjacent to a large municipal city (i.e., San Antonio). To increase the sustainability and resilience of its water system, Boerne—and other communities that are also undergoing and managing significant population growth—must address questions related to their water resources: what types of policies should the city pursue, if any? Which conservation strategies are most effective in reducing water demand and how would they fare under drought conditions? How can the city avoid a water deficit?

Answering these questions at present increases the adaptability of a city to future circumstances. Alternatively, delaying action can result in reactive measures during some future drought scenario. These issues become more salient as community populations grow, and the difference diminishes between supply—which has a physical upper limit— and demand—which is closely tied to decisions made within the community and is affected by growth in surrounding areas. In the Texas Hill Country, water supply and infrastructure are closely tied and limited, the threat of inter- and intra-city competition for limited resources will continue to be an issue in areas where both growth and potential resource shortages intersect.

This research will explore the effectiveness of various options and strategies to be tested, without the lag time (or risk) of experimenting on real systems. Refsgaard et al. [**4**] highlights the interaction between water management and modeling processes and the methodologies to assess uncertainty, including scenario analyses. **Figure 1** shows the interaction between relevant stakeholder(s) (on the left) and the modeling step they helped inform (on the right). We incorporate scenario analysis and the constant feedback of various stakeholder groups from Boerne, Texas throughout the modeling process.

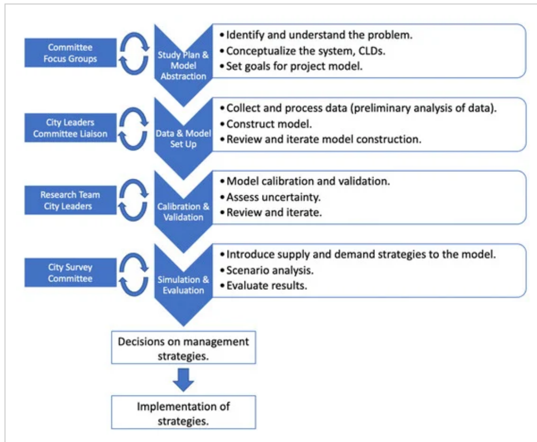


Figure 1. Interactions Between Stakeholders and the Modeling Process.

In this study, we use Causal Loop Diagrams (CLDs) and System Dynamics modeling for reasons described below. CLDs represent an individual hypothesis of how a system functions and is the first step in framing the scope of a System Dynamics (SD) model [**5**]. CLDs map causal relationships and identify feedback loops within a process or system [**6**]. In a CLD, the polarity of each arrow highlights the reinforcing or mitigating relationships that the arrow connects. The overall loop sign is obtained by multiplying the signs of the variables involved in the feedback [**7**].

Since its conception in the 1950s [**8**] and with further development [**9**], SD has been applied to a number of topics specific to water, such as illustrating the effects of proposed strategies while raising stakeholder awareness of resource problems [**10**]. The appropriateness of SD modeling techniques to address water management concerns specifically was shown by [**11**,**12**,**13**]. Elsawah et al. [**11**] found that SD modeling can be applied to water allocation problems at various scales, with a tendency to use this type of modeling for decision-making and social education. Additionally, Winz et al. [**12**] found that, because it requires explicit acknowledgement of assumptions and identification of uncertainties, SD modeling represents a transparent method that can confidently inform policy recommendations. Finally, Karimlou et al. [**13**] reasoned that SD can help choose the most efficient management strategies by helping managers observe the linked changes occurring in the system.

Stave [**14**] explains that SD emphasizes finding the *causes* of problematic behavior, assisting investigators and stakeholders as they propose solutions. This is important because one difficulty of resource management is the inability to comprehend or foresee the cascading effects of changes made to the system due to a lack of understanding of how system components are interconnected. Martone et al. [**15**] explains similar observations. Newell et al. [**16**] further this argument, explaining that linear thinking suggests that doubling a cause doubles the effect, when in reality causation in complex systems is impacted by feedback. The usefulness of SD is enhanced by feedback analyses, which have the capacity to visually demonstrate how changes in some elements affect other elements and the overall dynamics of the system [**16**,**17**,**18**,**19**].

While the above literature indicates the usefulness of SD modeling in water-related fields, to our knowledge, we are unaware of studies dedicated specifically to understanding the effectiveness of strategies in reducing sector-demand at a municipal/city scale, while also incorporating stakeholder participation throughout the modeling process, distinguishing demand from different sectors, and incorporating different adoption levels in strategy combinations. The five case studies used by Karimlou et al. [**11**], for example, are not local scale, but instead include a metropolitan region, groundwater systems, and a river basin. Stave [**10**], on the other hand, uses SD modeling to assist stakeholders in Las Vegas, Nevada to understand management options based on their capacity to reduce demand, but the produced model incorporates all demand as either indoor or outdoor. Unlike Winz et al. and Karimlou et al. [**10**,**11**], this research breaks indoor and outdoor demand further into residential, municipal, and business sectors to generate a greater understanding of the effect of each sector on the local system. Altogether, this research incorporates SD modeling, demand-reducing interventions, stakeholder participation, and a more detailed understanding of demand, at the municipal level.

The chosen approach was tailored based on local knowledge and direct feedback by utility managers and stakeholders. The value of stakeholder participation and bottom-up approaches to water management and planning is exemplified in the Texas State Water Plan [**20**] as well as in the literature [**21**,**22**,**23**,**24**,**25**,**26**,**27**,**28**,**29**]. As part of the socio-hydrological system, Boerne residents are as important and relevant as the economic, political, and scientific aspects of water management and planning. Residents demand the majority of water entering the city, and they create an important leverage point in the system where conservation strategies can be introduced; through their support or opposition, residents can influence the success or failure of these actions.

The overall goal of this research is to demonstrate the usefulness of community engagement and SD modeling in creating water management plans. We use the community of Boerne, Texas as the case study, though we note that this workflow and community engagement outcomes can be applied in other cities focusing on improving sustainability and resilience of their water systems. Effectiveness of a policy here is measured based on the ability of an intervention to delay a deficit in water supply. Through stakeholder engagement, other communities can incorporate data specific to their situation.

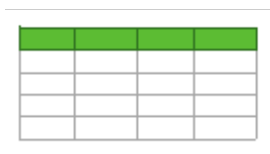
2. Materials and Methods

2.1. Study Area

Located in the south of Kendall County, the City of Boerne is a medium-sized community in the San Antonio MSA and is surrounded by the Texas Hill Country. Cibolo Creek, an important component of the water distribution system (WDS) in Boerne, is a tributary of the San Antonio River and flows through the city, feeding into Boerne City Lake. With respect to water, the city lies within many important geographical and governmental boundaries, being within the jurisdiction of the Cow Creek Groundwater Conservation District (GCD), the 9th Groundwater Management Area (GMA), and the Region L Planning Group. Climate in the area around Boerne is humid subtropical to semi-arid [**30**], with an average annual temperature between 15.6–18.3 °C (60–65° F) and less than 88.9 cm (35 in.) of precipitation per year [**30**]. High summer temperatures and low precipitation make the region prone to moderate to severe droughts.

The city obtains its water supply from surface and subsurface sources. Boerne obtains ~33% of its water from the Trinity Group Aquifers. Boerne City Lake supplies 25% and the remaining 42% comes from Canyon Lake through a contract with the Guadalupe Blanco River Authority (GBRA) [**31**]. Specific yearly permitted allocations can be found in **Table 1**. By the end of the 2020 calendar year, the city had only purchased approximately 36% of its total contract with GBRA and has been purchasing below their GBRA contract supply for the last ten years [**32**] (**Figure S1 in Supplementary Materials**). This is because demand has not reached levels of consumption necessary of greater purchases, and because the City of Boerne has maintained a very proactive water resources planning programming, especially given the current and expected growth in the region and the vulnerability of the community to droughts. The future water supply from GBRA will depend on water availability and possible policy decisions regarding curtailment.

Table 1. Water Supply by Source.



Efforts to increase supply of reclaimed water have also increased. Currently, the city operates the Esser Road Wastewater Treatment Plant, with a capacity of 4542 m^3 (1.2 MGD), and the Old San Antonio Road Wastewater Treatment and Recycling Center, with a capacity of 5300 m^3 (1.4 MGD). The vast majority of reclaimed water from Esser Road is used for maintaining streamflow in Cibolo Creek. The majority of reclaimed water from the Old San Antonio Road facility is used for outdoor irrigation in residential areas, city parks, and other public areas [**2**]. From October 2019 to October 2020, reclaimed water accounted for approximately 11% of total water used by the city. Through consultation with the Utilities Director, we decided that water reclamation was best classified as a conservation strategy. We reasoned that wastewater reclamation is not an increase in supply that can be used for indoor consumption. Rather, its use reduces pressure on potable water supply that would otherwise be used for outdoor irrigation. Therefore, increased use of reclaimed water represents a conservation strategy for reducing potable water use.

2.2. Focus Groups and Community Survey

As **Figure 1** indicates, the workflow includes focus group sessions with Boerne residents and a community-wide distributed survey. The sessions and survey were intended to provide information and context for understanding community perception of supply and demand of their municipal water system. Briefly here (more details in **Appendix A**), focus group sessions were organized around four specific stakeholder groups (municipal and county agencies, business leaders, community service organizations, and environmental groups). Members were identified through local networks, but with a goal of ensuring a diversity of backgrounds, perspectives, and influence. During focus group sessions, participants discussed their understanding of system components and existing relationships between these components, eventually