Recycling water in U.S. cities: understanding preferences for aquifer recharging and dual-reticulation systems

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Abstract

Recycling of effluent water from urban water-supply systems is often a more sustainable water source than increased use of surface sources, groundwater sources, and desalination. However, water-supply organizations (WSOs) often do not take full advantage of recycled water. Although recycling water for direct potable use is efficient, public concern with safety has tended to cause WSOs to favor other uses for recycled water. This study examines patterns in the degree of utilization of two main indirect uses of recycled water: dual-reticulation systems and groundwater recharge. Drawing on case studies of four U.S. cities that are leaders in the use of recycled water, the study identifies conditions that favor the choice of one option over the other. Where cities are concerned with groundwater recharge of potable water supplies, they tend to prefer non-recycled water if available for recharge projects. However, where non-recycled water supplies are limited, recycled water may be prioritized for aquifer recharge. Otherwise, the preference is for use by large industrial partners such as power plants or for exchanges for higher-quality potable water resources with rural systems. In contrast, dual-reticulation (purple-pipe) systems for direct nonpotable recycling face steep economic and technical challenges.

Keywords: Aquifer recharge; Dual-reticulation systems; United States; Water policy; Water recycling

Introduction

Population growth, climate change, aquifer depletion, and increasing demand from industry and agriculture are among the primary factors that have put stress on the world’s urban water-supply systems (Grant et al., 2012; Vo et al., 2014). In the response, water managers and policymakers have become increasingly aware of the important role that conservation and efficiency can play in demand management. Among the changes that reduce demand on water supplies are systems that reuse wastewater after treatment. By recycling some treated wastewater back into the urban water-supply system, the approach to water supply has a high potential for increasing the sustainability of water-supply


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systems (Russo et al., 2014). Similar to other approaches that use ‘closed loops’ design for manufacturing and materials (McDonough & Braungart, 2002), the use of recycled water can be considered an aspect of the broader efforts to bring about sustainability improvements in urban water-supply systems.

Although it makes sense that water recycling should be included as an important element of the sustainability of urban water-supply systems, adoption and implementation are not straightforward processes. Water-supply organizations (WSOs) face a range of challenges when adopting recycling technologies, and they tend to prefer greater use of freshwater supplies where available (Richter et al., 2013). Furthermore, even when adopting recycled water technologies, WSOs tend to avoid the most sustainable option, direct potable recycling, because of factors such as public perception, public health concerns, and cost (Po et al., 2003). Direct potable recycling is arguably the most sustainable form of water recycling in terms of its effects on the broader regional water ecology because it reduces intakes from upstream sources and has limited effects on downstream users once the closed-loop system is in place. Furthermore, by reducing the energy embedded in extracting and storing water from distant sources, the system would likely have a lower energy footprint than the other two options (Leverenz et al., 2011).

However, direct potable recycling is very rare in the United States. As in many countries, the adoption of this technology faces significant hurdles (Po et al., 2003). This study instead focuses on choices among the more common approaches to the use of recycled water: indirect potable recycling, which occurs by recharging aquifers for future potable water supply and direct nonpotable recycling through the second system of urban water-supply pipes known as ‘dual reticulation’ or purple pipes. The second option offers strong sustainability benefits because it conserves water and energy, reduces demand on more distant water sources, and reduces local groundwater extraction. A third option, exchanges of treated effluent with agricultural water-supply systems, can also be found. Although WSOs in the United States tend to prefer these forms of water recycling to direct potable recycling, cities are not all rushing into these technologies. Furthermore, when WSOs adopt water-recycling technologies, they do not always give primacy of place to dual-reticulation systems. By exploring how and why this happens, this study will improve understanding of choices among the types of nonpotable water-recycling technologies. In the process, it will make a general contribution to the study of why some sustainable niches do not always scale up to achieve their full potential. The study does so by developing a comprehensive framework that includes psychological, technical, economic, institutional, and political factors.

Background

This study draws on the research field of transition studies by treating water-supply systems as technological systems (TSs). TSs are complex networks of elements that include natural resources, sociotechnical systems (organizations, consumers, infrastructures, regulations, and technologies), and cultural systems (cognitive and normative categories for orienting action; Geels & Schot, 2007). TSs tend to stabilize into a configuration known as a regime, and a group of ‘regime actors,’ such as WSOs and their partners, is generally responsible for maintaining the TS. When significant changes occur in the configuration of elements of a TS, we say that it has undergone a transition. Innovations are developed by ‘niche’ actors, which can be located in a variety of organizational settings, sometimes in the regime organizations themselves but also in civil society, businesses, universities, or the government. Sometimes, the innovations are compatible with the regime, may even be supported by regime
actors, and face relatively easy adoption pathways, but in other cases, regime actors may view the innovations as disruptive and threatening, and they may resist the scaling up of the innovations (Geels, 2014).

Sometimes, the transitions occur from endogenous processes of niche-regime dynamics within a TS and marketplace dynamics within an industry, but the multilevel perspective in transition studies emphasizes that changes are also driven by external factors such as natural resource availability and government policy. Of particular interest for this study is one type of transition – a sustainability transition – which is understood as occurring when the TS undergoes a change that significantly increases its level of sustainability. In turn, sustainability is understood here according to the Daly (1996) criterion of an ideal steady state that occurs when withdrawals by the TS from the natural environment are less than the capacity of the environment to replenish them, and the waste injected into the environment from the TS is below the environment’s limits to process the wastes. In aquifer and riparian systems, concepts, such as ‘safe yield,’ are a good approximation of this approach to sustainability. Because TSs are themselves complex, heterogeneous systems, the depth and pace of a sustainability transition are determined by a variety of factors, including institutional and political ones (de Haan et al., 2015; Markard et al., 2016).

The comprehensive perspective of sociotechnical transition studies has great policy relevance because it can help to identify a wide range of constraining factors that reduce the pace of a sustainability transition and strategies for overcoming slowed or stalled transitions. These factors go beyond the public acceptance, technical, and economic explanations that are sometimes popular among engineers and water-supply managers by integrating these factors with the ‘landscape’ of government regulations and policies, institutional priorities, organizational coordination, and political conflict. Thus, this study utilizes a comprehensive explanatory framework. Specifically, we focus here on the combination of public acceptance factors, technical and economic factors, and institutional and political factors in the transition of urban water-supply systems to much higher levels of water recycling. The terms ‘recycling’ and ‘reuse’ are often conflated in public perception and colloquial discussions, but there is a distinction. Water reuse is a more general class of using water more than once in a system. Thus, the category ‘water reuse’ includes recycled water, which has undergone treatment. In contrast, the term ‘reclaimed water’ is used to refer to wastewater before treatment (United States Environmental Protection Agency, 2012).

Public acceptance is an issue for some types of water-conservation policies such as mandated restrictions on lawn-watering or price increases (Larson et al., 2009; Brown & Hess, 2017). Public acceptance is especially important for water-recycling policy because of the difficulty of gaining acceptance for direct potable recycling. With respect to public perception of water-recycling systems, the ‘yuck factor’ and public health considerations are well-known challenges in the water research literature (Schmidt, 2008; Morgan & Grant-Smith, 2015). Even though treated wastewater often enters surface water systems that are a source of drinking water for downstream users, phrases such as ‘toilet-to-tap’ help to frame public rejection and concern with direct potable recycling of water. However, it is possible to overcome psychological barriers even to direct potable recycling, provided that there are good communication and public education (Russell & Lux, 2009). Consumer acceptance is enhanced when terms, such as ‘pure water’ or ‘100% fresh water,’ are used instead of terms such as ‘reclaimed’ or ‘recycled’ (Ellis et al., 2019).

Although the ‘yuck factor’ may not be the strong barrier that is sometimes assumed, WSOs and policymakers nevertheless favor the nonpotable types of innovation over potable recycling. Researchers have found that communities will accept nonpotable recycling projects, especially when public
acceptance barriers are addressed through effective program communication, consumer involvement in the decision-making process, and fairness assurances (Po et al., 2003; Pearson et al., 2010; Leonard et al., 2015). Public acceptance also improves if the WSOs provide information about the safety of the water, cost savings, environmental benefits, and the resilience benefits of having a diversified water supply (Hurlimann et al., 2008; Leonard et al., 2015). The most successful recycling proposals have consumer involvement in planning, ample technical and public safety information, and a clear economic benefit (Vo et al., 2014). After projects have been successfully implemented, public acceptance has been as high as 94%, such as in a South Australian suburb designed as an environmentally friendly model of the urban development (Hurlimann et al., 2008).

The second main group of factors that affect the adoption of water-recycling technology is economic and technical. Although nonpotable recycling systems have high capital costs to implement, they provide other economic benefits, including the reduction of environmental side effects from the over-withdrawal of region’s freshwater supply sources. For example, recycling can reduce demands on aquifers and upstream surface water sources, and thus, it may reverse ecosystem degradation and increase drought resistance. One problem from an economic perspective is that these externalities are difficult to quantify and to operationalize as traditional cost–benefit analyses (Grant et al., 2012; Molinos-Senante et al., 2012). Despite this difficulty, nonpotable recycling systems can reduce energy costs associated with drinking water treatment, even to the point of offsetting the capital costs required for building a dual-pipe infrastructure (Stillwell et al., 2011). Likewise, for cities with strong limitations on new water supplies, direct nonpotable recycling systems tend to be more cost-effective than desalination (e.g., Ray, 2010).

The economic feasibility of nonpotable recycling projects also varies according to factors such as technical design, the service area’s unique topography, energy sources, quality of the source water, and existing infrastructure (Chee et al., 2009; Kavvada et al., 2016). For example, the distance between the user and the wastewater treatment plant is directly related to the cost of the system. If there are industries, parks, golf courses, and other potential large users of nonpotable water located in proximity to each other and to the water treatment plant, then it is easier to build a limited and cost-effective system of nonpotable supply pipes. Conversely, as the distance from the treatment plant to the large user’s increases, the system requires more infrastructure and energy to pump the water. Furthermore, pumping water uphill also increases the cost, and the traditional sewage infrastructure model locates wastewater treatment plants at the lowest elevation points of cities to benefit from gravity. Systems that have to go over hills or mountains, or through rocky terrain, also will cost more. Even accounting for such costs, local reclamation systems with centralized treatment and distribution will reduce potable demand and will often be more cost-effective than individualized graywater systems (Newman et al., 2014).

A factor that includes both public acceptance and technical–economic considerations involves the minimization of public health risks. Because the risks increase with a higher likelihood of human contact, higher treatment processes are required with increasing potential for human contact. Additional steps to minimize these risks include redundancies in the treatment process and close monitoring of microbes, pharmaceutical residues, and other harmful pathogens and chemicals. Here, public perceptions interact with the technical and economic factors because recycled water systems may prioritize public health and safety beyond technical necessity, thereby driving up the costs (Foley et al., 2007). Frequently, public health risks are addressed by having a separate system of pipes for recycled water. In addition to the costs of such systems, they affect the amplitude, number, and timing of demand.
peaks for the existing potable system. If the demands are improperly modeled or anticipated, the built infrastructure may fail (Willis et al., 2011).

After water managers have found solutions to the factors described above and proceeded with implementation, the systems may still reach technical build limits. Nonpotable recycling systems face difficulty scaling up to serve an entire water system. As previously mentioned, connecting to users farthest away from the treatment plant is expensive. Doing so is also highly disruptive because new infrastructure must be constructed, and there can be public acceptance issues due to the disruption of construction and the destruction of streets (Miller, 2015). In such circumstances, the cost of treatment for direct potable recycling may be comparable to the cost of expanding the nonpotable recycling system (Lazarova, 2013).

The third set of factors, which we group under the rubrics of institutional and political, is also significant for nonpotable water-recycling systems. From an organizational perspective, WSOs focus on their primary mission of ensuring a stable supply of water sources with a minimal risk (Lach et al., 2005). Thus, WSO managers have shown concern with ‘demand hardening,’ or the loss of resilience that occurs when loops are closed, and conservation measures are adopted extensively (Kenney, 2014). In other words, if water recycling remains available as a future, untapped source of water, the system has resilience in the event of extreme drought or other threats to existing water supplies. More generally, Fuenfschilling & Truffer (2016) argue that advocates of niche innovations such as water recycling must convince WSOs and political leaders that the new technologies are not disruptive to the fundamental institutional logic of the existing system and the interests of other actors. For example, in one case, desalination advocates labeled wastewater recycling as ‘pooh’ water, thus pointing to the risks of recycled water even if desalination is more expensive. This was not a public perception issue per se, but a risk that other actors in the system could frame the innovation in ways that trigger public rejection. This framing situated desalination as a more attractive alternative water source and won support from legislators (Fuenfschilling & Truffer, 2016).

Thus, niche actors who advocate water recycling must carefully assess their strategies, including how much they want to ‘fit and conform’ with the existing regime or attempt to ‘stretch and transform’ it (Smith & Raven, 2012). Werbeloff et al. (2016) argue that in addition to assessing the relationship with regime actors, the niche actors must analyze the political, hydrological, and other conditions of the city where they are working and build strategies adapted to the local context. The strategies can include building networks of stakeholders, having continual engagement with actors associated with the policy and regulatory framework, and aligning the innovation with specific local needs and responses to crises such as droughts or floods. Recycling advocates must also assess how their strategies must shift in response to both the changing circumstances and the scaling up of the innovation.

In addition to compatibility with the regime’s institutional logic and general local conditions, another important institutional and political factor is coordination among different organizations and compliance with different regulatory systems (Brown & Farrelly, 2009). Coordination problems are especially salient for water recycling because wastewater treatment and drinking water supply are typically controlled by separate organizations (Grant et al., 2012). Furthermore, the introduction of treated wastewater into the city’s water supply, even if for nonpotable purposes, shifts the regulatory purview of the wastewater, especially with respect to public health. Because recycled water lies at the intersection of two types of water systems, there are often regulatory gaps for recycled water. For example, in the United States, there are no national regulations governing wastewater recycling; instead, the Environmental Protection Agency provides suggested guidelines and leaves each state with the ability to
craft its own regulations (United States Environmental Protection Agency, 2012). As such, states differ in policy, funding, and support for recycled water schemes (Bracken, 2012).

A further institutional-political hurdle is that regulations require different levels of treatment for recycled water depending on its end use. The United States Environmental Protection Agency (2012) provides suggested uses for each of the treatment levels (see Table 1). Primary treatment, which only separates out solids, can typically be used only for groundwater recharge of nonpotable aquifers via spreading grounds. However, if the nonpotable aquifer is recharged using injection, then secondary treatment is recommended. This level of treatment uses biological processes, including activated-sludge and aeration, to remove dissolved solids. In addition to its use for nonpotable aquifer recharge, secondary treatment can be adequate for use in single-pass cooling towers. A disinfection step beyond secondary treatment is recommended for environmental uses, such as wetland or stream flow augmentation, recirculating cooling towers, nonpotable projects with restricted public access, and crops that are either non-edible or are commercially processed before consumption. Finally, an additional filtration step beyond secondary treatment with disinfection is recommended for nonpotable recycling projects in municipal settings with unrestricted public access and for irrigation of crops that are edible when raw. Additionally, groundwater recharge of potable aquifers can be conducted using this level of treatment if the recycled water is applied via spreading grounds. However, if the purpose is injection into potable aquifers or directly adding the treated water to surface water supplies, advanced treatment is recommended in addition to secondary treatment, filtration, and disinfection.

The complex rules governing recycled water, together with the different regulations and organizations that govern drinking water and stormwater, create a difficult terrain for WSOs to negotiate when attempting to implement recycled water systems. Even after a pilot project has proven successful, the lack of expertise makes a scale shift of the innovation difficult. Nevertheless, case studies of Australian projects have shown that effective coordination among the multiple offices and experts, coupled with clear and convergent government policies from each government office, will help WSOs that wish to expand recycled water use to overcome the institutional hurdles (Tjandraatmadja et al., 2014). More generally, in cities, where there is high stress on water supplies because of either competing demand

Table 1. Summary of water treatment levels and appropriate recycling uses.

<table>
<thead>
<tr>
<th>Level of treatment</th>
<th>Primary</th>
<th>Secondary</th>
<th>Secondary with disinfection</th>
<th>Secondary with filtration and disinfection</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of treatment</td>
<td>Physical separation of oils and large solids</td>
<td>Biological removal of dissolved solids</td>
<td>Removal of disease-causing pathogens</td>
<td>Removal of nutrients</td>
<td>Purification</td>
</tr>
<tr>
<td>Recommended uses for water</td>
<td>Nonpotable groundwater recharge via spreading grounds</td>
<td>Nonpotable groundwater recharge via injection and once-through cooling systems</td>
<td>Environmental uses; recirculating cooling systems; nonpotable restricted access; and non-edible crop irrigation</td>
<td>Nonpotable unrestricted access; food crop irrigation; and potable groundwater recharge via spreading grounds</td>
<td>Potable water via aquifer injection, surface water addition, or pipe to pipe</td>
</tr>
</tbody>
</table>
for existing water supplies or hydrological conditions, WSOs have shown the capacity to overcome the barriers, at least for nonpotable recycling.

This study uses the background literature on the barriers for sustainability transitions in water-supply and water-management systems to examine why cities favor some types of recycling over other types. There are four main types of recycling: highly treated wastewater to augment directly the potable supply, the use of treated wastewater for aquifer recharging for potable water, exchanges with agricultural systems of treated wastewater for access to potable freshwater supplies, and the development of dual-reticulation systems in urban areas to supply large consumers with nonpotable water for industrial or landscaping uses (direct nonpotable recycling). Because direct potable recycling is not widely disseminated in the United States, this study focuses on choices among the remaining three types of recycling. As noted above, the dual-reticulation systems, which use their own designated infrastructure of purple pipes, do not require the same level of energy as is used in pumping water into and out of aquifers or to distant locations for agricultural exchanges. Furthermore, the level of treatment required can be lower for some urban uses of nonpotable water than for potable aquifer recharging. Yet, in some cases, WSOs prefer to use recycled water for aquifer recharging and agricultural exchange rather than to invest in dual-reticulation systems (direct nonpotable recycling), even if the latter may be more sustainable or even more cost-effective. Thus, our central research questions involve understanding why choices are made between different design options among the niche alternatives:

1. What leads a city to prefer to use recycled water for aquifer recharging or agricultural exchange rather than direct nonpotable recycling?
2. What leads a city to halt or slow its development of direct nonpotable recycling systems?

More generally, this study contributes to the analysis of sustainability transitions by examining the interplay of technical–economic and institutional–political conditions under which competing niches are selected, and why potentially less sustainable niches are selected for development. We build on work in the water policy literature that calls for holistic analyses of water recycling that includes a range of factors from the psychological, economic, and technical to the institutional and political (Brown & Farrelly, 2009; Russell & Lux, 2009; de Haan et al., 2015; Mekala & Davidson, 2016).

Methods

This study is part of a broader research project that has examined water-conservation policies in U.S. cities. The project has a quantitative component that involved the creation of an index of water-conservation policies for 195 U.S. cities and the measurement of factors that affect higher and lower levels of policy adoption (Hess et al., 2017; Gilligan et al., 2018). It also has a qualitative component that involved interviews with 46 stakeholders in four U.S. cities (Brown & Hess, 2017; Brown, 2018). One of the issues that emerged from the project was the question of why cities have not moved full-speed ahead with the transition to higher levels of use of recycled water. This study emerged from this broader background analysis.

From the broader research project, four large U.S. cities were selected for this in-depth study because they had developed unique and extensive uses of recycled water: Los Angeles, Phoenix, San Antonio, and Tampa. These cities are all located in the southern part of the country, and all four are in...
water-stressed areas. Los Angeles, Phoenix, and San Antonio are located in the arid southwestern portion of the country, and Tampa is located in Florida, where water stress has less to do with rainfall than with saltwater intrusion, water rights arrangements, and the declining availability of groundwater because of competition with agriculture. Three of the cities were also sites of extensive interviews for the broader project (Brown & Hess, 2017; Brown, 2018). Information for the case studies is based on extensive consultation of reports; information provided directly by the WSOs; and secondary literature about the cities, including both peer-reviewed studies and reports from research centers and nongovernmental organizations. After the comparative case-study analysis was completed, follow-up contact was made with WSO managers to check the accuracy of the summaries and to answer remaining questions. Their comments, answers, and updates were included in the case studies.

Results are presented in two parts. The first part summarizes the four cases, with each case divided into an overview, a review of aquifer recharging programs, and a review of direct nonpotable recycling programs. The second part analyzes the results according to the two research questions, and it presents an overview of the summary decision-making process that emerged from the results.

Results 1: description of the cases

Los Angeles, California

The Los Angeles Department of Water and Power (LADWP) has the lowest percentage of water recycling of the cities in this study, but it utilizes recycled water for groundwater recharge and in a dual-reticulation system, and it has the intention of expanding both systems. The sources of LADWP water vary based on California’s drought conditions, but there is typically a heavy reliance on importing potable supplies via the Metropolitan Water District of Southern California (MWD). Sources of water are from the State Water Project, the Colorado River Aqueduct, and local groundwater and transfers. In 2014, Mayor Eric Garcetti issued Executive Directive #5, which called for a reduction in per-capita potable water use by 20% by 2017 and a reduction in LADWP’s imported water by 50% by 2024 (Garcetti, 2014). In this policy context, LADWP recognized the potential for recycled water systems as an important part of the mix of strategies to reduce water importation. Recycling efforts, including groundwater recharge at the seawater intrusion barrier, a dual-reticulation system, and environmental uses, amount to roughly 36,700 acre-feet per year (AFY), or 10% of the 366,000 AFY of treated wastewater. Future plans call for an increase to a total of 59,000 AFY by 2025 (Los Angeles Department of Water and Power, 2015). To achieve this goal, LADWP plans to invest in expanding both groundwater recharge projects and the dual-reticulation system. Both are more cost-effective than importing additional water, which is governed by a complex network of state regulations and interstate agreements (Morrow et al., 2012).

With respect to groundwater recharge, the city contributes approximately 4,000 AFY of advanced treated water to injection at the Dominguez Gap Barrier, which is located near the ocean, in order to prevent saltwater intrusion to the groundwater drinking water supply (Los Angeles Department of Water and Power, 2015). Future plans for groundwater recharge include expanding the use of recycled water to recharge aquifers that serve as potable water sources. LADWP recharges the San Fernando Groundwater Basin, located north of the city, by channeling stormwater to percolate through spreading grounds. Because the recharge site and extraction wells already exist and are in proximity to the Donald
C. Tillman Water Reclamation Plant, LADWP needs to expand only the advanced water treatment capacity at that plant before beginning a 30,000 AFY recharge project with recycled water. LADWP’s 62-mile dual-reticulation system delivers roughly 6,000 AFY of recycled water for nonpotable uses, including cooling at the generation station and irrigation at public parks and golf courses (Los Angeles Department of Water and Power, 2015). Out of three plans with varying combinations of dual reticulation and groundwater recharge projects, LADWP chose the plan with the smallest expansion of the dual-reticulation system, which would add 19,000 AFY. Los Angeles has ideal technical conditions for a dual-reticulation system, including over 50 irrigation-only customers with high nonpotable demands and wastewater treatment plants already conducting tertiary treatment. However, it is cost-prohibitive for the dual-reticulation system to service every large user when factoring in the costs for infrastructure and energy to pump from the reclamation plant to the user (Morrow et al., 2012). In summary, LADWP has determined that the aquifer-recharge approach described above for the Donald C. Tillman Water Reclamation Plant is a more cost-effective project than expanding the pipelines of the nonpotable recycling system to convey an additional 30,000 AFY (Morrow et al., 2012). Thus, although the dual-reticulation system will expand, the expansion will be modest in comparison with aquifer recharge.

**Tampa, Florida**

The City of Tampa Water Department also uses recycled water in a dual-reticulation system and plans to develop groundwater recharge projects. The city’s Water Department is responsible for treating water, distributing water, and charging customers within the City of Tampa. The City of Tampa’s primary water source is the Hillsborough River, which runs through the city. The river supplies the first 82 MGD of city demands during typical conditions and the maximum withdrawal amount during drought conditions. Tampa Bay Water, the regional six-government wholesale utility, provides drinking water for the rest of the Tampa Bay Region and supplements the City of Tampa’s supply, especially in times of drought (City of Tampa, 2017). Tampa Bay Water sources a majority of its water from the Floridian Aquifer, Hillsborough River, and other local surface water, with a small amount from desalination (Tampa Bay Water, 2019).

Because there is substantial surface water available, Florida does not have the same hydrological constraints as Western cities such as Los Angeles. However, extensive depletion of aquifers has led to ecological damage, saltwater intrusion, and risks to real estate from sink holes. These factors have motivated strong concern with aquifer levels. In response to the concerns, the Southwest Florida Water Management District (SWFWMD), a regional regulatory unit of the Florida Department of Environmental Quality, called for increased water recycling in the Tampa Bay Planning Region in order to decrease stress on traditional surface water supplies and to aid in the recovery of their associated wetland ecosystems (Southwest Florida Water Management District, 2015). The City of Tampa recycles approximately 13,500 AFY (20%) of its 72,000 AFY of treated wastewater. The recycled water is consumed in the wastewater treatment plants, in nearby industry, and through the dual-reticulation system servicing irrigation users. The 20% recycling rate is significantly lower than the rest of SWFWMD’s Tampa Bay Planning Region, which had an overall recycling rate of 40% in 2010 (City of Tampa, 2016). By 2035, the Tampa Bay Planning Region of SWFWMD plans to achieve a 70% water recycling rate (Southwest Florida Water Management District, 2015).

The City of Tampa does not use recycled water for recharging groundwater supplies. However, Tampa has explored the feasibility of developing the Tampa Augmentation Project, an indirect potable
recycling system via aquifer recharge with recycled water (City of Tampa, 2019). Tampa’s wastewater treatment facility already conducts advanced treatment due to the Wilson-Grizzle Act of 1987, which requires the heightened treatment of wastewater entering Tampa Bay, and the city has existing aquifer storage and recovery sites. Investment into some additional water treatment and new recharge/recovery sites may be necessary, but efforts would be focused on expanding the existing technology, which faces fewer obstacles than introducing new systems (City of Tampa, 2016).

Tampa’s dual-reticulation system delivers roughly 2,400 AFY and services approximately 7.5 square miles of the department’s 211 square mile service area. The city does not plan an expansion of the system. The expense to build infrastructure beyond the existing area is cost-prohibitive, and the service area lacks ‘anchor points,’ or high-demand, easily-convertible users such as the ones that are still available in Los Angeles. Without anchor points, the cost per AFY for nonpotable water made available through the dual-reticulation system would not be competitive with potable supplies.

San Antonio, Texas

The San Antonio Water System (SAWS) sources the majority of its water from the Edwards Aquifer, which supports fragile ecosystems and endangered species (San Antonio Water System, 2012). Federal court rulings over endangered species and state government regulation of the Edwards Aquifer have motivated the WSO to engage in a high level of water-conservation policies, and it is widely recognized as a national leader. However, leadership also means that future strategies are more constrained than for Los Angeles and Tampa because San Antonio has largely reached limitations to water recycling.

In a dry year, SAWS produces about 125,000 acre-feet of effluent. Of that amount, 50,000 acre-feet are contractually committed for use at local power plants, and another 25,000 acre-feet are allocated for direct recycling in the purple pipe system (Clouse, 2016). SAWS was seeking Bed and Banks Authorization through the Texas Commission on Environmental Quality to use the remaining 50,000 AFY for instream flow purposes in the San Antonio River, so that the water will make it all the way to the bay and estuary in the Gulf of Mexico. In its role as an environmental steward for the region, SAWS initiated the request on a voluntary basis in support of legislative and regional stakeholder initiatives because it will provide both economic and environmental benefits for the region.

In an effort to become more drought resilient, SAWS was seeking to diversify its water supplies and to increase the potable supply to meet future demands. Consequently, the organization’s future planning initiatives largely focus on water banking of any current excess potable supplies and on increasing future potable supplies through desalination and importation projects such as the Vista Ridge pipeline project (San Antonio Water System, 2016).

SAWS does not use recycled water for aquifer storage and recharge. SAWS does undertake aquifer recharge, but it does so with potable water largely as a water storage strategy. Specifically, the WSO stores excess groundwater from the Edwards Aquifer during rainy seasons in a large aquifer storage and recovery facility in the Carrizo Aquifer, and the stored water can be drawn upon during the dry season. Although SAWS has investigated stormwater recharge and recycled water recharge for the Edwards Aquifer (San Antonio Water System, 2017), at present, there is not sufficient effluent to use recycled water for recharge.

With 130 miles of pipes capable of conveying up to 35,000 AFY of recycled water, San Antonio has the most extensive dual-reticulation system of the cities in our study, and it has the largest direct non-potable recycling delivery system in the United States. The dual-reticulation system was driven by its...
cost-effectiveness compared to importing more potable water and desalination. However, the allocation decisions described above have meant that other uses for the total of 125,000 AFY of effluent have been prioritized. As of 2017, 13,000 AFY of recycled water was used consumptively (water that is not returned to the river directly), another 6,000 AFY was used non-consumptively for streamflow augmentation purposes (including for the famous San Antonio River Walk), and 6,000 AFY of recycled water in the dual-reticulation system remained uncontracted. The goal is to have 25,000 AFY of consumptive recycling and not to count the 6,000 non-consumptive water as part of the 25,000 AFY goals. Combined, 12,000 AFY of recycled water was still available in the system, but heightened demands from golf courses and other seasonal irrigation use nearly accounted for all the available supply in the summer months (Clouse, 2016). The long-term plans leave open the option of expanding the system as new water supplies become available (e.g., from the Vista Ridge pipeline) and as the total water consumed in the system increases (San Antonio Water System, 2017).

Phoenix, Arizona

The City of Phoenix receives about half of its water from the Central Arizona Project, which provides water via a large aqueduct from the Colorado River, and a half from Salt River Project, which sources regional water. Phoenix recycled approximately 168,000 AFY, or 80–90% of its wastewater, with plans to increase utilization to 90% in the future (City of Phoenix Water Services Department, 2017). Thus, the city’s Water Services Department, also known as Phoenix Water, has the highest rate of water recycling of the cities in our study. Despite this achievement, the WSO does not utilize recycled water for either groundwater recharge or for a dual-reticulation system.

The main reason why Phoenix does not directly store recycled water underground is that it has access to preferred alternatives. The Central Arizona Groundwater Replenishment District and the Arizona Water Banking Authority store excess water from the Central Arizona Project and effluent in underground facilities, and in the future, the City of Phoenix can have access to this stored water. In addition, the City of Phoenix has also periodically stored its unused allotment from the Central Arizona Project at various sites (City of Phoenix Water Services Department, 2011). The city also has an in-lieu recharge arrangement with the Roosevelt Irrigation District, which serves as a Groundwater Savings Facility. Phoenix sends its treated wastewater to the Roosevelt Irrigation District, which uses the water largely for irrigation of non-edible crops. In turn, the Roosevelt Irrigation District withdraws less water from the Aquifer Management Area, and the Phoenix WSO then receives credits to withdraw an equivalent amount of water elsewhere in the aquifer, provided that regulatory conditions are met regarding the effects of the withdrawal on the aquifer (City of Phoenix Water Services Department, 2017; Silber-Coats & Eden, 2017). In the future, Phoenix may expand these arrangements to trading recycled water for potable water rights with neighboring WSOs that lack the infrastructure to receive their Central Arizona Project allocations (City of Phoenix Water Services Department, 2011). None of these uses of water storage involves using recycled water for aquifer recharge.

Phoenix uses its recycled water in several other ways. In the ‘three-way exchange,’ Phoenix exchanges approximately 33,500 AFY of treated wastewater with the Roosevelt Irrigation District, which delivers the water to farms. However, instead of Phoenix water receiving credits for the water, the Roosevelt Irrigation District provides groundwater to the Salt River Project for use by Phoenix, in effect allowing the city to exchange recycled water for groundwater. Approximately 67,500 AFY of recycled water is also delivered to the nuclear power plant, and 66,500 AFY is utilized for wetland mitigation. Phoenix previously operated
a dual-reticulation system on the north side of the city. However, the system is no longer utilized because the Cave Creek Wastewater Treatment Plant, which serviced the system, suspended its operations. The closure was due to a lack of development in the Cave Creek service area, which reduced the wastewater flows to the plant and economic efficiency of the system. Without a nearby recycled water supply, the dual-reticulation system is less feasible than ‘in-lieu’ recharge and similar trade agreements. The Phoenix WSO prioritizes recycling projects that augment potable supply for the existing water-supply system rather than diverting resources toward expanding the dual-reticulation system (City of Phoenix Water Services Department, 2011).

**Results 2: analysis**

With respect to groundwater recharge, only Los Angeles was using recycled water for groundwater recharge at the time of the study, but Tampa had developed plans for doing so. Both cities are concerned with saltwater intrusion into groundwater sources, and both are also interested in recycled water for potable groundwater storage. San Antonio appears to have hit regulatory barriers that would make it difficult to gain approval for the use of recycled water for groundwater recharge of the Edwards Aquifer. Instead, its primary use of aquifer recharging involves banking its excess allotment from the Edwards Aquifer by pumping it to a storage site in the Carrizo Aquifer. Phoenix also stores excess surface water, including from the Central Arizona Project (Colorado River), and it engages in indirect or in-lieu recharge by exchanging its recycled water with a rural district and receiving equivalent groundwater rights. This option may only be available when the farms do not involve food supply; in Florida, the option was rejected because the water for farms had to be of higher quality. These patterns suggest the following two overall preferences:

1. If there is a suitable source of non-recycled water that can be used for groundwater recharge (either surface water or other groundwater), then the preference is to use this source before recycled water.
2. If the WSO is facing a problem of saltwater intrusion, and if other sources of water for recharge are limited, it will likely prioritize the use of recycled water for groundwater recharge.

With respect to ‘purple-pipe’ or dual-reticulation systems, the systems faced significant economic and technical barriers. Only Los Angeles had plans for additional construction. Tampa faced diminishing returns due to the lack of additional large consumers of nonpotable water near its existing system. San Antonio faced a build-out limitation for the entire system because of its commitment to provide a determined amount of water for instream flows. However, the planning document indicated that additional construction could occur as the total water consumption of the system increases with population growth. Phoenix also had a limit because it is recycling approximately 90% of its wastewater, and it closed its one dual-reticulation system. The city’s WSO has found other ways to use its recycled water, including a contract with a nuclear energy facility and the exchanges with the local rural WSO. These patterns suggest the following underlying preferences:

3. WSOs face diminishing returns and build-out limitations in the construction of dual-reticulation systems because large consumers of nonpotable water are not always located near the water treatment plant and the main pipelines.
4. If there are other uses for recycled water allowing for direct delivery to one user – such as a power plant or an agricultural exchange – then the WSO may prefer these uses.
Furthermore, several of the planning documents also mentioned that there was a long-term potential to shift to direct potable recycling as the concept becomes more acceptable to customers, regulations become clearer and convergent among departments, and water-supply needs intensify.

Results are summarized in Table 2. Combinations of factors make it more or less likely that a WSO will adopt groundwater recharge or dual reticulation. There are two main advantages of dual-reticulation systems over groundwater recharge. First, dual-reticulation systems can be more sustainable than groundwater recharge from an energy perspective. Groundwater recharge that involves future potable use of the water requires that the water is treated to higher standards, pumped to the storage areas, and then pumped out when needed later and treated again. Thus, aquifer recharge is likely to be more energy intensive. Even in-lieu aquifer recharge requires additional energy to pump the recycled water to agricultural users for in-lieu aquifer recharge credits. Second, decision-making for dual-reticulation systems is less complex than for groundwater recharge projects because the ‘yuck’ factor is minimal in nonpotable projects compared to indirect potable projects. Despite these two advantages, dual-reticulation systems face steep challenges due to technical factors such as demand management and economic feasibility. If there are high nonpotable demands, such as irrigation for large public parks and golf courses or cooling towers for industry, and if these customers are located near the anchor points of the system, then it may be possible to expand dual-reticulation systems. However, at a certain point, dual-reticulation systems face diminishing returns because of the distance among large users and their distance from the water treatment plant.

### Table 2. Factors favoring two types of water recycling.

<table>
<thead>
<tr>
<th>Type of water recycling</th>
<th>Conditions that favor its use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater recharge</td>
<td>Accessible groundwater storage site.</td>
</tr>
<tr>
<td></td>
<td>No other sources of ‘cleaner’ water for groundwater storage.</td>
</tr>
<tr>
<td></td>
<td>High concern with saltwater intrusion or groundwater loss.</td>
</tr>
<tr>
<td>Dual reticulation</td>
<td>Large consumers are located near the waste treatment plant.</td>
</tr>
<tr>
<td></td>
<td>Consumers are downhill from the waste treatment plant.</td>
</tr>
<tr>
<td></td>
<td>No options for agricultural exchange of waste water.</td>
</tr>
<tr>
<td></td>
<td>Limited options for a single, large user to consume waste water.</td>
</tr>
</tbody>
</table>

Conclusion

From a water policy perspective, managers and policymakers, who are developing their water recycling programs, are faced with a choice between direct recycling to potable water and two main forms of indirect recycling: groundwater recharge and dual reticulation. Direct recycling to potable water tends to result in a public reaction known as the ‘yuck’ factor, and this can be a barrier to adoption if other options are available. With respect to indirect recycling, groundwater recharge requires a high level of treatment if the water from the groundwater source will be used later for drinking water. Dual reticulation offers sustainability benefits because the water is not being used for drinking purposes when retrieved from storage, and it does not require such a high level of treatment. However, dual-reticulation systems can be expensive to implement and to maintain, and they can also face technical challenges such as the need to pump water uphill because water treatment plants are often located at the lower
ground level than wastewater sources to allow the system to feed water to the plant by gravity. Thus, there is no single best answer to choosing between the two types of indirect recycling; it depends on local conditions and factors that were described in Table 2. In general, it appears that groundwater recharge strategies will be favored when available.

From a research perspective on innovation in water-supply delivery systems, the study provides an example of the comparative analysis of competing niches and the conditions under which one is favored over the other. Explaining the selection of competing niches requires a comprehensive framework that includes public perception issues, technical and economic factors, and institutional and political dimensions. Public perception and technical and economic factors clearly played an important role in the extent of adoption and design choices implemented for recycled water. The fact that the planning documents mention direct potable recycling, but only as a long-term possibility, suggests the staying power of the ‘yuck’ factor associated with the ‘toilet-to-tap’ framing. For example, in a chapter titled ‘Projects that Merit Further Consideration,’ the SAWS noted that ‘the technology is well established and mature’ and names U.S. cities where it is in use, but it added that the largest obstacle was ‘public perception’ (2017:52).

Furthermore, this factor likely affected the high restrictions on recharge projects in the Edwards Aquifer Authority area, and it may have also motivated the exchanges of recycled water for non-recycled water that Phoenix has developed with the Roosevelt Irrigation District. In addition to public perception factors, technical and economic factors were especially important for the lack of interest in the expansion of dual-reticulation systems. Although the investment can be recuperated with future revenue, the systems hit diminishing returns after the large consumers closest to the water treatment plants are connected. Furthermore, in cities located in a basin (such as Los Angeles), the cost of pumping over mountains may be prohibitive.

Finally, institutional and political barriers are also important if not determining factors. The case of Phoenix is instructive because a system of interstate and intrastate regulations has provided the desert city with access to freshwater from the Colorado River. Furthermore, because Arizona is destined to receive the lion’s share of reductions when the volume of water in Lake Mead declines, there is strong motivation to store excess freshwater underground and also to acquire water from neighboring WSOs. Institutional factors are also important for explaining the choices that San Antonio has made. The city has won accolades for its strong water-conservation policy, but its planning documents also show that even with a significant projected decline in per capita water consumption, absolute demand will continue to grow because of rapid population growth. This situation has motivated a strategy of water diversification by seeking new sources and by banking water from the Edwards Aquifer allotment when it is seasonally available. Los Angeles does not have the option of seeking out new supplies from distant sources, and it is forced to turn inward to recycling as a less expensive alternative to desalination. Tampa has access to surface water, but SWFWMD has prioritized replenishing depleted groundwater reserves and restoring minimum flows in surface water bodies. Aquifer recharge projects align with both of these priorities. The project will reduce the city’s reliance on the Hillsborough River Reservoir, thus increasing surface water to meet minimum flows and Tampa Bay Water’s demand in a growing region.

In summary, this analysis does not imply that the use of recycled water is a failure. However, it points to the need to treat recycled water as comprised of various design choices and to examine each city’s choices on a case-by-case basis in the context of water resources, public perceptions, economic and technical aspects of the different recycling systems, and institutional arrangements. With respect to general theories about how to scale-up sustainable niche technologies, our analysis suggests that it is
necessary to understand the varieties of related niche innovations (in this case, the different uses and configurations of recycled water) and to examine which of the different niche variants makes the most sense in the context of local institutions and TSs. This approach suggests that one should not assume that a single pathway will occur by which one new technology squeezes out alternatives. Instead, there will be a patchwork settlement pattern in which the choices among the forms of water recycling match local conditions.

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