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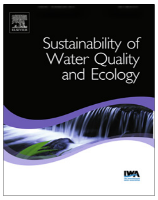

Technologic resilience assessment of coastal community water and wastewater service options

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ABSTRACT

The technologic resilience of water and wastewater service options was compared for a coastal community. Options included a centralized, conventional system; decentralized wastewater options such as composting and urine diversion toilets paired with a centralized drinking water system; and centralized drinking water with on-site graywater and rainwater reuse along with a centralized blackwater pressure sewer and digester. Four characteristics of resilience were reviewed based on literature for each option: the robustness, adaptive capacity, rapidity, and resourcefulness. Each system was evaluated for a cold weather event, storm event, power outage, short-term drought, wildfire, and predicted climate changes. Across all events, the service options utilizing graywater reuse and a blackwater pressure sewer and digester were considered the most robust. This was due to the potential advantages of water savings during drought and less environmental contamination during storms, assuming the addition of a backup generator at the household level; however, responsible management of the on-site components of these systems was important for resourcefulness. A scenario with multiple storm, wildfire, and drought events was constructed to quantitatively compare the resilience of the options with respect to water and wastewater service over a 100-year service life. Overall, no one system was the clear resilient choice given the selected events and assumptions, and resilience based on past event frequency over-predicted performance compared to the projected frequency given climate change. Key uncertainties include the duration of event failure, the frequency of future events, and the possible impact of water saving technology on the availability of source water.

1. Introduction

Community water systems are typically long-lived with expected useful lifespans ranging from 50 to 100 years (Qureshi and Shah, 2014). This long lifespan alone provides reason for considering future conditions or challenges when investing in

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Abbreviations: BAU, business-as-usual; CT, composting toilets; SS, septic tank; UD, urine-diverting toilets; BE, blackwater pressure sewer for energy/nutrient recovery; GR, on-site graywater treatment and reuse; RR, on-site rainwater collection treatment and use; GRR, on-site graywater and rainwater treatment and reuse; DW, drinking water; WW/RR, wastewater or resource recovery; HH, protection of human health from infectious diseases; S, reliable supply of water for household and firefighting demands; ES, protection of ecosystem services; I, protection of infrastructure.

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infrastructure. However, when considering the enormous expense of restoring or repairing water systems, it is also clear that infrastructure resilience should be considered. For example, the estimated cost to restore the United States' buried drinking water infrastructure exceeds $1 trillion over the next 25 years (Water Utility Coucil, 2012). The cost of reconstruction after a major catastrophic event is also staggering, such as the $2.6 billion bill to repair, rebuild, and make the water and wastewater infrastructure systems more resilient in New Jersey following Hurricane Sandy (Johnson, 2013). The selection of the next-generation water system should consider possible future challenges upfront to both protect the enormous investment and minimize additional costs from reconstruction and adaptive measures (Bettini et al., 2013; Kingsborough, 2013). The aim of the present work was to conduct a comparative technological resilience assessment for the selection of the next-generation water system.

The concept of resilience is related to the performance of complex systems under changing conditions (Ayyub, 2014). Here, resilience was defined as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" (Ayyub, 2014). The adopted definition of resilience straddles both the possibility of event disruptions, such as an earthquake or deliberate attack, and long-duration changes, such as landscape changes or sea level rise (Ayyub, 2014). For a system to be resilient to disruptions, the characteristics of the natural-engineered system are important, as are human dimensions of the system, which rely on governance, community outreach, and education (Ananda and Proctor, 2013; Bettini et al., 2013; O'Rourke, 2007). For event challenges, resilient systems have the following characteristics:

- *Robustness:* strength, or the ability of the system to withstand a given level of stress or demand without suffering degradation or loss of function.
- *Redundancy:* the extent to which the system and other elements satisfy and sustain functional requirements in the event of disturbance.
- *Resourcefulness:* the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt the system (i.e., monetary, physical, technological, and informational and human resources).
- *Rapidity:* the capacity to achieve goals in a timely manner in order to contain losses, recover functionality, and avoid future disruption (Bruneau and Reinhorn, 2007).

While partly related but missing from the above list and highlighted in the definition of resilience is the adaptive capacity of the system.

- *Adaptive capacity:* the ability to re-organize while undergoing change (Folke, 2010) and for water services, we add to this definition, to prevent loss of function.

Although the above characteristics were defined for event challenges, they apply to long-term changes as well.

Using the characteristics of a resilient system, we identified differences in community resilience resulting from the selection of water and wastewater service, rather than focusing on a complete resilience assessment of the entire community. A previous review of the current state of resilience analysis of community water and wastewater service options found a general lack of data for alternative community water systems across multiple challenges and for various functional services, as well as a lack of economic valuation (Xue et al., 2015). The goal of the present work was to provide a comparative resilience assessment of alternative community water systems based on a case study that addresses multiple event and long-term challenges with suggestions for important considerations in the area of economic valuation for the selected systems.

2. Case study

This resilience assessment was part of an overall effort to evaluate innovative water and wastewater technology from a system sustainability perspective (Malmqvist et al., 2006). Water systems applicable to semi-rural and developing communities that largely rely on septic systems were investigated using data relevant for Falmouth, Massachusetts. Falmouth had a population of 31,500 in 2011 and faces expanding urbanization and increased seasonal tourism, with the predominating use of aging septic systems resulting in excessive nutrient exports and coastal eutrophication. To assist in identifying community water systems to mitigate eutrophication and provide for sustainable activities, our initial work has focused on life-cycle assessment, human health risk assessment (Schoen et al., 2014), system capital costs, and, presented here, resilience. Xue et al. (2015) presented a review and description of the metrics and tools used in the case study for the sustainability assessment of water and wastewater service options. Future work will present a summary of all sustainability metrics results for the Falmouth case study, including resilience.

Five community water and wastewater service options to replace traditional septic (see Fig. A1, Supporting information) were considered. The business-as-usual (BAU) system consisted of a conventional, centralized drinking water system and a centralized wastewater treatment system. In the first alternative, the centralized wastewater treatment system was replaced with composting toilets (CT) and on-site graywater treatment by septic tank (SS), CT-SS, whereby graywater refers to non-toilet wastewater generated from sinks, showers, washing machines etc. In the second alternative, the centralized wastewater treatment was replaced with urine-diverting toilets (UD) and on-site fecal solids treatment by septic tank (UD-SS). For the CT-SS and UD-SS options, all potable and non-potable water uses were supplied by a centralized drinking water system. In the third alternative, a low flush toilet and blackwater pressure sewer (BE) was utilized with a community