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Technologic resilience assessment of coastal community water and wastewater service options

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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.

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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...
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 (Bruno 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
energy recovery system. Blackwater is the feces and urine with more concentrated organic material and nutrients when kept separated from graywater. In addition, this system option included on-site graywater treatment and reuse (BE-GR) for toilet flushing and outside irrigation, as well as potentially to water homegrown salad crops. The final system considered (BE-GRR) was identical to BE-GR with the addition of on-site rainwater collection, treatment, and use (RR) for showering. All systems had a conventional separated storm system and, therefore, it was not addressed in the comparative analysis. There were additional assumptions relevant to each system that are discussed in the Section 4.

In the following analysis, community water and wastewater service options other than the BAU were referred to as alternative systems or options. System components were discussed by categories, such as those related to drinking water (DW) collection, distribution, and treatment, and to all other, wastewater, or resource recovery (WV/RR) processes. The WV/RR processes included wastewater and blackwater collection and treatment, or graywater treatment and reuse. Also, components were categorized as centralized (e.g., the BAU systems or the BE treatment component) or decentralized (e.g., CT/UD-SS or GR/R).

3. Methodologies applied

3.1. Qualitative analysis

We conducted a comparative, qualitative resilience analysis for select events and long-term changes relevant to the Cape Cod community. The events were selected based on a hazard ranking in the Multi-Hazard Mitigation (MHM) Plan for Cape Cod (Cape Cod Commission, 2010). The events included: (1) an extreme cold-weather event with snow and ice accumulation; (2) an intense storm event with the possibility of wind and storm surge that floods the local community; (3) a multiple-day power outage (not included in the MHM plan but relevant); (4) a widespread wildfire; and (5) a short-term (seasonal) drought with tourist influx increasing water demand. In addition to event challenges, long-term challenges resulting from climate change for Massachusetts for year 2050 included: (6) increases in winter and summer temperatures; (7) changes in precipitation (e.g., increase in winter precipitation and decrease in summer precipitation); and (8) sea level rise (Executive Office of Energy and Environmental Affair, 2011). Droughts are also projected to increase in frequency given climate change; however, drought was included as event challenge 5 (Executive Office of Energy and Environmental Affair, 2011).

We evaluated each community water system for the characteristics of a resilient system (i.e., robustness, adaptive capacity/redundancy, rapidity, and resourcefulness). Robustness was evaluated based on a literature review of each system’s vulnerabilities and the functional services impacted by each vulnerability. The MHM plan identified the critical resources that were prioritized for protection for Cape Cod. Those included life, property, infrastructure, and natural, cultural, and economic resources (Cape Cod Commission, 2010). All of the critical resources from the MHM plan are linked with community water systems. For the purposes of this resilience analysis, the critical functions or resources provided by community water systems were specified as: (1) protection of public health from infectious diseases; (2) reliable supply of water for household needs and other demands; (3) protection of infrastructure; and (4) protection of ecosystem services. Options with no apparent vulnerabilities across all critical functions or resources were categorized as robust for a particular hazard.

We considered the system’s ability to adapt to changing conditions when vulnerabilities were identified, described above, given the prescribed system components. Additionally, we identified from the literature review additional measures that could improve the ability of each system to satisfy critical services in the event of reduced functionality. Adaptive measures that return the option to a robust state were noted for each event type.

The time to recover the critical functions of infrastructure and service was discussed using specific examples of systems in the Northeast region of the United States that were impacted by recent events. The time to recovery is closely linked with the resourcefulness of each system. We considered resourcefulness as it relates to the ability to mobilize resources for a particular system configuration when conditions exist that threaten to disrupt the system. Broader considerations of community resourcefulness were not considered, since this comparative assessment only captured differences in resilience resulting from selection of water and wastewater service.

3.2. Quantitative analysis

A major limitation of the qualitative approach was that the magnitude of functionality loss was not considered. To address this, we used a resilience model to quantitatively compare the resilience of the alternative systems for selected events over the system service life based on information collected for the qualitative analysis. This provides a comparative, quantitative assessment of differences among systems for some critical functions but not a comprehensive resilience assessment. The selected resilience model proposed by Ayyub (2014) was developed to incorporate the characteristics of a resilient system described above. The proposed model measures resilience with respect to a particular function or quality of a system (e.g., physical infrastructure, economy, and environment) over time as:

\[ \text{Resilience (Re) = } \frac{(T_i + F\Delta T_f + R\Delta T_r)}{(T_i + \Delta T_f + \Delta T_r)} \]
where $T_i$ is the time to the incident, $F$ is the failure profile, $\Delta T_f$ is the duration of the failure, $R$ is the recovery profile and $\Delta T_r$ is the duration of the recovery.

The failure-profile value can be considered as a measure of the robustness and redundancy (or adaptive capacity) and the recovery profile can be considered as a measure of resourcefulness and rapidity (Ayyub, 2014).

The failure profile is measured as follows:

$$ F = \int_{T_i}^{T_f} f dt \int_{T_i}^{T_f} Q dt $$

Fig. 1 displays the time of incident ($t_i$), time of failure ($t_f$), failure event curve ($f$), and target performance curve ($Q$) for two types of events. In addition, Fig. 1 displays the time of recovery ($t_r$) and recovery event curve ($r$) for two types of recoveries relevant to the selected event scenarios. The recovery profile is measured as follows:

$$ R = \int_{T_f}^{t_r} r dt \int_{T_f}^{t_r} Q dt $$

Fig. 1 is a simplification of the possible pathways for failure and recovery proposed by Ayyub (2014). In particular, we assumed no change in the target performance ($Q$) over time and that the recovery profile attained the target performance at time $t_r$. For this analysis, sudden recovery ($r = 0$), where $\Delta T_r = 0$, was possible. In this case, the recovery profile ($R$) was not computed or included in Eq. (1).

To perform the quantitative assessment, each quality, here a critical function or resource, was assigned a metric. The reliable supply of water for household needs and other demands was represented by volume of water delivered per day to customers. The protection of critical infrastructure was also represented by the volume of water delivered to customers per day or volume of water treated per day. In all cases, the target was set to 1 with residual performance ($Q_r$) a fraction of 1. The remaining critical functions were not modeled but discussed, given their complexity.

A proposed modified resilience model was used to measure resilience for each option, given a hypothetical 100-year lifespan with the occurrence of multiple challenges. In order to include multiple events, we modified the resilience model of one event in Eq. (1) to account for failures over the system lifespan:

$$ \text{Resilience} (R_l) = \frac{\sum_j (T_{ij} + F_j \Delta T_{fj} + R_j \Delta T_{rj})}{\text{lifespan}} $$

where $j$ is the challenge index. In Eq. (4), the time to the incident $T_{ij}$ is measured starting after the recovery of the previous incident. We assumed that the community completely recovers after each event so that the target performance was achieved.

Sensitivity analysis was conducted to examine the importance of the duration of failures and recoveries and the frequency of events under future climate change. Selected inputs to Eqs. (1)–(3) were changed one at a time, with the other parameters set to the best estimates.
4. Results

4.1. Qualitative resilience analysis

4.1.1. Vulnerabilities and robustness

The vulnerabilities, technical advantages, and impacted critical functions associated with each option are summarized for the selected future challenges in Table 1 from the literature review (presented in Supplemental Table S1). Challenges that resulted in vulnerabilities or technical advantages that were shared across all options are briefly discussed first, followed by scenarios with differences among options.

The centralized drinking water system was shared by all options. While the BE-GR/R options reduced municipal water demand through water reuse and rainwater capture, they still relied entirely on the municipal system for the provision of drinking water. The shared drinking water components resulted in the same vulnerabilities across options for most future challenges considered here (presented in Supplemental Table S1) – extreme cold weather event, storm with increased surge, wildfire, and increase in temperature (National Association of Clean Water Agencies and Association of Metropolitan Water Agencies, 2009); or, they shared the same advantages. For example, drinking water service was assumed to be uninterrupted for short-term power outage when backup generation was available. However, there were differences in the WW/RR components across options (see Supplemental Fig. 1) that resulted in different vulnerabilities among options during future challenges.

Starting with the extreme cold weather event (Challenge 1), there were potential WW/RR treatment failures associated with BAU and the blackwater pressure sewer options (BE-GR/R), depending on treatment design and especially for those systems not protected or insulated for cold weather. There may be additional stress on the biological treatment systems, and collection pumps may fail given the increased density of cold water (Day, 2000). As a result of leakage or poorly treated effluent, ecosystem services may be affected (Charles et al., 2010; World Health Organization Regional Office for Europe, 2011). We did not find in the literature review vulnerabilities that impacted the critical services for urine collection and composting toilets. Generally, domestic sewage rarely drops below 50–55°F (Day, 2000). This high temperature prevents pipes from freezing if maintained properly and in frequent use. However, septic system components may freeze when temperatures drop below freezing for a sustained period of time (Onsite Sewage Treatment Program University of Minnesota, 2010).

None of the WW/RR options were robust under the storm event (Challenge 2). The BAU and CT/UD-SS options were subject to flooding of sewerage into homes and the BAU and BE-GR/R options may sustain damage to the treatment, collection, or pumping system elements (Charles et al., 2010). A potential technical advantage of the BE-GR/R options was the prevention of sewage backup into homes; additionally, the pressure sewer may prevent leakage from the conveyance system to the surrounding environment when submerged but undamaged (Environmental One Corporation, 2008). Whereas, because groundwater and floodwater can enter the systems, the BAU and CT/UD-SS options were vulnerable to flooding of sewage and graywater into the surrounding environment and homes with an impact on the critical services of human health and ecological services protection (Charles et al., 2010). However, if physical damage to the BE-GR/R pressure sewer conveyance system does occur, the technical advantage is potentially lost, which could cause flooding of sewage such as that caused by failure of the BAU and CT/UD-SS options. Also, intrusion of water into the grinder pump vault could result in an overflow, either to additional storage or the surrounding environment (Water Environment Federation, 2008).

The most compelling technical advantage of the BAU and CT/UD-SS options’ WW/RR infrastructure was the continued operation during power outage (Challenge 3). The BE-GR/R options had the additional vulnerability that the pump and grinder connection from the home to the conveyance system stops operating (Kinstedt, 2012). Each connection generally has some storage capacity; however, this capacity will likely be exceeded over a multiple-day power outage (Environmental One Corporation, 2008). In addition, the GR and RR treatment fails without backup; however, we assumed that DW can be used to supplement these water demands. The BAU had the technical advantage of continued operation of wastewater services during a power outage, assuming that backup generators were available for treatment and pumping. The CT/UD-SS options had continued service, assuming that an electric fan was not required to vent.

All options were potentially affected by wildfire (Challenge 4) with potential damage to physical structures and treatment from both the heat of the fire and the activities to contain the fire (Centres for Disease Control and Prevention, 2010; Sham et al., 2013). The scale of infrastructure loss depends on the location of the fire relative to key centralized infrastructure or homes with on-site systems.

During short-term drought conditions accompanied by increased water demand by tourists (Challenge 5), all options were vulnerable to possible drinking water shortage, saltwater ingress to groundwater, and ingress contamination in distribution water (Charles et al., 2010; Teunis et al., 2010), depending on the degree of drought. However, the impacts may be less severe for the alternative options due to the reduced water demand from the WW/RR elements (Kinstedt, 2012; The Green Centre, 2014). In terms of water usage, the CT-SS had zero water consumption; the UD-SS consumed only a small fraction of the BAU flush; and the BE-GR/R systems used 1.5 L per flush compared to the 3–5 L per flush for the BAU (Kinstedt, 2012; The Green Centre, 2014). In addition, the GR and RR systems had additional advantages of directly treating and using alternative sources of water. Although these technical advantages in reduced water demand were apparent, the resulting impact on water supply cannot be quantified without additional modeling.
Table 1: Summary of vulnerabilities and technical advantages (bold typeface) of individual water service scenarios under future challenges.

<table>
<thead>
<tr>
<th>Challenge</th>
<th>System</th>
<th>Options</th>
<th>Critical function</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Extreme cold weather, snow, and ice</strong></td>
<td>WW/RR</td>
<td>BAU</td>
<td>On-site pipe damage to septic system and other components, environmental contamination, sewage backup in homes&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>CT-SS</td>
<td>Centralized treatment failure, collection failure from pumps&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>UD-SS</td>
<td>On-site damage to septic system and other components, environmental contamination, sewage backup in homes&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>BE-GR</td>
<td>Centralized treatment failure, collection failure from pumps&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>BE-GRR</td>
<td>Eliminates sewage backup in homes and leaks when collection system is submerged but undamaged, centralized treatment damage, collection damage, environmental contamination&lt;sup&gt;h&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>2. Storm with increased surge</strong></td>
<td>WW/RR</td>
<td>BAU</td>
<td>On-site damage to septicsystem and other components, environmental contamination, sewage backup in homes&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>CT-SS</td>
<td>Centralized treatment failure, collection failure from pumps&lt;sup&gt;d&lt;/sup&gt;</td>
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<td>On-site damage to septic system and other components, environmental contamination, sewage backup in homes&lt;sup&gt;e&lt;/sup&gt;</td>
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<tr>
<td></td>
<td>WW/RR</td>
<td>BE-GRR</td>
<td>Eliminates sewage backup in homes and leaks when collection system is submerged but undamaged, centralized treatment damage, collection damage, environmental contamination&lt;sup&gt;h&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>3. Power outage</strong></td>
<td>WW/RR</td>
<td>BAU</td>
<td>Pressure sewer failure, on-site graywater and rainwater treatment failure&lt;sup&gt;i&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>CT-SS</td>
<td>Centralized treatment damage, collection damage&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>UD-SS</td>
<td>On-site damage to septicsystem and other components, environmental contamination, sewage backup in homes&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
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<td>BE-GR</td>
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</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>BE-GRR</td>
<td>Eliminates sewage backup in homes and leaks when collection system is submerged but undamaged, centralized treatment damage, collection damage, environmental contamination&lt;sup&gt;h&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>4. Wildfire</strong></td>
<td>WW/RR</td>
<td>BAU</td>
<td>On-site damage to septicsystem and other components&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>CT-SS</td>
<td>Centralized treatment damage, collection damage&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>UD-SS</td>
<td>On-site damage to septicsystem and other components, environmental contamination, sewage backup in homes&lt;sup&gt;e&lt;/sup&gt;</td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>BE-GRR</td>
<td>Eliminates sewage backup in homes and leaks when collection system is submerged but undamaged, centralized treatment damage, collection damage, environmental contamination&lt;sup&gt;h&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>5. Short term drought (3 months) with tourist influx</strong></td>
<td>DW</td>
<td>BAU</td>
<td>Less water demand from WW/RR technologies preceding and during drought potentially reduces shortage, saltwater ingress to groundwater, and ingress contamination in distribution&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>WW/RR</td>
<td>CT-SS</td>
<td>Centralized treatment damage, collection damage&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
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<td>UD-SS</td>
<td>On-site damage to septic system and other components&lt;sup&gt;e&lt;/sup&gt;</td>
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<td>WW/RR</td>
<td>BE-GRR</td>
<td>Eliminates sewage backup in homes and leaks when collection system is submerged but undamaged, centralized treatment damage, collection damage, environmental contamination&lt;sup&gt;h&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>6. Increase in temperature</strong></td>
<td>WW/RR</td>
<td>BAU</td>
<td>No vulnerabilities identified</td>
</tr>
<tr>
<td><strong>7. Changes in precipitation</strong></td>
<td>WW/RR</td>
<td>BAU</td>
<td>See Challenges 2 and 5</td>
</tr>
<tr>
<td><strong>8. Sea level rise</strong></td>
<td>WW/RR</td>
<td>BAU</td>
<td>See Challenges 2 and 5</td>
</tr>
</tbody>
</table>

<sup>a</sup> Drinking water (DW) and wastewater/resource recovery (WW/RR) processes and components.
<sup>b</sup> BAU: conventional drinking water treatment coupled with conventional wastewater treatment services; CT-SS: conventional drinking water treatment coupled with composting toilets and on-site graywater treatment by septic tank; UD-SS: conventional drinking water treatment coupled with urine-diverting toilets and on-site fecal solids treatment by septic tank; BE-GR: conventional drinking water treatment, with on-site graywater treatment and nonportable reuse coupled with a low flush toilet and blackwater pressure sewer; BE-GRR: same as BE-GR, except that on-site rainwater collection, treatment and use for showering is added.
<sup>c</sup> HH is protection of human health from infectious diseases; S is reliable supply of water for household and firefighting demands; ES is protection of ecosystem services; I is protection of infrastructure; NA is not applicable.
<sup>d</sup> World Health Organization Regional Office for Europe (2011).
<sup>e</sup> Charles et al. (2010).
<sup>f</sup> Onsite Sewage Treatment Program University of Minnesota (2010).
<sup>g</sup> Author's engineering judgment based on systems.
<sup>h</sup> Environmental One Corporation (2008).
<sup>i</sup> Kinstedt (2012), The Green Center (2014).
<sup>j</sup> Centers for Disease Control and Prevention (2010).
<sup>k</sup> Teunis et al. (2010).
<sup>m</sup> Parry et al. (2007).
From the WW/RR perspective, the BAU was potentially more vulnerable to blockages within the wastewater collection system during times of low flow and higher pollution loads in downstream water bodies (Charles et al., 2010). These vulnerabilities affected the critical services of protection of human health (Centers for Disease Control and Prevention, 2010) and ecological services (Charles et al., 2010). The alternative options were designed to operate with less water and without blockages (Kinstedt, 2012; The Green Centre, 2014). However, the CT/UD-SS systems may still result in potentially higher pollutant loads in downstream water bodies when these systems fail.

Although the event challenges are discussed individually above, events may be connected. For example, a drought may lead to conditions that result in wildfire and a resulting power outage. For these combined events, there may be additional vulnerabilities or the degree of damage may increase. For example, the quality of drinking water supply is severely impacted by drought or wildfire followed by a severe storm event (Sham et al., 2013; Wright et al., 2014).

The future climate changes, although listed separately in Table 1, will occur in combination. The future changes in temperature and precipitation, combined with sea level rise, may affect the supply of fresh surface and ground waters (Masterson, 2004). As described for the drought event (Challenge 5), less water demand from WW/RR technologies (Kinstedt, 2012; The Green Centre, 2014) preceding and during drought potentially reduces DW vulnerabilities. However, additional modeling is necessary to identify the effectiveness of alternative water saving technologies when temperature, precipitation, and sea level change are considered in combination.

The possible increase in temperature due to climate change is thought to have a direct impact on WW/RR components (Tram Vo et al., 2014). Systems composed of concrete have the vulnerability of corrosion of raw wastewater pipelines (KWL, 2008; Saracevi et al., 2007). However, the systems considered were constructed with alternative materials that are not vulnerable to corrosion. No vulnerabilities were identified for CT/UD-SS systems.

Decrease in summer precipitation may result in vulnerabilities similar to those for the drought event (Challenge 5) (Charles et al., 2010). Increase in winter precipitation may result in vulnerabilities similar to those for the extreme storm event (Challenge 2) (Charles et al., 2010). The vulnerabilities associated with sea level rise included those of the storm event (Challenge 2), including inundation, flooding, storm surges, erosion, and salt water intrusion (Parry et al., 2007).

4.1.2. Additional adaptive measures

Below we summarized the adaptive measures in the form of additional capital investments that may increase the adaptive capacity of the community water system options with particular attention to those that return the options to a robust state. As with the vulnerability analysis, shared components across options resulted in shared adaptive capacities across options. For example, the drinking water system adaptive measures for the storm event (Challenge 2) include adapting water treatment to respond to changing water quality and designing flood storage areas on rivers to mitigate the impacts of floods (Charles et al., 2010). Since these adaptive measures were shared by all options, they were not considered in the comparative assessment.

During a cold-weather event (Challenge 1), the WW/RR components of the BAU and BE-GR/R options had additional adaptive measures that reduced, but not necessarily eliminated, the vulnerabilities of treatment or pumping failure. For example, anaerobic digesters are typically insulated or heated to maintain a constant temperature, given the scale of operation considered. Likewise, during a storm event (Challenge 2) and for sea level rise (Challenge 8), numerous additional adaptive measures increased the adaptive capacity of WW/RR components. Additional measures such as emergency pumps can mitigate pumping failures (Charles et al., 2010), and SS systems can be modified with a non-return valve to reduce sewage backup into homes (Charles et al., 2010). The BE pump vault can be designed to overflow to additional storage or drain fields (Water Environment Research Foundation, 2010). However, it is difficult to identify adaptive measures that will return the system options to a robust state during these events.

During power outages (Challenge 3), the BAU and SS options were robust. The BE-GR/R options may also be robust with the addition of a backup power supply. A centralized, locally generated power source can be distributed, or homeowners can have standby generators on-hand for the GR, RR, and BE system components (Water Environment Research Foundation, 2010); however, these measures come with additional costs.

No adaptive measures were identified for the WW/RR components given wildfires (Challenge 4); however, protective measures included clearing areas surrounding infrastructure of flammables and adding flame-retardant insulation to buildings (Sham et al., 2013).

During short-term drought (Challenge 5), water shortage was a key vulnerability for additional problems. For example, higher pollutant loads in downstream water bodies (Charles et al., 2010) would require additional measures to adapt to changing concentrations of contaminants or more valued components in sewage (Charles et al., 2010; Cordell and Neset, 2014). Considering the WW/RR elements, the BAU system had additional adaptive measures such as groundwater recharge with treated wastewater (Charles et al., 2010) or centralized wastewater treatment and distribution for reuse; however, these large-scale changes were assumed to be beyond the scope of BAU and not considered in the final assessment. For the CT/UD-SS and BE-GR/R systems, adaptive measures with the aim to save water were adopted in the original designs.

Adaptive measures for changes in precipitation and sea level rise (Challenges 7 and 8) were shared with the drought and storm events (Challenges 5 and 2) described above.
4.1.3. Rapidity

The time to recover the functionality of stressed WW/RR infrastructure or drinking water supply was based on previous events. No examples, however, were found in the literature for the time to recovery during a short-term cold weather event (Challenge 1) in which pumps, pipes, or treatment could require repair. Some of the problems could be alleviated when the cold period is over, such as poor treatment performance.

Under the storm event (Challenge 2), there may be differences in the time to recovery for the decentralized versus the centralized elements. In the case of centralized systems, the collection/distribution system may require extensive repair. The time to recovery of operation for both the DW and WW/RR system elements for BAU was potentially weeks to months or more, based on the reported time to recovery from utilities affected by Hurricane Sandy (Kenward et al., 2013; New York State Department of Health, 2012; Reed et al., 2013). In the case of distributed systems, portions of the system may be operational. For example, the composting toilet of the CT-SS option may be well sealed; or, for the BE-GR/R, the grinder pump may be well sealed and protected. If system components need to be replaced, the time to recovery is affected by the logistics of providing these items. No examples were found in the literature for the time to recovery for a community with CT/UD-SS options. In the best-case scenario where sufficient supply of these items and individuals qualified to install them are available, systems could potentially be restored in the first few days following the event. It is possible that a major event would result in a shortage of supplies, which would result in longer recovery times. The rapidity for the storm event (Challenge 2) is relevant for the wildfire event (Challenge 4), where both centralized and decentralized elements may be affected.

No specific example of time to recovery was found for a blackwater pressure sewer following destruction. At a minimum, BE-GR/R pumps require a service call to continue operation during power outage (Challenge 3). The reported service call time for an individual house connection ranges from 20 min to 3 h (Water Environment Federation, 2008). The shallow burial depth and width may simplify the finding and repairing of leaks compared to a conventional collection system, which potentially reduces the repair cost and time (Water Environment Research Foundation, 2010).

The amount of time that it takes to recover the critical service of a reliable water supply varies in drought conditions (Challenge 5). For Falmouth, the groundwater supply is recharged mostly by rainwater (Alibrandi et al., 1999). Therefore, the time to recovery of the water supply is subject to natural variation in precipitation. The recovery time is potentially shortened or improved by the use of the alternative systems. However, this requires the use of models to verify and was outside the scope of this work. Under future climate change (Challenges 6–8), estimating the amount of time that it takes to recover the critical service of a reliable water supply is more complex, given the various changes in temperature, precipitation, and sea level rise.

4.1.4. Resourcefulness

Resourcefulness is affected in part by the type of management, that is, whether it is centralized, community organized, or individually managed. Components of the BAU are already operated and managed by the town of Falmouth with dedicated and trained staff. The staff have the responsibility of ensuring that the wastewater treatment plant (WWTP) complies with mandated effluent limits as well as the responsibility of overseeing the system’s operation, maintenance, emergency preparedness, and inspection. The centralized management enhances the resourcefulness of the BAU (World Health Organization Regional Office for Europe, 2011).

The septic systems are currently regulated under the Massachusetts sanitary code for on-site wastewater systems and are permitted by local boards of health and the Massachusetts Department of Environmental Protection. The septic systems for UD/CT-SS are generally not monitored for performance after receiving a permit and are inspected only when sold. Similarly, the CT and UD elements would be permitted but maintained by the homeowner (Cape Cod Commision, 2013). Generally, the lack of centralized management has resulted in improperly maintained systems (Crites and Tchobanoglous, 1998; World Health Organization Regional Office for Europe, 2011). It seems reasonable to assume that decentralized management has decreased resourcefulness when compared to a centralized response in BAU, given that BAU had emergency plans and dedicated staff; however, it is likely that some form of organized emergency management may arise from the outside during challenges, which would aid in the response and maintenance of decentralized services.

There are various management options for the GR, RR, and BE components. The GR and RR components may be primarily the responsibility of the owner once permitted by the regulatory authority. Like septic systems, the lack of centralized management may result in improperly maintained systems (Crites and Tchobanoglous, 1998; World Health Organization Regional Office for Europe, 2011) and therefore may have a decrease in resourcefulness compared to centralized management. However, these systems are also redundant with the possible use of DW for non-potable water purposes.

The BE system included both decentralized and centralized components, with a collection system and centralized treatment, but also grinder pumps located on the premises. For these systems, it is preferable to have a management agency that is responsible for inventory, design, installation, inspection, water quality monitoring, and reporting (Crites and Tchobanoglous, 1998). It may be possible to operate the blackwater recovery system as a business, in which case resourcefulness may be different from that of the traditional, centralized management. Overall, resourcefulness for the BE-GR/R options depends on the type of management selected by the community.

4.1.5. Qualitative resilience summary

Overall, the BE-GR/R systems were potentially the most robust option (when considering additional adaptive measures) with continued WW/RR operation during times of drought, continued operation during power outage with the addition of
backup generation, and continued WW/RR operation, given increased temperatures. This option also had the potential benefits of less environmental contamination during storm events and less water demand during times of drought. The BAU and CT/UD-SS options were robust during power outage (Challenge 3) and under increased temperature (Challenge 6). The BAU had the advantage of increased resourcefulness. This advantage may also apply to other options such as BE-GR/R depending on the selected management structure. Based on this qualitative summary, there was no clear preferred resilience option in the case study.

A limitation of the qualitative analysis was the inability to evaluate differences in loss of critical function and rapidity over the set of events in Table 1. This inability was particularly true concerning differences in resourcefulness and the loss of critical function resulting from damage to critical centralized system components verses on-site systems where pockets of functioning units may remain during an event.

4.2. Quantitative resilience assessment

4.2.1. Event scenario

We used a resilience model to quantitatively compare the resilience of the community water and wastewater service options for selected events over the system service life, based on information collected for the qualitative analysis. The aim was to assess the possible differences in resilience, given differences in the magnitude of service loss and rapidity among options. A scenario was constructed to capture the events with the most severe, widespread loss of function and frequent occurrence based on the frequencies of events from the Multi-Hazard Mitigation (MHM) Plan for Cape Cod (Cape Cod Commission, 2010). Multiple storm (Challenge 1), wildfire (Challenge 2), and drought (Challenge 5) events were modeled over a hypothetical 100-year service life.

For resiliency modeling, it was assumed that the community will be repeatedly challenged by both the storm and wildfire events. For each event, the BAU and BE-GR/R options were parameterized to assume that central treatment facilities will be damaged and eliminate service for the total population. The WW/RR components of the CT/UD-SS options, on the other hand, will have some residual performance across the community, but a longer time of recovery to get back to the target service as a result of the individual repairs required for damaged on-site systems. The repair of the on-site components of the BE system was also assumed to have a longer recovery time compared to the centralized system. The GR and RR elements were not considered since these systems have a built-in redundancy with DW.

For wildfire and storm, the quality modeled (see Fig. 1) was the critical function of “protection of infrastructure” and measured as the fraction of total wastewater volume that is treated. Because the DW elements were identical for storm and wildfire events, they were excluded. The characteristics of the repeated events were modeled as identical for each option. Options CT/UD-SS were combined and BE-GR/R based on shared vulnerabilities and adaptive measures. The best estimate inputs for Eqs. (1)–(3) are presented in Table 2 for the selected events along with the high and low limits used in the sensitivity analysis. The best estimate time to incident ($T_i$) was based on the frequencies of events from the Multi-Hazard Mitigation (MHM) Plan for Cape Cod (Cape Cod Commission, 2010). Given the uncertainty in frequency of extreme events resulting from climate change, the number of storm and wildfire events per 100 years was varied over the range of 20–100 (i.e., a time to incident of 7200 or 360 days). For all events, all systems were assumed to fail suddenly (failure type $f_1$), assuming the events cover a large area in a short time.

The duration of the failure event ($\Delta T_f$) for all systems for the storm event was based on the times of recovery for WW and DW treatment plants following Hurricane Sandy (Kenward et al., 2013; New York State Department of Health, 2012; Reed et al., 2013). The duration of failure of service resulting from a wildfire is uncertain and was based on an assumption of a storm event causing major damage. The duration of the recovery ($\Delta T_r$) was assumed to be zero with profile r0 for BAU during the storm and wildfire events when a major repair of the WWTP restores service. In reality, this assumption may be a simplification when potential conveyance or on-site damage results in the restoration of service incrementally. For BE and SS components under the direction of the homeowner, the duration for restoration was assumed to be longer by 60 days but with some residual performance; this assumption was highly speculative and was further explored by sensitivity analysis with the duration varied over the range of 0–182 days.

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Storm or wildfire</th>
<th>Short-term drought</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of incident, $T_i$ (days)</td>
<td>3600 (360, 7200)</td>
<td>36000 (0, 9000) *</td>
</tr>
<tr>
<td>Duration of the failure, $\Delta T_f$ (days)</td>
<td>30 (0, 182)</td>
<td>90 (0, 182)</td>
</tr>
<tr>
<td>The duration of the recovery, $\Delta T_r$ (days)</td>
<td>0 BAU * 60 others (0, 182)</td>
<td>0</td>
</tr>
<tr>
<td>Residual performance, $Q_r$</td>
<td>0.10 CT/UD–SS 0 others</td>
<td>0.25 BAU 0.75 others</td>
</tr>
</tbody>
</table>

* Best estimate followed by low and high values for sensitivity analysis in parenthesis.

BAU: conventional drinking water treatment system coupled with conventional wastewater treatment services; CT-SS: conventional drinking water treatment coupled with composting toilets and on-site graywater treatment by septic tank; and UD-SS: conventional drinking water treatment coupled with urine-diverting toilets and on-site fecal solids treatment by septic tank.
For the drought event (Challenge 5), there were potential differences among options in the protection of the supply of water identified in the qualitative analysis. Although this requires additional modeling to validate, the resilience model was used to explore the potential impact on resilience of water shortage. For this challenge, the function modeled was the critical function of “protection of the supply of water” and computed as the fraction of required water that is supplied to customers. In all cases, we assumed that community water use will be restricted at time $t_i$ and that the restriction is lifted at time $t_f$ for all systems when the drought duration is completed (presumably due to precipitation). For the DW residual performance during drought, we assumed that the amount available for use is controlled by the DW authority based on the availability of water. We assumed increased residual performance for SS and BE systems based on the advantage of water-saving technologies. Finally, the frequency of drought was varied from 0 to 25 events (i.e., a time to incident of 0 or 9000 days), with the upper limit based on the predicted climate changes (Executive Office of Energy and Environmental Affair, 2011).

4.2.2. Quantitative results

The quantitative resilience analysis results (Fig. 2a–e) display the possible differences in resilience among system options and the impact of uncertain characteristics (or parameters) on resilience. The possible resilience of the wastewater and
resource recovery components of the options, given storm and wildfire challenges, is presented in Fig. 2a–d for the 100-year time period. Overall, the resilience of the alternative options with regard to wastewater or resource recovery service was similar over a range of input parameters, assuming the best estimate frequency of 10 events per 100 years for each storm and wildfire (Fig. 2a–c). When the frequency of events increased, the differences in resilience among options increased, with the BAU outperforming the alternative options in terms of wastewater and resource recovery service (Fig. 2d), but the opposite was true when considering drinking water service. The possible resilience of drinking water service, given drought, is presented in Fig. 2e for the 100-year time period. The resilience of the alternative options with regard to drinking water service was similar, especially when the low-event frequency from the MHH Plan for Cape Cod was assumed. As the frequency of drought events increased, the difference in resilience between options increased, with the alternative options outperforming the BAU in terms of water service, assuming an increased residual performance from water-saving technology for the alternative options.

5. Discussion

For a linked natural and infrastructure system, the capacity of the system to adapt to changes and withstand and recover rapidly is complex and includes environmental, societal, economic, governance, and infrastructure aspects. Although it is a daunting task to assess resilience at this large scale, it is essential at least to consider the characteristics of resilience (i.e., system robustness, redundancy, adaptive capacity, rapidity, and resourcefulness) for future infrastructure investments. Here, we proposed and conducted a comparative technical resilience assessment of community water and wastewater service options to determine differences in resilience due to option selection. This process helped to identify systems with key disadvantages or advantages. Following the qualitative analysis, a limited quantitative analysis was performed to evaluate the impact on resilience of differences in the robustness and resourcefulness among options.

The qualitative and quantitative analyses are most useful when considered together, given the limited scope of the quantitative analysis and the inability of the qualitative analysis to accurately consider the magnitude of impacts on critical functions. The evidence in the qualitative analysis indicated that the alternative community water system options may be more robust overall; however, the alternative systems were potentially less resourceful, depending on the management structure. The quantitative analysis illustrated that overall resilience was a combination of the robustness, rapidity, and resourcefulness (we did not model any additional adaptive measures, but they may also be an important factor to the quantitative model of resilience). The quantitative model results indicated that there was little difference in predicted resilience among options considering only water and wastewater service under a low frequency of events, given the increased resourcefulness of centralized options and assumed increased residual function of alternative, on-site options. However, these results may differ, if the characteristics of these systems were such that the centralized systems actually had a much longer recovery time due to major damage to the distribution system.

When the modeled frequency of the events increased to account for possible climate changes, the differences in resilience were more prominent among options, and they favored the more resourceful wastewater and resource recovery options as well as the water-saving technologies. The frequency of future events under climate change was an important and uncertain factor in the comparative resilience analysis.

There are extensions from this work to further inform the comparative resilience of community water and wastewater service options. Although we compared the resilience of the water-saving options to the BAU during short-term drought, additional modeling is required to quantify the water availability due to climate changes in temperature, precipitation, and sea level (as well as land use) and water demand from alternative options. Likewise, additional modeling is required to compare the environmental impacts of drought on source water, and particularly the possibility of saltwater intrusion, under different community water systems.

For the events modeled, we did not consider the critical function of protection of human health or the environment. For example, water quality impacts from wildfires can take decades to recover and in some cases the source water has been abandoned altogether (Sham et al., 2013). These longer lasting impacts may more drastically reduce the resilience. Furthermore, there may be differences in impact on environmental services and human health among options resulting from certain events. For example, during a storm or flooding event, the pressure sewer may keep the sewage relatively contained if it is not physically damaged, whereas the other system options result in the backup of sewage into homes and possible overflow into surrounding waterbodies. These releases may result in human health burdens or nutrient export problems.

Also, if there are differences in environmental and human health damage, these costs should be quantified for a full understanding of the differences between system options, including costs associated with damage to the environment from contamination or the resulting human health burden. When comparing options, a relatively small difference in the resilience metric may be associated with a large difference in cost. In addition, future economic valuation should consider the additional costs of additional adaptive measures that may have a significant impact on the robustness of a system. In this analysis, backup electric generation for the BE, GR, and RR elements potentially increases the robustness of the alternative options as well as offers multiple benefits (i.e., also providing heat, lighting, cooking, etc., during a power outage).

Finally, much of the resilience assessment for future climate change assumes that the world will be similar to how it is today. However, the comparison may be different when accounting for a radically different environmental, economic, and technological future. Rapidity and resourcefulness may be improved with increased technology, or economic conditions may greatly change in the region, making the resourcefulness much lower or higher.
6. Conclusions

- The technological resilience analysis is useful in that it specifically considers event and changing future conditions, which may be outside the scope of other metrics in sustainability assessment.
- Decisions based on current estimates of event frequency, rather than future possible event frequency under climate change, may over-predict technological resilience.
- Overall, no one community water and wastewater service system option considered was most resilient, with each option having advantages and disadvantages.
- Key uncertainties for future research include the duration of failure and recovery following an event, the frequency of future events, and the possible impact of water-saving technology on the availability of source water under future climate changes.

Conflicts of interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.swaqe.2015.05.001.

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