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Cost, energy, global warming, eutrophication and local human health impacts of community water and sanitation service options

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ABSTRACT

We compared water and sanitation system options for a coastal community across selected sustainability metrics, including environmental impact (i.e., life cycle eutrophication potential, energy consumption, and global warming potential), equivalent annual cost, and local human health impact. We computed normalized metric scores, which we used to discuss the options' strengths and weaknesses, and conducted sensitivity analysis of the scores to changes in variable and uncertain input parameters. The alternative systems, which combined centralized drinking water with sanitation services based on the concepts of energy and nutrient recovery as well as on-site water reuse, had reduced environmental and local human health impacts and costs than the conventional, centralized option. Of the selected sustainability metrics, the greatest advantages of the alternative community water systems (compared to the conventional system) were in terms of local human health impact and eutrophication potential, despite large, outstanding uncertainties. Of the alternative options, the systems with on-site water reuse and energy recovery technologies had the least local human health impact; however, the cost of these options was highly variable and the energy consumption was comparable to on-site alternatives without water reuse or energy recovery, due to on-site reuse treatment. Future work should aim to reduce the uncertainty in the energy recovery process and explore the health risks associated with less costly, on-site water treatment options.

1. Introduction

Planning for a sustainable community water system requires a comprehensive understanding and assessment of the integrated source water, drinking water, and sanitation services over their life cycles. In previous work, we described the need for and use of integrated sustainability assessment to evaluate community water systems within a stakeholder-driven framework (e.g., integrated municipal water management (Thomas and Durham, 2003)). In addition, we selected a set of technical metrics and tools which we consider critical to evaluate built water services, but also of reasonable effort to calculate (Xue et al., 2015). Then, we evaluated a selection of water service options for the coastal community of Falmouth, MA, using the proposed technical metrics, including environmental impacts (Xue et al., 2016), local human health impacts (Schoen et al., 2014), cost (Wood et al., 2015), and technical resilience (Schoen et al., 2015). In this companion paper, we summarize the strengths and weakness of the selected community water systems across the previously calculated, technical sustainability metrics using newly calculated normalized scores and discuss insights that can only come from looking at these metrics together.

Throughout, we refer to metrics, defined as a measurable value

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of an attribute (e.g., equivalent annual cost), as well as the various input parameters (e.g., discount rate), which were used to calculate the metrics. An input parameter, metric, or score is referred to as variable if the variation in value cannot be reduced with collection of additional information; whereas uncertainty can be better estimated with collection of more or better data (Vose, 2000).

The metrics previously described include: local human health impact from pathogen and chemical exposures resulting from community-wide water system use; equivalent annual cost (EAC), which quantifies the monetary costs and benefits of each system; life cycle energy consumption; life cycle global warming potential (GWP) from on-site and supply chain greenhouse gas emissions including CO_2, CH_4, and N_2O; life cycle eutrophication potential, which is based on on-site and supply chain releases of aqueous and atmospheric nitrogen and phosphorus; and technical resilience, which qualitatively evaluates the water system's capacity to deal with potential future event and climatic challenges. Based on stakeholder input, only a selection of the available life cycle analysis impact categories was included in the evaluation of environmental impacts. Resilience was not included in the following comparative analysis because we were unable to differentiate the selected water system options (Schoen et al., 2015).

This assessment is the first we are aware of to evaluate both water (i.e., potable and non-potable) and sanitation services (i.e., septic/sewage and greywater) across cost, environmental, and local human health impacts. Portions of community water systems (i.e., either water or sanitation) have been assessed by others using integrated or sustainability assessments for water supply (Lai et al., 2007; Rygaard et al., 2014), energy and water recovery options (Lee et al., 2013), and firefighting flows (Aydin et al., 2014). These studies rarely include metrics that span health, environment, economic, and technological aspects (Malmquist, 2006), especially the local human health impact (Lai et al., 2007; Rygaard et al., 2014) and resilience metrics (Rygaard et al., 2014). A further common deficiency is the lack of systematic consideration of variability and uncertainty across metrics when comparing system options (although, the variability in a subset of quantitative metrics was discussed by Fagan et al. (2010) and Rygaard et al. (2014)).

The options considered here, described in the following section, include novel treatment and energy recovery elements not yet widely implemented or evaluated across the cost, local human health, and environmental metrics. As such, there remains considerable uncertainty associated with the input parameters used to calculate the metrics. The objectives of this work are to identify system options with clear advantages across the sustainability metrics while accounting for natural variability and/or uncertainty; and identify results that may change with collection of additional data to guide future information collection efforts for these novel technologies. While this paper focuses on the technical sustainability assessment results, and not the entire decision-making process, our discussion emphasizes how the results could be used in a stakeholder-preferred decision approach (e.g., Multi-Criterion Decision Analysis [MCDA](Belton and Stewart, 2002)).

2. Approach

2.1. Case study

The case study town of Falmouth, MA, faces expanding urbanization (with a population of 31,500 in 2011) and seasonal tourism, yet the predominating septic systems have resulted in excessive nutrient exports and coastal eutrophication (Cape Cod Commission, 2015). We evaluated five community water and wastewater service options to replace the current traditional septic systems.

The business-as-usual (BAU) system consisted of a conventional, centralized drinking water system and a centralized wastewater treatment system, referred to here as the conventional system (see Supporting Information Fig. S1 for diagrams of the BAU treatment technology). The Falmouth community consumes about 4.6 million gallons per day (MGD) of water, approximately 60% of which is extracted from surface sources (Falmouth Department of Water, 2013). Considering the byproducts from wastewater treatment, the effluent entered the groundwater through filtration basins and the sludge was transported (after dewatering) out of the watershed to a management facility. There was no additional treatment of the byproducts or subsequent reuse. The following “alternative” options maintained the centralized drinking water system, but replaced the centralized wastewater treatment system. Two alternatives using septic systems were proposed by the stakeholders and two additional options were selected based on the concepts of energy recovery and water reuse.

The first alternative included dry composting toilets and on-site greywater treatment by the existing septic system (an absorption trench system) (CT-SS), where “greywater” refers to non-toilet wastewater from sinks, showers, washing machines, etc., within households (refer to Supporting Information Fig. S2 for CT-SS technology diagrams). In the second alternative, the centralized wastewater treatment was replaced with urine-diverting toilets and on-site fecal solids (and greywater) treatment by the existing septic system (UD-SS) (refer to Supporting Information Fig. S3 for UD-SS technology diagrams). For these septic-based options, the generated compost or urine was collected and transported out of the watershed to a less nutrient-sensitive area for use as soil amendments. No additional treatment of the generated byproducts was considered. All potable and non-potable household water uses were assumed to be supplied by the existing centralized drinking water system.

In the third alternative, a low-volume flush toilet and blackwater pressure sewer were modeled to provide the community with energy recovery via a combined heat and power (CHP) anaerobic digester system with community food residuals co-digestion. Blackwater was assumed to be supplied only via the toilets and kitchen food-waste grinders, hence containing more concentrated organic material and nutrients than traditional sewage, which is roughly 70% greywater. The dewatered digestate was assumed to be applied to local agricultural fields in the environmental assessments, but shipped out of the watershed in the EAC assessment (discussed in Sections 2.2.2 and 2.2.3). The on-site greywater was assumed to be collected; treated using biological sand filtration followed by ultraviolet disinfection; and reused for toilet flushing, outside irrigation, and watering homegrown salad crops, hence providing blackwater energy with greywater reuse (BE-GR). The final alternative was identical to BE-GR with the addition of on-site rainwater collection, treatment by in-line filtration and ultraviolet disinfection, and use as a hot-water supply for showering (BE-GRR) (refer to Supporting Information Fig. S4 for BE-GR/R technology diagrams). The Cape Cod region has an annual precipitation average of 123 inches (based on the last 50 years) (NOAA, 2013). Falmouth has an existing separate stormwater system; therefore, stormwater was not addressed in this comparative analysis.

2.2. Metrics

2.2.1. Local human health impact

The local human health impact from the operation and community–wide use of each option was estimated using quantitative risk assessment including both operating and possible failing conditions (Schoen et al., 2014). The resulting key pathogen and chemical risks were translated into DALYs (Disability-Adjusted Life