Water Research 121 (2017) 186–196

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

An evaluation of the sustainability of onsite wastewater treatment systems for nutrient management

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A R T I C L E I N F O

Article history:
Received 2 March 2017
Received in revised form
3 May 2017
Accepted 4 May 2017
Available online 5 May 2017

Keywords:
Decentralized wastewater treatment
Nutrient management
Life cycle assessment
Life cycle cost analysis

A B S T R A C T

The impairment of water bodies from nutrient pollution is a challenging environmental problem that could lead to high eutrophic conditions, fish kills, and human illness, while negatively impacting industries that rely on thriving water bodies. Onsite wastewater treatment systems (OWTSs) are a major source of nutrients, however no prior studies have conducted a holistic sustainability assessment of OWTSs that considers their ability to manage nutrients at the household-level in the United States. The aim of this study is therefore to evaluate the environmental and economic impacts of conventional and advanced OWTSs with respect to their ability to remove total nitrogen (TN). Septic tank and drainfield materials were varied for conventional systems, and the advanced systems evaluated consisted of aerobic treatment units (ATUs) and passive nitrogen reduction systems (PNRSs) with nitrification and denitrification stages. Life cycle assessment and life cycle cost analysis were performed to evaluate OWTSs operating in different soil and temperature conditions. Nutrient management of the advanced OWTSs outperformed the conventional systems (96.7–100% vs. 61–65% TN removal), and resulted in less than 40% of the freshwater (0.06–0.14 vs. 0.37–0.40 kg P-eq/kg TN) and marine eutrophication (0.04–0.06 vs. 0.54–0.65 kg N-eq/kg TN). However, the tradeoff for nutrient management was higher life cycle costs ($101-$121 vs. $45-$58 USD 2015/kg TN) and environmental impacts for the remaining impact categories. Lastly, when the TN removed by the drainfield was <20%, the advanced system had lower impacts than conventional OWTSs across all impact categories except ecotoxicity.

1. Introduction

The impairment of water bodies due to nitrogen (N) and phosphorus (P) pollution is a critical concern in the United States (US), and one of the most challenging environmental problems to overcome (NAE, 2016; US EPA, 2011). The number of nitrate violations in public drinking water systems nearly doubled between 1998 and 2008 (State-EPA NITG, 2009). High nitrate concentrations in drinking water have been linked to an increased risk of blue baby syndrome, a disease also known as methemoglobinemia, which can be fatal to bottle-fed infants (Knobeloch et al., 2000; World Health Organization, 2016). Moreover, an alarming 78% of the estuarine surface area evaluated by Bricker et al. along the US coastline exhibited moderate to high eutrophic conditions (Bricker et al., 2008), which can lead to fish kills, human illness, and the death of mammals and shore birds (Smith et al., 1999; WRI, n.d.). Bricker et al. predicted that 65% of the estuaries assessed would have worsened conditions by 2020, in part due to population increases along the coastline.

In many coastal ecosystems, the primary nutrient responsible for eutrophication is nitrogen (Howarth and Marino, 2006) and septic systems are a major source of nutrient pollution. For example, 425 water bodies were impaired by nutrients in Florida alone (Badruzzaman et al., 2012), and septic systems are the second highest source of nitrogen in Florida with estimated emissions ranging from 2.4×10^{10} to 4.9×10^{10} g-N/year (Badruzzaman et al., 2012). Approximately 30% of Florida's population rely on a septic tank or some form of onsite wastewater treatment system (OWTS) (FL DOH, n.d.), which is almost two times the percentage of US households using a septic tank, cesspool, or chemical toilet for wastewater disposal (18.6%) (US Census Bureau, 2015).

Considering that the treatment of wastewater for the safe release of effluent (e.g., for the protection of human health and the environment) is the primary role of an OWTS, many research studies have evaluated the performance of these systems with respect to their ability to remove potentially harmful constituents.

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http://dx.doi.org/10.1016/j.watres.2017.05.005
0043-1354/

Nomenclature

i	discount rate (−)
m_{TN}	mass of TN removed per year (kg/year)
L	functional life (years)
PV	present value (USD)
ATU	Aerobic Treatment Unit
BNR	Biological Nitrogen Reduction
CBOD5	5-Day Carbonaceous Biochemical Oxygen Demand
DF	Drainfield
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
N	Nitrogen
OWTS	Onsite Wastewater Treatment System
PNRS	Passive Nitrogen Reduction System
P	Phosphorus
PE	Polyethylene
PVC	Polyvinylchloride
SF	Sensitivity Factor
STA	Septic Tank Assembly
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UAC	Uniform Annual Cost
US	United States

A conventional OWTS is typically comprised of a septic tank and drainfield. The septic tank can reduce the 5-day carbonaceous biochemical oxygen demand (CBOD5) and total suspended solids (TSS) by 49% and 74%, respectively (Lowe et al., 2009). In a review by the US Environmental Protection Agency, drainfields were found to be capable of removing 90–98% biochemical oxygen demand, 10–40% total nitrogen (TN), 8–12% total phosphorus (TP), and 99–99.99% fecal coliforms (US EPA, 2002). Additionally, several research studies have investigated the removal of viruses, personal care products, pharmaceuticals, and other trace organic constituents in onsite and small-scale wastewater treatment systems (Lowe et al., 2009; Matamoros et al., 2009; Teerlink et al., 2012; Van Cuyk and Siegrist, 2007).

Since septic tanks remove only small amounts of nitrogen, if any at all (Lowe et al., 2009), other unit processes in OWTSs have been designed and investigated to improve nitrogen removal and reduce nutrient pollution from these systems (FL DOH, 2015; WA DOH, 2005). The processes mainly rely on biological nitrification and denitrification since they are "economically and technically feasible" for onsite systems (WA DOH, 2005). For example, Siegrist et al. studied the impact of supplementing a septic tank with a membrane bioreactor or a textile biofilter and found that the average nitrogen removal was 61% and 30%, respectively (Siegrist et al., 2013). An aerobic treatment unit (ATU) alone can achieve 50% or more TN reduction via biological nutrient removal (Hoot Systems, 2015). Moreover, projects for the Florida Department of Health have designed and tested onsite systems implementing two-stage nitrification and denitrification systems that can achieve more than 90% nitrogen removal (Hazen and Sawyer and AET, 2015a; Smith et al., 2008).

In addition to assessing a technology's ability to manage nutrients, evaluating the sustainability of an OWTS allows researchers to understand the tradeoffs between indicators across the environmental, economic, and social dimensions, and inform policy makers, OWTS designers and manufacturers, and homeowners about the potential impact of their onsite systems. Life cycle assessment (LCA) is a commonly used tool for assessing the environmental and human health impacts of a technology or system. Thus far, the focus of LCAs of wastewater treatment systems has not been on onsite systems at the household-level, but rather on small- to large-scale wastewater treatment plants (Corominas et al., 2013). Furthermore, most of the studies that evaluate the sustainability of OWTSs have a geographical scope outside of the United States (Brown et al., 2010; Hellström and Jonsson, 2006; Lehtoranta et al., 2014; Weiss et al., 2008), focus solely on economic indicators (Hazen and Sawyer and AET, 2015b; Smith et al., 2008; Williams et al., 2004) or environmental indicators (Cornejo et al., 2016; Weiss et al., 2008), or consider only one or two phases of the life cycle of the system (Kautz, 2015). To the knowledge of the authors, no holistic sustainability evaluation of onsite wastewater treatment systems has been conducted with reference to the system's ability to manage nutrients.

The aim of this article is therefore to provide an evaluation of the life cycle environmental and economic impacts of OWTSs to understand the tradeoffs of effectively managing nutrients. Moreover, the influence of the materials used in the construction of OWTSs, the effectiveness of reducing nutrient emissions, and the location of the installation site will be evaluated across environmental and economic indicators in order to provide insight about the sustainability of OWTSs.

2. Methods

2.1. Goal and scope

The goal of this study is to evaluate the sustainability and nutrient management capabilities of OWTSs. A three bedroom household occupied by three people with a wastewater loading rate of 0.57 m^3 per day (50 gpd per person (Bounds, 1997)) was assumed across all systems analyzed. A functional unit of 1 kg of TN removed was used since nitrogen is the primary nutrient of interest in this sustainability evaluation.

The life cycle phases from material extraction to the maintenance phase were considered in this study; the end-of-life phase was assumed to be negligible considering the high material requirements of the construction phase, a long operational life, and the option to keep the systems installed at the end of their functional life. The analysis of OWTSs was conducted for hypothetical installations in Tampa, FL. Tampa is located in Hillsborough County and soils consist primarily of fine sands (USDA, n.d.) in areas with high concentrations of OWTSs (see Fig. 1). The Tampa Bay spans nearly 400 square miles, making it Florida's largest open-water estuary (TBEP, n.d.).

2.2. Scenario design

Eight hypothetical scenarios were evaluated in this assessment (see Fig. 2) to consider the impact of material selection and nutrient management capabilities. Scenarios 1 to 4 were "conventional OWTSs" that consisted of ~3785 L (~1000 gal) septic tanks and a drainfield. The septic tank materials were varied across the scenarios; they were constructed of concrete (Scenarios 1 and 2), high-density polyethylene (Scenario 3), and fiberglass-reinforced plastic (Scenario 4). Scenario 1 had a conventional drainfield consisting of aggregate materials and polyvinylchloride pipes for distribution, while Scenarios 2 to 8 incorporated the Multi-Pipe System (MPS), a