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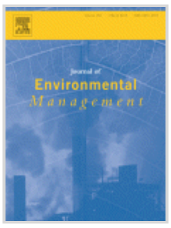

Cost-effectiveness of nitrogen mitigation by alternative household wastewater management technologies

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Highlights

- A household nitrogen mass balance is estimated for various wastewater systems.
- A model of cost-effectiveness of nitrogen removal is applied to Falmouth, MA.
- Flushing and dry urine-diversion toilets show low cost and high cost-effectiveness.
- A conventional central system is the most expensive, least cost-effective option.
- Using a greywater recycling system increases cost with minimal nitrogen benefits.

Abstract

Household wastewater, especially from conventional septic systems, is a major contributor to nitrogen pollution. Alternative household wastewater management technologies provide similar sewerage management services but their life cycle costs and nitrogen flow implications remain uncertain. This paper addresses two key questions: (1) what are the total costs, nitrogen mitigation potential, and cost-effectiveness of a range of conventional and alternative municipal wastewater treatment technologies, and (2) what uncertainties influence these outcomes and how can we improve our understanding of these technologies? We estimate a household nitrogen mass balance for various household wastewater treatment systems and combine this mass balance with life cycle cost assessment to calculate the cost-effectiveness of nitrogen mitigation, which we define as nitrogen removed from the local watershed. We apply our methods to Falmouth, MA, where failing septic systems have caused heightened eutrophication in local receiving water bodies. We find that flushing and dry (composting) urine-diversion toilets paired with conventional septic systems for greywater management demonstrate the lowest life cycle cost and highest cost-effectiveness (dollars per kilogram of nitrogen removed from the watershed). Composting toilets are also attractive options in some cases, particularly best-case nitrogen mitigation. Innovative/advanced septic systems designed for high-level nitrogen removal are cost-competitive options for newly constructed homes, except at their most expensive. A centralized wastewater treatment plant is the most expensive and least cost-effective option in all cases. Using a greywater recycling system with any treatment technology increases the cost without adding any nitrogen removal benefits. Sensitivity analysis shows that these results are robust considering a range of cases and uncertainties.

Keywords

Household wastewater; Nitrogen; Compost toilet; Diversion toilet; Advanced septic; Blackwater digestion; Cost-effectiveness

1. Introduction

Nutrients such as nitrogen tend to lead to eutrophication issues when they are released into waterbodies as constituents of wastewater streams (U.S. EPA, 2013). Their beneficial action in agricultural applications is exactly what makes large quantities of them undesirable in natural waters, where they cause cyanobacterial and algal blooms: in addition to causing problems of reduced water clarity, taste, odor, and cyanotoxins in drinking water, these blooms lead to losses of dissolved oxygen overnight and during their biodegradation, all of which can significantly diminish water quality and ecosystem services. Eutrophication is the primary reason that nitrogen must not be released into waterways in large quantities.

One example of excessive nitrogen pollution is in Falmouth, Massachusetts, a town of approximately 30,000 people on Cape Cod (U.S. Department of Commerce n.d.). Approximately 94–96% of the homes in Falmouth use septic systems to manage their household wastewater (Potamis, 2014 and Town of Falmouth, 2013b). These septic systems, along with other sources, allow nitrogen to reach the nearby coastal waters in quantities exceeding federal limits for water quality. The problem is exacerbated by the sandy soils and high water table of Cape Cod, a situation that allows nitrogen-containing groundwater to flow easily into surface waters. Falmouth is seeking to reduce the amount of nitrogen released into sensitive coastal waters and thus to mitigate the eutrophication problem, which has impacted aquatic life and fisheries and may well negatively impact tourism, a major local industry. To reach nutrient targets, set as total maximum daily loads (TMDLs), controllable nitrogen loads must be reduced by as much as 83% in some sub-basins; “septic system sources of nitrogen are the largest controllable sources” in Falmouth, so improving household wastewater management is crucial (Commonwealth of Massachusetts Executive Office of Energy and Environmental Affairs et al., 2007).

Literature detailing the flow of nitrogen through households and municipal wastewater systems is scant, even though as much as 63% of nitrogen entering sensitive coastal systems in the northeastern U.S. comes from sewage wastewater (Howarth, 2008). Existing literature primarily focuses on the sources and paths of nitrogen flowing through the environment outside of the household sphere (Gottschall et al., 2009, Hong et al., 2013, Liptzin and Dahlgren, 2014, Pelletier and Leip, 2014 and Xue and Landis, 2010), and on the consequences of nitrogen pollution in waterbodies (Dodds et al., 2009, Hernández-Sancho et al., 2010, Pretty et al., 2003 and Van Grinsven et al., 2013). Some literature is dedicated to the flow of nitrogen through conventional municipal wastewater treatment at the system scale (Charles et al., 2003, Kampschreur et al., 2009 and Short et al., 2014). Baker et al. (2007) detail nitrogen flows at the household level including various nitrogen-containing streams other than wastewater, such as lawn fertilizers and vehicle emissions, but the study does not further disaggregate sewage streams for the consideration of alternative wastewater treatment technologies.

Alternative treatment technologies may play important roles in mitigating nitrogen pollution. In addition to centralized solutions such as large wastewater treatment plants (WWTPs), there are *satellite* or *cluster* solutions that typically treat neighborhoods rather than whole towns, and *decentralized* solutions such as septic systems that are installed on each property where waste is produced. Conventional centralized treatment with gravity sewers (referred to collectively as “centralized treatment”) is often assumed to be the best or only viable alternative to problematic septic systems, but centralized systems are expensive. In Falmouth, for example, estimated centralized system costs led the town to consider alternative treatment options (Cape Cod Commission, 2013).

Literature on cluster and decentralized wastewater treatment systems primarily focuses on aspects other than the flow of nitrogen. For example, energy implications (Remy and Jekel, 2011 and Xue et al., 2014) and nutrient recovery potential (Meinzinger, 2010 and Vinnerås, 2002) are explored. Hill and Baldwin (2012) consider the advantages of vermicomposting over other methods for composting toilet waste. Studies on the costs of alternative treatment systems (Kinstedt, 2012 and Wang, 2014) complement the body of literature on the costs of centralized wastewater treatment (Hardisty et al., 2013, Rehan et al., 2011, Rehan et al., 2013, Rehan et al., 2014a and Rehan et al., 2014b; Termes-Rifé et al., 2013).

Decision makers seeking to implement nitrogen mitigation strategies need information on the nitrogen mitigation potential of a range of technological options along with the costs and other implications of these technologies, many of which have not been deployed in the U.S. beyond isolated test cases or remote locations lacking infrastructure. Studies on the watersheds of Narragansett Bay, RI (Industrial Economics, 2012 and U.S. Environmental Protection Agency. (n.d.),) and Chesapeake Bay, MD (Chesapeake Bay Commission, 2004, Chesapeake Bay Program, 1997 and Nutrient Reduction Technology Cost Task Force, 2002) have combined cost and nitrogen data on large scales, focusing on agricultural fertilizers and wastes and conventional wastewater treatment options. A Barnstable County (MA) Wastewater Cost Task Force (2010) has similarly examined the costs and nitrogen mitigation potential of a few treatment systems at the scale of the county. Meinzinger (2010) considers a wider range of treatment technologies, including alternative management of rainwater and organic solid wastes, along with the cycling of nutrients from an urban area to fertilize enough agricultural land to supply that urban population with food.

In the current study, we examine both household nitrogen flows and the total system costs of a variety of municipal wastewater treatment technologies to further inform decision makers considering unconventional wastewater treatment technologies. We focus on the cost-effectiveness of nitrogen removal and life cycle costs as part of a larger project that also examines the emergy, global warming, and pathogen implications and system resilience (Schoen et al., 2014 and Xue et al., 2014). We use the household scale as “a socially meaningful and practical unit of measurement” (Baker et al., 2007) and include technologies that are not common in the U.S., along with options that are currently widespread or gaining popularity. We apply our cost and nitrogen models to Falmouth, MA as a case study of a coastal U.S. town facing a nitrogen pollution problem. We address two key questions:

1. What are the total costs, nitrogen mitigation potential, and cost-effectiveness of a range of conventional and alternative municipal wastewater treatment technologies?
2. What uncertainties influence these outcomes and how can we improve our understanding of these technologies?

2. Methods

2.1. Technology selection and nitrogen management

Table 1 shows the technologies included in the analysis. With the exception of centralized collection and treatment (WWTP) and advanced septic systems (innovative/advanced, or I/A, septic), the technologies listed in Table 1 do not treat all household wastewater streams: urine, feces, and greywater (effluent from sinks, showers, clothes washers). To manage all of these streams, discrete technologies were assembled into the combinations indicated in Table 1. As summarized in the table, greywater can be managed using either a conventional septic system or an on-site treatment system that allows for reuse as nonpotable water, which we call a greywater recycling system.

Table 1.

Technology Packages to Manage Urine, Feces, and Household Greywater.

Full-size table

Any nitrogen remaining within the watershed after treatment may eventually contribute to the pollution problem through stormwater runoff or atmospheric deposition. We thus consider a kilogram of nitrogen “mitigated” when it is physically removed from the watershed. This can occur through active transportation of wastes or biochemical conversion to inert N_2 gas, a harmless component of Earth's atmosphere. The paths by which nitrogen may remain in the watershed after treatment include atmospheric deposition of reactive volatiles and release of nitrogen-containing liquid effluents directly into the watershed. A small percentage, around 3–8%, of nitrogen in household wastewater resides in the greywater stream (Leal et al., 2011 and Meinzinger, 2010); because this is a small contribution and because our focus is on managing household sewage, the nitrogen content of greywater and the nitrogen mitigation potential of greywater management technologies are outside the scope of this paper.

Most nitrogen flow values are reported as milligrams per liter (mg/L): these concentrations refer to conventional wastewater diluted by flush water from a standard toilet. However, the amount of nitrogen excreted by humans is typically reported as a mass per time and for some of the technologies considered here the dilution volume will vary while for others, namely composting toilets, it is nonsensical to discuss an aqueous concentration of nitrogen. We therefore converted flows of nitrogen given in mg/L to flows in kilograms per person per year (kg c^{-1} y^{-1}), using as the dilution volume the amount of water used by a household with standard flush toilets (U.S. EPA, 2014).

For this analysis, we draw from disparate studies that partially characterize household flows to estimate a complete mass balance of nitrogen for our alternative technologies. Meinzinger (2010) and Baker et al. (2007) estimate the total quantity of nitrogen in human waste and its partitioning between urine and feces that we take as our base case. The nitrogen flows in WWTP effluent were taken from Gerardi (2002). Data on volatilization of N_2O in sewer systems came from Short et al. (2014).

All nitrogen flow data for I/A septic systems came from the Barnstable County Department of Health and the Environment, which has collected performance data on over 1500 systems installed on properties around Cape Cod; they publish median, minimum, maximum, and upper and lower quartiles of the nitrogen concentration in liquid effluent of each installation. We used the median values from all installations of the four I/A brands that are currently most popular on Cape Cod and that meet septic performance standards: Orenco's AdvanTex systems, Aquapoint's Bioclere unit, Norweco's Singulair systems, and FAST systems by Biomicrobics. For our base case, we averaged the values from all installations of these four systems. The range explored in the sensitivity analysis is plus and minus 50% of the base case value, which is approximately the standard deviation of the published summary statistics (Barnstable County Department of Health and Environment, (2014)).

In the absence of empirical values for discrete nitrogen flows, we used mass balance calculations to find the quantities of nitrogen in compost and urine collected from eco-toilets and the quantity of N_2 that volatilizes during treatment at a WWTP. Our assumptions about volatilization of nitrogen include (1) no nitrogen compounds other than ammonia will volatilize from collected compost or urine during storage, transport, or treatment; (2) ammonia volatilization from stored urine is independent of the time of storage and so can be conceptualized as occurring entirely during the storage phase (not the transport phase); (3) the volatilization of ammonia from stored compost from composting toilets is the same as from stored urine; (4) 100% of volatilized reactive nitrogen compounds will be re-deposited within the watershed (base case); and (5) there is no volatilization of any nitrogen compounds in pressure or vacuum sewers, because these are designed to have no headspace (completely full pipes) and thus there is no opportunity for volatilization. Negligible to no N_2 volatilizes during composting and urine diversion, due to lack of anaerobic conditions needed for denitrification, nor from blackwater digestion (Baek and Pagilla, 2006, Gallagher and Sharvelle, 2010 and Lin et al., 2013), thus nitrogen is mitigated in these systems by physical removal from the watershed, which we assume is achieved by truck transportation.

Both WWTP and I/A septic system technologies mitigate nitrogen primarily by converting it, through biochemical processes, to N_2. However, both treatments also produce nitrogen-containing residuals: solids in a treatment plant or sludge that is pumped from septic tanks, including those paired with flush diversion toilets. We assume that solids and septage are incinerated, landfilled, or potentially used for agriculture outside the watershed. This assumption is based on current practice in Falmouth, in which the existing treatment facility collects sewage from 4–6% of homes and also accepts septage: the septage is nominally dewatered before being combined with solids from wastewater treatment and sent to an incinerator out of state and outside the watershed (Potamis, 2014).

Finally, we assume no other leakage or loss of nitrogen from any wastes during storage, transport, or treatment. The validity of this assumption may be a fruitful avenue for future research, particularly considering potential losses during unusual circumstances such as power outages and floods, as well as leakage from aging conventional sewers (Guérineau et al., 2014). The possibilities for operators' errors leading to nitrogen leakage into the watershed may also be an important point to consider in the future.

We use sensitivity analysis to address the uncertainties in the underlying data and assumptions. We vary the per capita input of nitrogen to the wastewater system according to ranges found in literature (Kelsay et al., 1978, Liu et al., 2014 and Tarnopolsky et al., 1988). We vary the amounts of nitrogen remaining in the watershed after treatment due to atmospheric deposition of volatiles and release of liquid effluent into the watershed by plus and minus 50% of the base case values. The nitrogen mitigation potential of each system is calculated from these ranges, according to Equation (1), providing a range of mitigation values for each system.

$$\mathrm{N}input-(volatile\mathrm{N}+\mathrm{N}inliquid\mathrm{effluent})=\mathrm{N\ mitigatedbytechno}log\mathrm{y} \tag{1}$$

Turn MathJax on

where *N input* is the amount of nitrogen in human waste, *volatile N* is the amount of nitrogen in reactive volatiles that may redeposit within the watershed, and *N in liquid effluent* refers to liquid effluents released into the watershed. We calculate the low case mitigation value using the low case for input and the high cases for volatiles and liquid effluents; we calculate the high case mitigation value using the high case for input and the low cases for volatiles and liquid effluents. Thus *N mitigated by technology* is a measure of how much nitrogen the technology removes from the watershed, not a measure of how effectively it meets mitigation goals.

A summary of all assumed nitrogen flow base case values, ranges, and references can be found in the supplementary information.

2.2. Total cost and cost effectiveness analysis

For each technology option, capital and operating cost data were assimilated to estimate equivalent annual costs per typical household as shown in Equation (2) (Whitman and Terry, 2012).

(2)

EAC is equivalent annual cost; *capital* and *O&M* are capital and O&M costs, respectively, of each component of the technology package; *q* is the number of installations per household of the component; *i* is the discount rate or interest rate; and *L* is the service lifespan of the component. In all cases we assume that the technology has no salvage value and that costs do not increase over time. We do not explicitly consider the possible costs associated with significant failures of any of these systems.

We calculated cost-effectiveness (CE), or dollar per kilogram of nitrogen mitigated, according to Equation (3).

(3)

We calculated costs both on a per-household basis and scaled to Falmouth's wastewater service area, using sensitivity analysis to examine uncertainty in our assumptions. For our base-case model, we assume each existing household has two conventional toilets serviced by a conventional septic system. We assume all technology swaps occur in "year 0" or immediately. We consider discount rates of 3%, 5% (base case), and 7% (National Center for Environmental Economics, 2010). The sources and assumptions underlying all other cost estimates are given in Table 2.

Table 2.

References and assumptions for capital and O&M cost data.

Cost item	Capital cost references	O&M cost references	Notes and assumptions
WWTP and gravity sewers	(Comprehensive Wastewater Management Plan Review Committee, 2010 and Town of Falmouth, 2013b)	(Barnstable County Wastewater Cost Task Force, 2010 and Buchanan et al., 2010)	Assumes 100 gallons per person per day, 1.4 people per home in Falmouth.
I/A septic systems	(AquaPoint, 2008, Cape Cod Winwater Work Co, 2014, Miller, 2014, Rowland, 2014, Shea Concrete, 2014, Short, 2014 and Siegmund Environmental, 2014)	(David J. Burnie Septic Services, 2014, Rowland, 2014, Short, 2014 and Siegmund Environmental, 2014)	Includes costs for Orenco's AdvanTex systems, Aquapoint's Bioclere unit, Norweco's Singulair systems, and FAST systems by Biomicrobics.
Standard toilet	(RS Means 2013)	Assumed	Includes multiple mounting options. O&M assumes one $100 servicing every 10 years for base case, annual $100 servicing for high case, no maintenance for low case.
Urine-diversion toilet	(Ecovita Products and Tools,, Jaffe, 2014 and RS Means, 2013; "Separett Waterless Toilets" n.d.)	(Noe-Hays, 2014), assumed	Includes dry and flush toilet options. Installation costs are 'bare labor.' Assumes 500-gallon urine tank (⅓ of standard septic tank), located outdoors. Flush toilet O&M is ⅔ of septic O&M cost, assuming some fixed costs. Dry toilet O&M comes from flush toilet O&M and compost toilet O&M.
Compost toilet	(Clivus Multrum, 2013a and RS Means, 2013)	(Clivus Multrum, 2013b and Sunmar, 2013)	Includes dry toilet and foam flush options, two sizes of composter. Installation costs are 'bare labor.' Capital costs are for a pair of toilets with one compost container.
Blackwater digesters and pressure or vacuum sewers	(Kinstedt, 2012)	(Kinstedt, 2012)	Euros converted to USD at €1 to $1.37. Includes pressure and vacuum sewer network options.
Vacuum toilet	(EAGO TB326 Ultra Low Flush Eco-Friendly Toilet,, Sun-Mar Sealand 510 Plus Ultra Low Flush Toilet.,, GreenGain Toilet,, Hawn, 2014 and Kinstedt, 2012)	Assumed	Euros converted to USD at €1 to $1.37. Installation is 'bare labor.' O&M assumed same as standard toilet.
Conventional septic system	(Capewide Enterprises, 2014 and RS Means, 2013)	(Septic Systems and Their Maintenance., and Septic Tank Pumping Cost, 2012)	All new tanks in Massachusetts are required to be 1500 gallons; some legacy tanks are 1000 gallons. Assumes annual pumping to be conservative.
Retrofitting or upgrading an existing septic system	(Capewide Enterprises, 2014 and Oceanside Septic Services, 2014)		Includes using existing tank as-is, upgrading existing tank, filling or removing existing tank and installing a new one.

Greywater recycling system	(Holt and James, 2006 and RS Means, 2013)	(Holt and James, 2006)	Australian dollars converted to USD at $1AUS to $0.89. Costs for Nubian, Perpetual Water, Clearwater Aquacell, and Rootzone vertical filter systems
Variable drinking water supply cost		(TenBrink, 2013 and Town of Falmouth, 2013a))	Uses rate for excess usage on household bill. Range for sensitivity analysis comes from Falmouth budget line DPW Water Utilities Other Expenses for two years.
Decentralized monitoring		Assumed	Assumes $70,000 per year for one inspector, 6–10 inspections per day, working 250 days/year.
Removal of existing standard toilet	(Wood, 2014)		

Table options ▼

We do not include the costs of any additional treatment or storage of the byproducts of waste treatment for reuse; we do include the cost of transport of waste products for final disposal or use. For a WWTP, I/A septic systems, and eco-toilets, we assume these transport costs are included in the operation and maintenance (O&M) cost estimates given by sources, since disposal is a critical component of O&M in these cases. For blackwater digestion, we explicitly include estimates for the cost of transporting the entire digestate slurry (liquids and solids).

Compared to the WWTP and I/A septic system, the other technologies will incur lower potable water supply costs because less (or no) water is required to flush the toilets in those systems. To estimate the monetary savings from the alternative systems, we used Falmouth's block pricing structure, which includes a fixed base rate and a variable rate that depends on usage (TenBrink, 2013). We assumed that the fixed costs are constant across scenarios and used end-use demand estimates (Cape Cod Eco-Toilet Center,, Ecovita Products and Tools,, Merck, 2013, Rosie’s Natural Way, and Vacuum Toilets Australia,).

A summary of all cost data with references and assumptions can be found in the supplementary information.

3. Results

3.1. Nitrogen flows

Fig. 1 shows the estimated flows of nitrogen through the five primary household wastewater treatment systems investigated in the study: flush and dry diversion toilets are shown as a single flow. If digestate is physically transported out of the watershed, then blackwater digestion results in 100% mitigation of nitrogen. The nitrogen remaining in the watershed under all other scenarios is from deposition of volatiles and from liquid effluent released into the watershed.

Fig. 1.

Nitrogen flows through household blackwater treatment systems. All mass flow values are in units of kilogram of nitrogen per capita per year; base case value is shown in bold, ranges for sensitivity analysis are given in parentheses.

Figure options ▼

3.2. Total cost and cost-effectiveness

For a typical household, we couple the equivalent annual cost estimates (see Equation (2)) with the mass balance estimate in Fig. 1 to estimate the cost-effectiveness of N mitigation. We differentiate between new construction and retrofits of existing homes: existing homes have wastewater systems in place that can be used with some technologies but must be modified or replaced if other technologies are installed, while newly constructed homes will need entirely new systems installed regardless of technology choice, leading to modeling differences in capital costs between the two scenarios. We considered two retrofit cases: a usable existing septic tank and an existing septic tank in need of replacement. For I/A septic systems, the costs for both usable and failing existing septic systems are within the cost range used in the sensitivity analysis. Fig. 2 shows cost and cost-effectiveness on a per household basis.

Fig. 2.

Equivalent Annual Cost (A) and Cost-Effectiveness (B) of Alternative Technologies on a Per-Household Basis. *EAC* is equivalent annual cost; *CE* is cost-effectiveness; *New* is new construction; *Retrofit* is retrofits of existing homes, including those with usable septic tanks and cases in which the existing septic tank is irrelevant; *Retrofit (Failing)* is retrofits of existing homes with failing septic tanks that must be replaced. Error bars show cost range from sensitivity analysis (see 3.3 Sensitivity Analysis for more detail).

Figure options

In all cases, the preferred technology – least expensive and most cost-effective (least cost per kilogram of nitrogen mitigated) – is the flush diversion toilet, followed by the dry diversion toilet with conventional septic system for greywater. Composting toilets with conventional septic system are third best in all cases, though I/A septics are very similar in cost for new construction and retrofits of homes with failing septic systems. Blackwater digestion is the most cost-effective option after eco-toilets.

Several technologies are clearly unfavorable. The most expensive and least cost-effective option in all cases is the centralized WWTP. The pairing of a greywater recycling system with any treatment option is always more expensive than a conventional septic system paired with the same treatment technology.

We scaled the per household results in Fig. 2 to Falmouth's wastewater service area assuming 20% of the homes have failing septic systems, according to data for Massachusetts (U.S. EPA, 2002). Fig. 3 shows the results for the entire service area, incorporating this assumption. At this scale, the preferred options are still the flush diversion toilet and the dry diversion toilet with conventional septic systems for greywater management. The next least expensive and most cost-effective technology is compost toilet systems with conventional septic treatment of greywater. Blackwater digestion is still the most cost-effective option after eco-toilets.

Fig. 3.

Equivalent Annual Cost (A) and Cost-Effectiveness (B) of Alternative Technologies for the Entire Service Area, Assuming 20% Existing Septic Systems are Failing. *EAC* is equivalent annual cost; *CE* is cost-effectiveness; *New* is new construction; *Retrofit* is retrofits of existing homes, including those with usable septic tanks and cases in which the existing septic tank is irrelevant; *Retrofit (Failing)* is retrofits of existing homes with failing septic tanks that must be replaced. Error bars show cost range from sensitivity analysis (see 3.3 Sensitivity Analysis for more detail).

Figure options

3.3. Sensitivity analysis

For our sensitivity analysis, we include here (Fig. 4) only a few illustrations of key points in the uncertainty of equivalent annual system cost and cost-effectiveness. Additional sensitivity analysis can be found in the supplementary information.

Fig. 4.

Uncertainty for cost-effectiveness, in retrofit case, of WWTP system (A), I/A Septic System (B), Blackwater Digester with Greywater Recycling (C), and Flush Diversion Toilets with Failing Existing Septic System (D). Each bar shows the range of system cost-effectiveness values as one factor ranges between the endpoints shown. Cost factors are all on a per-household basis.

Figure options ▾

In all cases, nitrogen mitigation is the most uncertain factor in determining cost-effectiveness of a system; for digesters paired with greywater recycling, the O&M cost for greywater recycling is as uncertain as nitrogen mitigation. In all systems incorporating greywater recycling, the capital and O&M costs for greywater recycling are two of the three greatest sources of uncertainty in the cost of the system (*e.g.*, Fig. 4C). In all retrofit cases employing septic systems, the septic cost is the first or second most important factor affecting uncertainty in system cost (*e.g.*, Fig. 4B, D). The least uncertain factors in all cases are, as applicable, the cost of water supply, the cost of decentralized monitoring, and the cost of removing existing toilets before installation of eco-toilets or vacuum toilets.

The discount rate's most prominent role is in the equivalent annual cost of the WWTP (Fig. 4A), followed by its role in the cost of both types of diversion toilet and the blackwater digester paired with conventional septic. For other systems, the discount rate does not contribute to the overall uncertainty as much as other factors (*e.g.*, Fig. 4B, C, D).

Some options are clearly more expensive than others, even accounting for uncertainty. Over their entire cost ranges, the WWTP is more expensive than any eco-toilet or blackwater digester paired with a septic system for greywater treatment, except in the case of blackwater digestion paired with an existing septic system that is failing and needs replacement, which at its most expensive is similar in cost to a WWTP at its least expensive. In the lowest cost case, the WWTP is about the same cost as I/A septic is in the highest cost case. Similarly, compost toilets or digesters paired with greywater recycling at their least expensive are more costly than, or about the same cost as, the most expensive case for flush and dry diversion toilets paired with septic systems in new construction, and any eco-toilet paired with a usable existing septic tank in the retrofit case. Also in the retrofit case, a flush diversion toilet paired with a usable existing septic system is always cheaper than a dry diversion toilet paired with a greywater recycling system and about the same as or cheaper than a blackwater digester paired with a septic system.

There are fewer mutually exclusive ranges of cost-effectiveness. The WWTP at its most cost-effective (lowest dollar per kilogram of nitrogen mitigated) is less cost-effective than the entire cost-effectiveness range, in the new case, for flush diversion toilets and dry diversion toilets paired with septic systems; in the retrofit case the WWTP is less cost-effective than any eco-toilet or a blackwater digester with a usable existing septic tank, and flush and dry diversion toilets paired with failing existing septic systems.

4. Discussion

In all cases, we found that the most cost-effective alternatives for mitigating nitrogen are decentralized systems, paired with conventional septic systems as necessary. Sensitivity analysis shows that a WWTP is in no case the preferred option, with centralized systems being at least $40 more per kilogram of nitrogen mitigated than flush diversion toilets, assuming conservative ranges for model inputs, and at best equally cost-effective as the worst-case scenario for other eco-toilets. Sensitivity analysis also shows that flush and dry diversion toilets, paired with septic systems, are preferred in most cases, with other decentralized systems presenting potentially viable options. According to our results, decentralized options paired with greywater recycling systems are generally not as attractive as other options, including short-run reductions in potable water costs associated with greywater recycling. The relative appeal of I/A septic systems is heavily dependent on the cost and the nitrogen mitigation of the specific system installation.

Centralized WWTPs and sewer networks are very expensive in Falmouth, MA, where housing density is relatively low and a coastal geography increases costs. In Falmouth, it might be feasible to sewer certain portions of the town where housing density is currently higher, while employing decentralized technologies in other areas. However, without a highly efficient nutrient reduction technology, ocean discharge may still be problematic. We found that when decentralized technologies are implemented, pairing them with greywater recycling systems increases the package cost without adding nitrogen mitigation benefits, making conventional septic systems preferable for greywater management. However, some homeowners who choose to install decentralized systems may also choose to recycle their greywater to reap environmental benefits other than nitrogen mitigation, so understanding the costs of these systems can be useful.

If Falmouth, MA were to adopt a single solution for wastewater treatment in all homes, the results of this study indicate flush diversion toilets as the preferred option according to equivalent annual cost and cost-effectiveness measures, but flush diversion toilets do not completely eliminate household waste nitrogen from the watershed. All eco-toilets release some nitrogen into the watershed: less than a WWTP or I/A septic systems, but more than blackwater digesters, which release zero nitrogen into the watershed if the digestate slurry is exported. Blackwater digestion systems paired with conventional septic systems are competitive with diversion toilets in cost-effectiveness, within the bounds of uncertainty. Therefore, neighborhood scale blackwater digesters may be a preferred solution to Falmouth's nitrogen pollution problem, while flush diversion toilets are the preferred technology for household wastewater treatment with consideration for nitrogen mitigation, according to our results. If blackwater digesters were chosen for implementation, it would be important to consider other impacts the systems might have, such as emissions from trucking digestate and environmental impacts in the disposal location.

Selection of one or more decentralized technologies would allow for immediate replacement of critical systems and future replacement of systems that are currently functioning adequately. For example, installation of the chosen technology could be mandated at the time of existing septic system failure: since failing conventional septic systems are significant contributors to the environmental problem, replacing systems as they fail would improve the worst sources of the problem. Homes with adequate septic systems could be required to install the new technology by some later date, such as the time of title transfer of the property. In this way, use of decentralized technologies would allow for immediate redress of the most urgent needs while providing additional compliance time in less urgent situations.

In addition, decision-makers could allow individual homeowners to choose which of several decentralized options they prefer to install. Homeowners could install eco-toilets independent of their neighbors' choices; neighborhoods could collectively elect to install blackwater digestion systems. This freedom of choice might also increase acceptance of technological change, whereas a narrow mandate might meet some resistance. Eco-toilets are currently uncommon in U.S. homes, and homeowners may be resistant due to real and perceived operation and maintenance differences relative to conventional toilets. Flush diversion toilets have the advantage of allowing all waste to be stored outside the home, in buried tanks, but they still require “aiming” in the toilet. Blackwater digestion systems operate with vacuum toilets, which offer a similar user experience to standard toilets. I/A septic systems are almost the same as conventional septic systems from the homeowner perspective. For owners considering the future resale value of their properties, more familiar, easy to use toilet systems may be more appealing than novel technologies.

Technologies that allow for resource recovery – both nutrients and biogas – may become more attractive but costs and benefits become less certain. Sale of compost as fertilizer is one of the easier benefits to quantify, since biosolids from wastewater treatment are already included in commercially available products in the U.S.: we estimate the benefits of selling compost to range from about $10 to about $200 per year, per household. Regulations governing the sale of other waste-derived products are currently immature but a market for recovered resources may alter the decision context in the future.

Other uncertainties that might benefit from further research include household nitrogen flows, mitigation potential of technologies, and cost increases over time, particularly for water and energy. Further work could also improve our understanding of what discount rates are appropriate given anticipated householder preferences and potential financing strategies (*e.g.*, municipal bonding, rate financing) and incentives for adoption (*e.g.*, rebates, rate reductions). If monetary incentives were used for decentralized technologies, then individual discount rates should be used to model technology adoption at the household level and municipal discount rates should be used to model public financing. This could affect the technology adoption rate and ultimate penetration rate, and thus the net cost-effectiveness. The cash flow implications may similarly influence selected technologies. A new WWTP would cost about $1.1 billion in short-term financing. If a decentralized system were chosen, the cash could be spread over a longer time period, reducing the burden of short-term financing.

In any implementation of novel technologies, it is important to remember that there might be unintended or unanticipated consequences. For example, if all homes installed composting toilets and thus drastically reduced their water consumption, the water supply utility might see reduced revenues, increased water age in distribution systems, and other possible effects. Treatment might become less efficient on a per-unit basis, even while becoming more sustainable overall. As with a centralized WWTP, the cost-effectiveness and other measures of efficiency of a centralized potable water utility depend on the local housing density. Researchers exploring these new technologies should do our best to anticipate possible direct and indirect consequences of their use, but we must also watch closely as these technologies are implemented to observe what we could not anticipate.

The ultimate driver in Falmouth, MA and other similarly affected areas is to avoid eutrophication of surface waters. Thus an ideal measure for our study would be technology life cycle cost per eutrophication potential; however, the fate and transport modeling required to support such an analysis is outside the scope of this study. A model that integrates fate and transport with the engineering economic assessment performed herein for a wider array of nitrogen management alternatives would be a powerful tool for eutrophication mitigation.

5. Conclusions

We develop a mass balance of nitrogen flow through households and estimate the cost-effectiveness of nitrogen "mitigated" by conventional and alternative household scale wastewater technologies in Falmouth, MA. Across a range of assumptions, we find that flush diversion toilets paired with conventional septic systems are the lowest cost and most cost-effective option for managing nitrogen in household wastewater, with dry diversion toilets paired with conventional septic systems as the second best option. Composting toilets are also attractive options in some cases, particularly best-case nitrogen mitigation; innovative/advanced septic systems designed for high-level nitrogen removal are cost-competitive options for newly constructed homes, except at their most expensive. A centralized wastewater treatment plant is the most expensive and least cost-effective option in all cases. Using a greywater recycling system with any treatment technology increases the cost without adding any nitrogen removal benefits. Sensitivity analysis shows that these results are robust considering a range of cases and uncertainties.

Disclaimer

The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Appendix A. Supplementary data

The following is the supplementary data related to this article:

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