



Contents lists available at ScienceDirect

Ecological Engineering

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



Nitrogen control through decentralized wastewater treatment: Process performance and alternative management strategies

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ARTICLE INFO

Article history:

Received 12 November 2009
Received in revised form 7 April 2010
Accepted 28 April 2010
Available online xxx

Keywords:

Nitrogen removal
Decentralized wastewater treatment
Denitrification

ABSTRACT

Decentralized or onsite wastewater treatment (OWT) systems have long been implicated in being a major source of N inputs to surface and ground waters and numerous regulatory bodies have promulgated strict total N (TN) effluent standards in N-sensitive areas. These standards, however, most of which have effluent limitations of <10 mg/L TN, were generally developed without data on treatment performance and attainable compliance levels of operating OWTs designed to remove N. This paper reviews OWT technologies that rely on preanoxic or postanoxic denitrification, or simultaneous nitrification–denitrification, and frequently include compact, mechanized components. TN effluent data from 20 OWTs in 3 long-term N removal demonstration projects in Florida, Oregon, and New Zealand are analyzed and compared with the performance of 15 centralized N removal treatment plants from the US and Canada. A reliability and stability analysis shows that only one of the 20 OWTs approaches the reliability and stability of centralized plants, and can comply with a <10 mg/L TN effluent standard with a 99% probability; all of the remaining 19 OWTs have a <50% probability of compliance. The lower reliability of OWTs, many of which are energy-intensive, scaled-down models of centralized plants, is due to the inherent variability of decentralized wastewater characteristics and the challenges of operationally controlling N removal processes at the level of residences. However, the small footprint (required land area) of these compact designs offers important opportunities for retrofitting OWTs on small lots, in shoreline developments where land is at a premium and where communities wish to foster and sustain compact, village developments that reflect “smart growth” strategies. Other approaches to decentralized N management emphasizing passive, robust, ecologically engineered designs are reviewed and include natural wastewater treatment systems such as single pass sand filters with denitrifying bioreactors, which performed better than any other OWT technology; shallow trenches and drip irrigation for denitrification or plant N uptake in the carbon-rich root zone; denitrification beds/layers installed down gradient from effluent plumes; and the consideration of watershed N sinks in estimating the risks of N loading to receiving waters. These alternative approaches require further research and development, but can offer alternatives or additional treatment to mechanized OWTs. More comparative studies of long-term operation of OWTs under field conditions in other parts of the world are needed to further quantify performance capabilities.

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1. Introduction

The contribution of reactive N (N_r) from human wastes to the environment is estimated at 25 Tg N/year. While only about 17% of that is from agroecosystems, it is nevertheless significant in its

impacts on aquatic ecosystems and public health (Galloway et al., 2003). In 2004 it was estimated that 49% of the world's population of 6.4 billion was urban, and that 80% of this population was sewered (WHO/UNICEF, 2006). Thus, of the 25 Tg N/year generated by human waste, approximately 9.8 Tg N/year is collected by centralized sewerage and discharged to aquatic ecosystems, the vast majority without any treatment for nitrogen removal. The effects of discharges from centralized wastewater N_r on aquatic ecosystems, especially lakes, estuaries, and coastal waters, is well documented in the US (Driscoll et al., 2003; NRC, 2000; US EPA, 1993; US EPA, 2008a) and worldwide (Howarth and Ramakrishna, 2005; Selman et al., 2008), and N removal in centralized wastew-

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ater treatment plants is now required in many N-sensitive areas of developed countries (US EPA, 1993, 2008a). The remaining 15.2 Tg N/year, 61% of the total, is therefore decentralized waste that is discharged to soils through wet (e.g. septic systems) or dry (e.g. pit privy) onsite waste treatment/disposal systems. In developed countries, wet systems are known as onsite wastewater treatment systems (OWTs), for which septic systems are the most common. The US EPA defines OWTs as those that collect, treat and release the wastewater of fewer than 20 persons. OWTs in the US serve 26 million homes, businesses, and recreational facilities, and release approximately 4 billion gallons of effluent per day, the vast majority being discharged to the soil subsurface where it eventually migrates to groundwater (US EPA, 2002).

OWTs contribute significant N inputs to both surface waters (rivers, lakes and coastal areas) and groundwater. For example, it was estimated that 55–60% of the N load to the San Lorenzo River in California came from onsite systems during summer months as recharge to base flow (Ricker et al., 1994) and N inputs from OWTs have been implicated in the eutrophication of New Zealand lakes (Scholes, 2006), nuisance algal growth and declines in eelgrass beds in Buttermilk Bay, Massachusetts (US EPA, 2002), and the hypoxia problems of Hood Canal in Washington state (Fagergen et al., 2004).

Decentralized OWTs are oftentimes the major source of nitrate-N groundwater contamination, a drinking water contaminant, especially where housing density is high and N loadings per unit area exceed dilution through infiltration of rainwater (Gold et al., 1990; Bouchard et al., 1992; County of Butte, 1998; Gold and Sims, 2000; Hallberg, 1989; Hantzche and Finnemore, 1992; Rich, 2005).

Because of the sheer costs of centralized systems, OWT systems are no longer considered a temporary solution to be replaced eventually by centralized collection and treatment (US EPA, 2002). However, the conventional septic tank/soil absorption system design is not particularly effective for N removal, reducing N loading by only 10–20% before discharge to the environment (Keeney, 1986; Siegrist and Jenssen, 1989; Lamb et al., 1990). As a result, various alternative technologies have been developed over the last 20 years, and numerous studies have monitored OWTs designed for N removal (Ayres Associates, 1998; Brooks, 1996; County of Butte, 1998; CRWQCB, 1997; Rich, 2005; Scholes, 2006; US EPA, w/o date; Whitmeyer et al., 1991). These different designs and operation and maintenance regimes have generated great variability in treatment performance. Nevertheless, regulatory agencies often require stringent N removal by OWTs in areas where surface waters are impacted, or where systems discharge to sensitive aquifers used for drinking water (Table 1), yet it is not clear

which OWT technologies and designs are capable of meeting these limits.

We will review and evaluate the performance of N removal systems for OWT; our review will focus on single residence designs employed to nitrify and denitrify the wastewater, sources of variation, and recent advances in operation and maintenance. Our evaluation will take two forms: we will apply traditional metrics used to evaluate treatment reliability and stability based on effluent concentrations. This will permit direct comparison with the results typically obtained from centralized treatment approaches to N removal. Brief treatment failures in centralized systems can generate catastrophic consequences to the estuaries and rivers and lakes that receive their effluent. However, because OWT distribute to more diffuse soil environments, we will also present arguments suggesting that design standards based on annual or seasonal loading rates may be more applicable for OWT performance, particularly when viewed in conjunction with natural or ecologically engineered processes that may enhance the extent of denitrification as the effluent travels through terrestrial and aquatic denitrification hotspots (Schipper et al., this issue; Kellogg et al., this issue). The issue of septage management – septage is the semi-liquid of settled organic solids, and liquid and surface scum layer, that must be periodically removed and treated (Crites and Tchobanoglous, 1998) – an important component of decentralized N control (Hamersley et al., 2001), will not be considered in this paper due to space limitations. While the focus of this paper is N removal, there are also other concerns with OWTs relating to pathogens, phosphorus, organic chemicals, and heavy metals, and interested readers are referred to Chapter 3 of the US EPA Onsite Wastewater Treatment Systems Manual for further information and references (US EPA, 2002).

2. Nitrogen cycle in wastewater treatment

2.1. N transformation processes in wastewater treatment systems

Sequential nitrification/denitrification processes, which attempt to optimize natural biological processes through engineering, form the basis of essentially all biological N removal technologies that are currently being used in wastewater treatment (Fig. 1). Aerobic processes are first used to remove carbonaceous biochemical oxygen demand (CBOD) and nitrify NH_4^+ -N. Anoxic processes then reduce NO_3^- -N to N_2 gas, either using the wastewater or bacterial cells as a carbon source, or an external carbon source such as woodchips. Although there are other biological (e.g., Van der Star

Table 1
Examples of TN effluent standards for OWT systems in N-sensitive areas.

Location	Standard or mass loading for effluent TN	Statistical basis	Sampling frequency
California ^a	<10 mg/L	Monthly average	None stated
European Union	<170 kg/ha-year (discharge to soil)	None stated	None stated
Finland	40% removal	None stated	None stated
Florida ^a	<3 mg/L @ 0.6 m below drainfield <10 mg/L @ outlet of treatment unit	None stated	None stated
Massachusetts	≤4110 L/ha-day (hydraulic load) or <10 mg/L (N removal OWT)	None stated	None stated
New Zealand	<15 mg/L	None stated	None stated
Oregon ^b	<10 mg/L	None stated	None stated
Rhode Island	<19 mg/L	None stated	None stated
Virginia ^a	<5 mg/L @ property line w/dilution <5.6 kg/ha-year (≤305 m from tidal waters) <9.0 kg/ha-year (≤305 m from surface waters) <14.9 kg/ha-year (all others)	None stated	None stated

Sources: Cal/EPA (2009), Finnish Environment Institute (2008), Gill et al. (2009), Anderson (2006), MassDEP (2007), Scholes (2006), Rich (2005), RE DEM (2008), VDH (2009).

^a Proposed.

^b Standard used in La Pine demonstration project.

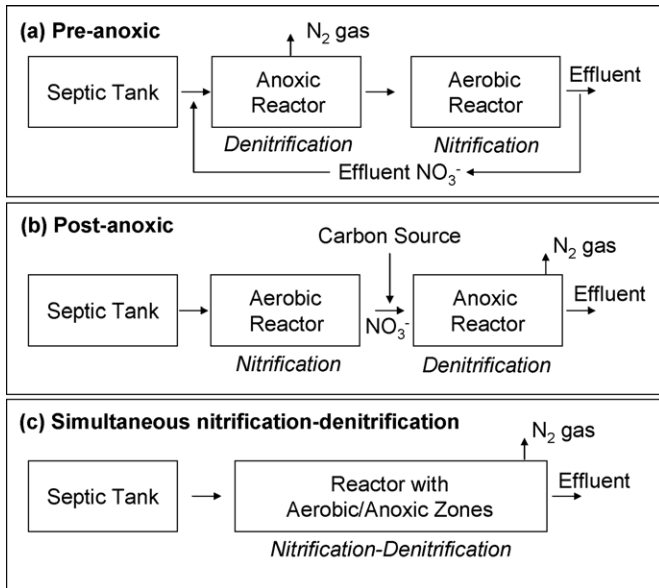


Fig. 1. Schematic of pre- and post-anoxic, and simultaneous nitrification/denitrification processes.

et al., 2007) and non-biological processes (Metcalf and Eddy, 1991) that have been used, biological nitrification/denitrification is the principal process that has been demonstrated to be feasible, both economically and technically, for nitrogen removal in both centralized and decentralized systems (US EPA, 1993, 2002, 2008a; Oakley, 2005).

Both nitrification and denitrification can be mediated by suspended-growth or attached-growth processes. Suspended-growth processes are biological treatment processes within tanks or reactors. The microorganisms responsible for treatment are maintained in suspension within the liquid through mechanical or diffused-air aeration (e.g., activated sludge plants). Attached-growth processes are those in which the microorganisms responsible for treatment are attached to an inert medium such as sand, gravel, or plastic media, and can include either submerged (e.g., upflow filter), or non-submerged processes (e.g., trickling filter) (Crites and Tchobanoglous, 1998; Metcalf and Eddy, 1991). In centralized systems, suspended-growth processes are typically used for both nitrification and denitrification, although attached-growth denitrification is occasionally seen (US EPA, 2008a,b; US EPA, 1993). Attached-growth processes are predominantly used for nitrification in OWTs, while both attached and suspended-growth systems have been used for denitrification (Oakley, 2005).

2.2. N removal process configurations

There are three common N removal process configurations used in centralized wastewater treatment plants and OWTs: preanoxic, postanoxic, and simultaneous nitrification–denitrification (Fig. 1, Metcalf and Eddy, 2003). In preanoxic systems a denitrifying anoxic tank using the wastewater as the carbon source precedes the aeration tank where nitrification occurs, and the nitrified effluent from the aeration tank is recycled back to the influent side of the anoxic tank; this is the most common configuration used in municipal wastewater treatment (US EPA, 1993, 2008a, 2009) and is very commonly used in OWTs (Rich, 2005; US EPA, w/o date). In postanoxic systems, the denitrifying anoxic reactor follows the aeration tank and the carbon source can come from either endogenous respiration of bacterial cells or an external source, methanol is the most commonly used external carbon source in centralized

plants (US EPA, 1993, 2008a,b, 2009), and acetate, ethanol, and wood chips have been used in OWTs (Oakley, 2005; Robertson et al., 2005). In simultaneous systems, both nitrification and denitrification occur in the same reactor. Simultaneous configurations are most often used in suspended-growth designs, and preanoxic and postanoxic are most commonly in attached-growth or combinations of suspended/attached-growth (Metcalf and Eddy, 2003; US EPA, 1993). While there are a great number of proprietary technologies used in OWT biological N removal, and it is beyond the scope of this paper to discuss them, all are based on the above configurations (Ayres Associates, 1998; Rich, 2005; Scholes, 2006; US EPA, 2009, w/o date).

3. Process performance of OWT nitrogen removal

3.1. Effluent standards and reliability analysis of OWT technologies

Reliability in wastewater treatment is defined as the percentage of time the effluent concentrations comply with specified standards. Niku et al. (1979) developed a coefficient of reliability (COR) relating mean effluent concentrations to effluent standards on a probability basis to assess wastewater treatment plant performance. According to Niku et al. (1979), the relationship between the mean and the effluent standard is

$$m_x = (\text{COR}_{1-\alpha})X_S \quad (1)$$

where m_x is the mean effluent concentration, X_S the effluent discharge standard, and $\text{COR}_{1-\alpha}$ the coefficient of reliability at the $1 - \alpha$ probability of success (α is the probability of failure). The $\text{COR}_{1-\alpha}$ is calculated from the coefficient of variation, COV, (SD/mean)

$$\text{COR}_{1-\alpha} = \sqrt{(\text{COV})^2 + 1} \left(\exp \left\{ -Z_{1-\alpha} \sqrt{\ln((\text{COV})^2 + 1)} \right\} \right) \quad (2)$$

where $Z_{1-\alpha}$ is the standard normal deviate. The probability of compliance for a measured m_x is calculated from

$$Z_{1-\alpha} = \frac{\ln X_S - (\ln m_x - 0.5 \ln((\text{COV})^2 + 1))}{\sqrt{\ln((\text{COV})^2 + 1)}} \quad (3)$$

Using the method originally developed by Niku et al. (1979) that is presented in major wastewater engineering textbooks (Metcalf and Eddy, 1991, 2003; Crites and Tchobanoglous, 1998), and most recently presented by Oliveira and Von Sperling (2008) to analyze 166 full-scale wastewater treatment plants in Brazil, these equations have been used to estimate the probability of compliance and percentile concentrations for a measured m_x for all of the OWTs addressed in this review. The reliability approach assumes that concentration data follow a lognormal distribution, which has been reported for TN effluent concentrations in both centralized (Oliveira and Von Sperling, 2008; US EPA, 2008a,b) and decentralized systems (Charles et al., 2005).

Limits on N loads from centralized facilities require routine monitoring and statistical evaluation. Under the National Pollutant Discharge Elimination System (NPDES) permit program of the US EPA in the United States, TN standards for centralized wastewater treatment facilities are written for specific receiving waters, with effluent concentration averages (annual, monthly, weekly, daily) calculated from required sampling frequencies during operation (Table 2). In this way treatment performance can be rigorously assessed to be sure the TN standards are being complied with on a statistical basis in terms of percentiles, such as the maximum daily (99.7 percentile) or maximum month (91.7 percentile) effluent concentration (US EPA, 2008a). European countries utilize a

Table 2
Examples of TN effluent standards for centralized systems under the US EPA's National Pollutant Discharge Elimination System (NPDES) permit program (US EPA, 2008b).

Location	Standard for Effluent TN, mg/L				Max limit, kg/year
	Annual average	Monthly average	Weekly average	Daily max	
Smithfield, NC	13,926	Daily			25,545 ^a
Lee Co., Florida	10,681	Daily	3	4.5	
Clearwater, Florida	18,522	Daily	3	3.75	65,454 ^c
Fairfax, Virginia	160,212	Weekly	Report ^b	Report ^b	
North Cary, NC	23,660	3/week			
Upper Marlboro, MD	77,740	5/week	4.0	3.0	

^a Equivalent to 3.7 mg/L @ 5 mgd.

^b To develop data base for N removal and loadings.

^c Equivalent to 3.94 mg/L @ 12 mgd.

similar performance requirement of not-to-exceed discharge limits set at the 95th percentile (Metcalf and Eddy, 2003).

With the exception of the proposed effluent standard for California, none of the effluent standards for the OWTs shown in Table 1 have a basis in statistical considerations in terms of sampling frequency and exceedence percentiles or accepted level of compliance; even the proposed standard for California does not consider the required sampling frequency to determine the monthly average. In order for the calculated monthly mean to have statistical validity, the US EPA (1991) suggests a minimum of 10 samples. For the proposed California standard, this would be one sample every 3 days, an impossible proposition for wide-spread use on the multitude of OWTs at individual family residences. If a system has high variability about the mean, which is a measure of instability, even more samples could be needed (US EPA, 1991).

To circumvent the high logistical and monetary costs associated with routine, wide-spread monitoring of individual OWT performance, organizations such as the National Sanitation Foundation (NSF) in the US and various states and local agencies have certified certain proprietary OWTs to meet a given TN effluent standard or percent removal; approved systems are thus implicitly assumed to comply with standards. For example, the State of Rhode Island requires decentralized N removal systems to meet <19 mg/L TN in N-sensitive areas, but approval is given to specific designs, based on performance trials from a limited number of those systems and does not require routine, site-specific monitoring (RE DEM, 2008). This approach, while understandable from a regulatory perspective, does not assure compliance for individual OWTs on a continuous basis. Instead, it relies on the distributed nature of OWT to minimize the extent of risk to a receiving water or aquifer. Where regulators are considering design standards based on monitoring results, one evaluation approach commonly applied to centralized systems is to define the percentage compliance (i.e., the probability of the effluent being below a certain standard) based on performance characteristics and reliability analysis; the analysis performed herein is the first time this approach has been applied to OWTs.

3.2. Monitoring studies

Most studies of N removal in OWTs have focused on specific research issues and design components, often at a specific research installation or pilot project. As a result, the existing knowledge base for routine operating performance over the long-term is sparse compared to centralized plants (Gold and Sims, 2000). Detailed monitoring data from three long-term demonstration projects are available, however, permitting a comparative analysis of full-scale systems with various processes and technologies, all operating under field conditions.

The three decentralized N removal demonstration projects selected for analysis were: (1) The Florida Keys Onsite Wastewater Nutrient Reduction Systems Demonstration Project, which consisted of five systems installed at a central test facility in the Keys, and used raw wastewater from a 27 m³/day prison facility. System start-up occurred in October 1996, and monitoring continued until August 1997 (Ayres Associates, 1998). The Florida Keys have a tropical maritime climate, with an annual mean high temperature of 28 °C and an annual mean low of 24.1 °C, and an average of 1.25 m/year of precipitation (Ayres Associates, 1998). (2) The La Pine National Decentralized Wastewater Demonstration Project in the Upper Deschutes River in Oregon (Rich, 2005; US EPA, w/o date) where 40 innovative OWTs designed for N removal at individual family dwellings were installed and monitored (2–3 installations of 12 different technologies) from January 2001 to December 2004. These results represent performance capabilities under actual field conditions rather than those obtained at a test facility (Rich, 2005; US EPA, w/o date). The La Pine region has a high desert climate (elevation = 1280 m above mean sea level) with mean monthly minimum and maximum temperatures ranging from 6 to 27 °C in summer (June–August) and from –8 to 8 °C in winter (December–March); mean annual precipitation ranges between 0.35 and 0.53 m (US EPA, w/o date). And (3) the Nitrogen Reduction Trials of Advanced On-Site Effluent Treatment Systems in New Zealand, which selected and installed five systems at a test facility in Rotorua that used domestic wastewater from the city sewer system as the wastewater source. The systems were operated and monitored on a regular basis from May 2005 to April 2006 (Scholes, 2006). The climate of the test facility in Rotorua is temperate, with an annual mean temperature of 12.8 °C, with maximums in summer of 21–26 and 10–14 °C in winter; annual precipitation averages 1.4 m (NIWA, 2010). These projects, which comprise the principal long-term N removal evaluation studies conducted over the last 15 years in decentralized wastewater management, were selected because of (i) the quality and quantity of the data; (ii) the number and generic classes of technologies investigated; (iii) and the length and frequency of the monitoring program. These projects also provide insights into the reliability and consistency of performance, and costs of equipment, construction, and operation and maintenance.

All of the OWT technologies used in the demonstration projects can be generally classified as preanoxic, postanoxic, and simultaneous nitrification/denitrification (some may have combinations of each), and most use attached-growth processes (Table 3, Fig. 1). Of the 20 technologies monitored overall, 18 used proprietary devices or units. Two postanoxic systems used an external carbon source: one a powdered source mixed with bacteria (system 13, Table 3) and the other a solid media comprised of wood chips (system 14). The technologies selected for each demonstration project represent the state-of-the-art of decentralized N removal as determined by the project investigators.

Table 3
 Process configurations used in decentralized N removal demonstration projects.

System	Process	Preanoxic or postanoxic processes					Simultaneous nitrification–denitrification		Proprietary technology
		Nitrification process			Denitrification reactor		A	S	
		Attached growth		Other					
		Media filter ^a	Media type	RBC ^a	A	S			
<i>Florida Keys Demonstration Project (1998)</i>									
1	Preanoxic	X	Sand						
2	SN/D					X			
3	SN/D					X	X		X
4	SN/D						X		X
5	Preanoxic			X					X
<i>La Pine National Demonstration Project (2005)</i>									
6	Preanoxic	X	Textile						X
7	Preanoxic	X	Textile						X
8	SN/D					X			X
9	Preanoxic	X		X					X
10	Preanoxic				X	X			X
11	SN/D						X	X	X
12	Preanoxic							X	X
13	Postanoxic							X	X
14	Postanoxic	X	Sand						X
15	Preanoxic	X	Peat						X
<i>New Zealand N Reduction Trials (2006)</i>									
16	SN/D						X	X	X
17	SN/D						X		X
18	SN/D						X	X	X
19	Preanoxic	X	Textile						X
20	SN/D						X		X

^a Systems 1, 6, 7, 9, 15 and 19 were recirculating filters and system 14 was a single pass filter. SN/D, simultaneous nitrification/denitrification; RBC, rotating biological contactor; A, attached growth; S, suspended growth.

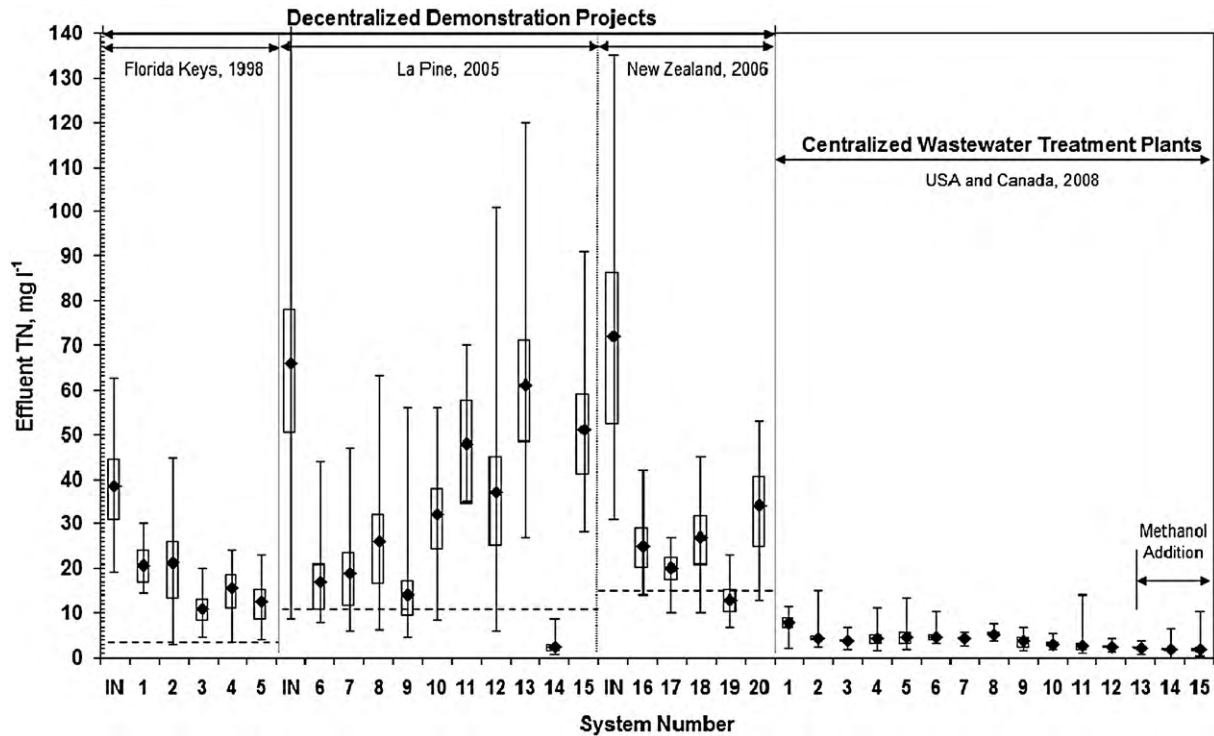


Fig. 2. Mean, range, and interquartile range of effluent TN concentrations for decentralized and centralized N removal. The horizontal dashed lines for each demonstration project indicate the project TN effluent objective.

3.3. TN effluent concentration results

The mean, range and interquartile range of the effluent TN for all of the decentralized N removal systems are shown in Fig. 2. Effluent concentrations from 15 state-of-the-art N removal centralized treatment plants (US EPA, 2008a,b) are also shown for comparison. All of the centralized systems can also be generically classified as preanoxic, postanoxic, or simultaneous, or combinations of each, and can use either suspended or attached growth, or combinations. The last three installations (systems 13–15) used methanol as a supplemental carbon source.

With the exception of one OWT technology that consistently generated TN concentrations <10 mg/L (system 14), OWTs do not approach the level of centralized treatment performance in terms of long-term mean effluent concentration and variability (range and interquartile range). The mean effluent TN data for centralized plants clearly show they can routinely meet a <5 mg/L TN effluent standard using wastewater as the carbon source (systems 1–12), and <3 mg/L TN with the use of methanol for a postanoxic external carbon source (systems 13–15) (US EPA, 2008a,b). High variability existed in most OWT systems, even in trials conducted in controlled test facilities with constant influent flowrates. Effluent goals for each demonstration project were, for the most part, beyond the capabilities of the available technologies operating under best-case scenarios.

The poorer performance of OWTs in terms of high mean effluent concentrations and variability is a reflection of the difference in the TN loads and management and control options between centralized and decentralized systems. Influent TN concentrations in the La Pine and New Zealand projects varied considerably (ranges from 8 to 233 and 31 to 135 mg/L, respectively), with mean values (66 and 72 mg/L) typical of septic tank effluent, but about twice as high as what is generally found in centralized systems (decentralized systems typically have higher influent concentrations due to water saving devices, minimal infiltration, etc.). The mean values and

variability of the OWTs in these two projects are generally higher than the Florida Keys project, which had overall better performance among systems, but also had a mean influent TN concentration of only 38 mg/L. The highly variable performance of the OWTs in the La Pine project reflects individual OWT performance under actual field conditions, where influents display considerable temporal variability in flowrates and loadings depending on the specific water use of a single household (US EPA, 2002). In contrast, centralized systems receive the aggregate of a large number of discharges, and typically exhibit much less variability in flowrates and constituent inputs (Metcalf and Eddy, 2003).

Once constructed and in use, there are only a limited set of operational options to improve OWT performance. This contrasts with centralized treatment plants, where operator attention and process control occur continuously, and raises important challenges with regard to long-term reliability and stability of decentralized N removal with OWTs.

3.4. Reliability analysis results

The 50th and 90th percentile effluent TN concentrations for the three demonstration projects were calculated from the respective $COR_{1-\alpha}$ values using Eq. (1) (Fig. 3a). At the 50th percentile, which is the long-term mean concentration, one OWT (system 14) complied with a 2 mg/L standard, and 6 OWTs complied with a 15 mg/L standard. At the 90th percentile, the same single OWT (system 14) would have complied with a 5 mg/L standard, while only 3 could comply at the next best reliability level at 20 mg/L.

With the exception of one system (again #14), all of the remaining 19 systems have a <50% probability of compliance for an effluent standard of 10 mg/L (Fig. 3b). The results of the three demonstration projects show, with the exception of one technology to be discussed later (system 14), that compliance with most of the standards shown in Table 1 cannot generally be satisfied even at the 50th percentile concentration.

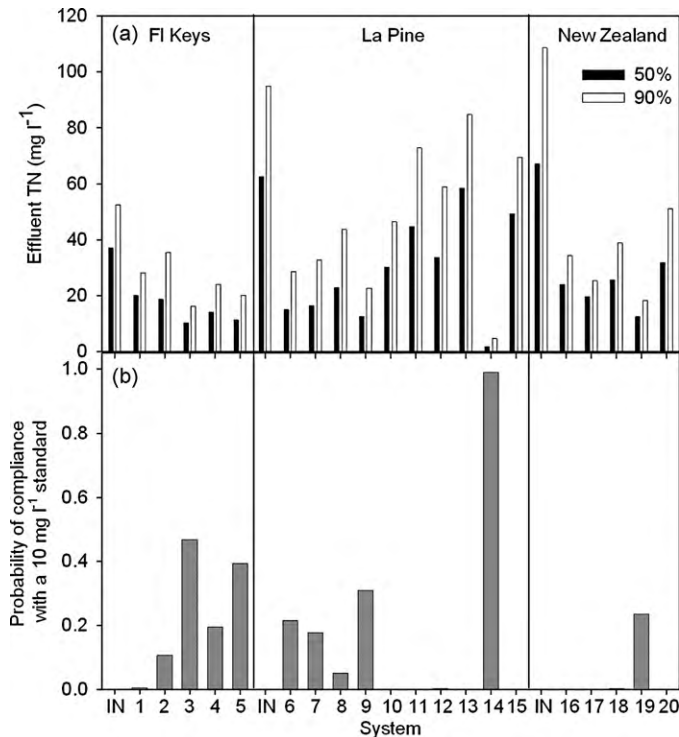


Fig. 3. Results of reliability analysis for the three OWT demonstration projects. (a) 50th and 90th percentile TN effluent concentrations. (b) Probability of compliance for a 10 mg/L TN effluent standard.

3.5. Reliability of performance among identical OWT technologies at different locations

The La Pine data permit a comparative analysis of performance of identical OWT designs operating under different loading conditions, thus enabling an assessment of the limits and variability of the technology itself under field conditions. The three best performing systems were chosen for this detailed analysis: OWT 6 and 7, preanoxic media filters (6 systems); OWT 9, preanoxic rotating biological contactor (RBC) (3 systems); and the best performing OWT of all, system 14, a single pass sand filter with a postanoxic denitrifying reactor filled with woodchips (2 systems) (Fig. 4).

Preanoxic systems that use wastewater for the carbon source perform differently among sites both in terms of long-term mean values and variability of output (e.g., the mean concentrations for preanoxic media filters vary by a factor of two from systems 6a to 6b). The differences among the installations for the same type of OWT are likely due to the quality and quantity of carbon inputs from the wastewater from different households (the La Pine project was the only one assessing performance at individual dwellings). In a centralized treatment plant, operational flexibility would permit adjustments to improve performance through process control or chemical addition. Despite the many sophisticated technologies evaluated at La Pine, it was the simplest system tested in the demonstration projects, a single pass sand filter with a woodchip denitrification reactor, that surpassed all other systems and exhibited a performance on par with centralized treatment plants (Fig. 4b,c).

3.6. Stability analysis of OWTs

Stability is defined as the measure of variations from the annual mean concentration (Niku et al., 1982). Stable processes do not

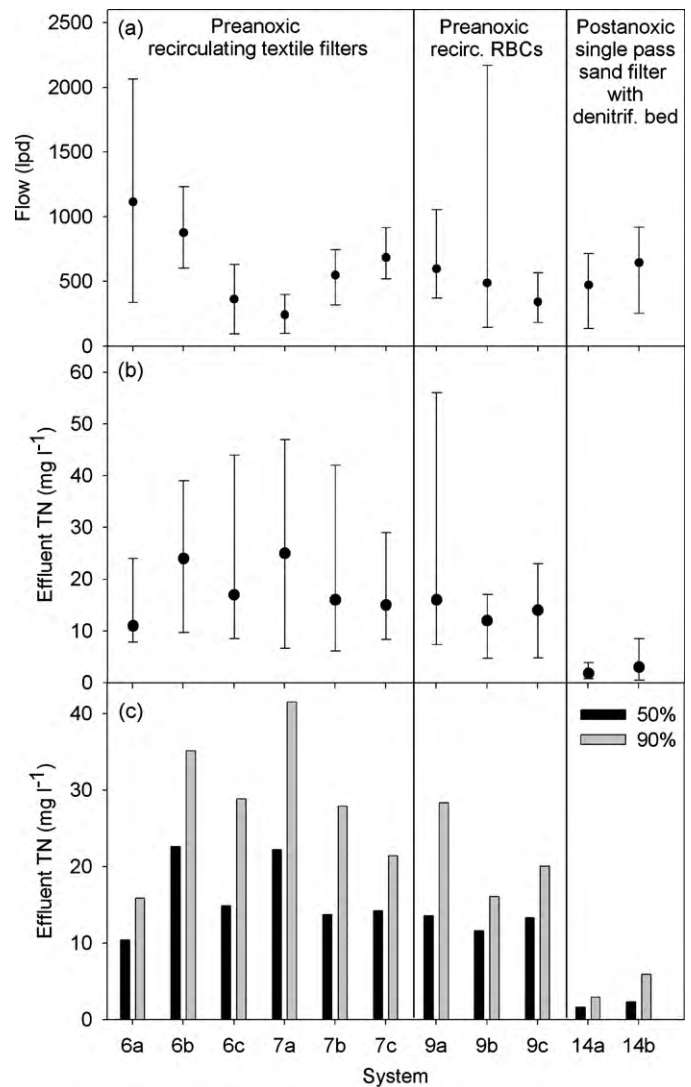


Fig. 4. Select preanoxic and postanoxic OWTs monitored at multiple sites for the La Pine National Demonstration Project (a) mean and range flowrate data. (b) Effluent TN mean and range concentrations. (c) Reliability analysis results for effluent TN 50th and 90th percentile concentrations.

exhibit large variations in effluent quality, while unstable ones do. A treatment process can be considered stable when fluctuations in input loadings, environmental conditions, and operational parameters, factors always encountered in practice, do not cause large variations in effluent quality. Niku et al. (1982) used descriptive statistics (plotting the mean, standard deviation and range versus the standard deviation) to determine the stability cutoff point, which they defined as the standard deviation value below which plants are considered stable. Using a modification of their method, the mean values and 10–90 percentile ranges versus standard deviation are plotted in Fig. 5; the 10–90 percentile range was used instead of the range because it is not as sensitive to outliers (McBean and Rovers, 1998). A visual cutoff point was selected at SD = 3.0 mg/L. Below the cutoff point processes exhibit much less variation, and more stability, than those above it. All of the centralized systems and a sole decentralized one (system 14) are below the cutoff point, with the majority of decentralized systems far above it.

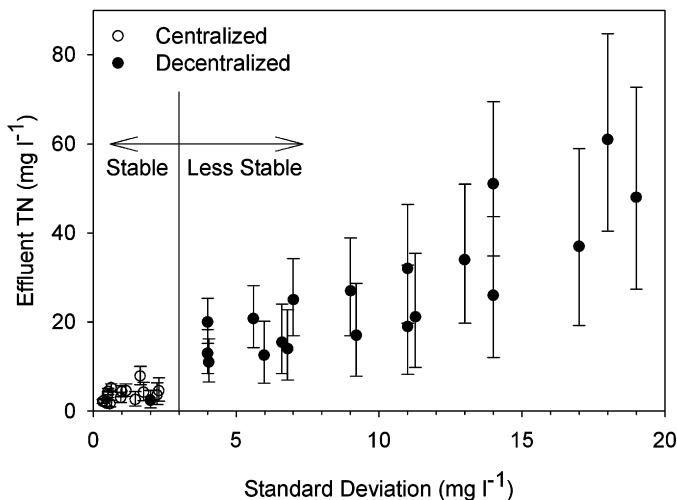


Fig. 5. Results of stability analysis for decentralized and centralized systems. Mean and 10–90 percentile range effluent TN concentrations versus standard deviation.

4. Performance factors for N removal in wastewater treatment

4.1. Wastewater characterization for design

To lower what would otherwise be prohibitive design costs, OWT designs are often based on generic prescriptive parameters for flowrates and constituent loadings. While this approach has been very successful for BOD and TSS removal (Crites and Tchobanoglous, 1998; US EPA, 2002), where the principal failure mode due to soil clogging (from system age or design overloading) is sewage backup in the home or ponding of effluent on the ground surface, it is most likely one of the major factors contributing to the wide variability of N removal performance (i.e., poor stability) seen in the OWT demonstration projects. OWTs, most of which are scaled-down models of centralized plants, have physical/biological/chemical requirements identical to centralized systems. In contrast to centralized systems, where wastewater variability from any individual system is diminished within the aggregated waste stream, and wastewater characterization studies are performed in the initial stages of design (US EPA, 1993; Metcalf and Eddy, 1991, 2003), OWT systems display wide temporal and inter-system variation in hydraulic loading and wastewater characteristics (e.g., TN and BOD) creating challenges for stable performance in the absence of operational control.

To illustrate some of the sources of variation in OWTs, the average U.S. daily residential wastewater flowrates range from 99 to 322 L per capita per day (US EPA, 2002). Depending on the number of occupants in a given dwelling, average daily flowrates to an OWT could range from 198 L per day (Lpd) to 1610 Lpd if, for example, only two occupants discharge at the low range or five at the highest range (See also variability shown in Fig. 4a). Wastewater is generated by discrete events and typical wastewater hydrographs from single family residences show that wastewater flow varies widely throughout a 24 h period, with most of the hydraulic load occurring over relatively short time periods. Minimum hourly flows of zero are typical, and maximum flows of 380 L per hour are not unusual (US EPA, 2002). This wide fluctuation in flowrates can also have a significant effect on N removal processes, such as the recycling of nitrified effluent to mix with influent for denitrification.

While the 5-day biochemical oxygen demand (BOD₅) concentrations in septic tank effluent have previously been reported to only range from 140 to 250 mg/L (Crites and Tchobanoglous, 1998;

US EPA, 2002), the data from 20 systems in the La Pine Project showed a range of 22–1000 mg/L, with a mean of 261 mg/L (Rich, 2005), much higher than the 140 mg/L typically assumed for design of OWTs (Crites and Tchobanoglous, 1998). Variability of BOD₅ directly impacts N removal, where high concentrations of BOD₅ could inhibit nitrification, while low concentrations could cause low denitrification rates in preanoxic systems. Although alkalinity in OWT wastewater can also be quite variable, the few field studies that have reported influent concentrations have found sufficient alkalinity to achieve almost complete nitrification (Gold et al., 1992; Scholes, 2006; US EPA, w/o date).

TN in septic tank effluent is usually reported to range from 40 to 100 mg/L, with a mean around 70 mg/L (Crites and Tchobanoglous, 1998; US EPA, 2002). These values are much higher than that of centralized raw wastewater, which typically ranges from 30 to 50 mg/L TN (US EPA, 1993, 2008b). As with BOD, variations in TN concentrations in septic tank effluent can be quite different from typically assumed values. For example, TN ranged from 8 to 233 mg/L in the La Pine project, and the 80th percentile TN concentration was found to be 250 mg/L in a study of 200 OWT systems in Australia (Rich, 2005; Charles et al., 2005). Because of the higher, variable concentrations of TN coupled with highly variable flowrates and BOD loadings, N removal in the majority of OWT designs cannot produce the stability or reliability of centralized treatment.

4.2. Operational control: monitoring and process adjustments

Apart from design, the vast differences in reliability and stability between centralized and OWT systems are largely due to the extent of real-time operational control of processes. Continuous monitoring of flowrates and select constituents in centralized plants enables trained operators to adjust processes and add chemicals as required (US EPA, 1993, 2008a,b).

Personnel limitations and costs obviously preclude this possibility in OWTs and, as a result, their N removal performance is highly variable even under controlled conditions at test facilities. The only flexibility many OWTs systems have is the ability to change dosing rates on media filters and recirculation ratios for preanoxic systems. Recent advances in telemetry now permit monitoring of influent flow volume on OWTs, which can be used to optimize dosing regimes for the nitrification component and anoxic conditions in the denitrification component of the system. More than 500 N removal systems employ such telemetry in Rhode Island (G. Loomis, personal communication). Large septic/pump tanks and flow equalization tanks using timed dosing with programmable times adjusted to proactively manage peak flowrates to eliminate large surges can manage peak flowrates better and have a higher potential for nitrogen removal with recirculating media filters.

In addition to the wide range of reliability and stability in N removal due to variable flows, CBOD, TN and alkalinity, it is also possible that an OWT will not remove any N due to toxic compounds in the wastewater that inhibit nitrification (autotrophic nitrifiers are much more sensitive than heterotrophic organisms) (US EPA, 1993). Without routine monitoring, this N failure mode (as opposed to the conventional OWT failure of effluent ponding) will not be detected. Fig. 6 illustrates the effect of an inhibitor on nitrification in an experimental OWT at an individual residence; in this particular case a carpet cleaning solvent that was flushed down the toilet contaminated the septic tank and destroyed the nitrifying bacterial population in the attached-growth media (Oakley, 2005). If this system had not been continuously monitored, the effects of the inhibitor on nitrification and N removal would have passed unnoticed.

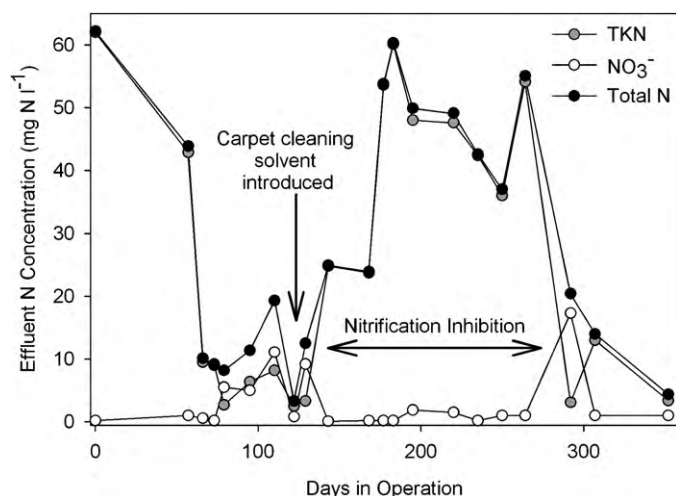


Fig. 6. Nitrification inhibition in a septic tank-recirculating trickling filter N removal system. After Oakley (2005).

5. Integrated ecological engineering for decentralized N interventions

5.1. Alternative approaches to decentralized N management

The results presented in this paper demonstrate that decentralized N removal with OWTs has a limited capacity for meeting the majority of promulgated guidelines based on effluent concentrations at the point of discharge into the environment. This is an economy of scale problem due to the inherent variability of decentralized wastewater characteristics and the difficulty of operationally controlling N removal processes at the level of the individual family residence. (The one exception from the La Pine project will be discussed below.) Alternative approaches to managing decentralized N treatment are available that are more robust, and that take into consideration (i) passive, natural system designs such as denitrifying bioreactors (Schipper et al., this issue; Robertson et al., 2005; Leverenz et al., this issue) and opportunities for enhancing N removal in the receiving soil/groundwater system, such as drip irrigation (Jnad et al., 2001; US EPA, 2002); and (ii) ecosystem-serviced design, where the mitigating effects of ecosys-

tems on ultimate N loadings to receiving waters are included in the TN budget analysis (Kellogg et al., this issue).

5.2. “Ecological Design” for OWT systems

Natural systems for wastewater treatment rely on long hydraulic retention times and low constituent loading rates per unit area or volume (e.g., subsurface soil infiltration trenches, constructed wetlands, and wastewater stabilization ponds). These designs have higher buffering capacities and more stable effluents than the types of smaller footprint OWT systems described thus far (WEF, 2001; Oliveira and Von Sperling, 2008; Crites and Tchobanoglous, 1998). The treatment by natural physical, chemical and biological processes (e.g., sedimentation, solar radiation, biodegradation, plant nutrient uptake, etc.), are simpler to construct and operate, are much more robust than smaller mechanical systems, and as a result can be a cost-effective choice for small installations in disperse settings. Constructed wetlands are often considered the prime example of natural systems for wastewater treatment.

The value of extended treatment areas and long retention times for both removal and stability can be seen by comparing the results (Fig. 4) from a small footprint preanoxic recirculating textile filter (RTF), with a much larger postanoxic single pass sand filter w/denitrification bed of solid carbon (SPSF/DB). The RTF (systems number 6 and 7) had more variability and mean effluent concentrations vary by a factor of 2 at different sites (Fig. 4b); the SPSF/DB (system 14), with 30 times the area of the RTF, exhibited the most robust (stable and reliable) performance with the lowest TN concentrations of any OWT assessed in the three demonstration projects. While the RTF used as much or more energy per kg N removed or per m³ of wastewater treated as centralized wastewater treatment plants as shown in Table 4, the SPSF/DB relied on single pass dosing and gravity flow for denitrification, and used the least amount of all systems, either decentralized or centralized. The subsurface infiltration area for final effluent disposal would be the same for both systems.

While the SPSF is a well-proven technology, the carbon DB used in system 14 has only been recently developed and there are still various unknowns for design such as media type, loading rates, hydraulic retention times, construction costs, and useful life (Schipper et al., this issue; Leverenz et al., this issue). More operating data from long-term projects are needed, preferably from

Table 4
 Comparison of flowrates and energy use in centralized and decentralized wastewater treatment systems.

System	Mean flowrate, m ³ /day	Equivalent number of persons	Mean influent TN, mg/L	Mean effluent TN, mg/L	Energy consumption ^c	
					kW-h/m ³ treated	kW-h/kg N removed
Single pass sand filter w/denitrification bed (2 systems) ^a	0.47–0.64	1.7–2.3	66	1.8–3	<0.1	1.1
Recirculating textile filter (6 systems) ^a	0.22–1.00	0.8–3.5	66	11–25	0.7–3	12–73
Recirculating sand filter ^b	0.64	2.3	38	20	4.5	257
Centralized treatment: N removal fraction	10,680–160,212	23,545–353,200	28–56	1.6–5.3	0.1–0.8	5–28
Centralized treatment w/o N removal	151–3785	333–8344			0.5–2.4	
N production: Haber-Bosch process						13

^a Results of La Pine demonstration project.

^b Results of Florida Keys Demonstration Project.

^c Energy consumption for single pass sand filter estimated from measured mean flowrate dosed to filter using a 0.37 kW pump @ 200 Lpm. Energy consumption for recirculating textile filter measured @ 0.65 kW-h/day from New Zealand Nitrogen Trials data (Scholes, 2007) and assumed to be similar for La Pine data. Energy use for recirculating sand filter measured for Florida Keys project. Energy use for centralized systems and Haber-Bosch process is from US EPA (2008b) and Brix (1999).

peer-reviewed investigations such as those presented in this issue. Nevertheless, the available data strongly suggest the natural system approach with the SPSF/DB used in the La Pine project is a promising advance in the fields of decentralized N removal and ecological engineering, with the performance results comparable to the best centralized treatment plants while using the least amount of energy and operational control of any process, whether OWT or centralized.

The small footprint, mechanized OWTs do offer advantages over the larger passive systems for retrofits on small lots and shoreline developments where land is at a premium. In addition, the compact, mechanized OWTs can foster and sustain “smart growth” developments that are increasingly popular with planners due to their compact environmental footprints (i.e., lower transportation costs) compared to the sprawl associated with large lot developments (Litman, 1995). Because many of the mechanized OWTs can reliably lower BOD and suspended solids, soil dispersal often consists of very small absorption systems with configurations that can be blended into existing patches of open space – permitting considerable treatment. Successful applications of the mechanized OWTs have been integrated into existing villages, with aerobic components placed in basements or beneath decks and soil dispersal achieved in narrow zones between buildings (Joubert et al., 2003).

The relative installation costs of small footprint, mechanized OWT systems versus conventional systems vary widely based on site conditions, labor costs and regulations. Based on a survey we administered to Onsite Wastewater State Extension Specialists from three states (Rhode Island, Texas and North Carolina), the costs of recirculating OWT systems are comparable or lower than a conventional septic tank and drainfield on small lots (<0.15 ha), with high water tables, because of the expense associated with the fill and retaining walls required for a gravity-fed “conventional” drainfield. However, for a site that is well-suited for conventional treatment (lot size > 0.3 ha; water tables > 1.0 m) the costs of a new recirculating system can be 2–5-fold greater than conventional systems – with the range largely a result of labor costs and regulations governing installer qualifications.

5.3. Mitigating effects of ecosystems for decentralized systems

Because centralized treatment plants discharge directly to surface waters, brief periods of poor performance can have profound and immediate consequences on receiving waters. In contrast, the effects of erratic performance from any individual decentralized system are attenuated by the relatively small scale of the loading from the system and by the lengthy travel time (weeks, months or years) of effluent before it reaches a valued aquifer, lake or estuary. Thus, the mean or median value expressed at a seasonal or annual time scale may be more reflective of the aggregated risks to aquifer recharge zones or coastal watersheds from decentralized systems.

The potential for denitrification of OWT effluent before it reaches an aquifer, lake, or estuary can be enhanced by ecological engineering practices at the discharge site. While traditional drainfield designs discharged effluent into the subsoil to minimize the risks of surface ponding, this precluded the potential for plant uptake of nutrients and/or denitrification of effluent within the root zone. Because N removal OWTs substantially decrease soil clogging due to the reduced BOD and suspended solids in their effluent, the use of either shallow trench or subsurface drip distribution or irrigation (SDD/I) systems can serve as an additional measure to enhance N removal in the soil ecosystem after discharge from an OWT (Ayres Associates, 1998; Crites and Tchobanoglous, 1998; Holden et al., 2004; Oakley et al., 1999; Jnad et al., 2001; US EPA, 2002). Both systems have the potential to promote nitrogen removal or sequestration if effluent is discharged directly within

the root zone. Lawns, for example, can be effective N sinks, capable of sequestering substantial amounts of N through immobilization in soil organic matter (Raciti et al., 2008). With improved understanding of “hot moments” conducive to denitrification (Groffman et al., 2009), timing of wet/dry cycles associated with effluent dosing may be tailored to generate partial saturation and optimize N removal within the dispersal zone. The data for centralized wastewater reuse for irrigation of crops throughout the US demonstrate that N concentrations in the soil percolate can easily be reduced below 10 mg/L TN due to plant uptake if application is timed with the growing season (WEF, 2001; US EPA, 1981). To date, the results on the use of shallow trenches or SDD/I systems in unmended soil for onsite nitrogen removal is mixed, with removal efficiencies of total N ranging from 0 to 40% (Ayres Associates, 1998; Bohrer and Converse, 2001; Oakley et al., 1999). Below the topsoil, reactive solid carbon bioreactors, using sawdust or woodchips as a carbon source, can serve as an additional treatment to foster denitrification. The bioreactors are used as horizontal layers to intercept percolating wastewater or as walls to intercept groundwater flux from a site (Schipper et al., this issue).

In some situations, an aquifer or watershed-scale perspective may demonstrate additional opportunities for denitrification of domestic wastewater – as the waste stream moves from the point of discharge to a receiving water or community well field. While limited or negligible transformations and dilution of OWT plumes have been observed in aerobic, unconfined sand aquifers (Robertson et al., 1991; Ptacek, 1998; Harman et al., 1996), NO₃⁻ plumes can exhibit rapid declines in nitrate levels over very short distances (3 m) if the plume traverses denitrification hotspots (Groffman et al., 2009), such as carbon enriched deposits along shorelines (Robertson et al., 1991); in these instances the plume must contact carbon-rich medium for denitrification to occur. Limestone aquifers exhibit extremely limited NO₃⁻ transformations (Keeney, 1986; Dillon et al., 1999), while NO₃⁻ removal, presumably from denitrification, has been observed in anaerobic plumes moving through some sand aquifers with elevated solid phase organic carbon, and in aquifer zones dominated by pyrite rich deposits (Pederson et al., 1991; Robertson and Cherry, 1992; Aravena and Robertson, 1998; Postma et al., 1992; Korom, 1992). Other NO₃⁻ sinks include riparian wetlands, lakes and reservoirs, and headwater streams (Kellogg et al., this issue).

6. Conclusions

OWTs have long been implicated as being a major contributor to N inputs to the aquatic environment in certain N-sensitive areas and as a result many regulatory bodies have promulgated TN effluent standards for OWT discharges. These standards, however, unlike those for centralized wastewater treatment, have been developed without statistical consideration of sampling frequency, percentile limits, and acceptable levels of compliance. The results of the reliability and stability analysis of the best available data for decentralized N removal studies presented here show the vast majority of OWTs do not approach the reliability and stability of centralized treatment and cannot comply with most effluent standards with 50% probability. Given the difficulties in controlling key performance factors at the decentralized level (variable flows and constituent loadings, inhibitory compounds, analytical monitoring, process adjustment), even identical OWTs at different sites can exhibit mean effluent concentrations that vary by a factor of two.

Passive, natural systems designs offer a more robust alternative, use the least amount of energy of any OWT system, and exhibit treatment performance equivalent to centralized plants; the postanoxic SPSF/DB is a good example of this design. However,

the large areal footprint of these systems restricts their use to large lot settings and argues for the use of compact, mechanized OWTs to improve N removal in settings with limited land area. After discharge from an OWT, further N removal in the immediate vicinity of the discharge zone can be enhanced with shallow trenches and sub-surface drip distribution/irrigation systems designed to promote denitrification in the carbon-rich root zone and N uptake by plant roots, and the installation of solid carbon denitrification walls or layers. Optimizing denitrification of residential wastewater warrants an approach that considers the trade-offs between treatment area, reliability, energy use, potential for mitigating sprawl, and potential for removal in natural sinks to minimize the consequences of elevated N loading at the aquifer and watershed scale. More comparative studies of long-term operation of OWTs under field conditions in other parts of the world are needed to further quantify performance capabilities.

Acknowledgements

This paper is a product of the workshop “Denitrification in Managed Ecosystems” held May 12–14, 2009, at the University of Rhode Island Bay Campus, Narragansett, RI, with support from the Denitrification Research Coordination Network of the National Science Foundation, award DEB0443439, and the USDA CSREES Northeast States and Caribbean Islands Regional Water Project, award 2008-51130-19504.

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