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Toward Better Decentralized Wastewater Treatment

Editor's Note: The National Environmental Health Association strives to provide up-to-date and relevant information on environmental health and to build partnerships in the profession. In pursuit of these goals, we have partnered with the Office of Research and Development (ORD) within the U.S. Environmental Protection Agency (U.S. EPA) to publish two columns a year in the *Journal*. ORD is the scientific research arm of U.S. EPA. ORD conducts the research for U.S. EPA that provides the foundation for credible decision-making to safeguard human health and ecosystems from environmental pollutants.

In these columns, authors from ORD will share insights and information about the research being conducted on pressing environmental health issues. The views and conclusions in these columns are those of the author(s) and do not necessarily represent the views or policies of U.S. EPA. Any mention of trade names, manufacturers, or products does not imply an endorsement by the U.S. government or U.S. EPA. U.S. EPA and its employees do not endorse any commercial products, services, or enterprises.

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Introduction

Clean water is essential to human and ecological health and robust economies. Many pollutants can impair water quality, and domestic wastewater is an important source of pollutants. An estimated 32 million housing units in the U.S., more than 25%, are not connected to sewers and centralized wastewater treatment plants but instead use decentralized or onsite wastewater disposal systems that vary in form and function (Maxcy-Brown et al., 2023). In at least 15 states, households have straight pipes that discharge raw sewage to open pits or streams. Cesspools and septic systems that discharge effluent below ground can contaminate drinking water wells and groundwater-receiving surface waters. Direct and indirect exposure to wastewater containing bacteria, viruses, nutrients, pharmaceuticals, and per- and polyfluoroalkyl substances (PFAS), among other regulated and emerging contaminants, contributes to a wide range of potential hazards for people and ecosystems.

In coastal counties, where approximately 40% of the U.S. population live (National Oceanic and Atmospheric Administration, 2013), onsite wastewater treatment systems (OWTS) are found at high densities, largely in the form of conventional septic systems. Pollutants in effluent are only partly treated by underlying soils, sediments, and associated microbial communities. Groundwater is often the sole source of drinking water, and it transports nutrients and co-pollutants in wastewater to aquatic ecosystems. Along with rising temperatures, excess nutrients increase the likelihood of nuisance and harmful algal blooms (HABs). Blooms can deter tourism, produce toxins harmful to humans and animals, cause fish kills, and destroy habitats over time. In the Northeast, effluent from dense unsewered housing has overloaded estuaries, which have lost seagrass, fish, and shellfish, undermining blue economies and ways of life that depend on coastal waters.

Solutions-Driven Research

The Office of Research and Development (ORD) within the U.S. Environmental Protection Agency (U.S. EPA) works closely with local, regional, and federal partners to advance remedies for excess nutrients and co-pollutants across the country. In Cape Cod, the southeast arm of Massachusetts, estuaries are impaired by excess nitrogen that is predominantly sourced by OWTS. Estuarine total maximum daily loads (TMDLs) call for significant reductions in wastewater nitrogen to restore

Photo 1. Installation of a NitROE Waste-Water Treatment System with woodchip bioreactor in a neighborhood-scale demonstration study in Cape Cod, Massachusetts. Photo courtesy of Dr. Laura Erban, U.S. Environmental Protection Agency.

FIGURE **1**

Location of the Study Area in Cape Cod, Massachusetts

Note. The study area is where the field performance of enhanced innovative/alternative septic systems with woodchip bioreactors is being evaluated.

ecological functions (Cape Cod Commission, 2015). Partners are pursuing sewer extension, treatment plant upgrades, and advanced septic systems, locally known as innovative/alternative (IA) OWTS, among other approaches, to meet TMDL targets. IA OWTS designed for nitrogen removal enhance biological treatment prior to effluent discharge and vary in process configuration, performance, cost, and availability to potential users.

OWTS technologies are permitted by each state, and homeowner access varies among them. For instance, the Massachusetts Department of Environmental Protection requires 50 installations and 3 years of monitoring to consider general use approval for an IA septic system. Local jurisdictions and boards of health largely determine use requirements at specific locations. The Massachusetts Department of Environmental Protection has recently established a performance goal for Best Available Nitrogen Reducing Technologies (BARNT) of total nitrogen in effluent <10 mg/L. Currently there are no technologies approved for general use at this level in the state (Massachusetts Department of Environmental Protection, 2024), where IA septic systems have historically sought to achieve effluent total nitrogen levels of <19 mg/L. The NSF/ANSI 245 certification for residential wastewater treatment systems, which has not been accepted in most states, requires 50% total nitrogen reduction, but that is not enough in watersheds with higher removal targets (NSF, 2024).

Woodchip bioreactors offer a relatively simple way to achieve greater nitrogen removal (Photo 1). Long used to treat agricultural runoff and groundwater plumes, in a septic system they can help remove nitrogen by 80–90%, and significantly attenuate some organic contaminants from pharmaceutical and personal care products in domestic wastewater (Gobler et al., 2021). Woodchips provide an accessible substrate and carbon source for microorganisms that denitrify nitrogen in effluent under anoxic conditions. The wastewater must be aerated first (to nitrify it), either in unsaturated porous media or a mechanically aerated tank. Woodchips can be used in the lower layer of a septic system leach field, within a multi-compartment or stand-alone tank. Performance depends on both design and operations, as these influence flow, wastewater composition, and the growth, maintenance, and activities of diverse microbial communities needed for treatment.

ORD is engaged in an intensive evaluation of IA septic systems with woodchip bioreactors in Barnstable, Massachusetts (Figures 1 and 2). At 14 neighboring homes, the Barnstable Clean Water Coalition has installed two technologies in pilot and provisional phases of permitting in Massachusetts: the NitROE Waste-Water Treatment System and a nonproprietary modified leach field system designed by the Massachusetts Alternative Septic System Test Center (MASSTC), a division of the Barnstable County government.

Systems are sampled monthly by MASSTC. Discrete nutrient analyses and continuous flow monitoring are used to determine removal efficiency and final effluent loads. ORD, in cooperation with the U.S. Geological Survey's New England Water Science Center, has developed a network of monitoring wells with multiple sites in the area for enhanced wastewater treatment and surrounding areas with comparable unsewered housing density (2–5 per acre) to assess changes in groundwater quality.

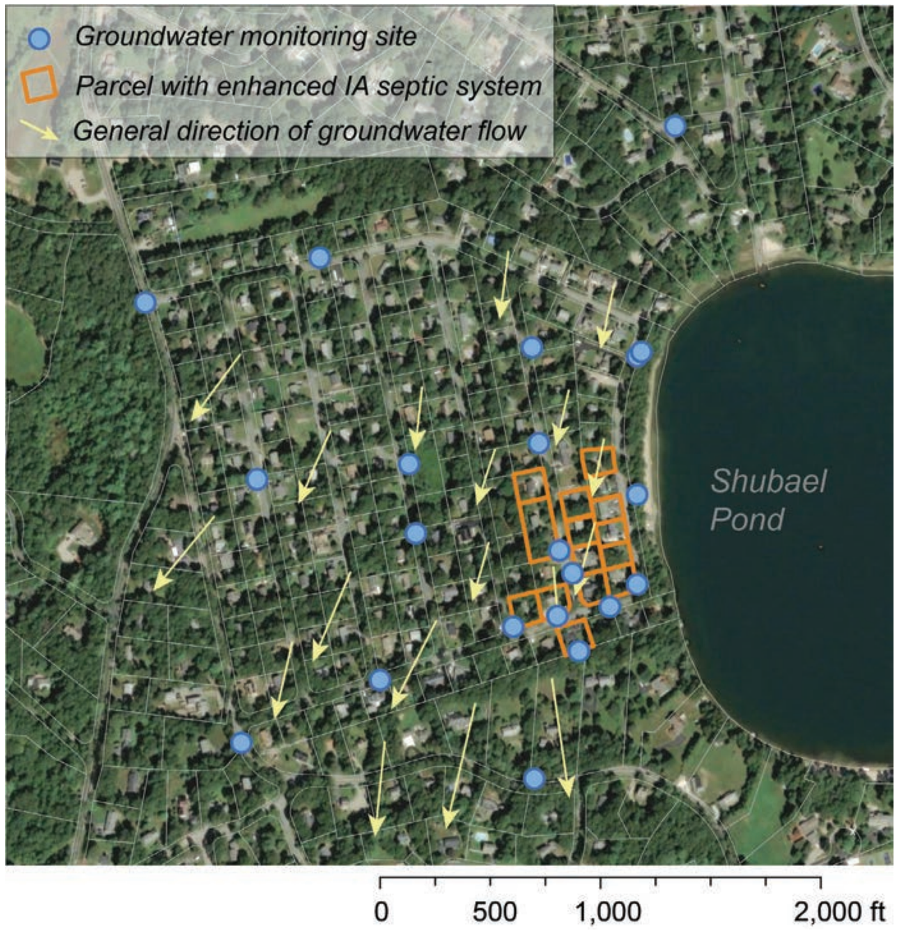
Over the first 2 years of monitoring, performance of the enhanced septic systems has been high overall. When operated at design consistent flow rates and adequately aerated, they have reduced nitrogen levels in the influent by 90–99% to a mean effluent concentration of 7.6 mg/L (median = 6.2 mg/L). The systems are capable of sustained effluent total nitrogen at <3 mg/L. Episodic departures from this level of performance have, however, occurred due to both recognizable and unexplained factors. Reliability with respect to meeting the goal of 10 mg/L total nitrogen in effluent has been found in 58–100% of the samples, depending on the system (Erban et al., 2024).

Phosphorus removal by the woodchip bioreactor enhancements, which are not designed for this purpose, has averaged 30%, for a median effluent total phosphorus level of 5.6 mg/L. Phosphorus is often sequestered in leach field or subsurface sediments, but can break through to sensitive freshwater bodies depending on local conditions.

Over additional time and installations, performance measures will become increasingly informative to interested partners. It is already clear, however, that ensuring high performance will depend on operations, maintenance, and monitoring. Management by homeowners is the de facto model for conventional septic systems, which not infrequently experience hydraulic failure when sewage backs up into homes or the surrounding environment. Enhanced septic systems are at greater risk of not achieving intended outcomes owing to additional hardware components, treatment contingencies, and less obvious modes of failure (i.e., exceeding effluent quality limits). The systems in this study formed part of the basis for a Responsible Management Entity at MASSTC known as the Septic Utility Program, with funding from U.S. EPA. Septic utilities can help guide decisions on technologic selection; economize on operations, maintenance, and monitoring; and verify and improve effluent quality.

FIGURE **2**

Study Neighborhood in Detail



Note. Parcels where the systems were installed are outlined in orange. Groundwater monitoring locations are indicated with light blue circles. Yellow arrows indicate the general direction of groundwater flow, inferred from monitoring well data. Basemap credit: Earthstar Geographics. IA = innovative/alternative.

Broader Impacts

Enhanced septic systems that perform well in the Cape Cod context have potential to do so more broadly. The area's cold winters, though mild relative to some parts of the U.S., are a challenge for biological treatment. Much of the Northeast, Southeast, Midwest, and Northwest areas of the U.S. experience comparable or warmer climatic conditions and rely on onsite or decentralized wastewater treatment. Where nutrient pollution is a recognized—or underappreciated—threat to water resources, decentralized systems that make use of woodchip bioreactors might be a feasible option for mitigation. The technologies tested in this work can be retrofit to existing septic systems, making use of functional tanks and leach fields, or serve clusters of homes or larger facilities.

Remedies and preventive measures for OWTS pollution depend on local conditions and alignment across sectors and scales of governance. On individual lots, available space, soils, depth to groundwater, regulations (local, state, and in select cases, federal), and service providers co-determine what can be installed. At parcel to municipal levels, treatment interventions include full sewer connection, liquid-only sewers, and enhanced septic systems with or without source separation (e.g., graywater, blackwater, urine diversion). Source control cannot address legacy wastewater pollution in groundwater, but that can be partly mitigated using nature-based solutions like wetland restoration.

Coordination is a challenge, as the responsibility for sources and receiving waters is broadly distributed. Focused collaboration is needed to implement technically effective, socially acceptable alternatives and improve environmental outcomes.

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Did You Know?

After a disaster—such as a hurricane, wildfire, or earthquake—septic systems might be damaged and fail to operate correctly. We worked with subject matter experts and national partners to develop a tool kit with guidance for these different types of emergencies. Learn more at www.neha.org/preparedness-septic.