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Septic systems as sources of organic wastewater compounds in domestic drinking water wells in a shallow sand and gravel aquifer

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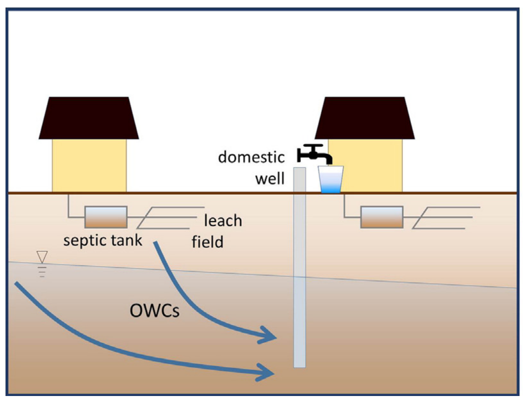
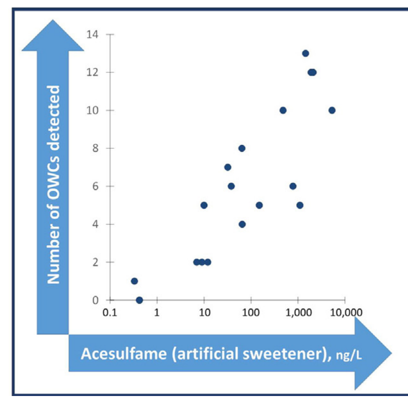
HIGHLIGHTS

- We tested 20 domestic drinking water wells for 117 organic wastewater compounds.
- PFASs, pharmaceuticals, and an artificial sweetener were most frequently detected.
- Nitrate, boron, and well depth were all correlated with PFASs and pharmaceuticals.
- Acesulfame (artificial sweetener) is a sensitive marker of OWCs in groundwater.
- Septic systems are likely the main source; landfills may also affect some wells.

GRAPHICAL ABSTRACT





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ABSTRACT

Domestic drinking water wells serve 44 million people in the US and are common globally. They are often located in areas served by onsite wastewater treatment systems, including septic systems, which can be sources of biological and chemical pollutants to groundwater. In this study we tested 20 domestic drinking water wells in a sand and gravel aquifer on Cape Cod, Massachusetts, USA, for 117 organic wastewater compounds (OWCs) and for inorganic markers of septic system impact. We detected 27 OWCs, including 12 pharmaceuticals, five per- and polyfluoroalkyl substances (PFASs), four organophosphate flame retardants, and an artificial sweetener (acesulfame). Maximum concentrations of several PFASs and pharmaceuticals were relatively high compared to public drinking water supplies in the US. The number of detected OWCs and total concentrations of pharmaceuticals and of PFASs were positively correlated with nitrate, boron, and acesulfame and negatively correlated with well depth. These wells were all located in areas served exclusively by onsite wastewater treatment systems, which are likely the main source of the OWCs in these wells, although landfill leachate may also be a source. Our results suggest that current regulations to protect domestic wells from pathogens in septic system discharges do not prevent OWCs from reaching domestic wells, and that nitrate, a commonly measured drinking water contaminant, is a useful screening tool for OWCs in domestic wells. Nitrate concentrations of 1 mg/L NO_3-N, which are tenfold higher than local background and tenfold lower than the US federal drinking water standard, were associated with wastewater impacts from OWCs in this study.

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1. Introduction

Domestic drinking water wells, which serve 14% of the US population (44 million residents; Maupin et al., 2014) and are common globally, are often impacted by wastewater and other contamination sources. They are often shallower than large volume public supply wells and thus more vulnerable to contaminants, which often exceed drinking water standards. Unlike public supply wells, domestic wells are not regulated under the US EPA's Safe Drinking Water Act and many well owners do not regularly test their well water quality. In 2009, the US Centers for Disease Control and Prevention initiated its Unregulated Drinking Water Initiative to address domestic well water quality. One of the Initiative's goals was to better understand current water quality conditions in domestic wells throughout the US (Backer and Tosta, 2011). In a sampling of over 3800 domestic wells in Wisconsin, USA, 47% exceeded at least one health guideline for nitrate, coliform bacteria, fluoride, or metals (Knobeloch et al., 2013), and a compilation of domestic well testing throughout the US showed exceedances of drinking water standards in 8.4% of wells for nitrate and 11% of wells for arsenic (Focazio et al., 2006).

Domestic wells are commonly used in communities that are served by onsite wastewater treatment systems (e.g., septic systems, cesspools), which can be sources of pathogens and chemical contaminants to groundwater. Leachate from septic systems is likely to contaminate domestic wells in areas with high septic system density (Bremer and Harter, 2012). Coliform bacteria counts and nitrate and phosphate concentrations were higher in domestic wells closer to septic tanks in Florida (Arnade, 1999), and diarrheal disease in children was associated with density of nearby septic systems in Wisconsin (Borchardt et al., 2003).

In addition to conventional pollutants like nitrate and coliform bacteria, septic systems are also sources of organic wastewater compounds (OWCs), such as pharmaceuticals, personal care products, and organophosphate flame retardants (Hinkle et al., 2005; Swartz et al., 2006; Conn et al., 2010). Some OWCs are endocrine disrupting compounds (EDCs) that can alter hormone signaling; some have been linked to reproductive effects in fish and other freshwater organisms (Brian et al., 2007) and recent studies have suggested a growing number of human health endpoints associated with EDC exposure (WHO/UNEP, 2013). Incomplete degradation or sorption during treatment in septic tanks and leach fields, as well as leaks of poorly treated sewage from aging and failing systems, allow some OWCs to percolate through vadose zone soils and enter groundwater. Some OWCs can persist during subsurface transport and end up in groundwater (Swartz et al., 2006; Phillips et al., 2015), surface water (Standley et al., 2008; Dougherty et al., 2010) and drinking water (Verstraeten et al., 2005; Schaider et al., 2014). We previously found 18 OWCs in public supply wells on Cape Cod, Massachusetts, a region served by a sand and gravel aquifer where 85% of residents rely on onsite wastewater treatment systems (Schaider et al., 2014). Verstraeten et al. (2005) detected 14 pharmaceuticals in domestic wells in a shallow sand and gravel aquifer in central US and Erickson et al. (2014) detected several pharmaceuticals in domestic wells in both glacial and bedrock aquifers. However, despite widespread reliance on domestic wells and their vulnerability to pollution from septic systems and other sources, there is little information about the types and concentrations of OWCs in domestic wells.

The goals of this study were: (1) to measure OWC concentrations in domestic wells in areas served exclusively by onsite wastewater treatment systems; (2) to compare these concentrations with reports on other drinking water sources; and (3) to evaluate whether the presence of OWCs in domestic wells is correlated with other factors that may be proxies for septic system impact. Understanding the types and concentrations of OWCs in drinking water provides a basis for assessing OWC exposure and health risks from consumption of drinking water contaminated by household wastewater. Our results also provide insight into the characteristics of drinking water wells most likely to contain OWCs, which can inform source water protection and drinking water quality monitoring.

2. Materials and methods

2.1. Selection of wells

To select wells for OWC analysis with a wide range of septic system impact, we recruited participants throughout Cape Cod (Barnstable County), Massachusetts, USA and used a combination of GIS land use analysis and nitrate and boron testing to select 20 homes for sampling. Eighty-five percent of Cape Cod residents are served by onsite wastewater treatment systems and 20% rely on domestic drinking water wells. We recruited participants through electronic mailings, posters in public buildings, and coverage in local media.

For each of 110 wells whose owners volunteered for the study and provided an address, we used ArcMap (ESRI, Redlands, CA) to analyze land use within a capture zone around each well. To identify capture zones, we followed Kerfoot and Horsley's (1988) methodology for developing protective zones around domestic wells on Cape Cod. This method incorporates typical groundwater velocities and accounts for potential seasonal fluctuations in the direction of groundwater flow and pumping rates on Cape Cod. The shape of each capture zone is roughly elliptical, with a 30-m radius drawn around a line that starts at the well and extends 60 m in an upgradient direction (total area: 6500 m^2). Within each capture zone, we calculated the fraction of the area used for varying densities of residential development. We used 2005 land cover/land use data from MassGIS (Massachusetts Information Technology Division, 2012), which included 33 land use types and had a 0.5 m resolution. We used the results of the land use analysis to calculate an average number of homes per unit area (average density) within each protective zone and to calculate the total fraction of land area within each capture zone used for residential development (%RES). Additional information about the process is provided in Supplementary Material. Of the 110 candidate wells, we selected 50 wells as follows: 20 wells with the highest average density (1.2–4.5 homes/acre), 15 wells with the lowest average density (<0.14 homes/acre), and 15 wells with intermediate average density (0.2–1 homes/acre). In selecting wells with the lowest and highest average density, we excluded several wells because they were within 400 m of another well with similar density, and in selecting wells with intermediate density, we prioritized several towns (Eastham, Wellfleet, Truro) that rely almost exclusively on domestic wells, while also aiming to include wells throughout Cape Cod.

In order to gain a more accurate assessment of potential septic system impact in each well, we asked each of the 50 selected households to collect a water sample for nitrate (NO_3^-) and boron (B) analysis and to complete a questionnaire about well depth, results of prior water quality monitoring, and known water quality concerns. We used these results to select 20 wells for OWC analysis. While our well selection was not designed to be a statistical representation of domestic wells across Cape Cod, we aimed to include wells with low, medium, and high NO_3^- concentrations and a wide range of residential land use density in their capture zones. Of the 43 wells that we tested for NO_3^- and B, we selected 20 wells for OWC analysis as follows, using categories developed for Cape Cod groundwater (Massachusetts EOEA, 2004): 5 of 14 wells with low NO_3^- (<0.5 mg/L) and B (≤20 μg/L), 6 of 13 wells with moderate NO_3^- (0.5–2.5 mg/L) and B (20–50 μg/L), and all 9 wells with high nitrate (>2.5 mg/L). We oversampled wells with NO_3^- above 2.5 mg/L (45% of final 20 wells compared to 21% of the 43 wells tested for NO_3^- and B) to more thoroughly characterize OWC concentrations in wells likely to be most impacted. Within the low and moderate NO_3^- categories, we selected wells with a wide range of residential land use density (<0.1–2.3 homes/acre). Concentrations of NO_3^- and B presented in this paper are from the second round of sampling collected at the same time as samples analyzed for OWCs.