

Septic Systems in the Coastal Environment: Multiple Water Quality Problems in Many Areas

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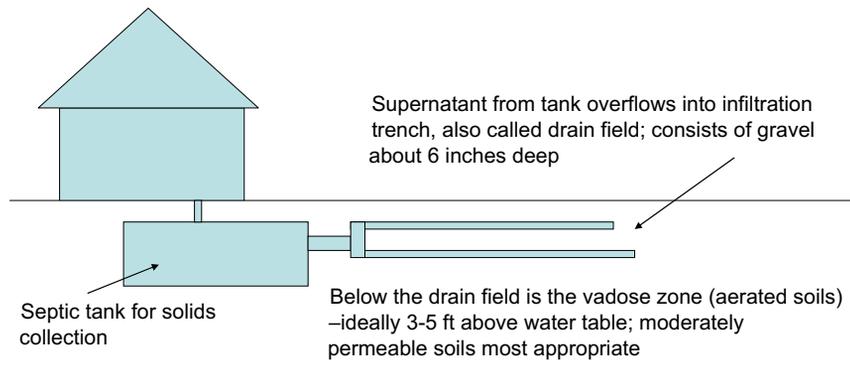
4.1 Septic Systems and Their Prevalence in the United States

The septic system is a relatively simple means of treating human sewage, also known as wastewater. These systems are the major subset of small-scale wastewater-treatment processes that fall under the acronym OWTSSs, or on-site wastewater-treatment systems. They play an important role in wastewater treatment because they provide a means of pollution abatement in rural areas, outlying suburban areas, and in areas that are distant from centralized sewage-treatment systems. A centralized sewage-treatment system requires a large capital expenditure (millions of dollars) and a consistent tax base to support its construction and maintenance [1]. In the areas mentioned above, one or both of the required financial support requirements may not be available. Septic systems can be small or large in that they have been used to treat human sewage from individual homes, multifamily structures, businesses and even hotels in both urbanized and rural areas. According to the United States Environmental Protection Agency (USEPA) [2], nearly one-fourth (23%) of homes in the US use septic systems, and they are particularly abundant in the Carolinas, Georgia, Alabama, Kentucky, West Virginia, Maine, Vermont and New Hampshire. Vermont has the highest septic-system usage (55%), and California has the lowest (10%). Reliance on septic tanks for wastewater treatment is often significant in waterfront areas in other coastal and inland areas [3]. This discussion will focus on septic systems for individual homes; for detailed information on multifamily or institutional systems, see Ref. [2].

How does a septic system function? At its simplest (Figure 4-1), a septic system consists of a septic tank and an overflow pipe connecting to a set of pipes that discharge liquid waste into a drain field [2,4]. Wastewater from the commode, sink, shower, and washing machine enters the septic tank, where solids are settled, grease is retained, and some anaerobic microbial digestion of sewage occurs. The remaining liquid waste (supernatant) passes through a filtered valve into a set of perforated pipes that discharge the waste in a diffuse manner into a drain field, which is also known as a distribution trench, leach field, soil absorption field, or subsurface wastewater infiltration system (Figure 4-1). The drain field is generally located 0.3–0.6 m (1–2 ft) below the ground surface and lined with gravel. In cold climates it may be from 0.9–1.2 m (3–4 ft) below the surface, to prevent freezing. The gravel and pipes are covered with a porous cloth which, in turn, is covered with soil and planted with grass. The drain field sits above a zone of aerated soil, called the vadose zone. The vadose zone is perched at some distance above the upper groundwater table, which is the eventual destination of the treated wastewater.

4.2 Septic System Pollutants and Treatment Processes

Wastewater contains pathogenic and other microbes (viruses, fecal bacteria, protozoans); organic material that exerts a biochemical oxygen demand (BOD) during decomposition; plant nutrients—total nitrogen (TN) and total phosphorus (TP) are of particular



Upper or surface water table receives treated leachate, which will flow in the direction of the groundwater movement

Fecal microbes, BOD and some nutrient species are treated in drain field by a combination of filtration, microbial consumption, microbial transformation, protozoan consumption; in underlying soil layer, adsorption of phosphate and ammonium can occur as well. Nitrate is not significantly removed in the septic-system process.

FIGURE 4-1 Stylized depiction of a septic system (not to scale). (For color version of this figure, the reader is referred to the online version of this book.)

importance to receiving aquatic ecosystems; surfactants from soaps and detergents; heavy metals; chemical cleaning agents; and other chemical environmental contaminants, such as personal care products including prescription medications, over-the-counter drugs and vitamins, makeup products, and anything else that people flush down sinks and toilets (Table 4-1). After wastewater enters the septic tank, the solids settle and the tank requires to be regularly pumped out to prevent problems. The remaining liquid

Table 4-1 Approximate Concentrations of Typical Pollutants in Raw Domestic Wastewater

Parameter	Concentration (mg/L)
Total solids	500–880
Total suspended solids	155–330
Biochemical oxygen demand (BOD ₅)	155–286
Ammonium-N	4–23
Nitrate-N	<1
Total nitrogen	26–75
Soluble phosphorus-P	7
Total phosphorus	7–12
Surfactants	9–18
Fecal coliform bacteria (as CFU/100 mL)	10 ⁶ –10 ⁸

From Refs. [2,47]; City of Wilmington, NC, records.

waste passes through a screened valve and is transported to the drain field. As the liquid waste is discharged over the gravel in the drain field, many of the constituent pollutants undergo removal or reduction. Some dewatering occurs by evaporation, especially in warm climates or seasons, and there is also some uptake and transpiration through overlying grasses. Pollutant removal occurs as a result of filtration, aerobic decomposition, chemical transformation and microbial interactions. A biological mat (biomat or biofilm) forms over the gravel in the drain field of a regularly used septic system. Within the biomat, nitrogen (N) and phosphorus (P) nutrients are taken up by soil microbes, and thus converted from inorganic nutrients into living material. These bacteria, in turn, are consumed by protozoans and small macrofauna such as nematodes. Microbial transformations of elements also occur, such as nitrification, which is the oxidation of ammonium to nitrite and nitrate under aerobic conditions facilitated by the bacteria *Nitrosomonas* and *Nitrobacter*. Another process is called denitrification, which is the microbial conversion of nitrate to elemental nitrogen gas, N_2 . This process is considered beneficial because it involves the microbial conversion of the pollutant, nitrate, into elemental nitrogen gas, N_2 . Little denitrification occurs, however: this process is most efficient under anaerobic conditions, which are the least efficient conditions for removal or reduction of the remainder of the pollutants in wastewater.

Labile carbon, which creates the majority of the BOD in wastewater, is used as a substrate by bacteria. As the liquid percolates from the drain field down through the vadose zone, other wastewater components such as orthophosphate, ammonium, and some metals are adsorbed by the soil particles. Some of the fecal bacteria are consumed by protozoans and other grazers; others are filtered within the biomat, and still others are adsorbed by soil particles beneath the drain field. Death to enteric microbes also occurs over time because they are removed from their optimal (intestinal tract) growth conditions into a hostile environment characterized by different conditions of temperature, DO concentrations, pH, etc. Treatment processes and efficacies for constituents such as nutrients, fecal microbes, and BOD are well documented, but effectiveness of treatment of residues from many personal care products is poorly documented for septic systems.

Aerated soils provide more effective treatment of fecal microbes than anaerobic soils. Regarding treatment efficacy, the greater the contact between wastewater and the soil particles in this aerated zone, the greater is the degree of treatment [4]. Under ideal circumstances septic systems can achieve nearly complete removal of fecal bacteria and BOD [2]. Unfortunately, under many circumstances septic systems and other OWTS have caused significant water-pollution problems involving microbial contamination of drinking water and bathing waters. Septic-tank leakage is the most frequently reported cause of groundwater (well water) contamination [5]. Such problems are largely caused by placing septic systems in locations inappropriate for adequate treatment.

What are the proper hydrological and geographical requirements for optimal septic-system usage? First, the soil should have moderate percolation capabilities. If the soils are

very rapidly drained, like many of the coastal sands, there will be little attenuation and adsorption of pollutants and many will pass through to reach groundwater. Alternatively, if the soil is too resistant to percolation (such as many fine-grained clays), surface ponding may result, wherein poorly treated wastewater sitting above the system is unable to drain through. Surface ponding obviously presents a health hazard to humans, pets, livestock, and wildlife. Thus, in permitting a site for septic-system usage, state agencies rely on soil tests of permeability to avoid surface ponding. A second key factor is the groundwater table. The USEPA [2] recommends that the vadose zone (aerated soil layer) should be at least 0.6 m (2 ft) and, ideally, up to 1.5 m (5 ft) in depth, but individual states often permit less depth to the water table. High water tables commonly lead to poorly treated sewage and pollution of nearby water bodies. An important consideration is that the depth of the upper groundwater table typically changes seasonally. In summer, the active terrestrial vegetation uses large quantities of groundwater and also transpires large volumes to the atmosphere. Evaporation is greatly enhanced in summer relative to winter; for example, in the Coastal Plain of North Carolina, a warm temperate state, evaporation increases by a factor of 6.5 between December and July [6]. Thus, in winter the seasonal groundwater table is normally closest to the surface relative to warmer seasons. Periods of rain cause the groundwater table to rise closer to (or even above) the surface, whereas drought lowers the groundwater table.

A third important factor influencing optimal septic-system usage is proximity to surface water bodies. In coastal areas characterized by relatively porous soils, plumes from septic-system drain fields move downslope until they encounter a body of water. Setback requirements vary widely among states and can be arbitrary [2]. For example, an analysis of off-site nutrient movement from septic systems on St. George Island, Florida, found that the legal setback limit of 23 m was inadequate to protect nearby surface waters from receiving elevated nutrients, and a 50 m setback was recommended for full protection [7]. Local ordinances should include science-based setback requirements from drinking wells, streams and lakes, and property lines to prevent off-site pollution.

In a given area, features such as the soil texture, the land slope, and the depth to the water table, control the area's carrying capacity for septic systems. Too many septic systems in the area will overwhelm the carrying capacity and render treatment ineffective [2,8,9]. Where there is excessive crowding, individual septic plumes may intermingle to pollute large areas of groundwater. Duda and Cromartie [9] working in six tidal watersheds in coastal North Carolina, found significant positive correlations between fecal and total coliform levels and increased densities of septic tank drain fields in the watersheds. They also reported that in watersheds where septic-system density exceeded 0.62 drain fields per ha (0.25 drain fields per acre), shellfish beds were closed due to high fecal bacteria counts; and in watersheds where drain field densities were less than 0.37 per ha (0.15 per acre), water quality was acceptable and shellfish beds were open. The USEPA has designated areas with greater than 0.15 septic tanks per ha (0.06 septic tanks per acre) as potentially problematic [5].

4.3 Septic Systems and Fecal Microbial Pollution

According to the USEPA (2002) [2], average water use in the US ranges from 150 to 265 L/day (40–70 gallons per day). Thus, areas with high septic-system density can contribute considerable pollutant loading to groundwaters and surface waters, if the septic effluent is not effectively treated by the soil. In the US, various documented disease outbreaks have been traced to drinking well contamination by fecal bacteria or viruses from septic-system drain fields [5]. In addition to the direct contamination of drinking waters, microbial pollution from septic-system drain fields was implicated as contributing to about one-third (32%) of the shellfish bed closures in a 1995 survey of US state shellfish managers (National Oceanic and Atmospheric Administration’s State of the Coast Report) [10]. Among coastal areas of the US, this type of shellfish-bed pollution was noted as particularly problematic in coastal areas of the Gulf of Mexico and the West Coast [10].

The location of septic systems in improper soils is a major fecal microbial pollution issue in surface waters and shallow groundwaters. Improper septic-system location occurs where drain fields are situated on porous soils such as sand, combined with a high water table. Research has demonstrated that at least 0.6 m of aerated soil is needed for adequate treatment of fecal microbes [4,11,12]. Accordingly, the USEPA (2002) [2] recommends that 0.6–1.5 m (2–5 ft) of aerated soil is needed to achieve nearly complete treatment of the wastewater before it enters the groundwater table. It is important to note that where soils are sandy, porous, and waterlogged, microbial pollutants such as fecal bacteria and viruses can flow through the soils laterally via the shallow groundwater to enter surface waters. For example, Scandura and Sobsey [3], found that septic-sourced viruses can travel rapidly in waterlogged soils—approximately 35 m in two days.

Another major microbial pollution problem occurs when septic systems are placed in soils that are too impermeable to permit proper percolation. This is primarily an inland phenomenon, where clay soils are common. As mentioned, in such circumstances, the polluted liquid from the drain field will seep to the surface, causing ponding. The high fecal microbial concentrations in such ponded wastewater make it an immediate health hazard to humans and animals that contact it. While ponded on the soil surface, the wastewater is also subject to rainfall, leading to storm water runoff that contains very high fecal bacteria concentrations [13].

4.4 Examples of Coastal Microbial Pollution from Septic Systems

4.4.1 Brunswick County, North Carolina

This area is characterized by sandy coastal soils that are poorly suited for wastewater treatment [8]. Nevertheless, it contains excessive densities of septic systems (20 per ha, or

8 per acre) and sampling within estuarine watersheds yielded the highest fecal coliform concentrations in association with septic tanks. Cahoon et al. [8] also reported high levels of N and P in septic-system-rich areas, with pollutant movement facilitated by ditching and draining activity.

4.4.2 Charlotte Harbor, Florida

Charlotte Harbor, the second largest estuary in Florida, is located on the west coast of that state. Approximately 37,000 septic systems are located within Charlotte County [14]. A study was undertaken to investigate the relationship between tidal movement and microbial water quality in a residential canal. The greatest abundances of fecal coliforms, *Enterococci* bacteria, and fecal coliphages were found at low- to outgoing tides, because the action of outgoing tidal water on the saturated soils drew septic-system-polluted groundwater into the canal on the falling tide. A further study of seven watersheds in the Charlotte Harbor system [15], found that fecal microbes were concentrated in areas of low salinity and high septic-system density. The highest pollution levels in this study were reported for a 292-ha (672-acre) watershed that contained 252 septic systems at a density of 0.94 septic tanks/ha (0.38/acre).

4.4.3 The Florida Keys

The Florida Keys presents a different problem with underlying soils. The Keys contain over 30,000 septic systems and injection wells into which raw sewage is disposed [16]. However, the soils are karst (limestone) and, thus, very porous [17]. Field experiments showed that fecal viruses injected into injection wells flow out through the porous soils into coastal waters within 10–53 h depending on location in the Keys, with movement as fast as 19 m/h in the Key Largo area [18]. Outgoing tides exacerbate this offshore movement of fecal waste [18]. Furthermore, microbial contaminants associated with human sewage have been isolated in mucus layers of coral heads in waters of the Keys [16], indicating that inadequate treatment by the abundant septic systems in that region can pose a health threat to humans (e.g., recreational divers) and beneficial aquatic life, even in marine waters away from the immediate coastline.

4.5 Septic Systems and Nutrient Pollution

Coastal water bodies, including tidal creeks, lagoons, riverine estuaries and the coastal ocean can be highly sensitive to nutrient pollution (i.e. eutrophication). This sensitivity to nutrient inputs is evidenced by formation of toxic and otherwise noxious phytoplankton blooms [19–21], overgrowths of periphyton and/or macroalgae that can smother seagrass beds and generate hypoxia (see Refs. [22,23] and references therein), and direct toxicity to sensitive seagrass species by nitrate or ammonium inputs (see Ref. [22]; and references therein). Production of noxious high-biomass algal blooms in many coastal waters has resulted in increased BOD which contributes to hypoxia [24].

Creation of more bacterial biomass provides more food for harmful algal species that can use mixotrophy for their nutrition (see Ref. [25]; and references therein). Mixotrophy is the concomitant use by algae of photosynthesis and heterotrophy to obtain nutrition. Eutrophic conditions typically are characterized by abundant dissolved organic substances from high organic loads and excreted or lysed materials, together with abundant particulate living matter such as bacteria, small phytoplankton, and protozoans, whose growth has been stimulated by the nutrient loading. These organisms are available for phagotrophy. Thus, all of these prey items and dissolved substances are available for consumption by mixotrophic harmful algal species (see Ref. [25]; and references therein).

In many coastal systems, N is the principal nutrient controlling phytoplankton growth (e.g., Refs. [26,27]), although P can limit or colimit algal growth in some situations [28]. Septic-system leachate can have high concentrations of ammonium in the tank (Table 4-1); in the drain field and beyond; inorganic nitrogen can be in the form of ammonium or nitrate, depending upon redox conditions.

The concentrations of nitrate known to cause enhanced algal growth can be quite low in these naturally oligotrophic coastal waters. Results of nutrient-addition bioassay experiments have shown that additions of 50–100 $\mu\text{g N/L}$ (3.5–7.0 μM) of nitrate can cause significant chlorophyll *a* increases over controls in systems as diverse as the coastal ocean [29], the lower Neuse Estuary [30], and North Carolina tidal creeks [31]. Mesocosm experiments have demonstrated that nitrate concentrations as low as 100 $\mu\text{g N/L}$ (7 μM) can cause direct toxicity to the seagrass *Zostera marina* (see Ref. [22]; and references therein). In coral reef systems, such as those near the shorelines of Caribbean islands, concentrations of inorganic nitrogen of 14 $\mu\text{g N/L}$ (1 μM) and concentrations of phosphorus of inorganic P of 3.1 $\mu\text{g P/L}$ (3.2 $\mu\text{g/L}$, or 0.1 μM) can promote eutrophication and coral reef degradation [32,33]. Thus, in coastal areas where septic systems are the dominant form of sewage treatment, excessive nutrients entering creeks, lagoons, and bays can cause serious environmental damage.

With sufficient aerated soil beneath the drain field, N in the wastewater is nitrified to nitrate, which is highly soluble and moves readily through soils. Plumes of nitrate sourced from septic systems have been documented to move more than 100 m from their source [2]. Under reducing conditions where nitrification is suppressed, elevated ammonia concentrations occur in the septic plumes [34]. While not as mobile in the soil as nitrate, under sandy, porous soil and waterlogged conditions, groundwater ammonia plumes can adversely affect nearby surface waters and increase eutrophication.

Nitrate pollution can be a human health problem where septic systems are placed near drinking-water wells. High concentrations of nitrate accumulate in groundwater, and can exceed national standards (USEPA, Canada) of 10 mg nitrate N/L to protect against methemoglobinemia (blue-baby syndrome; [35]). Studies have shown nitrate concentrations well in excess of this standard in groundwater plumes draining septic-system drain fields [4,12,34,36]; and drinking wells have been contaminated by nitrate from septic systems [37].

Phosphate in the wastewater plume binds readily to soils and is much less mobile than nitrate [4], such that considerable phosphate sorption occurs in the vadose zone [34]. Even so, under sandy soil conditions or conditions where long usage has led to saturation of phosphate sorption capacity in soils, phosphate concentrations exceeding 1.0 mg P/L in septic-system plumes have been documented as far as 70 m from point of origin [34]. For septic systems serving homes or cottages along lake shores, the phosphate from septic effluent leachate can contribute to algal blooms and the eutrophication of fresh waters. Karst regions (e.g., in Florida) and coarse-textured soils low in aluminum, calcium and iron present the biggest risk of phosphate movement and water contamination [2]. Thus, in Florida it has been estimated that nearly three-fourths (74%) of the soils have severe limitations to conventional septic-system usage [2].

4.6 Examples of Coastal Nutrient Pollution from Septic Systems

4.6.1 Florida Keys

The principal means of wastewater disposal in the Florida Keys is OWTSS—primarily 30,000 conventional septic tanks [16,17]. The soils are porous limestone in many areas and, as noted, subject to rapid transmission of septic-sourced nutrients. The vadose zone over the groundwater table is, on average, only 40 cm [17]. Numerous constructed residential canals, built to facilitate boaters' access to the ocean, provide inadequate space between septic drain fields and surface waters. Lapointe et al. [17] determined that groundwaters adjacent to septic drain fields were enriched 400-fold in dissolved inorganic N, and by 70-fold for soluble P. The wet season increases hydraulic head, and this, in combination with tidal movement, forces nutrients into the canals. The canal waters and nearby seagrass meadows outside of the canals, receive elevated N and P loading from septic leachate and show eutrophication symptoms of algal blooms and hypoxia relative to other, nearby ecosystems [28].

4.6.2 Chesapeake Bay

Seagrass beds are critical coastal habitat for production of commercially and ecologically important finfish and shellfish, and protect the sediments from erosion by wind, wave and currents (see Ref. [22] and references therein). In Chesapeake Bay a statistical analysis of factors influencing seagrass growth and survival in 101 subestuaries showed that a sharp decline in seagrass coverage occurred where watershed septic-system density exceeded 39/km² (0.39/ha or 0.16/acre) [38]. Another set of septic-system-impact studies was conducted at three Virginia Chesapeake Bay tributary watersheds [39]. This study found significant attenuation of TP and fecal microbes in the drain field, but the dissolved inorganic N concentrations reaching the estuarine shoreline were 50- to 100-fold higher than in nearby open waters. The groundwater

loads of dissolved N to shoreline waters were estimated to be equivalent to ground-water loads from row crop agriculture.

4.6.3 Maryland

A statistical study of land use factors potentially impacting nitrate concentrations in community well-water systems was undertaken in three Maryland provinces: the Eastern Shore, Southern Maryland, and the Piedmont [40]. A highly significant relationship was reported between community-well-water nitrate concentrations and the number of county septic systems. The models indicated that a 1% increase in the number of septic systems in a county was associated with a 1.1% increase in well-water nitrate concentration.

4.7 North Carolina's Outer Banks—Idyllic, but Not for Septic Systems

4.7.1 Background

This section describes in more detail a study conducted by the author.

The Outer Banks of North Carolina consist of a string of long, narrow islands stretching from the Virginia border south along the coast of the Atlantic Ocean for over 260 km. In historic times the Banks figured heavily in shipping commerce, but presently they are best known as premier vacation destinations for tourists, with abundant motels, rental homes, and second or third homes for inlanders with means. Most of the land is presently owned by the US National Park Service and is within the bounds of either Cape Hatteras National Seashore or Cape Lookout National Seashore. However, several municipalities that are densely populated (on a seasonal basis) abut Federal Park property. These population centers include the villages of Nags Head on South Bodie Island to the North, and the villages of Corolla, Rodanthe, Duck, Waves, Frisco, Hatteras and Ocracoke farther South. These villages are linked by Highway 12, which in some areas that are owned by the National Park Service is the only North-South road. Almost all of the human sewage produced on these islands is treated by septic systems.

As mentioned above, septic systems are most common in areas that are rural or otherwise decentralized, and the Outer Banks villages fall into this category. However, the hydrological and geological characteristics of these islands are not favorable to septic-system usage. The predominant soils in this area are Duckston fine sand and Corolla fine sand and have very rapid permeability above the water table, averaging from 0.3 to 0.5 m (12- to more than 20 inches) per hour [41,42]. Coupled with rapid soil permeability is a high local water table, which in much of South Bodie Island ranges from less than 0.3–1.2 m (less than 1–4 ft) from the soil surface [42]. In some areas of the Outer Banks wetlands are abundant, and some are subject to tidal water movement. These

characteristics lead to poorly treated waste and enhance the movement of pollutants to nearby waterways.

4.7.2 Sampling and Analysis

In 2007 a water sampling program was completed on surface waters within and near the northern portion of Cape Hatteras National Seashore (CAHA), where it borders the village of Nags Head on South Bodie Island. Nine stations were sampled on six dates between April and November, of which seven stations are described here. One is a control site; a pond located well away from human habitations designated CP. Another station (called URD) was near the terminus of a large drainage ditch (holding water continuously) that runs along the main road through urban Nags Head for several kilometers; the ditch subsequently empties into the Atlantic Ocean at a swimming beach located at CAHA ramp. The other sites were five large ditches, some of which were modified tidal creeks that flow westward from Nags Head into CAHA, then flow under Highway 12 and drain into Roanoke Sound. These ditches are strongly tidally influenced. They were designated as sites D1–D5 southward along Highway 12. The upper ends of these ditches are within a few meters of the last row of houses along the park border in Nags Head.

The sites were sampled for physical parameters including water temperature, salinity, turbidity, pH, dissolved oxygen (DO, sampled on-site using a YSI 6920 Multi-parameter Water Quality Sonde probe linked to a YSI 650 MDS display unit). DO concentrations were low on several dates at the ditch sites, especially D4 and D5. The two latter sites maintained mean and median DO levels below the North Carolina brackish water standard of 5.0 mg/L to protect aquatic life. Overall, DO concentrations in the drainage ditches were below the state standard on 33–83% of the sampling dates, depending on the site.

At each location water samples were collected from either shore or bridges for analysis of nutrients including TN (TN = TKN + nitrate), ammonium, nitrate + nitrite (hereafter referred to as nitrate), TP and orthophosphate. Analytical methods (see Refs. [43–45]) were as follows: TKN (USEPA 351.1), nitrate + nitrite (SM 4500-NO3-F), ammonia (SM 4500-NH3-H), TP (SM 4500-P-E) and orthophosphate (SM 4500-P-F). Chlorophyll *a* samples (in triplicate) were collected at all sites as a measure of phytoplankton biomass, and analyzed fluorometrically (USEPA 445.0). Septic leachate is a direct source of BOD, and as excess phytoplankton, periphyton, and macroalgae die, the decaying organic matter becomes another source of BOD which can subsequently depress DO [24]. Therefore, five-day BOD (BOD5) was sampled as well, and was analyzed using method SM 5210 B. Samples for two indicators of fecal pollution, fecal coliform bacteria and *Enterococcus*, were analyzed using membrane filtration methods (SM 922 D and USEPA 1600, respectively).

The data were subjected to summary statistical analysis in Excel (mean, standard deviation, median, range, geometric mean for fecal bacteria). Datasets were tested for normality using the Shapiro–Wilk test, with log-transformation required for subsequent

normalization of most parameters. Correlation analyses were used to investigate potential relationships between sampling parameters or between sampling parameters and environmental variables. These correlations included nutrient concentrations versus monthly municipal water use for the Town of Nags Head, with water-use data kindly provided by the Town of Nags Head, Department of Public Works, Water Operations. To investigate impacts of storm water runoff, fecal bacteria counts and nutrient concentrations versus local rainfall were tested in three ways (counts versus rainfall the day of sampling, counts versus rainfall the day of sampling plus total rain fallen within the previous 24 h, and counts versus rainfall the day of sampling plus cumulative rain fallen within the previous 48 h). Rainfall data for the nearest location, Manteo Airport on Roanoke Island (10 km from the sampling area), were obtained from the North Carolina State Climate Office in Raleigh, NC. Correlation analysis was used to investigate potential factors causing hypoxia, including BOD5 versus potential drivers including chlorophyll *a*, total organic carbon, and ammonium. A significance level of $\alpha = 0.05$ was used for all correlations except those involving fecal bacteria counts; due to the inherent high variability with bacterial counts (especially when caused by storm water), the significance level was set at $\alpha = 0.10$.

4.7.3 Findings

Average nitrate-N concentrations at most sampling sites were low to moderate (23–71 $\mu\text{g/L}$) and lowest at the control site CP (12 $\mu\text{g N/L}$). However, average ammonium concentrations in our sites were substantially greater, (175–247 $\mu\text{g N/L}$) with average ammonium at three ditches (D1, D5 and URD) exceeding 200 $\mu\text{g N/L}$. Average ammonium concentrations in those three sites were comparable to the average ammonium concentrations found in tidal Calico Creek, which accepts sewage effluent from a wastewater-treatment plant in Carteret Count, NC [46]. Thus, ammonium was the dominant inorganic N form, and was present in substantial concentrations in the sampled areas. Since, as discussed, an aerated vadose layer is required beneath septic-system drain fields for nitrification of sewage N to nitrate to occur, the high water table in the area [42] may have prevented appreciable nitrification of septic system waste. Ammonium is a by-product of sewage (see Ref. [47]; and also Table 4-1) and it was hypothesized that the primary source of ammonium loading to these waters was septic leachate (decaying organic matter is also a source of ammonium). Additionally, periodic low DO concentrations in the ditches may favor the predominance of ammonium (a reduced N compound) rather than the oxidized nitrate form of N. Thus, the elevated ammonium signal suggests that septic-system leachate impacts area groundwater and ditches. It predominates as the principal inorganic N form sourced from barrier island septic systems in sandy soils with a high water table [12]. Seasonally, ammonium concentrations peaked in mid-summer and showed a strong correlation ($r = 0.834$, $p = 0.039$) with monthly water use in Nags Head (Figure 4-2). Ammonium concentrations in summer, when human presence is highest and septic-tank usage is greatest, rose to 3- to 5-fold higher than levels in spring and fall.

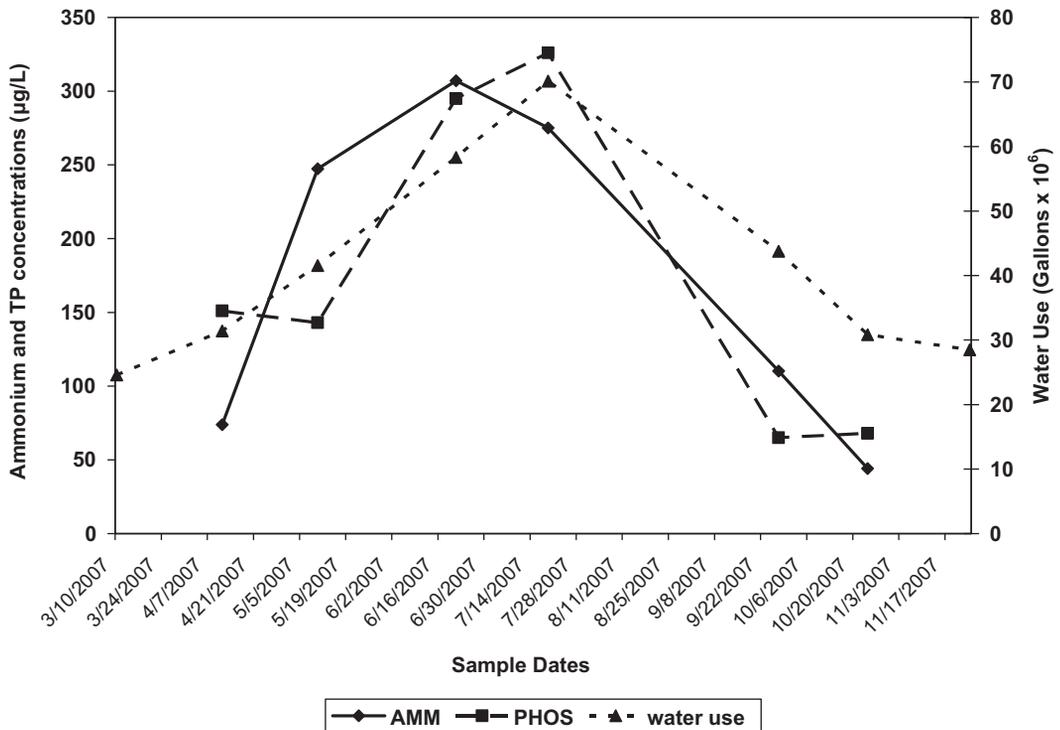


FIGURE 4-2 Ammonium-N and total phosphorus (TP) concentrations over time in South Bodie Island stations in and near Cape Hatteras National Seashore, compared with monthly municipal water use for the town of Nags Head. Nutrient data are averages of nine stations.

Orthophosphate concentrations were generally high, and highest in the first two ditches crossing Highway 12 (D1, 250 µg P/L; D2, 176 µg P/L) and the urban ditch in Nags Head (178 µg P/L). For all sites combined, the average and median TP concentrations were 249 µg P/L and 247 µg P/L, respectively. In comparison with stream and lake data, TP concentrations at all sites except the control pond (TP – 57 µg P/L) would be considered to be representative of eutrophic waters [48,49]. Seasonally, the highest concentrations were in June and July, and TP concentrations were strongly correlated with human water use in the Town of Nags Head ($r = 0.865$, $p = 0.026$; Figure 4-2). These data would also support the premise that septic leachate, which contains elevated phosphorus, is contributing significantly to water bodies near the populated areas.

Ratios of N to P in water bodies can provide insight into sources of nutrients; for example, fertilizer has generally high N/P ratios, so that if elevated N/P ratios are found in a lake or stream, the nutrients may originate from lawn, ornamentals or crop fertilization. Historically, N/P ratios much less than 16 (the Redfield ratio) were generally considered indicative of situations where N limited algal growth, while P was considered to be

limiting when ratios were considerably higher than 16. The control site in this study, control pond CP, had a median inorganic N/P ratio of 17.7, very close to the Redfield Ratio, while the TN/TP ratio was 11.3, indicating little sewage influence. This site had one of the lowest TN concentrations, and by far the lowest P concentration of any site in the dataset. However, at all of the other sites, the excessive nutrient concentrations and very low N/P ratios suggest stoichiometric imbalance (see [50,51]). Median inorganic N/P molar ratio (i.e. ammonium, nitrate, and orthophosphate data) for the five Highway 12 ditches considered collectively, was 5.4, whereas the median inorganic N/P molar ratio for the runoff ditch URD was 3.3. Median TN/TP ratios ranged from 1.5 to 5.5, except for the control site. Sewage is rich in P relative to N, and has inorganic molar N/P ratios of 1–7 (see Table 4-1); thus, the low N/P ratios found at most sites indicate strong sewage influence.

Phytoplankton blooms were a frequent occurrence particularly in some of the ditches passing under Highway 12 (Table 4-2). The North Carolina State standard for acceptable algal biomass as chlorophyll *a* is less than or equal to 40 µg/L [52]. Stations D3 and D5 exceeded the State standard on three of six sampling dates. All of the sites sustained at least one algal bloom exceeding the State standard during the study, while the control pond and the urban runoff ditch maintained the lowest median chlorophyll *a* concentrations (Table 4-2). Average BOD5 concentrations ranged from 3.5- to 6.9 mg/L, with high concentrations in the ditches along Highway 12, and the lowest concentration in the beach drainage ditch (Table 4-2). There was a significant relationship between BOD5 and chlorophyll *a* ($p < 0.001$), with chlorophyll *a* explaining 43% of the variability in BOD5.

Table 4-2 Chlorophyll *a*, BOD5, Dissolved Oxygen, Fecal Coliform Bacteria and *Enterococcus* Bacteria Concentrations at Several Sampling Sites on South Bodie Island, North Carolina. Data Presented as mean ± standard deviation/median, Fecal Bacteria Presented as Geometric mean/median. Units are µg/L for Chlorophyll *a*, mg/L for BOD5 and DO, and Colony Forming Units (CFU)/100 mL for Fecal Bacteria

Site	Chlorophyll <i>a</i>	Five-day BOD	DO	Fecal Coliforms	<i>Enterococcus</i>
D1	31 ± 15	4.1 ± 1.5	5.6 ± 3.2	194	596
	33	4.0	5.4	312	632
D2	28 ± 13	4.8 ± 3.3	7.1 ± 4.5	213	443
	30	4.0	6.4	198	463
D3	38 ± 18	4.4 ± 1.8	6.0 ± 3.7	216	348
	41	5.0	5.5	225	297
D4	36 ± 32	4.8 ± 2.1	4.3 ± 3.0	305	272
	23	5.0	3.8	213	317
D5	83 ± 99	6.5 ± 1.6	3.7 ± 1.9	95	367
	49	6.0	3.1	163	358
URD	25 ± 16	3.5 ± 2.3	7.9 ± 3.0	204	6267
	20	2.5	7.6	188	4560
CP	27 ± 19	4.3 ± 1.9	9.0 ± 2.4	29	80
	21	4.5	9.3	83	60

The analysis suggests that stimulation of algal blooms in the ditches by labile N from septic leachate, created a BOD load that contributed to the low DO levels found in the ditch/tidal creek sites.

High fecal coliform bacteria counts characterized most of the sampling locations. Of the 54 samples collected, 26 exceeded the state freshwater standard for human contact (200 CFU/100 mL) [45] for an exceedence rate of 48%. The geometric mean fecal coliform bacteria count for the five Highway 12 ditches considered collectively was 192 CFU/100 mL (Table 4-2). As mentioned, the ditch site URD was sampled just upstream from where the outfall enters the swimming beach at Ramp 1 of CAHA. The control pond maintained the lowest geometric mean count of 29 CFU/100 mL (Table 4-2).

Enterococcus samples indicated even greater fecal bacterial pollution than the fecal coliform counts. Geometric mean *Enterococcus* counts for the five ditch sites on Highway 12 considered collectively were 391 CFU/100 mL. The geometric mean for the drainage ditch URD was 6267 CFU/100 mL, while control pond CP had a geometric mean of 80 CFU/100 mL. The North Carolina (and USEPA) beach water *Enterococcus* standard of 104 CFU/100 mL was exceeded on 44 of 54 occasions for an 82% exceedence rate. Some sites (D1, D2, URD) exceeded the beach water standard on all sampling dates.

Rainfall had a strong influence on fecal bacteria abundance and movement. There was a strong positive correlation between rainfall the day of sampling and *Enterococcus* counts at URD, the roadside ditch within the developed area ($r = 0.869$, $p = 0.020$), although there was no significant correlation ($p > 0.05$) between rainfall lagged 24 or 48 h. The rapid response of fecal bacteria in the beach drainage ditch URD to same-day rainfall indicates that it received urban storm water runoff that likely was contaminated with fecal microbes from dogs, cats, and urban wildlife. Based on the high ammonium concentrations, this beach drainage ditch may also have received septic system leachate from dwellings located east of the ridgeline in Nags Head, but urban storm water runoff appeared to be the major source of fecal microbial pollution.

The westward flowing ditches also maintained high fecal bacteria counts, well in excess of the fecal bacterial densities in the control pond. Correlation analysis between rainfall and the mean *Enterococcus* bacterial counts in the five westward flowing ditches showed that, in contrast to the urban ditch, there was no significant correlation between *Enterococcus* and rainfall on the day of sampling. However, *Enterococcus* counts were strongly correlated with lagged rainfall (for 24 h, $r = 0.938$, $p = 0.006$; for 48 h, $r = 0.938$, $p = 0.005$). Some of these ditches began within a few meters of the last row of houses in the developed area (Figure 4-3), yet there was no same-day effect of rain. It was hypothesized that surface storm water runoff had little impact on these ditch/creek sites. Given the strong delayed (24–48 h) rain signal, the rainfall apparently saturated the surface and applied vertical head to the shallow groundwater table, thus forcing lateral movement of groundwater (and associated septic leachate) through the porous soils into the drainage ditches flowing westward through the park. Since most of these drainage ditches were influenced by the tides, the outgoing tide tended to draw fecal bacteria from septic-influenced saturated



FIGURE 4-3 Close proximity of housing in the town of Nags Head, North Carolina, to drainage ditches/tidal creeks within Cape Hatteras National Seashore. (For color version of this figure, the reader is referred to the online version of this book.)

soils into waterways toward and possibly into the sound. The presence of drainage ditches exacerbates the movement of fecal microbes from polluted groundwater near the septic systems [8]. The present-day extensive septic system usage within Nags Head, shallow groundwater, porous soils, and lack of centralized sewage treatment promote pollution of nearby public waters with human-derived fecal microbes.

There is evidence that fecal bacteria find an environment conducive to survival and even growth in river and creek sediments, due to elevated nutrients and protection from UV radiation. For instance, following an animal waste spill [21] and a human sewage spill [53] fecal bacteria concentration were found to persist for months in sediments, as opposed to days in the water column. It is likely that the N- and P-enriched groundwater in septic plumes also provide a similar refuge environment for fecal bacteria in water-logged soils in coastal areas.

Microbial contamination of the waterways near Nags Head is also increased by local human water consumption. Abundance of *Enterococcus* in the sampling sites was positively correlated with town of Nags Head water use ($r = 0.336$; $p = 0.013$). This finding supports the premise that with more people in this resort area, more water is used, more wastewater is subsequently discharged into septic systems, and more *Enterococci* appear in local waterways.

In summary, the ditches and altered tidal creeks on South Bodie Island are polluted with high concentrations of fecal bacteria, ammonium and phosphate.

These contaminated waters support frequent algal blooms, and have elevated BOD and hypoxia. The high ammonium and phosphate concentrations and very low N/P ratios suggest a sewage source, notably septic effluent leachate. The delayed (24–48 h) fecal coliform response to rainfall in the ditches suggests lateral forcing of septic effluent leachate and polluted groundwater into the ditches. The strong correlation between ammonium, phosphate, and *Enterococcus* counts at the sampling sites with municipal water use also supports the premise that septic system pollution is impacting human health (fecal microbial) and the ecosystem (algal blooms, hypoxia) along Cape Hatteras National Seashore. Standard septic systems are clearly inappropriate for the porous soils and high water tables in this environment. North Carolina Environmental Health regulations requires septic-system drain fields to be at least 0.3 m (12 inches) above the water table, and at least 0.15 m (6 inches) of soil above the infiltration trench (15A NCAC 18A.1955). In much of South Bodie Island, septic drain fields are in contact with the water table, in violation of these regulations. As mentioned, the USEPA (2002) [2] recommends 0.6–1.5 m (2–5 ft) of unsaturated, aerobic soil above the water table—which is not available in much of the Outer Banks—for effective removal of fecal bacteria and BOD in septic effluent. There are also exceedingly large numbers of septic systems per unit area in this community, considering that dwelling unit density along the beach areas in Nags Head averages about 7.5/ha (3.0/acre) [54].

Several other communities adjoin CAHA property to the south of Nags Head, and septic systems are commonly used within the communities and within the park. It is of interest to note that Cape Lookout National Seashore, just to the south of CAHA, managed to greatly reduce sewage disposal problems (either by chance or design) by purchasing all of the homes of former permanent residents, and leaving just a few seasonal cabins for tourist use.

The study described above provides an example of surface storm water runoff and septic-system pollution from a coastal community entering a large public nature park that contains extensive estuarine and marine resources. Barrier islands and many low-lying coastal mainland areas share the physical characteristics of porous sandy soils, high water tables, and drainage into adjoining estuaries and coastal waters, including areas where shellfishing is a common occupation or recreational pursuit. In the US, development of barrier and other coastal islands continues to occur, particularly in the Southeast, including sewage treatment by septic systems [55,56]. For example, regulations on septic-system usage devised by a stakeholder group and approved by the South Carolina Department of Health and Environmental Control were subsequently rejected by a legislative review committee [56], leaving formerly pristine marsh island areas subject to future pollution. Similarly, residential building on Georgia marsh hammocks is ongoing [55], and septic-system use is likely to pollute the adjacent waters. Clearly, in low-lying coastal areas it is imperative to use alternatives to standard septic systems to treat human waste in order to protect both ecosystem quality and human health.

4.8 Minimizing Pollution from Septic Systems

Under suitable conditions, septic systems can serve as efficient and safe means of disposal of human waste, but proper placement of septic systems is key. Movement of fecal microbes off-site will occur if the soils are too impervious and ponding occurs, or if the soils are too porous (sandy or karst) and the water table is too high for an appropriately aerated vadose zone. Where there is a high water table, a “mounded” system in which the drain field is essentially located above the ground surface can provide an aerated vadose zone to achieve proper pollutant removal, and this approach has been effective in coastal soils [57]. Corbett et al. [7] recommended that such a system should provide 1 m of vadose layer above the surface.

Even under the best circumstances, pollution can move off-site if there are excessive densities of septic systems in a given area. Based on the various research efforts cited above, having more than 0.61 systems/ha (0.25/acre) has been shown to be problematic in terms of fecal contamination, while densities as low as 0.39 system/ha (0.16/acre) have shown nutrient (N)-based impacts on coastal ecosystems. As seen within this chapter, some coastal areas have far higher densities. Movement of leachate-polluted groundwater toward sensitive coastal water bodies is further enhanced when an area is ditched and drained for development, providing rapid conduits for nutrients and other wastewater constituents. Finally, risks to the environment and human health are increased when septic system use is prevalent near drinking water wells, surface water bodies that are nutrient-sensitive and coastal waters where shellfishing occurs. The placement of septic-system drain fields less than 50 m from surface waters increases nutrient pollution risks [7].

4.9 Summary and Conclusions

Septic systems are very common means of wastewater treatment in mainland coastal areas and on barrier islands. Unfortunately scientific studies from a variety of locations along the east and southeast coasts of the US have demonstrated incomplete treatment of sewage and subsequent pollution of nearby waterways. The principal pollutants documented as coming from septic systems include fecal microbes and nutrients, especially ammonium and phosphorus. Thus the pollutants are both concerns to human health (i.e. infection from human contact or contamination of shellfish) and ecosystem-level (algal bloom formation, BOD, and hypoxia). The principal reasons for off-site pollution in coastal areas are hydrological and geological. The water table is often <1 m from the surface, saturating septic drain fields. The soils are sandy and porous, or else karst and porous, so that pollutants in saturated drain fields can move readily through groundwater until surface waters are reached. The continued development of coastal mainland and island habitats for human use will lead to further such pollution; thus alternative means of treatment such as mounded individual systems, or small-scale treatment plants must be more widely required and utilized.

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