Demographic, landscape, and meteorological factors controlling the microbial pollution of coastal waters

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Abstract

Coastal areas in the United States and many other countries are considered to be desirable regions to live and recreate. However, as human use of coastal land and water increases, so does the incidence of aquatic-borne disease from contact with contaminated water and eating contaminated shellfish. Movement of humans into coastal areas both greatly increases the number of sources of microbial pathogens and radically alters the landscape through increased construction activity and paving of former natural areas. On a regional scale, increases in human population over a 14-year period in coastal North Carolina were strongly correlated with increases in shellfish bed closures due to high fecal coliform bacterial counts. On a watershed scale, an analysis of several tidal creeks found strong correlations between mean estuarine fecal coliform bacterial counts and watershed population, percent developed area and especially with percent impervious surface coverage. Conversion of natural landscapes to impervious surfaces (roads, drives, sidewalks, parking lots and roofs) removes the land's natural filtration capability, allows for increased concentration of pollutants at the land's surface and provides a means of rapid conveyance of pollutants to downstream waterways. An analysis of rural watersheds in the Coastal Plain found that stream fecal coliform counts and turbidity were both strongly correlated with rainfall in the previous 24 h in watersheds containing extensive industrial swine and poultry operations, as well as watersheds containing more traditional agriculture and cattle husbandry. In contrast, in watersheds rich in swamp wetlands these relationships were not significant, even in watersheds containing extensive animal production. Based on these findings, we suggest that waterborne microbial pathogen abundance can be minimized in urbanizing coastal areas through reduced use of impervious surfaces and maximal use of natural or constructed wetlands for passive stormwater runoff treatment. In animal husbandry areas, retention of natural wetlands and management practices designed to minimize sediment runoff can likely reduce inputs of pathogenic microbes into streams.

Introduction

During the latter part of the 20th century, there was a significant population increase in U.S. coastal areas, with coastal counties currently containing over half of the country's population (NSTC, 1995). Population increases bring about concurrent changes in the landscape, sometimes of a profound nature. More and more natural area is converted to urban and suburban development, which has major effects on water quality, availability and movement. Increases in coastal tourism can also bring about water quality problems (Kocasoy, 1989). Since coastal population and tourism increases are often driven by ready access to water-based recreational activity, factors that degrade the quality of recreational waters are likely to have negative human health and economic effects.

One of these factors is the problem of microbial pollution of coastal waters caused by humans and other warm-blooded animals. Human health risks associated with microbial vectors are a serious problem in coastal areas and may be increasing (NSTC, 1995; Epstein, 1998). These risks include direct exposure of humans to pathogen-contaminated waters and indirect

exposure through consumption of contaminated shellfish. Increases in human population cause increases in the potential number of sources of microbial pathogens. Moreover, changes in the landscape associated with land development can provide increased concentration and conveyance of microbial pathogens to downstream waters (Mallin et al., 2000a).

Interacting with these physical changes to the landscape are natural forcing factors. Rainfall, for instance, leads to stormwater runoff. Major changes in the landscape, such as replacing natural ground cover with paved surfaces, results in a net loss of mature vegetation (especially trees), disturbance and compaction of natural soils, and large increases in the amount of impervious surface area (Booth, 1991). These changes cause increases in stormwater runoff volume and rate of overland transport (Booth, 1991; Schueler, 1994), and degradation of receiving stream water quality (Klein, 1973; Griffin et al., 1980). In this paper, we examine the relationship between aquatic microbial pollution and several of these potential population, landscape and meteorological forcing mechanisms.

Because of its commonly used human health implications, in these analyses we concentrate on fecal coliform contamination as representing aquatic microbial pollution. Whereas fecal coliform bacteria may not necessarily be the most appropriate indicators for pathogenic microbes such as viruses and protozoans, they are the most commonly used organisms for water quality regulatory standards. Shellfishing waters in the United States are regulated by a Federal standard of 14 colony-forming units (CFU) per 100 ml of water (USFDA, 1995). Human contact waters are generally regulated by individual states (North Carolina's freshwater human contact standard is 200 CFU per 100 ml; NCDEHNR, 1996).

Materials and methods

Several data sets within coastal North Carolina, U.S.A., were analyzed with the goal of assessing the impact of demographic, landscape, and meteorological factors on aquatic fecal coliform bacterial pollution. We collected estuarine fecal coliform bacterial samples throughout the New Hanover County tidal creek system (Fig. 1) on a monthly basis at the same stations at or near high tide. In each creek, the stations were chosen to represent all salinity regimes from marine to freshwater. High tide collections were made as this was the only time many of the stations

were boat accessible. We also collected monthly freshwater fecal coliform samples from a series of sampling stations representing drainage from different rural watersheds located in the Cape Fear River watershed (Fig. 1). In both studies, bacterial samples were collected by placing sterile bottles 10 cm below the stream surface, facing into the flow. Samples were returned to the laboratory on ice and analyzed within 6 h of collection. A membrane filtration method (mFC) was used to quantify fecal coliform bacteria as colony forming units per 100 ml of sample (APHA, 1995). In the rural watershed study, turbidity was measured on station by nephelometry using a YSI 6920 Multiparameter Water Quality Probe (sonde) linked to a YSI 610 display unit.

Other data used in these analyses included the amount of shellfishing area closed due to excessive fecal coliform counts (supplied by the Shellfish Sanitation Section of the North Carolina Division of Environmental Health), and coastal population data (collected by the U.S. Census Bureau) for Carteret, Onslow, Pender, New Hanover and Brunswick counties (Fig. 1). GIS land use data sources included the New Hanover County Planning Department and the North Carolina Division of Water Quality. Rainfall data were supplied by the North Carolina State Climate Office of North Carolina State University, Raleigh. Wetland percentages were calculated using National Wetlands Inventory digital data (U.S. Fish and Wildlife Service, St. Petersburg, Florida) and North Carolina Subbasins digital data (USDA, Natural Resource Conservation Service, Raleigh, N.C.) on Arcview 3.1 software. For the sampling areas discussed in the 'Landscape and Meteorology' section, rural subwatersheds were chosen that lacked major point source discharges and contained very little impervious surface coverage. Correlation and regression analyses were performed using the Statistical Analysis System (SAS).

Results and discussion

Regional-scale analyses

When analyzing the effect of pollution on coastal waters, one readily quantifiable metric is the amount of shellfish harvest area closed due to high fecal bacterial counts. In the U.S., approximately 37% of estuarine waters classified for shellfish harvesting are closed or under harvest restrictions (NRC, 1993). In North Carolina, 95% of the clams and 50% of the oysters are harvested south of Cedar Island (N.C. Division
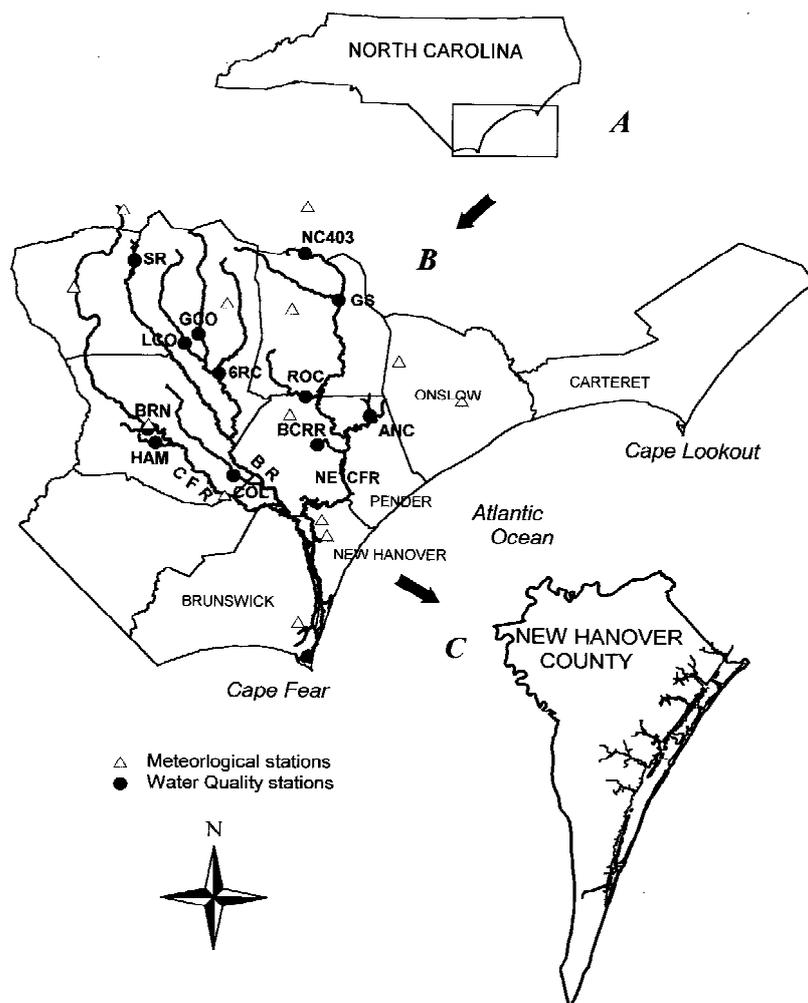
Figure 1. (A) Location of principal shellfishing counties in southeastern North Carolina, U.S.A. (B) Location of sampled agricultural subwatersheds in the Cape Fear River basin (station names are in text), and (C) Location of New Hanover County tidal creeks. CFR = Cape Fear River; BR = Black River; NECFR = Northeast Cape Fear River.

of Marine Fisheries records), or approximately within Carteret, Onslow, Pender, New Hanover and Brunswick Counties (Fig. 1). This is an area that has coincidentally been growing rapidly in terms of human population. Most of the population in these areas is served by regional sewage systems, some of which had incomplete treatment in previous decades. However, major improvements to wastewater treatment plants occurred in the 1970s and early 1980s (Barber et al., 1993), thus, most major point source problems were controlled by 1983. Since we were primarily interested in effects of non-point source inputs on coastal pollution, we limited our analysis to the years 1984–1997.

We correlated human population with closed shellfish acreage for that 14 year period, and found a strong and highly significant correlation ($r = 0.833$, $p = 0.0002$; Fig. 2). Regressing human population on shellfish closures indicated that approximately 70% of the variability in annual shellfish area closed by fecal bacterial pollution could be explained by human population increases alone (Fig. 2). This relationship would likely have been even stronger except for several incidents that reopened some shellfishing areas in 1995–1996. The major opening of shellfish waters (445 ha, or 1100 acres) was in 1995 near the South River in Carteret County. The area was first closed in 1992 following increases in bacterial counts subsequent to a forest clearcut. Several years after the
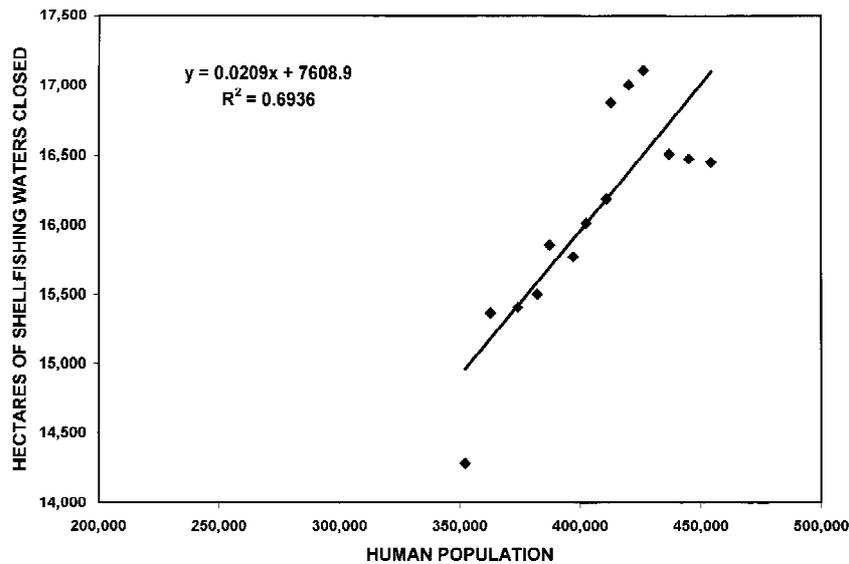
Figure 2. Relationship between increases in human population and shellfishing area closed by excessive fecal coliform counts in five coastal North Carolina counties (Fig. 1). Stars represent closed shellfishing area vs. human population for each years 1984–1997.

clearcut, regrowth of vegetation reduced runoff sufficiently to allow for reopening of shellfish beds. The second instance occurred when 49 ha (120 acres) were opened after improvements to human sewage treatment in an area of Pender County took place. The third reopening was achieved when a physical manipulation of the landscape (tidal creek-mouth dredging) led to reductions in fecal coliform counts that allowed 15 ha (38 acres) of shellfish area to be reopened in Futch Creek (Mallin et al., 2000b). Shellfish closures began increasing again in early 1999, when the North Carolina Division of Marine Fisheries closed an additional 253 ha (625 acres) of shellfishing area in the lower Cape Fear River basin because of high bacterial counts. Non-point source pollution from urban growth was cited as a major reason for the increased closures (SSS, 1999). It is clear that non-point source microbial pollution of coastal waters is intimately related to human population increases.

With increased population there is increased source material (humans and their animals) for fecal bacteria. Additionally, with increased human population there is often major alteration of the natural landscape, which may increase the delivery of fecal bacteria to coastal waters. To examine these effects more closely, a smaller scale approach is required.

Watershed-scale analyses

We conducted a more in-depth analysis in a rapidly urbanizing area; New Hanover County, North Carolina (Fig. 1). In 1997, the county population was 147 600 and total land area was 533 km^2. Previously, population growth in this county was correlated with closures of shellfish beds and loss of shellfishing-derived income (Maiolo & Tschetter, 1981). This county encompasses several tidal creeks that contain extensive shellfishing beds. The watersheds draining into these tidal creeks support human populations ranging from 2000 to 14 000, and the percent of developed land within the watersheds ranges from 40% to over 80%. Small watersheds such as these are good systems for urbanization studies because changes in land use within small basins have a major impact on hydrologic regimes (Booth, 1991). We conducted a 4-year (1993–1997) analysis of five tidal creeks, examining a number of physical, chemical, and biological parameters (Mallin et al., 2000a), including fecal coliform bacterial counts. These samples were collected monthly at or near high tide from all accessible salinity regimes within each estuary. We consider the bacterial counts to be highly conservative, as previous research demonstrated that the lowest counts in a tidal cycle were obtained when sampling at high tide (Mallin et al., 1999).

These data were assessed with respect to human population and land use in the five watersheds (Mallin
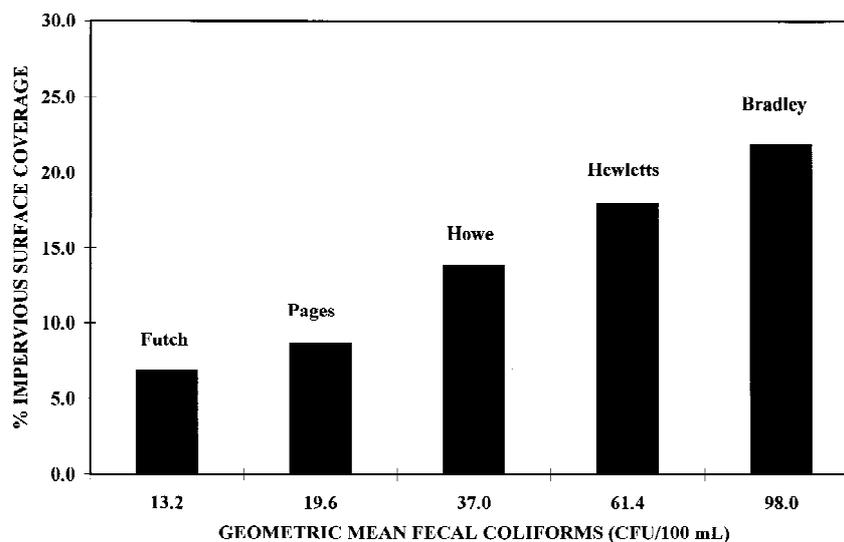
Figure 3. Percent watershed impervious surface coverage and corresponding geometric mean estuarine fecal coliform bacterial counts for five tidal creeks in New Hanover County, North Carolina, U.S.A.

et al., 2000a). Geometric mean fecal coliform abundance for each creek (all stations combined) correlated positively with watershed population ($r = 0.922$, $p = 0.026$). The percent of developed land within the watershed correlated even more strongly with mean fecal coliform abundance ($r = 0.945$, $p = 0.015$). However, the strongest correlation was between mean coliform abundance and the percent of impervious surface (roads, parking lots, sidewalks, rooftops) coverage in the watersheds ($r = 0.975$, $p = 0.005$; Fig. 3). The correlations do not necessarily mean that developed land or impervious surfaces cause the pollution, but that these factors are strongly associated with it.

Based on our data set from five tidal creeks over 4 years, we published a regression model that predicts the overall geometric mean fecal coliform count for a tidal creek based on percent watershed impervious surface coverage:

$$FC = 5.4\,(\%IMP) - 29, \quad r^2 = 0.95,$$

$$p = 0.005 \text{ (from Mallin et al., 2000a).}$$

Recently (1999–2000), we were able to test this model with a year-long fecal coliform analysis of a sixth urbanized tidal creek, Whiskey Creek, New Hanover County, N.C. Using the 1997 percent impervious surface coverage for this watershed supplied to us by the New Hanover County Planning Department, the model predicted a grand geometric mean for this creek of 84 CFU/100 ml. Our actual grand mean based on 12 months of field sampling at five stations was 79

CFU/100 ml, within 6% of the predicted value. Thus, impervious surface appears to be a valuable tool for predicting pollution impacts, as other research has suggested (Schueler, 1994; Arnold & Gibbons, 1996).

In our analysis, the two watersheds with less than 10% impervious surface coverage had generally good microbial water quality, with large portions of the creeks open to shellfishing. Watersheds with impervious coverage between 10% and 20% were impaired, with areas near the mouths maintaining low fecal coliform counts but the middle and upper areas maintaining high coliform counts (Mallin et al., 2000a). The watershed with greater than 20% impervious coverage was severely polluted, with all areas of the creek unsafe for shellfishing (Fig. 3). Increasing the amount of impervious surface coverage increases runoff, streamflow, and the amount of pollutants reaching surface waters (Griffin et al., 1980: Schueler, 1994; Arnold & Gibbons, 1996). In the case of coastal areas, this is especially critical because shellfishing beds are often located within meters of developed land, and much of the stormwater runoff reaching these areas does not receive any pretreatment before entering the estuaries. Stormwater runoff on streets draining residential areas has been found to contain high concentrations of fecal coliform bacteria (Bannerman et al., 1993; Young & Thackston, 1999). Sources of fecal bacterial pollution entrained in runoff from impervious surfaces in urban and suburban areas are rodents and other small mammals, avifauna and especially pets (Hus-

song et al., 1979; Trial et al., 1993; Weiskel et al., 1996; Mallin et al., 2000a). As well as pets, certain wild animals (i.e. raccoons) are abundant in and near residential areas (Mallin et al., 2000b). Visual inspections near sampling sites by the authors of the present research have noted numerous manure deposits (especially from dogs) on sidewalks, roadsides, tree lawns and around apartment dwellings, often within meters of storm drains. Impervious surfaces even well within a coastal watershed can serve as a means of concentration and rapid conveyance of fecal bacteria to tidal creeks (Mallin et al., 2000a).

Landscape and meteorological factors

Temporary closures to shellfish harvesting commonly occur after heavy rainfall events because of increases in fecal coliform levels exceeding approved area criteria. In coastal North Carolina, temporary increases in closed shellfishing areas of over 16 000 ha (40 000 acres) have occurred after such rain events in the area from Cedar Island to the South Carolina state line (Shellfish Sanitation Section records, North Carolina Department of Environment and Natural Resources). As population increases in the coastal area bring about changes to the adjacent shorelines due to development, increases in fecal coliform levels will occur and trigger additional permanent and temporary closures.

Domestic farm animals have many of the same potential pathogens as humans (Crane et al., 1983; Mawdsley et al., 1995; Hill & Sobsey, 1999). In agricultural areas, cattle, swine and poultry can be significant sources of microbial pollution to streams (Crane et al., 1983; Howell et al., 1995). Microbial pollution is likely to be greatest following rain events and subsequent overland runoff (NRC, 1993; Howell et al., 1995); also, rain events can disturb stream sediments and release sediment-bound fecal coliforms into the water column (Struck, 1988).

In regions where livestock production facilities are abundant, it is critical to assess the effect of rain events on the microbiological quality of downstream receiving waters. We examined the effect of rainfall and stormwater runoff on the water quality of 11 coastal plain streams in the lower Cape Fear River basin, North Carolina (Fig. 1). The stations we chose collected inputs from sub-basins dominated by non-point source pollution, including conventional agriculture, cattle and concentrated animal operations (CAO's). CAO's involve the housing of thousands of head of swine or poultry in large oblong facilities, in which

they are fed, grow and defecate. The feces and urine are washed through slats in the floor and are drained into nearby large open pits (called lagoons). Periodically some of the waste is pumped out and sprayed onto surrounding fields, many of which are located on river floodplains (Burkholder et al., 1997; Mallin, 2000). For the 6-month period March–August, 1998, we used correlation analyses to compare fecal coliform bacterial counts, turbidity and the amount of rain that fell in the watershed during the 24 h previous to the day of sample collection. For all streams combined, there were significant correlations between rain and fecal coliform counts ($r = 0.601$, $p = 0.0001$), rain and turbidity ($r = 0.512$, $p = 0.0001$), and fecal coliforms and turbidity ($r = 0.768$, $p = 0.0001$).

Each of the stream watersheds was then examined individually. Extremely strong correlations were found between rainfall and fecal coliform counts for several of the watersheds (Table 1). Several of these watersheds also showed strong correlations between rainfall and turbidity. Great Coharrie Creek (GCO), Little Coharrie Creek (LCO) and Six Runs Creek (6RC) drain watersheds containing numerous CAO's. Brown's (BC) and Hammond Creek (HC) watersheds contain grazing cattle and crop agriculture. It is instructive to examine the other end of the scale. Of the five watersheds containing the greatest percent land coverage of wetlands (Colly Creek (COL), Angola Creek (ANC), Rockfish Creek (ROC), South River (SR) and Goshen Swamp (GS), none had significant rain/turbidity correlations and four of the five had no significant rain/fecal coliform correlations. These watersheds all had 13.8% or greater wetlands coverage, while the remainder all had 12.7% or less wetlands coverage. (Table 1). Burgaw Creek (BC) had low wetland coverage and did not show a significant fecal coliform correlation with rainfall, but this watershed also had no CAO's. There was a significant rain/turbidity correlation in this basin, however. There were significant correlations between turbidity and fecal coliforms in several of the watersheds, but most of the watersheds with large wetland coverage did not show significant correlations between those two pollutants (Table 1).

Mass production of swine, poultry and cattle creates a reservoir of microbial pathogens that thus enter waterways via runoff events (Khaleel et al., 1980; Crane et al., 1983; Howell et al., 1995; Burkholder et al., 1997; Mallin, 2000). Some of these microbes are able to infect humans (Mawdsley et al., 1995; Hill & Sobsey, 1998). Both traditional agriculture and

Table 1. Correlation coefficients (*r*) and probabilities (*p*) for relationships between fecal coliform bacterial counts, turbidity, and area rainfall in the 24 hr preceding sampling for 11 coastal plain streams (Fig. 1), *n* = 6 months. Also presented is percent of each watershed comprised of wetlands, and number of CAO's per watershed. CAO's are concentrated animal operations containing more than 500 head of swine

Stream station	CAOs	% wetland coverage	Rainfall vs Fecal coliform counts		Rainfall vs Turbidity		Turbidity vs Fecal coliform counts	
			r	*p*	*r*	*p*	*r*	*p*
Colly Creek	6	55.2	−0.305	0.5572	0.477	0.3393	−0.349	0.4971
Angola Creek	13	27.4	0.459	0.3601	0.204	0.6985	0.339	0.5113
Rockfish Creek	74	16.7	0.797	0.0578	0.527	0.2830	0.902	0.0141
South River	16	14.5	0.999	0.0001	0.273	0.6001	0.299	0.5653
Goshen Swamp	119	13.8	0.607	0.2010	−0.369	0.4713	0.280	0.5912
Brown's Creek	3	12.7	0.997	0.0001	0.991	0.0001	0.987	0.0003
Little Coharrie Cr.	63	12.5	0.999	0.0001	0.999	0.0001	0.998	0.0001
Great Coharrie Cr.	95	11.8	0.995	0.0001	0.988	0.0002	0.974	0.0012
Six Runs Creek	153	8.5	0.996	0.0001	0.980	0.0006	0.977	0.0008
Burgaw Creek	0	6.3	0.718	0.1076	0.972	0.0012	0.809	0.0514
Hammond Creek	6	6.1	0.998	0.0001	0.924	0.0084	0.942	0.0051

construction and operation of CAO's cause major disturbances to soils and native vegetation, increasing the system's susceptibility to sedimentation and turbidity. Feces deposited on fields by cattle, and swine and poultry wastes sprayed or spread on fields are subject to runoff, particularly where sedimentation is occurring. Our results not only indicated that rain events were linked to both turbidity and fecal coliform increases, but also showed a strong correlation between fecal coliforms and turbidity. This relationship has been found in other studies as well (Sayler et al., 1975; Mallin et al., 2000a). Fecal coliforms readily associate with turbidity-causing particles, and can thus be transported downstream along with such particles. Additionally, particles likely provide protection from UV radiation (Kocasoy, 1989), which is a principle means of deactivation of fecal bacteria in the environment (Evison, 1988; Pommepuy et al., 1992). Land alteration that leads to increased sedimentation provides both a transport and protection mechanism for fecal-derived microbiota (Struck, 1988).

Conclusions

Increases in human population, increases in domestic animals and alterations of the natural landscape are all factors that can lead to increases in the amount of fecal coliform bacteria entering nearby waterways. Increases in point source sewage outfalls also co-occur with human population increases, and are thus poten-

tial reasons for increased microbial pollution. While effects from faulty point sources can be severe when they occur (for example, Boston and San Diego – see NRC, 1993), these situations are no longer widespread in developed regions. Instead, we suspect that general stormwater runoff, particularly from impervious surface areas, is the major source of microbial pathogen pollution. Increases in human populations lead to consequent increases in land development. With building and paving, the natural water purification function of vegetation and soil is greatly reduced, allowing high volumes of untreated runoff water to carry potentially pathogenic microbes into coastal waterways. As mentioned, rodents, other wild mammals, avifauna and especially dogs, cats and other domesticated animals such as horses are all common in developed and developing coastal areas, and their manure provides a widespread and abundant source of fecal microbiota (NRC, 1993; Weiskel et al., 1996). Movement of fecal-derived microbes into waterways can likely be reduced by a combination of behavioral and land management practices. These would include educational programs to reduce the amount of pet wastes deposited and left on the landscape, minimizing the construction of impervious surfaces wherever possible, and directing runoff from existing impervious surfaces into pervious area (such as constructed wetlands and biofilters) for passive treatment before reaching surface waters.

In more rural areas, traditional agriculture and industrial scale animal production both cause disturb-

ances to soil and native vegetation. This makes nearby streams more vulnerable to runoff-derived turbidity and bacterial pollution. The presence of large numbers of animals provides the source of fecal bacteria, while sedimentation can provide a means of bacterial transport into and along stream channels. The presence of extensive natural wetlands, even where CAO's are abundant, helps ameliorate this type of non-point source pollution. In the rural watersheds we examined, watersheds with 13.8% wetlands coverage or greater appeared to be buffered against excessive turbidity and fecal coliform runoff after rain events. Because of the strong correlation between turbidity and fecal coliform abundances in these watersheds, streamside management practices that can minimize sedimentation are also likely to reduce runoff of fecal bacteria into waterways.

Continuing coastal urbanization and the consequent replacement of natural vegetation with impervious surfaces will increase stormwater runoff and the loading of numerous pollutants into coastal waters. More shellfish bed closures, and possibly a general increase in the human health risks from contact with coastal waters, are likely consequences of continuing development of the coastal landscape. Likewise, loss of rural wetlands and conversion of natural landscapes to pollution-prone uses such as large-scale animal production encourages microbial pollution of coastal plain streams. If global warming brings about increased coastal rainfall, we speculate that this may have a synergistic effect with increased developed land in which microbial pathogen loading to coastal waterways increases in both frequency and concentration.

Acknowledgements

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