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EFFECT OF HUMAN DEVELOPMENT ON BACTERIOLOGICAL WATER QUALITY IN COASTAL WATERSHEDS

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Abstract. Human development along the land–seawater interface is considered to have significant environmental consequences. Development can also pose an increased human health risk. In a rapidly developing coastal region we investigated this phenomenon throughout a series of five estuarine watersheds, each of which differed in both the amount and type of anthropogenic development. Over a four-year period we analyzed the abundance and distribution of the enteric pathogen indicator microbes, fecal coliform bacteria and *Escherichia coli.* We also examined how these indicator microbes were related to physical and chemical water quality parameters and to demographic and land use factors throughout this system of coastal creeks. Within all creeks, there was a spatial pattern of decreasing enteric bacteria away from upstream areas, and both fecal coliform and *E. coli* abundance were inversely correlated with salinity. Turbidity was positively correlated with enteric bacterial abundance. Enteric bacterial abundance was strongly correlated with nitrate and weakly correlated with orthophosphate concentrations. Neither fecal coliforms nor *E. coli* displayed consistent temporal abundance patterns. Regardless of salinity, average estuarine fecal coliform abundance differed greatly among the five systems. An analysis of demographic and land use factors demonstrated that fecal coliform abundance was significantly correlated with watershed population, and even more strongly correlated with the percentage of developed land within the watershed. However, the most important anthropogenic factor associated with fecal coliform abundance was percentage watershed-impervious surface coverage, which consists of roofs, roads, driveways, sidewalks, and parking lots. These surfaces serve to concentrate and convey storm-water-borne pollutants to downstream receiving waters. Linear regression analysis indicated that percentage watershed-impervious surface area alone could explain 95% of the variability in average estuarine fecal coliform abundance. Thus, in urbanizing coastal areas waterborne health risks can likely be reduced by environmentally sound land use planning and development that minimizes the use of impervious surface area, while maximizing the passive water treatment function of natural and constructed wetlands, grassy swales, and other ‘‘green’’ areas. The watershed approach used in our study demonstrates that the land–water interface is not restricted to obvious shoreline areas, but is influenced by and connected with landscape factors throughout the watershed.

Key words: development; Escherichia coli*; estuary; fecal coliform bacteria; impervious surface; nonpoint source; planning; shellfishing; watershed.*

Introduction

The land–water interfaces along developed and developing seacoasts represent key regions where the sustainability of natural ecosystem functions can be compromised. Coastal ecosystems are under increasing stress from a variety of human activities that cause increased pollution, floral and faunal changes, and physical alteration of the environment (Vitousek et al. 1997, Epstein 1998). This increase in human activities stems from coastal population increases coupled with growing coastal tourism (USEPA 1992). Much of the attraction of coastal areas to both residents and tourists involves water contact, such as swimming, finfishing, and shellfishing. However, those who participate in such activities face increasing human health risk from pollutants resulting from growing coastal urbanization. Southeastern North Carolina, United States, is a rapidly developing area which typifies this situation. As human development has increased along this coastline, the numerous small estuaries subsequently have been closed to shellfish harvest for human consumption due to high fecal coliform bacterial counts (Mallin et al. 1998).

Pathogenic enteric bacteria enter the environment from human or animal excreta (Dadswell 1993). Both

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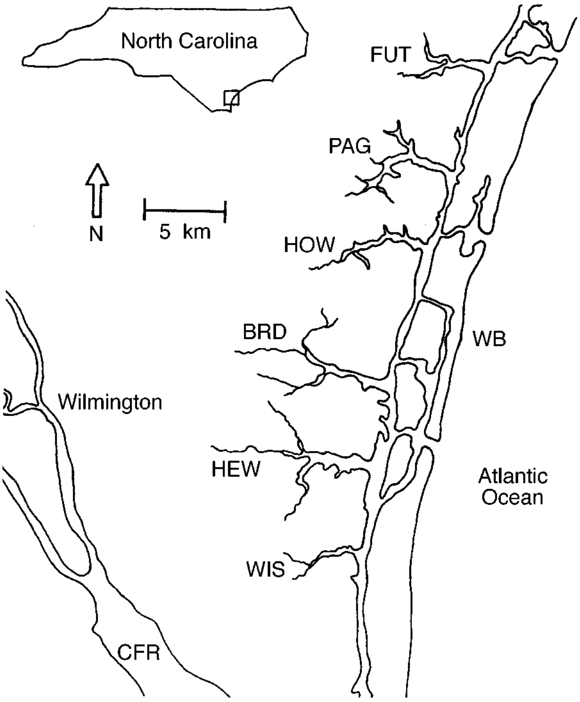

FIG. 1. Tidal creek system in New Hanover County, North Carolina, USA. Abbreviations are: CFR, Cape Fear River, FUT, Futch Creek; PAG, Pages Creek; HOW, Howe Creek; BRD, Bradley Creek; HEW, Hewletts Creek; WIS, Whiskey Creek; WB, Wrightsville Beach.

direct contact with contaminated water and consumption of contaminated shellfish can lead to human illness and even death (USFDA 1995, Ford and Colwell 1996, Epstein 1998). Over the past several decades public health officials worldwide have devised various water quality standards to protect human health (USEPA 1986, Dadswell 1993, Ford and Colwell 1996). While a variety of pathogenic indicators have been proposed, the most commonly used estimator of fecal pathogenic bacteria presence is fecal coliform bacterial abundance (Dadswell 1993, Ford and Colwell 1996, Rees et al. 1998). For example, in the United States, shellfishing waters must maintain geometric mean fecal coliform bacterial concentrations ≤14 colony forming units (CFU) per 100 mL, and <10% of the samples can have >43 CFU/100 mL (USFDA 1995). In the European Union, the Mandatory fecal coliform standard is 1000 CFU/100 mL and the Guideline fecal coliform standard for swimming beaches is only 100 CFU/100 mL (Rees et al. 1998). High use areas, where maintenance of these standards is most critical, are often the most highly contaminated areas along a coastline (Kocasoy 1995). Thus, anthropogenic activities along the land–seawater interface have a strong potential for contributing toward both ecological and human health problems.

In 1993 a comprehensive study was initiated to investigate five estuaries in urbanizing watersheds from perspectives of ecological and human health standards. Part of this study encompassed an analysis of the distribution and abundance of enteric bacterial indicators and how these indicators are associated with other water quality constituents. The discrete drainage areas, each with different populations and land use practices, allowed us to take a watershed approach to determining how human landscape practices affect the dynamics of coastal enteric bacterial assemblages.

Site Description

The five estuarine creeks are located in New Hanover and Pender Counties, in southeastern North Carolina, United States. These systems drain into the Atlantic Intracoastal Waterway (ICW), and have a salinity gradient ranging from over 30.00 (according to the practical salinity scale) at the ICW to fresh water 3–5 km upstream (Fig. 1). Principal marsh vegetation consists of marsh cordgrass *Spartina alterniflora* Loisel in mesohaline and polyhaline salinities and black needlerush *Juncus roemerianus* Scheele in oligohaline areas. By the early 1990s, these tidal creeks had all become either fully or partially closed to shellfishing because of increased enteric bacterial counts (NHCPD 1993). An advantage to the goals of our investigation was that the five separate estuarine watersheds targeted for study were similar in climate, geography, and soil type because of inter-watershed proximity (NHCPD 1993). Aside from physical aspects such as drainage area and hydrology, the major variables differentiating the watersheds were population density and land use differences (Table 1).

The sampling period for each project-year began in August and continued until the following July. During 1993–1994 fecal coliforms and *E. coli* were sampled at five stations in Howe Creek (HW-M, HW-FP, HW-GC, HW-GP, and HW-DT), and seven stations in Hewletts Creek (HC-1, HC-2, HC-3, HC-NWB, NB-GLR, MB-PGR, and SB-PGR). During 1994–1995 fecal coliforms and *E. coli* were sampled at eight stations in

TABLE 1. Demographic and land use factors of the five coastal watersheds.

Estuary	Land area (ha)	Population†	Percentage developed land	Percentage impervious cover	Percentage impervious cover/percentage developed land
Bradley	2448	13 657	77.8	21.9	33.3
Hewletts	2393	13 000	69.0	18.0	26.1
Howe	1210	3937	51.0	13.9	27.3
Pages	1230	4185	69.4	8.7	12.5
Futch	1257	2108	42.9	6.9	16.1

† Population is the number of people residing in the watershed.

Pages Creek (PC-M, PC-OL, PC-CON, PC-OP, PC-LD, PC-BDDS, PC-WB, PC-BDUS, and PC-H), and eight stations in Futch Creek (FC-2, FC-4, FC-6, FC-8, FC-13, FC-17, FC-20, and FOY). During 1995–1996 fecal coliforms only were sampled at the same stations in Futch Creek and eight stations in Bradley Creek (BC-M, BC-CM, BC-76, BC-J, BC-SB, BC-SBU, BC-NB, and BC-NBU).

Methods

Bacteria samples were collected monthly by lowering pre-autoclaved glass containers ~10 cm below the water surface, facing into the stream. Samples were kept on ice in coolers until processing at the laboratory, within six hours of collection. The method used in this study to assess fecal coliform concentrations was the membrane filtration method (mFC), described in *Standard Methods* (APHA 1995). This method utilizes an elevated temperature incubation to distinguish fecal coliforms from the total coliform group. *Escherichia coli* was processed and enumerated by the mTEC method (USEPA 1985). In each estuary a series of sampling stations was devised to represent all accessible salinity regimes and major tributaries. Sampling variability was minimized by collecting and analyzing samples in the same manner, at or near high tide, and by sampling the different estuaries within two days of each other. Approximately 650 fecal coliform and 400 *E. coli* samples were collected during the study and used in the analyses. Fecal bacterial counts, as colony forming units (CFU) per 100 mL, were normalized by log transformation with geometric means used for subsequent statistical analysis. While on site, water at each station was analyzed for water temperature, salinity, dissolved oxygen, and turbidity using the following instruments: a Solomat 803PS Multiparameter Water Quality Probe with a Solomat 803 datalogger (Solomat Neotronics, Norwalk, Connecticut), YSI Model 55 and 85 Dissolved Oxygen Meters (YSI, Yellow Springs, Ohio), and a LaMotte Model 2008 Turbidity Meter (LaMotte, Chestertown, Maryland). As part of a parallel study, nitrate and orthophosphate samples were also collected, filtered through 1.0 μm glass fiber filters, and analyzed using a Technicon AutoAnalyzer (Clindus Technologies, Paramus, New Jersey).

Watershed land use and demographic data were determined by the New Hanover County Planning Department. Watershed population estimates were obtained using average household size data from a 1990 census, updated by the number of housing units determined in a 1997 New Hanover County Planning Department field study. Land use data were obtained from the New Hanover County tax assessor's office. Impervious surface ratios were developed from a random sampling of parcels within each watershed and checked by measuring total impervious surface visible on digital orthophotography. Data are currently in the New Hanover County Planning Department geographic information system (GIS).

Table 2. Geometric mean fecal coliform counts (CFU/100 mL) for New Hanover County tidal creeks, grouped by salinity areas.

Creek	All stations	Salinity >30	Salinity 20–29	Salinity <20
Bradley	98	20	90	354
Hewletts	61	7	84	333
Howe	37	6	29	317
Pages	20	7	63	260
Futch	13	3	24	188

Note: Salinity values are based on the practical salinity scale.

Correlation analyses were performed on monthly bacterial and water quality data using the Statistical Analysis System (SAS). Additional correlation and regession analyses were performed to investigate the bacteriological quality of each individual creek compared with land use and demographic data. Mean fecal coliform abundance for each estuary represents the geometric mean of all samples collected in that estuary during the entire sample year(s). The demographic data on Table 1 are not necessarily the most recent figures; rather, demographic data closest in time to collection of fecal coliform samples were used for the correlation analyses.

Results

The data portrayed a general pattern within individual creeks of lowest fecal coliform concentrations at stations nearest the Atlantic Intracoastal Waterway (ICW) and highest concentrations at lower salinity stations (Table 2, Fig. 2). The population distribution of *Escherichia coli* was generally similar to that of fecal coliform bacteria (Fig. 3). At high salinities, concentrations were very similar between the two indicators. However, at oligohaline salinities *E. coli* abundances were noticeably higher than fecal coliform concentrations.

Certain physical parameters were related to the spatial patterns in the creeks. Correlation analyses indicated a strong inverse relationship between coliform counts and salinity (Table 3). This relationship was true for all creeks individually, although weakest in Pages Creek. *E. coli* abundances showed a similar, and somewhat weaker relationship with salinity (Table 3, Fig. 3). Turbidity data were only available for three creeks, but was significantly correlated with fecal coliform abundance in each of those creeks (Table 3). Neither water temperature nor dissolved oxygen was significantly correlated with either indicator group.

There was a highly significant correlation in general between fecal coliform abundance and nitrate concentration. This was also significant for all creeks individually, although strongest in Futch and Hewletts

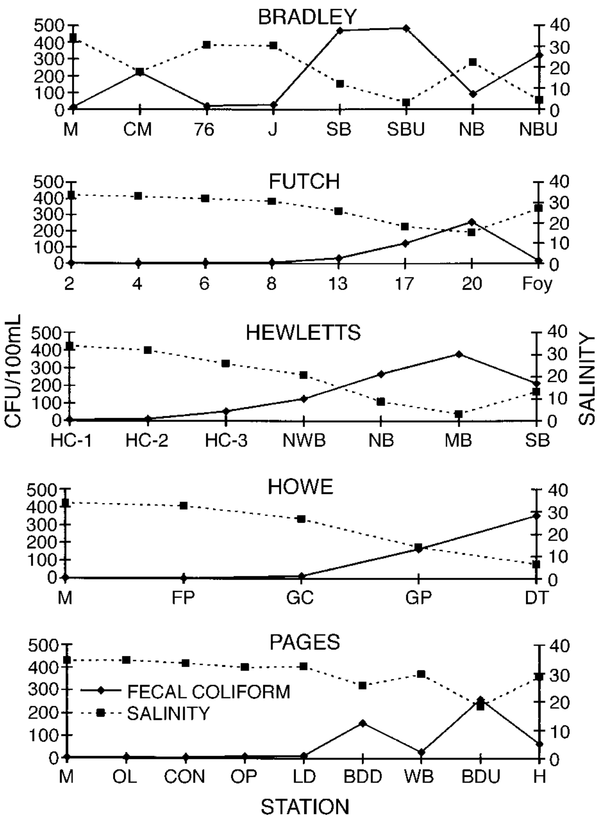

FIG. 2. Geometric mean fecal coliform bacterial concentrations and mean salinity (based on the practical salinity scale) by station for five coastal creeks.

Creeks and weakest in Howe Creek (Table 3). *E. coli* abundance was significantly related to nitrate, though not as strongly as fecal coliforms were. Fecal coliform abundance was also significantly, but weakly, correlated with orthophosphate concentrations. In most instances *E. coli* abundance was more strongly related to orthophosphate concentrations than were fecal coliform abundances (Table 3).

The magnitudes of fecal coliform concentrations differed considerably among the creeks. Pages and Futch Creeks displayed low average fecal coliform concentrations creekwide, Howe Creek concentrations were moderate, and Hewletts and Bradley Creeks average values were much higher (Table 2). When creek areas were normalized by grouping them into salinity groups, coliform concentrations also varied considerably with Bradley and Hewletts Creeks, again maintaining highest coliform abundances in general (Table 2). We applied U.S. standards for shellfishing waters to each of the creeks (Table 4). Based on these standards, Bradley Creek was clearly the most polluted creek, followed in turn by Hewletts, Howe, Pages, and Futch. When the North Carolina standard for human contact waters was applied (200 CFU/100 mL [NC DEHNR 1994]), all of the creeks had at least one station failing the standard and the more polluted creeks had several unacceptable stations (Table 4, Fig. 2).

Bradley Creek was first closed to shellfishing in 1947 (North Carolina Shellfish Sanitation Branch, *personal communication*). This creek is host to several areas of elevated fecal coliform concentrations. This watershed

TABLE 3. Results of correlation analyses between enteric bacterial indicators and various physical and chemical parameters.

Creek	Indicator	Correlation of enteric bacterial indicators with: Salinity	Turbidity	Nitrate	Orthophosphate
All creeks	FC	−0.697 (0.0001)	0.472 (0.0001)	0.585 (0.0001)	0.378 (0.0001)
	EC	−0.607 (0.0001)	0.422 (0.0001)	0.565 (0.0001)	0.366 (0.0001)
Bradley	FC	−0.628 (0.0001)	NA	0.607 (0.001)	0.427 (0.0001)
	EC	−0.474 (0.0001)	NA	0.420 (0.0458)	0.513 (0.0123)
Futch	FC	−0.742 (0.0001)	0.417 (0.0001)	0.700 (0.0001)	0.300 (0.0001)
	EC	−0.679 (0.0001)	0.425 (0.0001)	0.694 (0.0001)	0.141 (0.1132)
Hewletts	FC	−0.711 (0.0001)	NA	0.723 (0.0001)	0.345 (0.0106)
	EC	−0.681 (0.0001)	NA	0.716 (0.0001)	0.423 (0.0016)
Howe	FC	−0.809 (0.0001)	0.575 (0.0001)	0.401 (0.0001)	0.284 (0.0022)
	EC	−0.826 (0.0001)	NA	0.330 (0.0158)	0.473 (0.0003)
Pages	FC	−0.446 (0.0001)	0.473 (0.0001)	0.681 (0.0001)	0.485 (0.0001)
	EC	−0.400 (0.0002)	0.434 (0.0001)	0.624 (0.0001)	0.540 (0.0001)

Notes: Values given are Pearson correlation coefficients (r) with probability values (P) in parentheses. FC = fecal coliform bacteria, and EC = *Escherichia coli*. NA indicates no data available.

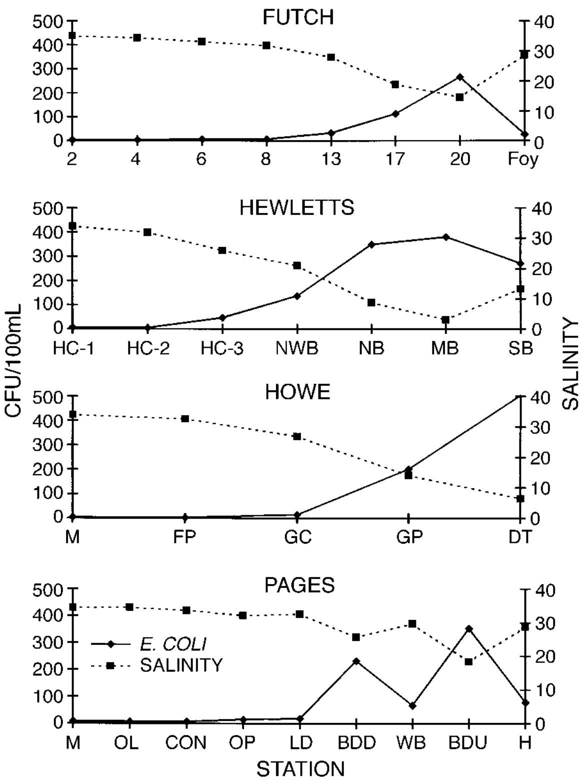

FIG. 3. Geometric mean *Escherichia coli* concentrations and mean salinity (based on the practical salinity scale) by station for four coastal creeks.

is highly populated and extensively developed, with large tracts of single- and multiple-family residential units, extensive institutional and retail areas, horse farms, and a marina. Bradley Creek had geometric means above the state shellfishing standard in seven of eight stations (Table 4, Fig. 2). Fecal coliform concentrations exceeded 43/100 mL more than 10% of the time at all stations. Bradley Creek is unacceptable for shellfishing throughout its watershed.

Hewletts Creek also exhibited poor microbiological water quality, except near the creek mouth (Table 4, Figs. 2 and 3). The three main branches drain subwatersheds which are either heavily developed or currently hosting ongoing construction projects. All of these branches supply elevated fecal coliform concentrations to the lower creek, with suburban runoff and nonpoint source runoff from land disturbing activities likely sources of fecal coliforms. In addition, occasional sewage spills have occurred at pump stations on the tributary branches.

Howe Creek had good microbiological water quality at the two stations nearest the creek mouth, probably a result of high salinities and flushing near the mouth. There is very poor microbiological water quality in the oligohaline marsh area (Table 4, Figs. 2 and 3). The upper creek drains extensive retail and dense residential areas.

Pages Creek yielded good quality water for shellfishing (Table 4, Figs. 2 and 3). The only areas of major concern are the two tributary stations (PC-BDUS and PC-BDDS) which abut a roadway serving an extensive suburban neighborhood of single family homes. These two stations are directly exposed to storm drains and road runoff. Additionally, these tributaries are lined with homes with yards extending to the water's edge, with very few vegetated buffer strips evident. However, dogs are commonly visible in yards bordering the creek, with manure likely contributing regularly to creek coliform pollution. Thus, suburban nonpoint source runoff appears to be the principal source of fecal coliform contamination to Pages Creek. It is notable that PC-BDUS and PC-BDDS maintained elevated fecal coliform counts despite relatively high salinity at these stations (Table 4, Figs. 2, 3).

TABLE 4. Fecal coliform data by creek, collected between August 1993 and July 1997.

Creek	Station	Geometric mean CFU/100 mL	Percentage of samples >43/ 100 mL	*n*
Bradley	BC-M	13	42	12
	BC-CM	219	83	12
	BC-76	21	42	12
	BC-J	27	58	12
	BC-SB	473	100	12
	BC-SBU	483	100	11
	BC-NB	86	92	12
	BC-NBU	321	100	11
Hewletts	HC-1	5	18	11
	HC-2	10	18	11
	HC-3	55	64	11
	HC-NWB	126	91	11
	NB-GLR	266	78	9
	MB-PGR	378	100	8
	SB-PGR	212	100	9
Howe	HW-M	3	0	21
	HW-FP	5	10	21
	HW-GC	19	25	20
	HW-GP	170	90	21
	HW-DT	387	100	21
Pages	PC-M	4	8	11
	PC-OL	4	17	11
	PC-CON	5	8	12
	PC-OP	9	36	11
	PC-LD	11	25	12
	PC-BDDS	157	64	11
	PC-WB	25	33	12
	PC-BDUS	234	92	12
	PC-H	63	55	12
Futch	FC-2	1	0	35
	FC-4	2	0	35
	FC-6	4	3	35
	FC-8	5	9	35
	FC-13	33	43	35
	FC-17	123	77	35
	FC-20	254	91	35
	FOY	17	23	35

Note: n = number of months sampled.

TABLE 5. Results of correlation analyses between geometric mean fecal coliform abundance for all stations within each creek and watershed demographic and land use factors.

	Correlation of fecal coliform abundance with:			
	Total land area	Population	Percentage development	Percentage impervious surface
r	0.897	0.922	0.945	0.975
P	0.039	0.026	0.015	0.005

Notes: Values given are Pearson correlation coefficients (r) with probability values (P); $n = 650$ samples.

Futch Creek had the best shellfishing water quality. The most polluted stations in Futch Creek were the three stations in the southern upper arm (FC-13, FC-17, and FC-20; Table 4, Figs. 2 and 3). This is a partially developed area that is probably poorly flushed. A series of tests carried out in 1996 found no coliform pollution present in groundwater springs but high coliform concentrations in small feeder streams draining into the creek near FC-17 and FC-20. One feeder creek was sampled 14 times in 1996–1997 and yielded a geometric mean fecal coliform count of 175 CFU/100 mL. Visual examination of the small watersheds surrounding these feeder creeks uncovered areas of concentrated mammal populations (especially raccoons [Mallin et al. 1998]) and wild animal dung, which likely are constant sources of fecal coliform pollution to the creeks. The undeveloped FOY branch had generally low coliform counts, approximately half as great as those in waters of similar salinity (FC-13) along the south branch (Table 4). Futch Creek had geometric means above the required 14 per 100 mL in four of the eight stations (Table 4). However, the lower creek below the split into two branches (FC-2–FC-8; Fig. 1) clearly met acceptable water quality standards for shellfish harvesting (Table 4).

We applied correlation techniques in an effort to ascertain if demographic and land use factors were related to fecal coliform abundance in the individual creeks. Our data demonstrated that watershed population and watershed size were significantly related to average fecal coliform abundance (Table 5). Additionally, we found that there was a stronger and more significant correlation between the geometric mean fecal coliform concentration of the individual creeks and percentage development of the watersheds (Table 5). However, the strongest relationship was found between percentage watershed-impervious surface area and average estuarine fecal coliform abundance (Table 5, Fig. 4). Impervious surfaces consist of roofs, paved drives, sidewalks, roads, and parking lots. For the watersheds tested in this study a highly significant predictive model for estimating average estuarine fecal coliform abundance (FC) is:

$$\text{FC} = 5.4(\text{percentage impervious surface coverage}) - 29.1.$$

($r^2 = 0.95$, $P = 0.005$.) A regression model using population alone explained less variability (85%) and was less significant ($P = 0.026$). Multiple regression models combining demographic and land use variables either proved to be nonsignificant or failed to explain any more of the variability in estuarine fecal bacterial abundance than percentage impervious surface coverage alone did.

We applied similar correlation analyses to *E. coli* abundance and land use data, although we note that we had only 400 *E. coli* measurements as opposed to the 650 available for the fecal coliform analysis, and *E. coli* samples for Bradley Creek were very limited. Percentage impervious surface again was highly correlated with average *E. coli* concentration ($r = 0.973$, $P = 0.005$), but percentage developed land was not significantly correlated ($r = 0.845$, $P = 0.071$). However, watershed population was highly correlated ($r = 0.986$, $P = 0.002$) with average *E. coli* concentration.

DISCUSSION

Enteric bacterial distribution within the creeks demonstrated an inverse relationship with salinity. This pattern, which has been noted elsewhere (Goyal et al. 1977, Esham 1994) is likely a result of several factors. A number of experiments have demonstrated that fecal coliform survival is shorter in waters of greater salinity (Hanes and Fragala 1967, Evison 1988, Solic and Krstulovic 1992). Also, higher salinity creek stations near the ICW are probably better flushed and diluted than the low salinity headwaters stations. Finally, the headwaters stations in general are closer to pollution sources than high salinity creek mouth stations. We emphasize that our samples were collected at or near high tide. During a series of 14 tidal cycle experiments carried out in 1995–1996 we found that fecal coliform

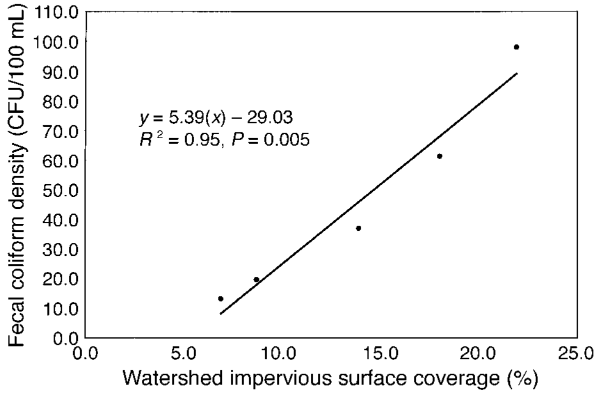

FIG. 4. Geometric mean fecal coliform bacterial concentrations vs. percentage impervious surface coverage for five coastal watersheds.

abundance in these coastal creeks was lowest at high tide and highest at mid-to-low tide (Mallin et al. 1999). Thus, our fecal coliform data should be considered conservative.

The significant correlation between turbidity and enteric bacterial abundance is not surprising. Research in the Chesapeake Bay found that a highly significant proportion of fecal bacterial indicators were associated with particulate matter in the water column, and suggested that transport of fecal bacteria via suspended sediments is an important mechanism in the aquatic environment (Sayler et al. 1975). Fecal bacterial indicators are known to have longer survival when in association with sediment particles (Gerba and McLeod 1976, LaLiberte and Grimes 1982, Pommepuy et al. 1992, Howell et al. 1996). When sediments are disturbed fecal bacteria can be re-released into the water column (Grimes 1975).

There was a positive correlation between fecal coliform abundance and nitrate and, to a lesser extent, orthophosphate. In some cases fecal coliforms and nutrients are derived from the same sources (i.e., sewage, animal waste, etc. [see Burkholder et al. 1997, Mallin et al. 1997]) while in other cases nutrients may arrive at a coliform-rich location from other sources such as fertilizer runoff. Regardless, there is some field and experimental evidence which suggests that nutrient loading can stimulate the growth and/or prolong survival of fecal bacteria indicators (Sheheta and Marr 1971, Evison 1988).

Bacterial inputs to coastal waters can originate from either point or nonpoint sources. With the exception of occasional sewer main or pump station leaks, point source inputs to our targeted watersheds are few, as are problems with septic systems (Mallin et al. 1998). Thus, general nonpoint source runoff is the major source of fecal coliform pollution to these estuaries. Nonpoint source impacts are likely to vary according to demographic and land use factors. We found a significant correlation between watershed population and both mean estuarine fecal coliform and *E. coli* abundance. Population is likely an important source function, with more humans and more domestic animals leading to more fecal bacteria. Maiolo and Tschetter (1981) found that population increases in two coastal counties were significantly correlated with estuarine acreage closed to shellfishing and reduced shellfish landings, with consequent significant dollar losses to the local communities. Population density has also been demonstrated to be a significant estimator of microbial pollution of coastal resort beach water (Kocasoy 1995). Specific sources of bacterial pollution and land use factors were not addressed in either of those two studies.

Our data demonstrate that the amount of developed land within a watershed is an important factor determining bacteriological receiving water quality. However, used alone, these data do not provide enough information to serve as a basis for mitigative action. In our analysis Howe Creek yielded higher average fecal coliform counts than Pages Creek, but the Howe Creek watershed was actually less developed than the Pages Creek watershed (Table 1). Further analysis showed that 27.3% of the developed land around Howe Creek consisted of impervious surface coverage, while only 12.5% of the developed land around Pages Creek consisted of impervious surface coverage (Table 1). When fecal bacteria is deposited on or near impervious surfaces these surfaces provide a means of concentration and rapid conveyance of bacteria and other pollutants to downstream water bodies. Thus the quality, rather than quantity, of land development is the most important influence on urban and suburban nonpoint source fecal coliform bacterial pollution. It is instructive to note that our statistical analysis also determined that watershed population was significantly correlated with percentage impervious surface coverage ($r = 0.932$, $P = 0.021$) but was not significantly correlated with percentage watershed development ($r = 0.809$, $P = 0.098$). These results likely occurred because the percentage of developed land in these watersheds contains large tracts of nonresidential land such as parks and golf courses, which consist largely of pervious surfaces. However, populated areas are intimately associated with drives, roads, parking lots, etc.

Percentage impervious surface area has been shown to be important in determining stream water quality as defined by ecological indicators such as benthic macroinvertebrate community composition and fish density and abundance (Klein 1979, May et al. 1997). These indices generally indicated impairment at ~10% impervious surface coverage (Schueler 1994, Arnold and Gibbons 1996). For our study the strongest correlation was found between percentage watershed impervious surface area and mean estuarine fecal coliform abundance. The two estuaries with less than 10% impervious coverage, Futch and Pages Creeks, both have extensive areas open to shellfishing while the other systems are either entirely or largely closed. This information, coupled with average fecal coliform abundance data (Tables 2, 4), demonstrates that acceptable microbiological water quality for these coastal systems occurs when percentage impervious surface of a watershed is less than 10%, impaired microbiological water quality occurs above 10% impervious surface, and highly degraded water quality occurs above 20% impervious surface (Fig. 4). Our analysis, therefore, moves beyond ecological indicators and provides a solid statistical link between land use factors and human health risk factors.

Urban and suburban nonpoint sources of fecal coliform bacteria include feces from birds, rodents, and other wild animals, domestic animals such as horses, and especially pets (Weiskel et al. 1996, Young and Thackston 1999). We suspect that dogs and cats are major fecal pollution sources in these watersheds. Results of a 1990 census indicated that there were at least 60 000 pets in New Hanover County, which roughly translates to about 1360 kg of manure produced per day (C. B. Williams, North Carolina Cooperative Extension Service; R. Curry, New Hanover County Health Department, *personal communications*). Weiskel et al. (1996) found 10^6 fecal coliforms/g of dog feces; thus, dog manure represents a sizable potential fecal bacterial load to receiving waters. A large portion of this manure is deposited on the landscape. Visual observations indicate that much pet fecal matter is deposited adjacent to impervious surfaces such as roads, sidewalks, driveways, etc., as well as on public and private lawns near creeks and drainage ditches. Suburban streets, drives, and lawns have been shown to be major source areas of fecal coliform bacteria in stormwater runoff (Bannerman et al. 1993, Young and Thackston 1999).

In urbanized watersheds nonpoint source runoff is considered to be a major general source of many pollutants (Klein 1979, Bannerman et al. 1993, Weiskel et al. 1996). Standard drainage designs commonly channel untreated runoff from impervious surfaces into storm drains, some of which feed wet detention ponds, while many drains lead directly into streams, lakes, or estuaries, including those containing shellfish beds. In contrast, vegetated pervious surfaces serve as passive runoff treatment systems in several ways. Lateral flow through vegetation settles out solids and associated bacteria, vegetation utilizes nitrogen and phosphorus through uptake, downward percolation achieves further nitrogen removal through denitrification by soil bacteria, and soil particles adsorb phosphate, ammonium, enteric bacteria, and other pollutants. Stormwater runoff that passes through vegetated buffers or through shallow groundwater reaches sensitive surface water bodies more slowly and in a much less impaired state than runoff from impervious surfaces.

Transformation of landscapes by humans, particularly in coastal regions, leads to a variety of negative ecological impacts (Vitousek et al. 1997). Our research analyzed five estuarine watersheds of varying population, amount of developed land, and type of land development. For all of these watersheds considered collectively, percentage watershed-impervious surface coverage alone explained 95% of the variability in average estuarine fecal coliform bacterial concentration. While known individual point sources of fecal bacteria should be removed whenever possible, on a watershed scale the greatest improvements in bacteriological quality of shellfishing and human contact waters likely will be achieved through implementing widespread specific voluntary or mandatory land management practices. These practices should involve advance planning to reduce the potential amount of impervious surface whenever possible. Where these surfaces are already extant or unavoidable, surface runoff should be directed into natural or artificial wetlands, grassy swales, and other porous areas before surface water runoff can enter coastal receiving waters.

To summarize, there is a basic spatial pattern within these coastal creeks of lowest fecal coliform abundance at creek mouth stations near the ICW (Intracoastal Waterway) and highest abundances in fresh or oligohaline stations upstream. This pattern is probably controlled by salinity, flushing, and proximity to pollution sources. There is another pattern of variable fecal coliform abundances among the creeks consisting of a decreasing pattern from Bradley, Hewletts, Howe, Pages, and Futch Creeks. This pattern is controlled primarily by degree of watershed development and especially by the amount of impervious surface in the watershed. The average amount of fecal coliform contamination in these estuaries could be predicted with a high degree of confidence by percentage impervious surface area within the watersheds; thus, in urbanizing coastal areas waterborne human health risks can be minimized by environmentally sound land use planning and development throughout a watershed. Future areas of research should involve more in-depth assessments of: (1) bacteriological quality of water draining specific types of urban and suburban usage, (2) the quality of drainage from various types of suburban housing developments (i.e., clustered, conventional, multifamily, etc.), and (3) how effective passive treatment systems such as wetlands and vegetated buffers are in reducing coliform loads to coastal waters.

Clearly, the land–water interface is not restricted to obvious areas such as beaches, marshes, and streamside wetlands. Our analysis demonstrates that anthropogenic changes to the natural landscape in areas seemingly well removed from shorelines can have significant impacts to the quality of water well downstream. Disturbances to land areas immediately adjacent to water bodies often result in immediate and visible impacts to these waters, and such disturbances should be minimized. However, we have demonstrated that, at least for sensitive shellfishing waters, the way humans alter the landscape throughout the entire watershed can also directly increase the health risks of humans contacting or eating shellfish from estuarine waters.

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