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Responses of Tidal Creek Macrobenthic Communities to the Effects of Watershed Development

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ABSTRACT: This study examined the effects of watershed development on macrobenthic communities in tidal creeks of Charleston Harbor, South Carolina, U.S. Two types of creeks were evaluated: upland creeks which drained watersheds consisting of at least 15% terrestrial land cover, and salt marsh creeks which drained no upland habitat (i.e., only intertidal habitat). Samples of macrobenthic organisms were taken along the longitudinal axis of twenty-three primary (first order) tidal creeks. Water and sediment quality data were also collected including measurements of dissolved oxygen, salinity, temperature, sediment characteristics, and toxic chemicals in the creek sediments. Hypoxic conditions occurred more than 15% of the time in both reference and developed creeks and were a natural attribute of these systems. The most severe and frequent hypoxia occurred in impacted salt marsh creeks. Salinity fluctuations were the greatest in developed upland creeks and salinity range was identified as a potentially reliable indicator of the degree to which watershed development has altered hydrodynamic processes. The creeks draining urban and industrial watersheds were degraded environments characterized by watersheds with high (> 50%) levels of impervious surface, broad fluctuations in salinity, severe hypoxia, and potentially toxic levels of chemicals in the sediment. These creeks had low macrobenthic diversity and abundance and were numerically dominated by the oligochaete *Monopylephorus rubroniveus* in mud sediments, and the polychaete *Laeonereis culveri* in sand sediments. Suburban watersheds had 15–35% impervious surface and creeks draining them were exposed to frequent hypoxia and broad salinity fluctuations. The levels of chemical contaminants in sediments of suburban and impacted salt marsh creeks were generally not different from the levels in reference creeks. Macrobenthic diversity and abundance were higher for suburban and impacted salt marsh creeks than for urban and industrial creeks. However, suburban and salt marsh impacted creeks were numerically dominated by a few pollution indicative species including the oligochaetes *M. rubroniveus* and *Tubificoides brownae* and the polychaete *L. culveri*. These creeks appear to be exhibiting early signs of degradation (e.g., a simplified food web). Two promising community-level macrobenthic metrics for assessing environmental quality were identified: the proportional abundance of pollution indicative taxa, and the proportional abundance of pollution sensitive taxa. These indicators were significantly ($p < 0.05$) correlated with the salinity range, the level of chemical contaminants in sediments, and amount of impervious surface in the watershed.

Introduction

Estuaries of the southeastern United States have 1.5–3.0 m tidal ranges, low relief, shallow depth, and expansive intertidal habitats (Nummedal et al. 1977; Wiegert and Freeman 1990). *Spartina alterniflora* and *Juncus roemerianus* salt marshes and the associated system of tidal creeks are characteristic features of these environments (Teal 1962; Hackney et al. 1976; Wiegert and Freeman 1990). These creeks provide nursery habitats for many species of juvenile fish and crustaceans as well as feeding grounds for wading birds and adult fish (Shenker and Dean 1979; Weinstein et al. 1980; Wenner 1992; Wenner and Beatty 1993; Dodd and Murphy 1996). Hydrodynamic processes in tidal creeks also trap fine-grained sediments, organic material, and chemical contaminants (Biggs et al. 1989) and serve as both conduits and repositories for pollutants (Olsen et al. 1982; Horlick and Subrahmanyam 1983; Sanger et al. 1999a,b).

Over the next several decades, the watersheds that drain tidal creeks in the southeastern United States, as well as globally, are projected to experience a high rate of human development (Edwards 1989; Culliton et al. 1990; Cohen et al. 1997). The construction of highway systems, residential housing, and industrial facilities that are projected to accompany this development will alter the topography and drainage patterns. These alterations will increase the rate and volume of freshwater inflow as well as the amount of fine sediments, toxic chemicals, organic materials, and nutrients introduced into estuaries (Driver and Troutman 1989; Vernberg et al. 1992; Fulton et al. 1993; Holland et al. 1996; Kucklick et al. 1997). Biological deg-

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radation associated with human-induced alterations to the ecosystem has been reported in many freshwater river and stream environments (Karr 1991; Schueler 1994). If development proceeds in an uncontrolled manner, the productivity and processes of tidal creek ecosystems may be irreversibly degraded (Vernberg et al. 1992; Sanger et al. 1999a,b).

This study was part of a larger project (Tidal Creek Project) evaluating the linkages between tidal creek environmental quality and human uses of coastal watersheds (Holland et al. 1996). The Tidal Creek Project used a comparative watershed approach that contrasted the physical, chemical, and ecological characteristics of tidal creeks draining relatively undeveloped watersheds with creeks draining urban, suburban, and industrial watersheds. Study elements included water quality, sediment quality, macrobenthic communities, and nekton communities. The specific objectives of this study were to evaluate the impacts of watershed development on macrobenthic communities and evaluate linkages with environmental parameters likely to affect them.

Materials and Methods

Study Area and Sampling Design

Twenty-three tidal creeks located in Charleston Harbor were sampled from July 5 to September 10, 1994 (Fig. 1). Eleven creeks were dominated by urban, suburban, and/or industrial land cover (developed creeks), and eight drained undeveloped forested watersheds (reference creeks). Four creeks that drained predominately salt marsh vegetation were also sampled. Creeks were classified into two subpopulations for analysis: upland and salt marsh. Upland creeks were further classified into four land use categories: forested or reference (i.e., $< 15\%$ of the watershed as urban/suburban land cover and some freshwater inflow); suburban ($> 45\%$ urban/suburban land cover with a human population density > 5 but < 20 individuals per hectare); urban (i.e., $> 70\%$ urban/suburban land cover with a human population density of > 20 individuals per hectare); and industrial (i.e., $>$ 45% urban/suburban land cover and presence of industrial facilities). Salt marsh creeks were either located in regions of the Charleston Harbor Estuary far removed from any source of pollution (reference) or were located adjacent to highly developed (impacted) watersheds.

All creeks had a water depth of < 10 cm at low tide, and were 2–3 m deep at high tide. The upper creek boundary was the point where depth at mean high tide was about 1 m, or where an impassable obstacle (a dike or security fence) was

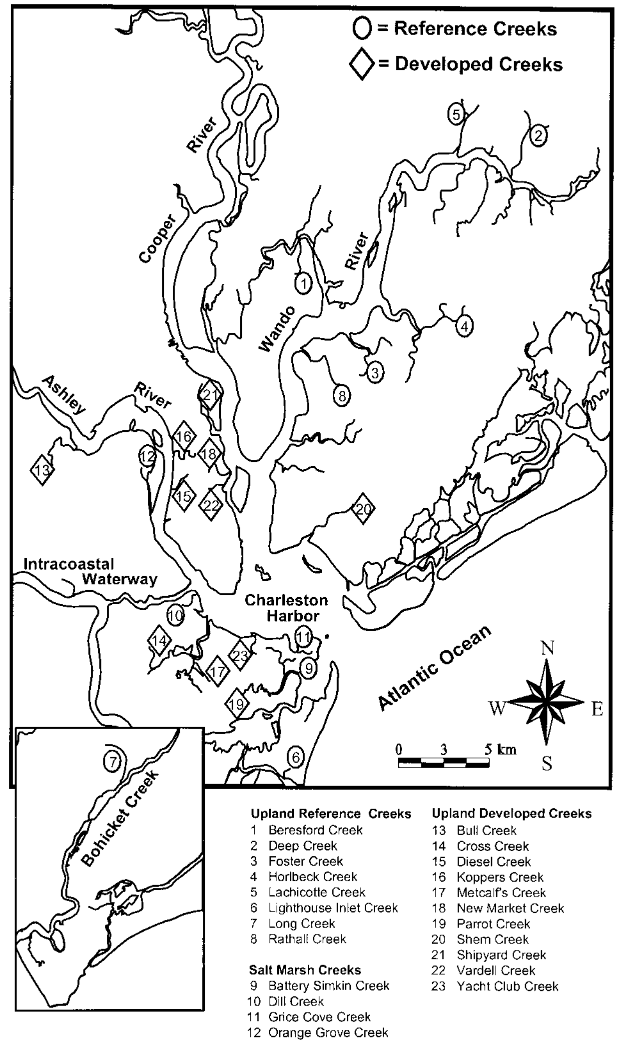

Fig. 1. Map of the Charleston Harbor Estuary showing the locations of the tidal creeks sampled (mouth at approximately 32°45′N 79°53′W). Circles indicate reference creeks. Diamonds indicate developed creeks.

reached. The lower boundary was the point where the creek converged with another water body, or the depth in the channel exceeded 3 m at high tide. The creeks represented the range of salinity distributions, sediment characteristics, creek lengths (231 to 1491 m), watershed sizes, land cover types, and levels of human disturbance that occur in Charleston Harbor (Table 1).

Creeks were stratified into 300-m reaches and macrobenthic community samples were collected randomly within each reach at approximately 1 m below the mean high tide line (mid-tide level). Six samples were collected with a 45.6-cm^2 coring device to a depth of 15 cm and sieved through a 500-μm screen. All organisms retained on the screen were identified to the lowest possible taxonomic

TABLE 1. Summary of land use and watershed condition indicators for upland and salt marsh creeks.

		Linear Measurements		Land Use Category						Watershed Condition Indicators	
Watershed Type	Creek Name, Code	Watershed Size (ha)	Creek Length (m)	Forest (ha)	Salt Marsh (ha)	Water (ha)	Barren/ Disturbed (ha)	Agriculture (ha)	Urban/ Suburban (ha)	Population Density (# ha^{-1})	Impervious Surface (%)
Upland Creeks											
Forested	Beresford Creek, BF	25.1	535	5.2	19.9	0.0	0.0	0.0	0.0	0.0	0.0
Forested	Deep Creek, DP	64.7	586	40.0	12.0	0.0	0.0	12.7	0.0	0.0	4.1
Forested	Foster Creek, FT	16.0	585	3.4	12.6	0.0	0.0	0.0	0.0	0.0	0.0
Forested	Horlbeck Creek, HB	237.5	895	184.6	9.1	3.6	17.9	22.3	0.0	0.1	1.8
Forested	Lachicotte Creek, LH	13.1	436	1.9	11.2	0.0	0.0	0.0	0.0	0.0	0.0
Forested	Lighthouse Creek, LC	37.3	899	2.7	31.6	0.0	3.0	0.0	0.0	0.0	0.0
Forested	Long Creek, LI	412.4	1,446	243.1	17.7	0.0	43.8	101.8	6.0	0.3	2.2
Forested	Rathall Creek, RT	72.1	1,200	30.3	35.3	0.0	6.5	0.0	0.0	0.6	0.8
Industrial	Diesel Creek, DL	105.3	784	0.0	32.8	0.0	8.9	0.0	63.6	6.9	50.0
Industrial	Koppers Creek, KP	116.6	880	0.0	11.6	0.0	12.3	0.0	92.7	3.3	52.7
Industrial	Shipyard Creek, SH	279.1	826	14.1	10.2	0.0	74.5	0.0	180.4	8.2	49.4
Urban	New Market Creek, NM	187.2	1,167	3.0	26.6	0.0	17.9	0.0	139.7	21.1	51.2
Urban	Vardell Creek, VR	68.7	450	0.0	9.5	0.0	0.0	0.0	90.5	31.8	70.4
Suburban	Bull Creek, BL	442.8	1,395	83.5	20.5	15.6	3.5	0.0	319.7	12.7	28.9
Suburban	Cross Creek, CC	312.9	536	28.6	5.2	2.4	41.0	8.9	226.8	10.6	26.4
Suburban	Metcalf's Creek, MC	129.7	874	17.4	7.0	0.0	17.1	0.0	88.2	8.9	30.8
Suburban	Parrot Creek, PC	147.2	1,491	23.6	14.5	1.4	30.6	7.8	69.3	7.0	19.5
Suburban	Shem Creek, SM	427.8	1,174	61.5	9.3	4.2	66.8	0.0	286.0	15.7	34.5
Suburban	Yacht Club Creek, YC	69.1	593	4.6	8.2	1.0	1.8	0.0	53.5	7.1	14.9
Salt Marsh Creeks											
Reference	Battery Simpkin Creek, BS	23.0	1,110	0.0	23.0	0.0	0.0	0.0	0.0	0.0	0.0
Reference	Grice Cove Creek, GC	20.6	577	0.1	20.5	0.0	0.0	0.0	0.0	0.0	0.0
Impacted	Dill Creek, PI	20.2	536	0.0	20.0	0.0	0.0	0.0	0.2	0.0	0.0
Impacted	Orange Grove Creek, OG	20.6	285	0.1	20.5	0.0	0.0	0.0	0.0	0.0	0.0

level and counted. Six surface (upper 2 cm) sediment samples were also collected and processed to determine percent moisture, percent silts and clays, and percent sand using the standard pipette protocol modified from Plumb (1981).

A Hydrolab DataSonde 3 (DS3) water quality monitoring system was deployed in the lower reach of each creek for 2 to 4 d prior to sampling. The DS3 was positioned approximately 5–10 cm above the creek bottom and measured salinity, water temperature, dissolved oxygen concentration, pH, and water depth at 30-min intervals.

Surface sediments (upper 2 cm) were also collected during the summer of 1995 for chemical analyses at one randomly selected site from the upper-most and lower-most reach of each creek sampled in 1994. These samples were homogenized then divided into three aliquots. One aliquot was placed in an acid washed plastic jar for trace metal analyses. The second aliquot was placed in a precleaned glass jar for organic contaminant analyses. The third aliquot was stored in a plastic bag for organic carbon analyses. The samples were then immediately placed on ice and stored at −60°C. Analyses were performed for 14 trace metals, 24 polyaromatic hydrocarbons (PAHs), and 20 polychlorinated biphenyls (PCBs) by the National Ocean Service Laboratory (National Oceanic and Atmospheric Administration [NOAA]-Charleston, South Carolina) using methods described by Sanger et al. (1999a,b). The contaminants measured during the study include the majority of the contaminants routinely monitored by NOAA's National Status and Trends Program (1991).

The boundary of each watershed was defined using topographic maps and Geographical Information System (GIS). The area was classified into land use categories based on a modification of the Anderson Land Use Classification System (Anderson et al. 1976). Human population statistics for each watershed were obtained from the Berkeley-Charleston-Dorchester Council of Governments (TIGER/Line Files 1992). The percent of each watershed that was impervious surface was determined by point sampling a minimum of 200 randomly selected points within each watershed on 1: 4,800 blackline aerial photographs (photographed in 1989) and counting the number of points that fell on roads, parking lots, roofs, or other impervious surfaces.

Statistical Analyses

Abundance data for the numerically dominant taxa was evaluated as the estimated number of individuals m^{-2} (absolute abundance) or as the percent of the total infauna (relative abundance) collected. Only the relative abundance data are presented in this paper. The absolute abundance data can be found in Lerberg (1997).

A two-way analysis of covariance (ANCOVA) using SAS (1989) with all significant interaction terms was used to contrast macrobenthic community characteristics among land use classes and between the upper-most and lower-most reaches of creeks. Community measures used included the number of species per sample, Shannon-Weiner Diversity Index (H'), total number of individuals per sample, percent dominance by most abundant species, and the relative abundance of the numerically dominant oligochaetes (*Monopylephorus rubroniveus, Tubificoides brownae,* and *Tubificoides heterochaetus*), polychaetes (*Laeonereis culveri* and *Streblospio benedicti*), and nemerteans. Covariates evaluated included the mean creek salinity, the silt-clay content of the sediments, and the percent of the time the dissolved oxygen concentration was hypoxic ($<$ 28% saturation). Covariates were included in the model if they were significant at $p < 0.10$. Abundance data were transformed using a $\log_{10}$ transformation. Proportional data were transformed using an arcsine square root transformation. Estimates of least square means and pair-wise comparisons were obtained for each ANCOVA model. The assumption that there were no significant differences in the slopes of the treatment lines was tested by determining if the covariate by main treatment effects interaction term was significant. The equal slopes model is presented. All statistical analyses were considered significant at $p = 0.10$.

This probability level ($p = 0.10$) was selected over a more standard $p < 0.05$ to reduce the probability of making a Type II error. We compared our results using both a 0.05 and 0.10 probability level and found relatively few differences. Use of the $p < 0.10$ therefore provided for an increased likelihood of identifying potential ecologically important problems. In all cases we have provided the observed p values and as much detail on the statistical testing as possible.

Wilcoxon rank sum and independent sample *t*-tests were also used to compare the physical-chemical data between reference and developed creeks. Associations (strength and direction) between environmental variables and macrobenthic community characteristics were evaluated using a Pearson's product moment correlation coefficient (SAS 1989).

A mean effects range-low quotient (ERLQ) was developed to provide a cumulative measure of trace metal, PAH, and PCB contamination in the sediments of these tidal creeks. This calculation involved dividing each concentration by the ERL value published in Long et al. (1995), summing the ratio values, and dividing by the number of individual compounds included in the calculation ($n = 23$) (Long et al. 1998). The specific procedures used and analytes included in the calculations are described in Sanger (1998).

Results

Land Use and Human Population Data

Watershed size in the population of creeks sampled ranged from 13.1 to 442.8 hectares (ha). The drainage areas of developed upland creeks (mean = 203.4 ha) were generally larger than the drainage areas of the reference upland creeks (mean = 109.8 ha). The larger drainage basins had the most complex land cover patterns. The four salt marsh creeks had the smallest drainage areas (range = 20.2 to 23.0 ha, mean area = 21.1 ha), and consisted of primarily one land cover type—estuarine salt marsh. Population density in developed upland watersheds ranged from 0 to 31.8 individuals ha^{-1} (Table 1). The human population density in forested watersheds never exceeded 0.6 individuals ha^{-1}. Creeks located in forested watersheds had little or no impervious surface in their drainage basins. Creeks in suburban and urban/industrial watersheds had 15–79% of their drainage area as impervious surface (Table 1). The amount of impervious surface in upland watersheds was significantly correlated ($p < 0.0001$, $r^2 = 0.62$) with human population density. When industrial watersheds were excluded from this analysis the r^2 value increased to 0.98.

Physical and Chemical Data

Salinity varied within creeks, among creeks, and among watershed classes (Fig. 2). Reference and developed creeks encompassed a broad range of salinities including euhaline (25–32 psu), polyhaline (18–25 psu), and mesohaline (5–18 psu) environments. Upstream-downstream salinity gradients (range = 0–11.7 psu, mean = 1.75 psu) were small because most of the volume of creeks (ranging in length from 231 to 1,491 m) was displaced on each tidal cycle. The mean salinity of upland creeks was about five psu lower during low tide than the comparable high tide salinity. Rainfall occurred shortly before or during almost every sampling event, with a measurable rain event occurring on 36 d of the 68-d sampling period. The average rainfall event resulted in 1.79 cm of rain. During rain events (e.g., thunderstorms) large, rapid declines in the low tide creek salinity occurred, even for the salt marsh creeks. Salinity fluctuations, as represented by the salinity range, were significantly greater ($p < 0.01$) in the suburban and urban/industrial creeks than in the reference (forested) upland creeks (Fig. 2). The salinity

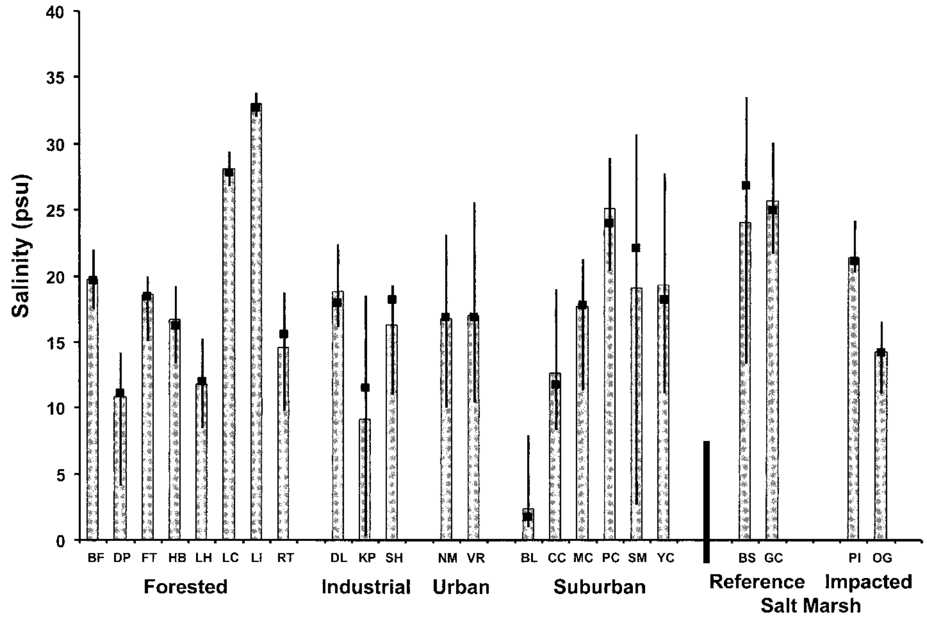

Fig. 2. The mean, median, and salinity range for each creek collected two to four days prior to each sampling event. The top of the bar represents the mean value and the shaded square represents the median value. The vertical line represents the range. The mean salinity range (mean SR_w ± SE) for each watershed class is as follows: Forested (6.9 psu ± 1.2), Industrial (12.8 psu ± 2.9), Urban (14.5 psu ± 1.4), Suburban (14.0 psu ± 3.2), Reference Salt Marsh (14.6 psu ± 5.5), and Impacted Salt Marsh (6.9 psu ± 1.9).

range of upland creeks was positively correlated ($p < 0.05$) with the size of the drainage basin.

Dissolved oxygen (DO) values varied with time of the day and tidal stage. In general, highest DO levels (% saturation) occurred in mid-afternoon. The lowest DO levels occurred during early morning low tides (Fig. 3). Mean DO levels were similar among watershed classes (Fig. 4). Values representing supersaturated conditions occurred during midday in upland and salt marsh creeks. Dissolved oxygen levels in both reference and developed creeks were frequently below 28% saturation (hypoxic). The percent of time upland creeks exhibited low DO levels was similar among watershed classes (Fig. 5, $p > 0.10$).

Mean creek water temperatures were > 25°C. Extreme values occurred during daytime low tides (> 32°C). No significant differences in water temperature occurred among creeks. The pH of creek water tended to be lower in forested (upland reference) creeks (7.1 versus 7.3) probably because of the higher levels of humic acids which are associated with runoff from forested environments.

Sediments varied in a heterogeneous manner along the lengths of creeks. Few consistent upstream-downstream gradients in the silt-clay content were found. Exceptions included the downstream increase in silt-clay content in Shem, Metcalf, and Diesel creeks. Silt-clay content in Parrot and Shipyard creeks exhibited the reverse pattern. Greater amounts of fine sediments were found in impacted salt marsh creeks than reference salt marsh creeks. Forested creeks were characterized by more fine sediment than suburban, industrial, or urban creeks. The urban creek class contained the greatest amount of sand sediments.

Surface sediments in creeks draining industrial and urban watersheds contained significantly ($p < 0.0001$) greater amounts of chemical contaminants than other creek classes particularly in their uppermost reaches (Fig. 6). A complete summary and analysis of the contaminant data is presented in Sanger et al. (1999a,b).

Macrobenthic Community Data

A total of 8,034 individuals representing 97 taxa were obtained from the 417 samples. The assemblage was dominated by annelid worms, particularly oligochaetes (mean = 2,208 individuals m^{-2}) and polychaetes (1,811 individuals m^{-2}). These taxa comprised 95.9% of the fauna. Molluscs (71 individuals m^{-2}) and crustaceans (45 individuals m^{-2}) accounted for only 2.8% of the fauna (Tables 2 and 3).

Forty-four of the 97 taxa collected occurred in only one or two samples. Nine taxa (*M. rubroniveus, S. benedicti, Heteromastus filiformis, L. culveri, T. heterochaetus, T. brownae, Capitella capitata, Tharyx* cf. *acutus,* and *Neanthes succinea*) accounted for 90% of the specimens collected (Table 3).

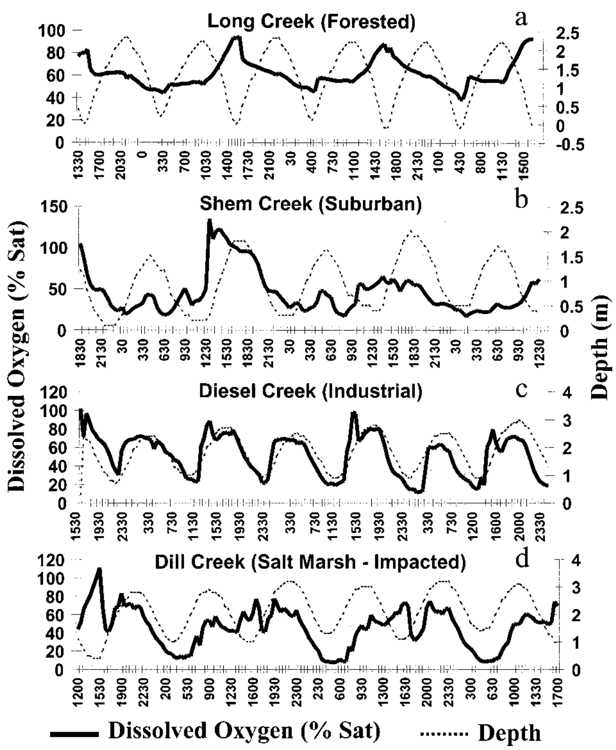

Fig. 3. Summary of dissolved oxygen and depth data for a representative (a) forested creek (Long Creek sampled July 24–July 28, 1994), (b) suburban creek (Shem Creek sampled July 18–July 21, 1994), (c) industrial creek (Diesel Creek sampled July 16–July 20, 1994), and (d) salt marsh impacted creek (Dill Creek sampled July 22–July 25, 1994).

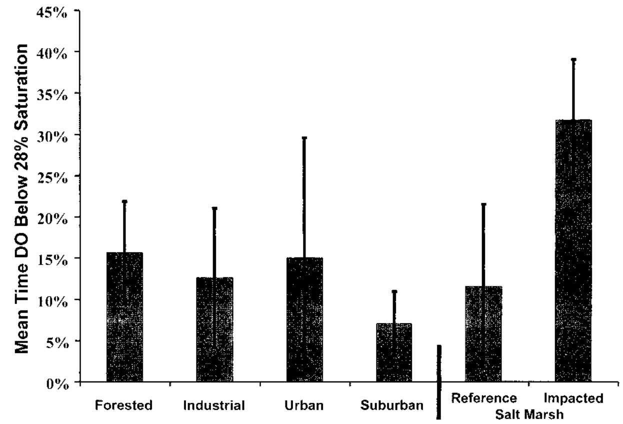

Fig. 5. The mean percent of time dissolved oxygen concentrations were less than 28% for creeks composing each watershed class. Error bars represent ± SE.

Macrobenthic Community Response to Natural Environmental Variation

Few taxa exhibited abundance differences between the upper-most and lower-most creek reaches. The relative abundances of the oligochaete *M. rubroniveus* ($p = 0.0079$), and the polychaete *C. capitata* ($p = 0.0403$) were significantly higher in the upper-most creek reaches than the lower-most reaches. Conversely, the abundance of the polychaete *H. filiformis* was significantly higher ($p = 0.0001$) in the lower-most reaches. When upstream-downstream gradients in abundance were

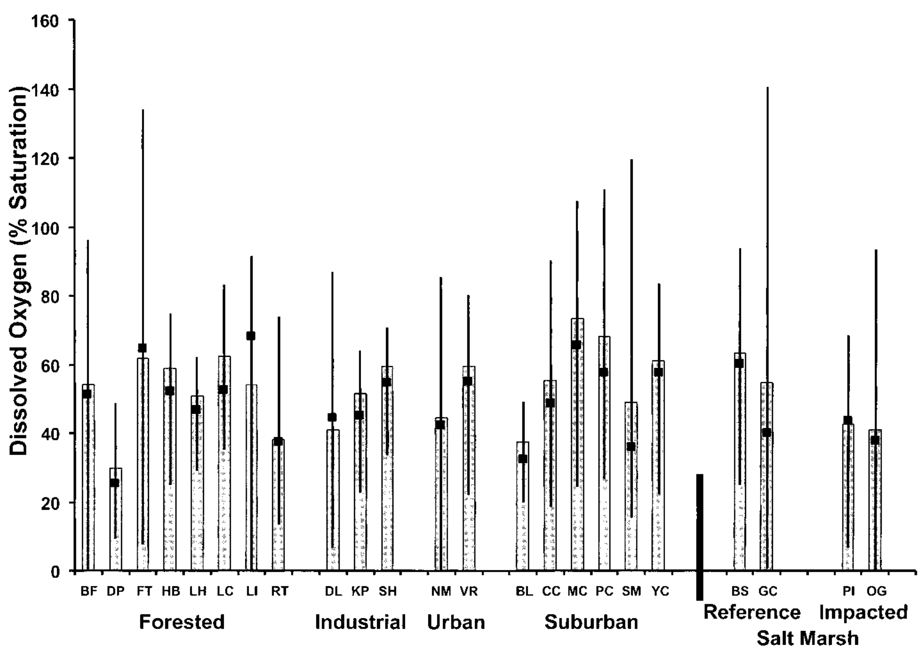

Fig. 4. The mean, median, and range of dissolved oxygen data for each creek two to four days prior to each sampling event. The top of the bar represents the mean value and the shaded square represents the median value. The vertical line represents the range.

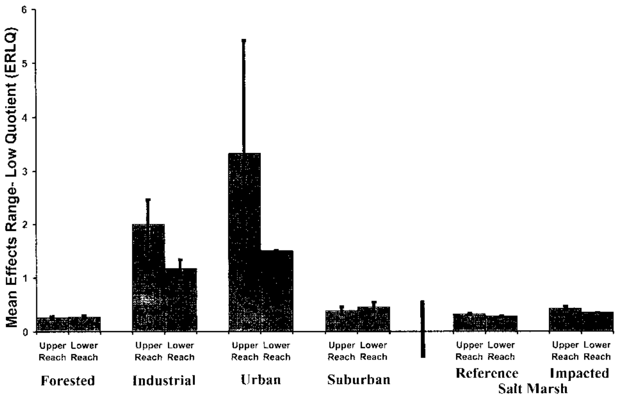

Fig. 6. Summary of the ERLQ (effects range-low quotient) values for the upper and lower reach of each watershed type. Error bars represent ± SE.

TABLE 2. Summary of the macrobenthic data for upland and salt marsh creeks by major taxonomic group (n = 417 cores).

Major Taxa	No. of Individuals Collected	Average Density (# m^{-2})	% Total Abundance
Oligochaeta	4,198	2,208	52.25
Polychaeta	3,443	1,811	42.85
Gastropoda	132	69	1.64
Nemertinea	130	68	1.62
Crustacea—Others*	61	32	0.76
Crustacea—Decapoda	24	13	0.30
Platyhelminthes	20	11	0.25
Pelecypoda	19	10	0.24
Hirudinea	4	2	0.05
Hemichordata	1	1	0.01
Hydrozoa	1	1	0.01
Sipuncula	1	1	0.01

* This group includes Amphipods, Isopods, Tanaids, Ostracods, and Mysids.

found, the actual amount of variation accounted for by longitudinal distance was relatively small ($<$ 5% of the total variation).

The salinity covariate was significant ($p < 0.10$) for 9 of the 14 metrics evaluated (Table 4) and was the most significant term in the ANCOVA model for five of these analyses accounting for at least 10% of the model variance. Metrics that were positively associated with salinity included the number of taxa, the total number of individuals, and the relative abundance of all polychaetes, *H. filiformis,* and *S. benedicti.* The relative abundance of all oligochaetes, *T. heterochaetus, L. culveri,* and the nemerteans decreased with increasing salinity.

The silt-clay covariate was significant for 7 of the 14 metrics evaluated (Table 4) and was the most significant term in the ANCOVA model for three metrics. However, the silt-clay covariate generally accounted for $<$ 2% of the variance in the ANCOVA models. The relative abundance of the polychaete *L. culveri* was the only metric evaluated that had substantial amounts of variance ($>$ 14%) associated with the sediment covariate. Metrics that were negatively correlated with the sediment silt-clay content included the number of taxa per sample, the relative abundance of all polychaetes, and the relative abundance of *L. culveri, C. capitata,* and *T. heterochaetus.* The total number of individuals per sample and the relative abundance of *M. rubroniveus* were positively correlated with silt-clay content.

The dissolved oxygen covariate was significant for 6 of the 14 metrics evaluated (Table 4) and was the most significant term in the ANCOVA model for three metrics. However, it accounted for small (2–5%) amounts of the variance. Metrics that decreased in value with decreasing dissolved oxygen levels were the number of taxa per sample, and the relative abundance of the polychaetes, *S. benedicti* and *L. culveri.* Metrics that increased in value with increasing exposure to low dissolved oxygen were the total number of individuals, the relative abundance of all oligochaetes, and the relative abundance of *M. rubroniveus.*

Macrobenthic Community Responses to Development

Tests comparing macrobenthic community metrics among watershed-types and reaches, and the identification of interactions between watershed and reach effects are presented in Table 5. Results for the upland creek classes are discussed first followed by a discussion of salt marsh creeks. Data for industrial and urban creek classes were combined for these analyses because of the similarity in the amounts of impervious surface for the two watershed classes. This combination also increases the power of significance tests to detect differences between this new urban/industrial watershed class and other creek classes.

The number of taxa per sample was significantly higher in creeks located in the forested ($p = 0.0566$) and suburban ($p = 0.0199$) watershed classes than in creeks draining urban/industrial watersheds. This pattern resulted because crustaceans and bivalves were reduced in creeks draining urban and industrial watersheds. Rare taxa that were not found in the industrial and urban creeks included *T.* cf. *acutus, Fabricia* sp., *Potamilla* sp., *Leptochelia* sp., *Melita nitida, Gammarus mucronatus, Cyathura burbancki, Macoma tenta, Tellinidae,* and *Polymesoda caroliniana.*

The total number of individuals per sample was higher in upland creeks draining suburban watersheds than in creeks draining watersheds dominated by forested ($p = 0.0032$) or urban/industrial (p

TABLE 3. Macrobenthic data collected from the upper-most and lower-most reaches of upland creeks and salt marsh creeks. Key to Major Taxonomic Groups: A = Amphipoda, G = Gastropoda, HE = Hemichordata, I = Isopoda, M = Mysidacea, N = Nemertinea, O = Oligochaeta, OS = Ostracoda, P = Polychaeta, PE = Pelycepoda, PLAT = Platyhelminthes, S = Sipuncula, T = Tanaidacea. Key to Species Code: PI = Pollution Indicative, PS = Pollution Sensitive, U = Ubiquitous, R = Rare.

		Forested (n = 93)		Suburban (n = 71)		Urban/Industrial (n = 56)		Marsh Ref. (n = 24)		Marsh Imp. (n = 17)	
Scientific Name	Species Code	Avg. No. m^{-2}	% Total	Avg. No. m^{-2}	% Total	Avg. No. m^{-2}	% Total	Avg. No. m^{-2}	% Total	Avg. No. m^{-2}	% Total
Monopylephorus rubroniveus (O)	PI	787.6	22.6	1,868.7	44.2	806.7	36.1	1,928.0	28.6	7,198.2	84.8
Tubificoides heterochaetus (O)	PS	573.0	16.4	262.5	6.2	50.9	2.3				
Heteromastus filiformis (P)	PS	474.0	13.6	139.0	3.3	82.2	3.7	849.8	12.6	270.9	3.2
Streblospio benedicti (P)	PS	466.9	13.4	444.8	10.5	246.7	11.0	2,412.3	35.7	528.9	6.2
Capitella capitata (P)	U	285.3	8.2	40.2	0.9	231.0	10.3	18.3	0.3		
Neanthes succinea (P)	U	207.5	6.0	139.0	3.3	78.3	3.5	173.6	2.6	38.7	0.5
Laeonereis culveri (P)	PI	113.2	3.2	417.0	9.9	513.0	22.9				
Nemertinea (N)	PS	108.5	3.1	40.2	0.9	70.5	3.2	64.0	0.9	64.5	0.8
Tubificidae (O)	U	84.9	2.4	83.4	2.0	39.2	1.8	100.5	1.5	90.3	1.1
Tubificoides brownae (O)	PI	82.5	2.4	525.1	12.4	82.2	3.7	721.9	10.7	270.9	3.2
Tharyx cf. *Acutus* (P)	PS	63.7	1.8	30.9	0.7			246.7	3.7		
Fabricia sp. A (P)	R	49.5	1.4								
Potamilla sp. (P)	R	42.4	1.2					91.4	1.4		
Tubificoides wasselli (O)	R	25.9	0.7	3.1	0.1						
Leitoscoloplos fragilis (P)	R	21.2	0.6	27.8	0.7	3.9	0.2	27.4	0.4	12.9	0.2
Monopylephorus irroratus (O)	R	16.5	0.5	37.1	0.9			9.1	0.1		
Polydora cornuta (P)	R	14.1	0.4	18.5	0.4			27.4	0.4		
Leptochelia sp. (T)	R	11.8	0.3								
Ostracoda sp. (OS)	R	11.8	0.3	6.2	0.1						
Eteone heteropoda (P)	R	7.1	0.2					9.1	0.1		
Mediomastus californiensis (P)	R	7.1	0.2			3.9	0.2				
Cassidinidea lunifrons (I)	R	4.7	0.1	18.5	0.4	3.9	0.2				
Melita nitida (A)	R	4.7	0.1	9.3	0.2						
Amphitrite ornata (P)	R	2.4	0.1								
Corbicula contracta (PE)	R	2.4	0.1								
Cyathura burbancki (I)	R	2.4	0.1	6.2	0.1			9.1	0.1		
Glycera americana (P)	R	2.4	0.1	3.1	0.1						
Hesionidae (P)	R	2.4	0.1	3.1	0.1	3.9	0.2				
Macoma tenta (PE)	R	2.4	0.1	6.2	0.1						
Sipuncula (S)	R	2.4	0.1								
Tellinidae (PE)	R	2.4	0.1								
Websterinereis sp. (P)	R	2.4	0.1								
Turbellaria (PLAT)	R			18.5	0.4	3.9	0.2				
Bocardiella sp. A. (P)	R			15.4	0.4						
Mysidopsis bigelowi (M)	R			12.4	0.3						
Gastropoda (G)	R			9.3	0.2						
Monticellina dorsobranchialis (P)	R			9.3	0.2			18.3	0.3		
Paraprionospio pinnata (P)	R			9.3	0.2						
Polydora socialis (P)	R			6.2	0.1						
Gammarus mucronatus (A)	R			3.1	0.1						
Hemichordata (HE)	R			3.1	0.1						
Lumbrineridae (P)	R			3.1	0.1						
Mysidopsis furca (M)	R			3.1	0.1						
Polymesoda caroliniana (PE)	R			3.1	0.1						
Prionospio sp. (P)	R			3.1	0.1						
Sphaeorsyllis longicauda (P)	R			3.1	0.1			9.1	0.1		
Corbiculidae (PE)	R					3.9	0.2				
Sabellidae (P)	R					3.9	0.2	9.1	0.1		
Terebellidae (P)	R					3.9	0.2				
Corophium lacustre (A)	R							9.1	0.1		
Gemma gemma (PE)	R							9.1	0.1		
Mulinia lateralis (PE)	R							9.1	0.1		
Acanthohaustorius intermedius (A)	R									12.9	0.2

= 0.0002) land cover (Table 5). Most of the higher abundances found in suburban creeks were associated with the oligochaete fauna. The percent of the macrobenthic assemblage represented by oligochaetes and the relative abundance of the two most abundant oligochaete species, *M. rubroniveus* and *T. brownae,* were significantly higher in the suburban creek class than in the forested or urban/

TABLE 4. Summary of the influence of environmental factors used as covariates in the ANCOVA models on community characteristics. A plus indicates a positive relationship between the covariate and the respective community characteristic. A minus sign indicates a negative relationship.

Habitat/Exposure Indicators	Salinity (mean from DS3)	Sediment Type (% silts and clays)	Dissolved Oxygen (% time below 28% saturation)
Community Parameters			
Species Richness (# sample^{-1})	+	−	−
Shannon-Weiner Diversity (H′)			
Total Number of Individuals (# sample^{-1})	+	+	+
Dominance by Most Abundant Species (% abundance sample^{-1})			
Dominant Taxa			
Polychaetes	+	−	
Heteromastus filiformis	+		
Streblospio benedicti	+		−
Laeonereis culveri	−	−	−
Capitella capitata		−	
Oligochaetes	−		+
Monopylephorus rubroniveus		+	+
Tubificoides brownae			
Tubificoides heterochaetus	−	−	
Nemertinea	−		

industrial classes (Table 5). Abundances of *M. rubroniveus* and *T. brownae* were lowest in creeks draining forested watersheds.

The relative abundance of the polychaete *L. culveri* was significantly higher ($p = 0.0592$) in creeks draining urban/industrial watersheds than in creeks draining forested watersheds. The abundance of this species in creeks draining suburban watersheds was intermediate and not significantly different ($p > 0.10$) from that in creeks draining urban/industrial or forested watersheds.

Several other taxa had abundance patterns that appeared to be negatively associated with increasing degrees of watershed development. For example, the relative abundances of *T. heterochaetus* ($p < 0.0001$), *S. benedicti* ($p = 0.0416$), and the nemerteans ($p = 0.0271$) were significantly higher in the forested creek class than in the suburban and urban/industrial creek classes (Table 5).

Engle and Summers (1998) and Van Dolah et al. (1999) suggest that the H′ measure of species diversity is positively correlated with estuarine envi-

TABLE 5. Summary of ANCOVA results evaluating the effects of watershed type and longitudinal position (reach) on community parameters. Values shown are p levels. Pairwise comparisons were analyzed using least square means. Treatments not connected by a common underline differed at p = 0.10. SR = salt marsh reference, SI = salt marsh impacted, U = urban/industrial, SU = suburban, and F = forested (upland reference), ns = not significant. An asterisk indicates that the models for these species were accomplished using data for only creeks located on upland watersheds.

Macrobenthic Community Parameters	Significant Covariates	Watershed Type	Reach	Interaction	Pairwise Comparisons
Number of taxa (# sample^{-1})	DO, sal, mud	0.0084	ns	ns	SR SU F SI U
Total number of individuals (# sample^{-1})		0.0001	ns	0.0439	SI SR SU F U
Shannon-Weiner Diversity (H′)	DO, sal, mud	0.0082	ns	ns	SR F SU U SI
Dominance by most abundant species (% abundance sample^{-1})		0.0145	ns	0.0433	SI SU U SR F
Oligochaetes (% abundance sample^{-1})	DO, sal	0.0002	ns	ns	SI SU SR U F
Monopylephorus rubroniveus	mud, DO	0.0001	0.0079	ns	SI SU SR U F
Tubificoides brownae		0.0001	ns	ns	SR SU SI U F
*Tubificoides heterochaetus**	sal, mud	0.0001	ns	ns	F SU U
Polychaetes (% abundance sample^{-1})	sal, mud	ns	ns	ns	SR SU F U SI
Streblospio benedicti	sal, DO	0.0609	ns	ns	SR F SI U SU
*Laeonereis culveri**	mud, DO, sal	ns	ns	0.0004	U SU F
Nemertinea (% abun sample^{-1})	sal	0.0047	ns	ns	F SR U SI SU

TABLE 6. Summary of the responses of the macrobenthic community to watershed development. Values presented for mean number of taxa per sample, Shannon-Weiner diversity (H′), % dominance by most abundant species, % relative abundance of rare taxa, % relative abundance of pollution indicative species, % relative abundance of potentially pollution sensitive taxa, % relative abundance of ubiquitous taxa, and mean total number of individuals per sample.

Macrobenthic Community Measures	Upland Creeks			Salt Marsh Creeks	
	Forested	Suburban	Urban/Industrial	Reference	Impacted
Number of taxa per sample	3.4	3.6	2.5	4.9	2.8
Shannon-Weiner Diversity (log10)	0.37	0.36	0.30	0.48	0.21
% dominance	48	58	52	48	80
% abundance of rare species	5.8	4.6	0.7	1.6	0.1
% pollution indicative species	27.3	64.8	60.5	38.7	84.3
Monopylephorus rubroniveus	21.9	43.1	34.8	28.2	81.2
Laeonereis culveri	3.1	9.6	22.1	0.0	0.0
Tubificoides brownae	2.3	12.1	3.5	10.5	3.1
% pollution-sensitive species	46.8	21.2	19.4	52.2	9.8
Tubificoides heterochaetus	15.9	6.1	2.2	0.0	0.0
Streblospio benedicti	13.0	10.3	10.6	35.2	6.0
Nemertinea	3.0	0.9	3.0	0.9	0.7
Heteromastus filiformis	13.2	3.2	3.5	12.4	3.1
Tharyx cf. *acutus*	1.8	0.7	0.0	3.6	0.0
% ubiquitous taxa	13.7	4.1	13.3	2.8	0.4
Capitella capitata	7.9	0.9	10.0	0.3	0.0
Neanthes succinea	5.8	3.2	3.4	2.5	0.4
Total number of individuals	3,348	4,294	2,562	6,402	8,423

ronmental quality at the regional scale. This study found that H′ was not significantly different among upland creek classes (Table 5). Diversity (H′) values did tend to decrease as the degree of development increased. The dominance measure evaluated (relative abundance of the most abundant species) was significantly higher ($p = 0.0381$) in suburban creeks than in forested creeks. Dominance values for urban/industrial creeks were intermediate between the values for suburban and forested creeks, but were not significantly different ($p > 0.10$) from either class of creek (Table 5).

The salt marsh reference creeks had significantly higher numbers of taxa ($p = 0.0924$) and diversity ($p = 0.0009$) than the impacted salt marsh creeks. Much of this difference was due to the absence of rare taxa, particularly crustaceans and bivalves, from impacted salt marsh creeks. Rare taxa that were not found in impacted salt marsh creeks included *T.* cf. *acutus, Eteone heteropoda, C. burbancki, Corophium lacustre, Mulinia lateralis,* and *Gemma gemma*. In addition, the impacted salt marsh creeks had significantly higher dominance values than the other watershed classes sampled ($p < 0.0555$). Macrofaunal abundance was consistently higher for salt marsh creeks than for upland creeks, although there was no difference in total macrofaunal abundance between the two salt marsh creek populations.

The oligochaete *M. rubroniveus* was the numerically dominant macrobenthic organism in salt marsh creeks. Densities of this species were significantly higher ($p = 0.0001$) in impacted salt marsh creeks than in reference salt marsh creeks. The oligochaete, *T. brownae,* exhibited the opposite pattern and had significantly ($p = 0.0556$) higher abundances in reference salt marsh creeks than in impacted salt marsh creeks. Two species, *L. culveri* and *T. heterochaetus,* that were numerically dominant in upland creeks were not found in salt marsh creeks. Both of these species appear to prefer sand habitats and the high levels of fine sediments that occur in the salt marsh creeks may have effectively excluded them from these environments.

A summary of the changes in relative abundance of numerically dominant species and community-level metrics among watershed classes is presented in Table 6. The relative abundance of three of the numerically dominant species (*M. rubroniveus, T. brownae,* and *L. culveri*) increased with increasing levels of watershed development and pollution stress. The two oligochaete species, *M. rubroniveus* and *T. brownae,* attained their highest abundance in the suburban creeks (Table 6). The high abundance of *L. culveri* in urban/industrial creeks may have resulted from the higher proportion of sand sediments in this class of creeks (e.g., Vardell and Shipyard).

The oligochaete *T. heterochaetus,* the nemerteans, and the polychaete *S. benedicti* declined in abundance with increasing levels of watershed development (Tables 5 and 6). Most research on ma-

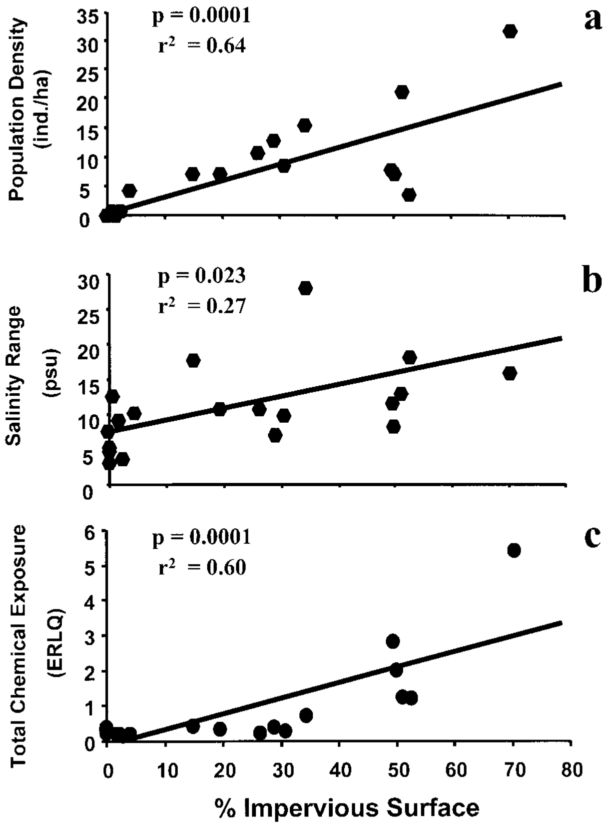

Fig. 7. Relationships between (a) human population density, (b) salinity range, and (c) total chemical exposure and the amount of impervious surface on the watershed. The coefficient of determination (r^2) and p-value are presented.

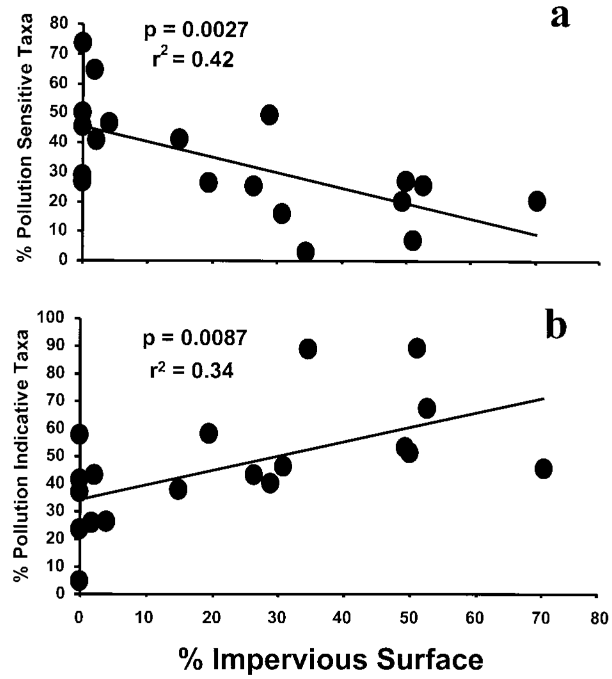

Fig. 8. Relationships between two indices of macrobenthic community measures and the amount of impervious surface in the watershed. Only data from the upland creeks were used. Potentially pollution sensitive taxa (a) include *Tubificoides heterochaetus, Streblospio benedicti, Heteromastus filiformis, Tharyx* cf. *acutus,* and Nemertinea. Pollution indicative taxa (b) include *Monopylephorus rubroniveus, Tubificoides brownae,* and *Laeonereis culveri.* The coefficient of determination (r^2) and p-value are presented.

crobenthic indicators suggest that *S. benedicti* is relatively tolerant to pollution and list this polychaete as a pollution indicative organism (Pearson and Rosenberg 1978; Levin 1984; Weisberg et al. 1990; Engle et al. 1994). However, our findings and the experiments of Sarda et al. (1996) suggest that *S. benedicti* is not as tolerant to chronic pollution exposure or hypoxia as the oligochaete *M. rubroniveus.*

Other species that are potentially useful as indicators of pollution stress include *T.* cf. *acutus* and *H. filiformis. Tharyx* cf. *acutus* decreased in abundance as the degree of watershed development increased, however, this species only occurred in high polyhaline and euhaline environments. *Heteromastus filiformis* had lower relative abundance in creeks located on developed watersheds (Table 6). These differences were not significant ($p > 0.10$) because of high within-habitat variability in creeks with forested watersheds. Lower abundances of these species in developed creeks do not unambiguously indicate the degree of development stress. In contrast, *N. succinea* and *C. capitata* were ubiquitous organisms which showed little differences in abundance with the type and degree of watershed development and appear to be not useful as indicators of pollution stress (Table 6).

The amount of impervious surface in a watershed has been found to be a good indicator of watershed condition by a number of studies (Schueler 1994; Arnold and Gibbons 1996). In this study there was a significant relationship between the amount of impervious surface in the watershed sampled and the human population density, the salinity range as determined from the DS3 data, and the cumulative level of chemical contaminants in creek sediments as estimated by the ERLQ (Fig. 7). The slopes of all the lines were positive and significantly different from zero ($p < 0.025$).

Relationships between the amount of impervious surface in the watershed and two promising macrobenthic community-level metrics, the percent abundance of pollution indicative species (*L. culveri, M. rubroniveus,* and *T. brownae*) and the percent abundance of potential pollution sensitive species (*T. heterochaetus, S. benedicti,* Nemertinea, *T.* cf. *acutus,* and *H. filiformis*), are shown in Fig. 8.

The relative abundance of potentially pollution sensitive taxa was negatively associated with the amount of impervious surface. The slope of the line was significantly different from zero ($p = 0.0027$) with a marked decline in abundance occurring when the percent impervious surface exceeded 30%. The relative abundance of pollution indicative taxa increased with increasing amounts of impervious surface. The slope of this line was also significantly different from zero ($p = 0.0087$).

Discussion

Tidal creeks are the primary linkage between upland and estuarine environments. Tidal creeks function as repositories and conduits for sediments, organic materials, and chemical pollutants (Olsen et al. 1982; Sanger et al. 1999a,b). The highest levels of toxic chemicals were generally found in the upper reaches of industrial and urban creeks and were mainly associated with historical industrial point source discharges. Sediment contaminant concentrations in suburban creeks were not substantially different from values reported for forested creeks and did not attain levels likely to affect living organisms. Shem Creek was a notable exception in that it had elevated levels of both sediment trace metal and organic contaminants. This was not surprising since the Shem Creek watershed has a relatively high human population density ($>$ 15 individuals ha^{-1}), receives runoff from commercial developments and a major highway corridor, and is used as a dockage facility for over 50 commercial fishing vessels and a dry stack boat storage yard (Sanger 1998; Sanger et al. 1999a,b). Suburban development produces few sources for trace metal input and generally low levels of organic contaminant input to tidal creeks (Fortner et al. 1996; Sanger et al. 1999a,b).

Sediments in salt marsh creeks were predominately fine grained pluff muds. Creek bottom habitats in upland creeks, particularly developed upland creeks, were frequently composed of large amounts of sand. Soils in the upland portion of the watersheds studied were predominately sandy. In addition, fine sediments may have been scoured from the creek channels due to altered hydrography and deposited on the marsh surface and/or in the deeper portions of the tidal creek and estuary.

Tidal creek DO dynamics were complex. Concentrations in both upland (forested and developed) and salt marsh (reference and impacted) creeks were frequently hypoxic ($<$ 28% saturation) indicating exposure to low DO is a natural phenomenon in these systems. The observed DO levels were frequently within ranges reported to adversely affect macrobenthic distributions (Gaston 1985; Diaz and Rosenberg 1995). Impacted salt marsh creeks had the lowest and most variable DO levels. Dissolved oxygen dynamics in these creeks were similar to that reported for poorly flushed dead-end canals (Baca et al. 1988; Maxted et al. 1997). Developed creeks generally experienced more frequent exposure to low DO concentrations and had more pronounced tidal periodicity in DO than reference creeks. For a more detailed description of the DO dynamics of the tidal creeks sampled refer to Wenner et al. (1999).

The tidal creeks sampled tended to have lower biodiversity relative to comparable estuarine habitats (Engle et al. 1994; Weisberg et al. 1997). In both upland and salt marsh creeks, species richness, number of taxa per sample, and percentage of rare species decreased as watershed development and environmental impact increased. The creeks with the fewest species, particularly rare species, were also characterized by the most severe and prolonged exposure to the low dissolved oxygen levels, the highest levels of sediment contamination, and the largest salinity fluctuations. This finding is supported by a number of other studies (Pearson and Rosenberg 1978; Broom et al. 1991; Engle et al. 1994).

Tidal creeks were numerically dominated by a few species of stress tolerant oligochaetes and polychaetes. Many of these species have life history characteristics which allow them to maintain high abundances in organically enriched environments that experience periodic hypoxia including rapid growth and development, multiple modes of reproduction including asexual reproduction, and the ability to recruit throughout much of the year (Grassle and Grassle 1974; McCall 1977; Pearson and Rosenberg 1978; Giere and Pfannkuche 1982; Levin 1984; Levin and Huggett 1990; LaSalle et al. 1991). Sarda et al. (1996) present evidence that long-term chronic exposure to organic enrichment and associated environmental conditions provide a competitive advantage to oligochaetes (e.g., *Monopylephorus evertus*), particularly during fall and winter when juvenile fish and crustacean predators are not abundant. These authors speculate that food resources and predation limit the abundances of oligochaetes during summer and suggest opportunistic polychaetes (e.g., *S. benedicti*) may be better adapted to respond to disturbance from spring and summer predation. McCann and Levin (1989) further indicate that mobile subsurface deposit feeding oligochaetes (e.g., *M. evertus*) inhibit growth of sedentary tubiculous polychaetes (e.g., *S. benedicti*) but not their recruitment. Additional information on the seasonal distribution of tidal creek macrobenthos and the effects of predation on recruitment patterns is needed. For example, the data in Sarda et al. (1996) and Sanger (1998) suggest that winter sampling may provide a more sensitive measure of the effects of watershed development on macrobenthic communities.

The ecological role of oligochaetes in estuarine systems is poorly understood (Diaz 1980; McCann and Levin 1989), although oligochaetes have high nutritional value and are a major food item in the diet of juvenile fish and crustaceans (Hunter and Arthur 1978; Van den Broek 1978; Giere and Pfannkuche 1982; Wiltse et al. 1984; McCann and Levin 1989). Many oligochaetes contain lipids which are critical for shrimp reproduction (Middleditch et al. 1979). The dominant oligochaete in South Carolina tidal creeks, *M. rubroniveus,* is ubiquitous in estuaries worldwide (Pfannkuche 1978) but little information is known about its environmental tolerances. A closely related Pacific species, *Monopylephorus cuticulatus,* is tolerant to anoxia, trace metal contamination, organic enrichment, and pulp mill effluents (Chapman et al. 1982). Our data suggest the same is true for *M. rubroniveus.* Additional research is needed to test this speculation.

Watersheds with urban and industrial development were associated with high levels of impervious surface ($> 50\%$) and had severe impacts on tidal creek habitats including alterations to the hydrodynamic processes (as indicated by salinity range), exposure to levels of chemical contaminants that cause mortality, altered growth, and reduced reproduction, and exposure to more frequent and severe hypoxia. The macrobenthic community in urbanized and industrialized creeks, especially the upper reaches, was characterized by low diversity, low numbers of rare and pollution sensitive species, and low macrobenthic abundances (Table 6). The physical/chemical and the biological impacts reported by this study indicate a severe impact to the nursery functions of tidal creeks in urban/industrial watersheds.

Suburban creeks had higher densities of pollution tolerant macrobenthic organisms, particularly the oligochaetes *M. rubroniveus* and *T. brownae* (Table 6). The levels of sediment contamination and hypoxia in these creeks were, however, generally not different than those in the forested upland creeks. The dominance in suburban creeks by a few species represents a trend towards a simplified food web and may be an early warning of degradation (Diaz 1992). Simplification of food webs may cause irreversible changes in ecosystem processes (Fretwell 1987; Pimm and Kitching 1987). These findings suggest that macrobenthic responses in suburban creeks may be a more sensitive and reliable indicator of adverse effects than water or sediment quality data.

The major physical alteration found for impacted salt marsh creeks was hypoxia. Elevated levels of sediment contaminants were not found in these creeks. Impacted salt marsh creeks were characterized by a high abundance of *M. rubroniveus,* a low abundance of *S. benedicti* and *H. filiformis,* and very low species diversity.

Salinity fluctuations in tidal creeks appeared to have potential as a measure of the degree to which development had altered hydrodynamic processes including the rate and volume of non-point source freshwater runoff. This metric was significantly correlated ($p < 0.005$) with both of the promising community-level indicators identified. Changes in stream flow regime, resulting from modifications of the land surface with changing land use, is one of the primary environmental factors affecting the biological integrity of aquatic biota in freshwater stream environments (Karr and Dudley 1981). Additional research in estuarine systems is needed to evaluate the effects of storm events, watershed size, and tidal creek type on this potential indicator of development impacts. Research is also needed to determine how much of the variation in macrobenthic response, especially in suburban creeks, is due to alterations to salinity distributions. If the salinity range indicator were proven to be reliable, high quality salinity data could be collected routinely and economically with any number of available remote water quality monitoring systems.

In freshwater stream environments, numerous studies (Miller and Mattraw 1982; Brown 1988; Schueler 1994; Arnold and Gibbons 1996) suggest the amount of impervious surface is a good measure of the degree to which human development has altered watershed condition. In these studies, when the amount of impervious surface exceeded about 10%, the ecological condition of streams was impacted. When the amount of impervious surface exceeds about 30%, streams became permanently degraded (Arnold and Gibbons 1996). Our findings suggest a similar pattern occurs in the tidal creeks. Clearly definable impacts to tidal creek water and sediment quality and macrobenthic communities did not occur until the percent impervious surface exceeded 30%. This is not surprising since South Carolina estuaries have relatively large tidal ranges (> 1 m) and large tidal mixing.

The two promising community-level indicators developed by this study based on the data collected (i.e., the relative abundance of pollution indicative taxa and the relative abundance of pollution sensitive taxa) were more sensitive indicators of ecological impact than other direct benthic metrics or measures of sediment and water quality. Other benthic metrics include the abundance of individual numerically dominant species and frequently used community-level metrics of condition (e.g., H′, McIntosh's Dominance Index). Numerous studies have found community-level indicators or multi-metric indices (e.g., index of biotic integrity) developed from broad scale comprehensive data to be sensitive and reliable measures of ecological condition (e.g., Pearson and Rosenberg 1978; Karr 1981; Bilyard 1987; Warwick and Clark 1991; Diaz 1992; Engle et al. 1994; Weisberg et al. 1997). Additional research is needed to validate these indicators at regional scales.

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