SPATIAL SCALES AND PROBABILITY BASED SAMPLING IN DETERMINING LEVELS OF BENTHIC COMMUNITY DEGRADATION IN THE CHESAPEAKE BAY

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Abstract: The extent of degradation of benthic communities of the Chesapeake Bay was determined by applying a previously developed benthic index of biotic integrity at three spatial scales. Allocation of sampling was probability-based allowing areal estimates of degradation with known confidence intervals. The three spatial scales were: (1) the tidal Chesapeake Bay; (2) the Elizabeth River watershed; and (3) two small tidal creeks within the Southern Branch of the Elizabeth River that are part of a sediment contaminant remediation effort. The areas covered varied from 10^{-1} to 10^{4} km^{2} and all were sampled in 1999. The Chesapeake Bay was divided into ten strata, the Elizabeth River into five strata and each of the two tidal creeks was a single stratum. The determination of the number and size of strata was based upon consideration of both managerially useful units for restoration and limitations of funding. Within each stratum 25 random locations were sampled for benthic community condition. In 1999 the percent of the benthos with poor benthic community condition for the entire Chesapeake Bay was 47% and varied from 20% at the mouth of the Bay to 72% in the Potomac River. The estimated area of benthos with poor benthic community condition for the Elizabeth River was 64% and varied from 52–92%. Both small tidal creeks had estimates of 76% of poor benthic community condition. These kinds of estimates allow environmental managers to better direct restoration efforts and evaluate progress towards restoration. Patterns of benthic community condition at smaller spatial scales may not be correctly inferred from larger spatial scales. Comparisons of patterns in benthic community condition across spatial scales, and between combinations of strata, must be cautiously interpreted.

Keywords: spatial scales, benthic communities, macrobenthos, degradation, Benthic Index of Biotic Integrity, Chesapeake Bay, Elizabeth River, contamination, low dissolved oxygen

1. Introduction

A wide variety of sampling designs have been used in marine and estuarine environmental monitoring programs (e.g., see case studies reviewed recently in Kramer, 1994; Kennish, 1998; Livingston, 2001). Allocation of samples in space and time varies depending on the environmental problems and issues addressed (Kingsford and Battershill, 1998) and the type of variables measured (e.g., water chemistry, phytoplankton, zooplankton, benthos, nekton). In the Chesapeake Bay, the benthic monitoring program consists of both fixed-point stations and probability-based samples. The fixed-point stations are used primarily for the determination of long-term trends (e.g., Dauer and Alden, 1995; Dauer, 1997) and the probability-based samples for the determination of the areal extent of degraded benthic community condition (Llansó *et al.*, this issue). The probability-based sampling design consists of equal replication of random samples among strata and is, therefore, a stratified simple random design (Kingsford, 1998).

Environmental Monitoring and Assessment **81**: 175–186, 2003.

As part of the restoration of the Chesapeake Bay, the benthic monitoring program serves to evaluate and direct restoration efforts to reduce eutrophication and contaminant levels in the Bay (Dauer *et al.,* 1992; 1993; Dauer, 1993; Dauer and Alden, 1995; Dauer, 1997; Dauer, *et al.* 2000). Benthic community condition is assessed using the benthic index of biotic integrity (B-IBI) that evaluates the ecological condition of a sample by comparing values of key benthic community attributes to reference values expected under undegraded conditions in similar habitat types (Weisberg *et al.*, 1997). In this paper we present an application of the B-IBI and probability-based sampling at multiple spatial scales to determine levels of benthic community degradation for areas ranging from 10^{-1} to 10^{4} km^{2} . The three spatial scales presented are the entire tidal Chesapeake Bay consisting of ten strata (total area of 11,607 km^{2}), the Elizabeth River watershed consisting of five strata (total area of 47 km^{2}) and an environmental restoration study of contaminated creeks consisting of two strata (both approximately 0.1 km^{2}). Within each stratum 25 random locations were sampled for benthic community condition. All data presented were collected in 1999 and sampling of the three spatial scales was separately designed and funded with independent monitoring objectives.

2. Materials and Methods

Within each stratum at each of the three spatial scales 25 random samples were collected in 1999 during the index period of the B-IBI (July 15 to September 30). All samples were collected using a Young grab with a surface area of 440 cm^{2}. Each sample was sieved on a 0.5 mm screen and preserved in the field. Samples were sorted, enumerated and identified to the lowest possible taxon. Ash-free dry weight biomass was determined for each taxon.

The tidal waters of the Chesapeake Bay were divided into ten strata (Figure 1). Probability-based sampling began in Maryland in 1994 and in Virginia in 1996 and has continued since. Here we present only the 1999 sampling of 250 random locations among the ten strata. The determination of the number and size of each stratum (Table 1) was based upon consideration of both managerially useful units for restoration and limitation of funding. The largest portion of the Bay, the Mainstem, was divided into three strata and five of the strata consisted of the major tributaries (James, York, Rappahannock, Potomac and Patuxent rivers). The final two strata included the remaining smaller tributaries on the Maryland western shore and Maryland eastern shore. The region labeled Deep Mainstem (Figure 1) is subjected to summer anoxia resulting in an azoic condition. The strata sampled represented the entire tidal region of the Bay from freshwater through polyhaline zones.

The Elizabeth River was divided into five strata (Figure 2). For the Lafayette River and Western Branch the downstream boundary was the north-south confluence with the Mainstem of the Elizabeth River. For the Eastern Branch and Southern Branch the downstream boundary was the confluence of both branches with the

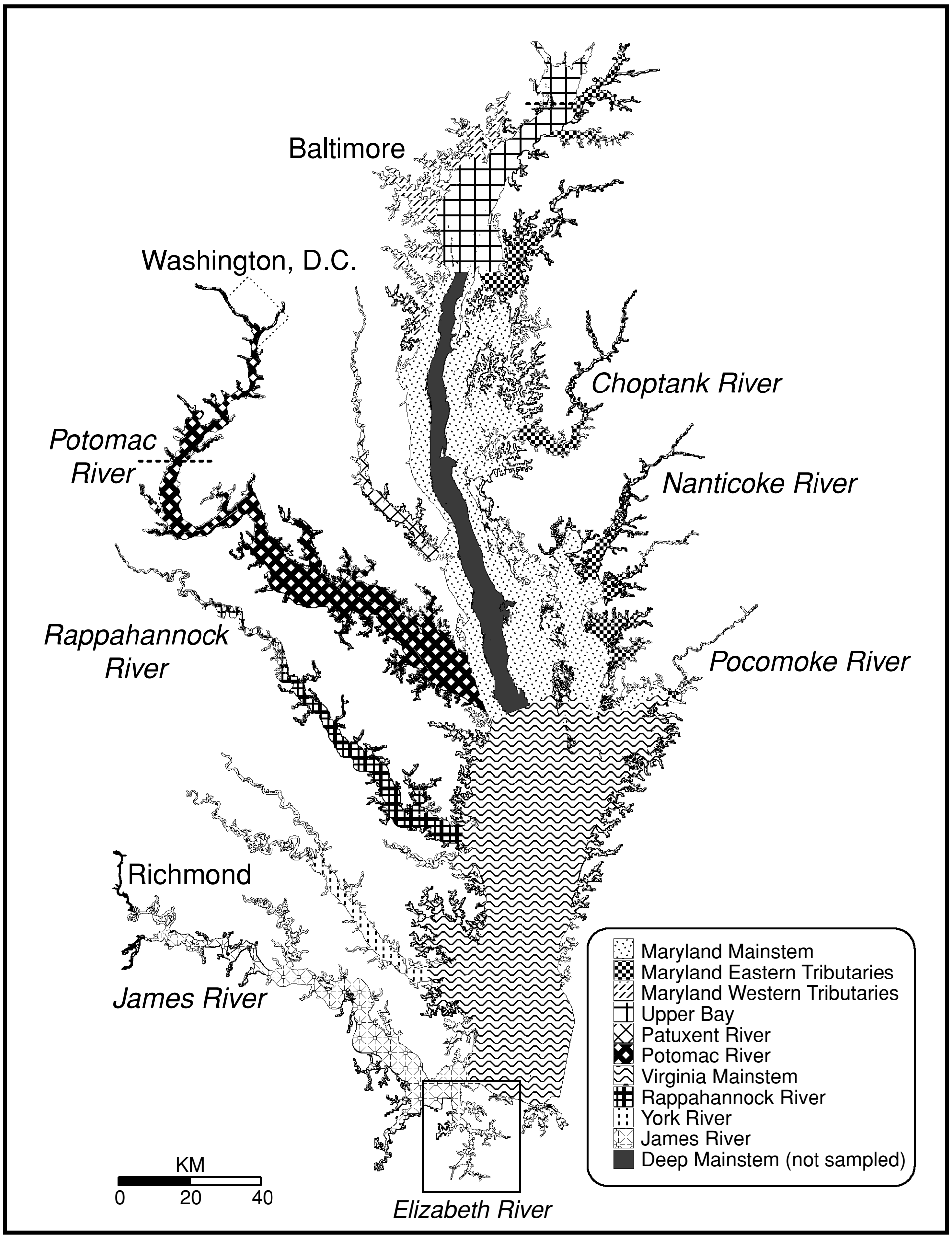

Figure 1. Location of ten strata of the Chesapeake Bay. Insert shows location of the Elizabeth River.

Table 1. Estimated tidal area in 1999 failing to meet the Chesapeake Bay Benthic Community restoration Goal. All columns except last two in km^2. A. Tidal Chesapeake Bay. B. Elizabeth River watershed. C. Sediment Contaminant Creeks. Abbreviations: SD = severely degraded, D = degraded, M = marginal, CI = 95% confidence interval in percentage. (See text for further information.)

	Total Area km^2	*SD*	*D*	*M*	*Total Failing*	*Percent Failing*	*CI*
A. Chesapeake Bay *(Bay Scale)*							
Combined Strata							
Chesapeake	11,607	3,121	1,648	681	5,450	47	7.7
Maryland Tidal Waters	6,244	2,423	1,137	374	3,935	63	9.3
Virginia Tidal Waters	5,362	698	510	306	1,515	28	12.6
Individual Strata							
Potomac River	1,276	663	153	102	918	72	18.0
Patuxent River	128	20	10	10	41	32	18.7
MD Western Tributaries	292	117	47	12	175	60	19.6
MD Eastern Tributaries	534	43	150	86	279	52	20.0
MD Upper Mainstem	785	188	63	63	314	40	19.6
MD Mid-Bay Mainstem	2,552	1,391	715	102	2,208	68	18.7
Virginia Mainstem	4,120	494	165	165	824	20	16.0
Rappahannock River	372	74	104	45	223	60	19.6
York River	187	75	22	15	112	60	19.6
James River	684	55	219	82	356	52	20.0
B. Elizabeth River Watershed *(River Scale)*							
Entire Elizabeth River	46.6	6.9	15.3	7.8	30.0	64	10.1
Individual Strata							
Mainstem	20.7	0.80	6.62	3.31	10.7	52	20.0
Lafayette River	5.7	0.68	2.05	0.91	3.6	64	19.2
Eastern Branch	5.7	0.68	2.28	0.68	3.6	64	19.2
Western Branch	6.9	1.38	2.21	1.38	5.0	72	18.0
Southern Branch	7.6	3.34	2.13	1.52	7.0	92	10.8
C. Sediment Contaminant Strata *(Creek Scale)*							
Scuffletown Creek	0.1	0.024	0.036	0.016	0.076	76	17.0
Jones-Gilligan Creeks	0.1	0.024	0.040	0.012	0.076	76	17.0

Mainstem. The downstream boundary of the Mainstem was set at the northern limit of Craney Island (Figure 2). The strata studied encompass salinities typically ranging from 19–24 psu. Here we present only the results from 125 random locations among the five strata.

Within the Elizabeth River, sediment contamination from heavy metals and polynuclear hydrocarbons has been identified as a major problem (Elizabeth River Project, 2000). The US Army Corps of Engineers is directing a feasibility study that includes a possible demonstration sediment clean-up effort in one small tidal creek (USACOE, 2001). As part of that study, two strata were sampled in 1999:

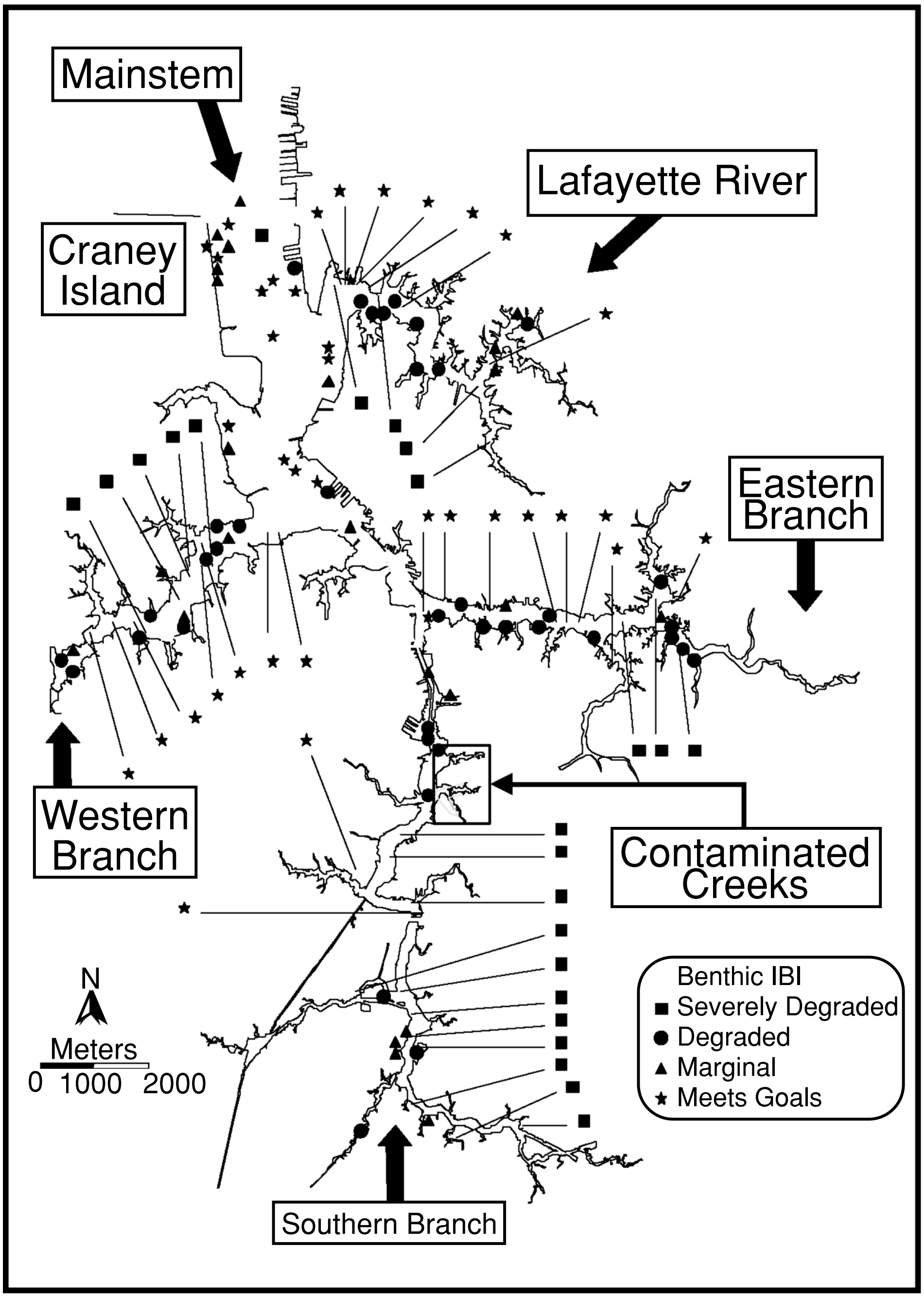

Figure 2. Elizabeth River watershed. Shown are five sampling strata and the location and condition of the benthic community at the 125 random locations sampled in 1999. For clarity, samples designated meets goal and severely degraded are shown outside of strata except for the Mainstem.

the demonstration project creek, Scuffletown Creek, and a similar creek system directly upstream, Jones and Gilligan creeks (see Contaminated Creeks of Figure 2). Fifty random locations were sampled among the two strata. Future sampling of these strata may occur if sediment remediation efforts occur.

The B-IBI was calculated for each of the 425 benthic samples of this study. The index was calculated by scoring values of benthic community metrics compared to values of the respective metrics at reference sites determined to be relatively free of anthropogenic stress. Selection of metrics and the values for scoring metrics were developed separately for each of seven benthic habitat types in Chesapeake Bay (Weisberg *et al.*, 1997). Metrics were scored 1, 3 or 5 and averaged. A score of 3.0 or greater indicated that the sample did not differ from reference conditions. The benthic community condition was classified as follows: meets goal (B-IBI ≥ 3.0), marginal (B-IBI = 2.7-2.9), degraded (B-IBI = 2.1-2.6) or severely degraded (B-IBI ≤ 2.0). The thresholds for scoring the benthic metrics can be considered benthic restoration goals for each habitat type. In that sense a B-IBI score of < 3.0 was characterized as failing the Chesapeake Bay benthic community restoration goal (Ranasinghe *et al.*, 1994).

Significant differences between strata were tested using the method of Schenker and Gentleman (2001). All reported differences are at $p = 0.5$.

3. Results

At the spatial scale of the tidal Chesapeake Bay, 47% of the bottom had benthic community condition that failed the restoration goal with 63% of Maryland tidal waters and 28% of Virginia tidal waters classified as failing the restoration goal (Table 1A, Figure 3). Among the ten strata, percentages of the benthos failing the restoration goal ranged from 20% to 72% with the best condition in the Virginia portion of the Mainstem of the Bay and the worst condition in the Potomac River. By absolute surface area, the middle stratum of the Mainstem (MD Mid Bay Mainstem) had the largest amount of poor quality benthic community condition.

At the Elizabeth River watershed scale, 64% of the bottom had benthic community condition that failed the restoration goal (Table 1B, Figure 2). Among the five strata, percentages of the benthos failing the restoration goal ranged from 52% to 92% with the best condition in the Mainstem of the river and the worst condition in the Southern Branch.

At the contaminated creek scale both tidal creeks had 76% of the bottom with benthic community condition that failed the restoration goal (Table 1C, Figure 4).

4. Discussion

Estuaries are dynamic and complex ecosystems with varying salinities, freshwater input, physical forces, bottom sediment types, etc. The spatial scale of potential an-

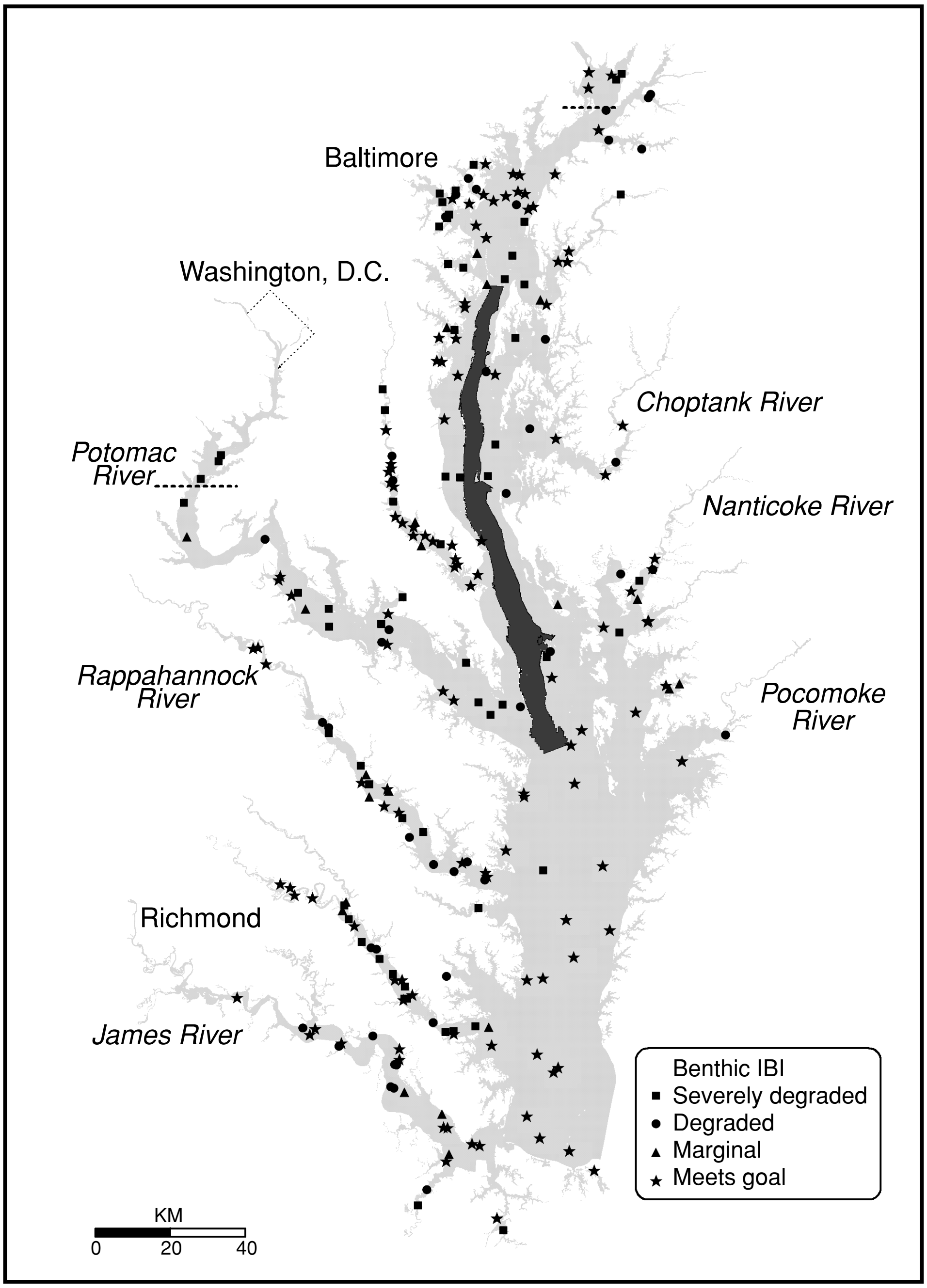

Figure 3. Benthic community condition using the B-IBI and location of the 250 random locations sampled in 1999. See text for definitions.

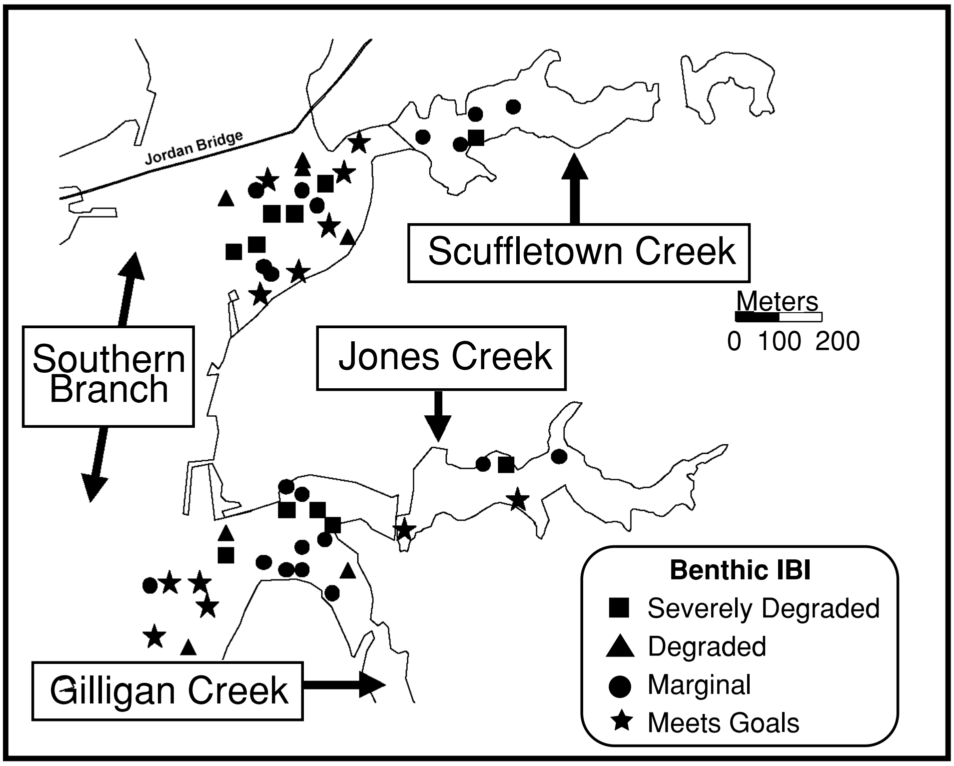

Figure 4. Scuffletown Creek, Jones Creek, and Gilligan Creek. Shown are the locations and condition of the benthic community at the 50 random locations sampled in 1999.

thropogenic stressors varies from large scale in the case of non-point inputs to potentially very small spatial scales for point-source inputs. Eutrophication is widely documented as adversely affecting benthic communities of the Chesapeake Bay (USEPA, 1999; Dauer *et al*., 2000) over large spatial scales. At the Bay scale, low dissolved oxygen events associated with eutrophication are well documented (Smith *et al*., 1992), geographically widespread in distribution (Dauer *et al*., 2000) and have known effects on benthic community structure (Diaz and Rosenberg, 1995). Low dissolved oxygen events are common and severe in the Potomac River and the Maryland Mid Mainstem (Dauer *et al*., 2000) and these two strata had the highest areal estimates of degraded benthic community condition, 72% and 68%, respectively and were significantly higher than the value for the entire Chesapeake Bay (47%). Additional resolution of patterns can be obtained by examining the areal estimates for the worst benthic condition—severely degraded areas (see SD in Table 1). For example, the three Virginia rivers (James, York, Rappahannock) showed similar levels of degradation when combining the marginal, degraded and severely degraded categories (52–60%). However, the percentages of severely degraded condition were 8% for the James River, 20% for the Rappahannock River and 40% for the York River. Bricker *et al.* (1999) characterized the eutrophic condition for the estuaries of the United States based upon a survey of over 300 experts on estuarine eutrophication. They listed the three Virginia rivers as follows: the James River as having a low eutrophic condition, the Rappahannock River as having a moderate eutrophic condition and the York River has having a high eutrophic condition. The areal extent of severely degraded benthic condition better conforms to the characterizations of Bricker *et al.* (1999) in comparison to the combined areas of marginal, degraded and severely degraded. Examining just the severely degraded condition, the Potomac River and Maryland Mid Mainstem still have the highest levels of severely degraded bottom with values of 52% and 55%, respectively. MD Eastern Tributaries have a total failing area of 50% but a value of 8% for the severely degraded condition. These tributaries have high agricultural land use, high nutrient load input, high chlorophyl values but low frequencies of low dissolved oxygen events compared to strata such as the Potomac River (Dauer *et al.,* 2000).

At the Bay scale, sediment contamination by toxic chemicals also adversely affects benthic communities of the Chesapeake Bay (Dauer, 1993; Dauer *et al*., 1993; 2000) but serious problems are spatially concentrated in three regions, Baltimore Harbor in Maryland, the Anacostia River in Washington, D.C. and the Elizabeth River in Norfolk, Virginia (CBP, 1999; USEPA, 1999). The areal extent of degradation of benthic community condition of the Elizabeth River can not be inferred from sampling at the Bay scale. For example, in 1999 only two stations of the 25 stations allocated to the James River stratum were in the Elizabeth River watershed.

At the River scale, the Elizabeth River is characterized by poor water quality but bottom oxygen levels are not low enough to cause adverse effects on benthic community condition (Dauer *et al.,* 1999). The level of areal degradation of the Elizabeth River watershed (64%) was significantly higher than the Virginia value (28%) but not significantly different from the values of the three major rivers in Virginia (52-60%). Among the five strata at the River scale, the Mainstem had a significantly lower level of degradation (52%) compared to the other River strata and the Southern Branch has a significantly higher level of degradation (92%) compared to the remaining River strata. Examining just the severely degraded benthic condition, the values were 4% for the Mainstem, 12% for the Lafayette River and Eastern Branch, 20% for the Western Branch and 44% for the Southern Branch. The Western Branch and the Southern Branch are the sections of the river characterized by the highest levels of sediment contaminants (ERP, 2000). The Southern Branch is the only stratum characterized by severe problems due to levels of heavy metals and sediment organic compounds. In the Western Branch all stations summarized in ERP (2000) indicated a problem with heavy metals. In the Mainstem, Eastern Branch and Lafayette River measured levels of metals or organic compounds were not considered to be at problem levels.

The US Army Corps of Engineers, when considering a demonstration project for sediment contaminant remediation, restricted their consideration to small portions of the Elizabeth River that were less than 1 km^2 (USACOE, 2001). The areal extent of degradation of benthic community condition at the Creek scale can not be inferred from sampling at the River scale. For example, none of the 25 samples allocated to the Southern Branch were in either of the two creek systems.

In summary, a stressor such as low dissolved oxygen is generally more spatially widespread and larger sampling strata capture the resultant pattern of benthic community condition. Sediment contamination is spatially less extensive and smaller strata are necessary to capture the resultant pattern of benthic community condition. In our study the significant benthic community degradation due to sediment contamination of the Elizabeth River is not obvious from the Bay scale (11,407 km^3) nor at the spatial scale of the James River stratum (863 km^2). Even within the Elizabeth River strata of a spatial scale of 10^1 km^2 may still be too large to define local sediment contaminant problems. Comparisons of patterns in benthic community condition across spatial scales and between combinations of strata must be cautiously interpreted. For example, the Virginia Tidal Waters value of 28% failing is significantly lower then the Maryland Tidal Waters value of 63% (Table 1A). However, this pattern is driven by the very low failure level of the Virginia Mainstem which accounts for 77% of Virginia tidal waters. In fact the three major Virginia tributaries (James, York and Rappahannock) are not significantly different from the Potomac River when using total area failing. However when using the severely degraded condition the James River and Rappahanock River both have significantly lower levels of degradation compared to the Potomac River.

Benthic monitoring program designs must be flexible and modified according to the stressor(s) of concern. Further, they must provide quantitative ecological information to environmental managers including a characterization of the ecological condition of the system and the spatial extent of the problem addressed. A validated, unambiguous approach to characterizing the condition of the benthic community is essential. In the Chesapeake Bay Benthic Monitoring Program, we accomplish this by using the B-IBI and a stratified random sampling design. The B-IBI has been shown by Alden *et al.* (in press) to be sensitive, stable, robust, and statistically sound. Two additional advantages of the B-IBI are (1) several levels of degradation can be defined (e.g., severely degraded, degraded, marginal) and (2) the pattern of individual metrics of the index can be examined for insight into the reasons for the determined condition.

Acknowledgments

We acknowledge the support of the US Environmental Protection Agency, the US Army Corps of Engineers, the Maryland Department of Natural Resources, the Chesapeake Bay Program Office of the Virginia Department of Environmental

Quality, the Tidewater Regional Office of the Virginia Department of Environmental Quality and the Elizabeth River Project. The comments of three anonymous reviewers greatly improved the manuscript.

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