

Bioassessment of Fish Communities of the Upper Delaware River

ELLEN VAN SNIK GRAY^{1,*}, ROBERT M. ROSS^{1,2},
AND RANDY M. BENNETT¹

Abstract - We assessed the biotic integrity of the middle-to-upper Delaware River. We sampled fish and assembled water quality data for eight stations and three habitat types (pool, riffle, and submerged aquatic vegetation [SAV]) of the Delaware River and applied an existing index of biotic integrity (IBI) recently developed for the northern mid-Atlantic slope drainages. We used Spearman's correlation to test IBI scores against measures of water quality (WQI) and cultural pollution. IBI scores were not significantly correlated with WQI, but were significantly negatively correlated with sewage load of adjacent tributaries ($r_s = -0.647$, $p = 0.08$). Sites ranged from good to fair in biotic integrity. Fish assemblage composition from all three habitat types was necessary in order to accurately characterize biotic integrity. Of the three habitat types, fish assemblages from SAV habitats had the greatest positive effect on biotic integrity. Continued application of the IBI may be useful as a long-term monitoring tool as this river corridor becomes increasingly urbanized.

Introduction

The overall health of many of our nation's large rivers has improved in recent decades due to sewage treatment compliance laws as well as point-and, more recently, non-point-source pollution reduction. However, many river corridors continue to face the impacts of increasing urbanization and other land use changes and/or practices that threaten aquatic resource quality. At the same time, past management of rivers for fish and fish habitat has focused on instream concerns rather than the entire watershed as an ecological unit (Imhof et al. 1991). Thus, there is a need to view/understand riverine biotic communities not only as longitudinally linked entities (Strahler 1957, Vannote et al. 1980), but also as aquatic communities directly influenced by riparian processes (e.g., Amoros 1991, Junk et al. 1989) and associated land uses (Wang et al. 1997, Wohl and Carline 1996). Studies of riverine habitat and fish biodiversity are needed to further understand how large river systems function (Harris and Silveira 1999, Johnson et al. 1995, Poff et al. 1997).

The middle and upper Delaware River has relatively good water quality, yet is under increasing development pressure from residential and urban land uses (Hansen 1991). Nearly one tenth of our nation's population depend on it as a water supply (Delaware River Basin Commission [DRBC] 1993).

¹United States Geological Survey, Leetown Science Center, Northern Appalachian Research Laboratory, 176 Straight Run Road, Wellsboro, PA 16901. ²Author to which reprint requests should be sent. *Corresponding author - thegrays@highstream.net

Protecting biotic communities in the Delaware River is an important goal of its multiple management jurisdictions, including several states (New York, Pennsylvania, New Jersey, Delaware) and federal agencies (National Park Service, Fish and Wildlife Service, Department of Defense), and new assessment techniques and tools are needed to accomplish this goal. Though physiochemical indicators of water quality have been established for these reaches of the Delaware River (DRBC 1996), biological indicators, other than bacterial, have not been previously developed or applied.

The index of biotic integrity (IBI), first developed by Karr (1981), has been effectively used throughout North America and abroad as an assessment tool for aquatic communities, for both benthic macroinvertebrates (Kerans and Karr 1994) and fishes (Karr et al. 1986, Miller et al. 1988). The IBI has been applied throughout North America and Europe (Lyons et al. 1995) in a wide range of lotic habitats, including small and mid-sized streams (Shields et al. 1995, Steedman 1988), large rivers (e.g., Bramblett and Fausch 1991, Hoefs and Boyle 1992, Hughes and Gammon 1987, Lyons et al. 2001, Oberdorff and Hughes 1992, Ohio EPA 1987, Scott 1999, Simon 1992, Simon and Emery 1995), and cool and coldwater streams (Langdon 2001, Leonard and Orth 1986, Lyons et al. 1996). We applied an IBI recently developed for the northern mid-Atlantic slope drainages (Daniels et al. 2002) to the mainstem of the middle-to-upper Delaware River to allow aquatic resource managers to assess the health of the river using fish assemblages. Our objectives were to (1) apply the northern mid-Atlantic slope IBI to the middle and upper Delaware River fish assemblages as a bioassessment tool, (2) examine the effect of upstream-downstream location on fish assemblages, (3) test the IBI against independent measures of water quality and associated land use, and (4) determine the influence of instream habitat type (pool, riffle, and submerged aquatic vegetation) on the bioassessment of resident fish assemblages.

Methods

Study area and design

Studies were conducted on the Delaware River mainstem between the Delaware Water Gap (75°08'W, 40°59'N; river kilometer 341) and Callicoon, NY (75°03'W, 41°16'N; river kilometer 488) (Fig. 1). All sample sites fell within a 182-kilometer segment of the Delaware River managed by the National Park Service (NPS) under the federal Wild and Scenic Rivers Act. We chose riverine sites associated with eight selected tributaries (2nd to 4th order) representing the entire range of perceived water quality and watershed land use, based on our own assessment and discussion with NPS natural resource managers (Gray et al. in prep). In this river system, the number of streams within the bounds or jurisdiction of the NPS and its lands in the Delaware River basin were limited to the 8 tributaries identified. The 8 sites were sampled twice per year 1 month apart at or near base flows (July and August) in each of two consecutive years (1993–1994).

Field and laboratory methods

Riverine sites ($n = 8$, one for each associated tributary) were selected to maximize potential influences of the corresponding tributary by sampling downstream of the tributary as close to the mouth as feasible (within 250 m) and on the same side of the river. We sampled three habitat types separately at each site: pool, riffle, and macrophyte bed (submerged aquatic vegetation [SAV]). SAV habitats typically occurred lateral to the main channel at depths of < 1.5 m and low current velocities (Ross et al. 1997). Anchored macrophytes comprising such dense vegetation beds included common waterweed (*Elodea canadensis* Michaux), redhead grass (*Potamogeton perfoliatus* Linnaeus), curly pondweed (*Potamogeton crispus* Linnaeus), wild celery (*Vallisneria americana* Michaux), and coontail (*Ceratophyllum demersum* Linnaeus) (Hurley 1990). This habitat type was somewhat ephemeral interannually due to system variation in discharge, channel morphology, bedload, sedimentation, and related hydrologic factors. Three fish-community samples (of the 24 habitat-specific samples obtained overall) not obtained in 1993–1994 due to riverine conditions at specific sites (lack of well developed riffles or SAV habitats) were obtained during base flows in 1998.

Riffles were sampled with a three-to-four person team using a backpack electrofisher (Smith Root® Model 12) set to deliver direct current in gaited bursts, with optimum-effect voltage varying by stream and its conductivity (Table 1). To standardize the area sampled, we used a 30.5 x 1.8 m seine (6 mm mesh) as a downstream block net held in place with metal brailles

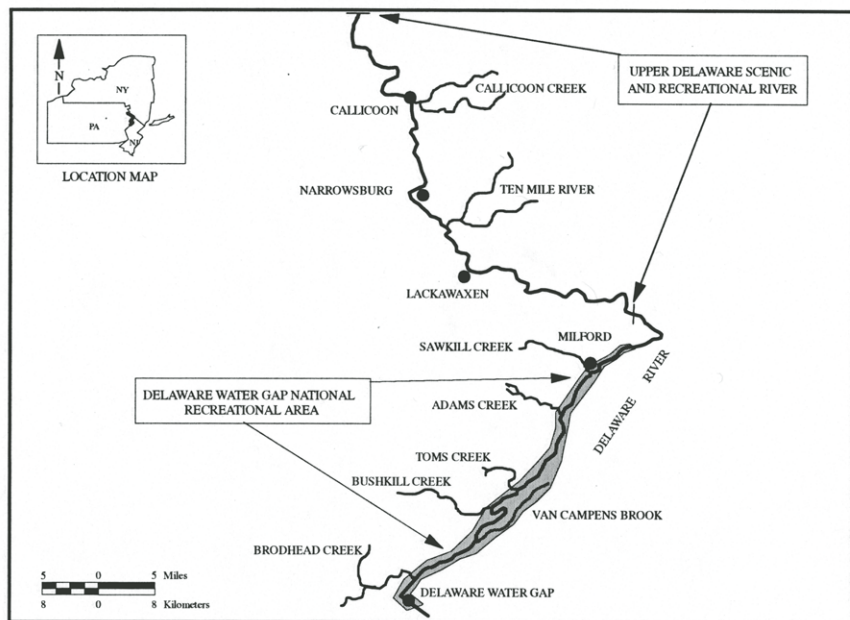


Figure 1. Map of middle and upper Delaware River showing tributaries below which the mainstem was sampled for assessment of the index of biotic integrity.

driven into the substratum 15 m apart. We fished from 2 m upstream of the (imaginary) interbraille line to the most downstream position inside the seine. Most fishes utilizing riverine riffles are small and seek cover in nearby substrate, rather than attempt to swim long distances to avoid capture. Thus, bias using this riffle-habitat sampling technique should be little different than that known for wadeable stream sampling in general with the use of backpack units. With the exception of large American eels, *Anguilla rostrata* (LeSeur), which were measured (nearest mm total length, TL) upon capture and returned to the stream behind the capture zone, all fish (> 25 mm TL) were retained, preserved in buffered 10% formalin, and returned to the laboratory for identification, measurement, and health assessment (evidence of disease/anomalies).

Shoreline SAV zones were sampled with a 30.5 x 2.4 m seine (6 mm mesh) deployed from the bow of a 5-m jon boat to approximate a 10-m square set. This effort required a four-person team, including a diver used to keep the seine snag-free while the seine was hauled to shore. Gear efficiency was previously determined to be relatively high (catchabilities ranging from 52–

Table 1. Site characteristics, water quality, and land use for the eight Delaware River stations identified by their associated tributaries. Water quality parameters are expressed as means, and land use categories are expressed as percent of each tributary drainage area. DO = dissolved oxygen; BOD = biochemical oxygen demand; WQI = water quality index.

Parameter	Callicoon Creek	Ten Mile River	Sawkill Creek	Adams Creek	Toms Creek	Bush- kill Creek	Van Campens Brook	Brod- head Creek
Site Description								
River kilometer	489	457	398	388	372	365	354	341
Mean July discharge of associated tributary (cfs)	76	29	16	7	8	164	14	280
Percent of mainstem July discharge	6.2	2.1	0.5	0.2	0.3	5.1	0.4	8.3
Water Quality								
Temperature (°C)	20.7	22.0	23.4	24.3	24.0	23.2	25.7	23.8
DO (mg/L)	10.3	9.5	8.7	8.1	8.6	8.5	8.8	8.6
Conductivity (micromh)	96.8	67.3	67.9	71.5	70.0	62.3	72.7	82.3
pH	7.92	7.25	6.95	6.98	6.95	7.08	7.25	7.13
NO ₂ + NO ₃ (mg/L)	0.01	0.18	0.14	0.21	0.22	0.14	0.05	0.23
NH ₃ , NH ₄ (mg/L)	0.03	0.01	0.02	0.03	0.02	0.01	0.02	0.02
Totkjel-N (mg/L)	0.38	0.39	0.28	0.39	0.30	0.28	0.58	0.39
Orthophosphates (mg/L)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total phosphates (mg/L)	0.01	0.02	0.04	0.09	0.01	0.01	0.02	0.02
BOD-5 day (mg/L)	0.48	0.32	0.68	0.74	0.59	0.60	0.44	0.65
Fecal coliforms (100mL ⁻¹)	6.00	79.25	40.00	18.50	48.00	7.50	7.00	13.50
Turbidity (ntu)	2.52	1.02	0.94	0.86	1.14	0.68	0.72	1.40
WQI	82.48	79.42	81.25	81.58	81.19	82.42	83.78	82.78
Land Use								
Drainage area (km ²)	583	342	128	42	48	813	46	1351
Forested	52	76	89	86	56	86	73	74
Urban/developed	2	1	6	9	25	4	17	9
Agricultural/farm	45	19	2	0	2	1	6	13
Sewage flow (kl/day)	34	795	0	0	0	11,985	0	13,896

80%) when using this technique on juvenile American shad, *Alosa sapidissima* (Wilson), in the same habitat type (Ross et al. 1997). Captured fish were retained as previously described for riffle habitats.

Given the normally good (typically 5 m) visibility in the river, pool habitats were sampled with transects and diving techniques to assure that representative fishes of riverine channels and other deepwater mesohabitats were sampled. Two 50-m lines were laid from shore toward midchannel approximately 25 m apart. A diver then swam each transect from shore to channel and enumerated all fish (> 25 mm TL, visually estimated) within 2 m of the transect line, bottom to surface. Though total area sampled by visual enumeration on pool transects was greater than that by electrofishing riffles or seining SAV beds (200 versus 100–120 m²), most of the deepwater mesohabitats were found to be relatively depauperate of fish. Censusing fishes by snorkelling along transects may be inherently biased against small benthic species, while favoring larger vagile species (Helfman 1983).

Fish sampled from riffle and SAV habitats were identified in the laboratory and examined for disease, tumors, fin damage, and skeletal anomalies. Quality control was assured by assigning a second specimen identifier to the entire collection of 7406 fish, with re-examination of all discrepancies by R. Ross. When resolution of an identity problem was unattainable (primarily involving juvenile cyprinids), the specimen was identified by a museum curator with working expertise for a particular family or taxonomic group.

Water quality and land use

We obtained water quality data for all stations matched for year and season from a monitoring program co-sponsored by NPS and DRBC (Table 1). We calculated the National Sanitation Foundation Water Quality Index (WQI, Ott 1978), a nine-variable index originally developed by Brown et al. (1970), to assess the water quality of each site. Due to incomplete data, we used an eight-variable WQI (dissolved oxygen, pH, 5-day biological oxygen demand, nitrates, phosphates, temperature, fecal coliform, and turbidity) with a maximum (best) score of 92. Associated land use data, including sewage load and proportion of watershed area as agricultural and urban/developed, were obtained from Gray et al. (in prep) for each monitored tributary.

IBI application and statistical analysis

Daniels et al. (2002) developed an IBI for the northern mid-Atlantic slope including the Hudson, Delaware, and Susquehanna River drainages. We applied this IBI to our data, including classifying the 39 species collected into trophic groups and habitat affiliation according to Halliwell et al. (1999) and calculating and scoring metrics as in Daniels et al. (2002). The twelve metrics were: total number of fish species; number of benthic insectivorous species; number of water column species; number of terete minnow species; percentage of dominant species; percentage of individuals that are white suckers, *Catostomus commersoni* (Lacepede); percentage of individuals that are generalists; percentage of individuals that are insectivores;

percentage of individuals that are top carnivores; number of fish per sample; percentage of species represented by two size-classes; and percentage of individuals with disease, tumors, fin damage, or other anomalies (Daniels et al. 2002). We did not need to modify the metrics or scoring criteria developed by Daniels et al. (2002) in this study, as their IBI appeared to be very suitable for this application.

All statistical analyses were conducted using SAS (SAS Institute Inc., Cary, NC) software (6.12), and differences were considered statistically significant at $p < 0.10$. As a preliminary analysis of fish assemblage patterns, cluster analysis was performed using Jaccard's similarity coefficients and the average linkage method. Jaccard's similarity coefficient compares the fish assemblage of each station pair based on species presence and is calculated using the following formula: $J = C/(A+B+C)$, where C is the number of species common to both stations and A and B are the number of species unique to each of the stations. In order to test the sensitivity of the IBI, its scores were compared to the WQI, sewage load, and proportion of tributary drainage area as agricultural and urban/developed lands using Spearman's correlations.

Results

A total of 7406 fish were collected from the 8 stations. They represented 39 species from 11 families. Common species included *Alosa sapidissima*

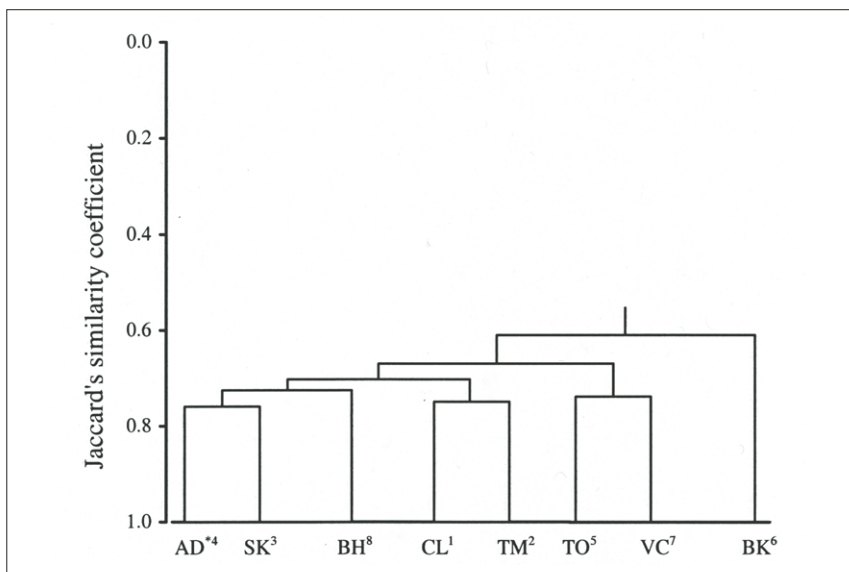


Figure 2. Similarity of Delaware River fish communities as shown by cluster analysis of Jaccard's similarity coefficients. Numbers indicate position upstream to downstream. Abbreviations: BH = Brodhead Creek, BK = Bushkill Creek, CL = Callicoon Creek, TM = Ten Mile River, TO = Toms Creek, VC = VanCampens Brook, AD = Adams Creek, and SK = Sawkill Creek. *Cluster with Sawkill is tied to cluster with Van Campens.

(American shad), *Notropis hudsonius* (Clinton) (spottail shiner), *Rhinichthys cataractae* (Valenciennes) (longnose dace), *Semotilus corporalis* (Mitchill) (fallfish), *Catostomus commersoni* (white sucker), *Ambloplites rupestris* (Rafinesque) (rock bass), *Micropterus dolomieu* Lacepede (smallmouth bass), and *Micropterus salmoides* (Lacepede) (large-mouth bass).

Cluster analysis of the mainstem stations indicated that upstream-downstream location did not have a large influence on river station fish composition (Fig. 2). In addition, there was no significant correlation between the IBI and river kilometer (distance to a fixed location; $r_s = 0.337$, $p = 0.42$; Fig. 3).

Index of biotic integrity scores did not range widely among the 8 stations, but varied from good to fair (Table 2). There was no significant relationship between the IBI and WQI ($r_s = 0.371$, $p = 0.37$). The IBI was significantly correlated to the sewage load of adjacent tributaries ($r_s = -0.647$, $p = 0.08$). No significant relationship existed between the IBI and proportion of watershed area as agricultural ($r_s = 0.434$, $p = 0.28$) or proportion of watershed area as urban/developed lands ($r_s = 0.370$, $p = 0.37$).

All three sampled habitats were needed to adequately characterize a station's biotic integrity. We omitted fish collection data from each of the three habitat types in turn to examine the influence of each habitat type on the

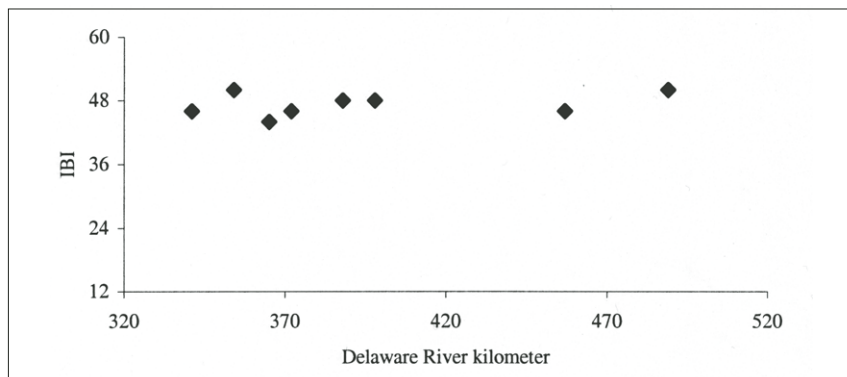


Figure 3. Relationship between index of biotic integrity (IBI) and Delaware River km.

Table 2. IBI score and assessment for each Delaware River station (listed in order upstream to downstream) identified by its associated tributary.

Associated tributary	IBI	Assessment
Callicoon Creek	50	Good
Ten Mile River	46	Good/Fair
Sawkill Creek	48	Good
Adams Creek	48	Good
Toms Creek	46	Good/Fair
Bushkill Creek	44	Fair
VanCampens Brook	50	Good
Brodhead Creek	46	Good/Fair

IBI. IBIs with all three habitat types included were as high or higher than the reduced IBIs, with omitted riffle, pool, or SAV habitats, in all but three cases (Fig. 4). Omitting SAV habitats from IBI calculations resulted in the lowest biotic integrity for half the stations, while omitting riffle or pool habitats resulted in the lowest biotic integrity for the remaining stations (Fig. 4).

Discussion

Bioassessment of water and habitat quality in large rivers based on fish assemblages poses challenges of scale, among other factors. We know, for example, that tributary confluences are important sites for hydrological and related processes that can affect benthic macroinvertebrate community composition downstream (Rice et al. 2001). However, a large river integrates all influences of the landscape and waters upstream of any point on the river, thereby diluting any single local influence and greatly increasing the sensitivity in the response variable needed to detect that influence. The Delaware River maintains good water quality, but is threatened by increasing development pressures. Application of Daniels et al. (2002)'s mid-Atlantic slope IBI to the river was successful; bioassessment of these fish assemblages based on water quality analyses or species lists alone would have been hampered because of little variation in site water quality or species composition. Furthermore, the adopted IBI was sensitive to environmental degradation in the form of wastewater input, although a larger-scale study with a larger range in IBI scores would be useful in exploring this relationship further. IBI

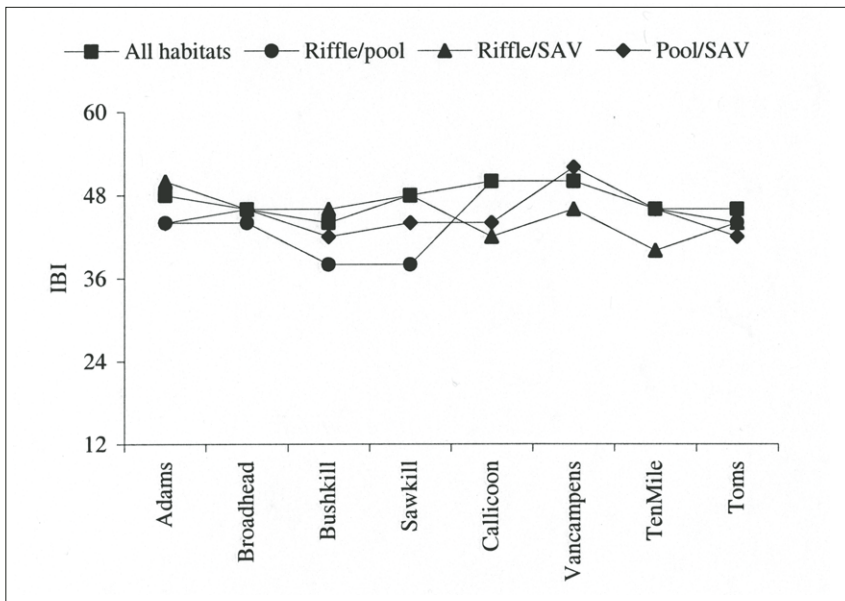


Figure 4. Comparison of IBI scores using complete habitat information to those with reduced habitat information (omitting riffle, pool, or SAV data).

metrics and/or scoring criteria are often adjusted to meet the objectives of individual studies (Angermeier et al. 2000, Roth et al. 2000, Simon 1999). The small data set of this study precluded adjustments of metrics or scoring criteria; however, future application of this IBI to the river may require minor adjustments.

Habitat diversity also increases in large lotic systems, elevating the risk of inadequately sampling fish assemblages to characterize the stream reach. The three habitat types (riffle, pool, and SAV) were important in describing biotic integrity of the river. IBIs with all three habitat types included were in most cases as high or higher than IBIs with omitted riffle, pool, or SAV habitats (Fig. 4). Of the three habitat types, fish assemblages from SAV habitats had the greatest positive effect on biotic integrity (Fig. 4). In lakes, fish abundance, particularly that of centrarchids, has been correlated to macrophyte cover (Hinch and Collins 1993), and in streams and rivers, vegetated edge habitats serve as nursery areas for young fish by providing protection from predators and a strong macroinvertebrate food base (Lobb and Orth 1991, Walters and Wilson 1996). In the New River of West Virginia, Lobb and Orth (1991) found the highest densities of fish in snags, vegetated pools, and riffles along the shoreline. Thus, inclusion of multiple habitat types and sampling regimes is definitely needed to properly characterize the ichthyofauna of a large river.

Because of habitat diversity considerations, gear choice clearly becomes an issue in riverine sampling, where backpack electrofishers are less reliable in characterizing both assemblage size and IBI score (Yoder and Smith 1999). Earlier whole-community assessments of large rivers using single sampling techniques such as boat-mounted electrofishers (e.g., Gammon 1980) provided little if any habitat-specific information on fish assemblages. Bramblett and Fausch (1991) obtained better habitat differentiation (riffles versus pools) by using a variety of seines and nets at 12 sites on a 7th order midwestern river. Because of the inherent biases of fish-sampling techniques needed to sample different habitats, more than one method is needed to accurately assess fish assemblages in large rivers (Bain 1992, Li and Li 1996, Vadas and Orth 1993).

Others have shown that large rivers are only adequately and efficiently sampled by using a boat-mounted generator and electrofishing methods with experienced crews (Yoder and Smith 1999). This single sampling method requires skill in maneuvering among obstacles in shallow-water habitats as well as judgement in determining the need for repeated coverage of fast-water habitats encountered in some river segments. Even so, it is likely that this method, particularly when used at night over longer river segments than those sampled in this study, will yield more deep-water species than can be visually encountered by the diving methods in pools of this study. Boat electrofishing is not likely to effectively sample the shallowest habitats that we examined, however, such as shallow riffles and dense inshore SAV beds. While the census methods in this study did not

cover the river segment lengths recommended for boat sampling (400 m to upwards of 100 mean river widths; Yoder and Smith 1999), boat methods are less intense, favoring larger fish, over a specific area sampled than those employed in our study.

Hughes and Gammon (1987) found that point sources of pollution did not affect fish community composition, but large distances did (i.e., gradual changes in water quality over distance). We found no evidence of a relationship to distance between communities on the Delaware River (Fig. 3), and cluster analysis (Fig. 2) indicated that upstream-downstream location did not have a large influence on river-station fish composition. Potentially harmful point sources of pollution (such as the leaking Cortese landfill downstream of the Ten Mile River) also did not appear to influence fish composition. The distance (281 km) over which fish assemblage changes were observed in the Hughes and Gammon (1987) study, however, was twice that (147 km) of our study. Notably, the sewage load from adjacent tributaries did impact biotic integrity scores. A test of the IBI against an independent measure of water quality (WQI) showed no relationship. In a major river basin with more seriously degraded component systems, the Seine River and tributaries in France, no relationship between the IBI and an independent WQI was observed (Oberdorff and Hughes 1992). Nonetheless, one potential cultural pollution measure from tributary watersheds (sewage loads) significantly impacted fish communities in the Delaware River. Human activities alter the physical and environmental characteristics of a watershed directly or indirectly to impair aquatic ecosystems and affect aquatic assemblages (Bryce et al. 1999, Schleiger 2000). The mid-Atlantic region has a long history of human disturbance (McCormick et al. 2000, 2001). Among wadeable, perennial, first-to-third-order streams in upland ecoregions of the mid-Atlantic, McCormick et al. (2001) found 52% to be in fair or poor condition. Wastewater or sewage load may alter biological assemblages through changes in sediment load, vegetation, and/or flow (Bryce et al. 1999). The fish assemblages of the middle-to-upper Delaware River were assessed to be fair to good in quality and further biomonitoring is warranted to prevent degradation of the assemblages over time as human activities in the watershed increase (Harris and Silveira 1999, Rahel 2000, Scott and Helfman 2001).

Our application of this bioassessment tool, developed for the Mid-Atlantic region, to the Delaware River mainstem may be useful to managers with assessment needs for this drainage as well as for particular instream habitats. Similar applications are routinely used to correct trends of degradation in some jurisdictions (i.e., Ohio EPA 1987), and we look forward to adoption of standards for this purpose by a state or federal agency. The IBI developed by Daniels et. al (2002) identified the relationship between fish assemblage composition and habitat types, distance along the river, and cultural pollution, and appeared to be sensitive to environmental degradation. The metrics and scoring chosen by Daniels et. al (2002) were tested with this data set, and

modifications of some metrics such as total number of fish species, number of benthic insectivorous species, and percentage of species represented by two size-classes, should be considered as more comparable data, to be analyzed in a similar fashion, becomes available for the Delaware River. This IBI application may be a useful monitoring tool as the middle and upper Delaware River corridors become increasingly urbanized over time, and the data presented herein may serve as a useful benchmark in the future.

Acknowledgments

We wish to acknowledge the long-term cooperation of the National Park Service (Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreation River) for their many conceptual, logistic, and informational contributions to this work. Elizabeth Johnson and Malcolm Ross, as natural resource planners, provided the need for this bioassessment and much of the field crew help. Tom Backman (Columbia River Intertribal Fish Commission) helped in identifying the need for and writing an early draft of the proposal. Keith High and Peter Graves provided land-use data using GIS techniques; Rich Evans, Debbie Straler, and DeNise Cooke provided data and insight on water-quality issues; and Don Hamilton, Spencer Hobe, Dave Pharo, Brendan Williams, Peter Miller, Eric Brown, Rose O'Connell, Cliff Easton, and Randy Brindza assisted with electrofishing. Karl Theune, Al Henry, and their colleagues on NPS dive teams assisted with transects. Permission to access streams via private property was provided by Edwin Gettel for Boy Scouts of America and Harvey Martin for the Rock-Tenn Company. Dave Dropkin provided quality control for fish identifications and Jay Stauffer (Pennsylvania State University) and Rob Criswell (Pennsylvania Game Commission) resolved discrepancies in minnow identification. We thank Matthew Gray (AstraZeneca LP) for statistical assistance and Paul Angermeier, Joe Margraf, Jim McKenna, and Rick Spear for commenting on the manuscript.

Literature Cited

- Amoros, C. 1991. Changes in side-arm connectivity and implications for river system management. *Rivers* 2:105–112.
- Angermeier, P.L., R.A. Smogor, and J.R. Stauffer. 2000. Regional frameworks and candidate metrics for assessing biotic integrity in mid-Atlantic highland streams. *Transactions of the American Fisheries Society* 129:962–981.
- Bain, M.B. 1992. Study design and sampling techniques for community-level assessment of large rivers. North American Benthological Society Technical Information Workshop 5:63–74.
- Bramblett, R.G., and K.D. Fausch. 1991. Variable fish communities and the index of biotic integrity in a western great plains river. *Transactions of the American Fisheries Society* 120:752–769.
- Brown, R.M., N.J. McClelland, R.A. Deininger, and R.G. Tozer. 1970. A water quality index: Do we dare? *Water and Sewage Works* 117:10.
- Bryce, S.A., D.P. Larson, R.M. Hughes, and P.R. Kaufmann. 1999. Assessing relative risks to aquatic ecosystems: A mid-Appalachian case study. *Journal of the American Water Resources Association* 35(1):23–36.
- Daniels, R.A., K. Riva-Murray, D.B. Halliwell, D.L. Vana-Miller, and M.D. Bilger. 2002. An index of biological integrity for northern Mid-Atlantic Slope drainages. *Transaction of the American Fisheries Society* 131:1044–1060.

- Delaware River Basin Commission (DRBC). 1993. Findings of the 1992 scenic rivers water quality monitoring program. Cooperative Monitoring Program (Report No. 15, DRBC/NPS), West Trenton, NJ.
- Delaware River Basin Commission (DRBC). 1996. Administrative Manual Part III: Water Quality Regulations. West Trenton, NJ.
- Gammon, J.R. 1980. The use of community parameters derived from electrofishing catches of river fish as indicators of environmental quality. Pp. 335–363, *In* Seminar on Water Quality Management Trade-offs, Chicago, Illinois. US Environmental Protection Agency (EPA-905/9-80-009), Washington, DC.
- Gray, E.S., R.M. Ross, and R.M. Bennett. In prep. A coldwater index of biological integrity for tributaries of the middle and upper Delaware River.
- Halliwell, D.B., R.W. Langdon, R.A. Daniels, J.P. Kurtenbach, and R.A. Jacobson. 1999. Classification of freshwater fish species of the northeastern United States for use in the development of indices of biological integrity, with regional applications. Pp. 301–338, *In* T.P. Simon (Ed.). *Assessing the Sustainability and Biological Integrity of Water Resources Using Fish Communities*. CRC Press, Boca Raton, FL.
- Hansen, C. 1991. Inventory and analysis of adjacent land uses as of July 1989 in the Delaware Water Gap National Recreation Area. National Park Service, Bushkill, PA.
- Harris, J.H., and R. Silveira. 1999. Large-scale assessments of river health using an index of biotic integrity with low-diversity fish communities. *Freshwater Biology* 41:235–252.
- Helfman, G.S. 1983. Underwater methods. Pp. 349–369, *In* L.A. Nielsen and D.L. Johnson (Eds.). *Fisheries Techniques*. American Fisheries Society, Bethesda, MD.
- Hinch, S.G., and N.C. Collins. 1993. Relationships of littoral fish abundance to water chemistry and macrophyte variables in central Ontario lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 50:1870–1878.
- Hoefs, N.J., and T.P. Boyle. 1992. Contribution of fish community metrics to the index of biotic integrity in two Ozark rivers. Pp. 283–303, *In* D.H. McKenzie, D.E. Hyatt, and V.J. McDonald (Eds.). *Ecological Indicators*, Vol. I. Elsevier Applied Science, New York, NY.
- Hughes, R.M., and J.R. Gammon. 1987. Longitudinal changes in fish assemblages and water quality in the Willamette River, Oregon. *Transactions of the American Fisheries Society* 116:196–209.
- Hurley, L.M. 1990. Field Guide to the Submerged Aquatic Vegetation of Chesapeake Bay. US Fish and Wildlife Service, Annapolis, MD.
- Imhof, J.G., R.J. Planck, F.M. Johnson, and L.C. Halyk. 1991. Watershed urbanization and managing stream habitat for fish. Pp. 269–285, *In* R.E. McCabe (Ed.). *Transactions of the Fifth-sixth North American Wildlife and Natural Resources Conference*, Edmonton, AB, Canada.
- Johnson, B.L., W.B. Richardson, and T.J. Naimo. 1995. Past, present, and future concepts in large river ecology. *Bioscience* 45:134–141.
- Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplane systems. *Canadian Special Publication of Fisheries and Aquatic Sciences* 106:110–127.
- Karr, J.R. 1981. Assessment of biotic integrity using fish communities. *Fisheries* 6:21–27.
- Karr, J.R., K.D. Fausch, P.L. Angermeier, P.R. Yant, and I.J. Schlosser. 1986. Assessing biological integrity in running waters: A method and its rationale. Illinois Natural History Survey Special Publication 5, Champaign, IL.
- Kerans, B.L., and J.R. Karr. 1994. A benthic index of biotic integrity (B-IBI) for rivers of the Tennessee Valley. *Ecological Applications* 4(4):768–785.

- Langdon, R.W. 2001. A preliminary index of biological integrity for fish assemblages of small coldwater streams in Vermont. *Northeastern Naturalist* 8(2):219–232.
- Leonard, P.M., and D.J. Orth. 1986. Application and testing of an index of biological integrity in small, coolwater streams. *Transactions of the American Fisheries Society* 115:401–414.
- Li, H.W., and J.L. Li. 1996. Fish community composition. Pp. 391–406, *In* F.R. Hauer and G.A. Lamberti (Eds.). *Methods in Stream Ecology*. Academic Press, New York, NY.
- Lobb III, M.D., and D.J. Orth. 1991. Habitat use by an assemblage of fish in a large warmwater stream. *Transactions of the American Fisheries Society* 120:65–78.
- Lyons, J., S. Navarro-Perez, P.A. Cochran, E. Santana C., and M. Guzman-Arroyo. 1995. Index of biotic integrity based on fish assemblages for the conservation of streams and rivers in west-central Mexico. *Conservation Biology* 9:569–584.
- Lyons, J., R.R. Piette, and K.W. Niermeyer. 2001. Development, validation, and application of a fish-based index of biotic integrity for Wisconsin's large warmwater rivers. *Transactions of the American Fisheries Society* 130:1077–1094.
- Lyons, J., L. Wang, and T.D. Simonson. 1996. Development and validation of an index of biotic integrity for coldwater streams in Wisconsin. *North American Journal of Fisheries Management* 16:241–256.
- McCormick, F.H., D.V. Peck, and D.P. Larsen. 2000. Comparison of geographic classification schemes for Mid-Atlantic stream fish assemblages. *Journal of the North American Benthological Society* 19(3):385–404.
- McCormick, F.H., R.M. Hughes, P.R. Kaufmann, D.V. Peck, J.L. Stoddard, and A.T. Herlihy. 2001. Development of an index of biotic integrity for the mid-Atlantic highlands region. *Transactions of the American Fisheries Society* 130:857–877.
- Miller, D.L., P.M. Leonard, R.M. Hughes, J.R. Karr, P.B. Moyle, L.H. Schrader, B.A. Thompson, R.A. Daniels, K.D. Fausch, G.A. Fitzhugh, J.R. Gammon, D.B. Halliwell, P.L. Angermeier, and D.L. Orth. 1988. Regional applications of an index of biotic integrity for use in water resource management. *Fisheries* 13:12–20.
- Oberdorff, T., and R.M. Hughes. 1992. Modification of an index of biotic integrity on fish assemblages to characterize rivers of the Seine basin, France. *Hydrobiologia* 228:117–130.
- Ohio Environmental Protection Agency (OHIO EPA). 1987. Biological Criteria for the Protection of Aquatic Life: Volume II. Users Manual for Biological Field Assessment of Ohio Surface Waters. Division of Water Quality Monitoring and Assessment, Surface Water Section, Columbus, OH.
- Ott, W.R.(Ed.). 1978. *Environmental Indices: Theory and Practice*. Ann Arbor Science, Ann Arbor, MI. 591 pp.
- Poff, N.L., J.D. Allen, M.B. Bain, F.R. Karr, K.L. Prestegard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime. *Bioscience* 47:769–784.
- Rahel, F.J. 2000. Homogenization of fish faunas across the United States. *Science* 288:854–856.
- Rice, S.P., M.T. Greenwood, and C.B. Joyce. 2001. Tributaries, sediment sources, and the longitudinal organisation of macroinvertebrate fauna along river systems. *Canadian Journal of Fisheries and Aquatic Science* 58:824–840.
- Roth, N.E., M.T. Southerland, J.C. Chaillou, P.F. Kazyak, and S.A. Stranko. 2000. Refinement and validation of a fish index of biotic integrity for Maryland streams. Maryland Department of Natural Resources. Annapolis, MD.

- Ross, R.M., R.M. Bennett, and J.H. Johnson. 1997. Habitat use and feeding ecology of riverine juvenile American shad. *North American Journal of Fisheries Management* 17:964–974.
- Schleiger, S.L. 2000. Use of an index of biotic integrity to detect effects of land uses on stream fish communities in west-central Georgia. *Transactions of the American Fisheries Society* 129:1118–1133.
- Scott, E.M. 1999. Tailwater fish index (TFI) development for the Tennessee River tributary tailwaters. Pp. 507–522, *In* T.P. Simon (Ed.). *Assessing the Sustainability and Biological Integrity of Water Resources Using Fish Communities*. CRC Press, Boca Raton, FL.
- Scott, M.C., and G.S. Helfman. 2001. Native invasions, homogenization, and the mismeasure of integrity of fish assemblages. *Fisheries* 26:6–15.
- Shields, Jr., F.D., S.S. Knight, and C.M. Cooper. 1995. Use of the index of biotic integrity to assess physical habitat degradation in warmwater streams. *Hydrobiologia* 312:191–208.
- Simon, T.P. 1992. Development of biological criteria for large rivers with an emphasis on an assessment of the White River drainage, Indiana. US Environmental Protection Agency Publication 905-R-92-026, Chicago, IL.
- Simon, T.P. (Ed.). 1999. *Assessing the Sustainability and Biological Integrity of Water Resources Using Fish Communities*. CRC Press, Boca Raton, FL.
- Simon, T.P., and E.B. Emery. 1995. Modification and assessment of an index of biotic integrity to quantify water resource quality in great rivers. *Regulated Rivers: Research and Management* 11:283–298.
- Steedman, R.L. 1988. Modification and assessment of an index of biotic integrity to quantify stream quality in southern Ontario. *Canadian Journal of Fisheries and Aquatic Sciences* 45:492–501.
- Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. *Transactions, American Geophysical Union* 38:913–920.
- Vadas, Jr., R.L., and D.J. Orth. 1993. A new technique for estimating the abundance and habitat use of stream fishes. *Journal of Freshwater Ecology* 8:305–317.
- Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37:130–137.
- Walters, J.P., and J.R. Wilson. 1996. Intraspecific habitat segregation by smallmouth bass in the Buffalo River, Arkansas. *Transactions of the American Fisheries Society* 125:284–290.
- Wang, L, J.Lyons, P.Kanehl, and R. Gatti. 1997. Influences of watershed land use on habitat quality and biotic integrity in Wisconsin streams. *Fisheries* 22:6–12.
- Wohl, N.E., and R.F. Carline. 1996. Relations among riparian grazing, sediment loads, macroinvertebrates, and fishes in three central Pennsylvania streams. *Canadian Journal of Fisheries and Aquatic Sciences* 53(Suppl. 1):260–266.
- Yoder, C.O., and M.A. Smith. 1999. Using fish assemblages in a state biological assessment and criteria program: Essential concepts and considerations. Pp. 17–56, *In* T.P. Simon (Ed.). *Assessing the Sustainability and Biological Integrity of Water Resources Using Fish Communities*. CRC Press, Boca Raton, FL.