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EVALUATION OF POOL-RIFFLE NATURALIZATION STRUCTURES ON HABITAT COMPLEXITY AND THE FISH COMMUNITY IN AN URBAN ILLINOIS STREAM

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ABSTRACT

Urbanization and its associated stressors such as flow alteration, channel modification and poor water quality is a leading cause of ecological degradation to rivers and streams. Driven by public concern to address this issue, there has been a dramatic increase in urban restoration projects since 1990 using in-stream structures. Attempts at restoring the ecological condition of urban streams using structures have produced varied results, but projects do not often meet planned ecological goals. A major challenge to improving the ecological health of urban streams is to better understand how to incorporate ecological assessments into a 'restoration' design framework with reasonable expectations for ecological recovery. A naturalization design framework was used in a project on a 0.62-km reach of the North Branch of the Chicago River in Northbrook, Illinois. Initial surveys of channel morphology, habitat and biota identified poor pool-riffle bed structure and fish biodiversity, which became the basis for research and development of a pool-riffle structure specifically designed for constrained, low-gradient channels. Habitat and fish surveys were conducted pre- and post-construction. The project improved mesohabitat structure, and fish abundance, and biomass and diversity were greater for 2 years following construction (2002–2003) compared to 3 years prior to construction (1999–2001). However, the improved fish metrics were in the low range when compared to rural streams in the same ecoregion, and the fish community consisted primarily of tolerant, slow-water species. Absent were intolerant and riffle dwelling species, such as insectivorous cyprinids and darters. Assessment of pre- and post-project ecological condition and the use of species information provided a basis for ecologically informed design and expanded our understanding of the limitations to restoring urban streams. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: naturalization; stream restoration; urban streams; habitat instream structures; ecohydraulics; bioassessment; fish

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INTRODUCTION

Urbanization, or conversion, of rural lands to urban lands, is a leading cause of ecological degradation to rivers and streams (Baer and Pringle, 2000; Paul and Meyer, 2001). Urbanization-related stressors on stream habitat and fish communities include flow alteration, channel modifications including physical barriers to organism movement and poor water quality (Booth and Jackson, 1997; Kemp and Spotila, 1997; Schleiger, 2000; Wang *et al*., 2000; Fitzpatrick *et al*., 2004; Blakely and Harding, 2005; Brown *et al*., 2005). These stressors are interrelated and highly variable, complicating the interpretation of ecological assessments to determine causes of degradation (Cormier *et al*., 2000; USEPA, 2000). It is well known that hydrological modification from urban development increase peak discharges and frequency and duration of stormflows (Hollis, 1975; Graf, 1977). Urban channels are often armoured with rock or concrete to prevent planform migration towards buildings, roads and utilities, or they are relocated altogether to accommodate development (Hess and Johnson, 2001; Paul and Meyer, 2001). Ultimately, meandering channels become constrained and isolated from their natural

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floodplain. Modifications to both hydrology and channel initiate subsequent rapid morphological adjustments creating frequent bank failures, knickpoint migration and channel incision (Hammer, 1972; Arnold *et al*., 1982; Booth, 1990; Bledsoe and Watson, 2001). These morphological adjustments degrade physical habitat quality and simplify streambed structure as pools aggrade and riffles erode (Gregory *et al*., 1994; MacRae, 1997; Pizzuto *et al*., 2000). As channels adjust, sediment transport and turbidity fluctuates (Davies-Colley and Smith, 2001; Simon *et al*., 2004), ultimately reducing biodiversity (Newcombe, 2003). Independent of channel adjustment processes, increased suspended solids and other water quality constituents, such as nutrients, toxics and elevated water temperatures add to the stressors experienced by urban stream ecosystems (Herricks, 1995; Roesner, 1996). Once a watershed is fully urbanized, the amount of sediment may be reduced, but the legacy of past sediment loadings, constraints to natural channel change and continuance of highly variable hydrologic conditions persist as stressors.

The public has shown an increasing concern about urban stream degradation, as evidenced by the increased number of restoration projects completed since 1990 (Bernhardt *et al*., 2005). Attempts at rehabilitating the ecological condition of urban streams by 'restoration' projects have produced varied results, but a common finding is that projects do not often meet planned ecological goals (Kondolf, 1998; Brown, 2000; Palmer *et al*., 2005). Clearly, a major challenge to improving the ecological health of urban streams is to better understand how stressors change basic ecological processes, and how to incorporate this understanding into a 'restoration' design framework with reasonable expectations for ecological recovery.

In order to evaluate the roles stressors play in limiting the ecological health of urban streams, habitat and biota assessments are essential for both pre-project design and post-project validation (FISRWG, 1998; Cairns, 2000; Morley and Karr, 2002; Moerke *et al.*, 2004). Pre-project assessments of biological conditions associated with geomorphic-habitat constraints provide critical guidance during restoration design process, whereby the recommended design may specifically target identified stressors (Rabeni and Sowa, 1996; Bond and Lake, 2003). Unfortunately, monitoring for pre-project assessment is often not conducted, and rarely reported (Bash and Ryan, 2002; Downs and Kondolf, 2002). Pre-design project assessments would avoid the use of a common assumption that 'if you build it', biota will return. This assumption does not account for habitat capacity potentials as determined by urban-modified geomorphic processes, whether organism sources in the watershed exist for recolonization, or limitations from poor water quality (Ebersole *et al*., 1997; Pretty *et al*., 2003; Herricks and Suen, 2006). Both pre-design and post-project assessments of habitat and biota can improve designs using adaptive management strategies (Downs and Kondolf, 2002; Johnson *et al*., 2002; Moerke and Lamberti, 2004). Pre- and post-project assessments of restoration projects, and the reporting of such assessments, will advance our understanding of ecological recovery potential within the varied domains of urban stressors.

The overall goal of this project was to illustrate the importance of pre- and post-design assessments in designing and evaluating the success of an urban in-channel project applying the naturalization concept. Although the term 'restoration' is generally used in literature and practice (Shields *et al*., 2003), naturalization more accurately characterizes restoration-related activities in human-dominated watersheds because naturalization acknowledges key social, political and economic constraints to restoration design (Rhoads and Herricks, 1996; Rhoads *et al*., 1999). A particular problem in urban streams is absence of a reference site, which would usually help to identify project ecological goals. Most practitioners are well aware that restoration to a pristine state is not possible in urban streams (Purcell *et al*., 2002). Naturalization is a design framework that recognizes geomorphic and ecological references or analogue sites do not exist, and the existing physical and water quality constraints are part of a technical, social and economic discourse that identifies actual restoration possibilities. Hence, the concept identifies that design strategies are socially determined and place-specific. Because of these constraints, habitat and biota pre-assessments, and prediction of limits to ecological recovery expected with various design approaches, are all the more critical to in-channel design.

Objectives of this study were to: (1) use geomorphic-habitat survey and biological monitoring data to guide the design of in-channel habitat enhancement structures; and (2) describe habitat changes and fish community response to a reach-scale manipulation of physical habitat. The reach-scale manipulation of physical habitat was specifically related to a unique pool-riffle design for low-gradient streams with no opportunity for planform change. This study also examines limitations of fish community recovery in an urban watershed, in terms of species traits, where the prospects for water quality improvement and recolonization potential remain poor.

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BACKGROUND

Study site

The study site is located on the West Fork of the North Branch (WFNB) of the Chicago River along a 0.62-km reach in the Village of Northbrook, Illinois (Figure 1). The regional climate is humid continental receiving an average rainfall of 81.3 cm (FEMA, 1998). The landscape is gently sloped ranging in elevation from 192 m to 212 m, a result of a geological history that includes Pleistocene glaciation and subsequent receding of Lake Michigan. Because of this geological history, the watershed drainage pattern is poorly integrated, and there is an absence of well-developed, stream-cut valleys.

This tributary of the Chicago River is a 3rd order stream that drains mostly residential areas in a fully 'built-out' watershed in the northern Chicago suburbs. Historic changes to flow of the Chicago River and the construction of multiple dams in the lower watershed effectively isolate the study reach. Within the study site the WFNB Chicago River was channelized decades ago and now abuts commercial and residential properties, and a city park. A narrow riparian corridor received minimal management. Stormwater runoff is drained by piped conveyances with outfalls often co-located with bridge crossings. Daily mean discharges during low-flow periods generally are below 0.5 m^3/s and peak daily discharges during floods are about 16 m^3/s (USGS Station No. 05535500).

Typical of many degraded urban streams, the WFNB Chicago River prior to restoration lacked quality in-stream habitat structure, supported a low diversity fish community and conveyed water of poor quality. The study reach was characterized by long glides and periodic short weir-riffle structures. These weir-riffle structures were reported to be as old as 70 years, consisting of concrete blocks and bricks placed across the stream. Aquatic life was reported as 'partially supporting' on the §303(d) list, in which biological impairment was attributed to organic enrichment, low dissolved oxygen and hydrologic/habitat modification (IEPA, 2004).

Project history and naturalization design

In the mid-1990's, Northbrook community leaders initiated planning for a city-centre river walk project because they felt the WFNB Chicago River was an eye sore with trash and overgrown riparian vegetation (Figure 2a). They believed aesthetics of the central business district would be enhanced with a riverwalk, and focused on bank clean-up, stabilization and revegetation. However, they did not originally consider in-stream habitat enhancements. In 1998, University of Illinois researchers arranged with village officials to work on a stream naturalization design incorporating habitat enhancement into the proposed project. Although many interrelated studies (i.e. geomorphological, hydraulic engineering, ecological and sociological) were conducted on the WFNB Chicago River as part of the larger project (Wade *et al*., 2002), this study focused on how bioassessment data was used to guide design and then used to confirm design criteria utility.

Because physical modification to the habitat was an integral part to the observed ecological response, details of the in-channel design are important. Principal investigators designed, without the use of analogue site, a pool-riffle

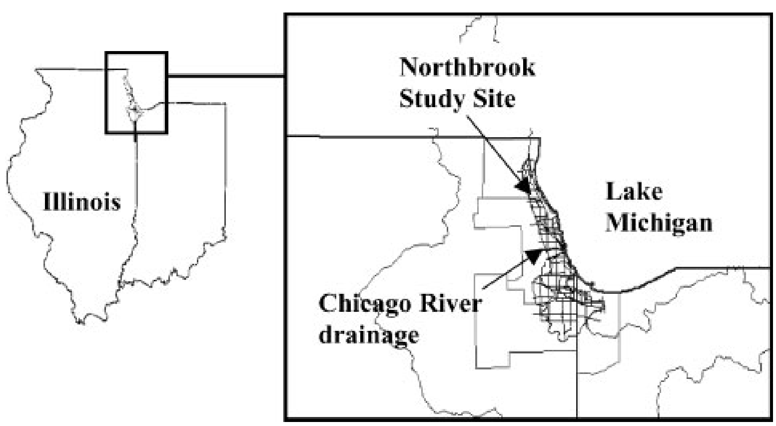

Figure 1. Location map of the study site on the WFNB Chicago River, Northbrook, IL. USA

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Figure 2. Photos of WFNB Chicago River (a) between Meadow and Shermer roads before construction of pool-riffle naturalization structures, June 1998 and (b) between Shermer and Walter roads after construction, February 2002

structure unique to low-gradient, constrained channels (Wade *et al.*, 2002). Design criteria were based on a preliminary ecological analysis of the 1999 field data that found degraded pool-riffle structure, lack of deep pools, and poor biodiversity throughout the reach, and compromised water quality (Schwartz *et al.*, 2002). The in-channel design focused on the creation of pools with a minimum depth of 0.5–1.0 m because it was in a single pool with this depth that the greatest fish abundance was observed (Figure 3). The reach design consisted of pool spacings equivalent to five to seven channel widths, and gradual transitions from narrower pool areas to wider riffle areas. Stable riffles were specified with 10-mm D_{50} bed material based on a maximum shear velocity of 0.14 m/s utilizing

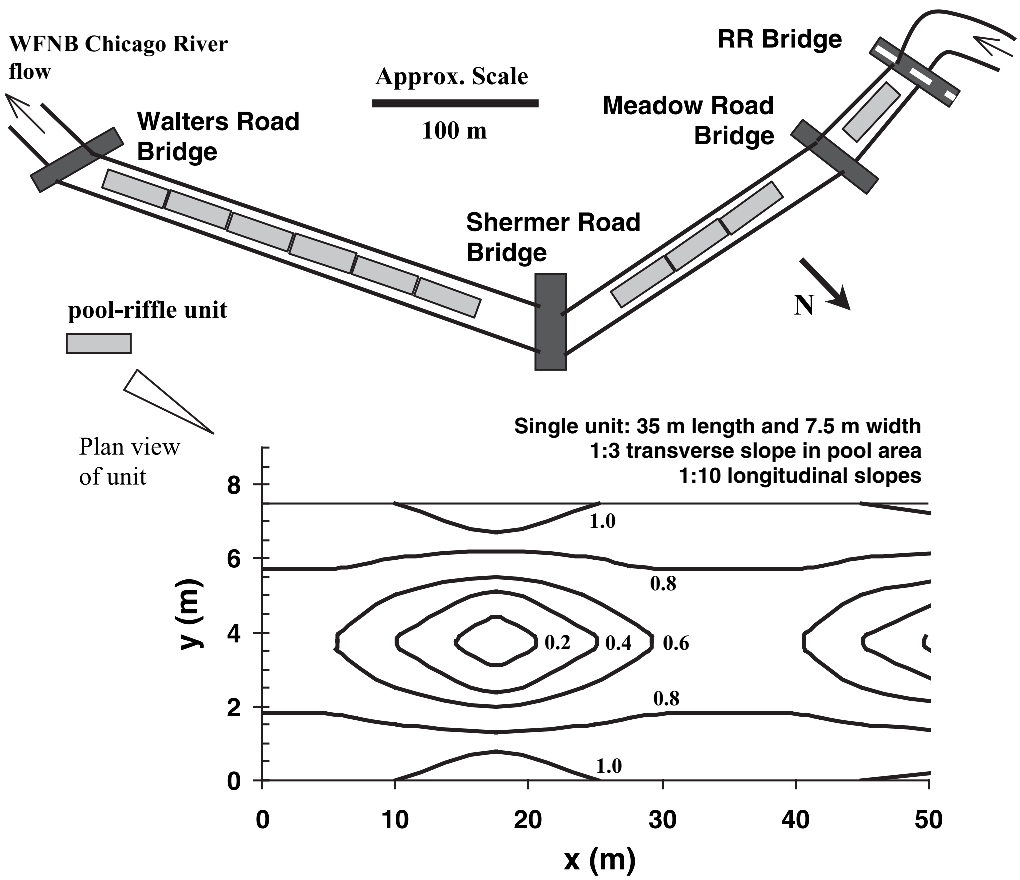

Figure 3. Reach layout and design dimensions of the pool-riffle naturalization structures on the WFNB of the Chicago River, Northbrook, IL

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a tractive force approach (Rodríguez *et al*., 2000). Hydraulically, the design criteria included creating acceleration-deceleration helical flow patterns through the pool-riffle structure to increase hydraulic diversity and self-maintenance of each structure. The idea was that during bankfull discharge, accelerated flows towards the pool centre would remove sediments from the newly created deep pools, while decelerated flows at the riffle would prevent scour. The design's hydraulic performance was tested using a 3D computational fluid dynamics model, and a 1/7-scale model flume experiment over a range of discharges (Rodríguez, 2003). In the testing process, design modifications were made to improve both habitat and physical stability.

The pool-riffle naturalization structures were constructed between Fall 2001 and Spring 2002 (Figure 2b). Ten pool-riffle units were placed in the project reach (Figure 3). Intended to prevent longitudinal displacement of riffles, limestone slabs approximately 1 m $\times$ 0.75 m $\times$ 0.2 m thick were placed at grade across the riffle and immediately downstream of the crest. As requested by the village engineer, boulders approximately 0.25-m diameter were placed along the bank from the toe to about 0.75 m vertically above the low-flow water surface level.

METHODS

Study approach

Physical habitat and fish surveys were completed before and after construction of pool-riffle structures. The initial habitat and fish surveys were conducted in June 1999 as the pre-design assessment supporting project design activities. Physical habitat surveys for the entire project site were completed in June 1999 as part of pre-design analysis for design criteria development, and in July 2002 as the post-project appraisal. Reach-scale summaries of various habitat metrics were compared before and after construction.

Fish surveys consisted of three annual surveys before construction and two annual surveys after construction. Annual fish surveys focused on five fish collection sites within the project; they were: (1) Railroad (RR) bridge, (2) Business District between Meadow and Shermer roads, (3) Shermer Road bridge, (4) City Park between Shermer and Walters roads and (5) Walter Road bridge. However, not all sites were collected each year, except for the Shermer Road site.

Fish sampling prior to project construction focused on differentiating the Shermer Road collection site from other collection sites. The Shermer Road site contained the single deep pool where fish abundance was found to be greater than any other pre-construction sampling location. In addition, fish and habitat data were collected at two sites downstream from the project site. The sites downstream were: (1) Elm Street easement and (2) Oak Street easement. These sites remained unaltered over the study period, and represented the study's 'no treatment' comparison.

Data from fish collections were pooled in order to statistically compare different treatment groups, in which the pooled data represented temporal pseudo-replications (Underwood, 1997). The treatment groups from pooled data were: (1) pre-construction, Shermer Road site only; (2) pre-construction, project reach sites combined, but excluding Shermer Road; (3) post-construction, project reach sites combined, but excluding Shermer Road; and (4) post-construction, sites downstream of project reach. Comparisons between treatment groups were used to construct null hypotheses of equal means (μ_i) to test the following research questions:

(1) were the Shermer Road site collections the same as the other collection sites in the project reach before construction ($\mu_1 = \mu_2$);
(2) were the collection sites in the project reach, excluding Shermer Road, the same before and after construction ($\mu_2 = \mu_3$); and
(3) were the collection sites in the project area, excluding Shermer Road the same as the downstream collection sites after construction ($\mu_3 = \mu_4$).

Physical habitat surveys

Physical habitat surveys were conducted during the same flow stage (0.18 m^3/s discharge as reported by the USGS Station No. 05535500) in June 1999 and July 2002. Habitat data collected before and after construction

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consisted of a streambed longitudinal profile, mesohabitat unit delineation and habitat quality attribute identification including bed substrate, large woody debris (LWD) and shade. Thalweg elevations within longitudinal profiles were measured using standard level and tape methods (Kaufmann *et al*., 1999). Mesohabitat units were defined as a pool, riffle, or glide based on unit descriptions in Arend (1999). Mesohabitat units were sequentially delineated along the stream profile, with unit boundaries recorded by longitudinal survey distance (Bisson and Montgomery, 1996). Physical dimensions were measured and recorded per unit, and habitat quality attributes were visually estimated per unit. Physical dimensions included estimated bankfull and wetted channel widths and average and maximum water depths.

Fish surveys

Fish were sampled annually during summer low-flow periods (June–August) from 1999 through 2003 to represent a common life history season. Daily mean streamflows ranged from 0.18 m^3/s to 0.53 m^3/s for the five annual collection efforts (USGS Station No. 05535500). Longitudinal positions of the collection sites were measured. Longitudinal lengths and average wetted channel widths were also measured during each sampling event, in order to compute a sample unit area. Collection sites were approximately 70 m in length.

Fish were captured between block-netted upstream and downstream ends of the collection site using standard electrofishing gear and dip nets (Reynolds, 1996). Uniform sampling effort was exercised with a travel time of 4 m/min upstream, followed by a second and equal downstream pass. Fish were identified by species, measured on a scale board to total length, and weighed to the nearest gram with an Ohaus LS2000 portable balance. After processing, fish were released back to their captured location, except for a few individuals preserved in 70% alcohol to maintain a laboratory reference collection for species verification.

Data analysis

Physical habitat metrics in pre- and post-construction periods were compared. Metrics included mesohabitat unit characteristics, bed substrate types by percent unit area; LWD pieces and volumes; and shade by percent unit area. Mesohabitat unit characteristics included total number of habitat units, percentages of unit number and length by unit type, average unit length by unit type and number of riffle-pool transitions. Mesohabitat unit dimensions were statistically compared between pre- and post-construction periods using the nonparametric Mann-Whitney U-test.

Fish data were summarized per collection site sample by density (#/100m^2), biomass (g/m^2) and Shannon diversity index. The diversity index (H) was computed as $-\sum p_i \times \ln p_i$; where p is the species i proportion of the total sample abundance (Begon *et al*., 1986). A statistical analysis using the nonparametric Mann-Whitney U-test compared density, biomass and diversity to test the three research questions listed in the Study Approach.

RESULTS

Physical habitat structure

The total number of mesohabitats after construction of pool-riffle sequences increased from 32 units to 39 units for an equivalent distance surveyed before construction (Table I). After construction, pools increased from 28.1% to 41% of the total mesohabitat units, while glides decreased from 37.5% to 23.1% of the units. Similarly, pools increased from 27.9% to 51% of the project reach length, while glides decreased from 48.1% to 16.6%. While the number of riffles did not increase, the total riffle length increased from 24% pre-construction to 32.4% post-construction. Before construction, the longitudinal habitat pattern was dominantly a glide-riffle sequence, whereas after construction the pattern was dominantly a pool-riffle sequence (Figure 4). The number of riffle-pool transitions increased from 5 to 12 from pre- to post-construction periods (Table I).

A statistical comparison of pre- and post project mesohabitat unit dimensions indicated significant differences in riffle and glide dimensions, but no significant difference in pool dimensions (Table II). Mean glide length was significantly reduced from 24.55 m before construction to 11.03 m after construction ($p = 0.05$). Glide units prior to construction were relatively deep with a mean maximum water depth of 0.44 m; this decreased to a mean of 0.28 m after construction ($p < 0.01$). Average water depth in glides also decreased after construction from 0.30 m to 0.22 m

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Table I. Differences in physical habitat metrics before and after construction of pool-riffle structures for the same 0.61-km reach on WFNB Chicago River, Northbrook, IL

Physical Habitat Metric	Pre-construction 1999	Post-construction 2002	% Difference between Pre- & Post-construction
Mesohabitat Unit Characteristics			
Total number of mesohabitat units	32	39	+19.7
% number of pools	28.1	41.0	+37.3
% number of riffles	34.4	35.9	+4.3
% number of glides	37.5	23.1	−47.5
Number of riffle-pool transitions	5	12	+82.4
% length of pools	27.9	51.0	+58.6
% length of riffles	24.0	32.4	+29.8
% length of glides	48.1	16.6	−96.9
Average length of pools (m)	19.0	19.6	+3.1
Average length of riffles (m)	13.4	14.4	+7.4
Average length of glides (m)	24.6	11.0	−76.0
Bed Substrate Characteristics			
Hardpan (% area per unit)	0.2	1.3	+148.7
Silt/sand (% area per unit)	15.4	35.6	+79.2
Gravel/pebble (% area per unit)	36.4	24.9	−37.5
Cobble (% area per unit)	31.8	34.6	+8.7
Concrete block (% area per unit)	16.2	1.2	−174.6
Flat rock (% area per unit)	0.0	2.4	+200.0
Large Woody Debris			
Total number of LWD pieces	5	3	−50.0
Total volume LWD (m^3)	0.93	0.02	−191.6
Mesohabitat Unit Shade			
% area of shade	75.1	14.0	−137.1

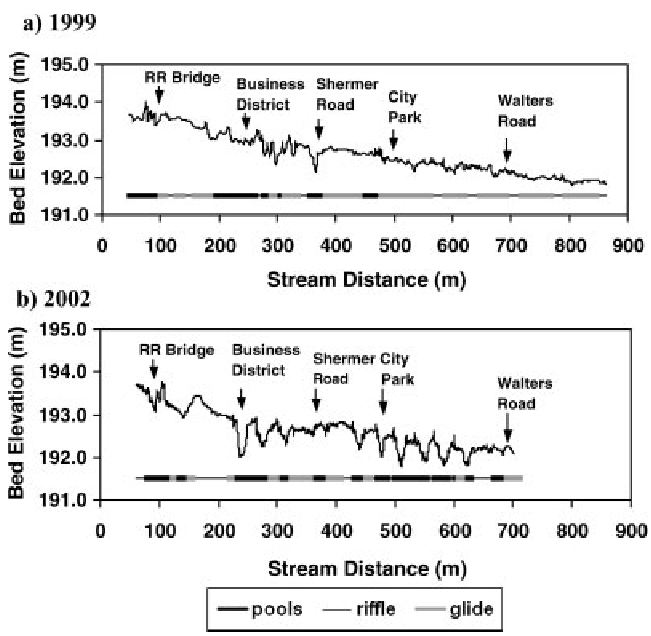

Figure 4. Longitudinal profile of bed elevations and mesohabitat delineations for the project reach (a) before and (b) after construction of pool-riffle structures. Fish collection site locations in the project reach identified along profile with vertical arrows

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Table II. Mesohabitat unit dimensions summarized by mean and coefficient of variance (CV) for pre- and post-construction periods of the pool-riffle structures on WFNB Chicago River, Northbrook, IL

Mesohabitat unit dimensions (m)	mesoabitat unit type	Pre-construction mean (CV)	Post-construction mean (CV)	Significance level
Unit length	Pool	19.0 (69.9)	19.6 (43.6)	0.67
	Riffle	13.4 (51.9)	14.4 (112.0)	0.48
	Glide	24.6 (81.9)	11.0 (81.0)	0.05*
Unit width	Pool	7.9 (23.0)	6.8 (11.0)	0.14
	Riffle	8.0 (14.6)	7.2 (14.2)	0.06
	Glide	8.8 (16.7)	7.1 (15.1)	0.14
Unit depth, average	Pool	0.50 (33.1)	0.44 (27.6)	0.65
	Riffle	0.24 (23.6)	0.13 (22.0)	<0.01**
	Glide	0.30 (23.8)	0.22 (11.4)	0.01**
Unit depth, maximum	Pool	0.75 (52.0)	0.64 (35.7)	0.48
	Riffle	0.32 (27.7)	0.21 (25.3)	<0.01**
	Glide	0.44 (23.6)	0.28 (8.6)	<0.01**

Mann-Whitney U-test used for statistical comparison of pre-and post-construction data; (*)denotes significance level less than 0.05 and (**)denotes significance level less than 0.01.

($p = 0.01$). The average and maximum water depths for pools, approximately 0.5 m and 0.75 m, respectively, did not significantly change from pre- to post-construction periods ($p = 0.65$; 0.48). However, average and maximum water depths for riffles significantly decreased from pre- to post-construction periods (both $p < 0.01$). For riffle units, average water depth decreased from a mean of 0.24 m to 0.13 m, and the maximum water depth decreased from a mean of 0.32 m to 0.21 m.

Habitat quality attributes (bed substrate, LWD and shade) generally declined from pre- to post-construction periods (Table I). Most notably, the quantity of silt-sand substrates increased from 15.4% to 35.6% of the stream bottom, while gravel-pebble substrates decreased from 36.4% to 24.9%. There was very little change in cobble substrate between pre- and post construction periods. The obvious changes in the largest substrates occurred during project construction when large concrete blocks were excavated, and flat limestone rocks were placed at the riffles. Hardpan clay always made up a very small portion of the substrate, but was observed at the bottom of excavated pools after construction. LWD was not a major component of microhabitat complexity before or after construction, consisting of only five and three pieces, respectively. The riparian corridor was greatly opened to sunlight due to removal of some trees and brushy bank vegetation during construction (Figure 2). Shade by percent area decreased from 75.1% pre-construction to 14% post-construction.

Fish community structure

Before construction of the pool-riffle structures, the dominant fish assemblage consisted of white sucker, green sunfish and bluegill, with one to three additional species collected annually in very low numbers (Table III). Fish densities and biomass in the single deep pool at Shermer Road were significantly greater than at all other sites (Table IV; $p = 0.03$ and $p = 0.02$, respectively). Overall, fish diversity was generally low, and diversity did not significantly differ among sampling sites within the project reach ($0.0 > H > 1.17$; $p = 0.19$).

Fish density, biomass and diversity significantly increased after construction (Table IV; all $p < 0.01$). During the 2-year post-construction period, average fish density and biomass per site increased five- to six-fold. Increases in fish density from pre- to post-construction periods were fairly uniform among the individual collection sites (Figure 5). Fish biomass also increased among the individual collection sites, except at Shermer Road where biomass before and after construction were similar. Because fish densities increased at Shermer Road, but biomass remained approximately the same, it is inferred that more abundant small fish occupied the Shermer Road site after construction.

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Table III. Average fish densities (#/100m^2) by species per year for sites sampled within the project reach on WFNB Chicago River, Northbrook, IL. Pre-construction years were 1999, 2000 and 2001; and post-construction years were 2002 and 2003

Fish species	Average fish density (#/100m^2) per Year				
	1999	2000	2001	2002	2003
Bluegill, *Lepomis macrochirus*	0.7	2.1	0.3	9.9	2.6
Common Carp, *Cyprinus carpio*	—	0.2	—	1.5	0.4
Fathead Minnow, *Pimephales promelas*	—	—	0.3	0.2	—
Gizzard Shad, *Dorosoma cepedianum*	—	—	—	0.3	0.5
Golden Shiner, *Notemigonus crysoleucas*	—	0.2	—	0.4	—
Goldfish, *Carassius auratus*	—	—	—	0.3	0.2
Green Sunfish, *Lepomis cyanellus*	0.7	1.1	1.4	3.4	4.3
Largemouth Bass, *Micropterus salmoides*	—	0.2	—	0.7	0.3
Orange-spotted Sunfish, *Lepomis humilis*	—	—	—	0.6	—
Spotfin Shiner, *Cyprinella spilopterus*	—	—	—	0.5	—
White Sucker, *Catostomus commersoni*	3.1	1.9	1.2	1.5	3.7
Yellow Bullhead, *Ameiurus natalis*	—	—	—	0.8	0.3

Dashed lines (—) indicate fish species was not collected during sampling effort.

White sucker, green sunfish and bluegill, remained the dominant fish after construction (Table III), but the fish diversity index (H) significantly increased from 0.49 before construction to 1.23 after construction (Table IV; $p < 0.01$). Overall, species richness doubled from an average of 4.3 species collected per year before construction to an average of 10.0 species after construction (Table III). While most species re-populating the site were moderately to highly tolerant of poor water quality, some fish found after project construction included species less tolerant to degraded stream conditions including the orange-spotted sunfish, spotfin shiner and gizzard shad (Barbour *et al*., 1999).

Table IV. Statistical comparison among treatment groups for fish metrics (fish density in #/100m^2, biomass in g/m^2 and diversity) on the WFNB Chicago River, Northbrook, IL. Treatment groups were: (1) Shermer Road site, pre-construction only; (2) project reach sites, excluding Shermer Road; pre-construction; (3) project reach sites, excluding Shermer Road; post-construction and (4) sites downstream of project reach

Fish metric	Treatment groups: metric mean (CV)		Significance level
	Shermer Road site; pre-construction	Project sites, excluding Shermer Road site; pre-construction	
Density	4.3 (35.3)	2.0 (44.7)	0.03*
Biomass	8.47 (14.4)	0.93 (129.5)	0.02*
Diversity	0.85 (10.8)	0.49 (94.4)	0.19
	Project sites, excluding Shermer Road site; pre-construction	Project sites, excluding Shermer Road site; post-construction	
Density	2.0 (44.7)	14.8 (36.7)	<0.01**
Biomass	0.93 (129.5)	5.44 (42.2)	<0.01**
Diversity	0.49 (94.4)	1.23 (15.3)	<0.01**
	Project sites, excluding Shermer Road site; post-construction	Sites downstream of project reach	
Density	14.8 (36.7)	7.0 (76.4)	0.06
Biomass	5.44 (42.2)	1.50 (135.9)	0.02*
Diversity	1.23 (15.3)	0.72 (13.2)	<0.01**

Mann-Whitney U-test used for statistical comparison of treatment group data; (*) denotes significance level less than 0.05 and (**) denotes significance level less than 0.01.

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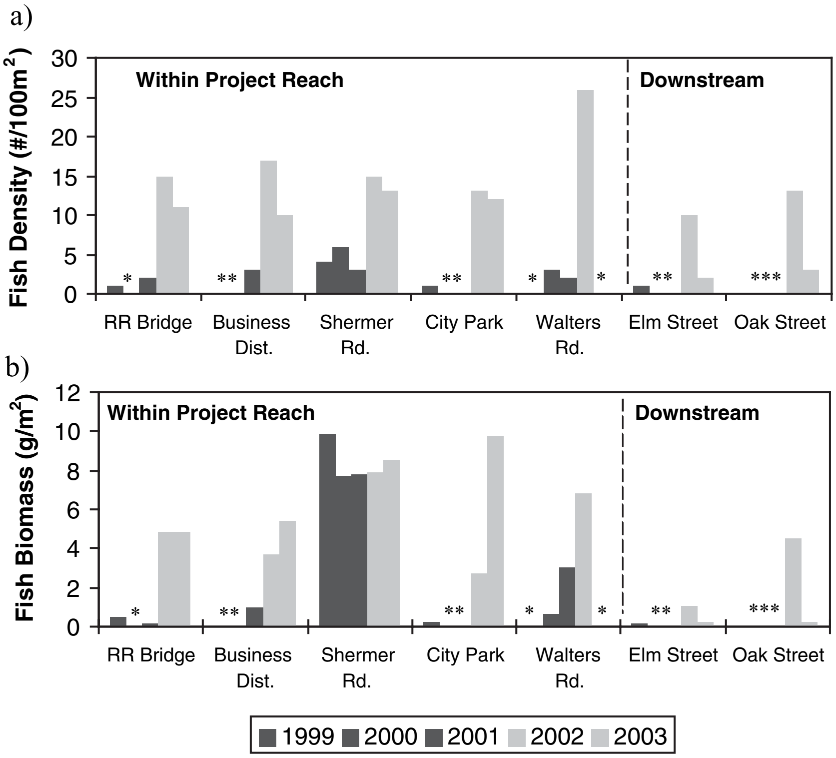

Figure 5. Within and downstream of the project reach, (a) fish density (#/100m^2) and (b) fish biomass (g/m^2) for years 1999, 2000 and 2001 (pre-construction) and years 2002 and 2003 (post-construction). Asterisks (*) indicate years without fish samples

Downstream from the project reach, physical habitat remained unchanged after construction, consisting mostly of riffle-glide units (Figure 4). Post-construction fish density, biomass and diversity, however, were significantly less downstream than in the project reach, excluding Shermer Road (Table IV; all $p = 0.06$, 0.02, <0.01, respectively). Green sunfish and bluegill dominated in the downstream reaches, while white suckers dominated the Shermer Road site.

DISCUSSION

The pre-design assessment of habitat and fish identified an urban channel with limited deep pool habitat consisting mostly of glide-riffle mesohabitat structure, and poor fish community structure. Identification of the single area of high fish abundance and biomass at Shermer Road suggested that increasing the number and depth of pools was a critical design criterion for the project. Pre-project assessments for habitat and biota have been shown useful for overall project appraisal (Charbonneau and Resh, 1992; Purcell *et al*., 2002). However, pre-design assessments in these projects relied on qualitative habitat surveys and did not specifically guide the in-channel design. The Northbrook project differed by specifically collecting mesohabitat structure and fish data, which were used to guide the design process. Similar to most urban stream restorations ecological considerations have to be balanced with urban-related constraints, such as existing development immediately adjacent to the channel, and local community perceptions for stream aesthetics (Morris and Moses, 1999; Purcell *et al*., 2002). Within the Northbrook reach constraints, the design effort focused on developing an improved pool-riffle structure, that integrated critical habitat needs for fish with hydraulic principles for self-maintenance, emphasizing maintenance of pool depth (Rodríguez *et al*., 2000; Schwartz *et al*., 2002).

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A major developmental aspect of this pool-riffle structure was incorporation of a hydraulic engineering approach to design (Rodríguez, 2003), an approach advocated by Shields *et al*. (2003) in urban streams or in unstable channels where reference analogue approaches cannot be applied. An initial option considered was a riffle-weir structure commonly used for hydraulic grade control (Newbury and Gaboury, 1993; Rosgen, 1996), but this structure was determined inappropriate for this low-gradient channel because it would create a backwater upstream during low-flow stages while failing to produce sufficient pool scour during high-flow stages. In addition, some studies have shown this weir structure may aggrade the bed in low-gradient channels, and fail structurally during floods in modified, urban fluvial regimes (Brown, 2000; Niezgoda and Johnson, 2005). In summary, the Northbrook project represents the application of designs consistent with current research that emphasizes improvement of pool-riffle designs based on geomorphic processes, hydraulic performance and self-maintenance (Booker *et al*., 2001; Emery et al., 2003; Sear and Newson, 2004; Smith and Prestegaard, 2005), and the Northbrook design provides an useful design approach that recognizes the importance of channel and bedform geometry, flow characteristics and bed sediment for habitat enhancement structures.

To achieve integration of ecological criteria with geomorphic and hydraulic criteria, designs must move beyond a solely structural approach and specifically target enhancement of critical habitat needs (Schwartz *et al*., 2001; Booker and Dunbar, 2004). Ecological concepts associated with habitat hydraulics need to be fully integrated into the design approach (Rhoads *et al*., 2003; Bockelmann *et al*., 2004; Crowder and Diplas, 2006). It has long been recognized that fish community structure is favourably influenced by the fluctuating flow patterns (i.e. changing depths and velocities) that occur through pool-riffle sequences (Bain *et al*., 1988; Aadland, 1993; Rabeni and Jacobson, 1993). In the Northbrook reach after construction, habitat hydraulics and mesohabitat structure were more complex, as indicated by an increase in the number of pool-riffle transitions, as well as an increase in depth differences between pools and riffles. Fish abundance, biomass and diversity were found to be greater after construction than before, which demonstrated how dominant the pool-riffle structures are as abiotic controls on fish community structure, even with persistent urbanization-related environmental stressors.

While fish response to habitat enhancements was positive, fish community metrics were still in lower range compared to non-urban streams in the same ecoregion, indicating some stressors originating within and outside of the project area still limit recovery. Typically in non-urban Illinois streams, 15 to 20 fish species are present with fish abundances ranging from 10/100m^2 to 800/100m^2, and biomass ranging from 1 g/m^2 to 30 g/m^2 with occasional large measures above 100 g/m^2 (Smith, 1979; Bertrand *et al*., 1996; Schwartz, 2002). Within the Northbrook reach, the project itself changed habitat quality, specifically riparian condition and the percentage of some bed substrates classes. Removal of dense woody vegetation on the banks reduced shaded area leaving only single trees and no overhanging vegetation that is important cover for young-of-year fish. However, it appears voids between the large round, submerged rocks at the bank toe may have substituted physical cover for vegetation cover for small fish (Schwartz, *field observation*). The quantity of gravel substrate decreased post-construction, possibly reducing spawning area for some fish species that require this substrate.

Because urbanization-related stressors are generated outside the Northbrook reach, limitations to fish community recovery should be interpreted at multiple spatial scales (Roth *et al*., 1996; Wang *et al*., 2001; Morley and Karr, 2002). The most obvious watershed-scale stressor affecting the Northbrook reach is poor water quality, as water quality conditions remained fair to poor during the study period (IEPA, 2004). Other stressors at the watershed scale include the presence or absence of flow regulation structures and quality of habitat refugia (Sedell *et al*., 1990; Jungwirth *et al*., 1995; Bond and Lake, 2005; Schwartz and Herricks, 2005). As noted the WFNB Chicago River is an urban stream with a 100-year history of drainage manipulations. Upstream from Northbrook, nearly the entire watershed is urbanized. Downstream, dams and other structures in the Chicago River prevent upstream fish migration. Habitat degradation upstream has diminished resident fauna, and migration barriers downstream limit the source of recolonizing organisms.

Whether or not fish species can survive poor water quality, barriers to movement or inadequate physical habitat is dependent on individual species tolerances, traits and life histories (Barbour *et al*., 1999; Poff, 1997). Before construction of the Northbrook project, the white sucker, green sunfish and bluegill were the dominant species, and were apparently reproductively successful based on the varied range in size classes collected (Schwartz, *data not shown*). These species preferentially occupied the single deep-water pool at Shermer Road. After construction, these dominant species expanded their range into the newly created pools, with the new habitats contributing to the

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increased fish abundance and biomass throughout the reach. The gizzard shad, largemouth bass, yellow bullhead and common carp, also primarily slow-water taxa that are fairly tolerant of degraded water quality conditions (Barbour *et al*., 1999), were also present in the post-construction collections. The most likely sources of these species are local lakes, ponds and stormwater control facilities connected to the channel. In fact, all species collected during this study period were pool taxa, preferring slow moving waters. Moerke and Lamberti (2003) observed similar results in Midwest streams, finding that only tolerant, slow-water species recolonized restored streams. Interestingly in the Northbrook reach, the orange-spotted sunfish and spotfin shiner were found in low numbers after construction, and these species are less tolerant to degraded habitat conditions (Barbour *et al*., 1999). Their presence suggests further improvement in fish community diversity may be possible with additional enhancement of water quality and microhabitats.

Species-habitat relationships and knowledge of basic biological needs (i.e. shelter, food, reproduction and flow refugia) can be used in design as well as interpretation of fish community change following habitat enhancements (Rabeni and Sowa, 1996; Kemp *et al*., 1999; Schwartz, 2002). Pre-construction surveys identifying critical habitat needs provided the basis for prediction of post-construction community potential. Using feeding and spawning habits as key elements of design criteria development, it is possible to focus on details of species-habitat relationships. Fish collected in the Northbrook reach were mostly omnivores (algae and aquatic insects) and bottom feeders (mud, detritus, plankton and hyporheic insects). Although, centrarchid species (bluegill, green sunfish and juvenile largemouth bass) were present, which could be expected to feed on terrestrial insects that fall onto the water surface, and on aquatic insects on vegetation and rocks at stream margins (Smith, 1979). A 1998 survey of benthic macroinvertebrates found 90% of the sampled abundances to consist of chironomids and isopods, and sparse numbers of Ephemeroptera (mayfly) species. This finding would support omnivores and impair insectivorous cyprinids (Schleiger, 2000), which is consistent with the Northbrook analysis.

Spawning habits for the fish collected were varied. Broadcast spawners, such as the white sucker and gizzard shad, are less selective in their spawning locations, and eggs are dispersed on the streambed adhering to bottom substrates and vegetation. But, yellow bullhead and fathead minnow typically build nests in fine sediments, such as silt and sand; the channel bed area of these substrates increased in the project reach. Gravel-bed areas, the preferred spawning substrates for centrarchids, were reduced in the project reach after construction. However, these species evidently find suitable substrates for spawning, because their populations have survived throughout the 5-year sample period and different age classes were collected. It is possible that centrarchids utilize gravel-rich areas outside the Northbrook reach for spawning, and juveniles move onto the Northbrook reach for summer rearing. A key insight is that sustainability of fish communities requires multi-scale ecological considerations for restoration planning and design, balancing the biological needs and habitat conditions at both reach and watershed scales.

The absence of species can also be an important aspect of the ecological analysis. For example, riffle fishes, such as darters and some cyprinids (minnows, shiners and chubs) remained absent after construction. Darters typically need small-sized gravel for refugia and are not tolerant of poor water quality (Smith, 1979). Clear water condition is required for visual-feeders such as riffle-orientated cyprinids that consume drifting aquatic insects. In concurrence with our field observations, the 1998 macroinvertebrate survey did not find that would meet feeding requirements of these fish species. Whether the macroinvertebrate limitation was caused by habitat or water quality conditions is unknown, but the lack of intolerant taxa suggests poor water quality. Similar findings were reported in other eastern United States watersheds, where some darter species, insectivorous cyprinids and lithophilic spawners were eliminated from the urban streams (Fitzgerald *et al*., 1998; Schleiger, 2000; Wang *et al*., 2000).

This analysis supports the view that a broader examination of the stream ecosystem and watershed-derived stressors is necessary to advance our restoration science. Important research questions on improving the biological integrity of urban streams remain, such as: (1) can critical ecological processes be restored by in-channel, reach-scale projects and (2) how can watershed-scale restoration be achieved by multiple reach-scale projects. The second question should consider what type of habitat enhancement, how many structures and where they are placed in the watershed. But more importantly, it must acknowledge or address the persistent hydrological and ecological stressors. Restoration practitioners and academics alike are interested in better understanding the ecological limitations to restoring urban watersheds (Palmer *et al*., 2005; Gillilan *et al*., 2005), and how to rehabilitate the lost ecological processes (Jannsson *et al*., 2005). The availability of quality mesohabitat structure will be a key element to any restoration initiative, as suggested by the more robust fish community developed after construction of the

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Northbrook project. However, improvements in watershed-scale restoration initiatives that better integrate stormwater programmes with in-channel projects are seriously needed (Urbonas, 2001). Restoration challenges are many in urban streams, with streams physically constrained by development and biota impaired by multiple stressors, but advances in restoration approaches can be achieved by baseline habitat and biota assessments, new design development integrated with assessments, effective project monitoring and improved watershed management.

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