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APPLICATION OF MesoHABSIM AND TARGET FISH COMMUNITY APPROACHES TO RESTORATION OF THE QUINEBAUG RIVER, CONNECTICUT AND MASSACHUSETTS, USA

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ABSTRACT

The study of the Quinebaug River in Massachusetts and Connecticut, USA was the first application of the Target Fish Community (TFC) and Mesohabitat simulation (MesoHABSIM) approaches to determine a river's biophysical conditions, habitat deficits and potential improvement measures. These approaches were created in concert with assessment of hydromorphology, fish and invertebrate fauna composition, as well as hydrology and water temperature. This paper presents how both approaches created a framework for comprehensive and quantitative analysis of human-induced alterations and helped to identify a list of effective restoration measures. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: river restoration; habitat simulation; quantitative models; reference conditions; biological template; integrative assessment

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INTRODUCTION

The need to identify mitigation measures for subsequent incorporation into rehabilitation plans has proved challenging for many projects. The Quinebaug River in Massachusetts and Connecticut, USA, presented an opportunity to apply the Target Fish Community (TFC) and Mesohabitat simulation (MesoHABSIM) approaches to determine a river's biophysical conditions, habitat deficits and potential improvement measures. The study objectives were to identify measures to mitigate the impacts of a water abstraction project to achieve compliance with the water quality standards of the State of Connecticut under provision of the Federal Clean Water Act.

The study was conducted between 1999 and 2004 and consisted of three major tasks:

1. Description and assessment of the existing biological and habitat structures.
2. Simulation of river habitat for fish.
3. Identification of habitat rehabilitation options.

The results of the study provided a basis for a long-term implementation plan. MesoHABSIM was the principal tool used in this investigation (Parasiewicz, 2001). The model provides a means of quantitatively predicting the outcomes of mitigation actions for fish habitat and therefore, serves as a foundation for development of a rehabilitation plan. MesoHABSIM was chosen for this study because of its ability to cope with the high diversity of Quinebaug River habitat. Use of standard microhabitat models such as Physical Habitat Simulation model (PHABSIM; Bovee *et al*., 1998) would require a great amount of effort to achieve the necessary accuracy.

The MesoHABSIM simulation model was developed in 2000 as a complement to PHABSIM and described for the first time by Parasiewicz (2001). The model uses units of meso-scale (mesohabitats), defined as areas where an animal can be observed for a significant portion of its diurnal routine. Fish meso-scale units typically correspond in size with hydromorphologic units (HMUs) such as pools, riffles and runs. Mesohabitats are defined by the configuration of hydraulic patterns in HMUs together with attributes that provide shelter and create favourable survival and development conditions. Consequently, MesoHABSIM modifies the data acquisition technique and

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analytical approach of similar models by changing the scale of resolution from micro- to meso-scales, and focuses more strongly on the contribution of cover to habitat quality. Due to this reduction in scale, the model takes variations in stream morphology along the river into account and is more applicable to coarse-scale issues. Typically mesohabitats are mapped under multiple flow conditions at representative sites along the river. Fish data are collected in randomly distributed mesohabitats where habitat surveys are also conducted. Based on observed fish abundances we develop multivariate habitat suitability criteria. The criteria are used to determine the habitat quality of mapped HMUs and subsequently the sites (detailed description of the approach can be found in Parasiewicz, 2007c).

The TFC approach developed by Bain and Meixler (2007) evaluates the status of a river based on a comparison between the current fish community and a regional model of the desired fish community. The TFC is formed using historical fish data from several high quality rivers with characteristics similar to the one being investigated. Its computational framework accounts for spatial and temporal variations of the native community and creates a robust, interannual representation of the expected native fauna composition at the watershed scale. The TFC is used to identify the species for which the habitat model is developed (Parasiewicz, 2007b).

The focus of this study was to determine the most beneficial measures for mitigating the effects of human alterations of physical and chemical attributes of the Quinebaug River for the native fish community at the catchment scale. Both TFC and MesoHABSIM approaches were used for this purpose. Due to the nature of the water withdrawals, the habitat availability under low-flow conditions, which occur in summer, was of the most concern. Therefore most of the effort was invested in the development of the habitat model for this season. Nevertheless, the seasonal habitat of resident fauna and the needs of anadromous species in other times of the year were also addressed. The material analysed in this paper summarizes only select results of the study to demonstrate the utility of MesoHABSIM and TFC approaches for a investigation of the effects of a water abstraction project. I will focus on the lessons learned from the first application of MesoHABSIM in tandem with the TFC approach in the selection of appropriate restoration measures. Therefore, only the summer model created for the adult life stage of resident fish is presented here.

METHODS AND STUDY AREA

The Quinebaug is a fourth-order river with multiple impoundments and a history of industrial use. It is a 122 km-long (76 mi) tributary of the Shetucket River in Eastern Connecticut and has a 2004 km^2 (774 mi^2) drainage area. Records from USGS Gauge Station at Quinebaug, Connecticut (located at the lower end of our study area, with 404 km^2 drainage = 156 mi^2) indicate that the average mean annual flow from 1931 to 1997 was 7.81 $m^3 s^{-1}$ (276 $ft^3 s^{-1}$), and the mean annual high- to low-flow ratio was 125:1. The river is morphologically highly heterogeneous, with contrasting gradient and hydraulic conditions that create a wide variety of habitat conditions. The reason for the heterogeneity is that it flows over the geological remnants of the collisions of tectonic plates that culminated in the formation of the super-continent Pangea. Presently the headwaters originate from Mashapaug Pond (Figure 1). Over its course, channel morphology changes from marshy plain to alpine stream in the upper portion, and an alluvial river confined by a relatively narrow valley below Southbridge, Massachusetts. The channel in the study area is dominated by cobble substrates with woody debris, and carries dark, tannin-stained water. The study area (37 km long = 23 mi) extends from the East Brimfield Dam to West Thompson Lake.

The upper portions of the study area are morphologically diverse, although they lack large amounts of woody debris which have been removed from the channel. The encroachment of mature vegetation upon the river indicates a lack of channel dynamics. In some areas the low-flow channel is entrenched and therefore disconnected from the floodplain. There is also a fair amount of historical channel regulation and the remnants of man-made structures (i.e. dams, bridge abutments) in the river. There are large amounts of trash on the riverbanks close to the urban areas.

Over 36 % (13.3 km) of the 37 km-long Quinebaug River study segment has been converted into impoundments (Figure 2). This affects the temperature and sediment regime of the river. As documented with a hydrologic model, landscape changes in the catchment have led to flow patterns that exhibit little short-term variability and higher amplitudes between low- and high-flow events (Parasiewicz, 2007a). Lack of low-flow variability could be an

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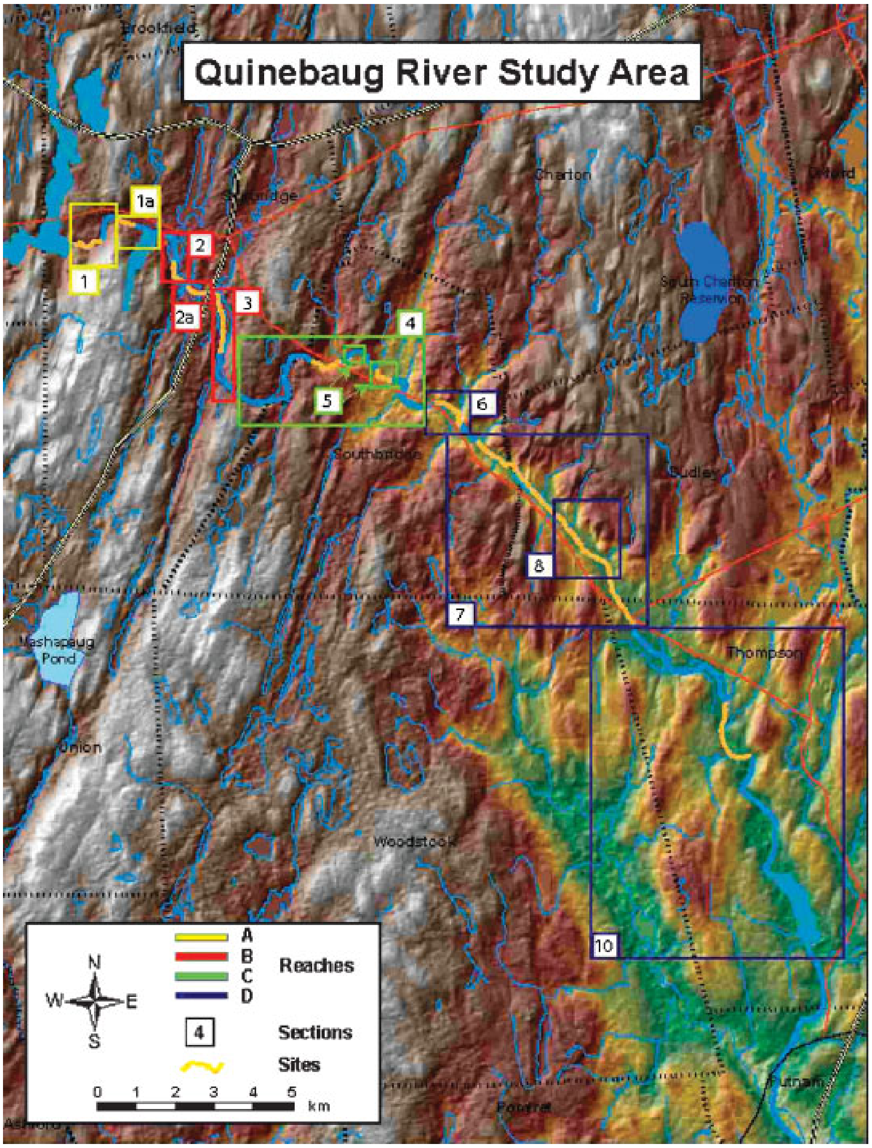

Figure 1. Relief of the Quinebaug River valley study area from East Brimfield to West Thompson Lake, including location of reaches, sections and sites. The Millennium Power Plant in Charlton is located north of Southbridge, and the water intake for the plant is downstream of Southbridge. The study area was divided into four reaches (A, B, C and D), which display uniform hydromorphologic characteristics as well as specific types of impacts within each reach. These reaches were then broken into morphologically uniform sections (creating a total of 11 sections in the study area) by taking into account gradient, channel form and level of human impact. In each section, we chose an approximately 1 km-long site best representing hydromorphologic conditions. The sites were than mapped several times using the MesoHABSIM approach

important negative factor in fauna modification. Although most of the impoundments are run-of-the-river, the Quinebaug River is exposed to instantaneous flow fluctuations that are usually of human origin. Most frequently these short fluctuations consist of a temporary reduction of the amount of water in the river, followed by rapid release of what has been stored.

Shallow impoundments serve as thermal collectors, raising temperature by several degrees at various locations in the watershed. This not only reduces available habitat area but also causes continuous increase in temperature (Figure 3). Consequently, the thermal gradient along the river is reversed, with temperature decreasing in a downstream direction.

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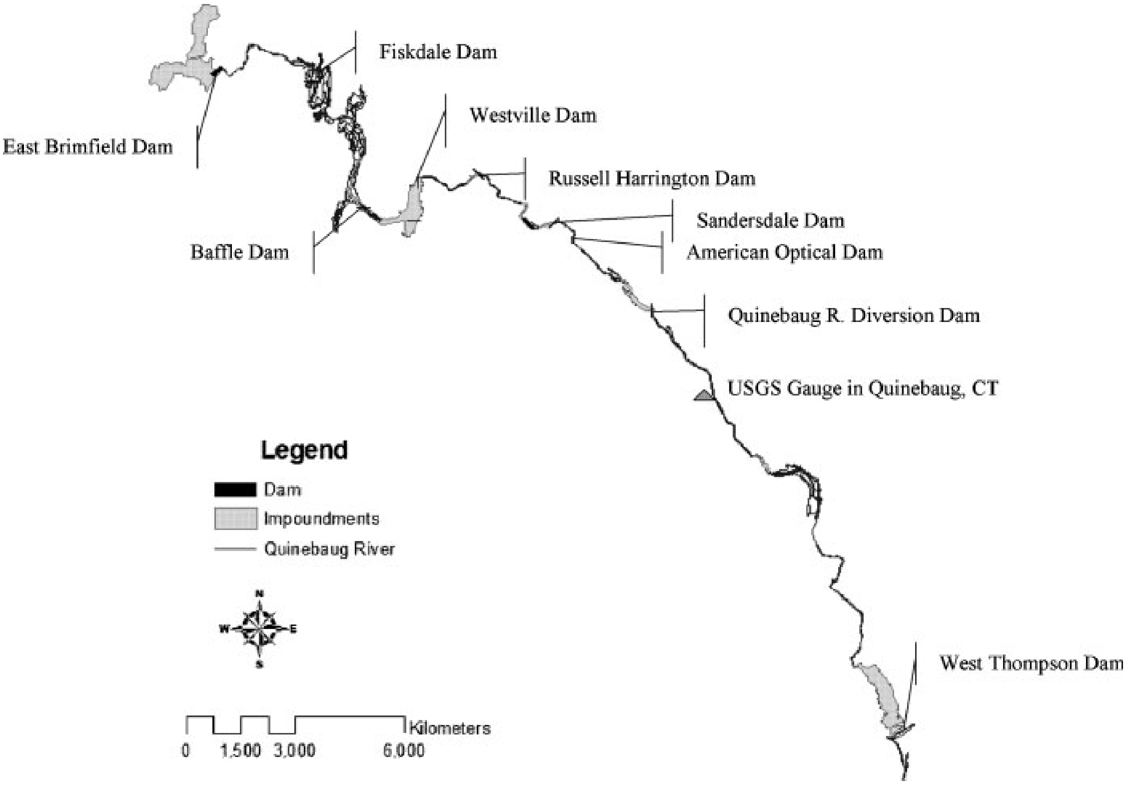

Figure 2. Location of dams in the study area

The assessment of biological status included developing a baseline TFC. Out of the suite of species identified by the TFC we selected indicator species, which form a sub-community for comparison with the existing fish community and habitat availability. As presented by Bain and Meixler (this issue), the Quinebaug River TFC demonstrates the under-representation of the six most dominant species in the TFC when compared to the Quinebaug River fish collections. These dominant species are fallfish (*Semotilus corporalis*), common shiner (*Luxilus cornutus*), white sucker (*Catostomus commersoni*), longnose dace (*Rhinichthys cataractae*), blacknose dace (*Rhinichthys atratulus*) and tessellated darter (*Etheostoma olmstedi*). These species made up 75% of the TFC and for this project we assumed that they use the majority of available habitat. All are fluvial specialists or fluvial dependant, and we selected them for development of the habitat model. However, the data available at the time did not allow for a reliable model for tessellated darter, and because the expected proportion of this species was 5%, we limited the model to the other five species only.[1] The TFC in this study was adjusted to reflect percentages for a community based on these five target species. The proportions of habitat necessary to support these species were assumed to correspond with the proportions of species in the community. We used the affinity index (Bain and Meixler, 2007) to determine the level of correspondence between the habitat and the community structure. We are fully aware that this is a gross approximation, but limited knowledge of life history information makes different adjustments complicated and hard to justify.

To obtain data on existing fish population and their habitat use we used grid electrofishing (Bain *et al*., 1985). Sampling was conducted between 25 June and 17 August 2000 with a Honda EX1000 generator and 15 amp Coffelt VVP-2C transformer using 350 V of alternating current. The locations of 687 grids ($6\,m^2 = 64.8\,ft^2$) were selected in stratified random fashion, that is, in five representative sites selected along the study area after first

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[1] At the time of model development, tesselated darter was ranked as the sixth species in the Target Fish Community for the Quinebaug River. In preparing this publication the underlying data have been reassessed and those with insufficient data quality removed (low number of individuals). This changed the tessellated darter to third in the ranking. This paper, however, is based on the original model.

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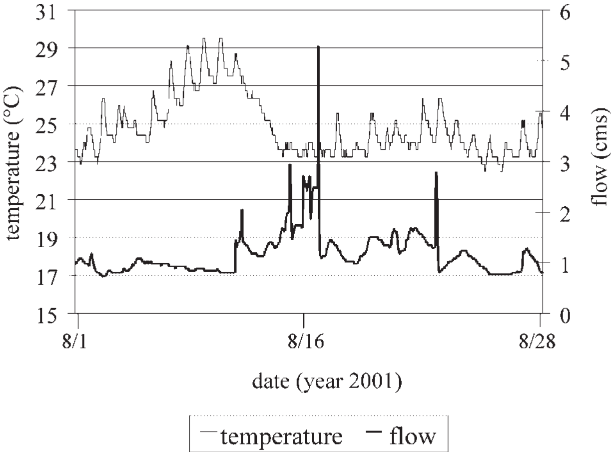

Figure 3. Flows measured in August 2001 at the gauge in East Brimfield, and temperatures recorded at the same location. Long-lasting low-flow conditions caused temperature to increase to over 30°C, and flow increase reduced it rapidly by 4°C

reconnaissance. Fish were captured, identified to species, measured (total length to nearest cm) and released. The average fish density was estimated for the site by dividing the total number of fish by the sampled area. Young-of-the-year fish were included in the samples, but in the analysis they were separated from the adults by their length.

Physical habitat data were collected for every sample. In contrast to the approach described in Parasiewicz (2007c), during this study, fish habitat was described combining the micro- and meso-scales (i.e. using discrete measurements at grid-corners to describe habitat parameters of the associated morphological unit). These data were used to establish multivariate habitat suitability criteria for selected adult fish fauna using logistic regression (see below and Parasiewicz, 2007c). We used the generic fish approach to determine habitat suitability for the sub-community (i.e. the habitat is considered suitable for the community as soon as it is suitable for one of the target species).

The habitat suitability criteria for the five target species during spawning were established using information found in scientific literature (Eddy and Underhill, 1974; Smith, 1985; Roberts and Grossman, 2001). The ranges of velocities and depth, as well as substrate and HMUs that can be associated with target species spawning were identified. For each species at least three of these criteria needed to be fulfilled in order for the habitat to be considered suitable for spawning. Similarly, the generic fish approach was used to determine community-spawning habitat.

The habitat model was limited to flows between $0.3 \times 10^{-2}\,m^3\,s^{-1}\,km^{-2}$ (cubic metres per second per square kilometre of drainage area) and $2.2 \times 10^{-2}\,m^3\,s^{-1}\,km^{-2}$ (0.3–2.0 $ft^3\,s^{-1}\,mi^{-2}$, cubic feet per second per square mile of drainage area). This covered the entire range of low-flow conditions. In summer and fall 2000, the study site was mapped to assess habitat distribution at the investigated flow range. The beginning and end locations of each mapped area were recorded with a Z-surveyor GPS unit, and an Impulse Laser Range Finder (LRF) was used to outline each HMU. The LRF transfers the data to a field computer, where the data appear as georeferenced polygons in PenMAP surveying software (Strata Software Ltd.). A GIS table is attached to each HMU polygon, where physical attributes are recorded. Measurements for depth and mean column velocity were measured with a Dipping Bar (Jens, 1968). Bottom velocities were measured with a Marsh–McBirney FlowMate 2000 at 5 cm (0.2 ft) above the substrate.

The first survey of the entire study area took place at flows of approximately $0.5 \times 10^{-2} m^3 s^{-1} m^{-2}$ (0.5 $ft^3 s^{-1} mi^{-2}$). The survey created a foundation for delineation of the study area into 11 sections and 4 reaches (Figure 1). The distribution of HMUs in sections was characterized by the percentage of coverage area for each HMU type. A sensitivity analysis was used to identify the representative sites for every section by visually comparing the graphs of quantitative distribution of HMUs (Parasiewicz, 2004). Subsequently mesohabitats of

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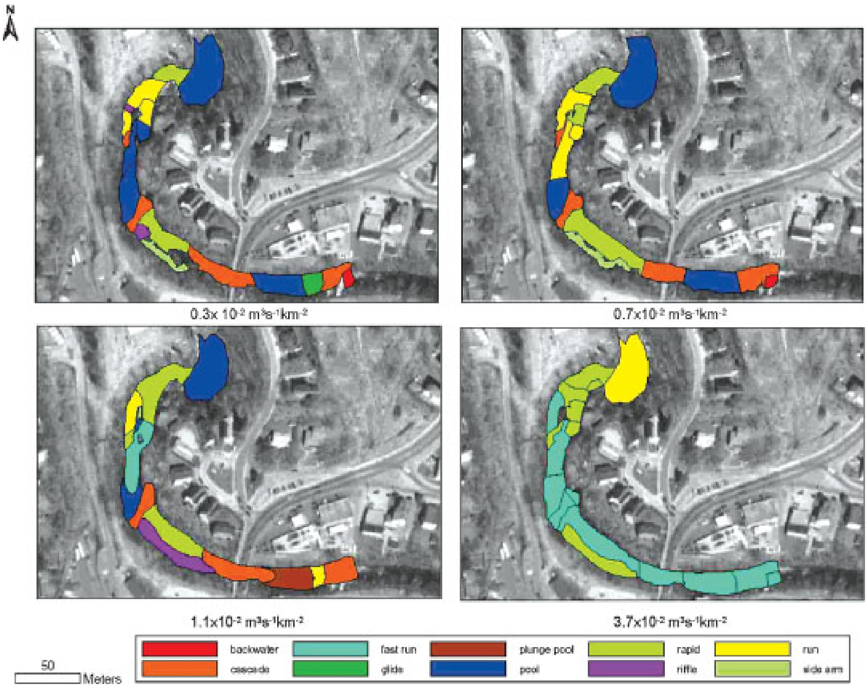

Figure 4. Example of map showing spatial distribution of HMUs at Site 5, mapped at four flow conditions

each site (9.2 km combined length = 5.9 mi) were mapped at two more discharges (0.3×10^{-2} and $1.1 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,m^{-2}}$; $0.3\,\mathrm{ft^3}$ and $1.0\,\mathrm{ft^3\,s^{-1}\,mi^{-2}}$).

Mesohabitat mapping was conducted at the highest discharge observed (between 2.2 and $4.1 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,m^{-2}} = 2.2$–$3.7\,\mathrm{ft^3\,s^{-1}\,mi^{-2}}$) by canoeing the site and drawing HMUs onto previously generated maps. When the collection of hydrologic data for the MesoHABSIM habitat mapping was not possible, a 1D hydrodynamic model was used to estimate velocity and depth distributions under high-flow conditions. After completing the mapping survey, we examined the distribution of habitat types to determine the number and location of transects for use in hydrodynamic calculations. Six to 11 transects were placed in each study site to ensure that all dominant HMU types in the site contained at least one transect. The hydraulic changes recorded at these transects (i.e. discharge-related changes in water velocity and depth) were considered representative of the hydraulic patterns occurring in each HMU type.

Subsequently, the HMU distribution at four different flows was described for each mapped representative site, and detailed coloured maps were created for each site (e.g. figure 4). The distribution of cover, substrate, vegetarian structure and riparian area was quantifed to describe the macrohabitat character of each site. Impoundments were differentiated from free-flowing sections and proportions of the river length were calculated for every reach.

The habitat suitability were used to determine the probability of fish presence in mesohabitats mapped during the survey of representative sites for individual species and for the community (Figure 5). Flow-habitat rating curves were created for resident adult species and spawning life stages for each representative site. The flow-habitat rating curves for the fish community were computed for the entire study segment using the representative-length-weighted average of the site curves. This provided an assessment tool for simulating various restoration options, such as improvements to the riverbed structure and dam removals. The curves also facilitated defining seasonal recommendations for flow manipulations (see Parasiewicz, 2007a).

Six restoration measures were simulated including various combinations of dam removals and channel improvements to analyse habitat benefits. The dam removals were simulated by the replacement of impoundments with the habitat sequences found in corresponding areas of the river. Similarly, the connectivity with the floodplain was increased by additional sidearms and backwaters that followed topographic depressions identified in aerial

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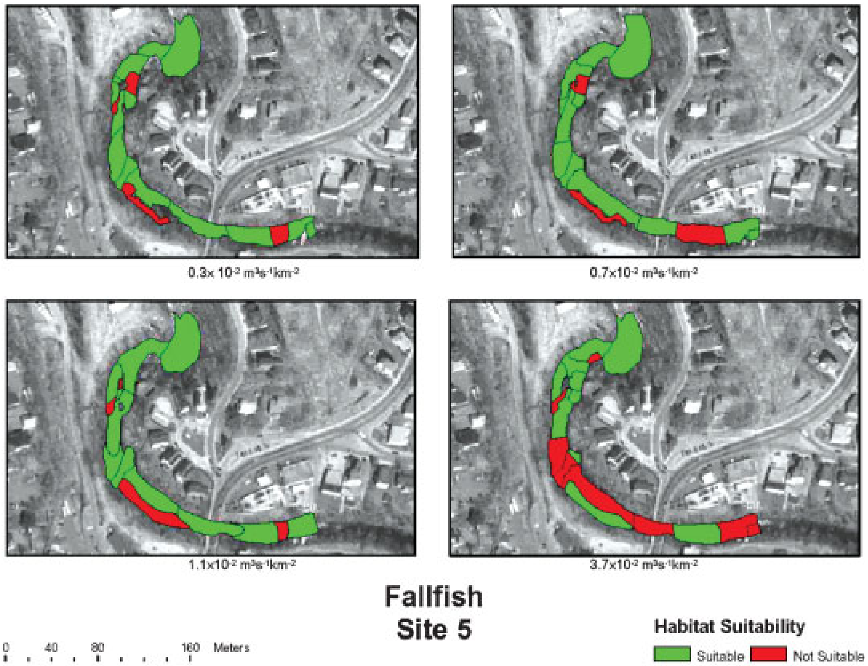

Figure 5. Example of map showing areas of suitable habitat for fallfish at Site 5

photographs. The first simulation defined the baseline condition, reflecting the habitat conditions resulting from the removal of all dams from the study segment and the implementation of feasible morphological improvements. The second simulation consisted of the removal of three dams with morphological improvements. Each of the subsequent simulations involved the removal of one dam and a subset of morphological restoration in the affected reach. The final simulation focused on channel improvements only, without removing any dams.

RESULTS

During the fishing surveys, a total of 2006 fish belonging to the target community were caught, equalling 77% of the total catch. Fallfish predominated, comprising 47% of the target community, with 934 individuals caught. Common shiner was the next in abundance, with 455 individuals (a representation of 23%). Longnose dace made up 16% of the community with 319 individuals, and 248 blacknose dace comprised 12%. White sucker were scarce, comprising only 2% of the target community (50 individuals caught). The estimated fish densities varied between 0.3 individuals m^{-2} (ind m^{-2}) in sites within Reaches A and D and 1.1 ind m^{-2} in sites within Reach C. The overall average was calculated with 0.5 ind m^{-2}. For the five selected species, the observed fish community structure's affinity index (Bain and Meixler, 2007) to the target community was 88% (Figure 6).

Table I represents habitat suitability criteria established for five target species. Figure 7 presents flow-habitat rating curves for generic fish in all representative sites. The habitat maximum varies between 30% and 100% of wetted area (WA).[2] Sites 4 and 5 provide the most of the suitable habitat, which is also the most stable over the range of flows. The study segment provides low amounts of total habitat for the target community (Figure 8). It does not exceed 30% of WA at any of the studied flows. It increases rapidly at flows up to $0.55 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($0.5\,ft^3\,s^{-1}\,mi^{-2}$), and at flows higher than $0.66 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($0.6\,ft^3\,s^{-1}\,mi^{-2}$) it drops gradually below 20%.

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[2] The wetted area of the sites in the Quinebaug River did not change significantly over the range of investigated flows and was approximated as constant.

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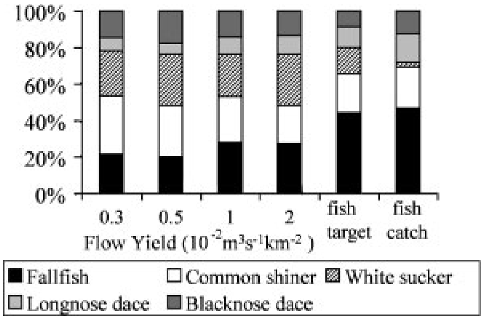

Figure 6. Relative distribution of habitat for target species at four selected flows ($0.3–2.2 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$) compared with proportions of these species in the target community model and with proportions of captured fish (adult life stage)

The most habitat available for individual species never reaches 22% WA (Figure 8). The most habitat available to a single species, common shiner, is 21% WA at flows between 0.55×10^{-2} and $0.66 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ (0.5 and $0.6\,ft^3\,s^{-1}\,mi^{-2}$). Both common shiner and fallfish habitat show the same increase and decline pattern as the total habitat.

The affinity between the modelled habitat structure and the structure of the TFC varies between 71% (at $0.55 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2} = 0.5\,ft^3\,s^{-1}\,mi^{-2}$) and 82% ($1.1 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2} = 1.0\,ft^3\,s^{-1}\,mi^{-2}$). At the two lower flows, the proportions of fallfish and longnose dace habitat are about 50% lower and then slightly increase at flows of $1.1 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ and $2.2 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($1.0–2.0\,ft^3\,s^{-1}\,mi^{-2}$). Common shiner and white sucker habitat are about two times higher than expected to support the TFC. When habitat structure is compared with proportions of captured fish (within five analysed species) the affinity drops to 63.5% for $0.55 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($0.5\,ft^3\,s^{-1}\,mi^{-2}$, the lowest) and 75% at $1.1 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($1.0\,ft^3\,s^{-1}\,mi^{-2}$, the highest). The habitat proportions for fallfish and longnose dace are substantially lower (about half) than the proportion of these species in the catch. The largest disproportion is between the habitat available for white sucker and the very low catch (a tenth of habitat availability) (Figure 6).

For each of the previously described restoration scenarios, changes in available adult target community habitat were quantified (Figure 9). The ratio of habitat (% WA) to flow (increases gradually from $0.3 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($0.3\,ft^3\,s^{-1}\,mi^{-2}$) to about $1.1 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($1.0\,ft^3\,s^{-1}\,mi^{-2}$) for restoration scenarios involving the removal of either the Fiskdale Dam or the Russell-Harrington Dam with associated morphological restoration (Figure 9). The habitat-flow ratios for those two scenarios remain nearly constant at approximately 30% WA until a downward trend begins near $1.87 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($1.7\,ft^3\,s^{-1}\,mi^{-2}$).

The Baffle Dam removal simulation produces a more rapid increase in habitat with increasing flow (Figure 9), and has a single optimal point (32% WA) at $0.87 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($0.7\,ft^3\,s^{-1}\,mi^{-2}$) before dropping at $2.42 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($2.2\,ft^3\,s^{-1}\,mi^{-2}$). The three-dam removal simulation mimics the Baffle Dam simulation, except there is a slightly higher % WA overall. In simulations limited to a single dam removal, the removal of the Baffle Dam provides the greatest habitat gain (32% WA) at a flow of $0.87 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($0.7\,ft^3\,s^{-1}\,mi^{-2}$).

The results of the channel restoration simulation indicate a moderate increase in habitat increasing flow (Figure 10) with a maximum ratio (29% WA) at $0.88 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($0.8\,ft^3\,s^{-1}\,mi^{-2}$). However, in contrast to present conditions the habitat does not decline until the flow reaches $1.87 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($1.7\,ft^3\,s^{-1}\,mi^{-2}$). The removal of all the three dams in addition to channel improvements would produce the greatest habitat availability (35% WA). The habitat created by either of the above scenarios does not approach the habitat available under baseline conditions, which would yield a maximum of 47% WA.

DISCUSSION

The most apparent indications that the system is affected are the low densities of fish captured in the river (about $0.5\,ind\,m^{-2}$). For comparison, the Mill River in Hatfield, Massachusetts, and Stony Clove Creek in the Catskill

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Table I. The logistic regression-based suitability coefficients for selected target species

Fallfish		Common shiner		White sucker		Longnose dace		Blacknose dace	
Presence (76%)	Beta	Presence (80%)	Beta	Presence (95%)	Beta	Presence (92%)	Beta	Presence (94%)	Beta
Boulder	1.95	Boulder	1.71	Depth (75–100 cm)	5.01	Riffle	2.05	Depth (0–25 cm)	3.03
Shading	−1.07	Riprap	1.4	Depth (50–75 cm)	2.19	Fast run	2.45	Boulder	2.57
Depth (0–25 cm)	−1.76	Shading	−1.48	Mesolithal	1.62	Xylal	4.6	Shading	−1.44
Velocity (45–60 cm)	1.06	Depth (50–75 cm)	−1.23	Undercut bank	1.66	Riprap	2.29	Shallow margin	1.65
Run	−0.57							Pelal	3.09
								Velocity (45–60 cm)	1.46
								Submerged vegetation	−1.44
High abundance (60%)	Beta	High abundance (69%)	Beta	High abundance (66%)	Beta	High abundance (73%)	Beta	High abundance (79%)	Beta
Overhanging vegetation	−0.97	Boulder	1.68	Depth (75–100 cm)	7.62	Velocity (45–60 ms^{-1})	3.35	Microlithal	−4.2
		Shading	−1.01						

The table displays two models for each species, for presence and high abundance. The beta coefficients are multiplicators of the significant attribute values. The number in parentheses defines the predictive power of the model.

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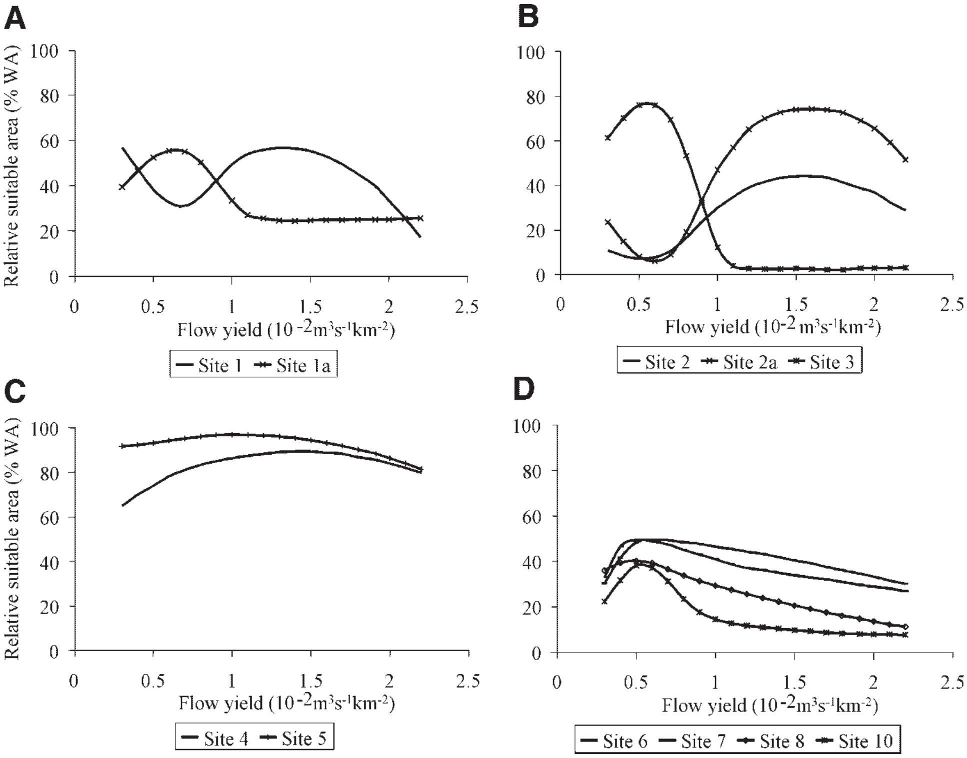

Figure 7. Flow-habitat rating curves for fish community developed for representative sites in (a) Reach A, (b) Reach B, (c) Reach C and (d) Reach D. The curves were computed using generic fish approach for five investigated species

Mountains, New York, had an observed density of 2.0 fish m^{-2} (Parasiewicz *et al.*, 2003a, 2003b). Bain and Meixler (2007) compared the TFC with the fish community structure in the Quinebaug River and concluded that it is shifted towards higher proportions of pond species. Nevertheless, fish community structure corresponds with the proportion of the target community.

No more than 30% of the free-flowing area of the Quinebaug River has suitable habitat for the TFC, with a peak around 0.66×10^{-2} m^3 s^{-1} m^{-2} (0.6 ft^3 s^{-1} mi^{-2}). Most of the habitat is suitable for fallfish, common shiner and blacknose dace. The structure of habitat does not correspond well with the TFC. Habitats for longnose dace and

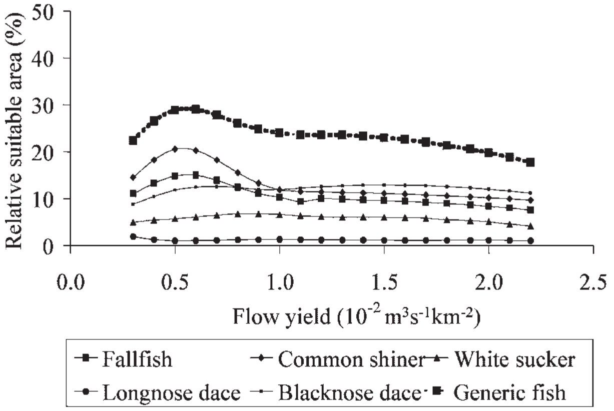

Figure 8. Rating curves showing habitat available in the entire study site across the range of mapped flows. The curves represent habitat for each of the investigated species, and all of them together (generic fish). The habitat used by more than one species is counted only once in the community model

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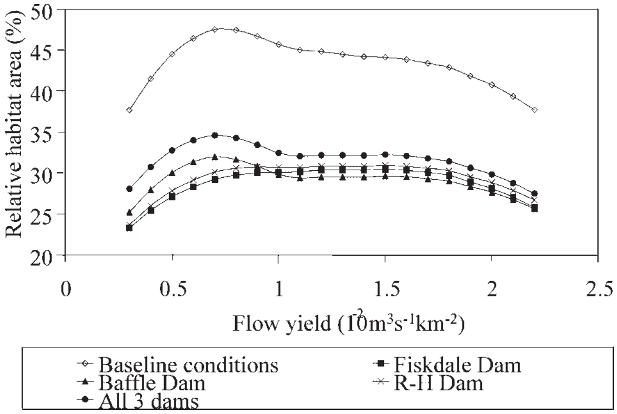

Figure 9. Flow-habitat rating curves representing available community habitat over the range of investigated flows for dam removal and restoration for each individual dam, and all three together. Baseline conditions represent the river with no dams and good connection to the floodplain

fallfish are under-represented and white sucker and common shiner habitat values are higher than expected, especially at flows below $1.1 \times 10^{-2}\,\mathrm{m}^3\,\mathrm{s}^{-1}\,\mathrm{m}^{-2}$ ($1.0\,\mathrm{ft}^3\,\mathrm{s}^{-1}\,\mathrm{mi}^{-2}$). Only blacknose dace meets the expected proportions. Higher flows increase the correlation between habitat and the target community structure.

The affinity between habitat structure and the structure of captured fish is poor. Common shiner was caught in proportions higher than expected in the TFC and it has a higher proportion of habitat than expected. In contrast, fallfish were found in expected proportions but the proportion of their habitat was half of that expected. The opposite relationship exists for white sucker and the corresponding low catches for this species (Figure 6). Another pattern exists for longnose dace; the habitat is limited only at low flows, and this species is under-represented in the fish community. The relative abundance of blacknose dace is consistent with the expected proportion of this species in the target community. However, the ratio of available habitat is lower. Nevertheless, because of low fish densities we can conclude that the habitat availability is not the limiting factor for this species. It is more likely limited by other factors (e.g. thermal stress, flow fluctuations). Conversely, sites with high habitat levels have higher fish densities and habitat structures corresponding with the proportions of captured fish (e.g. Site 4 has almost 100% of the WA suitable, fish density of $1.2\,\mathrm{ind\,m}^{-2}$ and shows 63% affinity). Similarly, areas of low fish densities and suitable area of about 50% WA also have much lower affinity (Site 1 has 48%, Site 6 has 42%, Site 7 has 50% and Site 10 has 49%). One hypothesis is that at the same level of environmental stress brought on by high temperatures, extended droughts or flow fluctuation, more habitat provides more refuge and thus increases the resiliency of the fish community.

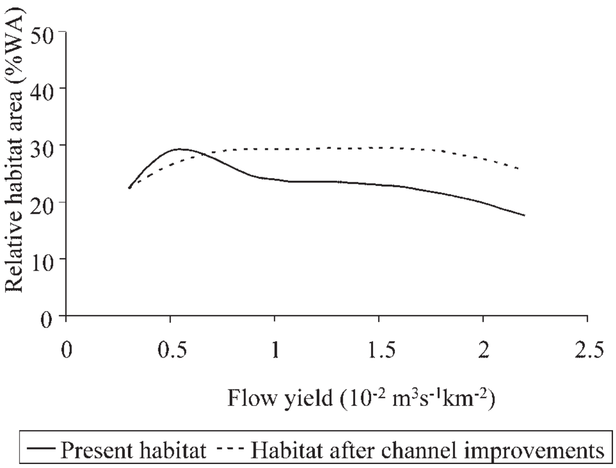

Figure 10. Flow-habitat rating curves for fish community representing present conditions and simulated channel improvements

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A consequence of low-flow channel entrenchment is that the most habitat for the investigated community is available at $0.66 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($0.6\,ft^3\,s^{-1}\,mi^{-2}$); higher flows provide less habitat than lower flows do. This is pronounced in Reach D where rating curves of all sites display this tendency, because most of the channel turns into deeper, fast flowing runs. Conversely, as presented in Figure 10, habitat availability is more consistent over a broader range of flows in simulations of channel restoration and dam removals.

The baseline established for the river (with no impoundments and with enhanced morphology) shows that habitat for investigated species could be almost doubled with restoration and dam removals. The highest amount of habitat for baseline conditions is available around $0.87 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($0.7\,ft^3\,s^{-1}\,mi^{-2}$), with an inflection point around $0.55 \times 10^{-2}\,m^3\,s^{-1}\,m^{-2}$ ($0.5\,ft^3\,s^{-1}\,mi^{-2}$), which corresponds with the most common summer flow in simulated hydrologic data.

Removing only three dams would not increase habitat as much but would still increase the present habitat availability by 25%. The removal of the Baffle Dam would produce the highest overall benefits from dam removal actions. The simulated channel improvements would increase the stability of habitat over the range of flows, but only include the addition of side arms and backwaters to connect the river back into the floodplain. Further improvements such as adding large woody debris can be expected to create even more benefits for fish habitat and should be simulated in the detailed design process.

The application of TFC and MesoHABSIM to the Quinebaug River study area has created a large-scale picture of fish habitat under several remediation scenarios. It is valuable to establish a restoration baseline, such as the expected proportions of dominating fish species and the amount of habitat necessary to support this structure. One could easily compare it with existing fauna and habitat to determine habitat deficits and the most beneficial restoration measures. We conclude that there is half as much habitat as there should be in the river, and it declines with flow increase. We also document that despite several impact sources and thermal or flow problems, increasing physical habitat availability could have a positive effect on fauna.

Probably the most unexpected result of this study is the conclusion that in terms of habitat improvements, more can be achieved by dam removals and channel restoration than by continuous increase in river flows. The simulation also underscored the importance of physical structure as a first building block of fish habitat. It led to the conclusion that the same amount of flow may create different habitat conditions in uniform conduits and highly diversified riverbeds. Therefore, one must consider that protective instream flows can provide only as much habitat as is allowed by riverbed structure. We cannot fully restore the ecosystem functions without taking into account alterations of a river channel by dams or channel modifications. Indeed, the direct comparison of habitat quantity and structure with fish community structure (target or existing) or abundance provides for the quantification of the relative contribution of habitat structure (e.g. geomorphology) as a limiting factor for both individual species and the community. Knowledge of habitat use of some species can indicate what type of structure could be missing. A shortcoming of the approach advanced herein is the assumption that $1\,m^2$ ($10.8\,ft^2$) of habitat is as valuable for fallfish as for longnose dace. This is inaccurate but difficult to correct, as habitat units for different species may be a factor of not only the size of the individual but its mobility and social behaviour. Therefore, unless more research will be invested in addressing this issue, the above conclusions can be drawn only if the discrepancies are at an order of magnitude, or if habitat for similar species is compared (e.g. blacknose dace and longnose dace).

A benefit of the MesoHABSIM application is that restoration measures can be analysed at a number of scales, that is, for short sites as well as for the entire study area. This allows for determining the benefits of individual measures for the ecosystem as a whole and weighing them against each other at the watershed scale. It is the first step in the planning process that allows one to select the types of applied measures to be focused on during designing restoration details. The greatest advantage of this application is that it can be integrated with other macro-scale conclusions (e.g. temperature regime), allowing for better understanding of causal relationships and identification of complex impact sources.

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REFERENCES

Bain MB, Finn JT, Booke HE. 1985. A quantitative method for sampling riverine microhabitats by electrofishing. *North American Journal of Fisheries Management* **5**: 489–493.

Bain MB, Meixler MS. 2007. A target fish community to guide river restoration. MesoHABSIM and Target Fish Community. *River Research and Application* DOI: 10.1002/rra1065.

Bovee KD, Lamb BL, Bartholow JM, Stalnaker CB, Taylor J, Henriksen J. 1998. Stream habitat analysis using the Instream Flow Incremental Methodology. Fort Collins, CO; U.S. Geological Survey, Biological Resources Division. (Information and Technical Report USGS/BRD-1998-0004), 131 p.

Eddy S, Underhill J. 1974. *Northern Fishes, With Special Reference to the Upper Mississippi Valley.* University of Minnesota Press: Minneapolis, Minnesota; 414.

Jens G. 1968. Tauchstäbe zur Messung der Strömungsgeschwindigkeit und des Abflusses. Deutsche Gewässerkundliche Mitteilungen, 12. *Jahrgang* **4**: 90–995.

Parasiewicz P. 2001. MesoHABSIM: a concept for application of instream flow models in river restoration planning. *Fisheries* **26**: 6–13.

Parasiewicz P. 2004. Ecohydrology Study of the Quinebaug River–Final Report to the Project Management Committee and the New England Interstate Water Pollution Control Commission, 385 p. http://www.neihp.org/projects/quinebaug/index.htm

Parasiewicz P. 2007a. Using a fish habitat time series analysis to define flow augmentation strategy for the Quinebaug River, Connecticut and Massachusetts, USA. *River Research and Application* DOI: 10.1002/rra1066.

Parasiewicz P. 2007b. Using MesoHABSIM to develop a reference habitat template and ecological management scenarios. *River Research and Application* **23**: 924–932. DOI: 10.1002/rra1044

Parasiewicz P. 2007c. The MesoHABSIM Model Revisited. *River Research and Application* **23**: 893–903. DOI: 10.1002/rra1045

Parasiewicz P, Ehmann SB, Corp. P. 2003a. Fish habitat assessment on Stony Clove Creek, NY using MesoHABSIM. Report for New York City Department of Environmental Protection,Green County Soil and Water Conservation District and New York State Water Resources Institute, 410 p.

Parasiewicz P, Kitson H, Snopkoski L, Jackson S, Destefano S. 2003b. Measuring ecosystem health in western Massachusetts – The Mill River, Hatfield, MA. Report for The Nature Conservancy and Massachusetts Environmental Trust. Ithaca, NY, 146 p.

Roberts JH, Grossman G. 2001. Reproductive characteristics of female longnose dace in the Coweeta Creek drainage, North Carolina, USA. *Ecology of Freshwater Fish* **10**: 184–190.

Smith CL. 1985. The Inland Fishes of New York State, New York State Department of Environmental Conservation, Albany, New York, 522 p.

Waddle TJ. (ed.). 2001. PHABSIM for Windows: user's manual and exercises. Fort Collins, CO: US Geological Survey. Open-File Report 01-340. 288 p.