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Use of quantitative habitat models for establishing performance metrics in river restoration planning

Piotr Parasiewicz,[1,2]* Kathleen Ryan,[1] Paolo Vezza,[3,4] Claudio Comoglio,[3] Thomas Ballestero[5] and Joseph N. Rogers[1]

[1] *Rushing Rivers Institute, 592 Main Street, Amherst, MA 01002, USA*
[2] *S. Sakowicz Inland Fisheries Institute, ul. Główna 48, Żabieniec, Poland*
[3] *DIATI, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*
[4] *IGIC, Universitat Politècnica de València, C/ Paranimf 1, Grao de Gandia, Valencia, Spain*
[5] *University of New Hampshire, Gregg Hall Room 238, 35 Colovos Rd, Durham, NH 03824, USA*

ABSTRACT

The ecological effectiveness and success of river restoration strongly depend on the resources invested in planning. Unfortunately, this trend of restoration engineering is frequently compromised by the application of qualitative assessment and resource intensive adaptive management processes. Habitat simulation models are effective tools for selecting ecologically effective restoration measures as part of the Environmental Benefits Analysis. Through the support from a mesohabitat simulation model, we identified three habitat metrics: (1) Habitat Quantity Deficiency; (2) Alteration of Habitat Structure; and (3) Habitat Stress Days Alteration to quantify and visualize differences between restoration options in Restoration Alternatives Assessment diagram. This concept of quantifying habitat models is supported by an example of application in the Wekepeke Brook in Massachusetts, in which the habitat metrics were used to define quantitative benchmarks, goals and targets to guide the restoration process from the design to the evaluation phase. The three habitat metrics are a cost effective alternative for evaluating the ecological benefits of a planned action. The methodology contributes to a high potential for designing and monitoring restoration projects. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS physical habitat models; restoration measures; UCUT; MesoHABSIM; effective planning; ecological evaluation; reference conditions; fish habitat

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INTRODUCTION

River restoration planning frequently lacks the identification of restoration endpoints consisting of quantitative descriptions of expected ecological benefits, habitat gains and numeric alternatives analysis. Therefore, many of such efforts happen without establishing benchmarks for successful evaluation (Lake, 2001). Ecological planning and validation are often conducted in a qualitative fashion (Toyne and Farley, 2000), while resources are dedicated towards construction, engineering and adaptive management without clearly quantified ecological outcomes (Lenzi, 2002; Zhao *et al*., 2012). Moreover, to perform Environmental Benefits Analysis (EBA, McKay *et al*., 2010), the evaluation techniques need to be quantitative in order to evaluate possible alternatives, define end states and report progress (Fischenich, 2008). Models and tools ought to be designed with emphasis on scientifically based metrics for the analysis of ecosystem restoration projects (e.g. quantifying suitable habitat for fish to evaluate environmental benefits of aquatic restoration actions, Killgore *et al*., 2008). Compared with other areas of construction engineering (e.g. road and bridge construction), this limited focus on quantitative planning stands out (Keddy, 1999; Lake, 2001). Lake (2001) highlighted the need for linking ecological research and restoration and reported how the poor design, the lack of satisfactory monitoring and the low spatial and temporal scale resolution constituted important limiting factors in the success of many restoration measures. A well-crafted restoration goal should identify the biological objective of restoration, address causes of habitat change, and ought to be linked to land use, economic and social objectives, although these objectives may constrain restoration options (Beechie *et al*., 2008). Wohl *et al*. (2005) suggest strategies in achieving the planned restoration objectives and, at the same time, address key limitations such as lack of scientific knowledge and poor institutional and political support; meanwhile, Woolsey *et al*. (2007) proposed guidelines and indicators related to both ecological attributes of rivers and socio-economic aspects in order to assess river restoration success. In any project, as outlined by Hobbs and Norton (1996), a considerable amount of reconnaissance and assessment needs to be carried out prior to initiating restoration measures. Toyne and Farley (2000) reported how restoration projects may not be successful without adequate consideration of design needs such as the gathering of historical data, the provision of control and/or reference sites and the setting of feasible goals. Without goal-oriented and quantitative performance measures,

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*Correspondence to: Piotr Parasiewicz, Rushing Rivers Institute, 592 Main Street, Amherst, MA 01002, USA. E-mail: piotr@rushingrivers.org

restoration activities can easily deteriorate into endless cycles of adaptive management with arbitrary endpoints and attendant scientific disagreement. This poor planning and the absence of clear objectives dramatically increase implementation costs and the risk of failure. Consequently, many restoration activities draw a wave of criticism, causing a backlash to the river restoration efforts (Bernhardt *et al.*, 2005). The USA alone is found to spend billions of dollars for carrying out river restoration measures based on loosely agreed-upon standards for ecologically successful restoration (Malakoff, 2004; Bernhardt *et al.*, 2005). Furthermore, as highlighted by Roni *et al.* (2002), planning is site-specific and not referred to in a watershed context. Projects that run on qualitative efforts rarely evaluate and assess restoration measures and techniques. They also focus mainly on the physical, hydrological and geomorphological response of the river, while lacking depth in assessing the biological (fish, invertebrates and other biota) area (Rosgen, 1997; Roni *et al.*, 2002; O'Hanley, 2011).

Palmer *et al.* (2005) argue the need for river restoration performance standards that require the following five criteria: (1) restoration follows a direction of a *leitbild* (i.e. guiding image), which identifies attributes of a future ecological state of a restored water body; (2) the ecosystem is improved; (3) the resilience has increased; (4) no impairments exist; and (5) the ecological post-restoration assessment has been completed.

A preliminary watershed assessment is essential in order to identify and understand restoration needs and reference conditions (both physical and biological) to be targeted during the planning phase and evaluated after the interventions (FAO, Food and Agricultural Commission – UN, 1998; Roni *et al.*, 2002). The efficiency of restoration planning is strictly related to a clear and quantitative definition of the reference conditions establishing: a baseline for determining the degree to which a given river deviates from optimal conditions, possible alternatives and the related objectives to be targeted when evaluating the restoration measures' success (Nestler *et al.*, 2010). The authors of this latter paper argue that river restoration planning not only requires the application of a reference river approach but also depends on quantitative rigour to evaluate alternatives. The authors develop a mathematical framework allowing numerical comparisons based on Euclidian distance between scenarios. The proposed quantitative method describes the state and dynamics of an ecosystem using two variables represented on a graph where, conventionally, low values of each variable indicate good conditions. Therefore, alternative ecosystem states can be evaluated by their closeness to the graph origin (no or low degradation) and by their relative distance on the graph (high distance means significant difference in state conditions). Ecosystem states can then be plotted on the graph, highlighting the distances and trajectories among pristine reference conditions, today's conditions and future conditions without restoration; the graph could also include potential alternative states that could be obtained by means of different restoration measures. Alternative restoration options can then be compared with reference, desired and best achievable states and the choice can be based on a cost/benefit analysis of various future state scenarios.

In their work (Nestler *et al.*, 2010) allow the users of the concept to use different metrics for the analysis. They demonstrated the utility of the concept by using the hydrology as one of five essential ecosystem characteristics established by Lubinski and Barko (2003) for the Mississippi River (the other characteristics included as follows: geomorphology, biogeochemical cycling, habitat and populations). These essential ecosystem characteristics were the basis of developing a template for analysing reference conditions. In this paper, we propose to use the dimension of habitat for the EBA as a more universal metric closely associated with biological response. This is mainly because of many rivers are affected not only by hydrological modifications but also by channel alterations; habitat time series take both into account allowing for comparisons across the rivers and project areas. We believe that the use of habitat metrics will define more stringent standards for definition of reference conditions. Defining reference conditions is a non-trivial issue; as demonstrated by Weber and Peter (2011), the choice of reference conditions and indicators influences the evaluation results and conclusions. This similarly goes along with the findings of Bernhardt *et al.* (2005), the objectives of restoration are not the same for each case. Hence, there is also a need for the standardization of the objectives of river restoration and consequently the applied performance metrics.

The goal of river restoration should be the improvement of the ecosystem (Palmer *et al.*, 2005). The performance of restoring a river ecosystem can be either measured by the status of the biota or by their habitat. The former is difficult to accomplish because of the following: (1) the time lag required for populations' recovery; (2) natural biological variability increasing uncertainty of monitoring observations; and (3) difficulties of biota observation because of their spatial and temporal mobility. Therefore, we postulate that the use of a spatial unit of physical habitat suitable for the desired aquatic community is a more pragmatic and accurate metric in describing current and expected states.

According to Hall *et al.* (1997), the habitat is defined as: 'the resources and conditions present in the area that produce occupancy – including survival and reproduction – by a given organism.' Because one of the primary purposes of river restoration is to secure such an environment or habitat, it is logical that the effort should be measured in the units of habitat rather than, for example, flow regime.

The process of habitat determination is based on a theory of biophysical templates (Poff and Ward, 1990; Townsend and Hildrew, 1994; Southwood, 1997) that assumes correspondence between the physical settings and the biological community structure. Such templates can be established using modern habitat models as discussed in Parasiewicz *et al.* (2011). Habitat suitability models (HSM), with their associated habitat suitability maps, are very useful and an increasingly popular tool in predicting the potential distribution of species in a river (Sillero, 2011). HSMs statistically relate environmental variables associated with the niche to field observations of the organisms. The result is the prediction of locations that have potential (suitability) for use by the targeted species (Hirzel *et al.*, 2006; Koehn, 2009). Application of HSM in simulation modelling (Parasiewicz and Dunbar, 2001; Tharme, 2003; Sillero, 2011), which quantitatively relates physical patterns (flow, geomorphology, chemical parameters, etc.) and biological response, offers a good foundation for the creation of mathematical models for reference rivers and for performance evaluation metrics.

This paper presents the concept of applying HSM for planning and evaluating river restoration and management scenarios. The products of application from the mesohabitat simulation (MesoHABSIM) model (Parasiewicz, 2007, 2007) are utilized to develop habitat evaluation metrics that can be incorporated into EBA as proposed by Nestler *et al.* (2010). In particular, we utilize the Virtual River concept (Parasiewicz *et al.*, 2011) and Euclidian distance analysis to compare habitat metrics for different scenarios and to identify best achievable and desired future conditions. The concept is demonstrated in the example of planned restoration and spring water withdrawals on the Wekepeke Brook in Massachusetts, USA.

THE CONCEPT

River restoration has been defined as a series of measures aimed at reducing or removing anthropogenic constraints on the development of natural patterns of biodiversity (Ebersole *et al.*, 1997; Nestler *et al.*, 2010). River restoration measures that can be adequately addressed by the methodology proposed here are those aiming to improve the habitat conditions by means of channel and/or discharge manipulations, as well as the improvement of habitat connectivity (e.g. nature-like fishways). We set the following as objectives: to increase the habitat quantity, improve habitat quantitative structure in order to correspond with targeted community structure and maintain temporal habitat patterns to avoid bottleneck situations *sensu* Bovee *et al.* (1998). Thereby, tasks are set to develop a habitat model of current and reference conditions and to identify metrics that will allow for performance evaluation for each of the aforementioned objectives.

River ecosystems are characterized by complex interactions between physical, chemical, and biological systems and natural processes, each operating at different characteristic spatial scales (reach to watershed) and frequencies (Nestler *et al.*, 2010; Wiley *et al.*, 2010). Nestler *et al.*, 2010 highlights five essential ecosystem characteristics of the reference ecosystem to be considered during restoration planning: hydrology and hydraulics, geomorphology, biogeochemistry, habitat and biota. The proposed habitat models, which are based on reference aquatic community structure and hydro-geomorphological features, can be considered the first building blocks of river restoration planning. Furthermore, the proposed methodology foresees the implementation of multivariate models that can incorporate in the analysis further elements of the aquatic interactions and processes (such as water quality, species interactions, seasonality, etc.) relating such patterns to the biological response of the expected or desired community. However, to investigate the broader picture, including natural and human processes at different scales and under different scenarios, the habitat models can then be used as an element of integrated multimodels (Wiley *et al.*, 2010). This can help in identifying further restoration measures to be carried out at watershed level. Furthermore, processes at wider spatial and temporal scale can then be evaluated over time within the monitoring and assessment phase of the restoration measures (Nestler *et al.*, 2010). In its simplest form, the reference river habitat template needs to consist of three key components: (1) reference aquatic community structure; (2) reference hydro-geomorphology; and (3) reference flow patterns. Such a template could be obtained by measurements of unimpacted river ecosystems and transferred to the river under investigation. Unfortunately, such situations are fairly rare, and there is a need for models that will recreate and define such conditions virtually. To create such virtual models, these components should be integrated into comparable habitat metrics that capture the habitat quantity, the habitat structure and the temporal patterns. The habitat quantity is the spatial amount of suitable habitat in relation to flow quantity. The metric proposed here is the habitat versus flow rating curve. This answers the question, ‘how much habitat should be available in the river for targeted fauna under reference conditions?’ Habitat structure describes the relative quantity of suitable habitat available for different members of the community. Determining habitat structure allows us to understand whether or not the current habitat distribution in the river supports the natural fish (or invertebrate) assemblage. The metric of habitat structure compares the reference aquatic community structure to the habitat structure. Lastly, the temporal pattern is described by the habitat time series, which indicate the availability of habitat at any given moment in time. Habitat time series are used to identify different events and specifically the times when habitat bottlenecks create stress to the fauna. The continuous duration of the bottleneck events is a proposed metric of habitat temporal patterns.

As recommended in Parasiewicz (2007b), the starting point in establishing reference habitat is the identification of a reference biological structure (i.e. quantitative composition of natural fish or invertebrate community), followed by the determination of hydro-geomorphic needs of all species. Our approach contrasts here with the typically used method of beginning with the physical habitat template; rather, we use the biological template as a starting point for developing the physical template. Habitat models use this information to quantify the amount of suitable habitats. This allows in turn an adjustment of physical attributes of a stream or river to create a hydro-geomorphic structure that matches the biological structure. Here, we can utilize the assumed compatibility of two templates in order to fill missing information gaps on both parts through adjustments. Because the amount of water in rivers (i.e. flow) is a primary factor influencing habitat availability, this relation is captured with help of flow-habitat rating curves. The rating curves are used to convert reference flow time series into habitat time series, which are analysed using the Uniform Continuous Under Threshold (UCUT) analysis to recognize Habitat Stressor Thresholds (HSTs) in terms of habitat magnitude, frequency and duration of habitat events as described in Parasiewicz (2007b). For each of the thresholds, we can calculate the typical number of habitat stress days that occur under those desired conditions and use it as a benchmark for comparative analysis. In the succeeding text, we describe the steps of this process in more detail.

Defining reference aquatic community structure

We first select seasonal assemblages of habitat indicators that will help to guide the assessment and restoration process. This can be fish, invertebrates, life stages, species groups, guilds or entire communities. The most comprehensive method is to establish a model of an expected or desired community consisting of a species list that includes the proportions of each species in the community (Target Fish Community by Bain and Meixler, 2000). The essence of the approach is to analyse historical fisheries data from a number of similar low impact rivers and compute expected proportions of species in the community (Parasiewicz, 2008; Pini Prato *et al.*, 2011). Another option for indicator species selection is to divide community into habitat-use guilds and select one or more species as guild representatives. The community composition will vary between bioperiods, especially in rivers with high levels of seasonal migration (Parasiewicz, 2007b; Parasiewicz *et al.*, in press). On this foundation, it is possible to identify the assemblages of mesohabitat types utilized by the species or guilds and potentially define the next level of habitat-based groupings.

Defining reference hydro-geomorphology

The next step in the planning process is to establish the target habitat state as a feasible quantitative restoration endpoint. For this purpose, the habitat evaluation process consists of (1) developing suitability criteria for the selected target community; (2) mapping the instream habitat conditions; and (3) adjusting biophysical templates to reflect reference hydro-geomorphological characteristics.

Habitat suitability criteria are developed to identify the combination of physical attributes that are correlated with the species' presence or abundance in the river. As described in Parasiewicz (2001, 2007a), the associations of mesohabitat descriptors (e.g. cover type and presence of shelters, water depth and flow velocity distribution, substrate composition, etc.) with the selected organisms are explored using probabilistic models. The most universal criteria can be developed using empirical data collected on one or more rivers, in which Hydromorphologic Units (HMUs) are sampled for fish using the methodology described by Parasiewicz (2007a) and Vezza *et al.* (2011). The obtained data serve as a basis for the calculation of multivariate models, most commonly using the Akaike Information Criterion (Sakamoto, 1991) along with logistic regressions (Hosmer and Lemeshow, 2000). Where detailed empirical data are not available, the habitat suitability information is obtained from literature studies to specify the species habitat requirements (i.e. range of velocities, depth and substrate as well as mesohabitat types and cover attributes).

The instream habitat description is performed at representative sites in order to capture conditions in the whole river with reasonable effort. The habitat description determines spatial proportions of HMUs along the river segment (see Parasiewicz, 2001 for details). The habitat descriptors collected during the habitat survey are reported in Parasiewicz (2007a). The survey is normally repeated a number of times over a selected range of discharges in order to describe the changes in habitat characteristics with flow (see Parasiewicz (2007a) for details). The amplitude of this range depends on the study objectives. However, as a general rule, the investigated range of habitat conditions is related to the key bioperiods for the considered reference community (e.g. rearing and growth stage or migration and spawning period of fish, *sensu* Parasiewicz, 2008).

With the help of the established suitability criteria, each surveyed HMU is evaluated to determine if it offers unsuitable, suitable or optimal habitat for the reference community at every surveyed flow. In particular, a probability threshold is set for a habitat evaluation using the receiver operating characteristic curves (Pearce and Ferrier, 2000) and provides the HMU classification into suitability categories (Parasiewicz, 2007a). The area of HMUs with suitable (or optimal) habitats is summarized for every site and plotted against a constant unit of area such as, the wetted area (WA) at the highest measured flow or the channel area of the site. The rating curves for each representative site are generalized by a length-weighted sum to represent river segments, defined as a portion of the river where a specific structure of the reference community would be expected. In addition to curves for individual species, rating curves for community habitat or generic fish are calculated (Parasiewicz, 2007a). The rating curve for community habitat is constructed by weighing the suitable habitat area of each species by its expected proportion in the community, whereas the generic fish habitat represents the total amount of habitat area that is suitable for any of the species in the investigated community. Those curves represent habitat conditions under current hydromorphology.

Defining reference hydro-geomorphology can be best accomplished with the help of iterative simulation of potential alternatives. As described in Parasiewicz (2007b), the simplest approach is to begin with the simulation of removing the most obvious human interferences, such as impoundments and dams or restoring the connectivity based on historic data and aerial imagery. A more effective approach is to directly investigate habitat needs of indicator species. It begins with comparing expected and current fish community and existing habitat structure and the identification of species that either lack or have a surplus in available habitat. In the subsequent step, we investigate the habitat suitability criteria as well as compare attributes in HMUs that were predicted to be suitable and not suitable for the species. The purpose of this screening is to isolate physical factors, which, if modified, would change the habitat structure to better support the expected community. These modifications can for example include change in the area of specific HMUs, adding woody debris, boulders and so on. The simulation is conducted in an iterative process, where we modify identified attributes from the database one at a time and then recalculate the model and test its sensitivity to the change. Finally, the model is created that offers the greatest gains in community habitat representing the reference or the Best Achievable Conditions (BAC).

Defining reference flow patterns

In the case where reference flow pattern conditions are unavailable, the recorded flow time series should be modelled. One option is to adjust available historical flow records even if they represent impacted situations. In the course of MesoHABSIM studies, we used two hydrologic models to calculate the reference flow time series. They are the QPPQ-transform method and Precipitation Runoff Modeling System (Leavesley *et al*., 1983; Fennessey and Vogel, 1990; Fennessey, 1994). Both models require a historical flow time series. The QPPQ method transfers the information from a nearby reference gauge (Q) using the probability of exceedence (P) from the flow duration curve. The assumption is made that this probability of exceeding a flow at the gaged site is equivalent to the probability of exceeding a flow at the ungaged site (P). Lastly, the equivalent exceedence probabilities and basin characteristics from the ungaged site are used to estimate streamflow (Q). Precipitation Runoff Modeling System (similar to HEC-HMS, HEC Hydrologic Engineering Center, 2001) is a parameterized geographic information system model in which all the watershed attributes are assigned equation parameters, which are adjusted in the model calibration process. These models have the ability to predict flow time series for future scenarios, such as build-out of the watershed or climate change. Another possibility is to apply the map-correlation method as described by Archfield and Vogel (2010).

The reference flow time series and reference habitat structure are used to develop a reference habitat time series, which describe the expected amount of habitat under reference conditions. The habitat time series are investigated with the help of UCUT curves to establish natural HST (more detail in Parasiewicz, 2007b). The purpose of this analysis is to investigate habitat duration patterns and to identify conditions that could create pulse stressor and press disturbances as described by Niemi *et al*. (1990). A *pulse stressor* is an instantaneous alteration in fish densities, whereas a *press disturbance* causes a sustained alteration of species composition. In the habitat analysis, these can be caused either by extreme habitat deficiency regardless of duration or by catastrophically long duration of events with habitat availability critically low. Therefore, to identify HST, we need to take into account habitat magnitude, as well as duration and frequency of non-exceedance events.

As documented by Capra *et al*. (1995), the UCUT curves are a good tool to predict impact of frequency and duration on biological conditions, as they evaluate the duration and frequency of continuous non-exceedance events for different habitat magnitudes. Once the curves are developed, rapid changes in frequency pattern are used to identify the HST for *rare* and *common* events together with their durations. *Rare* habitat events happen infrequently or for only a short period. *Common* habitat events demarcate the beginning of normal circumstances from uncommon events.

Because the HST captures rare and common habitat deficits together with their durations, the method specifies two duration thresholds: persistent and catastrophic, both based on the frequency of occurrence. Exceedance of those durations causes Habitat Stress Days (HSD). The cumulative frequency of events that are longer than the HST threshold value captures natural limitations shaping the aquatic community. Human interference often increases frequency of such events, ergo the number of HSD. The HSTs are most frequently used to develop criteria for ecological flow management, through calculation of the amount of flow associated with each of the thresholds. In particular, subsistence and base flows are defined as those corresponding with rare and common HST, respectively. Hence, the criteria include the subsistence and base flows, as well as durations of persistent and catastrophic events and are used for the development of flow pulsing strategies as described in Parasiewicz (2008).

Metrics

The model constructed as earlier allows developing universal performance metrics that can be used for the purpose of evaluation of habitat restoration objectives and can be incorporated in the concept presented in Nestler *et al.* (2010, Figure 1). We propose the following three metrics: Habitat Quantity Reduction (HQR), Alteration of Habitat Structure (AHS) and Habitat Stress Days Alteration (HSDA).

HQR. The overall habitat quantity for the aquatic community is captured by rating curves for the generic fish habitat. It ranges from no habitat to 100% of WA that is suitable habitat for any member of the aquatic community. We can assume that under natural conditions, most of the WA is used by the fauna, while human alteration reduces the suitable portion of the area. The restoration objective evaluated by the metric is to maximize the suitable area. The difference between two areas is captured by the differences in the areas under the

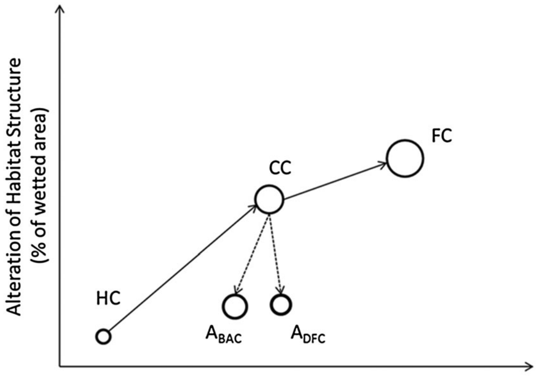

Figure 1. The concept of a RAA diagram. The metrics HSDA and AHS create the axes of the plot. The HQR is represented by the size of the circle.

rating curves (Figure 2). Therefore, we propose to use the integral difference between the two curves as a performance metric HQR.

AHS. The second metric of describing habitat structure is to determine the difference between the quantitative distribution of suitable habitat and suitable habitat expected under reference conditions. The objective here is to minimize the difference between the two distributions. As a surrogate of reference habitat structure, we can use the expected aquatic community structure, assuming that in natural systems the most common species will use the most suitable habitat and the least common will use only small areas. We propose to utilize the affinity index model, as described by Bain and Meixler (2000), which shows the proportion of affinity between two distributions according to the formula: $1 - 0{\cdot}5\ \sum|\mathrm{Pi} - \mathrm{Pj}|$, where Pi and Pj represent proportions in one category for each distribution. Because the subtracted value actually quantifies the dissimilarity of both distributions, it can be used as a basis for the performance metric AHS, with the restoration goal of reducing this value. Because the AHS can be change with flows, we propose to use the average value as a restoration performance metric.

HSDA. The third metric should capture temporal patterns of habitat. The HSD offers itself here as an appropriate measure. It can be obtained by overlaying threshold UCUT curves for reference and various alternatives (Figure 3). Typically, the HSD is calculated for four threshold values: rare-persistent, rare-catastrophic, common-persistent and common-catastrophic, and we propose to use the average of the four HSDA values as a restoration performance metric. Once again, the objective is to reduce the number of stress days to the level of reference.

The application of the three metrics in the context of performance evaluation described by Nestler *et al.* (2010) is proposed as a Restoration Alternatives Assessment (RAA) diagram that is presented in Figure 1.

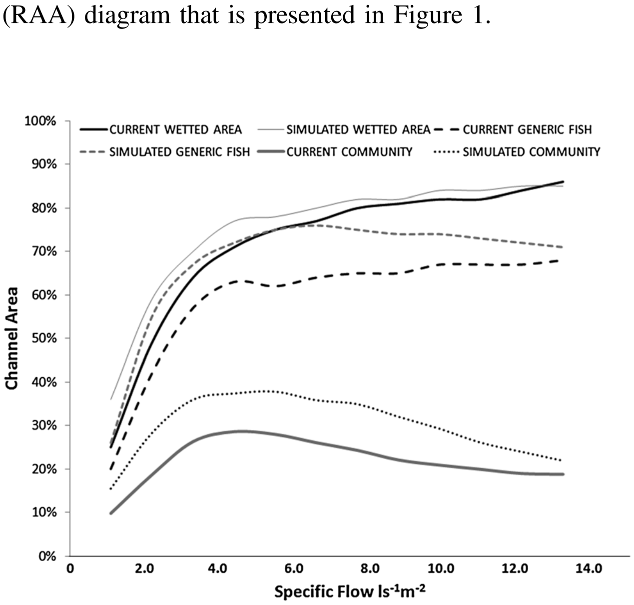

Figure 2. Comparing wetted area and effective habitat for current and $\mathrm{BAC_M}$ conditions.

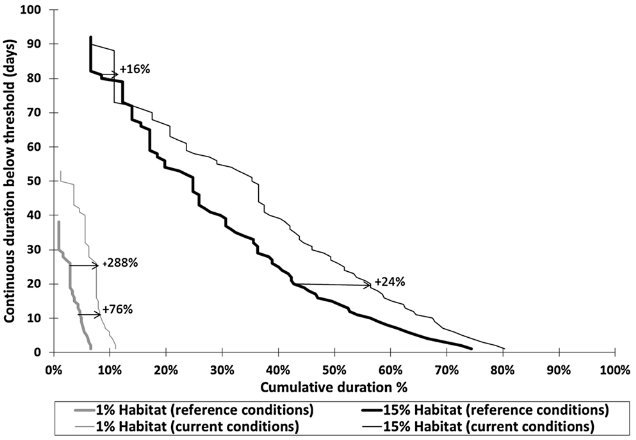

Figure 3. UCUT curves for fish community at rare and common habitat levels on the Wekepeke Brook under reference and current conditions. The arrows indicate the increase of Habitat Stress Days duration and the accompanying numbers the increase in relation to the reference duration.

CASE STUDY EXAMPLE

Methods

The 8·2 km-long Wekepeke Brook is a headwater stream in Central Massachusetts and was the site for an ecological offset study in compensating for spring water withdrawals (Figure 4). The study area of 3·4 km focused on the Brook's uppermost portion with the watershed area of approximately 7·8 km^2. The average width of the Brook is about 5 m. Although the area was dominated by forest, it is crossed by two secondary roads, some adjacent house lots and areas of agricultural land. Five reservoirs feed the upper watershed through a network of small streams and connected wetlands.

The study conducted on the Wekepeke Brook primarily researched the effects of stream flow alterations on fish habitat and abundance. The species diversity and population size of the Brook's fish were surveyed and compared with reference Target Fish Community models – part of developing performance metrics in habitat restoration. Mesohabitat distribution was surveyed three times during the 2008 field season in order to determine the spatial proportions of mesohabitat units within each section of the study area. For each HMU, the location and size was determined with GPS and ArcPad software in conjunction with aerial photographs, creating a detailed map of selected sites on the Brook. Within each HMU, mean column velocity, depth and estimated substrate were measured in at least seven stratified random locations. Each of the three surveys had specific targeted flows; these included 6 $\mathrm{l\,s^{-1}\,km^{-2}}$ on 4–6 August, 2 $\mathrm{l\,s^{-1}\,km^{-2}}$ on 26–27 August and 11 $\mathrm{l\,s^{-1}\,km^{-2}}$ on 19–21 November 2008.

A Target Fish Community model was created for the Wekepeke Brook and was used to determine the expected structure of natural fish assemblage. Five most dominant fish species [common shiner (*Luxilus cornutus*), common white sucker (*Catostomus commersoni*), longnose dace (*Rhinichthys cataractae*), blacknose dace (*Rhinichthys atratulus*) and brook trout (*Salvelinus fontinalis*)] were selected as indicators of ecosystem integrity.

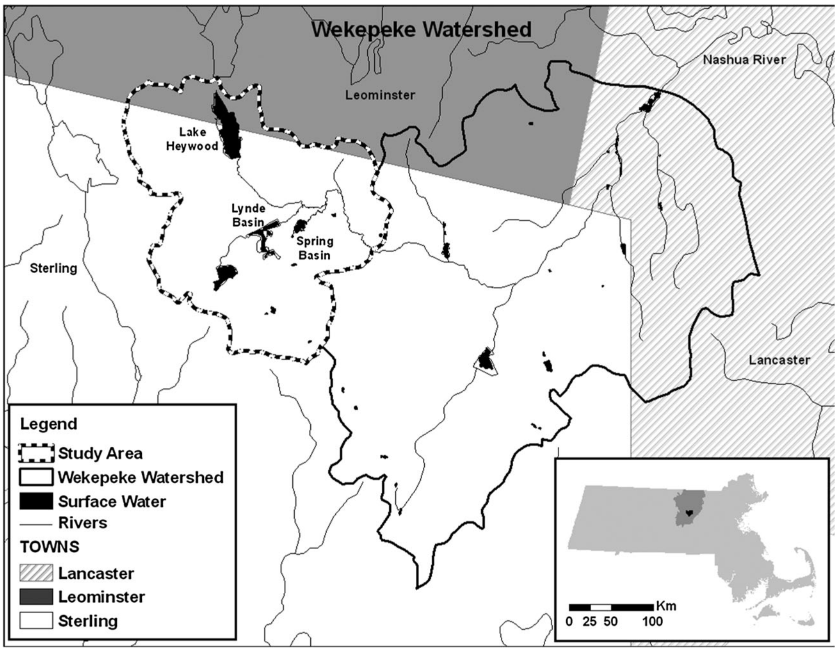

Figure 4. Map of the Wekepeke Watershed (outlined) and study subwatershed (dashed) showing remnant impoundments from earlier waterworks infrastructure.

Habitat suitability criteria (summer months) were established based on empirical data collected previously on 15 rivers in the Northeastern USA by Rushing Rivers. A logistic regression model was employed to identify the characteristics of habitat occupied, versus unused habitat, for each fish species. The probability of presence and abundance for each species was used as criteria to distinguish and calculate non-suitable, suitable and optimal habitat (Table I). The model was then applied to the data from the mapping survey, to calculate habitat/flow rating curves for species, generic fish and community habitat.

Habitat deficit analysis was conducted by comparing the structure of the expected and the current fish communities with the habitat structure. This allowed for identifying the species that lack habitat or have unlimited supplies of habitat in ultimately understanding the structure of fish assemblages. The suitability models for these species as well as contrasting the characteristics of identified suitable and not suitable HMUs allowed us to identify the measures that could lead to the creation of the best achievable condition scenarios. Six different simulations were carried out in an iterative process using different quantities of HMU's, choritopes, and attributes to modify the fish habitats. One of the six scenarios was selected to be morphologically the Best Attainable Condition ($\mathrm{BAC_M}$). In other words, the selected scenario would represent the best conditions that can be achieved under current and future land use patterns purely through morphological improvements.

The flow time series and flow duration curves were developed from the QPPQ method. United States Geological Survey stream gauges within 80 km and with watershed areas less than $250\,\mathrm{km}^2$ were identified as surrogates. Those gauges currently in operation and with none to very little impounded area were then selected for further analysis, yielding eight possible gauges. Concurrent flows at the Wekepeke site were then measured by field methods. These concurrent flows, as well as the data from stream gauges, were divided by the watershed areas in order to directly compare flow per unit area between gauges. The Nashoba River gauge (watershed area $33{\cdot}2\,\mathrm{km}^2$) was the better fit to the concurrent flow data. The Nashoba River time series and flow duration curve was then translated to that of the Wekepeke Brook by using the regression equation of the concurrent flows.

The UCUT analysis was used next to determine the duration of HSD for BAC. Subsequently, the HSD was calculated for another five scenarios and related to HDS of the $\mathrm{BAC_M}$. Each of the scenarios represented an option for management in the Wekepeke Brook. Table II includes the description of each scenario. Two flow management scenarios did not include habitat improvements such as in $\mathrm{BAC_M}$, but four scenarios did.

Lastly, we calculated HQR, AHS and HSDA metrics for each of the scenarios and plotted them on the RAA diagram. For the purpose of demonstration in this paper, we also made an estimate with regard to the metrics for historical conditions.

Results

Figure 5 presents the comparison of expected Target Fish Community and observed Existing Fish Community structure with habitat structure currently found in the Wekepeke Brook. The diagram indicated underabundance and overabundance of brook trout and blacknose dace, respectively. Similarly, the hydromorphologic habitat for brook trout is under-represented and is overly abundant for blacknose dace. A large proportion of habitat for longnose dace also exists; however, it is not reflected in the fish numbers. Common shiner was not captured despite habitat availability. These results necessitated morphological improvement objectives, such as an increase of habitat

Table I. Example of the habitat suitability criteria for brook trout presence and abundance models used in the Wekepeke Brook project.

Brook trout presence		SE	Brook trout abundance		SE
Calibration success	0·875		Calibration success	0·815	
Estimated success	0·840		Estimated success	0·600	
Area under ROC	0·851		Area under ROC	0·840	
Cut-off	0·28		Cut-off	0·32	
Attribute	B	SE	Attribute	B	SE
Constant	−4·908	0·672	Constant	−1·235	0·350
Boulders	0·221	0·110	Undercut banks	0·568	0·224
Riprap	−0·523	0·190	Shallow margins	−0·588	0·207
Overhanging vegetation	−0·417	0·134	Depth 50–75 cm	1·639	0·999
Submerged vegetation	0·537	0·142	Depth 75–100 cm	−10·566	5·309
Canopy shading	0·392	0·118	Depth 100–125 cm	58·199	23·714
Undercut banks	0·283	0·132	Velocity 60–75 cm s^{-1}	−3·808	2·475
Woody debris	−0·306	0·126	Velocity 90-105 cm s^{-1}	−39·246	24·258
Shallow margins	0·258	0·107	Velocity > 105	16·136	8·061
CASCADE	−1·132	0·665	MACROLITHAL	1·765	0·580
PLUNGEPOOL	2·343	0·880			
POOL	0·958	0·310			
RAPIDS	−0·966	0·469			
RUFFLE	−0·439	0·293			
SIDEARM	0·798	0·478			
Depth < 25 cm	2·231	0·541			
Depth 25–50 cm	1·433	0·598			
Depth100–125 cm	2·928	1·904			
Velocity < 15 cm s^{-1}	1·514	0·456			
Velocity 15–30 cm s^{-1}	1·830	0·488			
Velocity 45–60 cm s^{-1}	1·420	0·764			
Velocity 75–90 cm s^{-1}	−4·087	2·326			
AKAL	−5·953	1·820			
MICROLITHAL	−1·191	0·485			
PELAL	−5·637	2·605			
PSAMMAL	−3·979	1·078			

B represents regression coefficient. For better explanation of the criteria, see Parasiewicz (2007a).
SE, standard error; ROC, receiver operating characteristics.

Table II. Habitat modifications introduced in each simulation iteration.

	Habitat modifications	
	Increase	Reduce
Simulation 1	**pools**, **riffles**, **runs**, undercut banks, shallow margins, submerged vegetation, **mesolithal**, **phytal**	**ruffles and rapids**, **psammal and akal**
Simulation 2	**pools**, **riffles**, **runs**	**ruffles and rapids**
Simulation 3	**pools**, **riffles**, **runs**, **undercut banks**, **shallow margins**, submerged vegetation, **mesolithal**, **phytal**	**ruffles and rapids**, **psammal and akal**
Simulation 4	(None)	**impounded areas (Lynde Basin)**
Simulation 5	**pools**, **riffles**, **runs**, **undercut banks**, **shallow margins**, submerged vegetation, **mesolithal**, **phytal**	**ruffles and rapids**, **psammal and akal**, **impounded areas (Lynde Basin)**
Simulation 6 ($\mathrm{BAC_M}$)	**pools**, **riffles**, **runs**, **undercut banks**, **shallow margins**, submerged vegetation, **mesolithal**, **phytal**	**ruffles and rapids**, **psammal and akal**, **impounded areas (Lynde Basin)**

Text in bold indicates strong changes were made to the model inputs.

for brook trout and the reduction of blacknose dace habitats. Table II presents the morphological modifications included in each of the simulations aiming to establish $\mathrm{BAC_M}$.

Scenario $\mathrm{BAC_M}$ accomplished the key recommended objective by increasing habitat for book trout and increasing the habitat for blacknose dace as presented in Figure 6 and a change in average Affinity Index from 57 to 76%. Figure 2 presents the comparison of the rating curves for suitable community and generic fish habitat for current conditions and $\mathrm{BAC_M}$ scenario. The generic fish and community habitat rating curves increased substantially. The HQR for current and $\mathrm{BAC_M}$ was 17 and 10% of WA, respectively, and AHS for current and $\mathrm{BAC_M}$ was 43 and 24% of WA, respectively.

The visual inspection of UCUT curves pattern selected 1% of channel area and 15% of channel area as a rare and

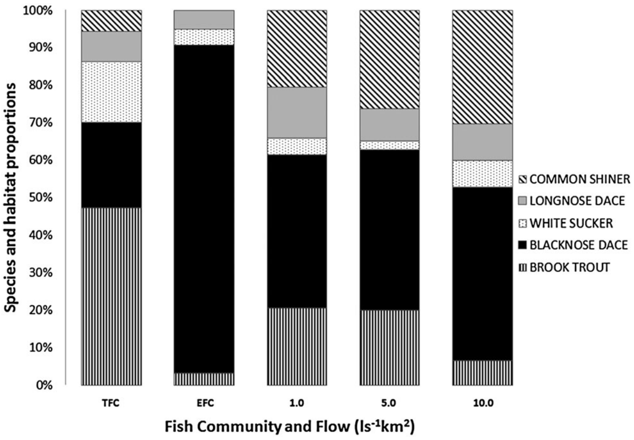

Figure 5. Comparing the structure of the TFC with the habitat structure occurring at selected flows. TFC and EFC refer to the species' proportion in the community. The other three bars indicate proportion of habitat available for this species at three selected flows.

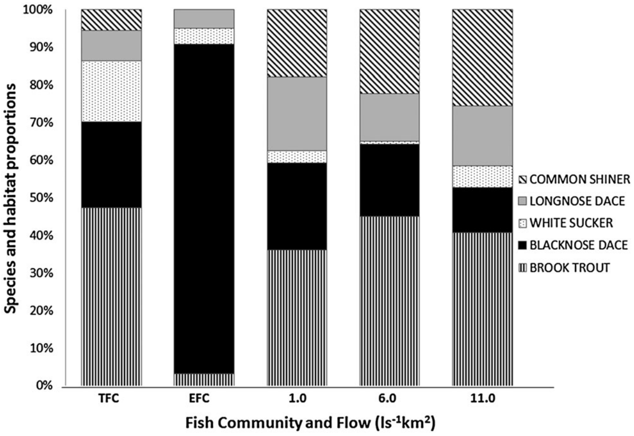

Figure 6. Comparing the structure of the TFC with the habitat structure occurring at selected flows under BAC_M scenario. TFC and EFC refer to the species' proportion in the community. The other three bars indicate proportion of habitat available for this species at three selected flows.

common HST, respectively; persistent durations were between 13 and 21 days and catastrophic durations were between 28 and 82 days for rare and common HST, respectively (Figure 3). Table III presents the HSDA for all described scenarios for each of the thresholds and the average. For the purpose of creating the RAA diagram, we estimated historical conditions as having HSDA close to the alternative with improved habitat and dynamic flow augmentation scenario of 20%, HQR of 5% and AHS of 20%. Figure 7 presents all three metrics in the RAA diagram. Most of the alternatives that use habitat improvements and flow mitigation create conditions closer to the historical than BAC_M showing the importance of flow augmentation even if some water will be withdrawn. The greatest reduction of HSDA and AHS is accomplished by the Alteration of Habitat Structure, followed by alternative with improved habitat and dynamic flow augmentation. The minimum flow alternative, alternative with improved habitat and minimum flow limit, offers conditions only slightly better than BAC_M. The worse alternatives are those allowing for temporarily unlimited withdrawals.

Table III. Summary for HSDA calculated for current conditions and the simulated scenarios.

	Habitat stress days alteration (% stress days)		
Location type	Persistent	Catastrophic	Average
CC: Current condition			
Common events	116	124	
Rare events	176	388	201
Future conditions: 6 l s^{-1} km^2 withdrawal			
Common events	129	160	
Rare events	243	525	264
A_M: improved habitat and 6 l s^{-1} km^2 withdrawal			
Common events	127	122	
Rare events	202	456	227
A_{MminF}: improved habitat, minimum flow			
Common events	127	122	
Rare events	61	56	91
A_{MSA}: improved habitat, static augmentation			
Common events	29	0	
Rare events	0	0	7
A_{MDA}: improved habitat, dynamic augmentation			
Common events	99	0	
Rare events	36	0	22
A_{DA}: current habitat, dynamic augmentation			
Common events	98	0	
Rare events	86	0	46

The numbers indicate the increase in stress from reference conditions in each scenario.
HSDA, habitat stress days alteration.

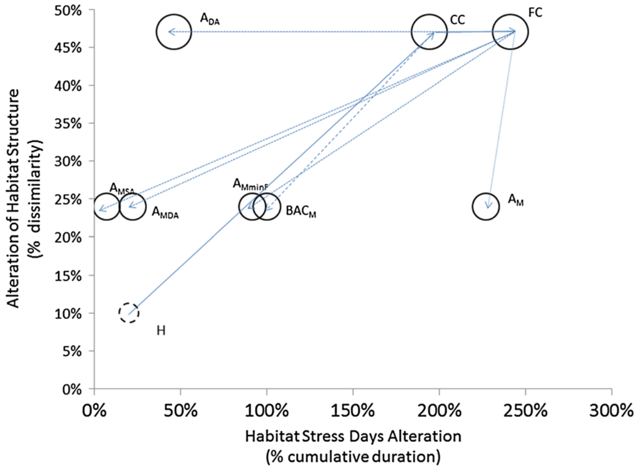

Figure 7. RAA diagram for the Wekepeke restoration project.

DISCUSSION

River restoration measures, even if focused on a short river reach, need to be placed within a watershed context for a better understanding of the natural processes characterizing the watercourse and of the human activities affecting its state (Roni *et al*., 2002). Furthermore, a proper watershed assessment is needed in order to identify the reference hydro-geomorphology and flow patterns together with the reference aquatic community structure. Thus, such physical and biological elements must be assessed during the planning phase (Hobbs and Norton, 1996) as a quantitative template for targeting the restoration needs, and in a post-restoration phase for evaluating the efficiency of the interventions carried out (Keddy, 1999; Lake, 2001).

The methodological approach proposed in this paper, based on the MesoHABSIM technique and Euclidian distance between habitat metrics, overcomes the usual shortcomings of the river restoration planning (as reported in Toyne and Farley, 2000), and can be incorporated in the concept presented in Nestler *et al.* (2010). The methodology relates the measured physical attributes of a stream with the sampled aquatic community structure through habitat suitability models. This approach provides decision makers with a quantitative framework for evaluating alternative scenarios and assessing restoration measures results.

The three metrics presented here (HQR, AHS and HSDA) take into account the habitat magnitude, its quality (i.e. structure) as well as frequency and duration of habitat bottle-necks; all expected to have direct influence on the condition of aquatic community. Use of MesoHABSIM model for this purpose is not necessarily a precondition of this application as any habitat model can be utilized for this purpose. However, MesoHABSIM allows performing the analysis in the watershed context. The model has been already applied on various river types (small and large) with small modification of sampling strategies and was proven robust and quite universal (Parasiewicz *et al.*, In press).

The utility of this concept is demonstrated in the example of an alternative analysis for spring water withdrawals from Wekepeke Brook. As the habitat study has documented, the Wekepeke Brook's study area is in need of morphological improvements in order to reduce the shifts in the native fauna compositions caused by human activities. Spring water withdrawals would create an opportunity to also augment the flows in the brook to reduce the temporal habitat deficits. The Euclidian distance analysis documents that implementation of both measures would offer conditions closer to the historical state than morphological improvements alone. Furthermore, the flow augmentation goes far beyond the BAC_M in reduction of stress days.

The purpose of intensive ecological planning is to reduce uncertainty about the outcomes of proposed actions and to reduce the costs of river restoration. Predictive habitat models are ideally suited for this purpose. The modern methods overcome the earlier limitations of these tools and are applicable to the variety of scales that concern the cumulative effects of human actions on entire river lengths and watersheds. Although they do not capture the full complexity of aquatic interactions (biological and chemical), they are the first and critical building blocks of river restoration planning. To investigate the broader picture, habitat models can be used as an element of multimodels as proposed by Wiley *et al.* (2010).

The restoration success is also related to the selection of appropriate physical and biological reference indicators, which can be easily monitored, including the relative low cost and the ease of sampling and processing (Keddy, 1999). However, as reported by Bernhardt *et al.* (2005), it is a common practice for the ecological success of river restoration to not be evaluated in the post-restoration phase. Hence, the results of river restoration are frequently unknown. The tools described earlier can also be used for the validation of planned improvements in terms of physical habitat and the results can then be compared with benchmarks of reference habitat metrics. This approach is less costly than the evaluation through biological observations, which are strongly affected by variability and species mobility. It also allows for conducting the evaluation process within shorter periods because there is no need to wait for the biological communities to adjust to the new circumstances.

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