6 Applications of the MesoHABSIM Simulation Model

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6.1 Introduction

The MesoHABSIM approach is a physical habitat modeling system created for the purpose of instream habitat management in applications such as hydro-power and water withdrawals mitigation, as well as river channel restoration planning. It has been developed and tested between 2000 and 2010 at Cornell University, the University of Massachusetts and the Rushing Rivers Institute. The first concept of the model was published in Parasiewicz (2001). The latest description of the method was presented through a series of papers in 2007 and 2008, which established a procedural benchmark of the model (Parasiewicz, 2007a; 2007b; 2008a; 2008b). The MesoHABSIM approach has been applied in over 30 rivers and the methodology has been refined and adapted to the particular circumstances of each project. The current software implementation of MesoHABSIM (Sim-Stream) includes a number of tools facilitating the interpretation and presentation of the results for use in regulatory environments. The purpose of this chapter is to present the current state of the methodology as well as to demonstrate the utility of the model in different environments and for varied applications. We provide a short description of key methodological steps and discuss variations that can be supported with examples of their application. For details of each methodological step, the reader should refer to Parasiewicz (2001; 2007a; 2007b; 2008a; 2008b).

6.2 Model summary

The process of model development consists of the following ~~steps~~:

1 Identifying biological targets and indicators.
2 Establishing habitat suitability criteria.
3 Mapping and developing an evaluation of instream habitats.
4 Adjusting biophysical templates to reflect reference habitat.
5 Time series analysis.
6 Interpretation and application.

Mesohabitat types are defined by hydromorphological units (HMUs), such as pools and rapids. Mesohabitats are mapped under multiple flow conditions at chosen representative sites along the river. The sites and their

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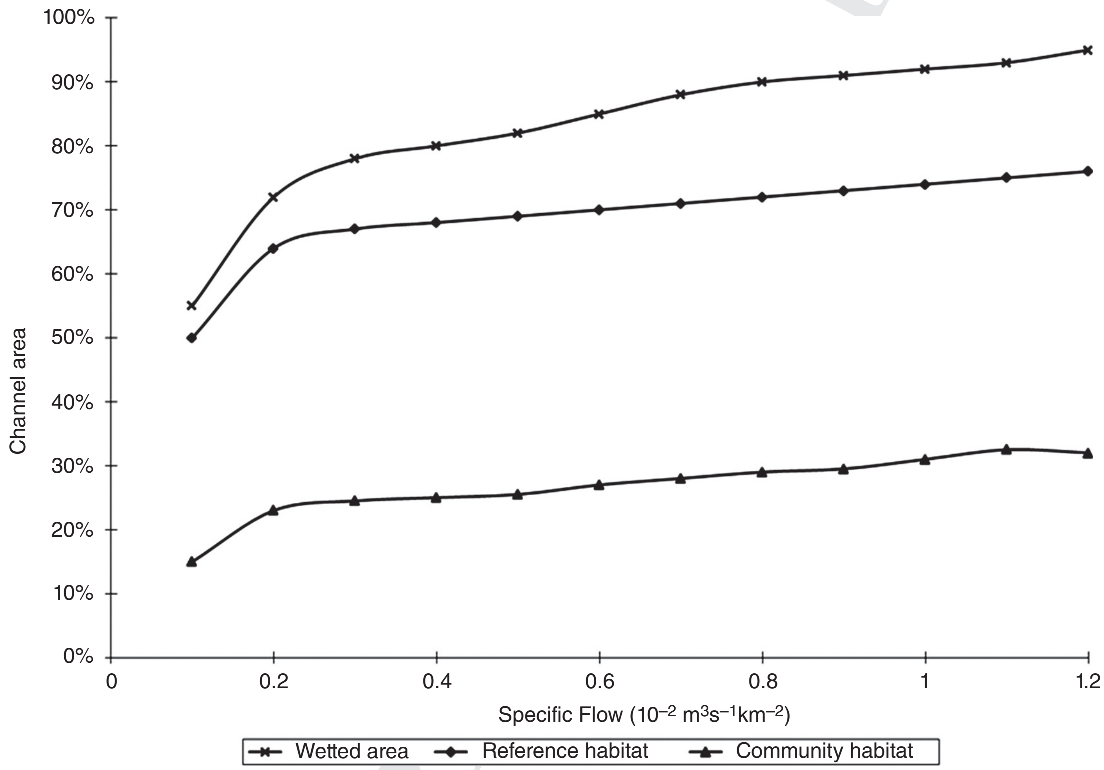

Figure 6.1 An example of habitat rating curves for generic fish representing the entire amount of suitable habitat and for community habitat, which is a sum of habitat for individual species weighted by their expected proportions in the community. The flows (*x*-axis) are standardized to the watershed area. The suitable habitat at reference conditions, expressed as proportion of river channel area (*y*-axis), is available across most of the wetted area, however the community habitat is much lower, indicating that more habitat is available to less common species.

quantitative representativeness are defined during an extensive reconnaissance phase. Fish and/or invertebrate data are collected in randomly distributed mesohabitats where habitat surveys are also conducted. These data are used for developing mathematical models that describe which mesohabitats are used by animals more frequently and hence are assumed to be more or less suitable. This allows the evaluation of habitat availability at a range of flows using suitable area as a metric.

Habitat rating curves represent changes in the area of suitable habitat for species and communities in response to flow and allow for the determination of habitat quantity at any given flow within the range of surveyed discharges (Figure 6.1). These rating curves can be developed for river units of any size, making them useful for drawing conclusions about the suitability of channel patterns or habitat structures for specific river sections as well as for the entire river.

In combination with hydrologic time series data, habitat rating curves are used to create Uniform Continuous-Under-Threshold (UCUT) curves for the analysis of frequency, magnitude and duration of significant habitat events (Figure 6.2). UCUT curves evaluate continuous durations of events when available habitat is less than a specified quantity and help to select probabilistic thresholds from the frequency of these events. UCUT curves serve as a basis for the development of ACTograms, which managers can use to determine habitat bottlenecks (Bovee *et al.*, 1998) (Figure 6.3). These ~~steps~~ are described in more detail below.

6.2.1 Identifying biological targets and indicators

In this step, we define the aquatic resource elements for which the model will be developed. We select seasonal assemblages of these resources as indicators of habitat

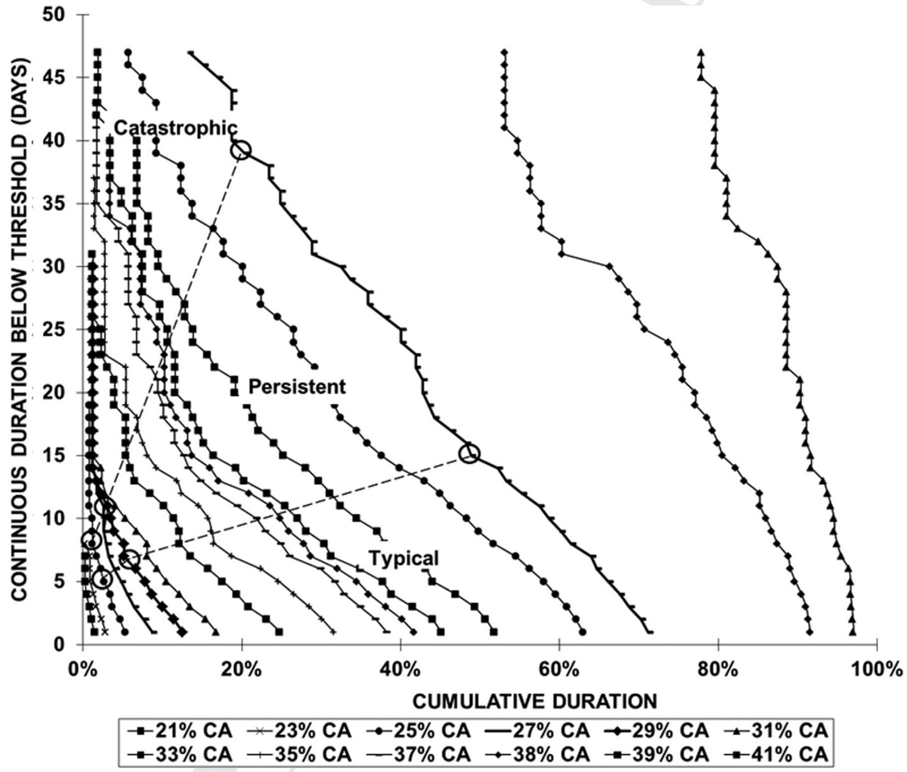

Figure 6.2 An example of Uniform Continuous Under-Threshold curves for determination of HSTs. Each curve on the diagram represents the cumulative duration of events when habitat is lower than a threshold (*x*-axis) for a continuous duration of days depicted on the *y*-axis. The reduction in slope as well as the increase of spacing between two curves indicates an increase in the frequency of 'under-threshold' events. We select the most outstanding curves to identify the rare, critical and common (lines with circles) thresholds and their inflection points (circles) to demarcate associated persistent and catastrophic durations of events with less habitat than indicated by the threshold (see Parasiewicz, 2007b).

use that will help guide the assessment of altered flow regimes or potential restoration actions. Seasonal aquatic resource elements selected can be fish, invertebrates, species-specific life stages, species groups, species guilds or entire aquatic resource communities. The most comprehensive approach 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. As described in Parasiewicz (2007b), we most commonly use the Target Fish Community (TFC) approach described by Bain and Meixler (2008) for this purpose. By comparing the proportional structure of the observed fish community with the expected structure and with available habitat, we can determine if the habitat is a limiting factor for some species or for a particular life stage and a potential reason for their low numbers (see Figure 6 in Parasiewicz, 2008b). This may serve as a basis for adjustment to the habitat template (i.e. modification of channel morphology) by increasing the habitat proportions for specific species. It may also be used as an end-point restoration model by which restoration success can be measured.

We sometimes develop a Reference Fish Community (RFC), which, in contrast to the TFC, represents the seasonal estimate of natural fish fauna composition. This includes species that are currently underrepresented in the recent stream surveys because they were extirpated or impacted by anthropogenic factors. The RFC gives better insight into the expected natural community structure, which allows modeling habitat structure that would support such a community in the target river. The estimates of expected proportions of these species have been established in two possible ways: either by approximating the species' expected percentage within the community with the assistance of expert opinion or by calculating the

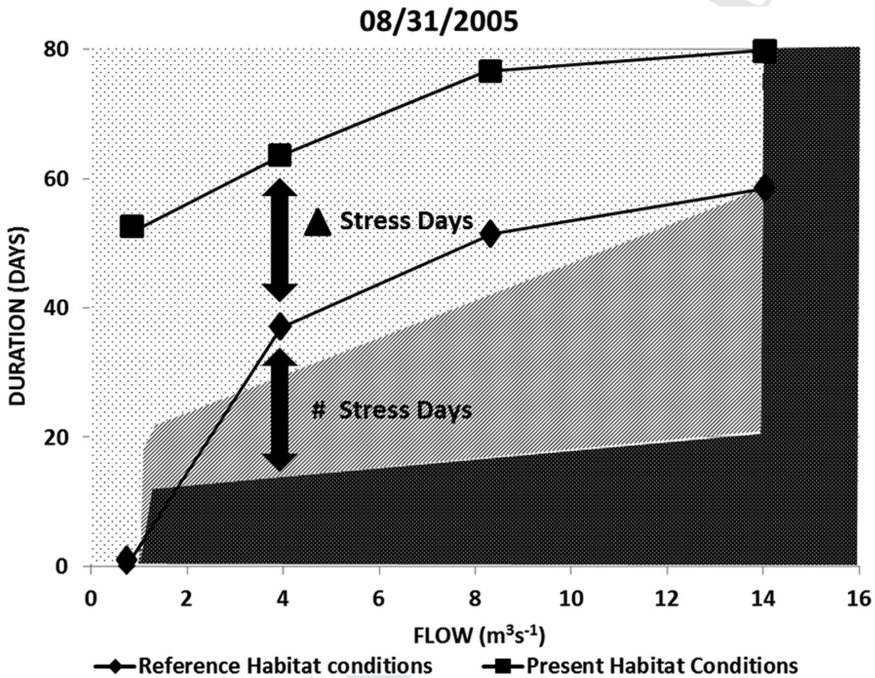

Figure 6.3 Example of an ACTogram for the Summer Rearing and Growth bioperiod for Eightmile River. The durations on the *y*-axis represent time in days for which flows have been below the level indicated on the *x*-axis. The colored areas indicate if the event duration should be considered typical (black), persistent (gray) or catastrophic (spotted). The squares and diamonds indicate the period of flows under a specific value (e.g. 4 $m^3 s^{-1}$) on August 31, 2005 for two different scenarios (reference and present conditions). The increase in the number of stress days represents the impact on habitat at any given flow level.

average density of these species with data from remediation projects or historical monitoring (e.g. Parasiewicz *et al.*, 2007a; 2007b).

The community composition will vary between seasons (or bioperiods *sensu* Parasiewicz, 2007b), especially in rivers with high levels of seasonal migration by specific species. To develop a model of habitat required to sustain the community structure in a bioperiod, we usually select representative species consisting of the most common species or a species of particular interest to use as indicators. This is a pragmatic approach because for rare species, establishing habitat suitability criteria offers a particular challenge due to the lack of observational data. Frequently, for the purpose of the determination of instream flows, the selected species belong to the macrohabitat guild of fluvial specialists and fluvial dependents, as defined by Kinsolving and Bain (1993).

Another option for indicator species selection is to divide the community into habitat-use guilds and select one or more species as guild representatives (Leonard and Orth, 1988; Vadas and Orth, 2001). One benefit of this approach is that the guilds are considered to be more universal in their application at regional scales. Welcomme *et al.* (2006) developed a set of 'environmental guilds' that group riverine fish species based on their response to hydrologic and geomorphologic changes in the ecosystem. This approach is particularly useful in rivers with a distinct hydrologic and geomorphic separation of habitat or where a large number of species or species groups with common habitat needs are present. Additionally, the guild approach provides the ability to use information from more abundant, representative species within a guild to help characterize habitat suitability information for a rare species that, on its own, would be too rare to gather adequate data for. The approach ~~is currently being~~ applied on the Niobrara River, Nebraska, USA, where the species compositions vary longitudinally within the Niobrara River (Wanner *et al.*, 2009), but common habitat requirements exist that allow creation of species subsets (Table 6.1). These commonalities then allow for an assessment of habitat availability using information from a collective suite of species rather than individual species where data

Table 6.1 Habitat guild definitions proposed for the Niobrara River. Guilds are defined using Welcomme *et al.* (2006) classifications.

Guild name	Definition
Eupotamonic benthic	Inhabit benthic habitats and typically found in the main channel. Generally intolerant of low dissolved oxygen.
Eupotamonic phytophilic	Longitudinal migrants that also use the floodplain (lateral movements). Juveniles found in or near floodplain.
Eupotamonic pelagophilic	Main channel residents that migrate long distances.
Parapotamonic	Generally species that prefer semi-lotic habitat and are intermediate between migrants and sedentary species.
Plesiopotamonic	Typically found in open water or along stream edges or in flooded floodplain. Tolerant to lower, but not anoxic, dissolved oxygen concentrations

may be limited. For example, pallid sturgeon (*Scaphirhyncus albus*) is a federally endangered species in the United States, which likely means this species is not abundant and information on its habitat use in the Niobrara River would be sparse. We do know that pallid sturgeons are in the eupotamonic pelagophil guild and that several other species have common mesohabitat requirements. Collectively, the information used to model and assess habitat information for the entire guild in this example could also be used to infer similar habitat availability for pallid sturgeon.

Therefore it is possible to identify the assemblages of mesohabitat types utilized by the guilds and potentially to define habitat-based groupings. Such an approach was utilized in the Powder River, Wyoming, USA, in which cluster analysis of mapped mesohabitats was applied to define habitat use guilds (Senecal, 2009).

At this point, individual target species can be modeled (e.g. Ballesterro *et al.*, 2006) or by selecting the species with the most flow-dependent habitat rating curve or by the development of a community habitat rating curve derived from proportional weighting of individual curves where the weights are derived from the species community level proportions.

The least comprehensive option, but also commonly applied in fish habitat studies, is to determine the indicators using a list of expected species without defining their expected proportions. This makes the model more coarse and insensitive to detecting changes in community structure, which is frequently the consequence of anthropogenic impacts. However, determining indicators is simplified in its approach, as qualitative data are much more frequently available. Vezza (2010) utilized this approach, where the target fish species expected to be found in small streams were identified using regionalized ichthyic zonation (Carta Ittica Regionale, 1992–2004).

Finally, the investigator or resource agency may decide *a priori* which species are of the greatest interest and develop the model for only these species. This is also a common habitat modeling approach as it directly addresses the management needs of resource agencies or public interest. However, this approach must be exercised with caution as recommendations do not explicitly consider potential benefits or impacts to other components of the aquatic community.

These approaches are applicable not only for fish, but also for macroinvertebrates or other aquatic resources. Since the identification of invertebrates at the species level may be prohibitively expensive, frequently family-level models are developed instead and have been used in other habitat assessment approaches for decades. In the Lamprey River study, we created a collective model for Odonata, Ephemeroptera, Plecoptera, Trichoptera and Generic EPT taxa, which shows the available habitat as a function of channel area for these four families of macroinvertebrates (Parasiewicz *et al.*, 2008) (Figure 6.4).

Models developed for freshwater mussels have also been successful in defining suitable habitat and recommended flow regimes. In one application, a model was developed for Unioids as a group on the Souhegan River in New Hampshire, USA. The developed habitat rating curves did not indicate a change in available habitat as a function of flow. This lack of sensitivity in available habitat versus changes in discharge is attributed to the community-level model that was based on a wide range of species-specific relationships. A second model created for the freshwater pearl mussel (*Margaritifera margaritifera*) in Wekepeke Brook indicated, for similar flow range, increased habitat

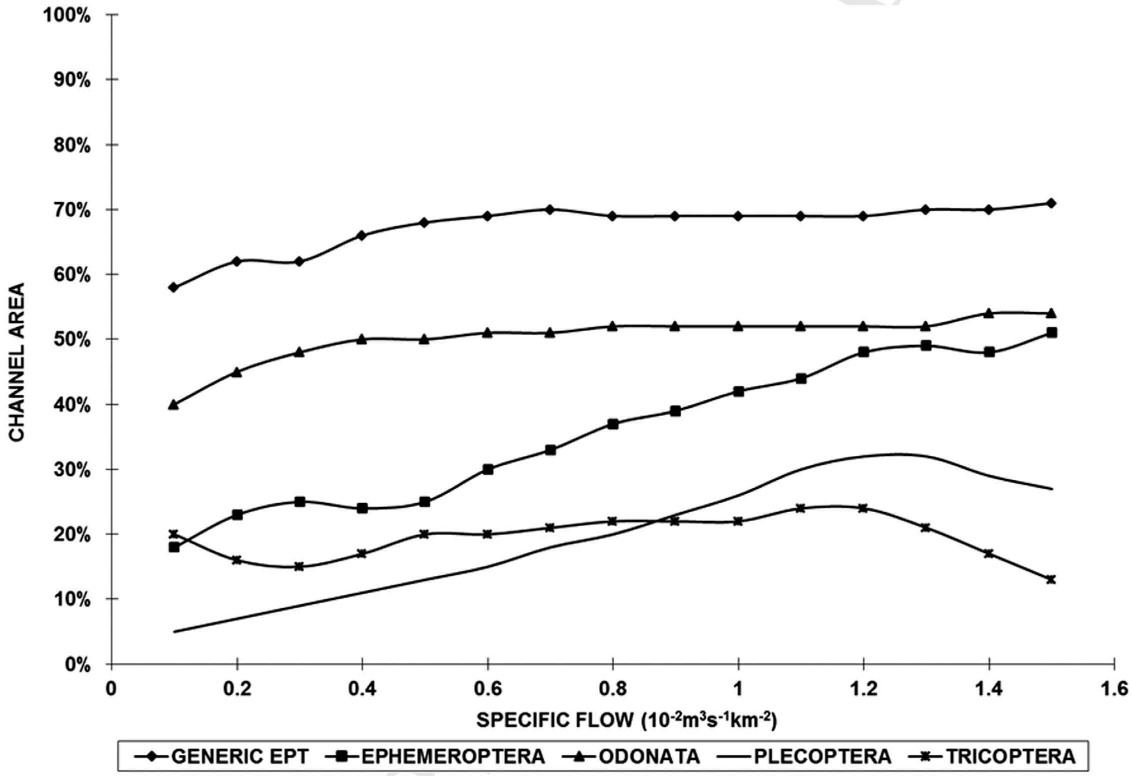

Figure 6.4 Habitat rating curves for selected invertebrate families developed for the Lamprey River, NH. Generic EPT indicates collective habitat for ephemeropterans, plecopterans and trichopterans (see Parasiewicz *et al.*, 2008).

area as a function of increasing flow rates. This confirmed what is known from literature reviews regarding the life history and habitat use of this species (Parasiewicz and Rogers, 2010).

6.2.2 Establishing habitat suitability criteria

The next analysis step is to establish habitat suitability criteria for the selected indicator species. The criteria describe the combination of physical habitat attributes that correlate with the species' presence, indicating suitable habitats, or high abundance, indicating optimal habitats. As described by Parasiewicz (2001; 2007a), every HMU is associated with categorical variables describing presence, absence or abundance of cover types such as woody debris or boulders, as well as the relative distribution of depth, velocities and substrate classes occurring within the units. MesoHABSIM allows for the use of different approaches for determining suitable combinations of these attributes as long as they are compatible with the above data structure.

The simplest approach is to use the information obtained from literature studies to specify the range of velocities, depths, substrate conditions, types of HMU and cover attributes that have been determined as adequate for the species presence. Each of these five HMU descriptive categories can then be defined as preferable or critical to a species presence. When HMU attributes from the field surveys fall within the specified ranges of the developed suitability values, then the HMU is determined to be suitable for a particular species. The number of fulfilled HMU descriptive categories is used as a factor separating suitable from optimal habitats (i.e. 3 is suitable, ≥4 is optimal). We typically use this method for biopériods where more detailed empirical data are not easily obtainable~~; hence,~~ the model can be less precise.

One option is to calibrate literature-based habitat suitability criteria with fish observations at the reach level. For example, in the Tajuña River study in Spain, habitat suitability criteria were adjusted based on linear regression analysis between observed brown trout density in the electrofished sites (ca. 100m-long reaches) and the amount of suitable habitat within the reach. Development of habitat suitability criteria followed a stepwise iterative process: at each step, one class of one variable (a single depth, velocity or substrate class, or a single HMU or cover type) was included in the model or excluded from it and the linear regression analysis between trout density and suitable habitat was calculated. If the regression analysis reflected a better fit, the change was included in the next model; if not, it was rejected (Gortazar *et al.*, 2011).

The most precise criteria for a target species or guild can be developed using empirical data collected from one or more rivers. Data collected from multiple rivers provide a wider range of habitat availability and utilization than those occurring in one river. Therefore, the model better captures the species-specific response to environmental variability. In such a case, numerous HMUs are sampled for target species or guilds, using the methodologies described by Parasiewicz (2007a). In recent years, the Rushing Rivers Institute has established a large database, with well over 1000 samples of HMUs obtained from over 15 rivers across the Northeastern USA. So far, over 36 fish species, 30 species of odonates and 3 invertebrate families are included in the database, which is growing continuously. This allows for the establishment of a more robust criterion, which can be transferred between rivers in the region and helps to limit the fish sampling effort on each project to those required for the model's validation. These data serve as a basis for the calculation of multivariate probabilistic models such as logistic regression. One important element in this process is to isolate the habitat attributes that have a significant influence on fish presence, such as the use of the Akaike information criterion (Sakamoto, 1991) instead of stepwise regression. ~~For example,~~ in the cross-validation procedure, we apply the computed formula to the validation data (e.g. 20% of available data) and compare the number of fish observations with the predictions of suitable habitat. This procedure is repeated 20 times and each time a new randomly selected dataset is retained for validation purposes. After 20 runs, the model generates a list of parameters that were selected in at least two of the runs and computes another model using only these parameters as input attributes. To further improve model quality, we investigate the standard errors of each final model and remove the attributes with high standard errors. The remaining attributes are then used in the calculations of the probability of presence or high abundance. Receiver Operational Characteristics (ROC) curves serve as the basis for the identification of probability cutoff values that distinguish between not suitable, suitable and optimal habitats (Metz,1986; Pearce and Ferrier, 2000). HMUs with probability of presence higher than the selected cutoff are considered to be suitable habitats. Out of those, the HMUs with probability of abundance higher than the cutoff are considered optimal. This analytical framework is currently supported within the Sim-Stream 8 modeling system (Rushing Rivers Inc., 2010).

The methods described above for development of habitat suitability criteria are illustrative of common approaches; the use of alternative approaches for criteria development external to the MesoHABSIM system are not precluded, as long as the criteria meet the basic input format for criteria curves.

6.2.3 Mapping and evaluation of instream habitat

The application of MesoHABSIM can be accommodated across a wide array of spatial scales from complete delineation to subsampling of representative river sections within longer homogeneous river reaches. The approach can be based on expert opinion or sophisticated analysis using statistical approaches. Time, cost and logistics constraints play an important role in selection of the appropriate ~~approach,~~ The section below demonstrates a few examples of selected sampling strategies.

The Stony Clove Creek, New York, USA study mapped the entire 16 km length of river multiple times (Parasiewicz *et al.*, 2003). This effort was time and cost intensive. Each survey by multiple parallel teams took two weeks to complete, during which time flows frequently changed, thus creating additional data-processing complications. In contrast, the reconnaissance survey of the Little River, CT indicated that it would be most effective to map the entire length of the study area (5 km) because of its short length and streamlined processing.

In the Eightmile River, Connecticut, USA study (28 km), watershed maps and aerial photographs were used by local fish biologists and residents to conduct a preliminary reconnaissance. This allowed the selection of representative sites (smaller portions of a stream segment that are proportionally representative) with a reasonable level of confidence (Parasiewicz *et al.*, 2007b), but without the ability to quantifiably justify our choice. In contrast, in studies on the Quinebaug (34 km, Connecticut, USA), Pomperaug (21 km, Connecticut, USA) and Mill (20 km, Massachusetts, USA) Rivers, the reconnaissance consisted of a detailed mapping of all HMUs in the study area and the representative sites were selected with the help of a sensitivity analysis of HMU distributions. Since this effort was

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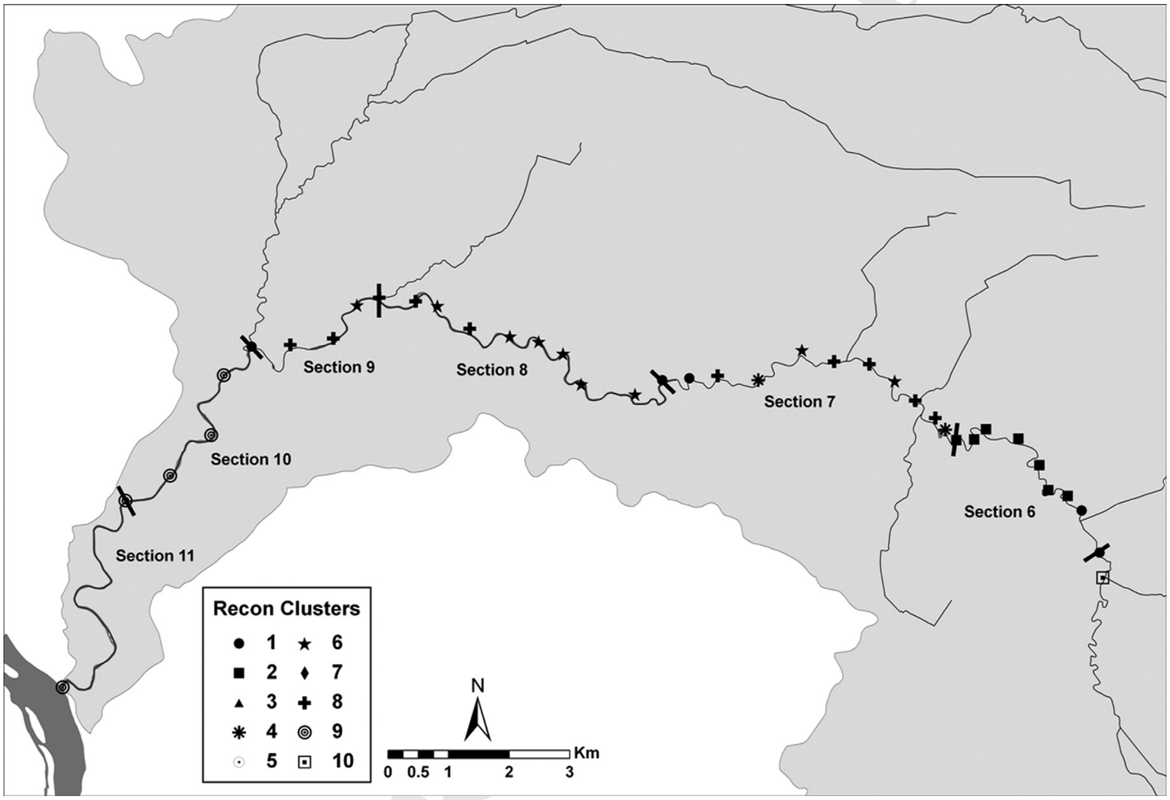

Figure 6.5 A map of the Świder River, Poland with locations of identified clusters and section boundaries. Each symbol is located at the end of a homogenous river reach and indicates the cluster classification. The thick section markers are placed in the locations where cluster patterns are changing.

intensive, we developed a more effective protocol for gathering the necessary information. This protocol involves hiking or boating the entire project area river length while estimating proportions of hydromorphologic units and mesohabitat characteristics for homogenous ~~portions~~ of river instead of mapping each individual HMU. Usually, such an on-the-ground survey overestimates the number of ~~homogenous~~ sections, which are later grouped with the help of cluster analysis. For example, the Świder River study in Poland, a 4th order river 75 km long, was delineated into 11 sections. For each section, we recorded the estimated proportions of different HMU types and habitat cover categories while excluding depth and velocity data collection. After the survey, the team identified the major observed breakpoints in river morphology. The cluster analysis supported these delineations and allowed us to identify locations where the habitat conditions changed by grouping the sections that were similar to each other (see Figure 6.5).

The Niobrara River, Nebraska, USA study required a slightly different approach for identifying homogenous sections and representative study sites due to its long study length (530 km) and small number of access locations. A helicopter equipped with mounted video was used to view the proposed project area. During the flight, a tablet PC loaded with aerial photos and basic GIS data layers was used to annotate observed points of interest (e.g. sandbars, islands, impoundments, tributaries, bank and valley characteristics, etc). Observations were spot-checked by landing at several locations and then later by ground truthing.

Using these GPS points along with the aerial photos, survey video and photo documentation, an initial section delineation was developed. Major considerations for section breaks were related to morphological changes, including the presence/absence of sandbars and islands, diversity of perceived hydromorphologic units, sinuosity and bank characteristics as well as the location of dams and major tributaries.

Alexander *et al.* (2010) developed a segment-scale geomorphic classification system for the Niobrara River and divided the study area into 25 distinct geomorphic segments. Our initial delineation resulted in 21 reconnaissance-based sections. The statistical analysis of data developed by Alexander and the qualitative analysis of reconnaissance data resulted in many similar proposed section breaks, which, in the end, were merged to form 16 project sections.

Using river access locations and aerial photo observations, we chose two- to three-mile representative sites in each section. We created whisker diagrams for each of Alexander's morphometric attributes at the section and site levels. These plots were compared to ensure that the means, first and third quartiles were statistically similar. The representative sites were lengthened or shortened to create a better fit and, in some cases, a new location was chosen altogether.

MesoHABSIM was also applied for the determination of minimum environmental flows in small first order streams in the entire region of Piedmont in NW Italy. Twenty-five streams were selected for their natural conditions with respect to flow regime, fish community composition and homogeneous spatial distribution across the region. Within each stream, the representative site was defined by its proximity to the drainage basin outlet, the absence of human impacts and the possibility to survey from 5 to 10% of the stream length in one day (Vezza *et al.*, 2011).

From this experience we conclude that, for the river sections up to 5 km, the best approach is a complete delineation of the study site. For longer rivers we recommend a representative site approach; however, the sophistication of the site selection methods increases with the length of the river. For rivers up to 100 km in length, we recommend on-foot or boat reconnaissance surveys such as the one conducted on the Świder River and aerial data analysis for longer sections. For the regional scale, GIS data can be used for site selections.

6.2.4 Habitat survey

The habitat survey describes all mesohabitats within the selected representative study sites. The purpose is to delineate the distribution and area of habitat types at each target flow. The number of surveyed flows strongly depends on the range of discharges being evaluated. If the assessment targets low flow conditions, then the mapping effort can be limited to a minimum of three flows distributed strategically (e.g. more surveys at the conditions where more dramatic changes are expected, i.e. lower flows). Obviously, the more surveys can be afforded, the greater resolution in the shape of the rating curve can be expected and the inflection points are defined more precisely. If higher flows need to be evaluated, additional surveys may be necessary, however, it should be noted that the habitat suitability criteria may change in response to flow increases (i.e. shifting between shelter versus foraging). This would require development of additional suitability curves for high flows~~,~~ ~~where~~ the ability to observe the species in such conditions may not be practical.

In general, most MesoHABSIM studies focus on low flow conditions. The survey consists of two processes: mapping of HMUs and the collection of hydraulic data in random locations. The following steps detail a basic MesoHABSIM surveying procedure:

1 Monitor the river for target survey flow occurrence (typically three to five) identified using flow time series analysis. Typically, the highest survey flow targets ~~normal~~ summer ~~high~~ flows and the lowest flow targets the annual ~~average~~ minimum flow experienced on that river during the rearing and growth period. The other surveys are distributed between the two, with a preference for capturing low flow events if more than three surveys are possible. This helps to define observed habitat availability changes typical at the lower flows. Surveys can be conducted within 10% of the target flow. It is imperative that the flows remain constant during the one-day survey to avoid complicated post-processing of field data that may compromise the development of habitat versus flow relationships.

2 Determine the extent of the first HMU as follows. Walk or canoe the river, depending on river depth and accessibility, and note water surface characteristics (ripples, slope), river bottom morphology and uniformity of bank and shore-use characteristics. Continue moving downstream until a noticeable change in one of these characteristics occurs (see Parasiewicz 2007a for details).

3 Note the location of this change and draw a polygon on a field computer to delineate that HMU. After the sketch is completed, record the observed characteristics including: the mesohabitat type, dominate substrate and wetted/bankfull width. Next, indicate the absence (<5% of area), presence (≤50%) or abundance (>50%) of instream habitat attributes such as: boulders, woody debris and undercut banks. Finally, note shoreline attributes, which include information on land use, erosion and irregular shores and comments (see Parasiewicz, 2007a for a list of all attributes).

4 A second team records depth, velocity and substrate information from the HMU. The HMU is divided into estimated zones of similar hydraulic and substrate conditions to better classify the range of observed characteristics. The HMU is sampled at a minimum of seven random locations distributed proportionally in each stratum to best characterize the conditions within the HMU.

These steps can be accomplished using any number of simple mapping techniques or with integrated GPS and field-based laptop computer systems.

6.2.5 Upscaling

The data collected during the habitat surveys serve as a basis for the development of habitat rating curves for each site. Using the developed suitability criteria, each HMU is evaluated to determine if it offers suitable or optimal habitat for each species at each surveyed flow (for details, see Parasiewicz, 2007a). The area of HMUs with suitable (or optimal) habitats is summarized for each site and plotted against a constant unit of area such as the wetted area at the highest measured flow, or the channel area of the site. Effective habitat is calculated as an aggregation of suitable and optimal habitat with different weights, to assure the high contribution of optimal habitat. Typically, we use 0.25 of suitable and 0.75 of optimal habitat as weights to define effective habitat.

Alternatively, composite habitat suitability indices can be used to weight the area of each HMU and create Weighted Usable Area (WUA). Although it is used widely in other studies, we do not recommend this method due to the fact that units with large areas and low suitabilities could produce the same WUA value as small units with high suitabilities. This could potentially lead to restoration efforts that create large, sub-standard, instead of high quality, habitats.

In addition to curves for individual species, habitat-rating curves for generic fish (the total amount of habitat available for the chosen fish community), as described in Parasiewicz (2007a), and community habitat-rating curves are calculated. The community habitat-rating curve is constructed by weighting the suitable habitat area of each species by its expected proportion in the Target or Reference Fish Community. Since a generic fish habitat approach represents the habitat area that is suitable for any of the species in the investigated community, it represents the total amount of habitat available. In contrast, the community habitat-rating curve takes into account the habitat availability that supports the desired structure of the fish community. Frequently, the habitat-rating curves for generic fish habitat are plotted together with the community habitat curves and the curve representing the change in the wetted area (Figure 6.1). This allows one to determine whether there is a lot of habitat available (generic curve) and whether the habitat structure does not reflect the community structure. This can be concluded if there is a substantial vertical distance between both habitat curves in the diagram. This diagram can also be used to assist in the evaluation of potential habitat improvements associated with potential restoration measures and can be used for planning purposes.

The habitat-rating curves for each site are upscaled by a length-weighed sum to represent river segments. The river segment length is usually defined as a portion of the river where we would expect a specific structure of the fish community. The change may be due to natural factors such as the confluence of a major tributary or waterfall, or anthropogenic factors such as dams or flow withdrawals. On the Souhegan River, for example, the river segment division was due to a major change in gradient and geology that coincided with a change between two Level III ecoregions (Omernik, 1987; Ballesterro *et al.*, 2006). In the case of the Pomperaug and Eightmile Rivers, the change in stream order from third to fourth at the confluence of two major river branches was the reason for developing multiple Reference Fish Communities (Parasiewicz *et al.*, 2007a; 2007b).

A different river segmentation took place in the regional application in Piedmont, Italy. The environmental flow requirements of fish communities were upscaled from the local level to the entire region of interest, integrating the MesoHABSIM results within the regional water planning process. The reference streams were grouped according to the Classification and Regression Trees (CART) algorithm, defining homogenous sub-regions distinct from both environmental flow needs of aquatic fauna and catchment/reach characteristics. Building the tree, CART split the learning sample (i.e. 21 catchment/reach characteristics as independent variables and the environmental flow needs as the dependent variable) by using a binary recursive partitioning algorithm (see Vezza *et al.*, 2011). Based on the resulting four groups of catchments represented by the terminal nodes of the regression tree, the resulting classification assigned the minimum environmental flow value to each group. First, latitude of the catchment centroid, then longitude and the maximum elevation were used for partitioning, identifying four sub-regions characterized by homogeneous hydro-ecological features (i.e. climate, flow regime, topography and fish community composition).

6.2.6 Adjusting biophysical templates to reflect reference habitat

The next step recommended in the MesoHABSIM approach is to consider and simulate structural improvements of the riverbed to create a habitat that would better support the targeted fish community. These simulations take place through appropriate modification of GIS maps and the information gathered in the project-specific database. As described in Parasiewicz (2007b), the simplest approach is to begin with the simulation of removing the most obvious anthropogenic factors, such as impoundments and dams or restoring the connectivity based on historic data and aerial imagery. More recently, we developed an approach directly investigating habitat needs of indicator species. It begins with comparing fish and habitat structure, as described above, and the identification of species that either lack or have a surplus in available habitat. In the subsequent step, we investigate multivariate criteria and compare HMUs that were predicted to be suitable and not suitable for the species. The purpose of this screening is to isolate physical attributes which, if modified, would change the habitat structure to better support the expected community. The simulation takes place in an iterative process, where we introduce proposed changes to the project database one at a time, to determine model sensitivity. For example, when comparing the target fish community structure with the current habitat structure on the Wekepeke River, MA, we noticed a particularly important lack of habitat for brook trout (*Salvelinus fontinalis*), which historically should dominate the fish community. At the same time, the habitat available for blacknose dace (*Rhinichthys atratulus*) appeared to be excessive. The analysis of habitat suitability criteria for these species pointed to the need for a greater area of pool, riffle and run HMUs, abundance of shallow margins and undercut banks as well as phytal (submerged plants, floating stands, etc.) and cobbles with a variable percentage of gravel and sand substrate. Six different simulations were carried out in an iterative process, varying the variables noted above by modifying HMU areas and abundance of cover attributes. This allowed us to calculate a reference habitat structure and to identify measures that would lead to these improvements (Parasiewicz and Rogers, 2010).

6.2.7 Reference flow time series

The final element necessary to determine reference conditions, in addition to the Reference Fish Community and reference habitat structure, is to develop a reference flow time series. This can be accomplished by a number of techniques based on the context of the study. Techniques range from the estimation of flow regime characteristics at an ungaged site based on an index gage (e.g. Fennessey and Vogel, 1990; Fennessey, 1994) to distributed parameter catchment-level rainfall-runoff modeling (e.g. Leavesley *et al.*, 1983).

6.2.8 Habitat time series analysis

The reference flow time series and reference habitat structure are eventually used to develop a reference habitat time series, which describes the expected amount of habitat that would exist given the reference flow time series. The habitat time series are investigated with the help of UCUT curves to establish natural habitat stressor thresholds (HSTs) (see Parasiewicz, 2007b). The purpose of this analysis is to investigate habitat duration patterns and to identify conditions that could create pulse and press disturbances, as described by Niemi *et al.* (1990). A pulse stressor causes an instantaneous alteration in fish densities, while a press disturbance causes a sustained alteration of species composition. In the habitat analysis, this can be caused either by extreme habitat limitation regardless of duration or by catastrophically long duration events with critically low habitat availability. Press disturbances can be caused by frequent occurrence of persistent-duration events with critically low habitat availability. Therefore, identifying HSTs requires taking into account habitat magnitude as well as the duration and frequency of non-exceedance events, as described below.

To identify an HST, a habitat time series and the UCUT curves are developed (see Parasiewicz, 2007b for detail). As documented by Capra *et al.* (1995), the curves are a good tool to predict the impact of the frequency and duration of biological conditions. The curves evaluate the continuous duration and frequency of continuous non-exceedance events for different habitat magnitudes. Rapid changes in the frequency pattern are used to distinguish between typical and unusual events and to identify HSTs for rare versus common events. Rare habitat events happen infrequently or for only a short period of time. The

Table 6.2 Flow management criteria developed for two flow levels on the Saugatuck River, CT. Base flow is equivalent to common habitat conditions, subsistence is equivalent to rare habitat levels and absolute minimum is the lowest flow on record.

Bioperiod Approximate dates	Rearing and growth July–Sept	Fall spawning Oct–Nov	Overwintering Dec–Feb	Spring flood Mar–Apr	Spring spawning May–June
Base flow ($10^{-2}m^3s^{-1}km^{-2}$)	0.74	0.40	2.09	2.09	1.10
Allowable duration under (days)	34	13	20	19	14
Catastrophic duration (days)	85	56	47	35	42
Subsistence flow ($10^{-2}m^3s^{-1}km^{-2}$)	0.06	0.06	0.44	1.10	0.40
Allowable duration under (days)	14	8	18	10	10
Catastrophic duration (days)	49	26	33	15	20
Abs. minimum flow ($10^{-2}m^3s^{-1}km^{-2}$)	0.002	0.006	0.052	0.204	0.051

common habitat threshold divides normal conditions that occur frequently from uncommon events.

The HST captures rare and common habitat characteristics together with their durations. The method specifies two duration thresholds: persistent and catastrophic based on the frequency of occurrence. Exceedance of those durations causes habitat stress days (HSDs). The cumulative frequency of events that are longer than the threshold value captures natural limitations shaping the aquatic community. Anthropogenic factors (e.g. flow diversions) often increase the frequency of such events, ergo the number of HSDs.

The HST can be used to develop criteria for ecological flow management. These criteria include the magnitude of rare, critical and common flows as well as the durations of persistent and catastrophic events and are used for the development of flow pulsing strategies (see Table 6.2), as described in Parasiewicz (2008b).

Eventually, these flow criteria are summarized in the form of ACTograms. The ACTogram approach attempts to capture all essential parameters (flow, habitat, duration and function) in a single set of graphs. The boundaries demarcating the black, striped and spotted areas (e.g. Figure 6.3) are defined by the flow–habitat relationship. Where boundary lines slope upward to the right, greater flows are indicative of greater habitat quantity. In such cases, persistent low flows may endanger ecological resources.

ACTograms plot the number of consecutive days that flows have persisted below a chosen threshold, typically the rare, critical and common thresholds mentioned above. Unlike traditional hydrographs, which plot flow on the ordinate (i.e. *y*-axis) and time (e.g. return period or event duration) on the abscissa (i.e *x*-axis), the ACTogram reverses this relationship. ACTograms are designed to answer: 'How long can the current flow condition persist before creating press or pulse stressor?', whereas hydrographs are designed to solve for flow at a particular time.

To plot flow data on the ACTogram, it is necessary to track the number of consecutive days that flows have remained below a threshold of interest. For example, in Figure 6.3, two curves are presented, each representing flow-duration conditions on ~~different~~ day~~s~~. The reference line indicates that the flow has been less than 1 m^3s^{-1} for 0 days, less than 4 m^3s^{-1} for 40 days, less than 8 m^3s^{-1} for 50 days and less than 14 m^3s^{-1} for 60 days. Note that these flow-duration conditions persist simultaneously on that day. A theoretically infinite number of flow thresholds may be plotted, but as a practical matter it is likely that three or four thresholds will be sufficient. It is sensible to track thresholds that are in the flow range in which changes in slope of between black/striped/spotted areas occur. To complete the plot, each flow/consecutive-day data point is connected with a line. The result shows a flow-duration frontier that begins on an *x*-axis intercept at the left edge of the ACTogram and generally slopes higher to the right as flows increase. Intrusion of any part of the frontier into the striped zone of the ACTogram is indicative of an anticipated stressed ecosystem. As dry days continue, the frontier will creep upwards. Upon entering the spotted zone, the ACTogram indicates that habitat quality has potentially suffered critical damage and the bioperiod function has been seriously impaired. However, an increase in flow will break the consecutive day streak at all thresholds less than the new, higher flow. In this case, the frontier to the left of the new flow will be returned to zero, but will remain high to the right of this flow. The flow/duration frontier is dynamic and new flows

Table 6.3 Summary of number of stress days calculated for current conditions and simulated scenarios. P refers to persistent and C to catastrophic events. Moderate changes in stress days are lightly shaded; severe changes are darkly shaded.

Current habitat structure										
Event duration	P	C	P	C	P	C	P	C	P	C
Withdrawal	0		0.001		0.014		0.028		0.15	
Mitigation	no		no		no		[illegible]		Dynamic augmentation	
Common events NSD	111%	102%	97%	100%	129%	160%	167%	402%	98%	0%
Rare events NSD	176%	388%	243%	525%	243%	525%	243%	525%	86%	0%
Improved habitat structure										
Event duration	P	C	P	C	P	C	P	C		
Withdrawal m^3s^{-1}	0		0.014		0.014		0.014			
Mitigation	no		Minimum flow		Static augmentation		Dynamic augmentation			
Common events NSD	127%	122%	127%	122%	29%	0%	99%	0%		
Rare events NSD	111%	188%	93%	97%	0%	0%	53%	0%		

must be plotted each day to monitor the river condition accurately.

6.2.9 Scenario comparison

The first step in this process is to define a list of viable scenarios that should be investigated. For example, the objectives of the Wekepeke Brook project were to define possible flow and habitat augmentation scenarios to compensate for planned water withdrawal sites in the brook's headwaters. To compare various flow scenarios for their impact on fish fauna, we simulated the modification of two factors: flow time series and habitat structure. Multiple flow time series were available: historical flows and simulated flows, which modeled three volumes of water withdrawals (0.001, 0.014 and 0.028 m^3s^{-1}). The water withdrawals could also potentially be mitigated by imposition of minimum flows and by flow augmentations from an upstream reservoir. Flow augmentation could take the form of continuous and pulsed releases (dynamic augmentation). There were two options for spatial habitat distribution patterns: reference and present morphology.

For each scenario, habitat time series were developed and UCUT analysis described by Parasiewicz (2007b; 2008a) was used for comparison. Plotting the UCUT for selected rare and common thresholds provides an insight into the change in frequency of such events. To further compare the change in persistent and catastrophic events, the HSD was computed. The cumulative duration for the lowest persistent and the shortest catastrophic events are related to those of the reference conditions and presented as proportions of reference durations. If the proportion is between 50% and 200%, the durations are considered to be similar (i.e. ~~the Number of Stress Days (~~NSD~~)~~ or the count of days that the current or simulated conditions are above the common level is less than twice the original). Cases where durations exceed 200% or are shorter than 50% are considered remarkable, and those exceeding 300% or less than 5%, severe. The results are presented by color-shaded tables to highlight the difference (see example in Table 6.3).

6.2.10 Interpretation and application

MesoHABSIM has been applied on over ~~25~~ rivers throughout the USA and Europe (www.MesoHABISM.org/projects). The majority of applications and model development took place on streams and small rivers of high to moderate gradient in the Northeastern USA. However, applications have been conducted on a variety of different systems such as prairie streams (Powder River, WY), a large coastal lowland river (Santee River, SC), a large braided river (Niobrara River, NE), alpine first order streams (Piedmont, Italy), a lowland meandering river (Świder River, Poland) as well as a Mediterranean river in the plateau of Castile (Tajuña River, Spain). These ~~applications were very successful, which~~ attest~~s~~ to the fact that there are no apparent limitations to MesoHABSIM's application in terms of river size and character. The main difference in application of MesoHABSIM across spatial gradients is related to field data acquisition, where larger systems are sampled using both photography and boats while smaller systems are sampled using ground-based techniques. A particular strength of MesoHABSIM is data collection in areas of complex and diverse habitat structure, where the precise collection of microhabitat data is very tedious. This is as much the case for dynamic, braided rivers as for small, high-gradient streams and has been documented clearly during the study of Piedmont's mountainous streams and the braided Niobrara River.

MesoHABSIM is often used for the analysis of a specific flow range. We consider this a strength of the model, because it prevents application of the developed habitat suitability criteria to high flow conditions. Furthermore, repeated surveys of representative sites at chosen flow thresholds allow for a detailed understanding of site specifics. Although this approach may require additional field effort and logistics, it offers returns and insights different from more remote techniques. In our experience, time spent in the field is very valuable for project understanding and outweighs the greater post-processing efforts of some hydrodynamic models.

Although MesoHABSIM has been developed with hydropower in mind, to date it has been most frequently applied in questions of instream flow management as related to industrial and municipal water withdrawals. Most notably, it serves as a method for determining Protected Instream Flows standards for the state of New Hampshire, where the flow regime developed by use of the approach was the basis for the implementation of the Water Quality Act on the Souhegan and Lamprey Rivers. The criteria developed by the model described flows protective to fish, invertebrates and rare and endangered riparian species. They are currently applied in the management of the Souhegan River.

Similarly, MesoHABSIM has been included as one potential tool for examination of instream flow regimes in The Nature Conservancy's Ecologically Sustainable Water Management Framework (ESWM). This approach consists of six consecutive steps that allow for the development of a proper management strategy, using available data supported by models such as those described in this chapter (Richter *et al.*, 2003). MesoHABSIM was used for the implementation of step 1 of this approach ('developing initial numerical estimates of key aspects of river flow necessary to sustain native species and natural ecosystem functions') on the Saugatuck/Aspetuck River in Connecticut. We considered multiple aspects of river ecology and defined flow needs for instream and riparian ecological targets in different seasons (Parasiewicz *et al.*, 2010).

In another, similar project on the Fenton River, CT, the flow criteria served as a regulatory basis for limiting well water withdrawals (Nadim *et al.*, 2007; Jacobson *et al.*, 2008). On the Pomperaug River, CT, the HSTs were used as a basis for developing a Habitat Meter, which signals in real time the habitat status on the Pomperaug River Watershed Association's website (www.Pomperaug.org). In this project, we used habitat time series to simulate future watershed development scenarios, demonstrating the applicability of the model to the questions of global climate change.

On several projects, our focus was on river channel restoration. The model can select restoration measures that are the most beneficial to fish fauna by offering focused habitat improvements. Such recommendations have, to date, been general in nature, as the model has a limited ability to address the detail necessary for construction planning. We recommend that for detailed site-specific designs, a micro-scale analysis is needed.

Overall, the ten years of MesoHABSIM's development and application have proved the utility of the model for river management and restoration. It has been applied on a variety of river sizes and types without major difficulty and can be used as an ecological status assessment tool as well as for planning instream flow management and channel restorations. It successfully addresses issues associated with hydropower generation, water supplies, channelization and river restoration. Compared to other meso-scale approaches such as MesoCASiMiR or the Norwegian Mesohabitat method (Borsanyi *et al.*, 2004; Eisner *et al.*, 2005), or mesohabitat typing used within the PHABSIM framework, the model incorporates scientific rigor in data collection as well as in analysis because:

1. The approach integrates expert habitat mapping with hydraulic measurements to characterize meso-scale features conducted at multiple flow conditions based on the analysis of detailed reconnaissance surveys.
2. It uses multivariate statistical models.
3. It uses multiple cross-validations for model calibration.

It offers not only advantages in data collection effort and sampling intensity, but also incorporates a number of innovative analytical possibilities such as quantification of habitat run-length (durations under threshold) and HSD analysis. The system provides a wide array of analytical possibilities and sophisticated approaches to the integration of habitat availability and flow regime assessments.

The approach offers a useful tool for river management planning that is critically needed for the implementation of modern water laws such as the European Water Framework Directive or the South African National Water Act.

It complements the micro- and macro-scale modeling of fish habitat, closing an important gap that impaired river management in the past. It also presents opportunities for the advancement of river science in general. Through the process of model development alone, we have learned a lot about habitat and ecological processes in riverine environments that may not have come easily without using this research tool.

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