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IMPLEMENTATION OF THE NATURAL FLOW PARADIGM TO PROTECT DWARF WEDGEMUSSEL (*ALASMIDONTA HETERODON*) IN THE UPPER DELAWARE RIVER

P. PARASIEWICZ[a,b]*, E. CASTELLI[c], J. N. ROGERS[a], P. VEZZA[d] AND A. KAUPSTA[b]

[a] *Rushing Rivers Institute, Livonia, Michigan USA*
[b] *S. Sakowicz Inland Fisheries Institute, Żabieniec, Poland*
[c] *ARPA Lombardia, Milano, Italy*
[d] *International Centre for Ecohydraulics Research (ICER), University of Southampton, Southampton, UK*

ABSTRACT

This paper demonstrates the use of a multiplex habitat model for flow management criteria development compliant with the natural flow paradigm using the Upper Delaware River (NY/PA—USA) as an example. The goal of this study was to identify strategies to protect and support the recovery of the dwarf wedgemussel populations in the mainstem Delaware River. We quantified potential habitat, developed instreamflow recovery scenarios and modelled the scenario outcomes. Mesohabitat simulation model and River2D have been used to allow the transfer of suitability criteria between scales. Habitat time series were investigated with the help of the uniform continuous under threshold technique to establish natural habitat stressor thresholds.

Exceedance of persistent and catastrophic durations results in habitat stress days (HSD). HSD served as a metric for the comparison of four flow and two habitat management scenarios. The greatest habitat improvements were accomplished through increasing the boundary Reynolds number, hence increasing the river bed diversity. The introduction of naturalized flows into the model did not cause any significant reduction of HSD, demonstrating that optimizing suitable habitat for dwarf wedgemussel may not be achieved without including morphological improvements. Both minimum and pulsed flow augmentation strategies were found to nullify rare stress days in our models. Our study found that, at a minimum, a pulsed flow regime would need to be created to promote the development of populations beyond the current mussel beds. To accomplish protection and enhancement of habitat fully, channel improvements that reduce boundary Reynolds number appear necessary. These recommendations are intended to create a starting point in the adaptive flow management process for the Upper Delaware River. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: mesohabitat; dwarf wedgemussel; MesoHABSIM; Delaware; environmental flows; adaptive management

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INTRODUCTION

According to the natural flow paradigm (NFP), ecologically sensitive river management needs to take into account the magnitude, frequency, duration, rate of change and timing of flow events (Poff *et al*., 1997). Although flow (or quantity of water) is considered a 'master variable' that shapes ecological processes and defines distribution of biota in a river, flow by itself does not directly affect the biota. It organizes spatio-temporal characteristics of habitat such as water depth or velocity, which can be perceived by the sensory systems of animals and plants and therefore cause a response (Lytle and Poff, 2004; Poff and Zimmerman, 2010; Thompson *et al*., 2011). Habitat in turn is defined as an area with discrete environmental conditions that promote occupancy by species and is an area constantly changing with flow over time (Morrison *et al*., 1992; Hatten *et al*., 2013). Hence, the NFP aims to maintain appropriate magnitude, frequency, duration, rate of change and timing of habitat events through managing those the same flow attributes.

The NFP is often implemented by manipulating flow conditions (Maddock *et al*., 2001; Kennard *et al*., 2010; Hermoso *et al*., 2011). Because habitat may be shaped by other environmental components (e.g. geology, air temperature and biology), this manipulation may not sufficiently enhance habitat conditions to secure species survival and promote thriving aquatic communities, especially for rivers with heavily modified morphology. A more comprehensive way of implementing the NFP principles is through spatio-temporal habitat management that takes into account flows as well as hydro-morphology (Parasiewicz *et al*., 2012b). This can be accomplished with the help of habitat simulation models.

Habitat simulation models have a history of application for instreamflow management planning (Parasiewicz and Dunbar, 2001; Acreman and Dunbar, 2004); however, temporal analysis is often not completed (Milhous *et al*.,

*Correspondence to: P. Parasiewicz, Rushing Rivers Institute, 19849 Livonia, Michigan 48152, USA.
E-mail: piotr@infish.com.pl

1990). Frequently, with this like with other methods, the flow management recommendations are limited to the identification of a low-flow threshold value, which should be always maintained as minimum flow. This violates the principles of NFP (Vezza *et al*., 2012; Vezza *et al*., 2014).

The mesohabitat simulation model (MesoHABSIM) approach (Parasiewicz, 2001, 2007a) emphasizes habitat time series analysis and offers recommendations of flow magnitude as well as duration of persistent and catastrophic events, identified based on their frequency patterns in different bioperiods (Parasiewicz, 2008). This addresses four of the five components of the NFP. The model has been utilized as a tool for NFP implementation in several river projects to offer management recommendations and for comparative scenario analysis (Parasiewicz, 2007b; Parasiewicz *et al*., 2007; Parasiewicz *et al*., 2008). Recently, it was also used to identify the environmental flow components protective for federally endangered dwarf wedgemussel (*Alasmidonta heterodon*) in the Upper Delaware River (Parasiewicz *et al*., 2012a).

The Upper Delaware River supports diverse aquatic fauna, including the federally endangered dwarf wedgemussel (hereafter DWM). The DWM has been historically recorded in approximately 70 locations in 15 Atlantic slope drainages from New Brunswick, Canada to North Carolina, USA (U.S. Fish and Wildlife Service, 1993). During the past 100 years, the species has declined precipitously. It is now thought to be extirpated from all but 20 locations, confined to eight drainages (Master, 1986) and is no longer found in Canada (Hanson and Locke, 2000). DWM is listed as federally endangered and is also locally listed in the states included in the Upper Delaware River study area; New York, New Jersey and Pennsylvania. There are five known sub-populations of dwarf wedgemussels within the Upper Delaware River basin, three in the mainstem along the border of Pennsylvania and New York (Lellis, 2001), one in the Neversink River, New York (Strayer and Jirka, 1997) and one in Flat Brook, New Jersey (Lellis, 2002). There were an estimated 4000 DWM distributed approximately equally among the three Delaware River mainstem sites with the bulk of individuals located along the Pennsylvania shoreline during the summer of 2002 (Lellis, personal communication).

River flow at the Upper Delaware DWM sites is highly variable and influenced by upstream reservoir releases entering from the East and West Delaware River Branches. Although periods of reduced flow may lead to the dewatering of areas inhabited by DWM, the flow regime required for protection and perpetuation of the DWM is not understood sufficiently to draw defensible conclusions about impacts to the species. This applies to reaches of both known and potential DWM habitation. Accordingly, there is a need to establish a scientific basis for a flow management policy that is protective to the DWM.

The search for conservation measures could be helped by an understanding of the optimal substratum for mussels, because sediment quality has long been thought to be one of the most important characteristics limiting mussel distribution (Box and Mossa, 1999). Anthropogenical siltation and sediment modification are, for example, listed among the principal sources of mussel habitat destruction (Scheder *et al*., 2015). The increased input of fine sediments, resulting from major changes in agriculture and forestry in the course of the 20th century, is considered a crucial factor for the decline of freshwater mussel populations all over Europe and North America (Williams *et al*., 1993; Box and Mossa, 1999; Haag and Williams, 2014; Scheder *et al*., 2015). Processes leading to sediment deposition are triggered by discharge modifications, changes of river morphology, for example, flood protection, hydropower use, as well as land use, for example, change of land cover type, and climate change (Leitner *et al*., 2015). Decreases in river discharge can affect mussel by decreasing water velocity, water depth, increasing sedimentation, changing the thermal regime and water chemistry (Gates *et al*., 2015). Fine sediments can lodge between coarser grains of the substrate to form a hardpan layer, thereby reducing interstitial flow rates (Boulton *et al*., 2010; Jones *et al*., 2015; Scheder *et al*., 2015). Fine sediments clog the interstices in which juvenile mussels must spend few years following excystment from their fish hosts; this clogging can lead to a critical shortage of oxygen that is often yet intensified by microbial metabolism effects in the fine sediments (Boulton *et al*., 2010). Several recent studies pointed to substrate composition and disturbance as one of the main limiting factors for mussel populations (e.g. Gosselin, 2015; Leitner *et al*., 2015).

The goal of this study conducted in period 2005–2009 was to identify strategies to protect and support the recovery of the DWM populations in the mainstem of the Upper Delaware River. Specific objectives were to

1 Quantify potential habitat available for DWM in the mainstem Delaware River.
2 Develop instreamflow scenarios that will protect and support the recovery of DWM habitat in the river sections containing potential habitat.
3 Develop models to predict the effect of various management scenarios on habitat conditions at known and potential DWM sites.

This paper will demonstrate the use of multiplex habitat models for the development of flow management criteria compliant with NFP using the Upper Delaware study as an example. It is the third in a series of papers describing the study and focuses on the results of DWM habitat simulations

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that concluded in habitat management recommendations. Parasiewicz *et al*. (2012a) presented the method used here to develop habitat suitability criteria for the endangered mussel fauna and Castelli *et al*. (2012) demonstrated how time series analysis was applied to develop water temperature management criteria protective to the mussels.

STUDY AREA

The Upper Delaware is located in Catskill Mountains Region about 200 km northwest of New York City (Figure 1). The Upper Delaware system consists of three main fourth-order rivers that flow into the Delaware's mainstem: the West Branch Delaware, East Branch Delaware and Neversink Rivers. They are part of an alluvial upland river system embedded in postglacial till with straightened-confined and meandering character, a pluvio-nival flow regime (i.e. high flows related to rain and snow melt in the fall and spring, and low flow in the summer, Pardé (1968)). The gradient is relatively low compared to headwater rivers and few wetlands accompany its course.

The upper Delaware underwent a dramatic transition over the past two centuries (Parasiewicz *et al*., 2009). Timber resources in the region were exploited from the beginning of the 19th century, including primary woodlands consisting of large white pine, hemlock and hardwood forests that served as a resource for high-quality wood, tannin, acid and charcoal production. Rivers, like the Delaware, that provided transportation pathways for the log raft industry were systematically cleared of obstructions and widened. Logging operations caused a dramatic change to the river bed resulting in a wider and shallower channel. In 1875, 240 km of the Delaware River was dredged to remove 'obstacles' for log rafting, causing a reduction of river bed variability and, together with periodic floods, caused further over-widening of the channel (The Hancock Herald, 29 October 1876). The resulting increase in solar radiation exposure and the generally shallower water depth, combined with lack of canopy cover and reduced subsurface water

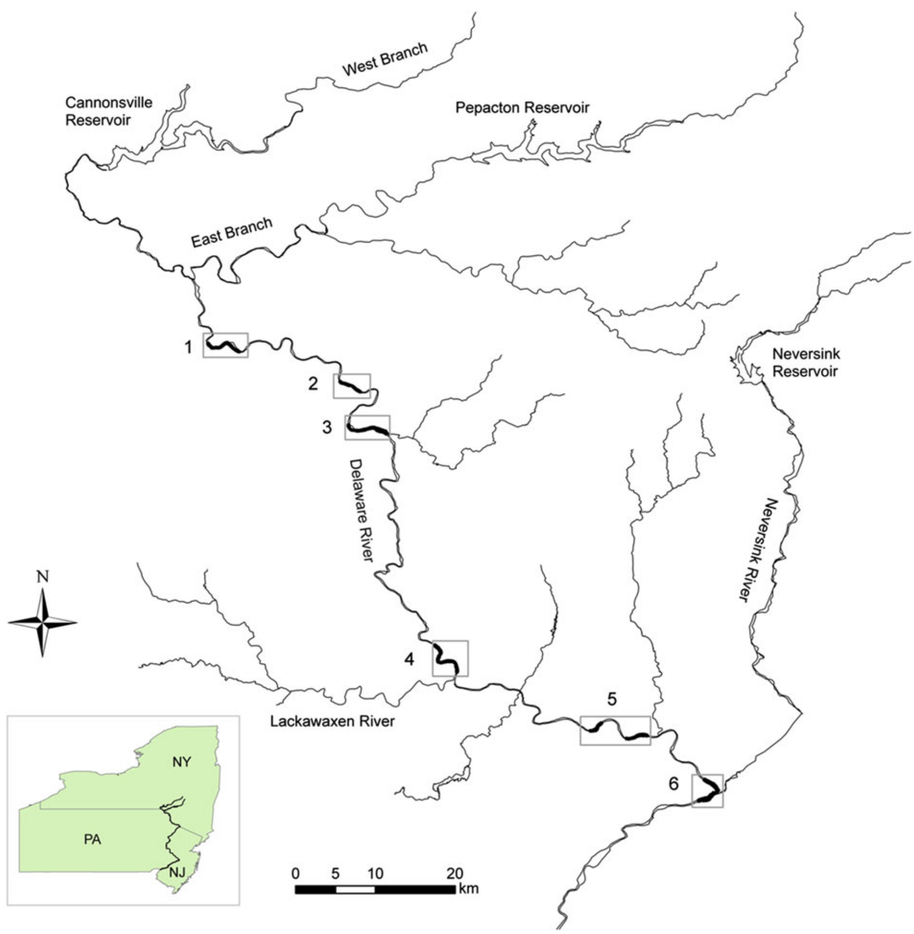

Figure 1. Map of Delaware River. Squares and numbers indicate the location of the study sites. Colour figure can be viewed at wileyonlinelibrary.com

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discharges, may have led to much warmer summer flows over the last century. Moreover, increased catchment sediment yields and bank erosion contributed to change in substrate composition within the river. In response to these factors, the faunal composition has shifted from a cold water community towards a more generalist and warm water assemblage (Parasiewicz *et al*., 2009).

For the most part, industry vacated the area in the late 19th and early 20th centuries, and the land was subsequently converted to agricultural use (Karas, 1997; Kudish, 2000). More recently, the forests have regrown; however, their water storage capacity is lower than it was under pristine conditions (Parasiewicz *et al*., 2009), thus supporting a flashy flow regime. With 22 million inhabitants and numerous industrial enterprises dependent on water from the Delaware River Basin, it is now an example of an intensively used resource with conflicting demands. Still, the sparsely populated upper portion of the basin represents a valuable ecological resource for both New York and Pennsylvania. Heralded as one of the most scenic rivers in the country and highly regarded for its fisheries and outdoor experiences, the river also serves as a local and regional (New York City) source of water supply.

New York City's Delaware system impounds three tributaries at Cannonsville Reservoir on the West Branch Delaware River, Pepacton Reservoir on the East Branch Delaware River and the Neversink Reservoir on the Neversink River. Approximately, 895.5 million m^3 (50% of mean annual volume) is diverted out of the Delaware Basin from these reservoirs each year through the Delaware Aqueduct. Typically, more than one fourth of the diverted water is from Neversink Reservoir, while Cannonsville Reservoir supplies less than a quarter and the Pepacton Reservoir provides the remaining half. The daily flows in the river are strongly influenced by releases from the three upstream reservoirs, and, because of complex management objectives, these flows can be erratic and unpredictable. Contrary to natural flows, the hydrograph patterns upstream of the Lackawaxen River (Figure 1) follow weekly or seasonal step functions. This is overlain by daily peaks downstream of the confluence that occurs during hydropower power generation at the Lake Wallenpaupack facility. A minimum flow target of $50\,m^3\,s^{-1}$ is maintained at the USGS gauge station in Montague, New Jersey, approximately 92 river km downstream of the nearest DWM site.

Our study area encompasses 125 km of the Upper Delaware River from the confluence of the East and West Branch Delaware River to the Montague USGS gauge. The watershed corridor along the study area is mostly rural and forested with small towns scattered along its length. The substrate throughout the study area consists mostly of fist to head size cobbles and numerous boulders (in excess of 2 m in places). Fine particles, such as silt and sand, occur in very small quantities, and overall embeddedness is very low. Woody debris and canopy shading are scarce in this section of the river, and shading is more often related to the orientation of steep valleys in portions of the river corridor. At flows of $5.47 \times 10^{-3}\,m^3\,s^{-1}\,km^{-2}$ (~ Q90) measured at USGS Gauge in Callicoon (downstream end of study site 3), the river consists of mostly pools and runs with areas deeper than 125 cm accounting for less than 50% of the measurements. Only a few very deep pools, rapids and backwaters could be found at this flow.

METHODS

The applied methodology is based on combination of River 2D hydrodynamic model, with MesoHABSIM approach and the uniform continuous under threshold (UCUT) analysis of habitat time series to develop environmental flow recommendations for the Upper Delaware River (Parasiewicz, 2001, 2007a, 2007b). The study focused on summer habitat conditions (so called Rearing and Growth bioperiod; 1 July–30 September). The methodological steps are (i) the application of multiplex habitat simulation models to define spatio-temporal DWM habitat distribution; (ii) the definition of hydrological and morphological improvements for the Upper Delaware River (Parasiewicz *et al*., 2012b); and (iii) the comparison of different habitat restoration scenarios.

Spatio-temporal habitat distribution

Because of the large geographical extent of the study area and the need to investigate the habitat suitability of DWM's at a very fine scale, a combination of two models; MesoHABSIM and River2D (Steffler and Blackburn, 2002) has been used to develop and transfer suitability criteria between scales. Multiplex habitat modeling applied calculated micro-scale suitability criteria to the river's mesoscale hydro-morphological unit mappings to determine suitable mesohabitats, which then served as a calibration data set for the coarser scale model as outlined subsequently.

Microhabitat suitability criteria were developed first using a large sample of random data points. Following a reconnaissance survey, six representative sites, total length 22.4 km, were selected throughout the study area (Figure 1). First three of the sites included currently existing mussel beds. The bathymetry and riparian corridor of five shorter subsites (toal length 15.2 km) were surveyed in high detail using a combination of light detection and ranging (LIDAR), on-foot topographic surveys using a total station and a radio transmitted kinematics Global Positioning System (GPS), as well as with bathymetric sounding with an echo sounder (AIRMAR P66) and an Acoustic Doppler Current Profiler unit (Sontek River Surveyor). A dense ($1\,m^2$) grid of digital elevation points was

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created in every study site. Mean column velocity and depth was computed with River2D for each of these points at 15 flow levels, covering a range from Q_{95} to Q_7.

To capture the influence of bottom substrate on the DWM, we followed the recommendations of recent studies that documented the good correspondence of complex hydraulic variables in the boundary layer (strongly influenced by substrate) for prediction of unioid distribution (e.g. Statzner *et al.*, 1988; Steuer *et al.*, 2008). These variables change with river flow and describe hydraulic forces directly affecting the animals. We therefore substituted measured substrate classes with corresponding Manning roughness and calculated boundary Reynolds number (turbulence in the boundary close to the river bottom, Re_* [Equation 1] and bottom shear velocity [friction velocity, U_* (Equation 2)]. Third complex hydraulic variable was Froude number [describing turbulence close to water surface, FR (Equation 3)]. The values of these variables were calculated for each point of the grid at each modeled flow according to the following formulas:

$$U_* = U[5.75log10(12Dk - 1)]^{-1} \quad (1)$$

$$Re_* = U^*kv^{-1} \quad (2)$$

$$FR = U(gD)^{-0.5} \quad (3)$$

Where

U is the mean column velocity [$cm\,s^{-1}$]
D is water depth [cm]
g is acceleration owning to gravity [$cm\,s^{-2}$]
k is substrate roughness
v is kinematic viscosity [$cm^2\,s^{-1}$]

Hence, as independent variables in a microhabitat model, we used a factorial combination of depth, velocity, bed roughness, Froude, shear velocity and boundary Reynolds number. Because mussels are sedentary organisms, the analysis took into account temporal changes in hydraulic patterns caused by flow fluctuations during the 2007 summer season (1 July to 30 Sept). This allowed us to capture the range of hydraulic conditions that mussels are exposed to during the water-limited time of the year. We computed a time series of depth, velocity, FR and Re_* at each point in our grid for flows recorded at 15-min intervals. We summarized the time series of the attributes with the coefficient of variation; the maximum; the minimum; and five percentiles: 5th, 25th, 50th (median), 75th and 95th.

Observations of *A. heterodon* from July 2008 were used for the selection of grid points occupied by the organisms. Five hundred (500) locations adjacent to the mussel beds were randomly sampled from within each of the three mussel containing sites. Multivariate statistics were applied to the simple and complex hydraulic data to find the best predictor variables for mussel habitat. We used classification and regression tree analysis (CART - a non-parametric technique that produces classification and regression trees) to determine which hydrological variables best separate the mussel locations from the random locations in the data set. The microhabitat models are then applied to identify the spot locations in all six sites with hydraulic characteristics similar to those where individual organisms have been found.

Four mesohabitat mapping surveys of each site between flows of 4.0×10^{-3} and $16.4 \times 10^{-3}\,m^3\,s^{-1}km^{-2}$ (Q_{99}, Q_{92} respectively—encompassing the range of low flows occurring in summer) described habitat features in hydromorphologic units (HMUs), such as e.g. pools, riffles and runs, following established MesoHABSIM protocols (Parasiewicz, 2001, 2007a). Mean column velocity, depth, substrate, embeddedness, shore properties and other attributes were collected for each HMU, and described above complex hydraulic variables were calculated. The mesoscale attributes are overlain by a detailed hydraulic survey indicating microhabitats with a high probability of finding mussels. The HMUs with large proportions of surface area covered by the suitable microhabitats are considered suitable as a whole and serve as calibration data for the mesoscale habitat model that predicts habitat suitability for the whole study area at different measured flows. The mesoscale habitat suitability criteria [assessed by 20 iterations of Akaike's information criterion analysis and logistic regression models as described in Parasiewicz *et al*. (2013)] defined moderately deep, slow-flowing and non-turbulent HMUs as providing good conditions for DWM (Table I). The model has a high-discrimination capacity due to an area under receiver operating characteristic curve higher than 0.8 and high-calibration success (Metz, 1978). The model indicated that the probability of DWM presence and high abundance was positively correlated with depths between 75 and 100 cm and Re_* between 55×10^3 and 65×10^3. The probability was reduced by more turbulent environments associated with the high-average Froude number, high velocity and extremely low Re_* numbers as well as boulders and rapids. More detailed descriptions of the methodology used to develop these multivariate habitat suitability criteria for DWM can be found in (Parasiewicz *et al*., 2012a).

Habitat suitability criteria were applied to each HMU to calculate the probability of mussel presence and classify it as not suitable, suitable or optimal. The total area of effective habitat (the weighted sum of areas with suitable and optimal habitat) was determined for both: sites with mussel beds (units where DWM were observed) and the entire study area at each flow. Habitat rating curves were created by linearly interpolating the effective habitat proportion of river channel area (CA) across the range of surveyed flows.

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Table I. Physical attributes correlating with the presence and high abundance of habitat for Alasmidonta heterodon

Presence model		Attributes	B	SE
Calibration success	0.76	Constant	2.78313	0.486
Estimated success	0.75	Rapids	−1.94694	0.534
Area under ROC	0.84	Ruffle	−1.13232	0.534
Cutoff (Pt)	0.70	$Re_*(55–65)·10^3$	6.966344	5.797
		$Re_*(25–30)·10^3$	−2.67517	0.994
		Average Froude	−4.7595	2.104
Abundance model				
Calibration success	0.80	Constant	4.7578	1.050
Estimated success	0.67	Boulders	−1.3832	0.367
Area under ROC	0.86	Rapids	−2.2077	1.374
Cutoff (Pt)	0.46	Depth 75–100 cm	4.2294	1.528
		Velocity 45–60 $cm\,s^{-1}$	−3.41	1.827
		Velocity >105 $cm\,s^{-1}$	−15.6197	12.825
		$Re_*(25–30)·10^3$	−6.5185	2.309
		$Re_* < 5·10^3$	−2.5947	1.040
		$Re_*(5–15)·10^3$	−4.3583	1.232
		Average Froude	−4.6123	2.908

The area under the ROC curve is a measure of the discrimination capacity of the model. Selected cutoff indicates the probability (Pt) separating not suitable, suitable, and optimal habitats. B represents regression coefficients of the logistic regression model. SE is standard error indicating the range of variability of selected attributes. See Parasiewicz (2001) for attribute definitions.
ROC, receiver operating characteristic.

The rating curves were used to create a habitat time series (habitograph) for the summer bioperiod. For this purpose, the river flow recorded on any given day is evaluated according to the calculated habitat area, which it provides for the species of interest (Parasiewicz, 2007b). The daily flow time series for the past 40 years were evaluated using two USGS gauges; in Callicoon (USGS 01427510—at site 3) as a reference for the upper river segment and Port Jervis (USGS 01434000—at site 6) for the lower segment. The flow time series were standardized to runoff units ($m^3\,s^{-1}\,km^{-2}$), dividing observed flow ($m^3\,s^{-1}$) by watershed area (km), to allow for spatial independence of the habitat data.

The habitat time series were investigated with the help of UCUT curves to identify habitat stressor thresholds (HST) (additional details in Parasiewicz, 2007a, 2007b). The purpose of this analysis is to investigate habitat duration patterns and to identify conditions that could create pulse and ramp disturbances as described by Lake (2000). A pulse stressor causes an instantaneous alteration in aquatic fauna densities, while a ramp disturbance causes a sustained alteration of species composition. In terms of habitat availability, a pulse stressor can be caused either by an extreme habitat limitation regardless of its 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 HST requires taking into account habitat magnitude, as well as duration and frequency of non-exceedance events as described subsequently.

Uniform continuous under threshold curves are used to evaluate the durations and frequency of continuous events with habitat areas lower than a specified threshold (e.g. 10% CA). Therefore, the sum-length of all events of the same duration within a bioperiod is computed as a ratio of a total duration in the record, and the proportions are plotted as a cumulative frequency (Parasiewicz, 2007b). This procedure is repeated for the entire set of thresholds with constant increments (e.g. 2% CA increment).

To identify HST, we analyzed the specific regions on the plot (Figure 3) with a higher or lower concentration of the computed curves. Common and less common habitat events are based on changes in area slope expressed by the shape of, and distances between, the curves. The applied procedure has two steps: (i) determination of pulse habitat threshold levels by selecting curves on the graphs and (ii) identification of critical durations to ramp HST by locating critical points of curve slope (Parasiewicz, 2007b; Castelli *et al*., 2012; Vezza *et al*., 2014).

Typically, the UCUTs that represent rare low-habitat availability, those that happen infrequently, are located in the lower left corner of the graph (Figure 3). They tend to be steep and very close to each other. As habitat area continues to increase, the UCUT pattern rapidly changes, and the distance between the curves increases. We selected the highest curve in the rare-habitat grouping as a rare habitat level threshold. The critical level defines a more frequent event than the rare condition, below which the habitat circumstances rapidly decrease. Therefore, the next higher UCUT line (the first that stands out) is identified as

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a critical level. The distance between the lines after exceeding the critical level is usually greater than in the previous group, but still close to each other. The next outstanding curve demarcating rapid change in frequency of events is assumed to mark the stage at which more common habitat levels begin (Parasiewicz, 2007a; Castelli *et al*., 2012). The corresponding flow levels creating rare, critical and common conditions are called subsistence, trigger and base flows.

The critical points on the UCUTs demarcate a change in the frequency of habitat underthreshold durations. This observation helps to identify the three types of duration events: typical, persistent and catastrophic. A persistent event is likely to occur every few years, but at the intra-annual scale, these long events are unusual (i.e. do not happen more than twice in a year). Catastrophic events are assumed to occur on a decadal-scale. Exceedance of duration thresholds to persistent and catastrophic ramp events (shortest persistent and longest persistent) results in habitat stress days (HSD). Anthropogenic factors (e.g. flow diversions) often increase the frequency of such ramp events, ergo the number of HSD.

The habitat time series analysis was repeated for different environmental settings in order to define HST and HSD for known mussel sites and the rest of the river under

a current conditions
b alternative flow management scenarios
c optimized conditions with enhanced hydro-morphology and flow patterns

Improving hydro-morphological conditions

Defining protected flows for DWM require the determination of conditions to which the species have adapted their behaviour (Kalmijn, 2000). The interplay of flow and natural morphological structure define the available habitat, within which natural selection favours the species utilizing that habitat. If the morphological structure is modified, even the most natural flows may be unable to create the patterns of depth and velocity suitable for the native fauna. If flow patterns and habitat structure are modified, finding suitable habitat conditions is even less likely, because the occurrence of habitat is a function of both flows and morphological structure. Therefore, to improve population status, we may need to maximize habitat availability by adjusting both flows and riverbed morphology.

In order to improve the flow component, we implemented the following logic: it is widely accepted that prior to human-induced alterations the populations of DWM were sustainable and not on the verge of extinction. Therefore, we expect that recreating hydrological characteristics close to historical conditions will capture those benefiting species adaptations and therefore should assure the survival and improvement of species status. Deducing from well-established hydrological trends associated with stream urbanization (e.g. Seaburn, 1969; Schueler, 1987) as well as from flow patterns observed in previous North Eastern USA studies (Parasiewicz, 2008; Parasiewicz *et al*., 2009), under historical conditions we would expect flow patterns to be less flashy, with higher and more consistent low flows and less dramatic high flows.

On the other hand, it is neither practical nor our intention to prohibit the use of water from the Upper Delaware River. Consequently, as a maximum achievable improvement, we investigated conditions that take major water withdrawals into account, while also reducing erratic fluctuations in the flow pattern. Hence, to adjust the modeled flows, we simulated flow releases minimizing instantaneous fluctuations by applying a 3-day running average to the flow time series measured downstream of the reservoirs. This provides an approximation of more naturalized flow patterns that compensate for landscape modification in the watershed while staying within the expected limitations of our study.

As a second-study component, structural habitat improvements were simulated with the goal of providing maximum habitat area and stable hydraulic conditions (high and flat rating curves) for DWM, such as those observed in the mussel beds throughout the study area. The analysis of habitat suitability criteria for DWM pointed to the need for an increase in the abundance of pool, glide and run habitats; shallow margins and canopy cover; as well as an increase of Re_* (Table I). Consequently, the following modifications were introduced to the model:

1. Hypothetical alteration of HMU proportions. Decreasing the area of each rapid and ruffle to 200–300 m^2 and increasing the area of all glides, runs and pools proportionally and conserving a static total area.
2. Changing Re*. Maximizing the proportions of areas with bottom Reynold's number between 45 and 55×10^3 and proportionally reducing areas with lower Re*.
3. Alteration of Depths: doubling the proportion of areas with depths between 75 and 100 cm and proportionally reducing areas with depth outside this range.
4. Changing canopy cover and shallow margin presence: the attributes were set to present for all HMUs where it was observed as absent.

A separate habitat model for DWM was calculated for each of these modifications. Rating curves for each model were analyzed and the percent habitat increase calculated. A final optimized habitat model was created by combining models 1 through 3 in accordance with the highest percent habitat increase.

Scenario comparison

To identify measures that could create the improvement of habitat conditions, we analyzed a few selected scenarios representing promising and realistic management actions.

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For comparisons of the results we followed a conceptual model presented by Nestler *et al*., 2010. The possible measures analyzed included naturalizing flow patterns, optimizing morphology as described earlier, as well as two flow augmentation strategies (minimum flow and pulsed flow augmentation).

In total, five scenarios were compared for each segment (DWM beds and study area):

1. Naturalized flow
2. Optimized morphology
3. Optimized morphology and naturalized flow
4. Minimum flow
5. Pulsed flow

For best achievable conditions (represented by scenario 3) improved hydro-morphological conditions for mussel sites (i.e. consisting of HMUs where species were physically observed) were created by applying simulated naturalized flow time series to the habitat rating curve calculated for the segment including DWM beds. In the same way, naturalized conditions for the whole river were developed by applying naturalized flow conditions to the simulated habitat rating curve representing optimized morphology.

In the first flow augmentation model (scenario 4), we established a minimum flow equivalent to subsistence flow levels determined for the existing DWM beds. In the second flow augmentation model (scenario 5), we simulated hypothetical pulse flow conditions. Here, the habitat quantity was allowed to decline under the critical threshold for existing DWM beds, but a flow pulse equivalent to base flow was released for 2 days when flows were continuously lower than trigger values for the duration exceeding the short persistent (SP) threshold.

Subsequently, we also investigated combination of scenarios 2 and 5 as desired future conditions according to Nestler *et al*. (2010).

The alteration of HSD was used as an evaluation metric to compare between current conditions and simulated settings (Parasiewicz *et al*., 2012b). HSD is calculated as a cumulative duration of days where the persistent and catastrophic durations for selected thresholds have been exceeded. The cumulative durations for the shortest persistent (SP) and the longest persistent (LP) threshold measured in each scenario are presented as proportions of those occurring in current durations. When the HSD is lower than 100%, then the simulated measure creates an improvement and vice versa.

RESULTS

Current conditions

The rating curves representing effective habitat conditions for the entire study area as well as for dwarf wedge mussel (DWM) sites are shown in Figure 2. They capture the habitat change during low flows between 3.28×10^{-3} and $19.68 \times 10^{-3}\,m^3\,s^{-1}\,km^{-2}$ (Q_{94} and Q_{51}). The percentage of channel area (CA) of the Delaware River suitable for DWM varies between 30% CA and 55% CA depending on the flow. In the mussel sites, the available habitat is higher and accounts for most of the wetted area. Over the range of modeled flows, suitable area begins at 63% channel area and continuously increased to 75% CA. The rating curve is very stable and does not vary much between flows.

Figure 3A presents UCUT curves for DWM habitat in the mussel segment of Delaware River under current conditions. The table in the curve demonstrates selected thresholds that can be interpreted as follows: available effective habitat is frequently lower than 74% CA. Typically, the duration of these events is shorter than 53 days (identified by the change in gradient on the curve). On the other hand, the effective habitat is rarely less than 70% CA (bottom-left corner), and when it occurs, the typical durations below the SP threshold are shorter than 7 days. If the event is longer than 13 days, it should be considered catastrophic ramp. Effective habitat falls into the critical-persistent ramp category if it stays under 71%

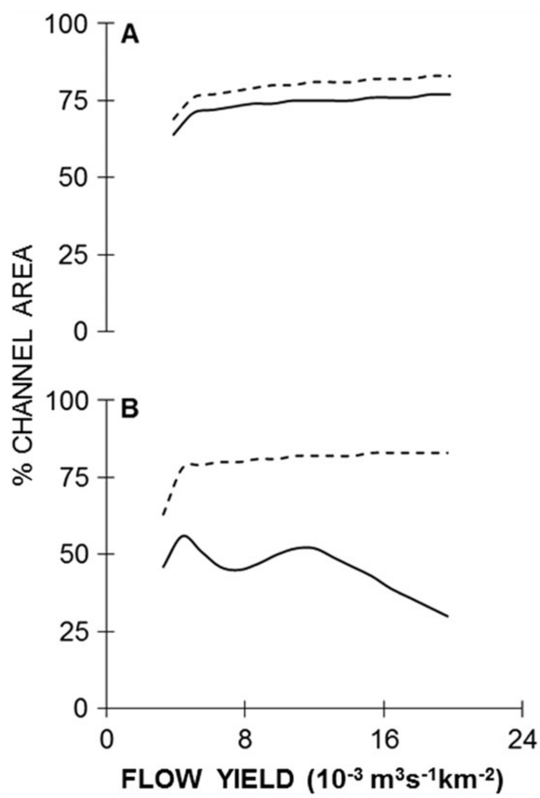

Figure 2. Flow-habitat rating curves for Dwarf wedgemussel in (A) sites with mussel presence, and (B) whole study area. The effective habitat availability is represented as a percentage of channel area.

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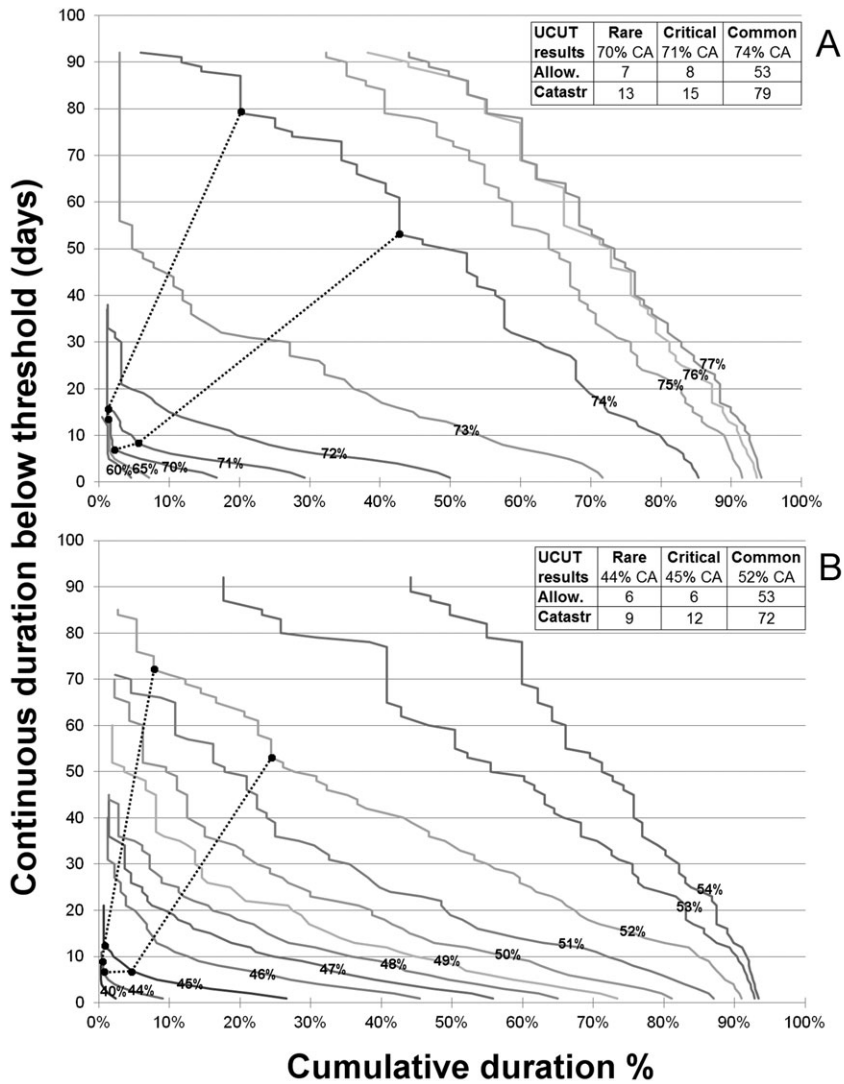

Figure 3. Uniform continuous under threshold (UCUT) curves for segments containing (A) mussel beds (B) study area during the summer bioperiod on the Delaware River. The table demonstrates the selected thresholds.

CA for longer than 8 days. If occurring for longer than 15 days, these conditions may be considered in the catastrophic occurrence frequency. The flows associated with these thresholds are the subsistence flow of $4.92 \times 10^{-3}\,m^3\,s^{-1}\,km^{-2}$ ($23.2\,m^3\,s^{-1}$ at Callicoon gauge) for rare threshold (70% CA), a critical flow of $5.47 \times 10^{-3}\,m^3\,s^{-1}\,km^{-2}$ ($26.3\,m^3\,s^{-1}$ at Callicoon gauge) for critical threshold (71% CA) and a base flow of $9.95 \times 10^{-3}\,m^3\,s^{-1}km^{-2}$ ($46.9\,m^3\,s^{-1}$ at Callicoon gauge) for the common threshold (74% CA).

Figure 3B presents UCUT curves for DWM habitat in the entire study area of the Delaware River under current conditions. Commonly, the effective habitat is lower than 52% CA. Typically, the continuous duration of such events is shorter than 53 days. On the other hand, the effective habitat availability is rarely less than 44% CA. If occurring for longer than 9 days, these conditions should be considered of catastrophic ramp. The effective habitat falls into critical-persistent ramp category if it remains under 45% CA for longer than 6 days. If it remains under these conditions for longer than 12 days, conditions may be considered catastrophic. The flows associated with these habitat events are equivalent to the same subsistence, critical and common flows as for the mussel habitat area.

Best achievable condition with optimized hydro-morphology

The flow-habitat rating curves for all simulations with improved morphology in the study area are presented in Figure 4. The greatest improvement is created under Simulation 2. The combination of all three improvements utilizes most of the available wetted area as suitable habitat,

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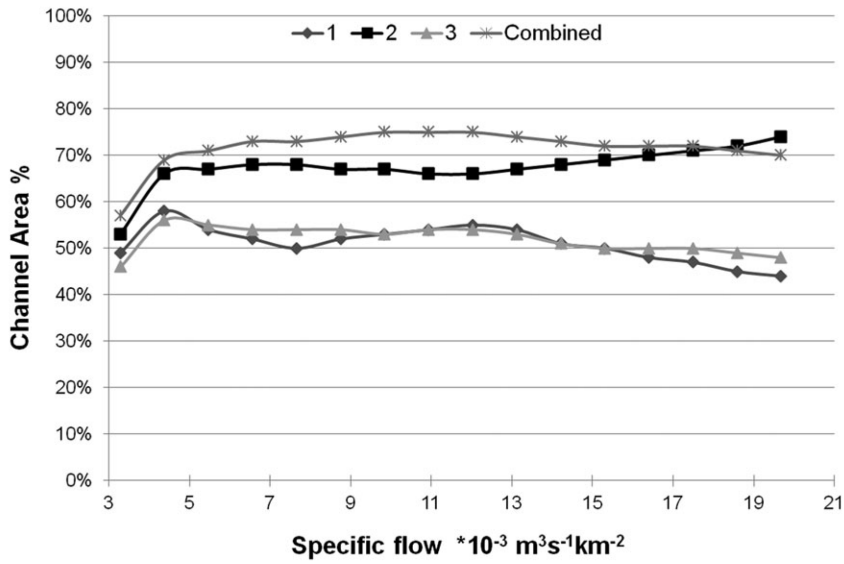

Figure 4. Simulated habitat rating curves for dwarf wedge mussel. (1) Suitability habitat rating curve with decreased area of unsuitable HMUs (rapids and ruffles) down to 200–300 m^2. (2) Suitability rating curve with increased bottom Reynold's value. (3) Suitability rating curve with modified depths at 75–100 cm in current conditions. (Combined) Rating curve that takes into account the combination of decreased area in rapids and ruffles, increased Reynolds number and modified depths.

doubling the amount of area currently available at higher flows. It also creates much more stable conditions that do not vary much with variation in flows.

UCUTs curves derived from the naturalized hydrograph for DWM sites are presented in Figure 5A. Rare habitat events occur with value less than 70% CA. Typical durations of these events are shorter than 5 days. If it persists longer than 13 days, the conditions may be considered catastrophic ramp. Most of the time, available habitat is under 74% CA, typically with a continuous duration of less than 34 days. This situation should be considered catastrophic if it persists longer than 83 days. The flows associated with thresholds are $4.70 \times 10^{-3}\,m^3\,s^{-1}km^{-2}$ for the rare threshold (70% CA), $5.36 \times 10^{-3}\,m^3\,s^{-1}km^{-2}$ for the critical threshold (71% CA) and $9.62 \times 10^{-3}\,m^3\,s^{-1}\,km^{-2}$ for common threshold (74% CA).

Figure 5B presents UCUT curves for DWM habitat in the study area for naturalized flow conditions (obtained applying the combined rating curve to naturalized flow). The common habitat threshold is 73% CA and typically lasts for durations of under 33 days. The habitat availability is rarely less than 70% CA and in those cases persists typically for less than 7 days. If the duration is longer than 14 days, then the event should be considered catastrophic ramp.

Scenario comparison

Table II summarizes stress day comparisons between the current conditions and the simulated scenarios. The greatest improvement to the study area was created by modifying the morphology of the river (comparison number 2), bringing the number of stress days to zero with respect to current situations. Naturalized or managed flow alone does not have a role in changing HSD when morphology is modified, as shown by comparison 2, 3 and 6. Managing the flow without optimizing morphology can also lead to improved habitat. In DMW sites, the number of rare stress days drops to zero when managing for a minimum flow (comparison 4) or a pulsed flow (comparison 5). In the whole river, while stress days are reduced significantly for rare events with both flow management scenarios, setting a minimum flow created a more than sevenfold increase in the number stress days for common events. This is a consequence of reducing the duration of rare events at the cost of extending the duration of events with habitat magnitude less than the common threshold. Hence, scenario 6 is offering the most effective habitat improvements.

DISCUSSION

Sedimentation, nitrogen enrichment and hypoxia have been suggested to affect mussels (Strayer and Malcom, 2012). Excessive amounts of sediments, especially fine particles, that wash into streams can potentially affect mussels through multiple mechanisms (Box and Mossa, 1999). The distribution of mussels is influenced by the composition of the bed material, dynamics of the suspended bed material load and changes in substrate composition. Michaelson and Neves (1995) performed substratum choice experiments on *A. heterodon* and found that they always moved toward finer sediments. Unionids can move considerable distances in a

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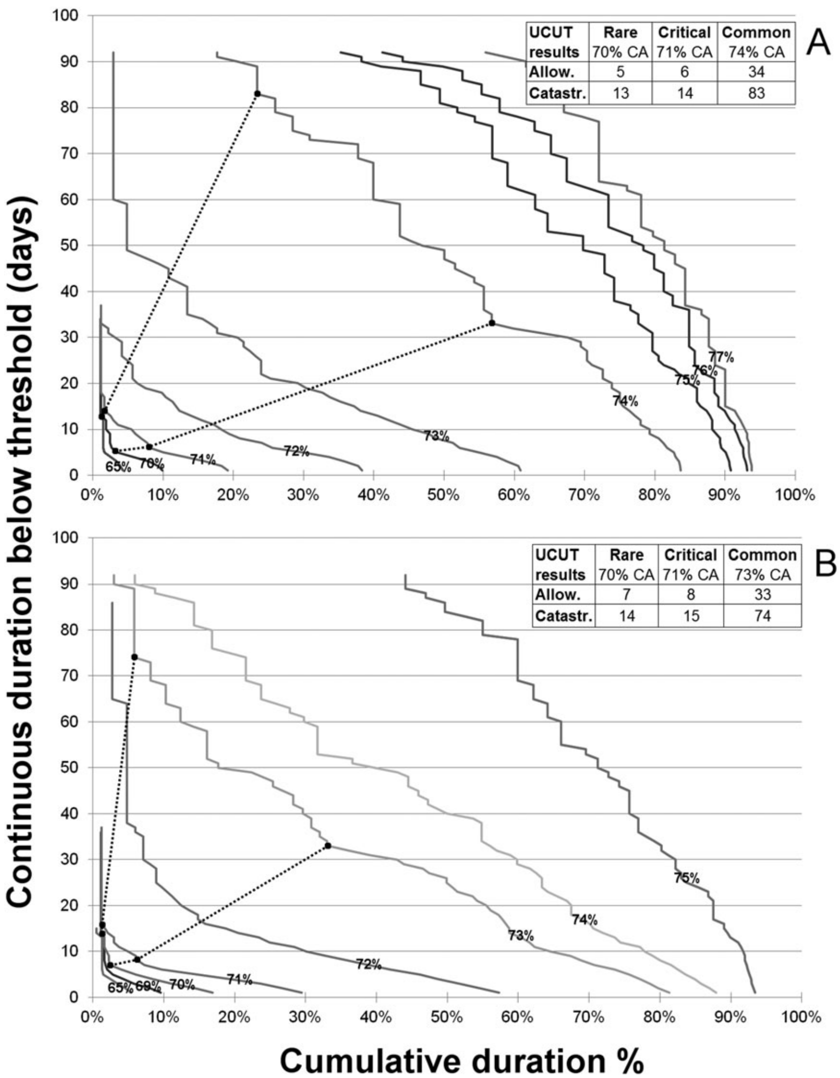

Figure 5. Uniform continuous under threshold (UCUT) curves under naturalized conditions for segments containing (A) mussel beds (B) study area during the summer bioperiod on the Delaware River. The table demonstrates the selected thresholds.

Table II. Change in stress days (% ratio) from current to simulated

		1		2		3		4		5		5 + 2	
		SP	LP	SP	LP	SP	LP	SP	LP	SP	LP	SP	LP
DMW sites (a)	Common	102	116	100	100	102	116	93	83	93	85	93	85
	Rare	130	70	100	100	130	70	0	0	0	0	0	0
Whole area (b)	Common	194	370	0	0	0	0	285	771	108	100	0	0
	Rare	139	50	0	0	0	0	23	0	46	0	0	0

(1) Current conditions versus unregulated flow; (2) current conditions versus optimized morphology; (3) current conditions versus optimized morphology and unregulated flow; (4) current versus minimum flow; and (5) current condition versus pulsed flow.
LP, longest persistent; SP, shortest persistent.

relatively short time during summer months (Schwalb and Pusch, 2007). *A. heterodon* occurred frequently in microhabitats contained patches of fine sediments and sandy substratum (Strayer and Ralley, 1993). *A. heterodon* was usually absent in highly silted water bodies, and this may be related to oxygen concentration both in surface substrata and

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hyporheic zone. Additionally, Strayer and Malcom (2012) found strong relationship between interstitial un-ionized ammonia and mussel (*Elliptio complanata*) recruitment.

On the Upper Delaware River, increased sedimentation and water quality impairment are not so prevalent to be a habitat limiting factor, as substrate distribution lacks abundant fines and the forested rural character of the watershed is not degrading water quality. *A. heterodon* beds were located in areas with lower shear stress and velocity relative to the main channel (Maloney *et al*., 2012), but Briggs *et al*. (2013) stated that a constant source of a cold ground water in stagnant areas may also be necessary for survival of a wedgemussel living in shallow areas near to river bank. Hence, the natural distribution of *A. heterodon* may not be due to substratum preference but to factors that alter the growth or survival of freshwater mussels, such as reproduction, predation or the chemical and physical characteristics of muddy and sandy habitats.

In Strayer and Ralley (1993) sediments, granulometry was also ineffective in predicting the distribution or abundance of Unionidae, including *A. heterodon*. The authors also suggest that including geomorphological descriptors of the streambed or working at spatial scales of hundreds of meters might be more useful than a traditional microhabitat approach for predicting the distribution of freshwater mussels in streams. In our study, we partially followed these suggestions by investing microhabitats to relate temporal variability of near-bed hydraulic attributes (dependednt on geomorphology and substrate) to DWM distribution, assessing habitat suitability at the geomorphic unit scale and puzzling it together for more coarse scale analysis.

Despite the large reservoirs within the watershed, potential disturbance to mussel beds that could be caused by high flows is currently beyond human control. However, lethal temperatures, lack of food supply, factors limiting host species and unstable hydraulic habitat were identified by local mussel biologists as a potential threats to DWM in the Upper Delaware River (Lellis pers. comm., see also Steuer *et al*., 2008). Consequently, when searching for factors potentially limiting the habitat distribution and also when developing feasible improvement options, we focused on low flow conditions occurring during the summer season.

The identification of HST from UCUT curves provided a means of quantitatively comparing the effects of those scenarios on the four (magnitude, timing, frequency and duration) habitat components recommended by the NFP. The analysis is based on the assumption that conditions occurring rarely in nature create stress to aquatic fauna and shape the community. Therefore, the criterion adopted here to assess the improvement of habitat conditions was the reduction of HSD for rare events with respect to the current setting.

As indicated by the shape of the rating curves for current and optimized conditions with introduced morphological modifications to the study area (Figures 2B and 4), we succeeded in creating habitat conditions similar to those found in the current mussel beds. The greatest improvements were accomplished by increasing the boundary Reynolds number into a suitable range. In practice, this could be accomplished through increasing the morphological diversity of river bottom, which would create substrate conditions and dynamics supporting DWM colonization. It has to be pointed out that in addition to the application of a multiplex habitat model, the use of complex hydraulic metrics to describe the substrate conditions is another particular innovation of this study that allowed the authors to consider substrate dynamics related to the flow conditions.

In comparison with the optimized habitat simulated for the entire river, current habitat availability would be classified as rare (effective habitat below 70% CA). This may explain why DWM mussel beds are located in locations where the frequency of suitable habitat area above 70% CA is much higher.

No significant change to the UCUTs could be observed for the mussel sites (compare Figures 3A and 5A) when introducing more naturalized flow patterns. This result is confirmed in the simulation comparisons in Table I, which shows that introducing naturalized flows into the model did not cause any significant reduction of HSD. However, in the whole area, it leads to increase in HSD for LP at the common level. This demonstrates that in the remaining section of the Upper Delaware without morphological improvements even the naturalized less flashy flows may be unable to create the patterns of depth and velocity suitable for DWM. This result is logical because the river's current condition is the product of 200 years of intensive human-induced morphological alterations described earlier.

Therefore, a flow management plan, which does not include morphological modifications of the riverbed, should aim to create improved flow conditions in the current mussel beds. Both flow augmentation strategies (minimum and pulsed regime) would nullify the rare stress days. This would fulfill the goal of better DWM protection in their current habitats. To promote the development of populations beyond the current mussel beds, at minimum, a pulsed flow regime reducing the frequency of persistent habitat deficits would need to be created. To accomplish it fully, channel improvements reducing Re* would be necessary.

The choice of a pulsed strategy is further supported by water temperature pattern analysis presented in Castelli *et al*. (2012). The paper demonstrates that setting a minimum flow of $4.70 \times 10^{-3}\, m^3 s^{-1} km^{-2}$ may not be enough to protect the mussel population because of exposure to potentially harmful temperatures (26.5 °C for a

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period longer than 6 days) during the summer bioperiod. Even if the temperature at the confluence of East and West Branches is lower than 21 °C when daily maximum of air temperature exceeds 25 °C and flow is less than $6.56 \times 10^{-3}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$, the thermal threshold at the Callicoon mussel site is exceeded after only 6 days. To avoid thermal stress in these circumstances, cold water releases are proposed. The pulsed strategy recommends after 6 days of flow lower than $5.47 \times 10^{-3}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$ a 2-day increase of flows to $9.84 \times 10^{-3}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$ concurs with the recommendations of this paper.

In our study, the habitat improvement scenarios were developed at two different scales: one scale that was limited to the segments of the river where the mussels are still present, and the second scale investigating the whole study area. Ensuring that any modifications aiming to improve habitat would not damage the existing mussel sites was an important consideration in simulation evaluation. This concern could not be confirmed because the number of stress days did not increase in any scenario.

New York City's future water needs may conflict with the habitat needs of the endangered DWM in the Upper Delaware River by reducing flow levels and increasing water temperatures, particularly during summer months. The objective of this study was to identify strategies to protect and support the recovery of the existing populations of DWM in the mainstem of the river. Creating more suitable habitat for the species expansion in the river through the structural restoration of river morphology may be costly and not practical to implement at least on a large scale. The pulse flow management strategy is therefore the first step to assure DWM protection and guarantee the survival of the species. The morphological improvements can be gradually introduced to increase potential habitat throughout the river.

Still, we also need to consider that the upper Delaware River supports a diverse community of aquatic fauna, including but not limited to the freshwater mussel. This paper describes the development of a strategy for the protection of an endangered species, but it is conceivable that the proposed scenarios could be damaging to other members of aquatic community. Therefore, it is important that impacts to the entire aquatic community be investigated as a part of adaptive management process. The MesoHABSIM model created in this study could be easily adapted to analyze habitat availability for fish and invertebrates by introducing the appropriate habitat suitability criteria. This has not yet been completed, but the authors highly recommend such an analysis together with efforts towards model verification.

The application of MesoHABSIM and habitat time series analysis provided a large-scale insight into freshwater mussel habitat and allowed for the quantification of changes to habitat under several remediation measures. Still, we need to be aware that, like all models, this one is based on many assumptions, which need to be verified during any potential implementation. There may be biological phenomena not recognized in this study due to lack of sufficient data for endangered species. Although unlikely, it could be argued that because we base our observations on only a few isolated populations centers, the organisms may be occupying conditions that are closer to subsistence rather than to optimal. Nevertheless, the conclusions of this study offer a concrete step toward an adaptive management process, which may allow us protect and expand this species' habitat availability. We are encouraged that the results of this study are similar to other unioid studies (e.g. Steuer *et al*., 2008; Maloney *et al*., 2012). This study also demonstrated the utility of an applied approach for the implementation of NFP as well as the potential drawbacks of the paradigm if applied without considering habitat limitations caused by the morphological alterations.

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