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HABITAT TIME SERIES ANALYSIS TO DEFINE FLOW AUGMENTATION STRATEGY FOR THE QUINEBAUG RIVER, CONNECTICUT AND MASSACHUSETTS, USA

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ABSTRACT

We developed a habitat augmentation strategy for the Quinebaug River (Connecticut and Massachusetts, USA) in order to reduce impacts on fish habitat, water temperature and pollutant concentrations attributable to consistently low water flows. Using the MesoHABSIM approach and a uniform continuous under-threshold (UCUT) analysis of simulated habitat time series, we determined allowable periods of low-flow conditions that follow natural patterns. The amount of water necessary to achieve the required habitat levels was calculated for various river restoration scenarios. We also created a set of detailed rules for a habitat augmentation release that applies short 'pulses' of water to increase habitat availability and mitigate the effects of persistent drought conditions. A set of flow chart templates was developed to guide the planning of an augmentation scheme by utilizing flow releases from reservoirs. To test our augmentation procedures, we performed evaluation tests by applying the rules to flows that occurred in 1994 (a drought year). The test showed that the number of flow interventions necessary was limited, underlining the feasibility of a pulse-based approach. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: bioperiod; UCUT curve; habitat threshold; flow augmentation; natural flow; drought response

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INTRODUCTION

Recent studies have shown that in fluvial ecosystems flow variability and dynamics create a physical habitat template, which shapes the composition and structure of the aquatic community (Jowett and Duncan, 1990; Poff and Allen, 1995; Poff *et al*., 1997; Richter *et al*., 1997). Magnitude, frequency and predictability of temporal variation are key components of such a template (Poff and Ward, 1990). Therefore, when evaluating environmental thresholds, it is essential to consider not only the magnitude of an impact, but also its duration and frequency.

Modifying the hydraulic character of an ecosystem by an extended duration of low flows creates lower velocities and depths. Such low flows lead to increased temperature and pollution levels, introducing stresses on the entire aquatic community (Hewlett and Hibbert, 1967; Bunn and Arthington, 2002; Parasiewicz, 2004). Over time it provides habitat more suitable to lentic and generalist fauna, giving these species a competitive advantage (Poff and Ward, 1989; Kinsolving and Bain, 1993).

Using historical flow records for the period of record 1948–1994 at the USGS gauge located at Quinebaug, Connecticut, Fennessey applied the QPPQ transform technique (Fennessey, 1999) to simulate a hydrograph for catchment without impervious areas created by humans (Fennessey *et al*., 2004) (Figure 1). The comparison of simulated and measured hydrographs and negative run time length analysis (Fennessey, 1997) shows that the number and duration of low flows under measured conditions is higher (Figure 2). This persistent low flows in the Quinebaug River (Connecticut and Massachusetts, USA) result in a constant suppression of fish habitat quality (Parasiewicz, 2004) and are a consequence of hydrologic modification of the watershed (e.g. sprawl, impervious areas). Hydrological modifications caused by landscape change are intractable and hard to mitigate for.

Presently, these detrimental flows are only in part related to reservoir operation, as most of the dams are operated using 'run-of-the-river' management practices. The presence of dams in the system offers opportunities for

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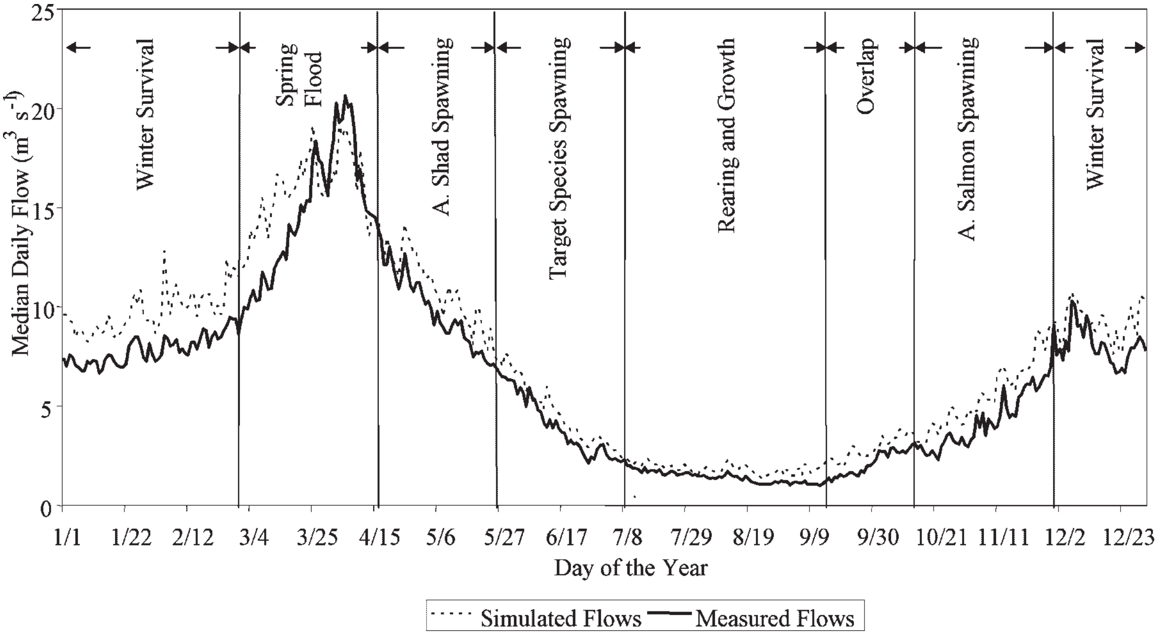

Figure 1. Measured and simulated hydrograph for Quinebaug River gauge (median of daily means) with superimposed bioperiods and lines indicating the beginning and end of each season

mitigating landscape impact through flow augmentation in critical periods. By releasing water in a way that mimics natural flow patterns, we can attempt to provide habitat conditions that more closely approximate those to which the native fish fauna are adapted. This paper presents this procedure using an example from the Quinebaug River project. The detailed site description, overall objectives and conclusion of the project can be found in the Quinebaug Ecohydrology Study Final Report (Parasiewicz, 2004).

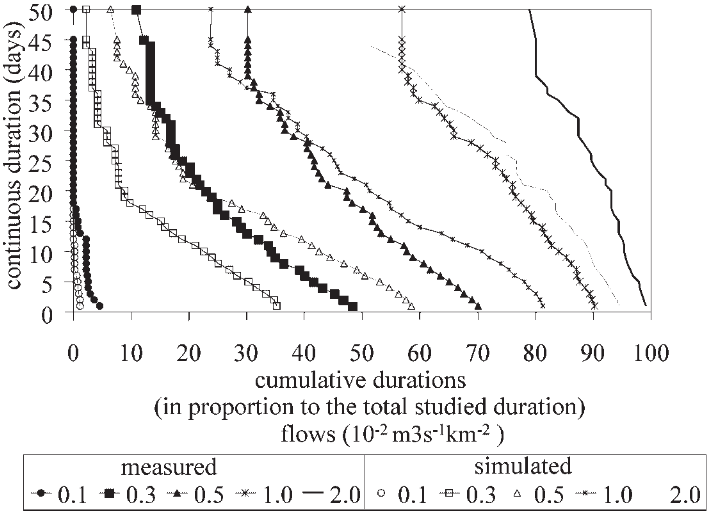

Figure 2. Comparison of flows measured by the Quinebaug River gauge in summer 1994 with simulation for the same period with the help of negative run time length. The curves are constructed similarly to the UCUT curves described below, just using flow-time series instead of habitat-time series. The curves associated with present conditions are shifted to the right when compared with those for simulated time series. This indicates that flows under values represented by curves are more frequent in measured time series. The events also last longer because the inflection points on the curves are higher on the graph

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METHODS

Of all the trends evaluated in the Quinebaug River study, the one most noticeable is the larger magnitude and different variability of the simulated natural flows when compared to the historically measured (altered) flows. The simulated, natural flow regime has fewer large peaks (in magnitude and frequency) than those measured at the Quinebaug gauge. The simulated base flows, on the other hand, are greater in magnitude than those observed at the gauge and are also more variable. Consequently, one of the apparent impacts on the Quinebaug River hydrology is extended duration of continuous low-flow events. These low flows not only alter hydraulic habitat (lower velocities and depth) but also lead to dramatic temperature increases (Parasiewicz, 2007a, this volume). Hence, the Quinebaug River-specific habitat template, as defined by Poff and Ward (1990), is altered. Consequences such as low fish density and a high proportion of temperature-tolerant pond species are well documented in the study of the Quinebaug River (Bain and Meixler, 2000; Parasiewicz, 2004). In order to reduce these flow alterations we needed to develop a procedure that would bring the habitat dynamics of the Quinebaug River closer to the natural habitat template. For the low-flow periods it means foremost to prevent press disturbances by increasing flow variability.

This study focuses primarily on low-flow conditions between $0.3 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$ (cubic meters per second per square kilometre of drainage area) and $2.2 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$ (0.3–$2.0\,\mathrm{ft^3\,s^{-1}\,mi^{-2}}$, cubic feet per second per square mile of drainage area). We developed rules for mitigation of persistent low-habitat conditions for various restoration scenarios, based on the MesoHABSIM model developed for the Quinebaug River described in Parasiewicz (2007b, 2007c). The avoidance of unnatural habitat stressors, which are identified by analysing the frequency and duration of seasonal habitat levels common under simulated conditions, are the goal of the development of our dynamic flow augmentation rules.

Selected bioperiods

A separate set of rules applies to the specific season (bioperiod), intra-annual seasons with specific biological functions. We assumed that change in flow patterns triggers the change in behaviour of fish species occupying the river. Therefore, to identify bioperiods the natural hydrological regime (Figure 1) was compared with biological life history information obtained from the literature (Scarola, 1973; Scott and Crossman, 1973; Smith, 1985; Jenkins and Burkhead, 1994). The beginning and end of each bioperiod were adjusted to coincide with changes of natural flow patterns on the simulated hydrograph.

We identified six bioperiods. A single collective spawning bioperiod (26 May–7 July) was selected for the five target species: fallfish (*Semotilus corporalis*), common shiner (*Luxilus cornutus*), white sucker (*Catostomus commersoni*), longnose dace (*Rhinichthys cataractae*) and blacknose dace (*Rhinichthys atratulus*) (Figure 1).

The shad spawning bioperiod of 16 April–25 May represents the time during which American shad (*Alosa sapidissima*) would typically be attempting to spawn in a river like the Quinebaug (mid-latitude eastern seaboard), if they were able to reach this segment of the river. The Atlantic salmon (*Salmo salar*) spawning bioperiod of 16 September–30 November was based on information indicating that this now-extirpated species would have been attempting to reproduce in the river during this time.

A rearing and growth (and summer survival) bioperiod begins 8 July (immediately following the termination of the spring spawning season for the five target species) and continues until 15 September. In this bioperiod, the lowest and warmest flows are expected to occur (Fennessey *et al*., 2004); young-of-the-year (YOY) fish are highly associated with shallow margins and adult fish are associated with deep and cool moving pools.

A combination of continued growth for YOY of the selected target species and the early spawning of Atlantic salmon resulted in the creation of an overlap bioperiod. This bioperiod, from 16 September to 15 October, was established to address the complexity of this time. In the Quinebaug River, the flows were still below $1.10 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$ ($1.0\,\mathrm{ft^3\,s^{-1}\,mi^{-2}}$) but increased continuously, which increase may be associated with slow reduction in evapotranspiration. During the following salmon spawning bioperiod the flows continuously increased until approximately $2.2 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$ ($2.0\,\mathrm{ft^3\,s^{-1}\,mi^{-2}}$) and displayed higher fluctuation. The water temperature dropped rapidly.

The winter survival bioperiod, defined as 1 December to the end of February, represents a time when the fauna must be able to find adequate habitat that will sustain them through the coldest months. The water is cold with relatively stable discharge levels right above $2.2 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$ ($2.0\,\mathrm{ft^3\,s^{-1}\,mi^{-2}}$).

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Finally, the spring flood and storage bioperiod was established from 1 March to 15 April, again based solely on the hydrograph. This delineation was made because there was a consistent period of relatively high and variable flows resulting from spring thaws and early rains, which is necessary for dispersal of early life stages of some species (e.g. Atlantic salmon). In the Quinebaug River the median of daily mean flows rose to approximately $4.4 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$ ($4.0\,\mathrm{ft^3\,s^{-1}\,mi^{-2}}$).

UCUT development

As described in Parasiewicz (2007b) we define two types of stressors that affect aquatic communities: a pulse stressor and a press disturbance (Niemi *et al*., 1990). The stressor thresholds are selected with help of habitat time series analysis. First, we defined the habitat variability and availability necessary to support the target fish community (Bain and Meixler, 2007). In order to analyse the habitat variations, we modified continuous under-threshold habitat duration curves (CUT curves) presented by Capra *et al*. (1995). The curves evaluate durations and frequency of continuous events with habitat lower than a specified threshold as a proportion of the entire study period, (Figure 3). To create our uniform continuous under-threshold habitat-duration curves (UCUT curves), we first 'translated' the simulated hydrological time series (mean daily flows from 1948 to 1994) into a

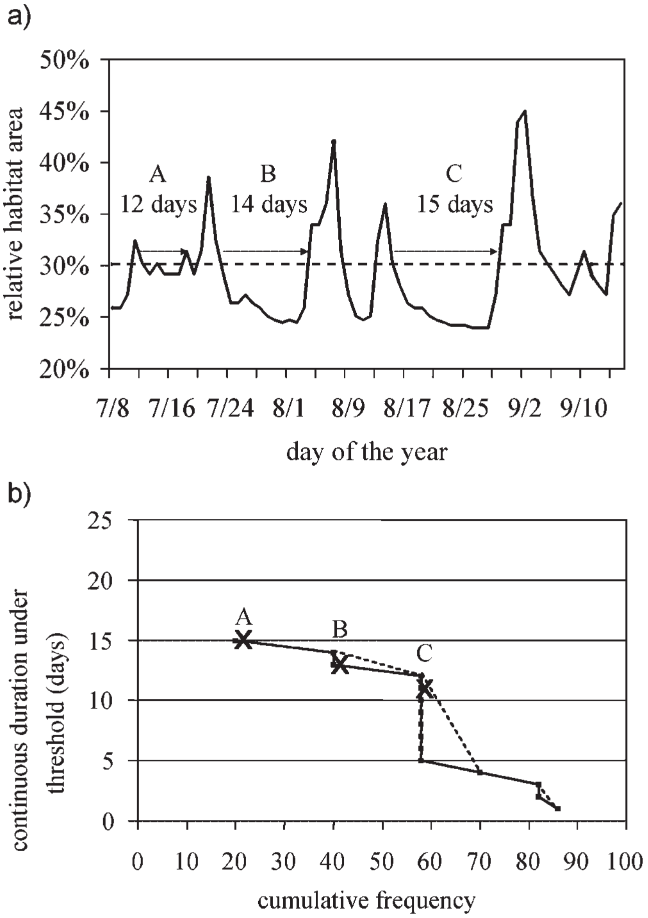

Figure 3. Schematic of UCUT curve computation. (a) The suitable habitat time series for summer 1994 and 30% of relative habitat area threshold. There are several periods when habitat stays under this threshold and the longest one is 15 days. This period makes up approximately 20% of the entire summer that is represented in (b). (b) The second longest period is 19% of the summer duration. It is plotted cumulatively with period A to represent the total duration that habitat was under the threshold for 14 days or longer. The difference between the CUT curves as defined by Capra *et al*., 1995 (dashed line) and UCUTs (solid line) is depicted here

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habitat time series (habitograph). Each incremental flow value was converted into a habitat value using flow-habitat rating curve (representing habitat as a function of flow) for a bioperiod under the baseline scenario (for details on channel restoration scenarios see Parasiewicz, 2007a, this volume). These data gave us an approximation of the habitat template that could correspond with the natural fish community structure of the Quinebaug River (for more details see Parasiewicz, 2007a, this volume).

Following Capra's procedure, a habitat event is defined as a continuous period in which the quantity of habitat (WUA, wetted usable area) stays under a predefined threshold. In our adaptation the UCUT curves describe the duration and frequency of events for a given bioperiod only. Therefore the first step is to extract bioperiod data for each year from the habitographs (Figure 3a). In the second step, the sum-length of all events of the same duration within bioperiods is computed as a ratio of a total duration of all bioperiods in the record. The proportions are plotted as a cumulative frequency, that is, the proportion of shorter periods is added to the proportions of all longer periods (Figure 3b).

For easier interpretation and calculation we further modified Capra's technique by including in the plot the continuous durations with 0% of cumulative increase (i.e. events that did not occur in the time series). For example, if the time series include the continuous durations of 14 and then 12 days, the CUT curve method will plot only those two points. In our method, we also plot the points for cumulative duration of 13 days (equal to the one of 14 days), dropping the line first vertically and than joining it with the plot for 12 days (see Figure 3b). To distinguish between the two approaches I called this adaptation uniform continuous under-threshold (UCUT).

The modification does not substantially change the shapes or positions of the curves on the graphs, but it helps in the interpretation of the curve shape. First, it sharpens the contrasts between continuous durations, allowing better identification of inflection points. Second, it allows determination of the continuous under-threshold duration for any given number of days, not only for those durations that occurred in the time series.

This procedure is repeated for the entire set of thresholds with constant increments. The magnitude of the habitat increments between the thresholds is selected on an iterative basis, that is, changing the increments until a clear pattern can be recognized. We look here for specific regions with a higher or lower concentration of the curves on the plot (Figure 4).

Habitat UCUTs were not developed for the seasons in which habitat information was sparse or non-existent for the fauna of interest (e.g. over-winter). Instead, for the over-winter bioperiod we evaluated negative run length (i.e. flow-based UCUTs) and derived criteria solely on these data, presuming again that the fauna have adjusted to the most common natural flow conditions. For the spring storage bioperiod, I did not generate flow- or habitat-based

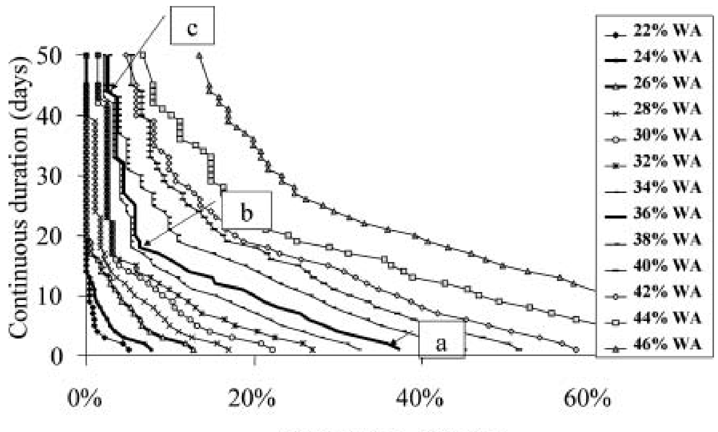

Figure 4. The series of UCUT curves for the rearing and growth season with 2% habitat increment value. On the Quinebaug River the change of wetted area within the range of investigated flows was minor and wetted area (WA) was assumed to be constant base for relative habitat area. Bold lines indicate selected HST for rare (circles), critical (triangle) and common (no markers) habitat availability. Point (a) is the shortest common duration, (b) the longest common and (c) the longest non-catastrophic duration

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UCUTs, since this study was focused on flows below a pulse threshold of $2.2 \times 10^{-2}\ \mathrm{m^3\ s^{-1}\ km^{-2}}$ ($2.0\ \mathrm{ft^3\ s^{-1}\ mi^{-2}}$), and this bioperiod commonly experienced flows above those of interest.

Interpretation of UCUT

The UCUT curves can be considered projected contours of a habitat surface area in the three-dimensional space of duration (X), frequency (Y) and habitat area (Z). We can identify common and less common habitat events based on the changes in area slope expressed by the shape of and distances between the curves. The procedure has two steps: (1) determination of habitat threshold levels by selecting curves on the graphs and (2) identification of critical durations by locating inflection points. Interpretation of these patterns is based on following observations:

- The curves in the lower left portion of the graph depict rare events (i.e. with low cumulative durations).
- The horizontal distance between curves indicates the change in frequency of events associated with a habitat increase to the next level (e.g. the larger the distance between two curves at the same continuous duration, the larger the change in the frequency of the events).
- Steep curves represent low change in event frequency.
- Inflection points reflect rapid change in frequency of continuous durations.

The relative position of a curve defines the magnitude of habitat and the ecologically relevant threshold demarcating pulse stressors (Parasiewicz, 2007b). We look for *extreme*, *rare*, *critical* and *common* habitat stressor thresholds (HSTs) for the low-flow conditions. *Extreme* indicates the maximum of environmental stress and is the lowest possible amount (>0) of habitat occurring under natural conditions. *Rare* habitat events happen infrequently and for only a short period of time. The *critical* level defines a more frequent event than *rare*, below, which the habitat circumstances rapidly decrease to the *rare* level. *Common* habitat levels are the highest defined and should demarcate the beginning of normal circumstances from the less common events (= no stress).

For the *extreme* level, we selected the lowest non-zero habitat level that occurred in the investigated (simulated) time series. To define the other three HSTs, the UCUTs are interpreted using the observations listed above. Typically, the UCUTs for rarely low habitat availability are located in the left corner, and are steep and very close to each other. Apparently, within this range small increases in habitat level have barely any effect on frequency. As habitat level continues to increase this pattern of UCUTs rapidly changes and distance between the curves increases. We selected the highest curve in the *rare*-habitat group of curves as a *rare* habitat level threshold (see Figure 4). In management framework the *rare* habitat should be exceeded most of the time. The next higher UCUT line (the first that stands out) is identified as a *critical* level. The distance between the lines after exceeding the *critical* level are 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.

The inflection points on the UCUT demarcate change in frequency of habitat under-threshold durations. This observation helps to identify the longest periods that a habitat condition is allowed to continue under a specified threshold. The events exceeding these durations are subdivided into one of two categories: persistent or 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). These are high frequency stress events that may influence ecological processes that regulate life cycle schedules of one generation (Poff and Ward, 1990). Threshold durations demarcating persistent events are the main inflection point of the associated habitat threshold curve, which indicates the longest commonly occurring durations of habitat under-threshold (see point b on Figure 4). Catastrophic droughts are decadal-scale catastrophic events, which are long in duration (more than 30 days) and occur seldom in nature (no more often than once in a decade). The consequences of these catastrophes affect multiple generations (Poff and Ward, 1990). As the catastrophic threshold we chose the shortest of the longest durations that occurred only once during the investigated period of at least five decades (point c on the Figure 4).

If persistent and catastrophic events occur too often, they may have detrimental effects on the fauna as press disturbances. To avoid this, the natural frequency of occurrence of persistent droughts should not be exceeded. For persistent events we defined the frequency indicating recurring catastrophe as three consecutive years, borrowing from the US Environmental Protection Agency's National Pollutant Discharge Elimination System Program (USEPA, 1986).

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Pulse definition

A simulated hydrograph for the Quinebaug River indicated that the natural summer low-flows vary between small and large peaks which occur on a regular basis. The small peaks rise for about 2 days before receding, and the larger peaks also rise for 2 days, but then recede more slowly. If, as assumed previously, the fauna is adapted to natural conditions, similar short pulses should give the fish temporary relief during persistent events. This is the logic behind the augmentation strategy concept, which aims to improve habitat conditions by: (1) not allowing the habitat amount to fall below the *extreme* level and (2) limiting the frequency of persistent and catastrophic events. Both objectives should be achieved by pointed flow releases. The mitigation of *extreme* conditions is based solely on habitat amount, and mitigation of persistent and catastrophic events is connected to their durations. Basically, if common or catastrophic durations (point b and c in Figure 4) for *rare* and *critical* habitat levels are exceeded, the water is released to temporarily increase habitat to higher, corresponding threshold levels. These increases last for a number of days (not hours) equivalent to the shortest common duration (point a in Figure 4) of the higher-level threshold (i.e. *critical* or *common*). Figure 5 shows application of these rules using criteria developed for the rearing and growth bioperiod with a hypothetical time series. We distinguish pulses 'to-*critical*-level' and 'to-*common*-level' depending on the duration of the drought. Another key rule is that to avoid sudden flow recession, the higher pulses are extended by lower pulses. To address the complexity of mimicking natural events we developed a set of detailed rules for these releases:

- The habitat must always exceed the *extreme* threshold.
- If a longest common (point b in Figure 4) duration for one threshold (*rare* or *critical*) is exceeded, the habitat is augmented with a water release, creating habitat equivalent to the next higher HST (*critical* or *common*, respectively).
- The duration of a release should equal the shortest common duration of natural pulse (point a in Figure 4).

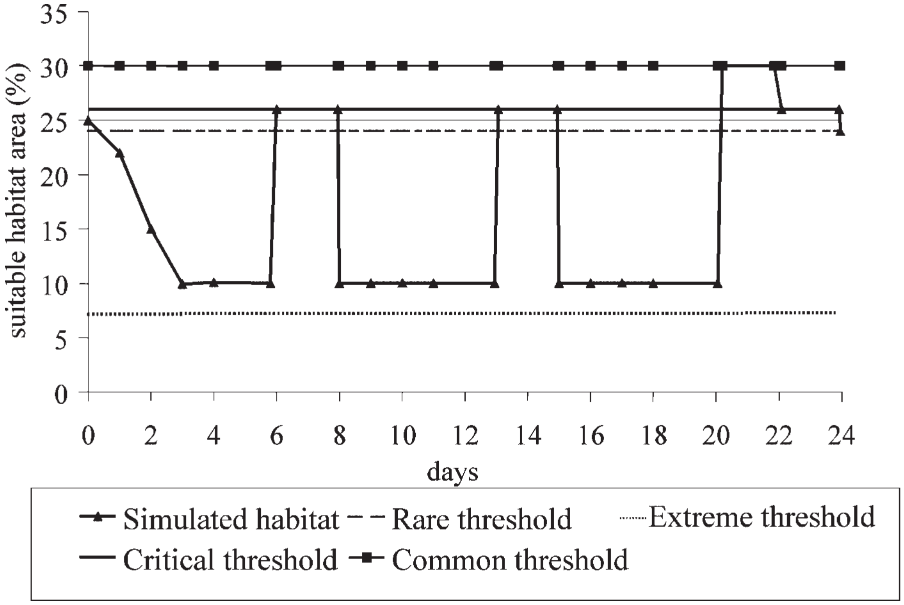

Figure 5. Hypothetical habitat augmentation. The habitat is allowed to decline under the rare threshold. The acute duration for the rare threshold in the rearing and growth season is 5 days. There is no need for action for the first 5 days. On the third day, the habitat is simulated to reach the extreme level, resulting in the need for augmentation in order to keep the habitat from falling below the rare threshold. On day 6, a pulse release is necessary to provide some relief to the fauna. The pulse is 2 days long and is followed by 5 days of augmentation to the extreme threshold. Since neither the critical nor the persistent durations are exceeded, the same cycle is repeated after day 13. At the end of the second cycle the allowable duration for the critical threshold is exceeded, and the subsequent pulse must increase the habitat to the common level for 2 days. This is followed by 2 days at the critical habitat level and the counters for the acute durations are then reset to zero. As long as no catastrophic duration is exceeded, this cycle repeats until the habitat increases naturally for longer than 2 days

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- Pulses that increase the habitat level over two thresholds (e.g. from below *rare* to *common* level) should be immediately followed by a pulse from the next lower level, mimicking natural low recession patterns.
- Pulses should be separated by at least one longest common duration (i.e. an augmentation cycle consists of a flow pulse and an allowable duration for rare threshold).
- Longest common durations for any threshold exceeded more often than two consecutive years are avoided to the extent practicable.
- Persistent durations for any threshold that occur in two or more consecutive years are classified as a press disturbance.
- If a press disturbance is unavoidable, it is considered catastrophic and should not occur more than once every 4 years.
- Catastrophic durations (point c in Figure 4) should not be exceeded more than once every 10 years.
- The need for augmentation to avoid catastrophic events overrides all persistent rules.
- Natural flow increases for more than the duration of the next planned pulse reset all augmentation counters.
- Every season is augmented independently (i.e. all counters set to zero at the beginning of each bioperiod).

This strategy does not restrain natural pulses, as they are necessary for the maintenance of many other processes in the system. The natural pulse event 'resetting all the counters' is defined as one in which the natural flow equals or exceeds the magnitude of the next required pulse for at least 1 day. The magnitude of a flow to create a given habitat pulse is determined by the habitat conditions that need to be met and may depend on selected restoration scenarios (Figure 6).

Implementation rules

Flow charts were developed for the augmentation scheme to make the decision-making process easier (Figure 7). Within the charts, the criteria address the number of consecutive days under a certain habitat level that will lead to a catastrophic event resulting from a chronic low-flow condition. These events should be avoided by taking the prescribed action on the flow chart.

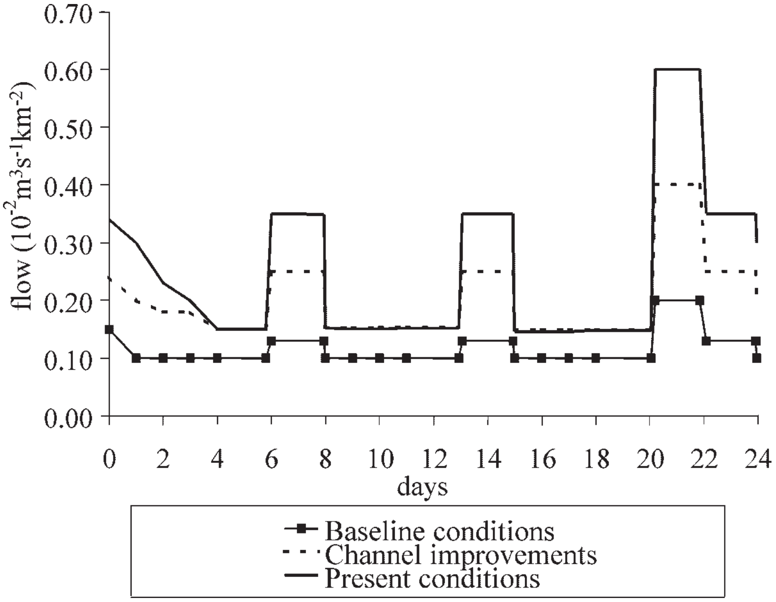

Figure 6. Flows necessary to perform the above augmentation for three different scenarios: base line conditions (maximum restoration), channel improvements with the removal of three dams and present conditions. The extreme for both feasible scenarios is a third higher than under baseline conditions. The pulses are fairly low under baseline conditions and are substantial under the other two scenarios

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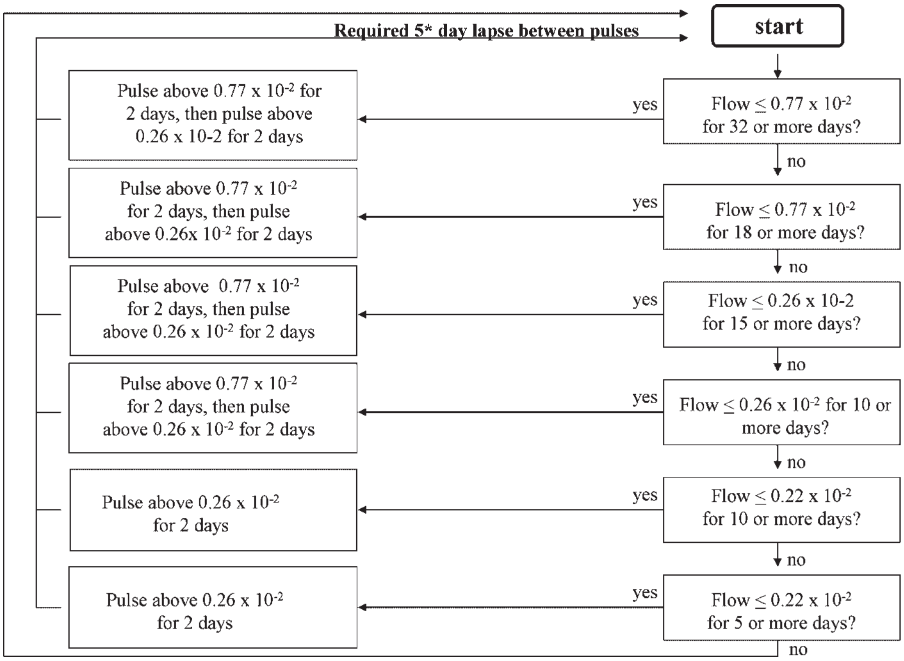

Figure 7. An example of a decision-making tree for flow releases depending on flow level

If the persistent criterion cannot be met for a particular bioperiod, a violation of the augmentation scheme occurs. Precautionary measures should be introduced to prevent a persistent condition from happening in the same or following year. If the persistent event occurs for a third time in the 4-year period, we consider the result to be a catastrophic and the same violation should not be allowed to occur for the next 10 years.

Sensitivity test

We tested the augmentation scheme for a full season, utilizing study criteria and historic flow data from the Quinebaug River, Connecticut gauge (# USGS 01124000). The feasibility analysis evaluated the frequency of the need for releases designed to bring habitat levels up to desired thresholds. Our goal was to determine if this concept would be practical in a drought year (i.e. if the required augmentation would not be too excessive). For the purpose of this test we assumed that when a threshold was surpassed, a pulse was released from a single reservoir. A feasibilty test taking into account real water availability was also conducted and described in Fennessey *et al.* (2004). We selected a restoration option consisting of the removal of the three targeted dams with associated channel improvements. The tested period was 12 December 1993 through 30 November 1994. We chose the year 1994 because it was a low-flow year, and likely represents one of the more demanding augmentation scenarios that would be encountered.

RESULTS

Table I presents habitat thresholds identified for each bioperiod with the key durations and frequencies described above. Table II provides an example of potential restoration alternatives and the resulting flows needed to obtain the specified habitat level derived from the UCUT. Flows which must always be exceeded are listed in Table III, and they vary considerably, from $0.1 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$ to $1.7 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$ (0.1–$1.5\,\mathrm{ft^3\,s^{-1}\,mi^{-2}}$), depending

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Table I. Habitat augmentation criteria (habitat amounts and event duration) developed for the Quinebaug River for different seasons

Bioperiod	Criteria	Common		Critical		Rare	
16 April–25 May shad spawning	Habitat (%)	54		51		45	
	Duration below triggering catastrophe (days)	37		31		28	
	Allowable duration below (days)	30		25		20	
	Duration pulse (days)	2		2		2	
26 May–7 July target species spawning	Habitat (%)	—		—		90	
	Duration below triggering catastrophe (days)	—		—		15	
	Allowable duration below (days)	—		—		6	
	Duration pulse (days)	—		—		2	
8 July–15 September rearing and growth	Habitat (%)	36		26		24	
	Duration below triggering catastrophe (days)	32		15		10	
	Allowable duration below (days)	18		10		5	
	Duration pulse (days)	2		2		2	
16 September–15 October overlap of salmon spawning (left column) and rearing and growth (right column)	habitat (%)	51	36	48	26	45	24
	Duration below triggering catastrophe (days)	40	32	30	15	23	10
	Allowable duration below (days)	40	18	25	10	20	5
	Duration pulse (days)	3	2	4	2	—	2
16 October–30 November salmon spawning	Habitat (%)	51		48		45	
	Duration below triggering catastrophe (days)	40		30		23	
	Allowable duration below (days)	40		25		20	
	Duration pulse (days)	3		3		4	
1 December–28/29 February winter survival	Flow	$2.75 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$		—		$2.2 \times 10^{-2}\,\mathrm{m^3\,s^{-1}\,km^{-2}}$	
	Duration below triggering catastrophe (days)	45		—		45	
	Allowable duration below (days)	35		—		15	
	Duration pulse (days)	2		—		2	

In the overlap bioperiod there is a need for special attention because threshold tracking extends between bioperiods. Adult survival and rearing and growth are still significant until the end of this bioperiod; the beginning of this bioperiod is when salmon start to spawn. Management criteria, therefore, need to meet both bioperiod requirements. In this table, the 8 July–15 September criteria apply until 15 October and the 16 October–30 November criteria actually apply beginning 16 September.

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Table II. Flows necessary to fulfil summer and early fall habitat augmentation criteria with different restoration scenarios

		Common	Critical	Rare
8 July–15 September rearing and growth	Habitat (%)	36	26	24
	Flow with Fiskdale, Baffle and Russel-Harrington dams removed and restoration	0.7	0.25	0.2
	Flow with Fiskdale dam removed and restoration	NR	0.4	0.35
	Flow with Baffle dam removed and restoration	NR	0.35	0.25
	Flow with Russel-Harrington dam removed and restoration	NR	0.4	0.3
	Flow with all dams removed and restoration	0.23	0.13	0.1

The plus sign in the table signifies that the criteria would be met above $2.2 \times 10^{-2}\,\mathrm{m}^3\,\mathrm{s}^{-1}\,\mathrm{km}^{-2}$ ($2.0\,\mathrm{ft}^3\,\mathrm{s}^{-1}\,\mathrm{mi}^{-2}$). However, we do not recommend flows above this threshold because the study did not specifically evaluate flows beyond that value. Since our investigation ends at a flow of $2.2 \times 10^{-2}\,\mathrm{m}^3\,\mathrm{s}^{-1}\,\mathrm{km}^{-2}$, this value is used in the flow charts instead of conjecturing to higher flow values.

Table III. Extreme habitat levels for bioperiods together with necessary flow levels at different restoration scenarios

	16 April–25 May	26 May–7 July	8 July–15 October	16 October–30 November	1 December–28/29 February
Habitat (%)	40	40	12	28	+
Flow with Fiskdale, Baffle, and Russel-Harrington dams removed and restoration ($10^{-2}\,\mathrm{m}^3\,\mathrm{s}^{-1}\,\mathrm{km}^{-2}$)	1.21	0.11	0.11	0.16	+
Flow with Fiskdale dam removed and restoration ($10^{-2}\,\mathrm{m}^3\,\mathrm{s}^{-1}\,\mathrm{km}^{-2}$)	1.54	0.11	0.16	0.22	+
Flow with Baffle dam removed and restoration ($10^{-2}\,\mathrm{m}^3\,\mathrm{s}^{-1}\,\mathrm{km}^{-2}$)	1.32	0.11	0.22	0.22	+
Flow with Russel-Harrington dam removed and restoration ($10^{-2}\,\mathrm{m}^3\,\mathrm{s}^{-1}\,\mathrm{km}^{-2}$)	1.65	0.11	0.22	0.22	+
Flow with all dams removed and restoration ($10^{-2}\,\mathrm{m}^3\,\mathrm{s}^{-1}\,\mathrm{km}^{-2}$)	0.22	0.11	0.11	0.16	+

on the restoration scenario selected for a given season. There is no extreme flow for the period of 16 December to 15 April as there is insufficient habitat information to make an assessment.

Example using historical time series

Application of developed criteria to historical time series from 1993 to 1994 documented that augmentation would be necessary in three bioperiods of this dry year (Figure 8). Although the spawning bioperiod experienced *rare* flow levels, only two augmentations were needed at the end of the bioperiod (Figure 8a). Interestingly, this is at a time when the simulated flows reached a peak that the measured flows did not emulate. The rearing and growth bioperiod 8 July to 15 September experienced low flows. This is the first period where the measured hydrograph did not closely reflect the simulated hydrograph. As a result, four augmentations were needed within the bioperiod. Again, the augmentations coincided with peaks in the simulated hydrograph (Figure 8b). In the Atlantic salmon-spawning bioperiod three pulses were required. Though the augmentation cycle was 20 days long, catastrophic criteria took precedence and the low flows in the previous overlapping bioperiod required the need for augmentation in this season (Figure 8c).

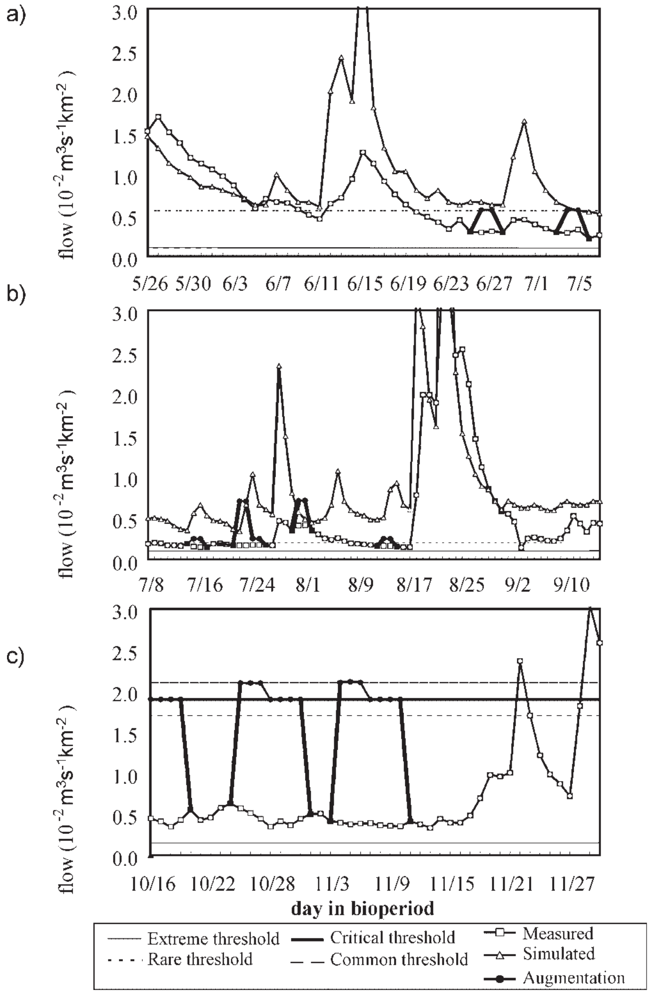

Figure 8. Hydrograph for 1994 indicating measured and simulated flows as well as potential augmentation pulses that would be necessary in bioperiods: (a) target species spawning, (b) rearing and growth, (c) Atlantic salmon spawning. The horizontal lines depict flows corresponding with various thresholds

DISCUSSION

The concept presented here is a means of providing a basis for the introduction of dynamic flow augmentation. It is not intended to prevent low-flow conditions, but to maintain flow patterns predictable for the native fish fauna by controlling frequency and duration of such events. Our strategy is designed to account for the need for inter- and intra-annual variability of flows with very limited water availability. Watershed-wide modifications of the flow regime have led to changes such that flows must be managed to improve condition of the native fauna. Using baseline habitat models, we established a virtual reference condition to simulate the habitat and flow requirements needed to sustain the targeted species in the Quinebaug River.

We built the concept for an augmentation scheme upon the idea of the relationship of environmental variation and species adaptation (Levins, 1965; Thiery, 1982). Discernment of various thresholds is based on defining an envelope of natural environmental variation of fish habitat. The UCUT technique provided information for assessing magnitude and frequency of habitat events that describe this envelope. I am aware that the justification of the threshold-level identification is presently only theoretical and that it requires more focused empirical research. More rigorous selection procedures that clearly reflect biological needs require iterative validation studies. The

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choice of *common* habitat threshold especially may seem intuitive and imprecise. At this time, I also do not have a better biological justification for this choice than observation of sudden increase in frequency. Because this particular threshold is not at the extreme low end of habitat availability, it is unlikely that this imprecision will harm species.

The sequencing strategy for flow augmentation represents an emergency-level approach replicating the pulsing characteristics of a natural system. We must note that the augmented flows are still much lower than the flows observed in the simulated time series, and the pulses are less frequent than the simulated runoff event peaks. Consequently, we must recognize that this strategy should be considered a tool for securing survival rather than for the full maintenance of the riverine fauna. For the Quinebaug River it is the best that can be done with present water availability, since replenishing the system with historic flow levels is not feasible (see Fennessey *et al*., 2004).

This is a low-flow evaluation and does not consider the requirements for the pulses or augmentation necessary to maintain other characteristics of the system, such as sediment transport and floodplain maintenance or historical sequence of events (e.g. drought following major flood). Similarly, ramping rates (for both rising and receding limbs of the hydrograph), as a function of basin size, should also be incorporated into the flow augmentation strategy. Finally, I want to underscore that pulses mentioned here should neither be confused with hydropeaking (which is of much shorter duration and different scope) nor with full restoration of natural flow regime.

Clearly, any augmentation strategy should include an evaluation of its practicality. The results of the feasibility test are preliminary but promising showing that augmentation is not required so often as to necessitate constant releases. In fact, a low amount of pulsing was required and natural flows were often above the desired thresholds (and consistently above the extreme thresholds). Moreover, the amount of water presently available in the system is sufficient to implement this scheme even during catastrophic drought conditions such as those that occurred in 1965 (Fennessey *et al*., 2004). Augmentation scheduling was also easily conducted utilizing a relatively simple programmable tracking procedure.

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