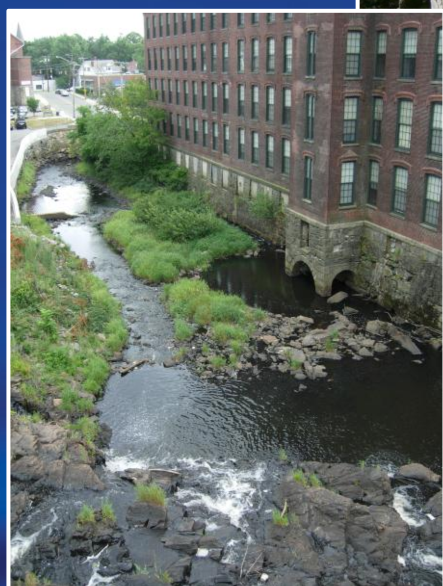
Methuen Falls Hydroelectric Project: Bypass Flow Study



Prepared For:
Olson Electric Development Co., Inc.
30r Hampshire Street
Methuen, MA 01844

Submitted By:
Normandeau Associates, Inc.
25 Nashua Road
Bedford, NH 03110

R – 23057.000
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NORMANDEAU ASSOCIATES
ENVIRONMENTAL CONSULTANTS

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1.0 INTRODUCTION

The Methuen Falls Hydroelectric Project is located on the Spicket River in the city of Methuen, MA. The Spicket River, a tributary to the Merrimack River, is a 17.7-mile-long river located in both New Hampshire and Massachusetts. The Spicket begins at the outlet of Island Pond in Derry, NH, and flows south into Salem, NH, passing through the Arlington Mill Reservoir. The river continues through Salem, and enters the city of Methuen, where it drops nearly 100 feet over a series of dams on its way to the Merrimack River in Lawrence. The drainage area is approximately 73.8 square miles. Spicket River discharge is measured by a USGS gage located approximately 1.5 miles upstream of the Project (USGS 01100561). For the period 2005-2011, mean monthly flow within the Spicket River ranged from a high of 320 cfs (March) to a low of 38 cfs (August).

As evidenced by sampling conducted by the Massachusetts Division of Fisheries and Wildlife, the Spicket River supports a primarily warmwater fish community. Documented fish species include American eel, bluegill, brown bullhead, common shiner, fallfish, largemouth bass, pumpkinseed, redbreast sunfish, redfin pickerel, tessellated darter, white sucker and yellow bullhead (Caleb Slater, MDFW, personal communication).

The Methuen Falls Project utilizes the Methuen Falls Dam to achieve its hydraulic head. Methuen Falls is the second of five existing dams on the Spicket River. The dam was originally constructed in 1880 to 1890 and is a gravity dam constructed of cut granite built on a bedrock foundation. The downstream face is vertical dry stone masonry laid on a running bond pattern. The maximum height above the river bed is twenty feet with three feet of plywood flashboards on the crest. The overflow spillway consists of three sections separated by two large masonry piers and has a total length of 130 feet. There are two 3' wide by 4' high fully automated flood gates located on the southern pier.

The Project intake is located on the northern side of the dam. The intake structure consists of a formed concrete box protected by 16' wide by 10' deep galvanized trash racks. The intake is sealed by a 10' by 10' fully automated aluminum head gate. Water is transported to the power house via a 150 foot long, 7' high by 10' wide granite topped brick channel that transitions into a 4' diameter steel penstock at a ninety degree angle. The penstock transfers water into a 7' high by 20' square concrete pressure case which houses Unit #1. A steel penstock (3' long, 3' diameter) supplies water from the concrete pressure case to a 6' by 6' square steel pressure case that houses Unit #2. Each pressure case passes water to the tailrace via conical draft tubes. Project turbines are both vertical Francis units (Unit 1: 405 hp; Unit 2: 120 hp).

The project operates as a true run-of-river project and discharges a continuous minimum flow of 3 cfs through the 150-foot long bypass reach. The project is also in compliance with its requirement to provide an instantaneous instream flow release of at least 37 cfs, or inflow, whichever is less.

The objectives of this study were to provide an assessment of the available habitat and to determine an appropriate minimum flow for the protection of aquatic resources within the Project bypass reach. This was accomplished using the PHABSIM (Physical Habitat Simulation) system of the Instream Flow Incremental Methodology (Bovee et al. 1998). PHABSIM allows for the simulation of river depths and velocities under varying flow conditions and links simulated depths and velocities and observed substrate and cover information to the suitability of these variables for target species and life stages based on past studies, as well as life history information about the species. The combination of the hydraulic data and habitat suitability criteria generates an index to habitat suitability for selected aquatic species. The habitat suitability index is commonly referred to as weighted usable area (WUA), or more accurately as a physical habitat index (PHI) (Payne 2007), and is defined as the surface area of the stream weighted by its suitability per 1,000 linear feet.

2.0 METHODS

2.1 HABITAT MAPPING

Normandeau staff mapped habitat types and collected substrate information within the Methuen Falls bypass reach. Habitat types were classified using definitions presented in Armantrout (1998):

- Pool: aquatic habitat with a gradient of less than 1% that is normally deeper and wider than aquatic habitats immediately above and below it.
- Riffle: shallow reaches with low subcritical flow (1-4% gradient) characterized by small hydraulic jumps over rough bed material, causing small ripples, waves and eddies, without breaking the surface tension.
- Run: swiftly flowing stream reach with a gradient greater than 4%, little to no surface agitation, waves, or turbulence, no major flow obstructions, approximately uniform flow, substrates of variable particle size and water surface slope roughly parallels to the overall stream gradient

Latitude and longitude coordinates for boundaries surrounding habitat units were collected using a GPS (Trimble Geo-XT). Latitude and longitude measurements were plotted on a digitized aerial photograph of the study reach using Arc View. Polygons were drawn around each identified habitat unit based on the collected points, and the surface area of each polygon was calculated based on the scale of the aerial photograph.

Within each habitat unit, the dominant and subdominant substrate types were evaluated and recorded. Substrate types were classified using size criteria presented in Table 1.

2.2 TRANSECT PLACEMENT

Following completion of the habitat unit map (See Section 2.1 above) transects locations were selected to represent the available habitat types. Following examination of the study reach and available habitat types, a total of four transects were selected for measurement (Figure 1). Of those transects, two were located within riffle habitat, one within run habitat and one within pool habitat. Prior to collection of field data, transect beginning and ending points (i.e., headpins and tailpins) were marked with iron bars driven into the river bank. Additionally, a permanent benchmark was installed to provide a reference mark for determining streambed elevations. The head/tail pins and benchmarks were placed at an elevation on the riverbank that would remain dry during each of the target discharges mapped during this study as well as during theoretical flows modeled later during the process.

2.3 DETERMINATION OF AQUATIC BIOTA AND SELECTION OF HABITAT SUITABILITY CRITERIA

Three fish species were selected for use in determining an appropriate minimum flow for the protection of aquatic resources within the Project bypass reach. Species used in this analysis were selected based on the recommendation of Caleb Slater at the Massachusetts Division of Fisheries and Wildlife. Due to their dependence on flowing water, common shiner (*Notropis cornutus*), fallfish (*Semotilus corporalis*) and white sucker (*Catostomus commersonii*) were selected. A review of peer-reviewed and grey literature produced previously used habitat suitability criteria for spawning as well as the adult, juvenile, and fry life stages of the common shiner and white sucker. Habitat suitability criteria for spawning and adult fallfish were also obtained. Habitat suitability criteria for depth, velocity and substrate preferences for each species-life stage combination are presented in Appendix A.

2.4 HABITAT MODELING

2.4.1 Field Methods

Field data needed to construct a hydraulic model for habitat calculations occurred at three different river discharges. During the lowest study flow discharge, field staff measured the elevation of the streambed relative to the elevation of the permanent benchmark at locations where a significant change in elevation occurred in order to properly model habitat changes over a range of flows. Interval width was based on transect length, In the absence of significant elevation changes, additional measurements were collected at a fixed interval such that an adequate number of bed profile measurements were made at each transect. Additionally, substrate and cover conditions were noted for each transect during the lowest measured discharge; for modeling purposes we assumed that these conditions did not vary significantly with flow. Dominant and subdominant substrate types were visually assessed using criteria presented in Table 1. Cover type and percentage of cell represented by each vertical were assigned to each measurement point along the transect following criteria in Table 2.

During the three study discharges, water surface elevations (relative to the permanent benchmark) were measured at the water's edge for both the left and right bank (right bank looking downstream) as well as a minimum of three points along the total transect length. During the highest flow discharge, the water depth (ft) and mean water column velocity (ft/s) were measured at each point where a bed elevation had been determined during the lowest study flow. Water velocities were collected using a Marsh-McBirney flowmeter. During all three study flows, depths and velocities for a representative river discharge were collected. Additionally, a discharge measurement was taken within both of the channels on either side of the island located within Transects 1 and 2. The additional discharge measurements were done to determine whether or not the flow allocation remained constant with changes in total discharge. Fluctuations in the flow allocation with discharge require separate modeling of the two channels.

2.4.2 Modeling Methods

RHABSIM, a software program developed and distributed by Thomas R. Payne and Associates (Payne 1994) was used to perform the hydraulic simulation and habitat modeling for this study.

Water Surface Elevation Calibration and Simulation

Two techniques were utilized to simulate water surface elevations in Project bypass reach. These were the use of an empirical log-log regression formula of stage and flow based on measured data (often called the IFG-4 method) as well as the channel conveyance method (MANSQ) utilizing Manning's equation (Bovee and Milhous 1978). The log-log method utilized a stage-discharge relationship to determine water surface elevations calibrated with three stage-discharge measurement pairs and produced acceptable simulations at transects 1 (left and right channels) and 4. The MANSQ technique was used for transects 2 (left and right channel) and 3. The MANSQ program simulated water surface elevations using Manning's equation calibrated to the high flow water surface elevations. Each cross section was simulated independently of all other cross sections in the data set. The MANSQ simulations assume that no backwater effect occurred between the cross sections.

Water Velocity Calibration and Simulation

Water velocities were simulated for the study transects using a "one-flow" technique based on the measured depths and velocities obtained during the high flow event and solving for Manning's *n* on an individual data point basis. The use of the high flow one-velocity method has been shown to be superior for upwards extrapolation of simulated flow conditions and nearly equivalent for downward extrapolation compared to results obtained using data collected at lower flows (Payne and Bremm 2003). At the simulated discharges, the model used Manning's formula and the previously derived Manning's *n* values together with the projected depth to simulate velocities.

In this sense, the one set of velocities was used as a template to predict the simulated velocities at other discharges.

Velocity calibrations examined the adequacy of velocity simulations over the range of modeled flows comparing velocity adjustment factors (VAF's) and velocity patterns, while preserving as closely as possible the measured velocities. In the cases when calibration adjustments were needed, individual data modifications were limited to minor velocity changes in shallow edge points or to points that either significantly deviated from surrounding patterns or contributed to substantial errors in discharge calculations. Calibration was generally accomplished by specifying an adjacent point's Manning's *n* roughness value and applying it to the target point. A second technique was to average Manning's *n* values or velocities from adjacent points, then substitute a new Manning's *n* in the target point.

Habitat Suitability Modeling

The hydraulic and HSC components were combined to generate a habitat suitability (WUA) index for target species in the Project bypass reach. Transect data used to estimate WUA were "weighted" according to the proportion of reach represented by each transect (Table 3). The habitat suitability index was generated for each target species – life stage over a range of discharges from 0.8 cfs to 36 cfs. Within RHABSIM, the standard option of multiplying individual variable suitabilities (velocity*depth*substrate/cover) for cell centroids to calculate the WUA habitat index was used.

3.0 RESULTS

3.1 HABITAT MAPPING

Habitat mapping was conducted within the Methuen Falls bypass reach on 18 July 2012. Discharge through the bypass reach on that date was estimated at approximately 2.5 cfs. Normandeau identified eleven unique habitat units within the bypass reach (Figure 1). The total area mapped during the field effort was 12,819 ft^2 (Table 4). Of that total, pool habitat comprised the majority of the wetted area, followed by riffle then run. Cobble was the dominant substrate type within pool and run habitat units as well as the majority of the riffle habitat units (Table 4). Two large islands were present during the habitat mapping (Figure 2). In addition, a large area of steep bedrock ledge is present at the upstream end of the bypass reach. Although this bedrock area comprised 29% of the total bypass reach area, it was not included in the habitat model due to the inability to effectively construct a hydraulic model for that area due to uneven water surface elevations. However, based on visual assessment, it is unlikely that the bedrock ledge habitat unit provides significant habitat for any of the three fish species examined (Figure 3).

3.2 HABITAT MODELING

Instream flow data was collected from the Project bypass reach on 24 July, 27 July and 6 August 2012. Discharge through the bypass on those dates was calculated at 2.0, 18.4, and 24.7 cfs, respectively. The surveyed bed profiles and water surface elevations and velocities simulated for a range of flows (0.8 and 36 cfs) are presented in Appendix B. Due to observed fluctuations in the flow allocation with discharge, the two channels on either side of island habitat unit 2 (Figure 1) were modeled separately.

The area of suitable habitat within the Project bypass reach for the adult, juvenile, and fry life stages as well as spawning activity for common shiner, calculated as the product of all suitability criteria (velocity * depth * substrate), is presented in Figure 4. Suitable habitat for adult common shiner showed minimal change over the range of modeled flows but did peak at the upper end of the modeled flow range. Suitable habitat for juvenile common shiner was greatest at the lower end of the range of modeled flows (0.8 cfs) and decreased with increasing discharge through the bypass reach. Similarly, suitable habitat for common shiner fry also peaked at the lower end of the range of modeled flows although the decrease in WUA with increasing discharge was not as steep as for the juvenile life stage. Suitable habitat for common shiner spawning was lowest at the lower end of the range of modeled flows and began to plateau around a discharge of 10 cfs.

The area of suitable habitat within the Project bypass reach for the adult, juvenile, and fry life stages as well as spawning activity for white sucker, calculated as the product of all suitability criteria (velocity * depth * substrate), is presented in Figure 5. Suitable habitat for the white sucker adult and juvenile life stages as well as spawning activity increased slightly over the range of modeled flows whereas suitable habitat for white sucker fry decreased slightly over the range of modeled flows.

The area of suitable habitat for adult fallfish and spawning ranged from 0 to 0.2% of the total habitat within the bypass reach over the full range of modeled flows. The low model-predicted occurrence of fallfish was driven by the lack of their preferred gravel habitat within the Project bypass reach.

Total WUA and the calculated area of suitable habitat within the Project bypass reach for each combination of species and life stage are presented in tables within Appendix C.

4.0 DISCUSSION

The objectives of this study were to provide an assessment of the available habitat and to determine an appropriate minimum flow for the protection of aquatic resources within the Project bypass reach. The Methuen Falls bypass reach is relatively short (150 ft) and is dominated on the upstream end by a large section of bedrock ledge which lies directly below the dam structure. Habitat for aquatic organisms is likely limited within the bedrock habitat due to the high gradient, fast water velocities and lack of substrate diversity. The remainder of the bypass reach is comprised of pool, riffle and run habitats with the dominant substrate throughout the reach being cobble.

When the combined habitat suitability (i.e., depth*velocity*substrate) was calculated, appropriate habitat for common shiner and white sucker adult, juvenile, fry and spawning habitat over the range of modeled flows (0.8 to 36 cfs) showed varied trends. Due to a lack of significant gravel habitat within the Project bypass reach, appropriate habitat for adult and spawning fallfish was very limited. As a result, fallfish were not considered in the selection and recommendation of a minimum flow. Peak suitable habitat was determined to be available for adult common shiner as well as adult, juvenile and spawning white sucker at the upper end of the range of modeled flows. In contrast, peak suitable habitat was determined to be available for the common shiner juvenile and fry life stages and the white sucker fry life stage at the lowest modeled flows. Peak suitable habitat for common shiner spawning was determined to occur over the upper half of the range of modeled flows.

Prior to the determination of a suitable bypass minimum flow, the seasonality of use for each species – life stage combination was considered (Table 5). Spawning activity for white sucker and common shiner generally occurs during late-April to May and May to June, respectively (Scarola 1987). Fry for both species are likely to be present during May-June (white sucker) and May-July (common shiner). The adult and juvenile life stages of both species have the potential to utilize the Project bypass reach throughout the year. As a result, we would recommend the use of two minimum flow values for the Project bypass reach. The first value will apply to the spawning and rearing period (April – July) and will take into consideration the needs of spawning and fry for both common shiner and white sucker. The second value will apply to the non-spawning months (August – March) and will take into consideration the needs for the adult and juvenile stages of both common shiner and white sucker.

An "optimization matrix" (Bovee 1982) was utilized to interpret the habitat-discharge relations for the series of species – life stages examined during the spawning and non-spawning periods. This optimization technique involved the identification of the species - life stage that has the least amount of habitat and then determining the flow necessary to maximize habitat for that life stage. During the spawning period, it was determined that habitat was most limiting for the spawning activity of both common shiner and white sucker (Table 6). When only common shiner is considered, a continuous flow of 6 cfs through the Project bypass reach would maximize habitat for the most limiting stage. Alternatively, a continuous flow of 36 cfs through the Project bypass reach would maximize habitat for the most limiting stage of white sucker. When both species are considered, the optimization technique suggests that a flow of 18.4 cfs through the bypass would provide the best conditions for spawning activity and fry rearing. A flow of 18.4 cfs would have the following effects on WUA for the evaluation of each species – life stage considered during the spawning period:

- Common shiner spawning would be within 6% of maximum WUA.
- Common shiner fry would be within 55% of maximum WUA.
- White sucker spawning would be within 29% of maximum WUA.

- White sucker fry would be within 2% of maximum WUA.

During the non-spawning period, it was determined that habitat was most limiting for the adult life stage of both common shiner and white sucker (Table 7). When only common shiner is considered, a continuous flow of 3 cfs through the Project bypass reach would maximize habitat for the most limiting stage. Alternatively, a continuous flow of 36 cfs through the Project bypass reach would maximize habitat for the most limiting stage of white sucker. When both species are considered, the optimization technique suggests that a flow of 16.0 cfs through the bypass would provide the best conditions for adult and juvenile use. A flow of 16.0 cfs would have the following effects on WUA for the evaluation of each species – life stage considered during the spawning period:

- Common shiner adults would be within 11% of maximum WUA.
- Common shiner juveniles would be within 36% of maximum WUA.
- White sucker adults would be within 14% of maximum WUA.
- White sucker juveniles would be within 7% of maximum WUA

The use of a spawning (18.4 cfs) and non-spawning (16.0 cfs) period minimum flows through the Project bypass reach would increase WUA for most life stages over that provided by the current minimum flow (3 cfs).

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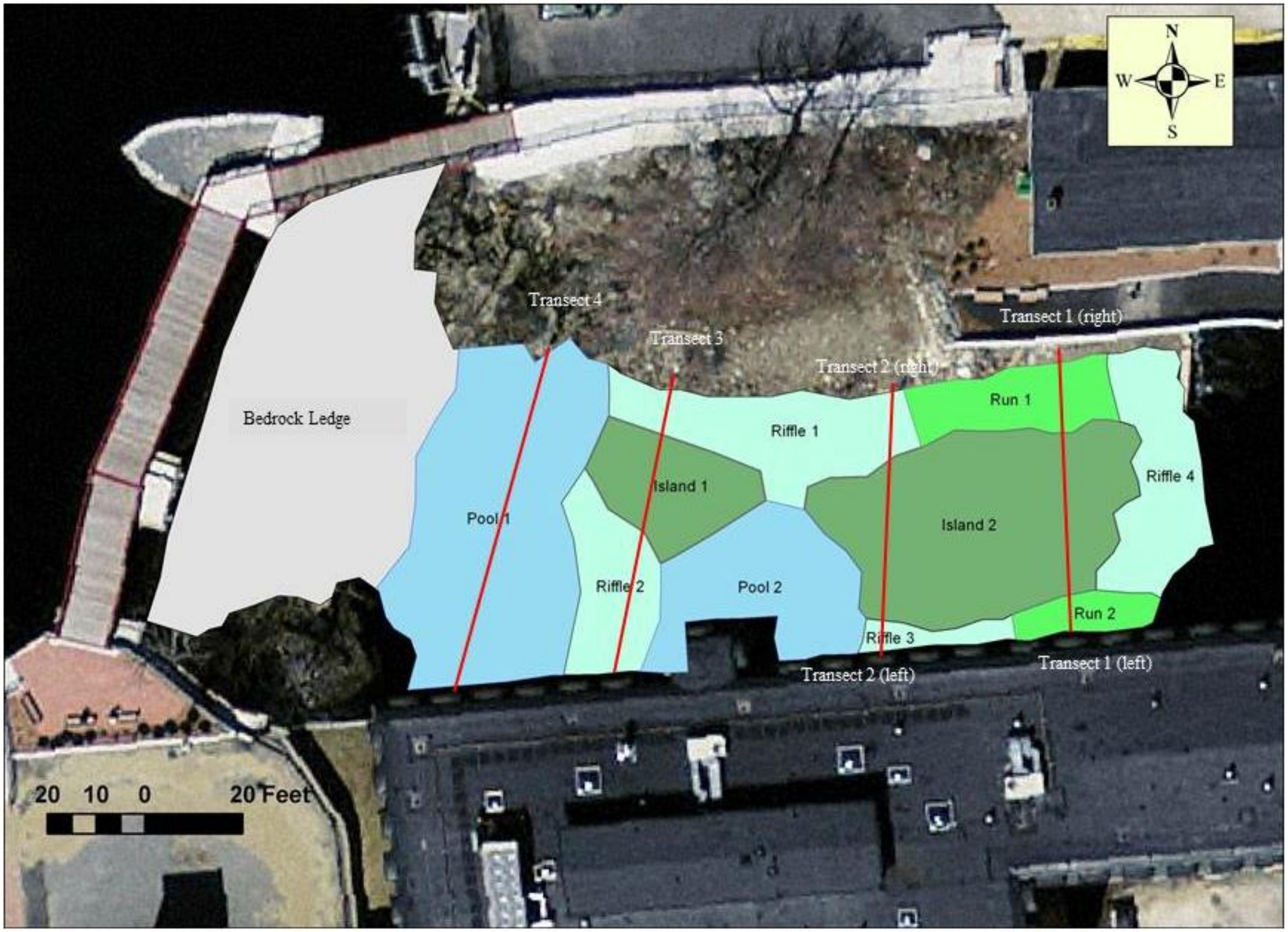


Figure 1. Habitat units and transect locations for Methuen Falls bypass reach .

Figure 2. Overview of the Methuen Falls bypass reach taken during habitat mapping, 17 July 2012.

Figure 3. Bedrock ledge habitat unit located at the upstream end of the Methuen Falls bypass reach.

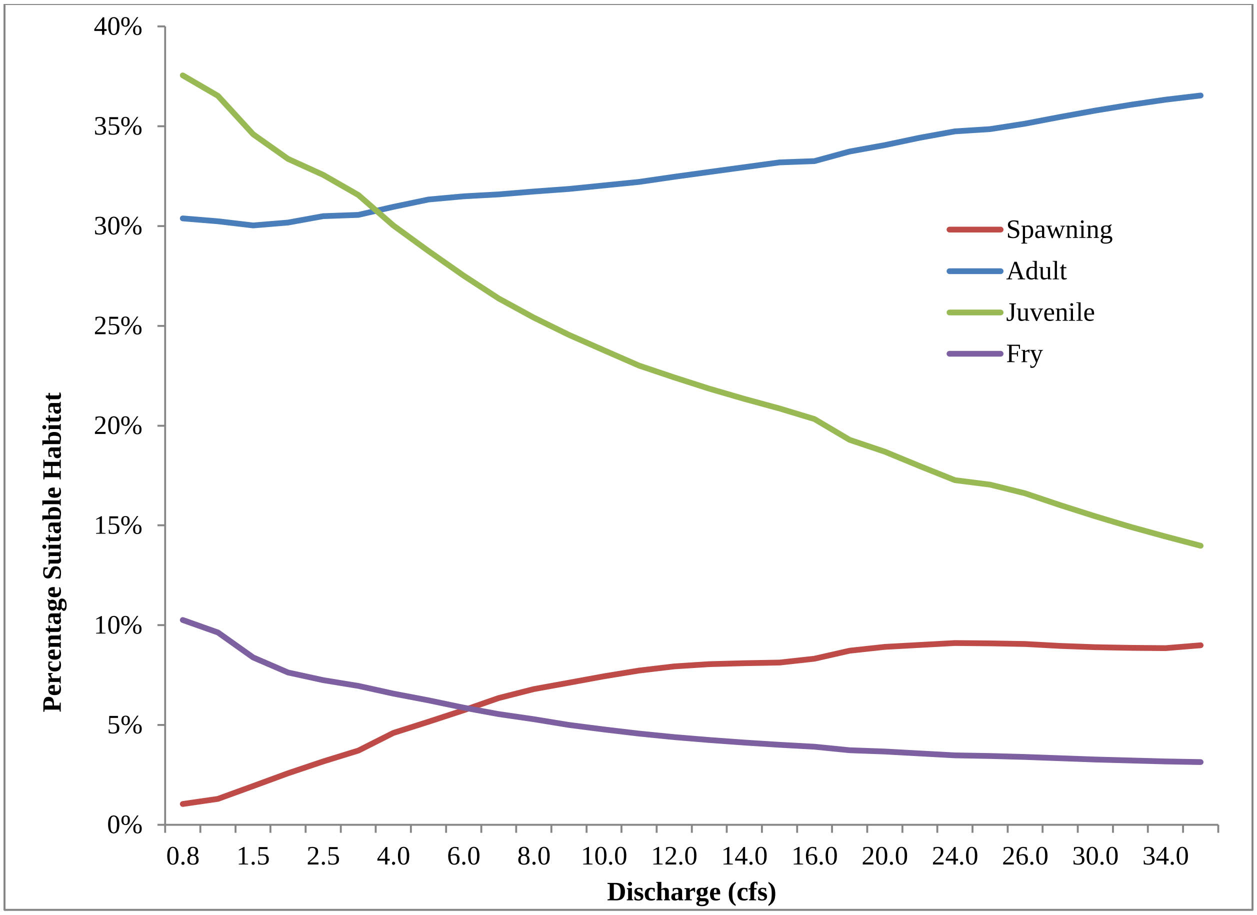


Figure 4. The percentage of suitable habitat for life stages of the common shiner within the Project bypass reach over the range of modeled flows (0.8 to 36 cfs).

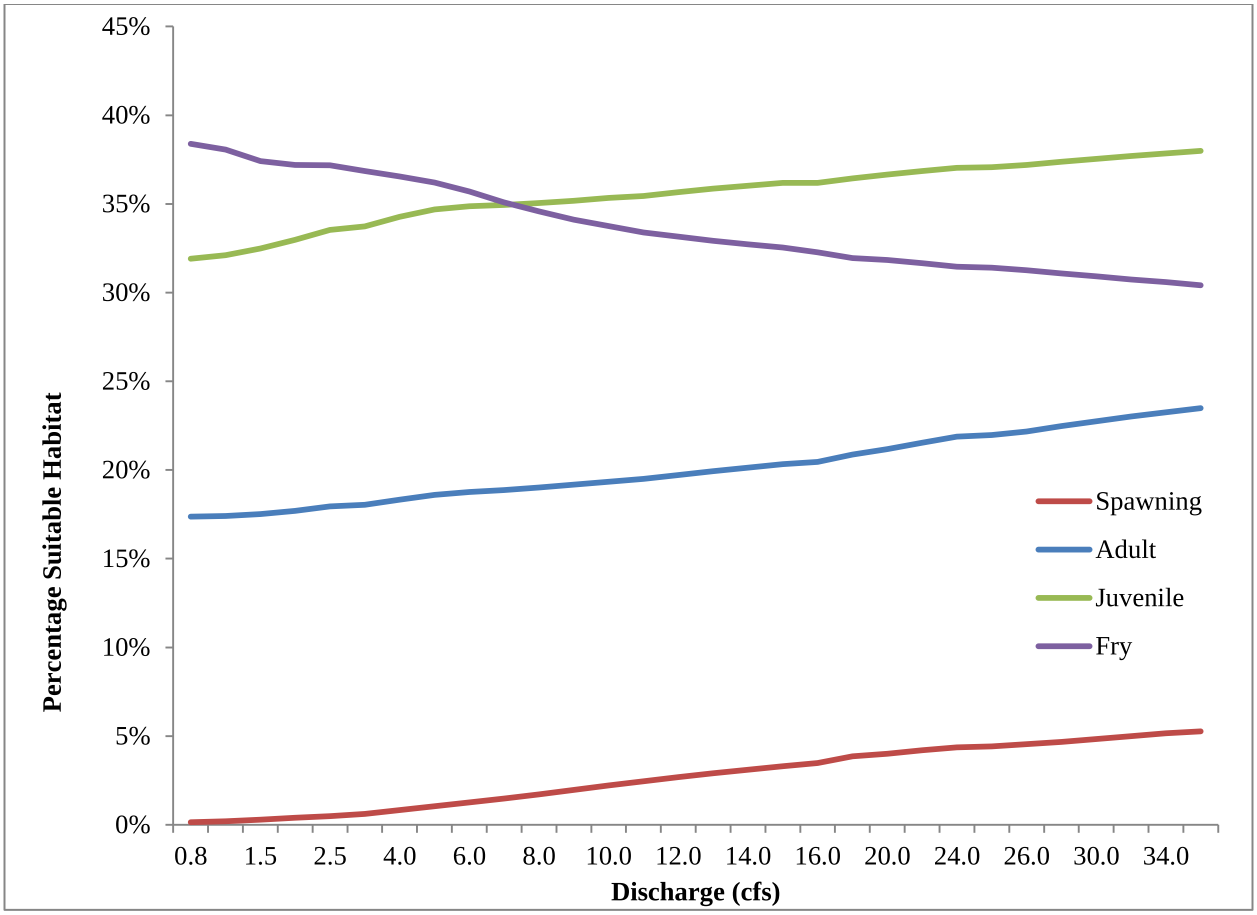


Figure 5. The percentage of suitable habitat for life stages of the white sucker within the Project bypass reach over the range of modeled flows (0.8 to 36 cfs)

Table 1. Substrate definitions and coding used in the Methuen Falls bypass reach flow study.

Substrate	Particle Size (mm/in)	Substrate Code
Fines	< 4 (0.16”)	1
Small gravel	4-25 (0.16-1.0”)	2
Large gravel	25-75 (1.0-3.0”)	3
Cobble	75-225 (3.0-9.0”)	4
Rubble	225-300 (9.0-12.0”)	5
Small boulder	300-600 (12-24”)	6
Large boulder	>600 (24”)	7
Bedrock	-	8
Other	-	9

Table 2. Cover type definitions and coding used in the Methuen Falls bypass reach flow study.

Substrate	Particle Size (mm/in)	Cover Code
No cover	-	1
Small object	<150 mm (6.0”)	2
Medium object	150-300 mm (6.0-12.0”)	3
Large object	>300 mm (12.0”)	4
Overhanging vegetation	<450mm of water surface	5
Root-wad or undercut bank	-	6
Surface turbulence	-	7

Table 3. Percentage and description of total reach represented by each transect for the Methuen Falls bypass reach.

Transect	Area (ft²)	% Total Reach	Reach Description
T1 LC	211	3.3%	Run 2
T1 RC	512	8.0%	Run 1
T2 LC	519.5	8.1%	Riffle 3, left side of Riffle 4
T2 RC	826.5	12.9%	Lower half of Riffle 1, right side of Riffle 4
T3	1030	16.1%	Riffle 2 and upper half of Riffle 1
T4	3304	51.6%	Pool 1, Pool 2
Total Reach	**6403**	**100.0%**	

Table 4. Total area and dominant-subdominant substrate types for each habitat unit within the Methuen Falls bypass reach observed during habitat mapping, July 2012.

Habitat Unit	Area (ft²)	Dominant Substrate	Subdominant Substrate
Pool 1	2,335	Cobble	Small boulder
Pool 2	969	Cobble	Small boulder
Riffle 1	900	Cobble	Small boulder
Riffle 2	580	Cobble	Small boulder
Riffle 3	143	Small boulder	Small boulder
Riffle 4	753	Cobble	Large gravel
Run 1	512	Cobble	Small boulder
Run 2	211	Cobble	Small boulder
Boulder Ledge	3,720	Bedrock	-
Island 1	621	Cobble (embedded)	Small boulder
Island 2	2,075	Cobble (embedded)	Small boulder

Table 5. Life stage seasonality matrix for adult, juvenile, fry and spawning common shiner, white sucker and fallfish within the Methuen Falls Project bypass reach.

	Jan	Feb	Mar	Apr	May	Jun
Common shiner:						
Adult	■	■	■	■	■	■
Juvenile	■	■	■	■	■	■
Fry					■	■
Spawning					■	■
White sucker:						
Adult	■	■	■	■	■	■
Juvenile	■	■	■	■	■	■
Fry					■	■
Spawning				■	■	
Fallfish:						
Adult	■	■	■	■	■	■
Spawning					■	

	Jul	Aug	Sep	Oct	Nov	Dec
Common shiner:						
Adult	■	■	■	■	■	■
Juvenile	■	■	■	■	■	■
Fry	■					
Spawning						
White sucker:						
Adult	■	■	■	■	■	■
Juvenile	■	■	■	■	■	■
Fry						
Spawning						
Fallfish:						
Adult	■	■	■	■	■	■
Spawning						

Table 6. Optimization matrix for the spawning and fry life stages of common shiner and white sucker in the Methuen Falls bypass reach during the spawning period (April-July). Values are total WUA for each life stage at each modeled discharge.

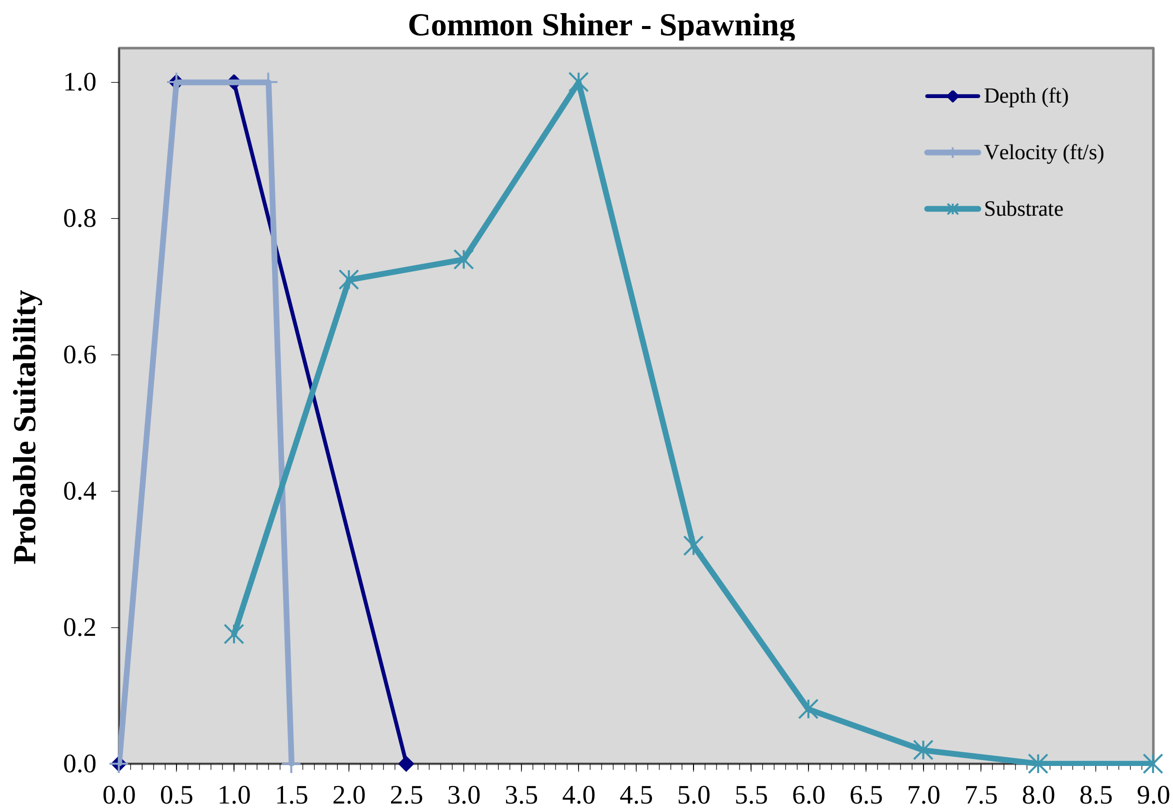
	Common Shiner		White Sucker		Minimum Value		
Discharge (cfs)	Spawning	Fry	Spawning	Fry	Common Shiner	White Sucker	All Stages
0.8	382	3788	56	14168	382	56	56
1.0	490	3618	71	14277	490	71	71
1.5	752	3242	110	14456	752	110	110
2.0	1011	2994	152	14589	1011	152	152
2.5	1253	2858	195	14682	1253	195	195
3.0	1486	2783	242	14759	1486	242	242
4.0	1872	2671	335	14865	1872	335	335
5.0	2129	2569	430	14921	2129	430	430
6.0	2401	2458	531	14946	2401	531	531
7.0	2701	2363	632	14932	2363	632	632
8.0	2932	2279	741	14903	2279	741	741
9.0	3100	2177	859	14861	2177	859	859
10.0	3269	2100	972	14838	2100	972	972
11.0	3426	2024	1084	14812	2024	1084	1084
12.0	3540	1960	1195	14783	1960	1195	1195
13.0	3607	1903	1302	14755	1903	1302	1302
14.0	3646	1855	1397	14735	1855	1397	1397
15.0	3674	1814	1495	14719	1814	1495	1495
16.0	3789	1783	1586	14708	1783	1586	1586
18.4	4010	1719	1773	14702	1719	1773	1719
20.0	4115	1696	1852	14705	1696	1852	1696
22.0	4186	1663	1947	14698	1663	1947	1663
24.0	4248	1624	2036	14686	1624	2036	1624
24.7	4253	1613	2069	14682	1613	2069	1613
26.0	4248	1591	2129	14660	1591	2129	1591
28.0	4217	1568	2204	14632	1568	2204	1568
30.0	4206	1546	2284	14604	1546	2284	1546
32.0	4201	1528	2368	14566	1528	2368	1528
34.0	4203	1510	2447	14524	1510	2447	1510
36.0	4280	1493	2503	14474	1493	2503	1493

Table 7. Optimization matrix for the adult and juvenile life stages of common shiner and white sucker in the Methuen Falls bypass reach during the non-spawning period (August – March). Values are total WUA for each life stage at each modeled discharge.

Discharge (cfs)	Common Shiner		White Sucker		Minimum Value		
	Adult	Juvenile	Adult	Juvenile	Common Shiner	White Sucker	All Stages
0.8	11213	13857	6413	11777	11213	6413	6413
1.0	11344	13700	6533	12043	11344	6533	6533
1.5	11603	13368	6766	12551	11603	6766	6766
2.0	11838	13086	6942	12937	11838	6942	6942
2.5	12043	12861	7088	13240	12043	7088	7088
3.0	12240	12637	7222	13508	12240	7222	7222
4.0	12596	12213	7455	13941	12213	7455	7455
5.0	12911	11846	7662	14297	11846	7662	7662
6.0	13184	11522	7852	14601	11522	7852	7852
7.0	13442	11222	8028	14868	11222	8028	8028
8.0	13677	10958	8193	15105	10958	8193	8193
9.0	13882	10698	8353	15332	10698	8353	8353
10.0	14089	10453	8507	15538	10453	8507	8507
11.0	14292	10212	8653	15728	10212	8653	8653
12.0	14478	9994	8794	15904	9994	8794	8794
13.0	14660	9790	8931	16067	9790	8931	8931
14.0	14835	9607	9064	16219	9607	9064	9064
15.0	15012	9437	9194	16363	9437	9194	9194
16.0	15155	9267	9319	16493	9267	9319	9267
18.4	15525	8873	9606	16769	8873	9606	8873
20.0	15735	8637	9784	16929	8637	9784	8637
22.0	15982	8345	10002	17111	8345	10002	8345
24.0	16215	8057	10208	17282	8057	10208	8057
24.7	16297	7969	10272	17336	7969	10272	7969
26.0	16474	7788	10402	17443	7788	10402	7788
28.0	16703	7539	10584	17595	7539	10584	7539
30.0	16905	7298	10748	17735	7298	10748	7298
32.0	17095	7074	10901	17858	7074	10901	7074
34.0	17257	6859	11045	17970	6859	11045	6859
36.0	17388	6653	11180	18077	6653	11180	6653

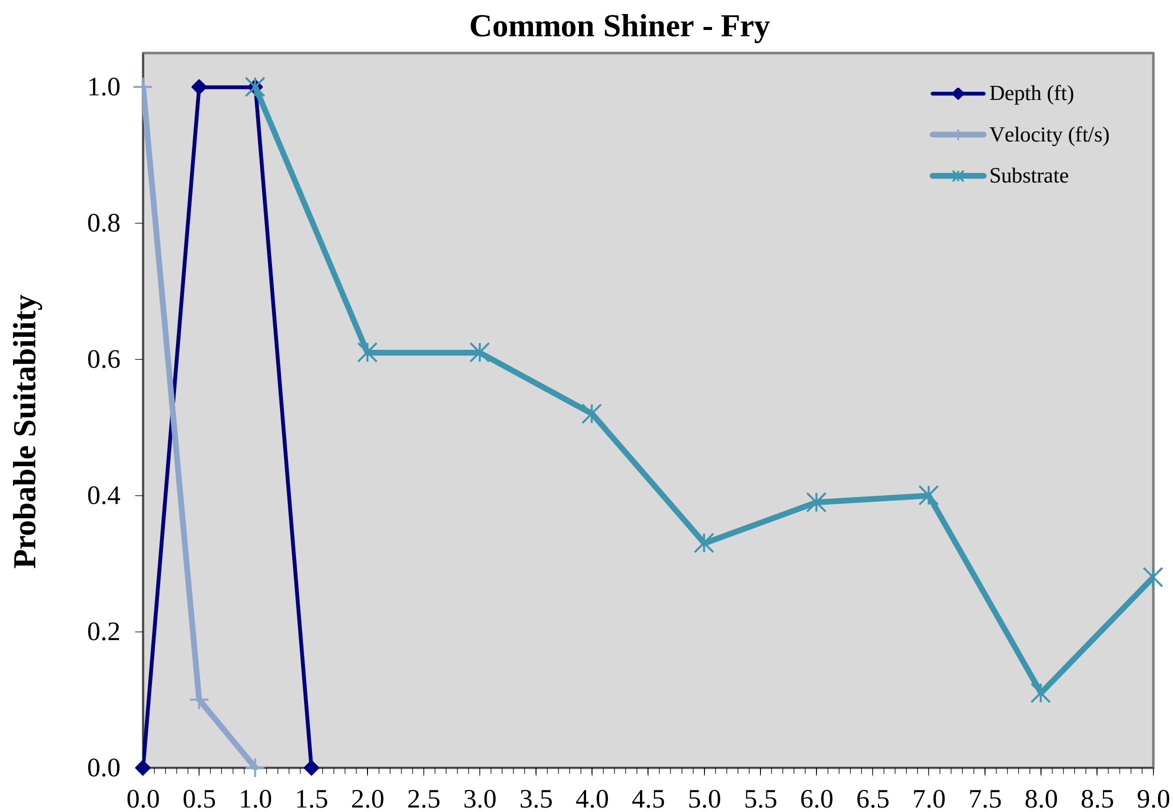
APPENDIX A

Habitat suitability criteria for depth, velocity and substrate preferences for common shiner, fallfish and white sucker.



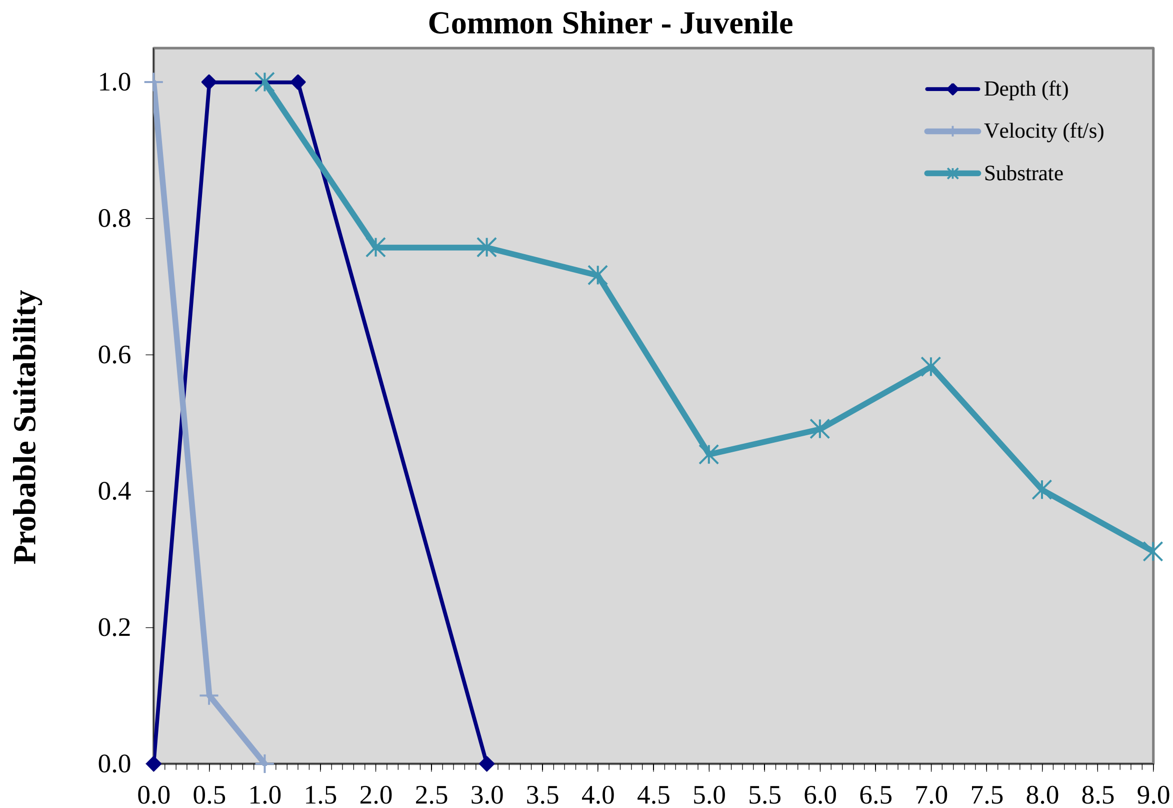
Velocity	Suitability [a]	Depth	Suitability [a]	Substrate	Suitability [b]
0.00	0.00	0.00	0.00	1	0.19
0.50	1.00	0.50	1.00	2	0.71
1.30	1.00	1.00	1.00	3	0.71
1.50	0.00	2.50	0.00	4	1.00
				5	0.32
				6	0.08
				7	0.02
				8	0.00
				9	0.00

a – Normandeau 2003
b – Aadland and Kuitunen 2006



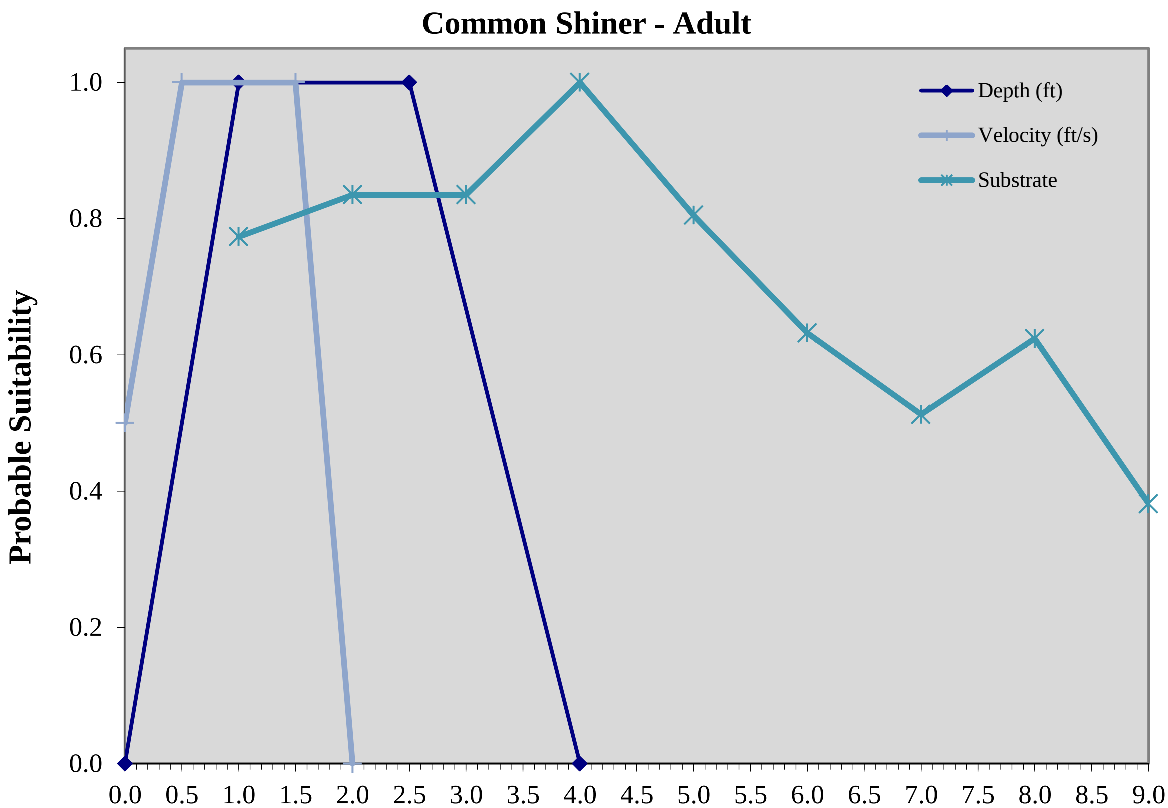
Velocity	Suitability [a]	Depth	Suitability [a]	Substrate	Suitability [b]
0.00	1.00	0.00	0.00	1	1.00
0.50	0.10	0.50	1.00	2	0.61
1.00	0.00	1.00	1.00	3	0.61
		1.50	0.00	4	0.52
				5	0.33
				6	0.39
				7	0.41
				8	0.11
				9	0.28

a – Normandeau 2003
b – Aadland and Kuitunen 2006



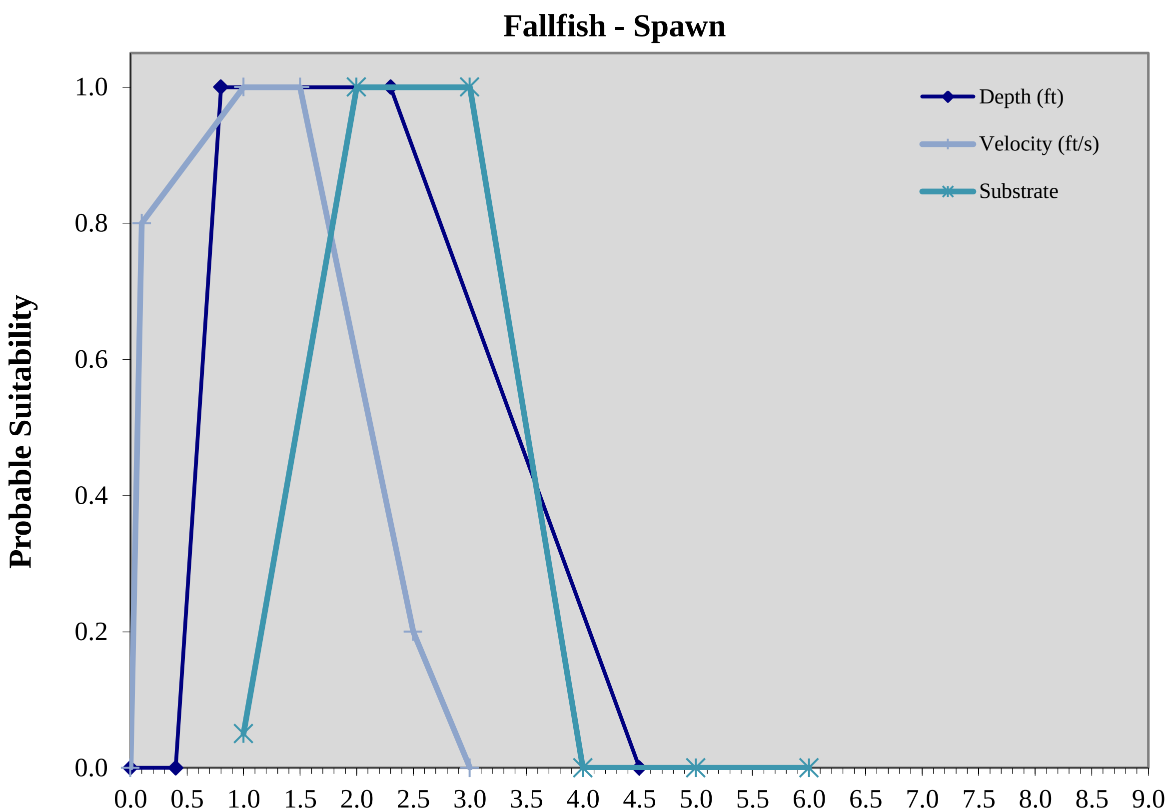
Velocity	Suitability [a]	Depth	Suitability [a]	Substrate	Suitability [b]
0.00	1.00	0.00	0.00	1	1.00
0.50	0.10	0.50	1.00	2	0.76
1.00	0.00	1.30	1.00	3	0.76
		3.00	0.00	4	0.72
				5	0.45
				6	0.49
				7	0.58
				8	0.40
				9	0.31

a – Normandeau 2003
b – Aadland and Kuitunen 2006



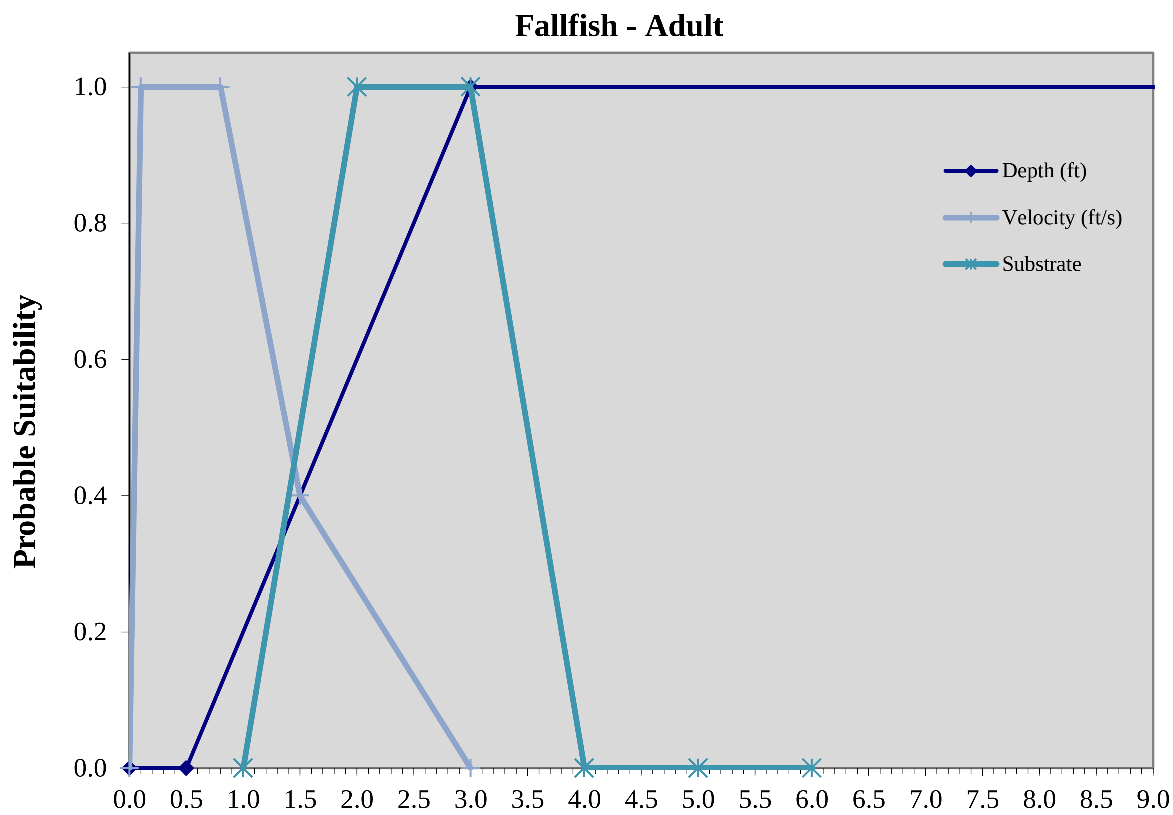
Velocity	Suitability [a]	Depth	Suitability [a]	Substrate	Suitability [b]
0.00	0.50	0.00	0.00	1	0.77
0.50	1.00	1.00	1.00	2	0.84
1.50	1.00	2.50	1.00	3	0.84
2.00	0.00	4.00	0.00	4	1.00
				5	0.80
				6	0.63
				7	0.51
				8	0.62
				9	0.38

a – Normandeau 2003
b – Aadland and Kuitunen 2006



Velocity	Suitability [a]	Depth	Suitability [a]	Substrate	Suitability [b]
0.00	0.00	0.40	0.00	1	0.05
0.10	0.80	0.80	1.00	2	1.00
1.00	1.00	2.30	1.00	3	1.00
1.50	1.00	4.50	0.00	4	0.00
2.50	0.20			5	0.00
3.00	0.00			6	0.00
				7	0.00
				8	0.00
				9	0.00

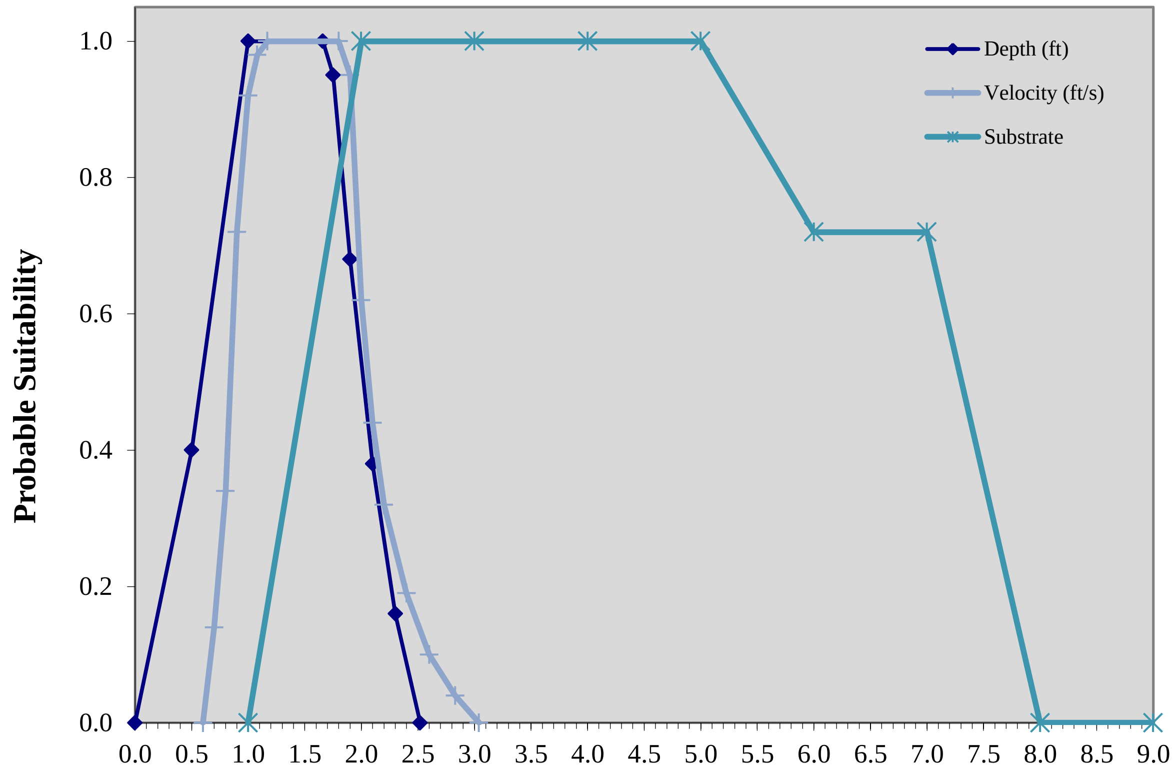
a – Normandeau 2003
b – Trial et al. 1993



Velocity	Suitability [a]	Depth	Suitability [a]	Substrate	Suitability [b]
0.00	0.00	0.50	0.00	1	0.00
0.10	1.00	3.00	1.00	2	1.00
0.80	1.00	10.00	1.00	3	1.00
1.50	0.40			4	0.00
3.00	0.00			5	0.00
				6	0.00
				7	0.00
				8	0.00
				9	0.00

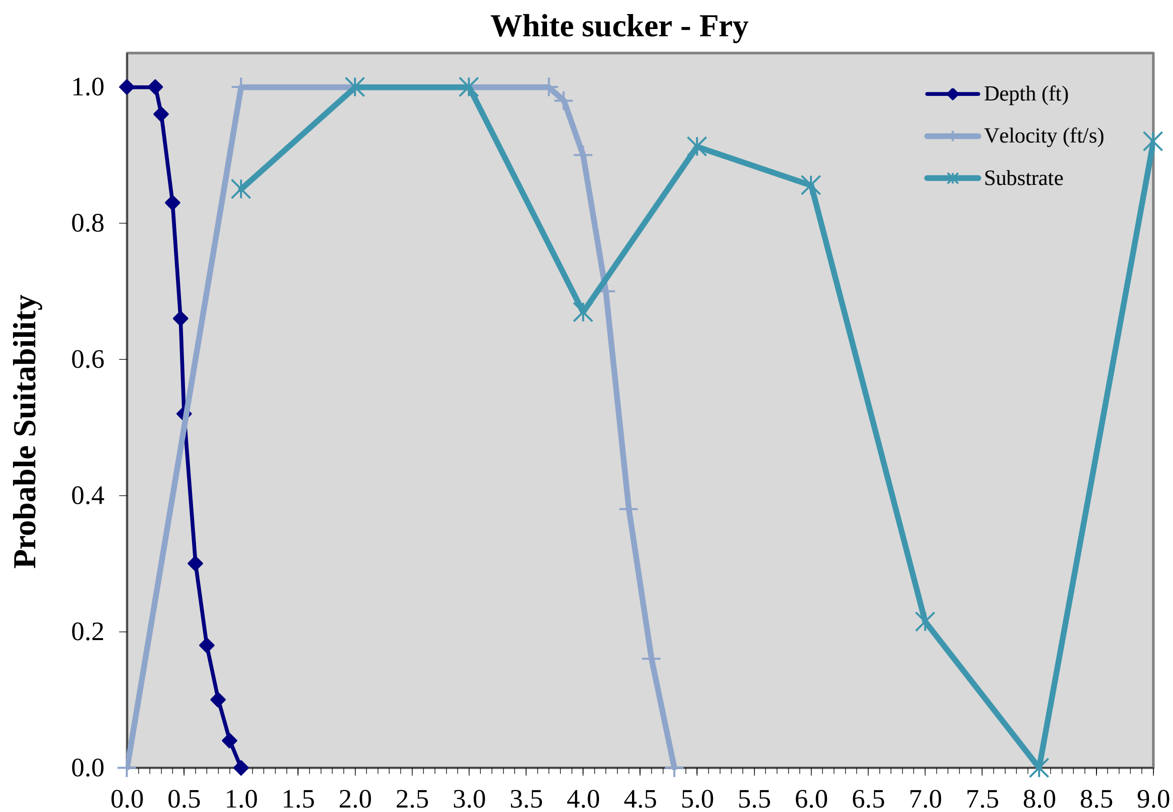
a – Normandeau 2003
b – Trial et al. 1993

White sucker - Spawn



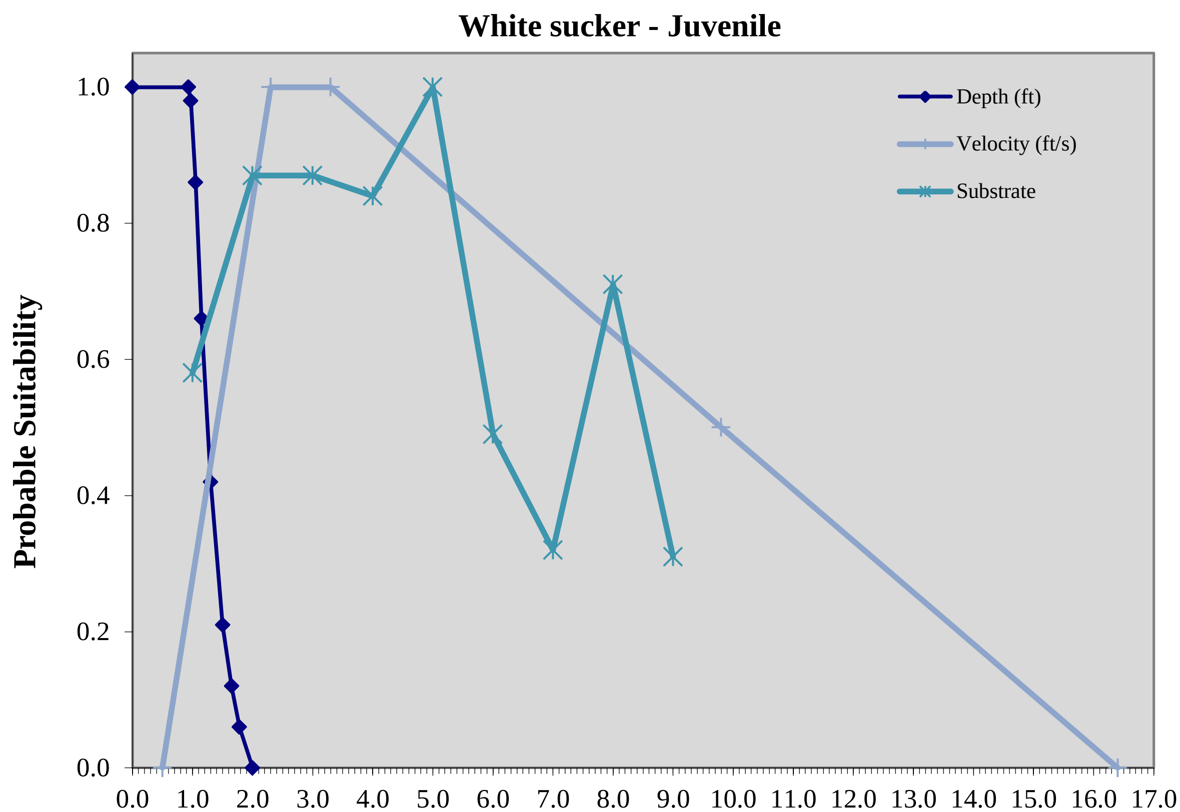
Velocity	Suitability [a]	Depth	Suitability [a]	Substrate	Suitability [a]
0.00	0.00	0.60	0.00	1	0.00
0.50	0.40	0.70	0.14	2	1.00
1.00	1.00	0.80	0.34	3	1.00
1.66	1.00	0.90	0.72	4	1.00
1.75	0.95	1.00	0.92	5	1.00
1.90	0.68	1.08	0.98	6	0.72
2.10	0.38	1.17	1.00	7	0.72
2.30	0.16	1.80	1.00	8	0.00
2.52	0.00	1.90	0.95	9	0.00
		2.00	0.62		
		2.10	0.44		
		2.20	0.32		
		2.40	0.19		
		2.60	0.10		
		2.83	0.04		
		3.04	0.00		

a – Twomey et al. (1984)



Velocity	Suitability [a]	Depth	Suitability [a]	Substrate	Suitability [b]
0.00	1.00	0.00	0.00	1	0.85
0.25	1.00	1.00	1.00	2	1.00
0.30	0.96	3.70	1.00	3	1.00
0.40	0.83	3.83	0.98	4	0.67
0.47	0.66	4.00	0.90	5	0.91
0.50	0.52	4.20	0.70	6	0.86
0.60	0.30	4.40	0.38	7	0.21
0.70	0.18	4.60	0.16	8	0.00
0.80	0.10	4.80	0.00	9	0.92
0.90	0.04				
1.00	0.00				

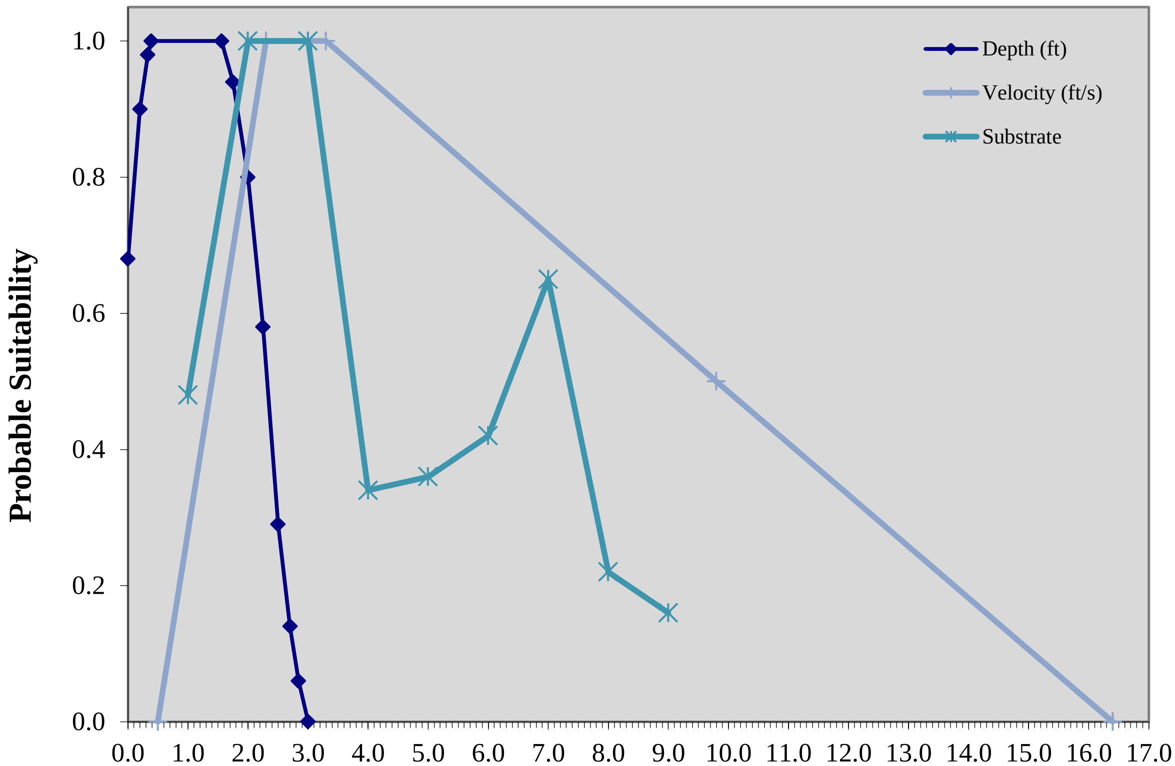
a – Twomey et al. (1984)
b – Aadland and Kuitunen 2006



Velocity	Suitability [a]	Depth	Suitability [a]	Substrate	Suitability [b]
0.00	1.00	0.50	0.00	1	0.58
0.93	1.00	2.30	1.00	2	0.87
0.97	0.98	3.30	1.00	3	0.87
1.05	0.86	9.80	0.50	4	0.84
1.15	0.66	16.40	0.00	5	1.00
1.30	0.42			6	0.49
1.50	0.21			7	0.32
1.65	0.12			8	0.71
1.78	0.06			9	0.31
2.00	0.00				

a – Twomey et al. (1984)
b – Aadland and Kuitunen 2006

White sucker - Adult

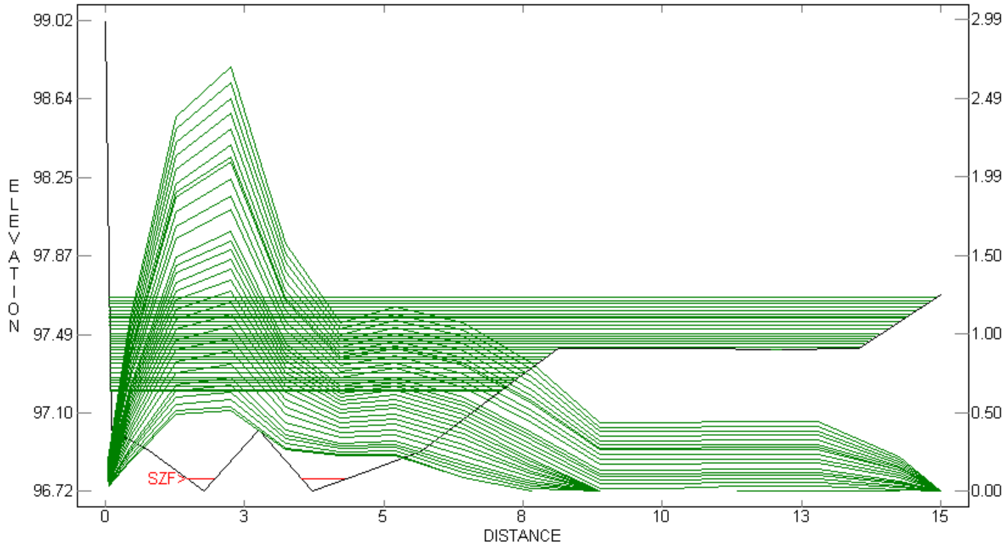


Velocity	Suitability [a]	Depth	Suitability [a]	Substrate	Suitability [b]
0.00	0.68	0.50	0.00	1	0.48
0.20	0.90	2.30	1.00	2	1.00
0.33	0.98	3.30	1.00	3	1.00
0.39	1.00	9.80	0.50	4	0.34
1.56	1.00	16.40	0.00	5	0.36
1.75	0.94			6	0.42
2.00	0.80			7	0.65
2.25	0.58			8	0.22
2.50	0.29			9	0.16
2.70	0.14				
2.84	0.06				
3.00	0.00				

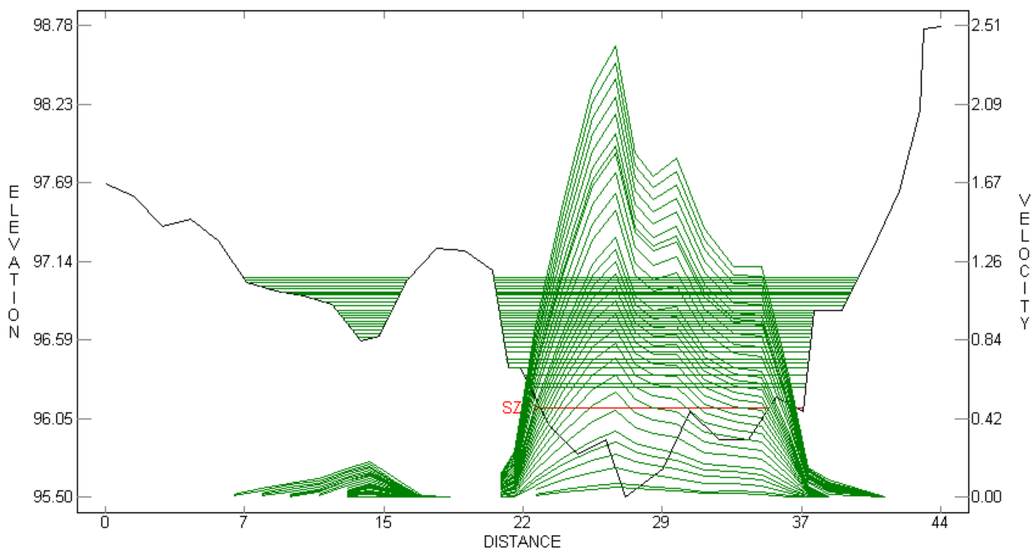
a – Twomey et al. (1984)
b – Aadland and Kuitunen 2006

APPENDIX B

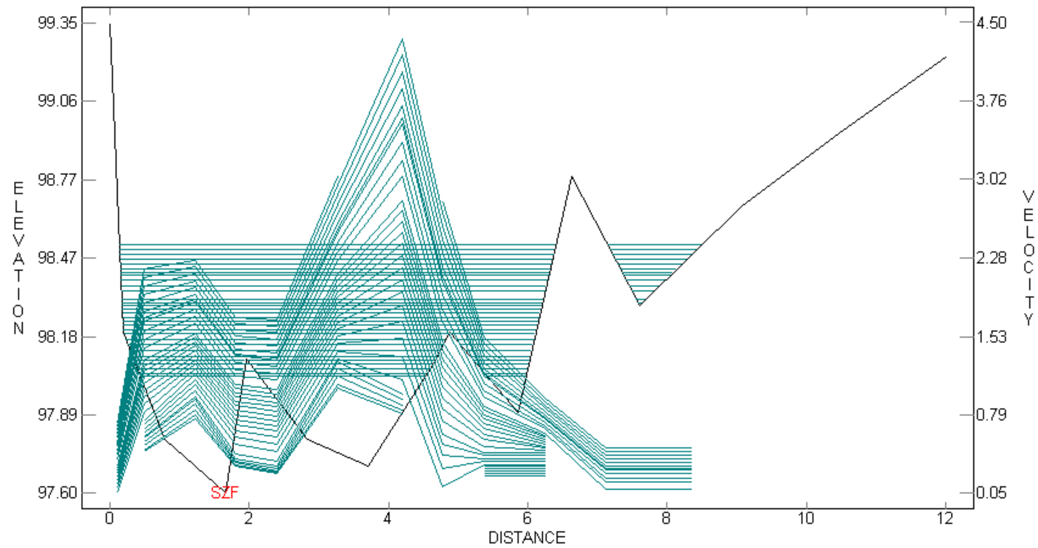
Simulated water surface elevations and velocities over the range of examined study flows (0.8 to 36 cfs) for transects 1, 2, 3, and 4 in the Project bypass reach.



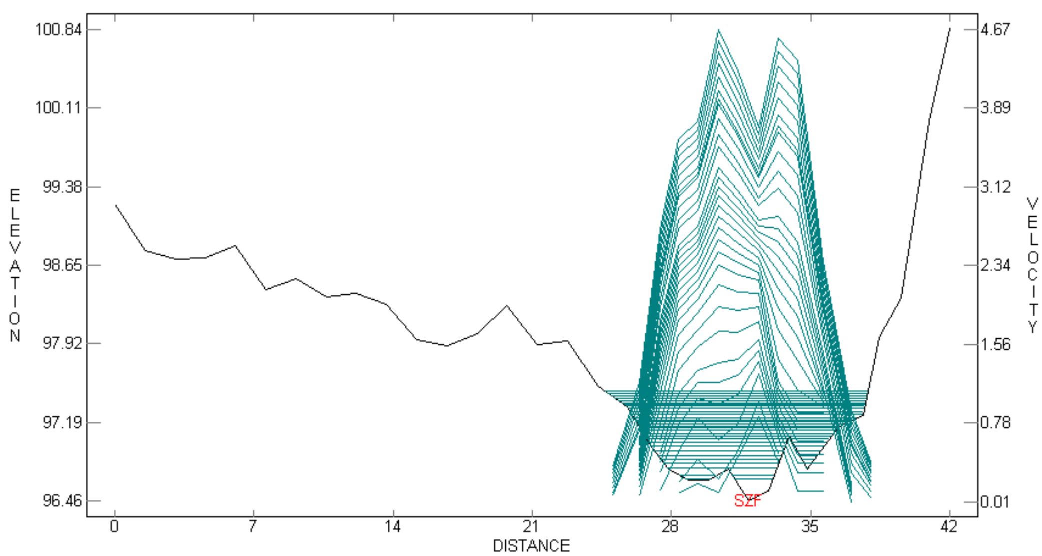
Bed profile and simulated water surface elevations and velocities for the range of study flows from 0.8 to 36 cfs at Transect 1 (left channel).



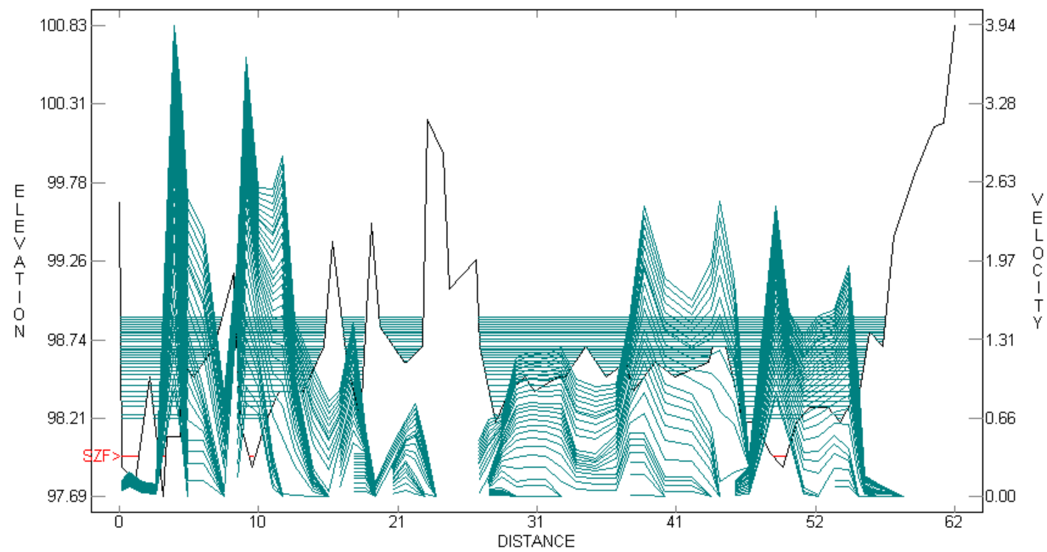
Bed profile and simulated water surface elevations and velocities for the range of study flows from 0.8 to 36 cfs at Transect 1 (right channel).



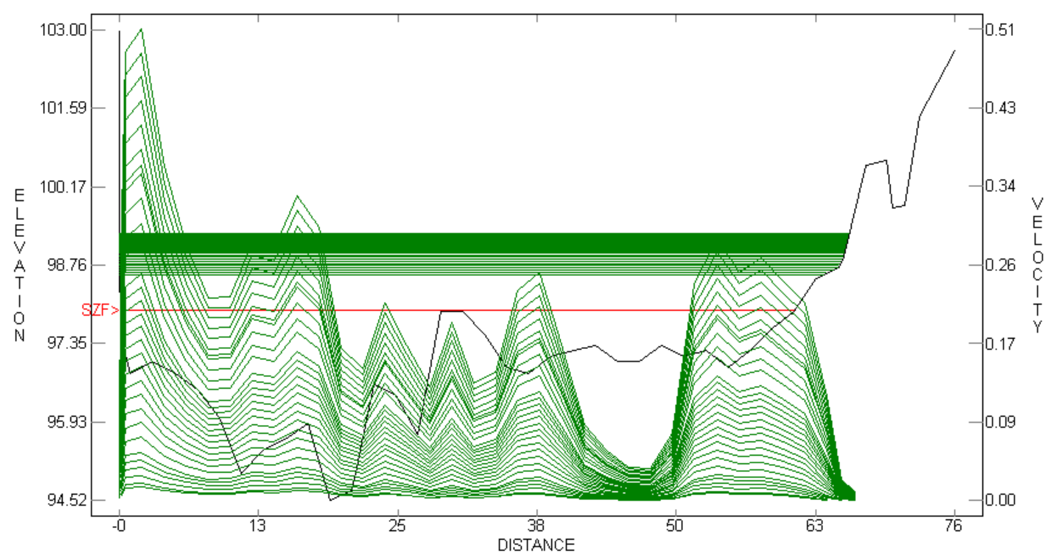
Bed profile and simulated water surface elevations and velocities for the range of study flows from 0.8 to 36 cfs at Transect 2 (left channel).



Bed profile and simulated water surface elevations and velocities for the range of study flows from 0.8 to 36 cfs at Transect 2 (right channel).



Bed profile and simulated water surface elevations and velocities for the range of study flows from 0.8 to 36 cfs at Transect 3.



Bed profile and simulated water surface elevations and velocities for the range of study flows from 0.8 to 36 cfs at Transect 4.

APPENDIX C

WUA estimates for common shiner, fallfish and white sucker within the range of modeled flows (0.8-36 cfs) in the Methuen Falls bypass reach

Estimated WUA and percentage of the total Methuen Falls Project bypass reach with appropriate habitat for common shiner spawning.

Common Shiner - Spawning		
Discharge (cfs)	**WUA (per 1,000 ft)**	**Percentage of Total Reach**
0.8	382.3	1%
1.0	489.7	1%
1.5	751.6	2%
2.0	1011.1	3%
2.5	1253.2	3%
3.0	1486.1	4%
4.0	1871.7	5%
5.0	2128.5	5%
6.0	2401.0	6%
7.0	2701.0	6%
8.0	2932.2	7%
9.0	3099.7	7%
10.0	3268.8	7%
11.0	3426.0	8%
12.0	3540.2	8%
13.0	3607.2	8%
14.0	3646.5	8%
15.0	3674.4	8%
16.0	3789.4	8%
18.4	4009.8	9%
20.0	4114.6	9%
22.0	4186.3	9%
24.0	4247.8	9%
24.7	4252.9	9%
26.0	4247.7	9%
28.0	4217.0	9%
30.0	4205.8	9%
32.0	4200.5	9%
34.0	4202.5	9%
36.0	4279.9	9%

Estimated WUA and percentage of the total Methuen Falls Project bypass reach with appropriate habitat for common shiner fry.

Common Shiner - Fry		
Discharge (cfs)	**WUA (per 1,000 ft)**	**Percentage of Total Reach**
0.8	3787.9	10%
1.0	3617.7	10%
1.5	3241.9	8%
2.0	2993.6	8%
2.5	2858.5	7%
3.0	2783.0	7%
4.0	2671.0	7%
5.0	2569.3	6%
6.0	2457.7	6%
7.0	2363.3	6%
8.0	2278.6	5%
9.0	2176.6	5%
10.0	2100.5	5%
11.0	2023.7	5%
12.0	1959.7	4%
13.0	1902.6	4%
14.0	1855.0	4%
15.0	1813.9	4%
16.0	1783.1	4%
18.4	1719.3	4%
20.0	1695.9	4%
22.0	1663.4	4%
24.0	1624.2	3%
24.7	1613.4	3%
26.0	1590.7	3%
28.0	1567.8	3%
30.0	1546.4	3%
32.0	1527.8	3%
34.0	1509.7	3%
36.0	1492.9	3%

Estimated WUA and percentage of the total Methuen Falls Project bypass reach with appropriate habitat for common shiner juvenile.

Common Shiner - Juvenile		
Discharge (cfs)	**WUA (per 1,000 ft)**	**Percentage of Total Reach**
0.8	13857.4	38%
1.0	13699.6	37%
1.5	13368.2	35%
2.0	13085.9	33%
2.5	12860.8	33%
3.0	12636.8	32%
4.0	12212.7	30%
5.0	11846.4	29%
6.0	11521.5	28%
7.0	11222.0	26%
8.0	10957.8	25%
9.0	10698.1	25%
10.0	10453.2	24%
11.0	10212.2	23%
12.0	9993.8	22%
13.0	9789.9	22%
14.0	9606.7	21%
15.0	9437.0	21%
16.0	9266.8	20%
18.4	8872.5	19%
20.0	8636.5	19%
22.0	8344.8	18%
24.0	8057.1	17%
24.7	7968.6	17%
26.0	7788.0	17%
28.0	7539.1	16%
30.0	7298.1	15%
32.0	7074.2	15%
34.0	6858.7	14%
36.0	6652.6	14%

Estimated WUA and percentage of the total Methuen Falls Project bypass reach with appropriate habitat for common shiner adult.

Common Shiner - Adult		
Discharge (cfs)	**WUA (per 1,000 ft)**	**Percentage of Total Reach**
0.8	11213.0	30%
1.0	11343.6	30%
1.5	11603.4	30%
2.0	11837.8	30%
2.5	12043.4	31%
3.0	12239.9	31%
4.0	12595.8	31%
5.0	12911.0	31%
6.0	13184.2	31%
7.0	13441.7	32%
8.0	13677.0	32%
9.0	13882.5	32%
10.0	14089.3	32%
11.0	14292.5	32%
12.0	14478.1	32%
13.0	14660.0	33%
14.0	14834.9	33%
15.0	15011.9	33%
16.0	15154.8	33%
18.4	15524.7	34%
20.0	15734.9	34%
22.0	15982.3	34%
24.0	16215.3	35%
24.7	16296.9	35%
26.0	16473.9	35%
28.0	16702.7	35%
30.0	16905.0	36%
32.0	17095.0	36%
34.0	17256.6	36%
36.0	17387.9	37%

Estimated WUA and percentage of the total Methuen Falls Project bypass reach with appropriate habitat for fallfish spawning.

Fallfish - Spawn		
Discharge (cfs)	**WUA (per 1,000 ft)**	**Percentage of Total Reach**
0.8	0.0	0%
1.0	0.0	0%
1.5	0.0	0%
2.0	0.0	0%
2.5	0.0	0%
3.0	0.0	0%
4.0	0.0	0%
5.0	0.0	0%
6.0	0.0	0%
7.0	0.0	0%
8.0	0.0	0%
9.0	0.0	0%
10.0	0.0	0%
11.0	0.0	0%
12.0	0.0	0%
13.0	0.0	0%
14.0	0.3	0.001%
15.0	2.3	0.01%
16.0	4.5	0.01%
18.4	10.8	0.02%
20.0	15.5	0.03%
22.0	22.1	0.05%
24.0	29.3	0.1%
24.7	31.8	0.1%
26.0	37.2	0.1%
28.0	45.6	0.1%
30.0	54.6	0.1%
32.0	64.2	0.1%
34.0	74.2	0.2%
36.0	84.8	0.2%

Estimated WUA and percentage of the total Methuen Falls Project bypass reach with appropriate habitat for fallfish adult.

Fallfish - Adult		
Discharge (cfs)	**WUA (per 1,000 ft)**	**Percentage of Total Reach**
0.8	0.0	0%
1.0	0.0	0%
1.5	0.0	0%
2.0	0.0	0%
2.5	0.0	0%
3.0	0.0	0%
4.0	0.0	0%
5.0	0.0	0%
6.0	0.0	0%
7.0	0.0	0%
8.0	0.0	0%
9.0	0.0	0%
10.0	0.0	0%
11.0	0.0	0%
12.0	0.0	0%
13.0	0.0	0%
14.0	0.0	0%
15.0	0.0	0%
16.0	0.0	0%
18.4	0.0	0%
20.0	0.0	0%
22.0	0.5	0.001%
24.0	1.5	0.003%
24.7	1.9	0.004%
26.0	2.7	0.01%
28.0	3.9	0.01%
30.0	5.3	0.01%
32.0	6.8	0.01%
34.0	8.3	0.02%
36.0	10.0	0.02%

Estimated WUA and percentage of the total Methuen Falls Project bypass reach with appropriate habitat for white sucker spawning.

White Sucker - Spawning		
Discharge (cfs)	**WUA (per 1,000 ft)**	**Percentage of Total Reach**
0.8	55.7	0%
1.0	70.7	0%
1.5	109.5	0%
2.0	152.2	0%
2.5	195.2	0%
3.0	242.4	1%
4.0	335.5	1%
5.0	430.3	1%
6.0	531.3	1%
7.0	632.3	1%
8.0	741.4	2%
9.0	859.3	2%
10.0	971.6	2%
11.0	1084.4	2%
12.0	1194.7	3%
13.0	1302.0	3%
14.0	1396.8	3%
15.0	1494.5	3%
16.0	1586.2	3%
18.4	1772.9	4%
20.0	1852.3	4%
22.0	1947.3	4%
24.0	2036.2	4%
24.7	2068.5	4%
26.0	2129.1	5%
28.0	2203.6	5%
30.0	2284.3	5%
32.0	2367.5	5%
34.0	2446.5	5%
36.0	2502.6	5%

Estimated WUA and percentage of the total Methuen Falls Project bypass reach with appropriate habitat for white sucker fry.

White Sucker - Fry		
Discharge (cfs)	**WUA (per 1,000 ft)**	**Percentage of Total Reach**
0.8	14168.0	38%
1.0	14277.5	38%
1.5	14455.5	37%
2.0	14588.6	37%
2.5	14682.0	37%
3.0	14758.7	37%
4.0	14865.1	37%
5.0	14921.4	36%
6.0	14946.3	36%
7.0	14932.1	35%
8.0	14902.6	35%
9.0	14861.4	34%
10.0	14838.3	34%
11.0	14811.7	33%
12.0	14782.7	33%
13.0	14754.8	33%
14.0	14735.1	33%
15.0	14718.5	33%
16.0	14707.8	32%
18.4	14702.4	32%
20.0	14705.1	32%
22.0	14698.0	32%
24.0	14685.9	31%
24.7	14681.9	31%
26.0	14660.2	31%
28.0	14632.5	31%
30.0	14604.3	31%
32.0	14566.2	31%
34.0	14523.8	31%
36.0	14474.1	30%

Estimated WUA and percentage of the total Methuen Falls Project bypass reach with appropriate habitat for white sucker juvenile.

White Sucker - Juvenile		
Discharge (cfs)	**WUA (per 1,000 ft)**	**Percentage of Total Reach**
0.8	11777.1	32%
1.0	12043.3	32%
1.5	12551.2	32%
2.0	12937.2	33%
2.5	13240.2	34%
3.0	13508.5	34%
4.0	13941.5	34%
5.0	14296.6	35%
6.0	14601.3	35%
7.0	14868.0	35%
8.0	15105.5	35%
9.0	15331.5	35%
10.0	15538.1	35%
11.0	15727.9	35%
12.0	15903.7	36%
13.0	16066.5	36%
14.0	16219.1	36%
15.0	16363.4	36%
16.0	16492.7	36%
18.4	16769.0	36%
20.0	16929.4	37%
22.0	17111.5	37%
24.0	17282.1	37%
24.7	17335.6	37%
26.0	17442.8	37%
28.0	17595.3	37%
30.0	17735.3	38%
32.0	17858.3	38%
34.0	17970.3	38%
36.0	18077.2	38%

Estimated WUA and percentage of the total Methuen Falls Project bypass reach with appropriate habitat for white sucker adult.

White Sucker - Adult		
Discharge (cfs)	**WUA (per 1,000 ft)**	**Percentage of Total Reach**
0.8	6412.7	17%
1.0	6533.1	17%
1.5	6765.9	18%
2.0	6942.3	18%
2.5	7087.8	18%
3.0	7221.9	18%
4.0	7455.4	18%
5.0	7662.5	19%
6.0	7852.1	19%
7.0	8028.4	19%
8.0	8193.2	19%
9.0	8353.1	19%
10.0	8506.5	19%
11.0	8653.4	20%
12.0	8794.2	20%
13.0	8930.8	20%
14.0	9063.8	20%
15.0	9194.3	20%
16.0	9319.4	20%
18.4	9605.7	21%
20.0	9784.3	21%
22.0	10001.7	22%
24.0	10207.8	22%
24.7	10272.0	22%
26.0	10401.7	22%
28.0	10584.3	22%
30.0	10748.5	23%
32.0	10901.1	23%
34.0	11045.3	23%
36.0	11179.6	23%