Technical Report for the Instream Flow Habitat Assessment and Zone of Passage Study

Lowell Hydroelectric Project (FERC No. 2790)

Prepared For

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Table of Contents

List of Tables

List of Figures

1 Introduction

Boott Hydropower, LLC (Boott) submitted their Revised Study Plan (RSP) to the Federal Energy Regulatory Commission (FERC) on January 28, 2019. Among the thirteen studies described in the RSP was the Instream Flow Habitat Assessment and Zone of Passage Study in the Bypassed Reach (the Study). FERC provided their Study Plan Determination (SPD) on March 13, 2019 and the Study was approved as filed. The purpose of this report is to describe study methodologies used to assess the flow:habitat relationship for target fish species and life stages in the Bypassed Reach (Bypass) and to evaluate the zone of passage assessment, and to detail the results of both Study components.

2 Objectives

As previously summarized in the RSP, there were two separate study elements requested to evaluate the bypassed reach, one pertaining to fish passage and one to aquatic habitat:

- Bypass Zone of Passage Assessment: determine flows which facilitate fish passage through the bypass reach through the use of detailed elevation and bathymetry data and two-dimensional (2D) modeling techniques;
- Instream Flow Habitat Assessment: determine impacts of a range of Project flows on wetted area and habitat for key aquatic species by conducting an instream flow study based on the Instream Flow Incremental Methodology (IFIM) process and one-dimensional (1D) modeling techniques.

These two study requests were subsequently combined into a single study. As detailed in the FERC-approved RSP, the Study was conducted via the application of a two-dimensional (2D) model of the bypassed reach to provide the results necessary to address both study elements and provide FERC with sufficient information to complete an environmental assessment.

3 Project Description and Study Area

The Lowell Project is located at River Mile (RM) 41 on the Merrimack River in the City of Lowell in Middlesex County, Massachusetts, with an impoundment extending approximately 23 miles upstream into Hillsborough County, New Hampshire. The existing Lowell Project consists of: (1) a 1,093-foot-long, 15-foot-high masonry gravity dam (Pawtucket dam) that includes a 982.5-foot-long spillway with a crest elevation of 87.2 feet National Geodetic Vertical Datum 1929 (NGVD 29) topped by 5-foot-high pneumatically-operated crest gates deployed in five independently-operable zones; (2) a 720-acre impoundment with a normal maximum water surface elevation of 92.2 feet NGVD 29; (3) a 5.5-mile-long canal system which includes several small dams and gatehouses; (4) a powerhouse (E.L. Field) which uses water from the Northern Canal and contains two turbine-generator units with a total installed capacity of 15.0 megawatts (MW); (5) a 440-foot-long tailrace channel; (6) four powerhouses (Assets, Bridge Street, Hamilton, and John Street) housed in nineteenth century mill buildings along the Northern and Pawtucket Canal System containing 15 turbine-generator units with a total installed capacity of approximately 5.1 MW; (7) a 4.5-mile long, 13.8-kilovolt transmission line connecting the powerhouses to the regional distribution grid; (8) upstream and downstream fish passage facilities including a fish elevator and downstream fish bypass at the E.L. Field powerhouse, and a vertical-slot fish ladder at the Pawtucket dam; (9) appurtenant facilities; and (10) a 4,000 ft Bypassed Reach, which is the subject of this Study. The Project operates essentially in a run-of-river (ROR) mode using automatic pond level control, and has no usable storage capacity. As part of its relicensing proposal, Boott proposes to remove the four mill powerhouses and associated canal infrastructure from the Project's FERC license, retaining only the Pawtucket Dam, Northern Canal, E.L. Field Powerhouse and fish passage facilities. More detailed information is provided in Boott's application for new license.

The study areas for the zone of passage assessment and the aquatic habitat assessment were identical and both confined to the Bypass. The study area encompassed the length of the Bypass from just below the School Street Bridge (yellow line in Figure 3-1) downstream approximately 3,000 ft to the confluence of the Bypass and tailrace (green line in Figure 3-1). The 2D model for the zone of passage component was initially extended upstream from the bridge through the series of concrete passage weirs, however the model was not able to accurately describe velocity patterns associated with the artificial weir structures and consequently the passage assessment focused on the bedrock habitat below the bridge.

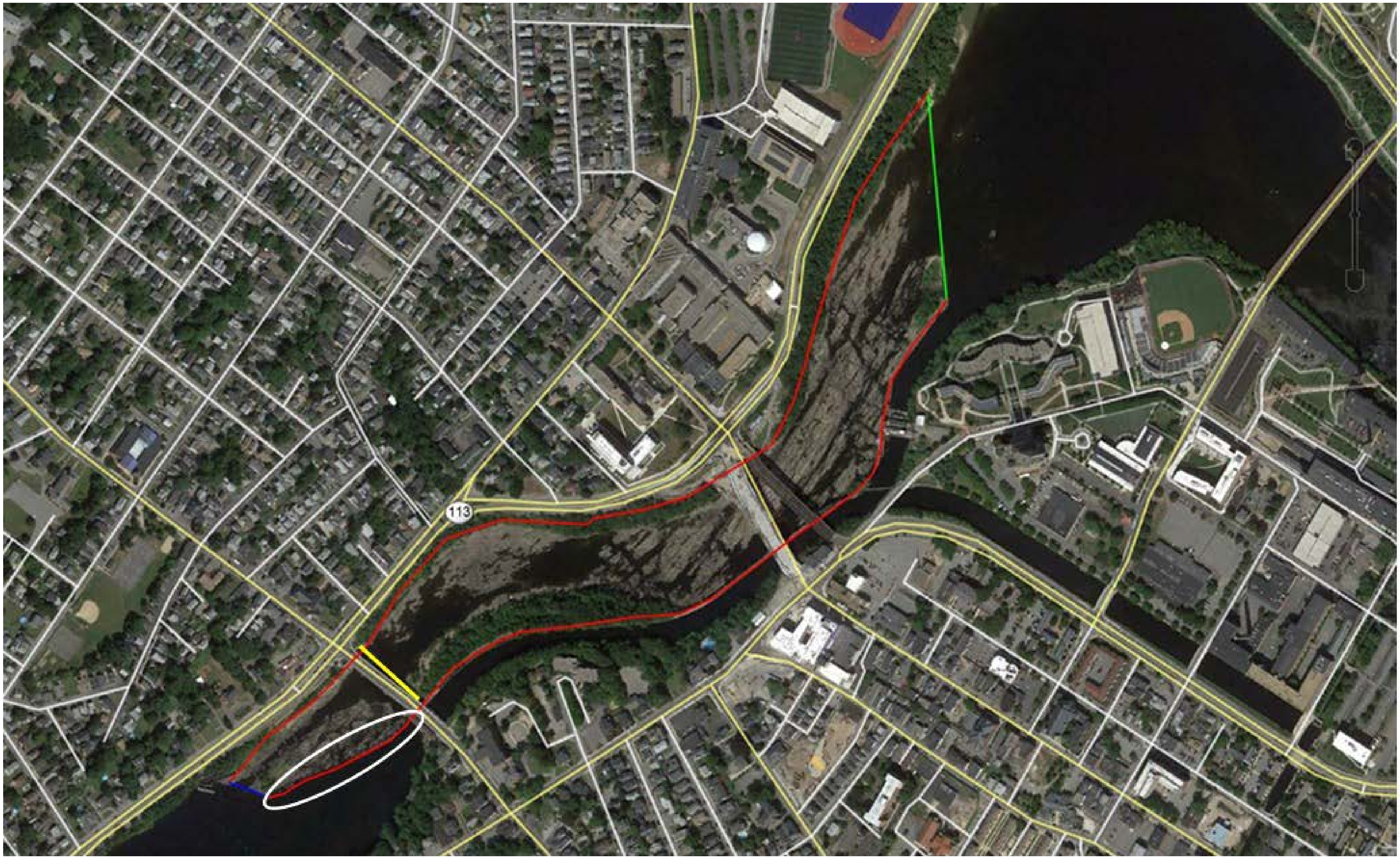


Figure 3–1. Spatial extent of the Bypassed Reach (red lines) showing the top boundary for both the zone of passage component and the aquatic habitat component (yellow line), the bottom boundary for both components (green line), and the parallel spillway (white oval) upstream of the modeled study reach.

4 Methods

4.1 2D Hydraulic Model

The 2D hydraulic model used to assess the zone of passage and aquatic habitat components of the instream flow study was River 2D (Steffler and Blackburn 2002), which is a depth-averaged model that incorporates Habitat Suitability Criteria (HSC) to evaluate the quantity and quality of aquatic habitat for selected species and life stages within the range of modeled flows. The River2D model uses a detailed topographic map of the study site to solve basic equations for conservation of mass and conservation of momentum in two horizontal directions to simulate water depths and velocities. Model inputs are bed topography, channel roughness, discharge at the upstream boundary, and water surface elevations at the downstream boundary. As noted in the River 2D manual "Obtaining an accurate representation of bed topography is likely the most critical, difficult, and time-consuming aspect of the 2D modeling exercise" (Steffler and Blackburn 2002). The topography for River 2D model is collected with higher density sampling in areas of more complex and/or rapidly varying habitat/bed features and lower densities in areas with more uniform topography (USFWS 2011). Some gaps in topography will occur in locations where depth, velocity, or other factors prevent safe data collection. The River 2D modules R2D_Bed and R2D_Mesh are used to generate bed topography and define the reach of interest using pointwise elevations and roughness.

Model calibration consists of adjusting the bed roughness values, if needed, in the model until a reasonable match is obtained between the simulated and measured water surface elevations. Water surface elevations predicted by the 2D model should be within 0.1 foot (0.031 m) of the water surface elevation measured at the upstream boundary (USFWS 2011). Once calibrated, the downstream water surface elevation and the inflow of the model are changed to simulate the flows of interest. Each flow change is run to a steady state solution. That is, for a constant inflow, the model is run until there is a constant outflow and the two flows are essentially equal. Typical convergence tolerance is within 1-5% of the inflow. Another measure of convergence is the solution change. Ideally, the solution change will become sufficiently small (0.00001) once converged. In some cases, the solution change will reach a relatively small value and not decrease any further, indicating a small, persistent oscillation at one or more points. This oscillation is often associated with a shallow node that alternates between wet and dry. This oscillation may be considered acceptable if the size of the variation is within the desired accuracy of the model (Steffler and Blackburn 2002). The ultimate goal is to define flow allocation through split channels and (in this case) accurately simulate fish migration pathways under low flow conditions.

The development of a 2D flow model requires the establishment of fixed boundaries at the upstream and downstream ends of the study reach. Those boundaries are required to be a single channel and be represented by a single water surface elevation (WSE) value for any given flow. The unique configuration of the spillway at the upstream end of the Bypass presents a challenge for establishment of the upstream boundary. The upstream fish ladder and associated attraction water system (AWS), as well as the 220 feet of pneumatic crest gate closest to the northern bank (blue line in Figure 3-1) will discharge water in a linear fashion down through the full length of the Bypass. However, under conditions where flows are released from any of the pneumatic crest gate sections along the 765 feet of spillway oriented parallel to the Bypass channel (white oval in Figure 3-1), that discharge will not enter the uppermost section of the Bypass in a linear fashion. Spill-related inflows converging into the upper section of the Bypass would confound the 2D model if the upstream boundary is placed above that inflow.

As a result, the upstream boundary for the zone of passage and the aquatic habitat components of the Study was placed just below the School Street Bridge (yellow line in Figure 3-1). With the upstream boundary located at the Bridge, inflows provided from either the fish ladder and associated AWS system or any of the pneumatic crest gate sections are available at the model boundary in a more uniform (non-converging) flow pattern, and as a result permits modeling over a wide range of inflows to assess both passage and aquatic habitat.

4.1.1 Calibration Flows

A minimum of three calibration flows are required for collection of WSE and total flow (Q) at the upstream boundary, and WSE at the downstream boundary. The RSP recommended low flow calibration flow of 500 cfs, which represents the discharge from the fish ladder and associated AWS. The suggested high calibration flow target was ~7,800 cfs, which was the maximum combined discharge for the fish ladder, AWS system and 220 foot pneumatic crest gate, with a middle flow target of ~4,150 cfs (the midpoint between low and high flow targets). The general rule of thumb for instream flow evaluations is the ability to model downwards approximately 50% of the low flow, and upwards approximately 2 to 2½ times the highest calibration flow. Following that guidance, the calibration flows proposed as part of this study will theoretically support modeling from 250 cfs up to over 15,000 cfs. Actual measured calibration flows were similar to the proposed flows and ranged from 482 cfs for the low flow, 4,345 cfs for the middle flow, and 7,011 cfs for the high flow. As a result, modeled estimates could be generated over a range of flows from 250 cfs to 14,000 cfs.

4.2 Field Sampling

4.2.1 WSE and Flow Measurements

Collection of low, middle, and high calibration flow data occurred on 23 October 2019, 10 December 2020, and 4 December 2020, respectively. At each flow, WSE data were collected at several locations: just below the dam, at the fish ladder entrance, and just below the School Street Bridge (the upper boundary of the 2D model, Figure 3-1). WSE's were measured with a Real-time kinematic GPS (RTK) with a vertical accuracy of 0.1 ft. Total Bypass flow at low flow was measured at the downstream side of the School Street bridge using a Teledyne RDI Rio Grande 1200 KHz Acoustic Doppler Current Profiler (ADCP). The high flow and mid-flow discharge values were provided by the Licensee prior to each data collection event. Bypass flows were estimated by subtracting the flow reported at USGS gage no. 01099500 (Concord River below River Meadow Brook, at Lowell, MA) from USGS gage no. 01100000 (Merrimack River below Concord River at Lowell, MA), yielding inflow to the Pawtucket Dam, then subtracting the calculated flow through the E.L. Field powerhouse turbines. Downtown canal flows were negligible during this period.

4.2.2 Bathymetry Measurements

As noted above, accurate bed elevation data is necessary to develop a 2D model that is representative of the actual study area. Stream bottom elevations within the Bypass were predominantly based on Light Detection and Ranging (LIDAR) data collected by Cornerstone Energy Services, Inc. on 24 October 2019 at a flow of 40 cfs. The estimated vertical and horizontal accuracy of the LIDAR output exceeded 0.1 ft. The LIDAR data was complemented by RTK measurements under riparian canopy and bridge structures where the LIDAR data was sparse or non-existent. RTK was also used to measure bathymetry in wadeable areas of the Bypass where LIDAR did not penetrate. This shallow water bathymetry data was collected during October 2019 under non-spill conditions within the Bypass. Bottom elevations in locations too deep to wade at low flow (i.e., depths >4 ft) were estimated using aerial photos, ADCP data, and RTK measurements. Substrate characterizations (see Section 4.2.3) were collected by two RTK crews at the same time.

4.2.3 Substrate Measurements

Bypass substrate was visually assessed on foot and via aerial photography in exposed bottom and shallow, wadeable areas using RTK to delineate polygons having specified substrate composition (Figure 4-1). Substrate was estimated in deeper, non-wadeable areas based on surrounding substrate characteristics and presence of eddy-forming features (e.g., bridge structures, point bars, etc.). Substrate composition was primarily used for assessing habitat suitability for each species and life-stage, according to their HSC (Section 4.4).

Polygons were defined by the percentage of dominant and subdominant substrate types in the following classes:

- Organics (ORG)
- Mud/Clay (MUD)
- Silt (SLT) (<0.003 inches)
- Sand (SND) (0.003-0.08 inches)
- Gravel (GRV) (0.08-2.5 inches)
- Cobble (COB) (2.5-10.1 inches)
- Boulder (BLD) (>10.1 inches)
- Bedrock (BED)

Where the substrate composition in a polygon was composed of two or more separate classes, the suitability of was calculated for each species and life-stage using the percentages of each type and the associated HSC values to calculate a weighted mean HSC value for that polygon. Crews noted that much of the gravel observed in the Bypass Reach was clean and laying on top of bedrock, suggesting it was very mobile and may not provide persistent habitat value.

4.3 2D Model Development

The RTK elevation data was combined with elevation data from the LIDAR to create the preliminary bed topography file. The resulting topography was edited in the River2D bed program by adding breaklines in order to refine the topography and interpolate between any gaps in coverage; resulting in the final digital elevation model used in the River2D program. In total, 692,252 survey points were used to create the topographic bed file (Figure 4-2), resulting in an overall point density of approximately 476 points/100 m^2. An artificial downstream extension was added to ensure a uniform outflow boundary and minimize any boundary effects in the model area of interest.

After finalizing the topographic bed file, a computational mesh was created for generating flow simulations. The final computational mesh had 18,223 nodes, 35,858 elements, and a mesh quality index of 0.38, which is within the River2D recommended quality index of 0.1 to 0.5 (Steffler and Blackburn 2002). Model calibration involved running the model at the three measured flows with a roughness value of 0.1. The modeled water surface elevations at the upstream end of the riffle were within 0.14 ft of the measured values (Table 4-1). After calibration, models were run to simulate flows from 250 cfs to 14,000 cfs. The downstream boundary conditions were set using a log-log rating curve created from the measured flows. A uniform Roughness (k_s) of 0.1 was used for all flow simulations

Model statistics for simulated flows are listed in Table 4-2. While solution change will ideally be below 0.00001 this is not always be achievable, especially at lower flows or in complex topography with many shallow depths. As noted in Steffler and Blackburn (2002):

> In some cases, the solution will reach a relatively small value of solution change (of the order of 0.03) and refuse to diminish further, regardless of the number of subsequent time steps. Usually, this indicates a small, persistent, oscillation at one (or sometimes more) points in the flow field. Often, the oscillation is associated with a shallow node that alternates between wet and dry. . . Finally, the oscillating solution may be considered acceptable, as the size of the variation may be within the desired accuracy of the simulation.

Given the high number of nodes in the model, the complexity of the topography, and the fact that the largest change was around our measurement accuracy, we found the results acceptable. In addition, the net Q was less than 1.1% in all of the model simulations, which is likely less than any error associated with flow measurements and the development of rating curves that were used to assign the upper and lower boundary conditions for the models, and the fact net Q was stable, we found the results to be acceptable. This rationale is consistent with findings in USFS (2011): "…we still considered these production cdg files for these sites to have a stable solution since the Net Q was not changing and the Net Q in all cases was less than 1.1%. In comparison, the accepted level of accuracy for USGS gages is generally 5%."

The bed elevations in wetted areas that were too dangerous or deep to collect topography with RTK were estimated using a combination of photos, aerial imagery, ADCP depth data and any nearby surveyed elevations.

4.4 Habitat Suitability Criteria (HSC)

HSC define the relative suitability of habitat variables for target species and life-stages, scaled from 0.0 (unsuitable habitat) to 1.0 (optimal habitat). HSC are the biological component of instream flow studies, and are directly incorporated into River2D for describing the flow:habitat relationship.

4.4.1 Target Species and Life-stages

Target fish species and life-stages were proposed for use in the RSP, then discussed and expanded upon during a May 21 2020 conference call with the relicensing participants. The species and associated life-stages used for the zone of passage component of this analysis are:

- American shad (adult passage)
- Blueback herring (adult passage)
- Alewife (adult passage)

HSC variables describing upstream passage criteria for each species were taken from USFWS (2019) and are presented in Table 4-3. The migratory species listed above (shad and river herring) are expected to require passage through the bypass reach to access upstream spawning habitat. Upstream passage criteria for American shad and river herring were generally taken from USFWS (2019) Fish Passage Engineering Design Criteria, which included maximum fish body depth, minimum weir opening depth, maximum weir opening velocity, and minimum weir opening width.

The species and associated life-stages used for the aquatic habitat component of this analysis are:

- American shad (juvenile, spawning)
- River herring (spawning)
- Smallmouth bass (fry, juvenile, adult, spawning)
- Fallfish (juvenile, adult)
- White sucker (fry, juvenile/adult, spawning)
- Longnose dace (juvenile, adult)
- Sea lamprey (spawning & incubation)
- Freshwater mussels (rearing)
- Benthic macroinvertebrates

The species and life stages listed above are those reasonably expected to utilize portions of the bypass for spawning and/or rearing. HSC variables describing aquatic habitat suitability for all species included mean column velocity, depth, and substrate are listed in Table 4-4, as well as the data sources associated with each HSC dataset. Graphical output of the HSC curves are presented in Appendix A.

Figure 4–1. Substrate polygon map of the Bypass Reach. See Section 4.2.3 for substrate code.

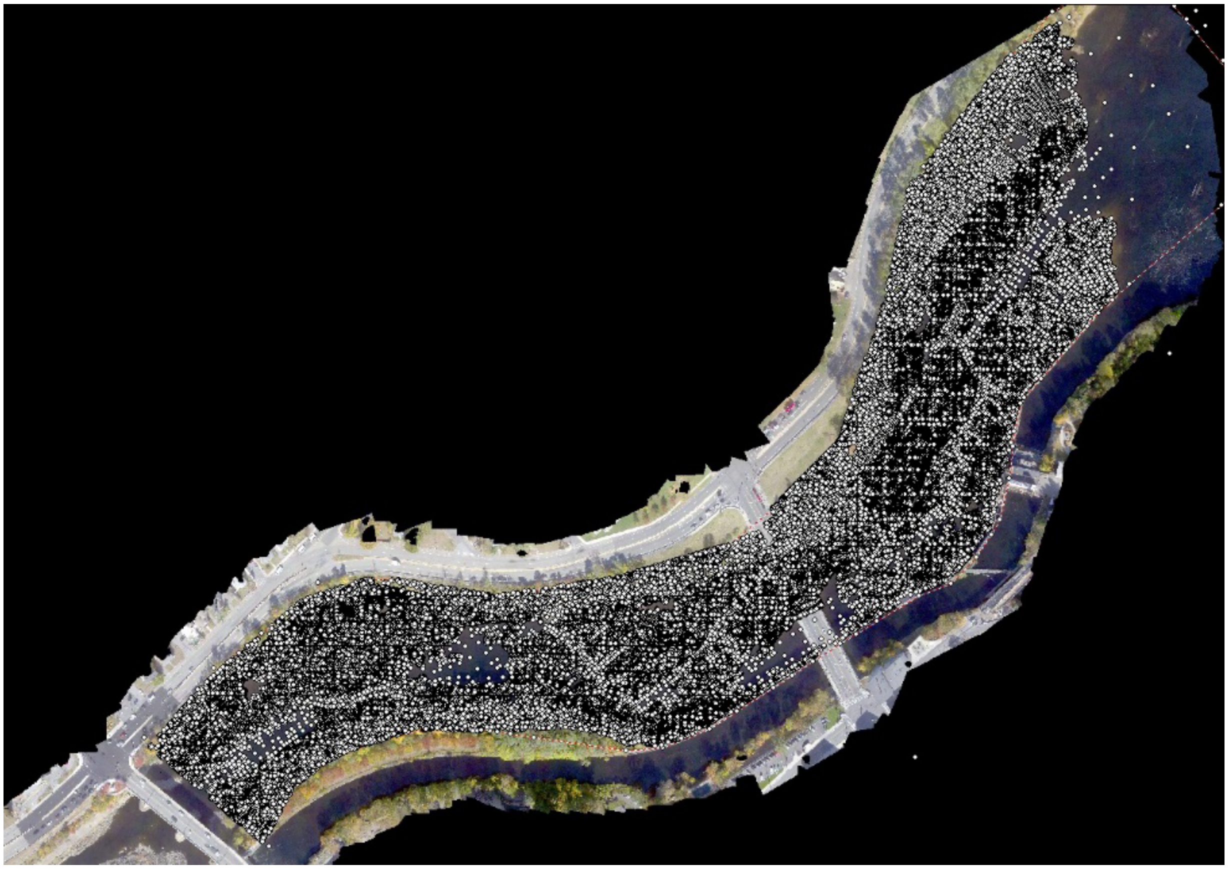


Figure 4–2. Topographic bed file for the 2D model (note-many nodes not visible in image).

Table 4–1. River2D calibration values.

Flow (cfs)	Measured stage (ft)	2D modeled stage (ft)	Difference (ft)
482	69.82	69.96	0.14
4,345	72.68	72.60	-0.08
7,011	73.74	73.62	-0.13

Table 4–2. River2D model simulation statistics.

Inflow (cfs)	Outflow (cfs)	Net Q	Solution Change
250.0	251.9	0.76%	6.94E-02
482.0	478.4	-0.74%	3.25E-02
1000.0	995.9	-0.41%	3.74E-02
2000.0	1977.9	-1.11%	4.87E-02
4345.0	4342.0	-0.07%	2.14E-02
6000.0	6000.2	0.00%	3.59E-02
8000.0	7999.6	-0.01%	3.41E-02
10000.0	9999.3	-0.01%	3.03E-02
12000.0	11993.6	-0.05%	2.82E-02
14000.0	14011.0	0.08%	4.25E-02

Table 4–3. Upstream passage criteria for river herring and American shad in the Bypass reach (criteria from USFWS 2019).

Species	Max Body Depth ft	Min Weir Depth ft	Max Weir Velocity fps	Min Weir Width ft
Blueback Herring	0.26	1.0	6.0	2.25
Alewife	0.29	1.0	6.0	2.5
American Shad	0.73	2.25	8.25	5.0

Table 4–4. HSC values according to species and life-stage. Data sources for mean column velocity (V), depth (D), and dominant substrate (S) HSC also shown.

Species	Life-stage	Velocity fps	HSC	Depth ft	HSC	Substrate	HSC	Source
American Shad	Juvenile	0.00	0.00	0.00	0.00	Organics	0.10	Stier & Crance 1985 (V), Greene et al. 2009 (D), Conowingo IFIM (S)
		0.20	1.00	0.66	0.50	Mud/clay	0.20	
		1.00	1.00	1.50	0.75	Silt	1.00	
		4.50	0.00	4.90	1.00	Sand	1.00	
				6.60	1.00	Gravel	1.00	
				13.20	0.75	Cobble	1.00	
				20.00	0.25	Boulder	0.60	
				50.00	0.00	Bedrock	0.40	
American Shad	Spawning	0.00	0.30	0.00	0.00	Organics	0.00	Hightower et al. 2012 (V), Hightower/Steir & Crance 1985 (D), Steir & Crance 1985 (S)
		0.70	0.75	1.60	0.40	Mud/clay	0.10	
		1.00	1.00	3.30	0.74	Silt	0.20	
		3.00	1.00	4.90	0.89	Sand	1.00	
		3.90	1.00	6.60	0.98	Gravel	1.00	
		5.60	0.00	8.20	1.00	Cobble	1.00	
				9.80	0.97	Boulder	0.60	
				11.50	0.92	Bedrock	0.40	
				13.10	0.85			
				14.80	0.77			
				16.40	0.68			
				18.00	0.60			
				19.70	0.53			
				21.30	0.46			
				50.00	0.00			
River Herring	Spawning	0.00	1.00	0.00	0.00	Organics	1.00	adapted from Pardue 1983 and Mather et al. 2012
		1.00	1.00	0.49	0.00	Mud/clay	1.00	
		1.01	0.00	0.50	1.00	Silt	1.00	
				9.80	1.00	Sand	0.10	
				9.90	0.00	Gravel	0.10	
						Cobble	0.10	
						Boulder	0.10	
						Bedrock	0.10	
Smallmouth Bass	Fry	0.00	0.60	0.00	0.00	Organics	0.10	Leonard et al. 1986
		0.19	1.00	0.28	0.06	Mud/clay	0.10	
		0.59	1.00	1.31	1.00	Silt	0.10	
		1.00	0.00	2.95	1.00	Sand	0.20	

Species	Life-stage	Velocity fps	HSC	Depth ft	HSC	Substrate	HSC	Source
				3.25	0.95	Gravel	0.30	
				4.59	0.40	Cobble	1.00	
				6.56	0.00	Boulder	1.00	
				10.00	0.00	Bedrock	0.50	
Smallmouth Bass	Juvenile	0.00	0.30	0.00	0.00	Organics	0.10	Groshens and Orth 1994 (V), Leonard et al. 1986 (D,S)
		0.17	0.66	0.52	0.00	Mud/clay	0.10	
		0.33	0.90	0.67	0.03	Silt	0.10	
		0.50	0.93	2.15	1.00	Sand	0.20	
		0.66	1.00	10.00	1.00	Gravel	0.30	
		0.83	1.00			Cobble	1.00	
		0.98	0.93			Boulder	1.00	
		1.15	0.87			Bedrock	0.50	
		1.31	0.84					
		1.47	0.77					
		1.64	0.70					
		1.81	0.62					
		1.98	0.47					
		2.30	0.27					
		2.62	0.17					
		2.95	0.09					
		3.94	0.03					
		4.59	0.00					
Smallmouth Bass	Adult	0.00	0.12	0.00	0.00	Organics	0.10	Groshens and Orth 1994 (V), Leonard et al. 1986 (D,S)
		0.17	0.66	0.92	0.00	Mud/clay	0.10	
		0.33	0.90	1.31	0.08	Silt	0.10	
		0.50	1.00	2.03	0.56	Sand	0.20	
		0.66	0.93	2.82	1.00	Gravel	0.30	
		0.83	0.82	6.00	1.00	Cobble	1.00	
		0.98	0.65	10.00	1.00	Boulder	1.00	
		1.15	0.53			Bedrock	0.50	
		1.31	0.46					
		1.47	0.42					
		1.64	0.36					
		1.81	0.32					
		1.98	0.25					
		2.30	0.15					
		2.62	0.08					
		2.95	0.06					
		3.94	0.04					
		4.59	0.04					
		5.00	0.00					
Smallmouth Bass	Spawning	0.00	1.00	0.22	0.00	Organics	0.00	Allen 1996 (V,S), Edwards et al. 1983 (D)

Species	Life-stage	Velocity fps	HSC	Depth ft	HSC	Substrate	HSC	Source
		0.45	1.00	0.50	0.02	Mud/clay	0.00	
		0.55	0.96	0.74	0.05	Silt	0.00	
		0.65	0.89	1.10	0.12	Sand	0.20	
		0.75	0.69	1.32	0.22	Gravel	1.00	
		0.85	0.34	1.53	0.34	Cobble	0.30	
		0.95	0.25	1.70	0.54	Boulder	0.00	
		1.05	0.20	1.90	0.90	Bedrock	0.00	
		1.15	0.16	2.05	0.97			
		1.25	0.14	2.18	0.99			
		1.65	0.11	2.40	1.00			
		1.85	0.09	4.75	1.00			
		2.35	0.04	4.95	0.97			
		2.55	0.02	5.10	0.91			
		2.75	0.00	5.40	0.62			
				5.80	0.40			
				6.10	0.27			
				6.50	0.17			
				6.95	0.09			
				7.30	0.04			
				7.75	0.02			
				8.00	0.00			
Fallfish	Juvenile	0.00	0.00	0.00	0.00	Organics	0.10	Gomez & Sullivan 2007
		0.10	0.60	0.40	0.00	Mud/clay	0.00	
		0.20	0.88	0.60	0.11	Silt	0.10	
		0.60	1.00	1.00	1.00	Sand	0.50	
		1.60	1.00	3.00	1.00	Gravel	1.00	
		2.00	0.40	4.00	0.27	Cobble	1.00	
		3.50	0.04	7.00	0.24	Boulder	0.20	
		4.30	0.00	8.00	0.07	Bedrock	0.00	
				100.00	0.07			
Fallfish	Adult	0.00	0.00	0.00	0.00	Organics	1.00	Gomez & Sullivan 2007
		0.10	1.00	0.50	0.00	Mud/clay	1.00	
		0.80	1.00	3.00	1.00	Silt	1.00	
		1.50	0.40	100.00	1.00	Sand	1.00	
		3.00	0.00			Gravel	1.00	
						Cobble	1.00	
						Boulder	1.00	
						Bedrock	1.00	
White Sucker	Fry	0.00	1.00	0.00	0.00	Organics	1.00	Twomey et al. 1984
		0.30	1.00	1.00	1.00	Mud/clay	1.00	
		1.00	0.00	100.00	1.00	Silt	1.00	
						Sand	1.00	
						Gravel	1.00	
						Cobble	1.00	
						Boulder	1.00	
						Bedrock	1.00	

Species	Life-stage	Velocity fps	HSC	Depth ft	HSC	Substrate	HSC	Source
White Sucker	Juvenile/ Adult	0.00	0.00	0.00	0.00	Organics	1.00	Twomey et al. 1984
		0.16	0.70	0.50	0.00	Mud/clay	1.00	
		0.33	1.00	2.30	1.00	Silt	1.00	
		0.49	1.00	3.30	1.00	Sand	1.00	
		0.66	0.70	9.80	0.50	Gravel	1.00	
		1.31	0.00	16.40	0.00	Cobble	1.00	
						Boulder	1.00	
						Bedrock	1.00	
White Sucker	Spawning	0.00	0.00	0.00	0.00	Organics	0.00	Twomey et al. 1984 (V,D), Gomez & Sullivan 2007 (S)
		0.50	0.40	0.50	1.00	Mud/clay	0.00	
		1.00	1.00	0.80	1.00	Silt	0.50	
		2.00	1.00	1.00	0.80	Sand	1.00	
		3.00	0.00	2.00	0.00	Gravel	0.90	
						Cobble	0.00	
						Boulder	0.00	
						Bedrock	0.00	
Longnose Dace	Juvenile	0.00	0.00	0.00	0.00	Organics	0.00	Gomez & Sullivan 2007
		0.75	1.00	0.75	1.00	Mud/clay	0.00	
		1.50	1.00	1.15	1.00	Silt	0.00	
		2.00	0.35	1.50	0.40	Sand	0.18	
		2.20	0.20	1.75	0.20	Gravel	1.00	
		2.50	0.13	2.00	0.14	Cobble	1.00	
		3.00	0.05	3.00	0.00	Boulder	0.50	
		4.00	0.00			Bedrock	0.00	
Longnose Dace	Adult	0.00	0.00	0.00	0.00	Organics	0.00	Gomez & Sullivan 2007
		0.75	1.00	0.10	0.00	Mud/clay	0.00	
		1.75	1.00	0.75	1.00	Silt	0.00	
		3.00	0.28	1.60	1.00	Sand	0.60	
		3.60	0.08	2.50	0.00	Gravel	1.00	
		4.50	0.00			Cobble	1.00	
						Boulder	0.80	
						Bedrock	0.00	
Sea Lamprey	Spawning	0.00	0.00	0.00	0.00	Organics	0.00	Kynard & Horgan (V,S), Kynard/GRH 2019 (D)
		0.30	0.00	0.13	0.00	Mud/clay	0.00	
		1.28	0.34	0.46	0.50	Silt	0.00	
		2.26	1.00	0.79	1.00	Sand	0.04	
		3.25	0.86	4.50	0.98	Gravel	1.00	
		4.23	0.30	5.50	0.78	Cobble	0.50	
		5.22	0.12	6.50	0.57	Boulder	0.02	
		6.20	0.08	7.50	0.43	Bedrock	0.00	
		6.23	0.00	8.50	0.28			
				9.50	0.15			

Species	Life-stage	Velocity fps	HSC	Depth ft	HSC	Substrate	HSC	Source
				10.50	0.07			
				11.50	0.04			
				12.50	0.01			
				13.50	0.00			
Freshwater Mussels	Rearing	0.00	0.50	0.00	0.00	Organics	0.00	Normandeau & Biodrawversity 2017
		0.10	1.00	1.50	1.00	Mud/clay	0.00	
		2.25	1.00	13.50	1.00	Silt	1.00	
		5.50	0.00	22.00	0.50	Sand	0.19	
				100.00	0.50	Gravel	0.72	
						Cobble	0.57	
						Boulder	0.29	
						Bedrock	0.17	
Benthic Macroinvertebrates	Rearing	0.00	0.00	0.00	0.00	Organics	0.50	Gomez & Sullivan 2000
		0.50	0.00	0.10	0.00	Mud/clay	0.50	
		1.50	1.00	0.40	1.00	Silt	0.20	
		3.50	1.00	3.00	1.00	Sand	0.10	
		4.60	0.50	5.00	0.50	Gravel	0.60	
		8.00	0.00	6.50	0.25	Cobble	1.00	
				8.00	0.15	Boulder	0.90	
				10.00	0.15	Bedrock	0.50	
				100.00	0.00			

5 Results

5.1 Zone of Passage Assessment

The zone of passage model was developed for three migratory species (Table 4-3) in the Bypass Reach from the School Street Bridge downstream 3,000 ft through the bedrock rapids to the tailrace confluence. The minimum flow that provided a continuous and unbroken pathway (or nearly unbroken pathway) meeting the passage criteria was estimated by modeling passage opportunities at flows ranging from 250 cfs to 14,000 cfs. The passage assessment utilized values for minimum passage depth and maximum passage velocity. The passage analysis did not account for channel widths, which are routinely used in assessing passage through weirs and ladders; however given the large scale of the Bypass Reach and the complexity of the bedrock habitat, it is unlikely that channel widths would be limiting.

Assessment of the zone of passage was problematic due to the highly complex bedrock habitat throughout most of the Bypass Reach. It should be noted that the 2D model utilized actual measurements for developing the elevation model, except in areas that remained too deep and fast at low flow to safely measure (Figure 5-1), and consequently is expected to be relatively accurate in most locations. In contrast, all velocities were estimated via the hydraulic model, and in a highly complex habitat such as the Bypass Reach, in particular the lower bedrock-dominated channel, the model resolution for velocities may not be sufficiently accurate or precise to confidently assess passability in some areas. Also, the estimated velocities represent mean column velocities and do not account for near bottom velocities, which would be expected to be lower than mean column. Likewise, the velocity assessment is not expected to accurately represent zones of slower velocities along the margins of bedrock channels. For these reasons, the passage assessment largely utilized the reliable depth bathymetry in association with species passage depth criteria to identify connectivity of passage channels for shad and herring, with focused comparisons of velocity characteristics at specific pinch-points, such as the steep, bedrock cross-over channels.

5.1.1 American Shad

Complete, uninterrupted connection from the lower boundary to the upper boundary and the series of passage weirs, when both depth and velocity was considered, was never achieved for American Shad (see Appendix B for passage conditions at all modeled flows and for depth-only and velocity-only passage maps). Looking at the 2.5 ft depth criteria alone showed that near full connectivity did not occur until flows exceeded 4,000 cfs. The lack of passage habitat at low flows was largely due to the deep passage criteria for shad (Table 4-3), which at 2.5 ft was more than double the average body depth of adult upstream migrants. As flows increased above 4,000 the depths became more suitable for passage, but estimated velocities began to exceed the 8.25 fps passage criteria in many of the bedrock channels, which resulted in additional gaps in passable habitat.

Because the deep depth criteria may not be realistic for shad swimming through natural channels (as opposed to jumping weirs or ascending ladders), this analysis was re-run using the same 1.0 ft depth criteria used for river herring. Decreasing the minimum depth criteria from

2.5 ft to 1.0 ft for shad resulted in almost continuous passage opportunities at just under 500 cfs when using depth alone (Figure 5-2), with multiple continuous pathways becoming available at flows of 1,000 cfs and above (Appendix B). Zooming in on one of the most critical passage locations at 482 cfs (yellow box in Figure 5-2) shows that the gaps in depth passage are relatively short (~5m) and are likely not an impediment to passage for adult shad (Figure 5-3, top map). Almost the entire area shown in Figure 5-3 possesses velocities less than the 8.25 fps criteria for American shad (Figure 5-3, bottom map). Depth suitability for passage continues to increase at higher flows (Figure 5-4), and velocities largely remain suitable for shad until flows exceed 6,000 cfs (Appendix B).

5.1.1 River Herring

Passage conditions for river herring, using a 1.0 ft minimum depth criteria are the same as for the reduced depth assessment for American shad (Figure 5-4), and show almost continuous passage opportunities at 482 cfs with multiple continuous pathways becoming available at flows over 1,000 cfs (Appendix B). Because the herring velocity criteria is somewhat slower at 6.0 fps than for American shad, the 2D model predicted more impassable area within the bedrock channels due to rapid currents, however it appears likely that herring could ascend the channels along the bottom or along the margins at 482 cfs (Figure 5-5). Velocities within the bedrock habitat increase with increasing flows, with excessive velocities through the bedrock at flows over 4,000 cfs (Appendix B).

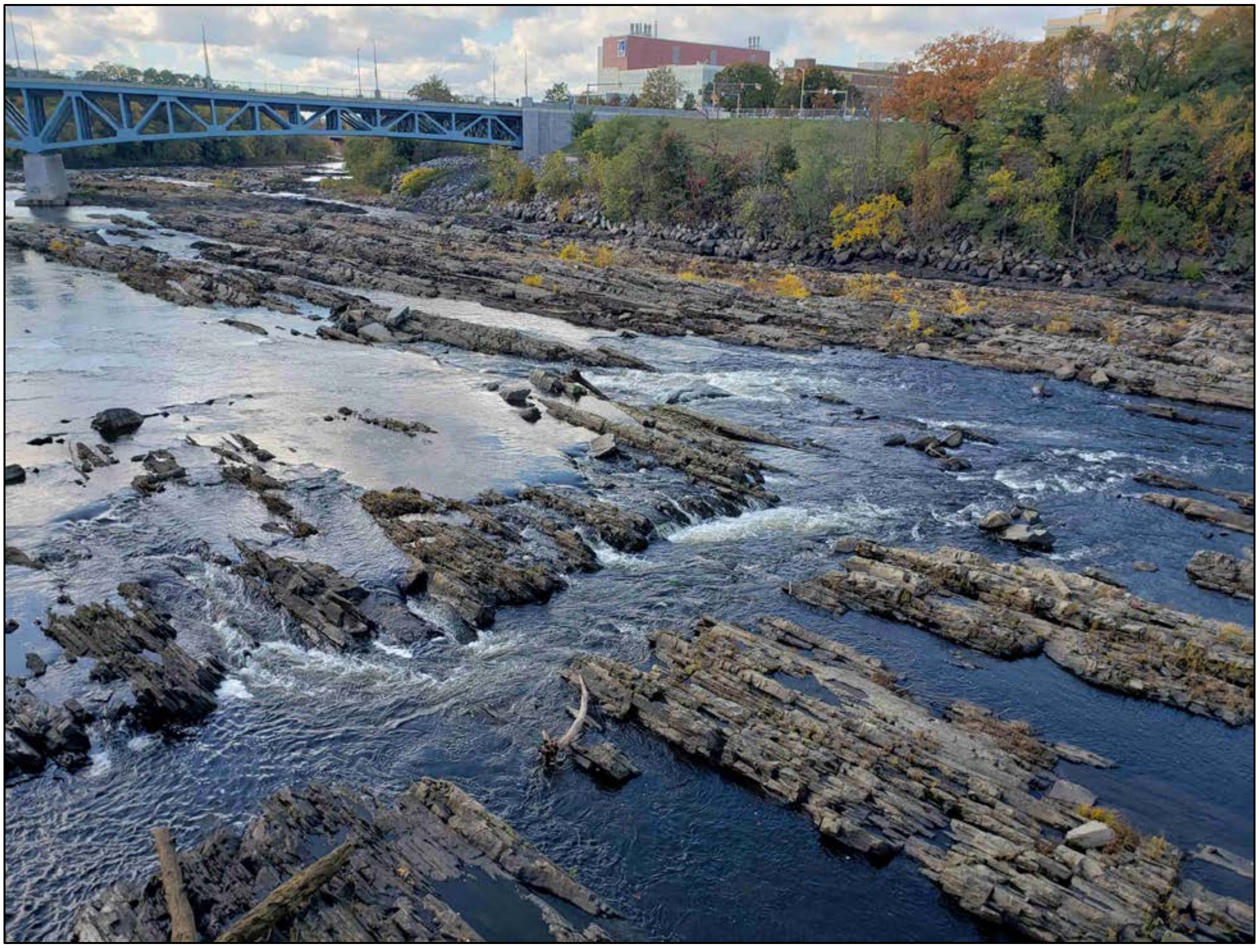


Figure 5-1. Complex deep and fast bedrock cross-over channels in the lower half of the Bypass Reach under low flow conditions. Image taken on Oct 23 2019 at a flow of approximately 480 cfs.

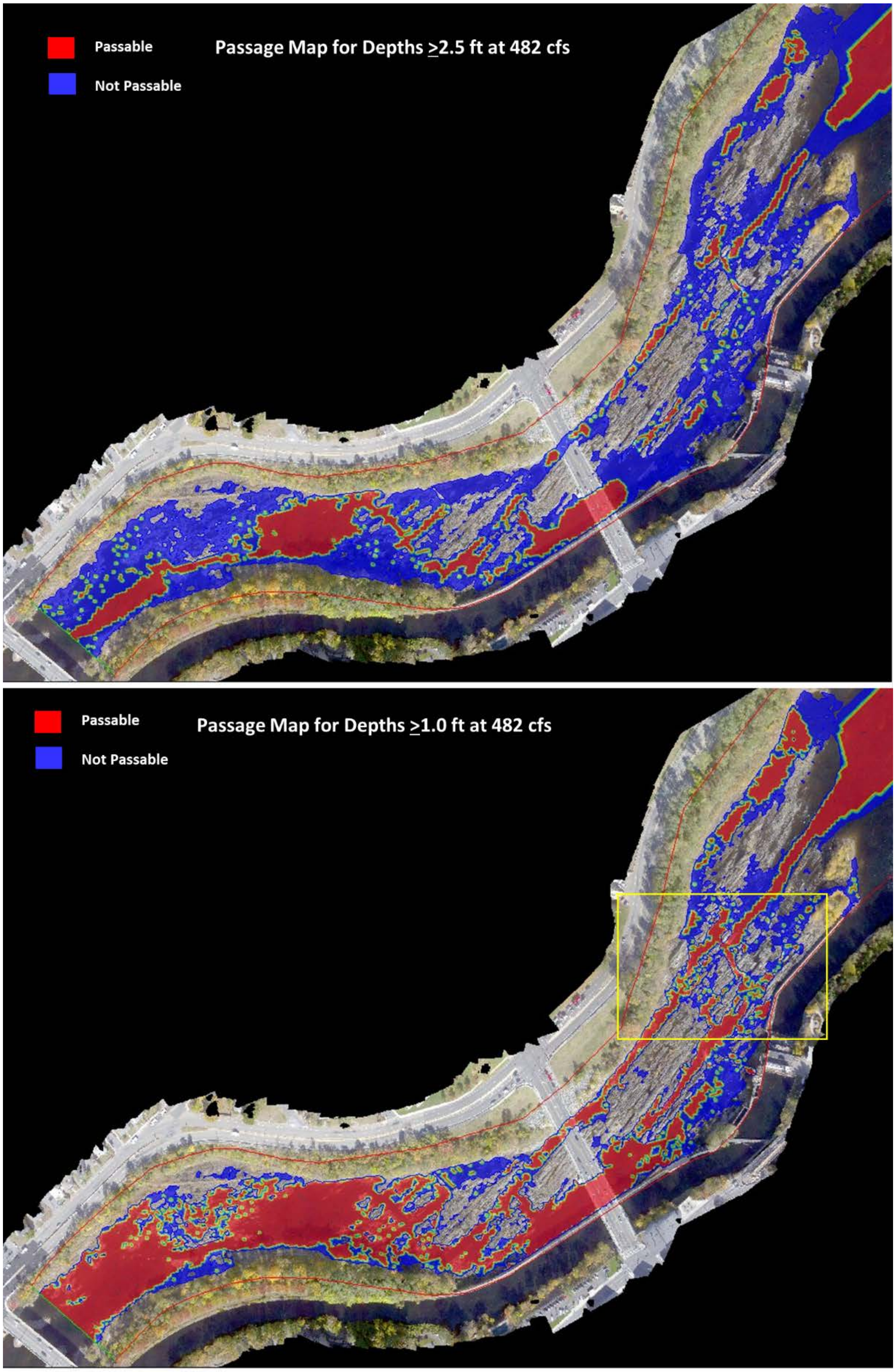


Figure 5-2. Comparative passage through Bypass Reach using minimum depth criteria of 2.5 ft (top map) and 1.0 ft (bottom map). Yellow box shows zoom area.

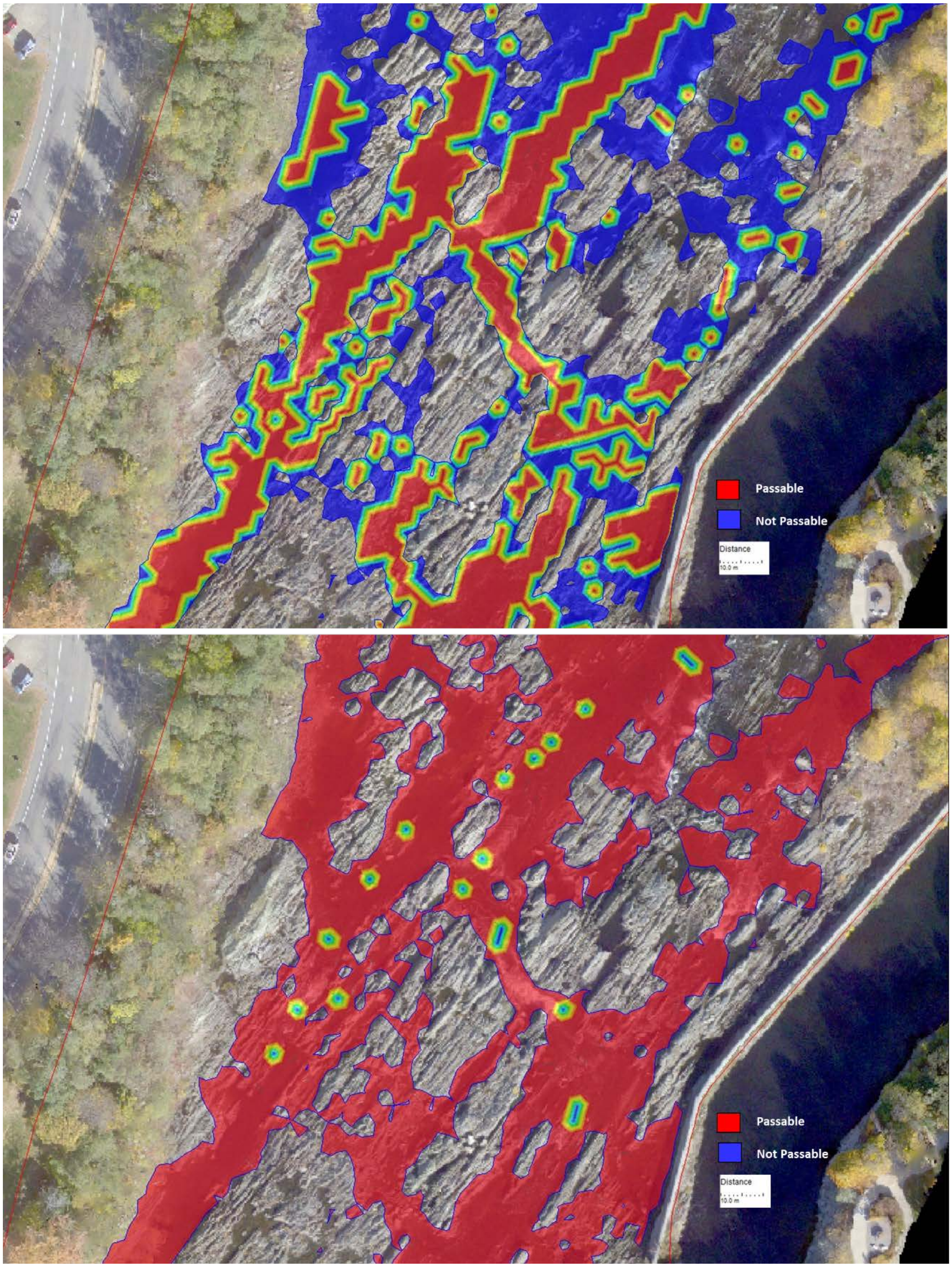


Figure 5-3. Close-up of bedrock cross-over channels in Bypass Reach showing 1 ft depth criteria (top map) and 8.25 fps velocity criteria (bottom map) for American shad at 483 cfs. (see Figure 5-1 for location of zoomed image).

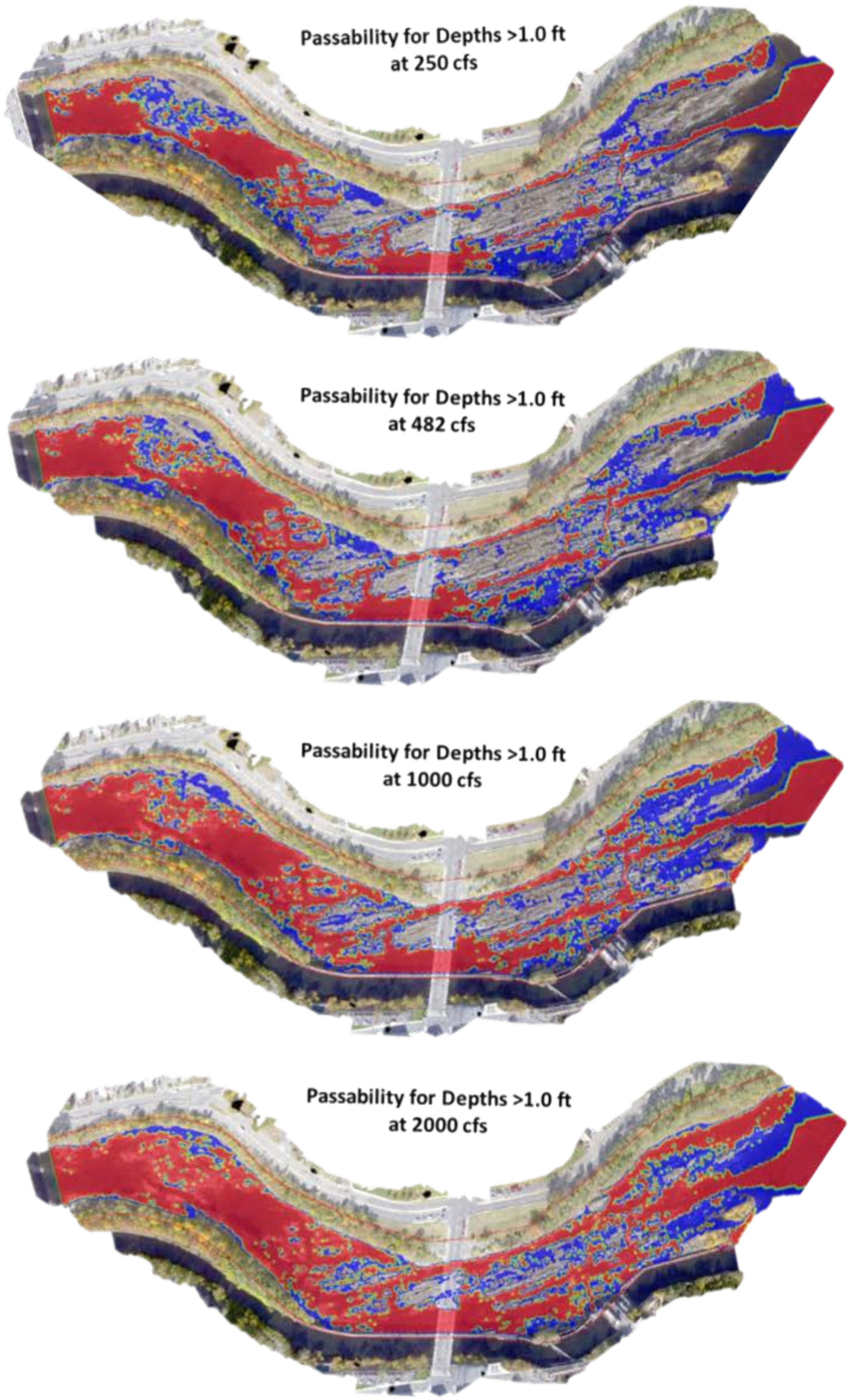


Figure 5-4. Comparative passage for American shad or river herring in the Bypass Reach for depths ≥1.0 ft at various flows. Red equal passable depth, blue non-passable.

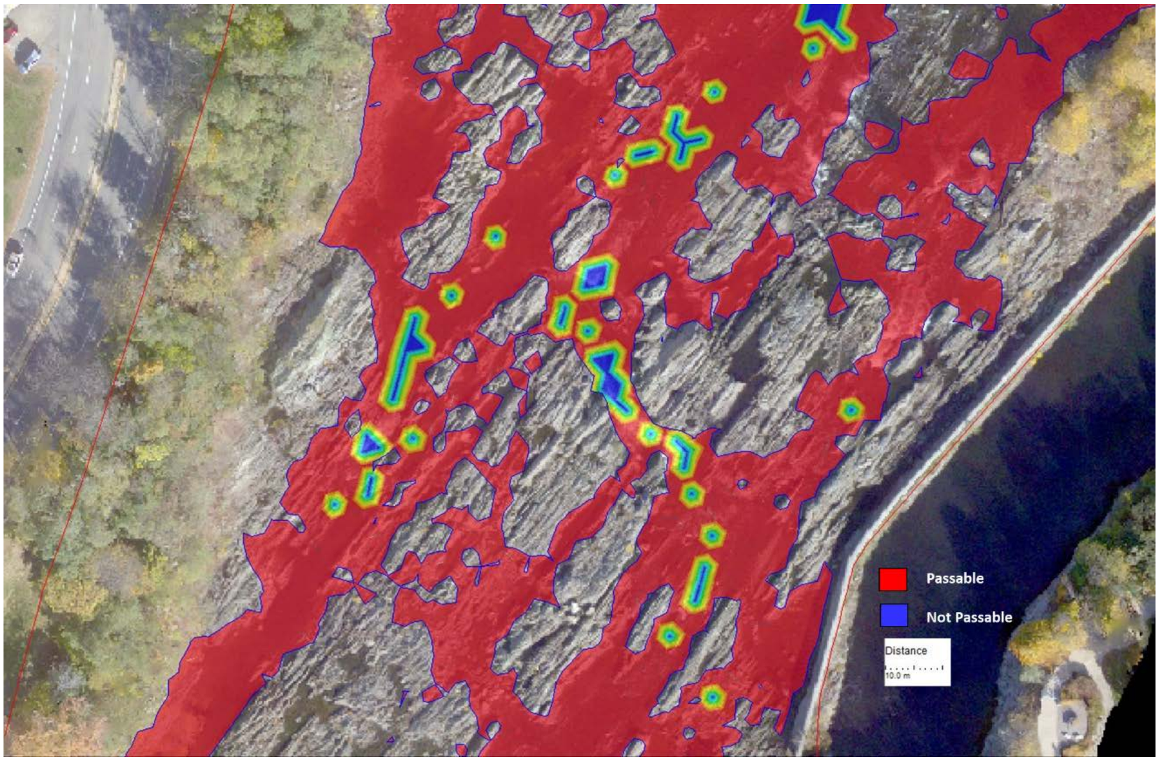


Figure 5-5. Close-up of bedrock cross-over channels in Bypass Reach showing 6.0 fps velocity criteria for river herring at 482 cfs. (see Figure 5-1 for location of zoomed image).

5.2 Aquatic Habitat Assessment

The aquatic habitat model was developed for 9 species and associated life stages in the Bypass Reach from the School Street Bridge downstream 3,000 ft through the bedrock rapids to the tailrace confluence at flows from 250 cfs to 14,000 cfs. An index of suitable habitat at each modeled flow, expressed as WUA in m^2, is presented in Table 5-1. Figure 5-6 illustrates the flow:habitat relationships for each species and life stage, and Figure 5-7 portrays the distribution and magnitude of WUA in the Bypass Reach for each species and life stage at the flow that provides maximum habitat.

5.2.1 American Shad

The index of suitable habitat (Table 5-1, Figure 5-6) for American shad juveniles remained relatively high (>10,000 m^2) at flows between 250 cfs and 2,000 cfs, with declining suitability to a minimum (3,641 m^2) at the maximum modeled flow of 14,000 cfs. The suitability index for shad spawning stayed high (>10,000 m^2) over a wider range of flows (1,000-8,000 cfs), with minima (~6,700 to ~5,700 m^2) at the lowest and the highest modeled flows, respectively. Most suitable habitat for both life stages occurred in the upper half of the modeled reach (Figure 5-7).

5.2.2 River Herring

The habitat index for spawning by river herring (Table 5-1, Figure 5-6) was highest at 3,110 m^2 at the lowest modeled flow (250 cfs), then progressively declined to 490 m^2 as flows increased to 14,000 cfs. Virtually all of the estimated habitat was of low suitability, due to the low suitability (0.1) for all rocky substrates (Table 4-4, Figure 5-7).

5.2.3 Sea Lamprey

Sea lamprey showed maximum habitat of 1,908 m^2 for spawning at 2,000 cfs flows (Table 5-1, Figure 5-6), with a declining habitat index to 355 m^2 at 14,000 cfs. Almost all of the suitable habitat occurred in the upper 1,000 ft of the modeled reach (Figure 5-7).

5.2.4 Fallfish

The habitat index for juvenile fallfish exceeded 1,000 m^2 at flows from 250 cfs to 2,000 cfs, with maximum habitat (3,134 m^2) at approximately 500 cfs (Table 5-1, Figure 5-6, Figure 5-7). Suitable habitat for adult fallfish was more available than for juveniles, with WUA estimates over 15,000 m^2 at flows from 250 cfs to 2,000 cfs, and a maximum of over 18,000 m^2 at 1,000 cfs. Juvenile habitat was largely restricted to the upper end of the modeled reach, whereas suitable habitat for adult fallfish was more widely distributed (Figure 5-7).

5.2.5 Longnose Dace

Suitable habitat for longnose dace juveniles was estimated at less than 1,000 m^2, except at about 500 cfs where WUA was 1,086 m^2 (Table 5-1, Figure 5-6). The habitat index for adult dace was somewhat higher, with WUA over 1,500 m^2 at flows from 250 cfs to 1,000 cfs, with a maximum of 2,414 m^2 at about 500 cfs. Most of the suitable habitat for both juvenile and adult dace occurred in the upper end of the modeled reach above the area dominated by bedrock ledges (Figure 5-7).

5.2.6 Smallmouth Bass

The index of suitable habitat was highest for smallmouth bass fry (10,617 m^2) and spawning (879 m^2) at the lowest modeled flow of 250 cfs (Table 5-1, Figure 5-6), which is not unexpected due to the fry's weak swimming ability and the associated need for low velocities at bass nests. Suitable habitat for juvenile bass remained relatively high (>10,000 m2) at flows from 250 cfs to 2,000 cfs, with a maximum habitat index of 13,820 m^2 at 1,000 cfs. Adult smallmouth bass also showed maximum habitat (8,021 m^2) at 1,000 cfs, with a progressive decline to 2,016 m^2 at a flow of 14,000 cfs. Moderate to highly suitable habitat for fry, juvenile, and adult bass was distributed in both upper and lower ends of the modeled Bypass Reach, although spawning habitat was rare and confined to the upper region near the School Street Bridge (Figure 5-7).

5.2.7 White Sucker

The estimated WUA for white sucker fry, juvenile/adult, and spawning life stages all maximized at low flows (Table 5-1, Figure 5-6). The fry life stage showed high WUA at flows from 250 cfs to 2,000 cfs, with a maximum of 25,085 m^2 at the lowest modeled flow. Juvenile/adult WUA was 12,398 m^2 at about 500 cfs, whereas spawning WUA maximized at only 159 m^2 at 250 cfs. The low habitat index for sucker spawning was likely due to the HSC, which gave zero suitability for any substrate other than silt, sand, and gravel, each of which were rare in the Bypass Reach (Table 4-4, Figure 4-1). Both moderate and high quality habitat occurred for sucker fry and juvenile/adult life stages throughout most of the modeled reach, although habitat was spotty in the bedrock ledges (Figure 5-7). Suitable habitat for spawning was very rare and of low quality, due to the relative lack of suitable spawning substrate.

5.2.8 Freshwater Mussels

The 2D model estimated relatively high values of WUA for freshwater mussels, with indexes over 10,000 m^2 at 1,000 and 2,000 cfs, and a maximum of 11,066 m^2 at 2,000 cfs (Table 5-1, Figure 5-6). The abundance of suitable habitat is likely due to the broad preferences for coarse substrate types (Table 4-4), although most habitat was of low quality except in the area just downstream of the School Street Bridge and a small area adjacent to the powerhouse tailrace (Figure 5-7).

5.2.9 Benthic Macroinvertebrates

BMI showed the highest estimates of WUA of all species groups, with a maximum of 24,062 m^2 at 2,000 cfs, and maintained high habitat values (>10,000 m2) from 500 cfs to 10,000 cfs (Table 5-1, Figure 5-6). The high magnitude of WUA was largely due to the BMI's relatively high HSC value for bedrock at 0.5 (Table 4-4), which likely overestimates suitability of bedrock for EPT taxa (mayflies, stoneflies, and caddisflies), in comparison to Simulids and other midge species that have broader substrate preferences. The 2D model predicted suitable habitat for BMI throughout the Bypass Reach, although the highest quality habitat occurred in the upper end of the reach and near the bottom of the reach (Figure 5-7).

Table 5–1. Weighted Usable Area (WUA) in m² in the Bypass Reach according to flow, species, and life stage.

Flow	American Shad		River Herring	Sea Lamprey	Fallfish	
cfs	Juvenile	Spawning	Spawning	Spawning	Juvenile	Adult
250	11,923	6,738	3,110	576	2,764	15,133
482	14,468	9,368	2,951	1,012	3,134	17,586
1,000	15,864	12,859	2,421	1,599	2,873	18,363
2,000	14,946	15,664	1,711	1,908	1,726	14,308
4,345	9,948	15,755	1,011	1,282	893	8,219
6,000	7,558	13,396	820	858	895	6,782
7,011	6,517	11,852	723	724	894	6,201
8,000	5,710	10,313	675	611	819	5,724
10,000	4,644	7,864	568	489	688	4,979
12,000	4,025	6,418	523	415	511	4,573
14,000	3,641	5,718	490	355	371	4,277
Flow	**Smallmouth Bass**				**Longnose Dace**	
cfs	**Fry**	**Juvenile**	**Adult**	**Spawning**	**Juvenile**	**Adult**
250	10,617	10,141	5,834	879	838	1,970
482	10,491	12,772	7,155	727	1,086	2,414
1,000	7,768	13,820	8,021	508	735	1,657
2,000	5,507	11,407	6,350	324	385	848
4,345	3,340	6,793	4,014	215	283	537
6,000	2,817	5,412	3,366	201	296	580
7,011	2,454	4,882	3,087	173	265	599
8,000	2,270	4,394	2,818	161	212	508
10,000	1,899	3,665	2,402	143	116	303
12,000	1,660	3,249	2,153	104	69	160
14,000	1,526	2,983	2,016	98	44	109
Flow	**White Sucker**			**Freshwater Mussels**	**Benthic Macro-invertebrates**	
cfs	**Fry**	**Juvenile**	**Adult**	**Rearing**	**Rearing**	
250	25,085	10,724	159	8,217	7,213	
482	22,449	12,398	95	9,686	12,031	
1,000	16,881	10,462	61	10,937	18,958	
2,000	11,986	6,989	21	11,066	24,062	
4,345	7,219	4,352	69	8,528	21,698	
6,000	6,041	3,758	123	6,679	17,847	
7,011	5,233	3,361	95	5,802	15,777	
8,000	4,787	3,165	66	5,039	13,819	
10,000	4,065	2,706	34	3,913	10,948	
12,000	3,657	2,481	12	3,244	8,867	
14,000	3,488	2,354	9	2,866	7,250	

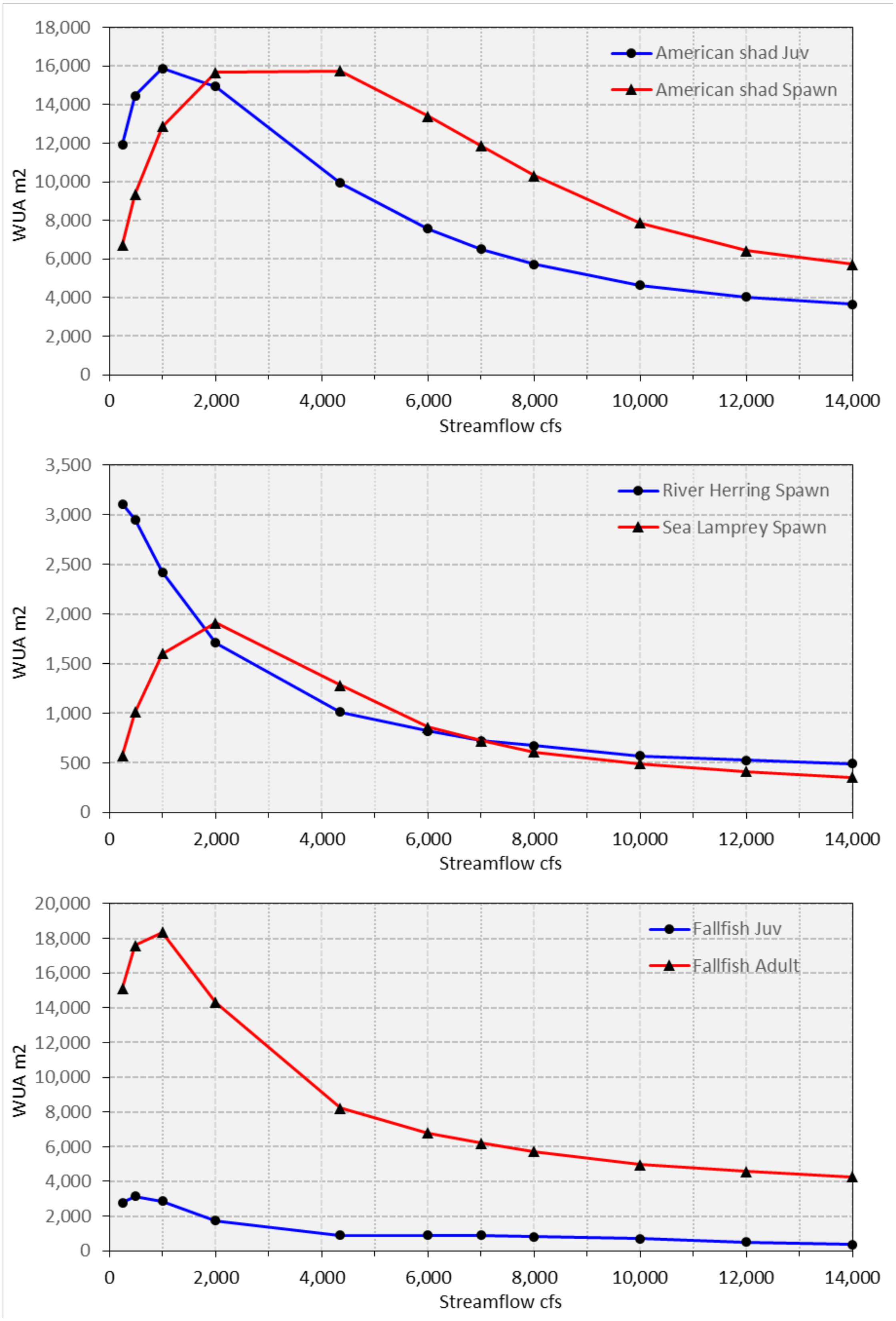


Figure 5-6. Relationship between WUA (m2) and flow (cfs) in Bypass Reach according to species and life stage.

Figure 5-6. (continued).

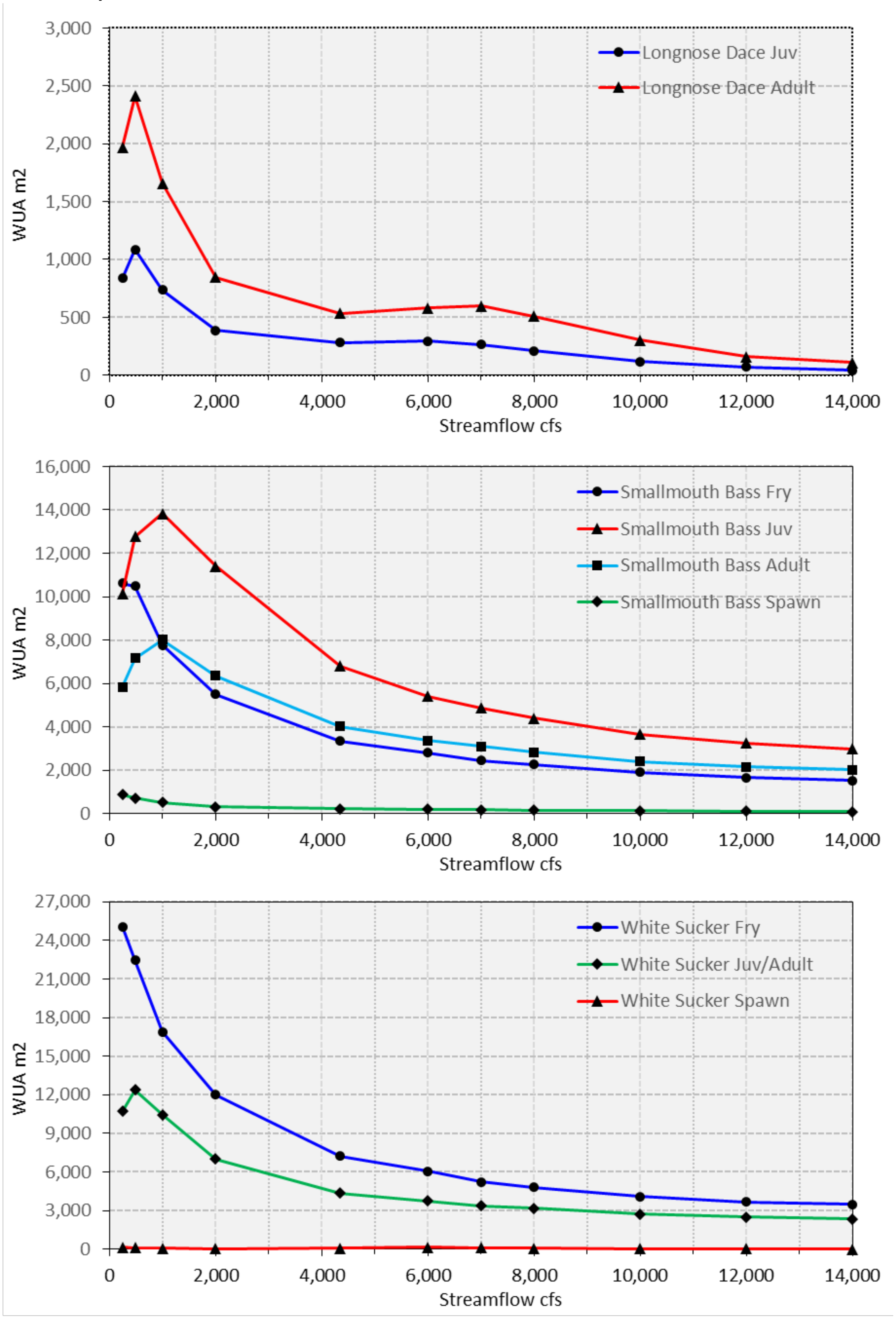
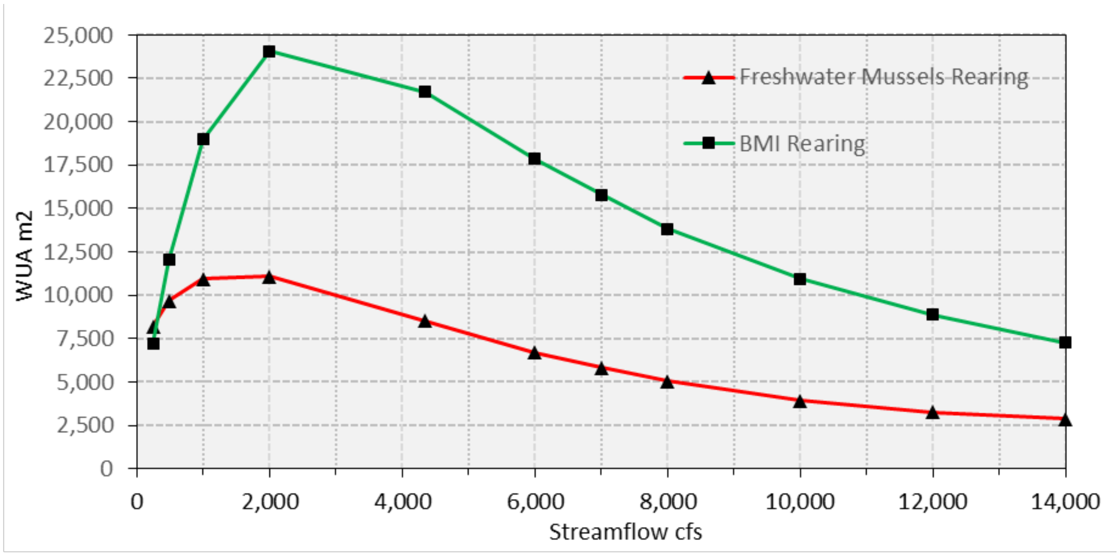


Figure 5-6. (continued).



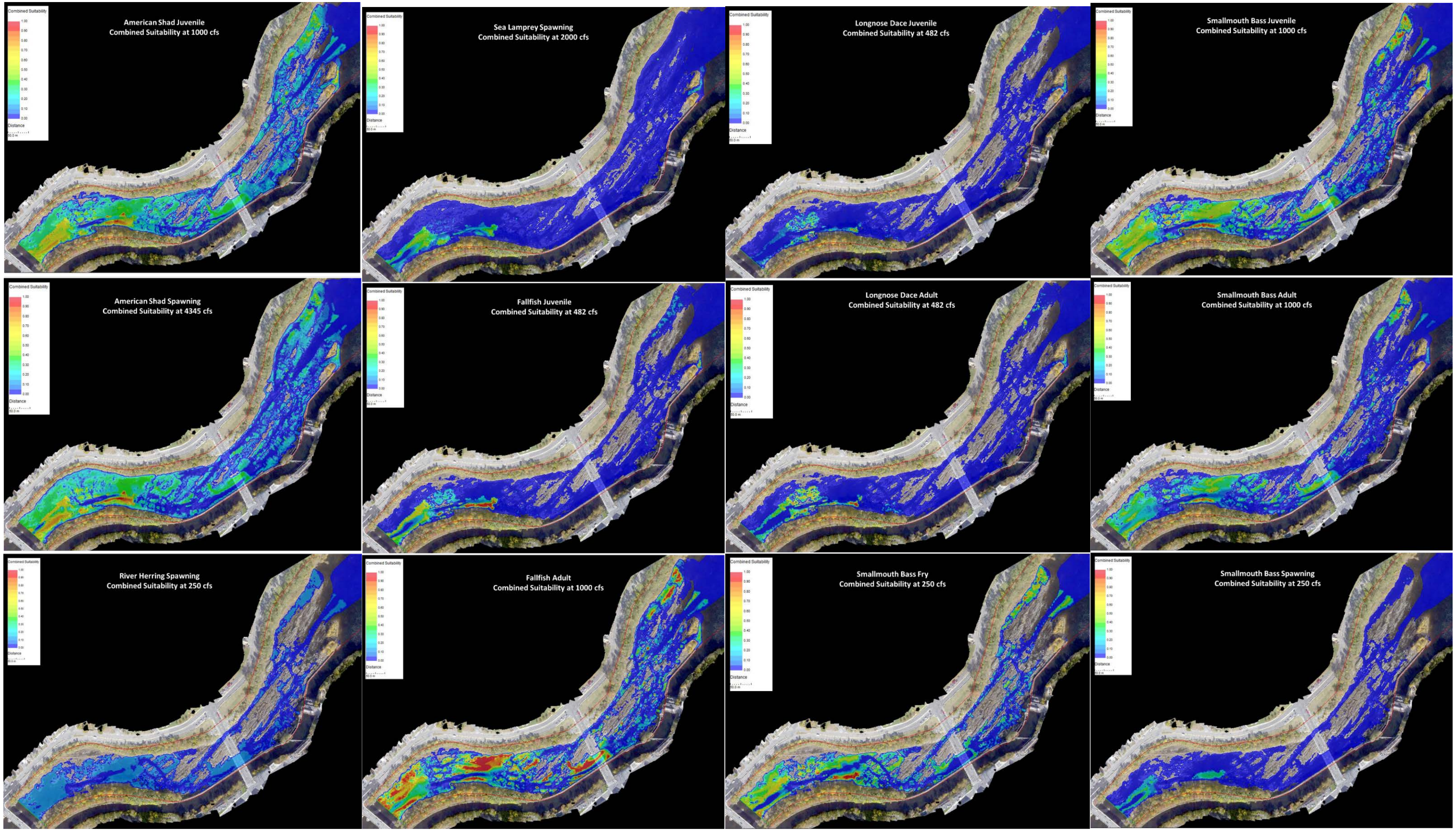


Figure 5-7. Bypass Reach showing combined suitability according to species and life stage.

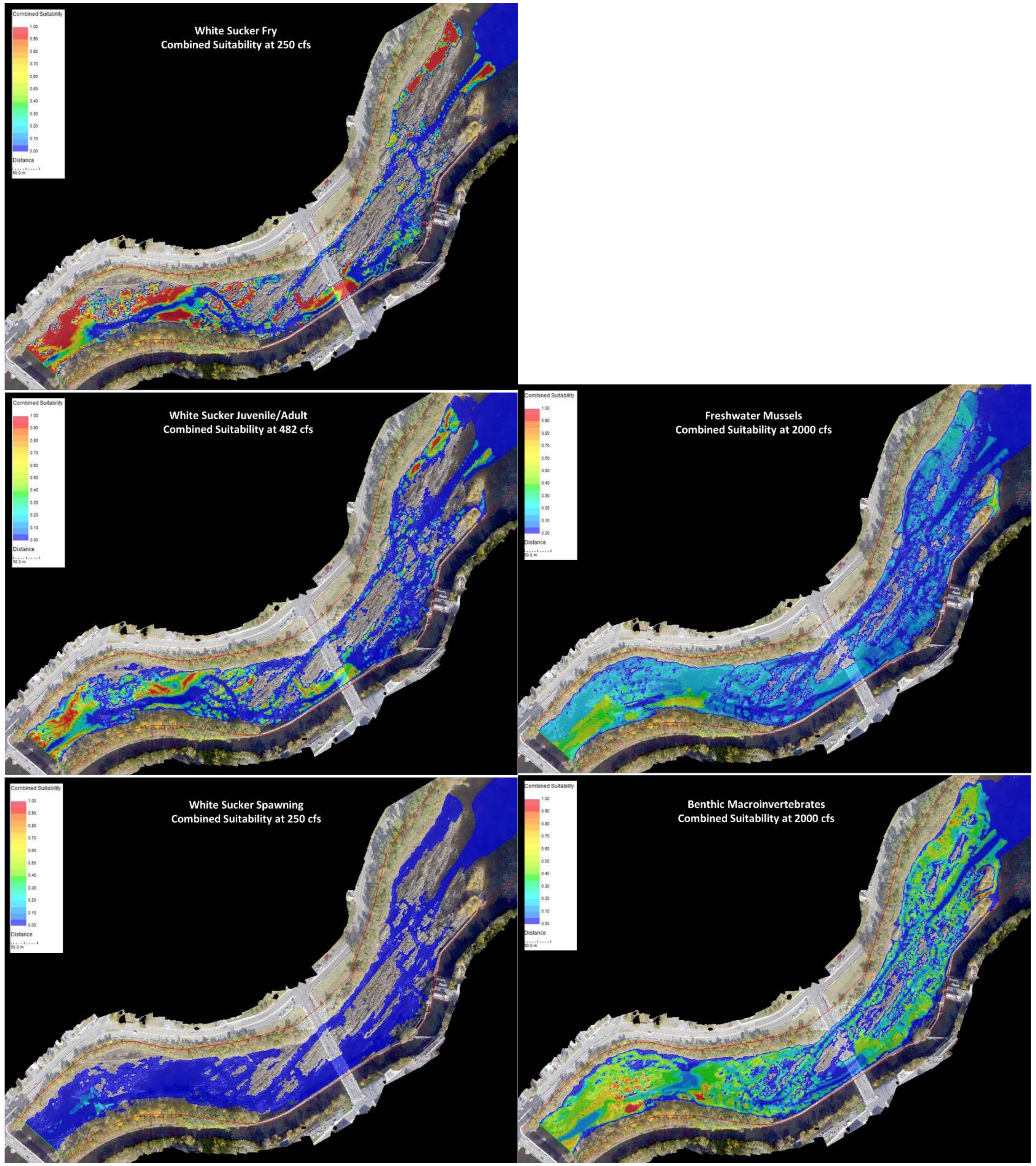


Figure 5-7. (continued)

6 Summary

A two-dimensional (2D) hydraulic model was developed in the Bypass Reach extending from the School Street Bridge downstream approximately 3,000 ft to the confluence with the powerhouse tailrace. The 2D model was calibrated at low (482 cfs), middle (4,345 cfs), and high (7,011 cfs) flows, with simulated flows ranging from 250 cfs to 14,000 cfs. Lidar and RTK measurements were utilized to develop a digital elevation model of the Bypass Reach. Visual surveys were also conducted on foot to delineate polygons consisting of specified substrate characteristics. The 2D model was utilized to assess the relationship between Bypass Flow and upstream passage through the bedrock dominated reach by adult migrant American shad and river herring (blueback herring, and alewife). The 2D model also assessed the relationship between Bypass flows and the quantity and quality of aquatic habitat, expressed as Weighted Usable Area (WUA), for 9 species groups and their associated life stages.

6.1 Summary of Zone of Passage Results

Assessment of the zone of passage was challenging due to the highly complex bedrock habitat throughout most of the Bypass Reach. Complete, uninterrupted connection from the lower boundary to the upper boundary at the School Street bridge, when utilizing passage criteria for both depth and velocity, was never achieved for either American shad or river herring. The 2D model identified numerous potential gaps in suitable passage habitat in the lower half of the Bypass Reach downstream of the University Avenue Bridge. From review of the zone of passage model imagery alone it is unclear if these gaps would be absolute barriers to upstream migration or if passage would be possible along the margins of the impassable gaps. Given the uncertainty in the modeled depth-averaged velocities through the lower, complex bedrock area, the passage analysis focused on flows meeting the depth criteria, with closer inspection of modeled velocities at identified pinch-points (e.g., narrow/fast bedrock channels).

In addition, the shad assessment was reanalyzed using a more realistic minimum depth of 1.0 ft (same as herring), which provided a near-continuous passage channel at flows of approximately 500 cfs, with multiple passage channels at higher flows (Figure 5-4). Passage opportunities based on depth alone increased with flows, but velocities became limiting at flows over 6,000 cfs (Appendix B). Likewise for river herring, depths became suitable for passage by 500 cfs, with excessive velocities through bedrock channels at flows of 4,000 cfs and greater. Note that these assessments do not account for channel widths, however given the large scale of the Bypass Reach and the complexity of the bedrock habitat, it is unlikely that channel widths would be limiting.

As part of the *Upstream and Downstream Adult Alosine Passage Assessment* study, movements of radio-tagged adult river herring and American shad were monitored within the Bypass Reach during spring 2020. As described in that technical report, flows through the Lowell Bypass Reach during the 2020 monitoring period were comprised of the ~500 cfs of water constituting the attraction and conveyance flow associated with the Pawtucket Dam fish ladder as well as incidental spill flow passing over the spillway. Incidental spill flows in excess of 500 cfs were present until May 21 after which incidental spill was reduced to near zero through the month of

June (Figure 6-1). A total of 105 unique foray events for radio-tagged adult river herring into the Bypass Reach were recorded during the 2020 study. These events were recorded over a range of dates from May 7 through May 23 with the majority of events occurring between May 17 and 19. When the average Bypass Reach discharge condition occurring during each upstream foray is considered, foray events resulting in successful passage at the Pawtucket Dam fish ladder occurred over a range of Bypass Reach flows from 883 to 4,432 cfs. Conversely, foray events which did not result in successful upstream passage and were determined to have ended at or near to the midpoint of the Bypass Reach occurred over a range of flows from 907-2,145 cfs and those that ended at the upstream end of the Bypass Reach occurred over a range of flows from 799 to 2,587 cfs. The probability of successful upstream passage for radio-tagged adult herring was evaluated using a Cormack Jolly-Seber model for the lower and upper portions of the Bypass Beach and was estimated at 72% and 92%, respectively. Although tagged adult herring were only detected through May 23 within the Lowell Bypass Reach, camera operations at the Pawtucket Dam fish ladder continued to document migrating river herring through the first week of June. Mean daily discharge values for flow through the Lowell Bypass Reach between May 24 and June 6 ranged from 900 to 546 cfs. A net total of 42,066 adult herring passed during that period (Figure 6-2)

Movements of radio-tagged adult American shad during the 2020 passage evaluation were limited to a single detection at the lowermost receiver station. When considered with findings from this zone of passage assessment it appears that shad have difficulty migrating upstream through the Bypass Reach. However, camera operations at the viewing window of the Pawtucket Dam fish ladder documented the upstream passage of 799 adult American shad over a range of dates from May 18 to June 26 with the majority of passage events documented during early and mid-June (Figure 6-3). Reported Merrimack River inflow during the period of peak shad detection in the Pawtucket Dam counting window during 2020 was below the E.L. Field Powerhouse capacity of 8,000 cfs; consequently no spill occurred over this period (Figure 6-1) and discharge through the Bypass Reach was limited to ~500 cfs from the Pawtucket Dam fish ladder (Figure 6-3).

Despite poor performance of tagged shad and the lack of passage connectivity through the Bypass Reach according to the 2D model (using the 2.5 ft minimum depth criteria), a proportion of adult shad were able to reach the Pawtucket Dam fish ladder under a Bypass flow of about 500 cfs. This is consistent with the revised 2D model using a 1.0 ft minimum depth criteria for shad, which suggested near continuous passage opportunities at a flow of approximately 500 cfs.

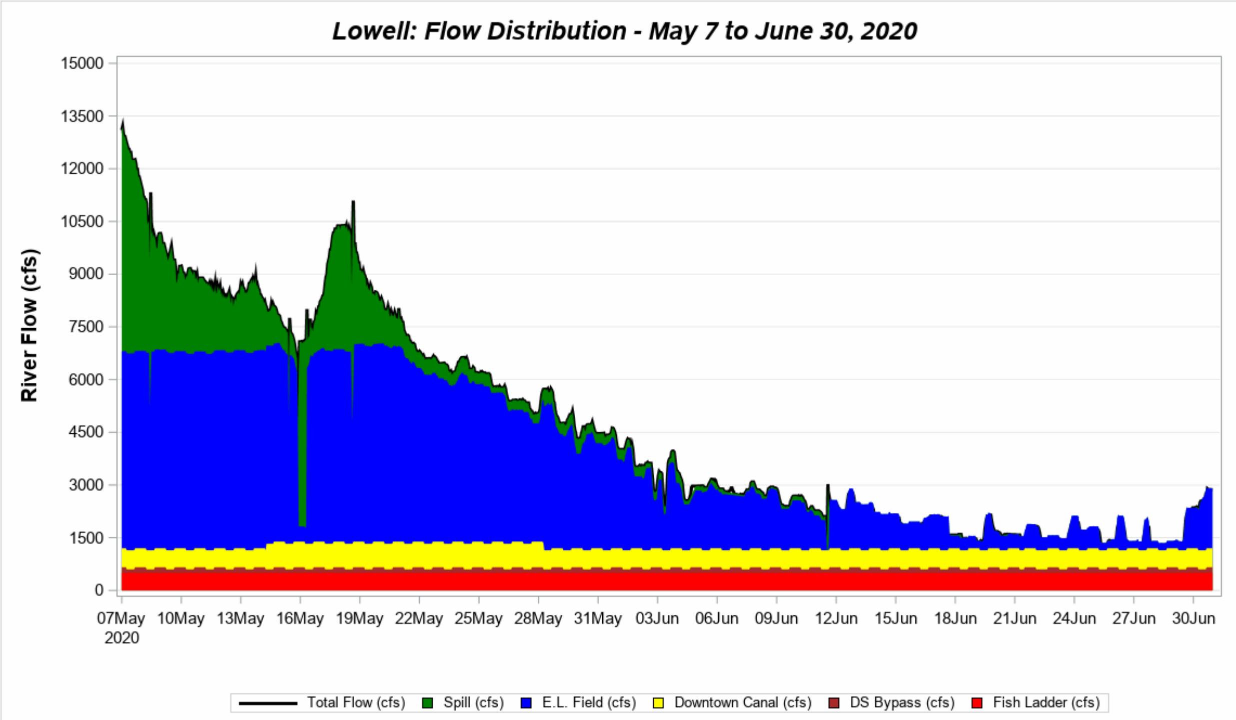


Figure 6-1. Total, spill, E.L. Field, fish ladder, downstream bypass and downtown canal system flow (cfs) for the period May 7 to June 30, 2020.

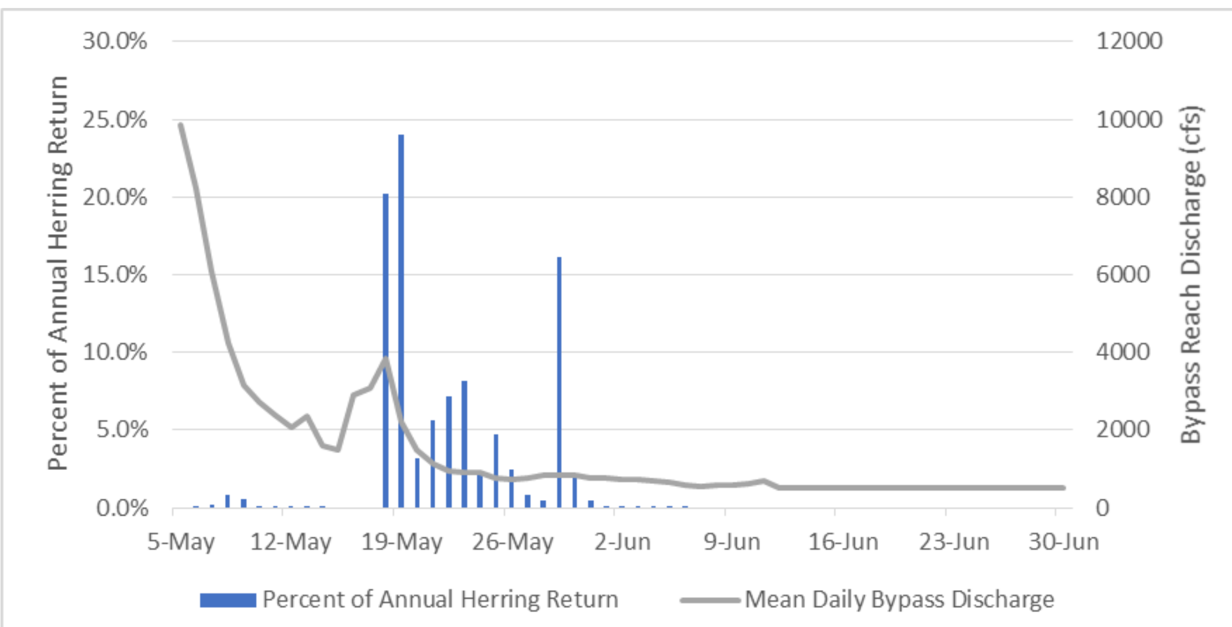


Figure 6-2. Pawtucket Dam fish ladder river herring counts and reported Lowell Bypass Reach discharge for the 2020 upstream passage season.

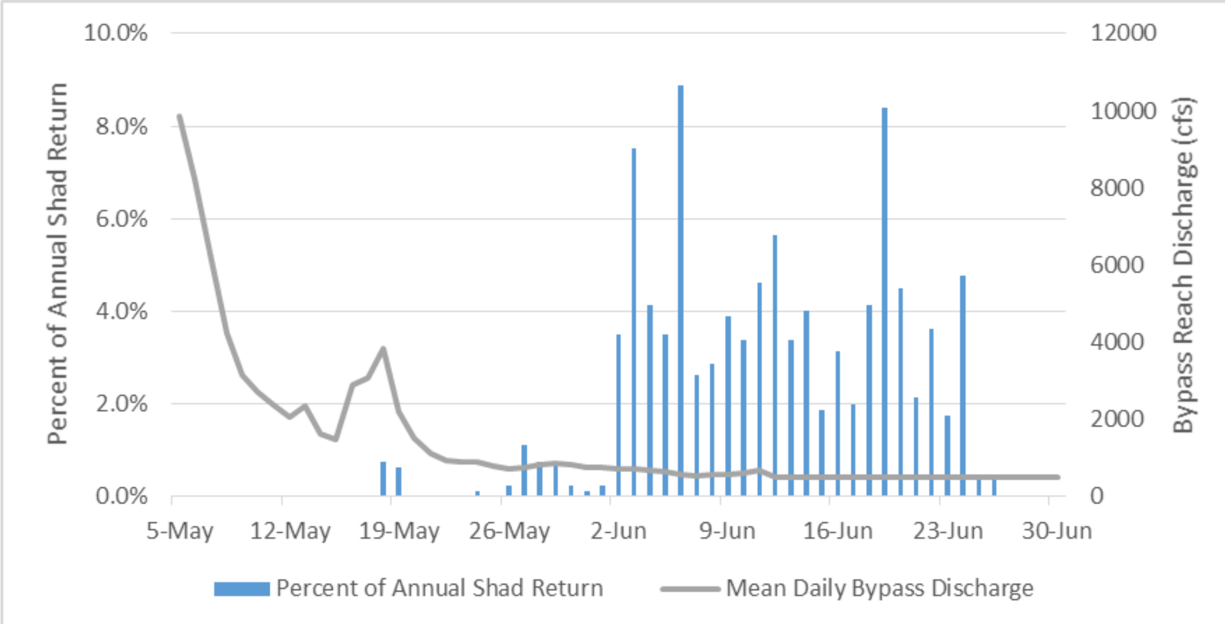


Figure 6-3. Pawtucket Dam fish ladder American shad counts and reported Lowell Bypass Reach discharge for the 2020 upstream passage season.

6.2 Summary of WUA Results

In most cases the habitat indexes for each species and life stage showed maximum suitable habitat at relatively low flows through the Bypass Reach (Table 5-1, Figure 5-6). Thirteen of the 17 assessments produced maximum WUA at flows of 1,000 cfs or less, with 3 other species/life stages (lamprey spawning, freshwater mussels, and BMI rearing) reaching maximum WUA at 2,000 cfs, and one species/life stage (shad spawning) showing maximum habitat at a higher flow (4,345 cfs). This result is primarily due to the steep, bedrock dominated habitat that characterizes the Bypass Reach. In terms of the magnitude of suitable habitat, the habitat index showed highest values for shad, adult fallfish, sucker fry, and BMI, each with maximum WUA estimates exceeding 15,000 m^2. In contrast, relatively little suitable habitat was predicted for lamprey spawning, bass spawning, sucker spawning, and juvenile longnose dace; all of which had maximum WUA values of less than 2,000 m^2. WUA distribution maps (Figure 5-7) revealed that most suitable habitat occurred in the upper 1,000 ft of the modeled reach, with limited suitable habitat in the lower, bedrock-dominated area.

7 Variances from FERC-Approved Study Plan

As previously noted, the 2D model for the zone of passage task was initially intended to encompass the series of weirs located in the upper end of the Bypass Reach upstream of the School Street Bridge. However the model was unable to run to a steady state solution due to unrealistically high velocities (greater than 2,000 fps) at nodes along the vertical edges of the weirs, which caused the time step to drop to infinitesimally small levels, and preventing the model from advancing beyond a few seconds. Consequently, the upstream boundary for both the zone of passage and the aquatic habitat elements of this study was placed just downstream of the School Street Bridge to avoid the transverse flow coming from the diagonal spillway.

The FERC-approved RSP notes that NMFS requested ADCP velocity data at randomly placed cross sections under the high calibration flow collection. Although not necessary for 2D model development, such data can be useful as validation data. However, we could not physically access locations for collecting validation data during the high flow event, and the current velocities in many areas was determined to be too fast and would exceed the capabilities of the ADCP trimaran. Consequently, transect validation data was not performed.

Due to the complexity of the bedrock-dominated habitat, both “minimum” and “optimal” passage flows were not identified. Instead, the minimum flow meeting passage depth criteria was identified for American shad and river herring, along with the range of potential passage flows based on both depth and velocity criteria.

There were no additional variances from the FERC-approved study plan in this task.

8 References

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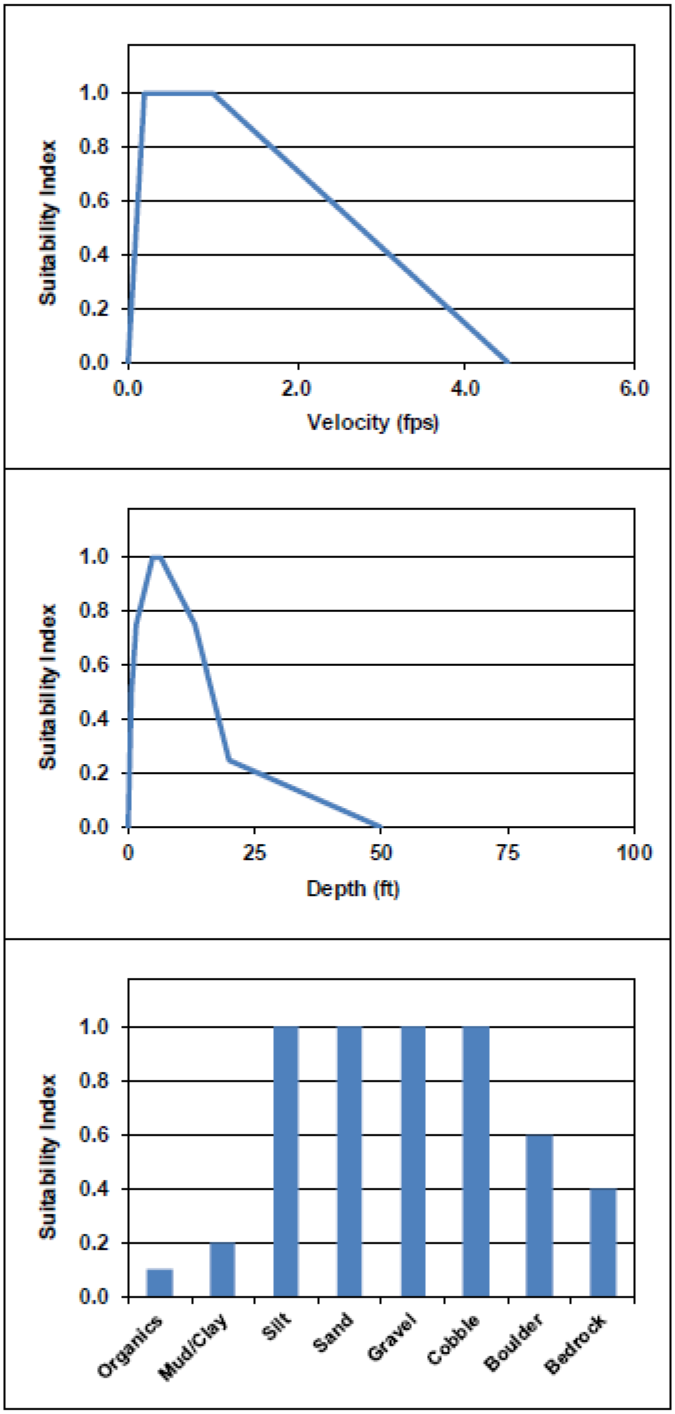
9 Appendices

Appendix A. Habitat suitability criteria for target species and life-stages.

American Shad Juvenile



Source:

Stier and Crance, 1985

Velocity (ft/s)	SI
0.00	0.00
0.20	1.00
1.00	1.00
4.50	0.00

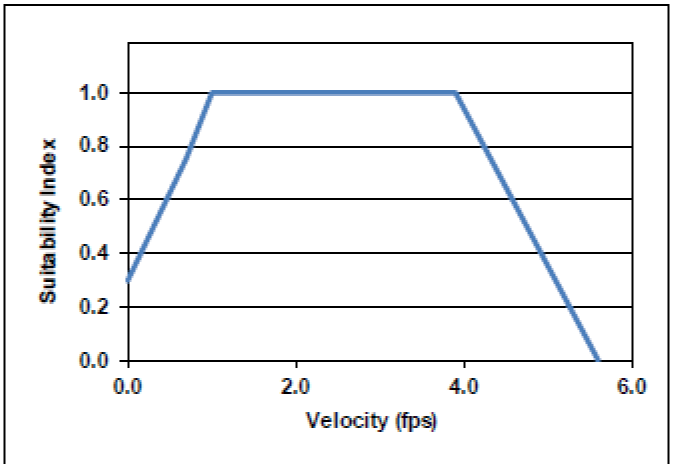
Greene et al., 2009

Depth (ft)	SI
0.00	0.00
0.66	0.50
1.50	0.75
4.90	1.00
6.60	1.00
13.20	0.75
20.00	0.25
50.00	0.00

Conowingo IFIM

Substrate	SI
Organics	0.10
Mud/Clay	0.20
Silt	1.00
Sand	1.00
Gravel	1.00
Cobble	1.00
Boulder	0.60
Bedrock	0.40

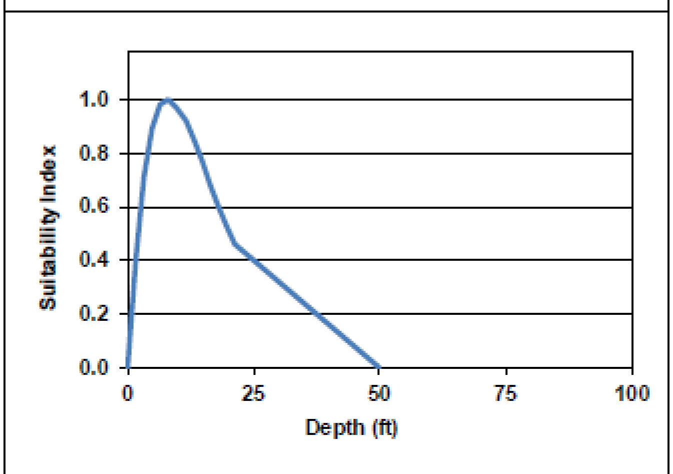
American Shad Spawning



Source:

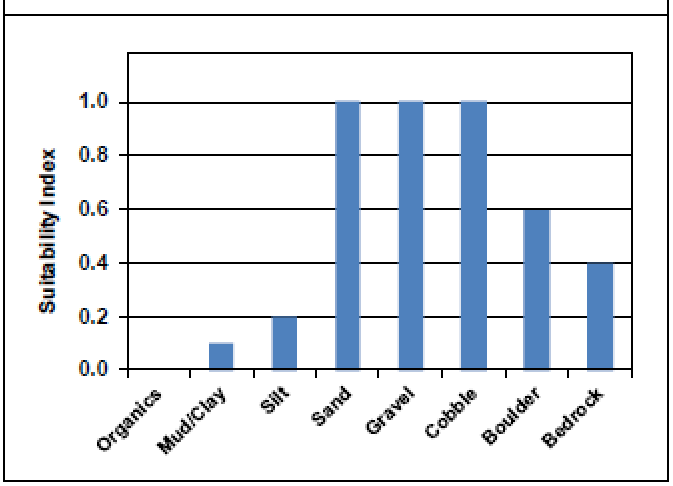
Velocity based on data from Hightower et al., 2012

Velocity (ft/s)	SI
0.00	0.30
0.70	0.75
1.00	1.00
3.00	1.00
3.90	1.00
5.60	0.00



Hightower et al., 2012 and Stier and Crance, 1985

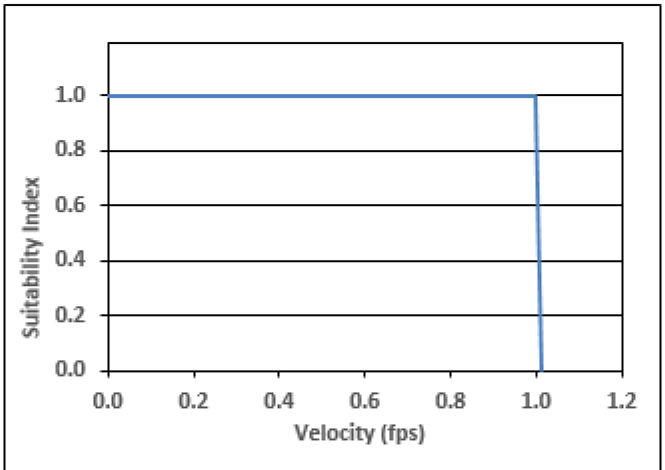
Depth (ft)	SI
0.00	0.00
1.60	0.40
3.30	0.71
4.90	0.89
6.60	0.98
8.20	1.00
9.80	0.97
11.50	0.92
13.10	0.85
14.80	0.77
16.40	0.68
18.00	0.60
19.70	0.53
21.30	0.46
50.00	0.00



Stier and Crance, 1985

Substrate	SI
Organics	0.00
Mud/Clay	0.10
Silt	0.20
Sand	1.00
Gravel	1.00
Cobble	1.00
Boulder	0.60
Bedrock	0.40

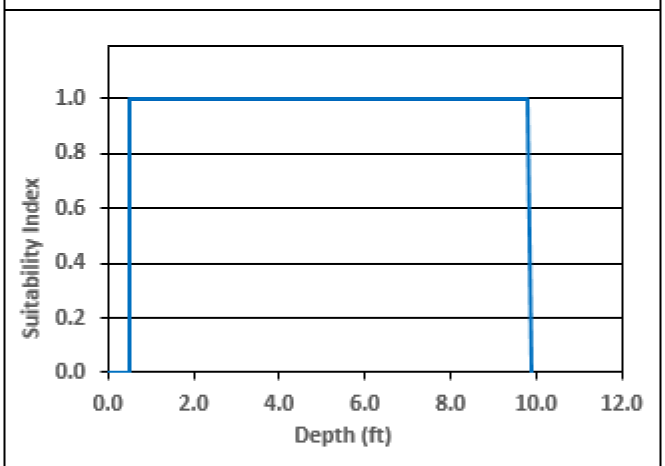
River Herring Spawning



Source:

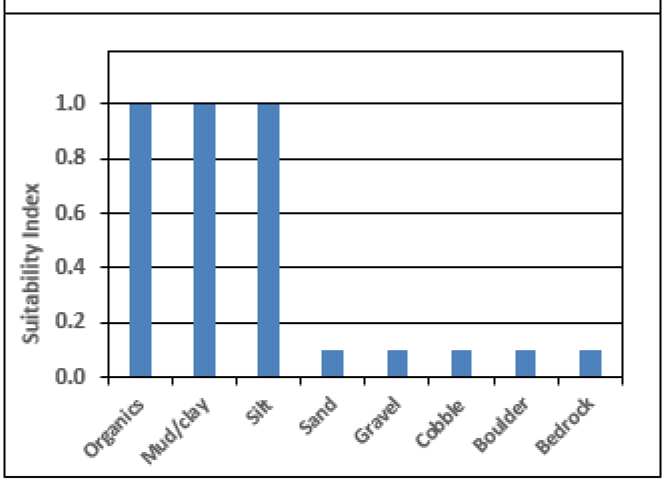
Adapted from Pardue 1983 and Mather et al. 2012

Velocity (ft/s)	SI
0.00	1.00
1.00	1.00
1.01	0.00



Adapted from Pardue 1983 and Mather et al. 2012

Depth (ft)	SI
0.00	0.00
0.49	0.00
0.50	1.00
9.80	1.00
9.90	0.00



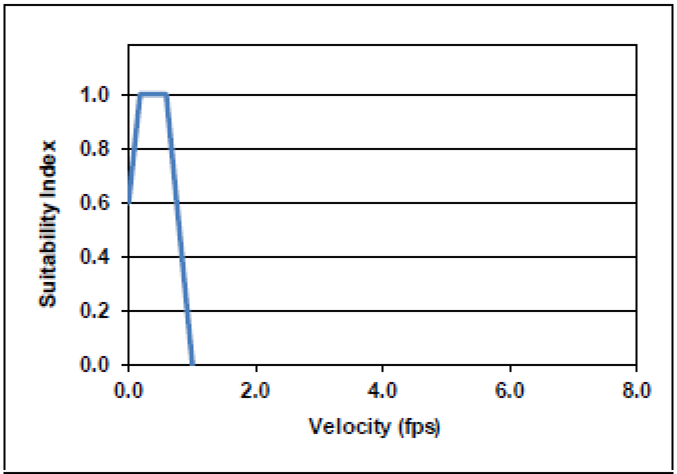
Adapted from Pardue 1983 and Mather et al. 2012

Substrate	SI
Organics	1.00
Mud/Clay	1.00
Silt	1.00
Sand	0.10
Gravel	0.10
Cobble	0.10
Boulder	0.10
Bedrock	0.10

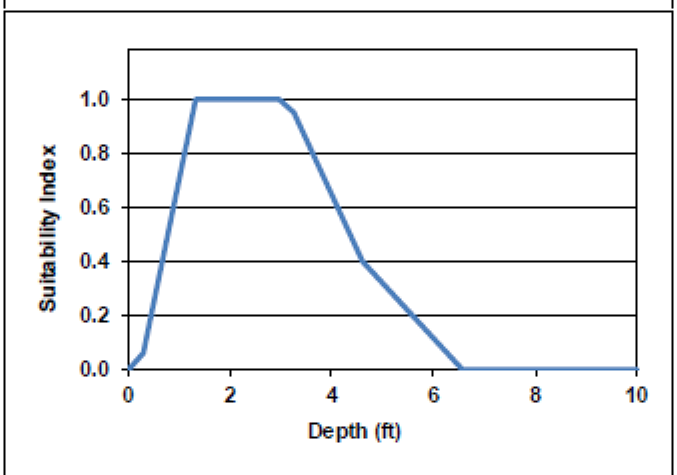
Smallmouth Bass Fry

Source:

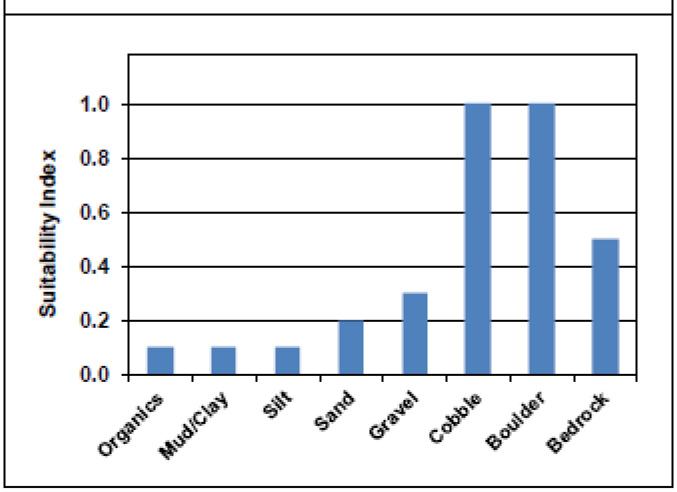
Leonard et al, 1986



Velocity (ft/s)	SI
0.00	0.60
0.19	1.00
0.59	1.00
1.00	0.00

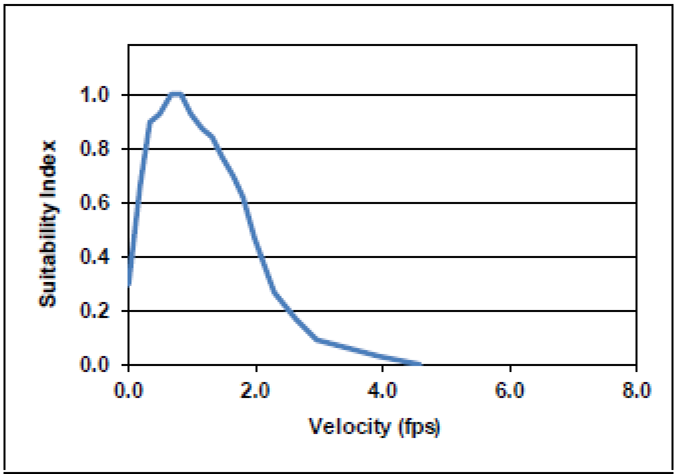


Depth (ft)	SI
0.00	0.00
0.28	0.06
1.31	1.00
2.95	1.00
3.25	0.95
4.59	0.40
6.56	0.00
10.00	0.00



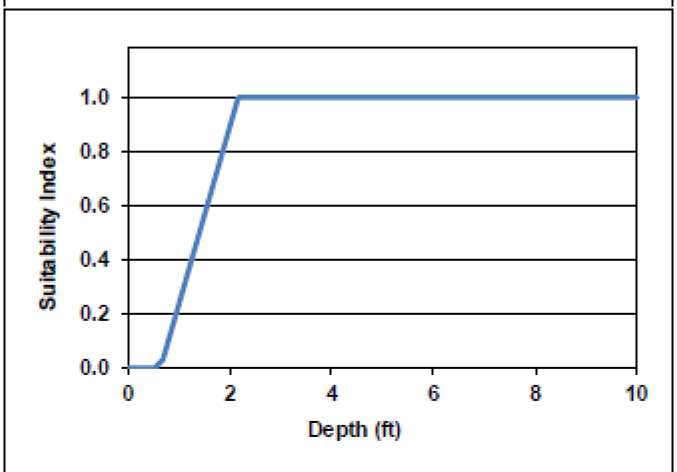
Substrate	SI
Organics	0.10
Mud/Clay	0.10
Silt	0.10
Sand	0.20
Gravel	0.30
Cobble	1.00
Boulder	1.00
Bedrock	0.50

Smallmouth Bass Juvenile



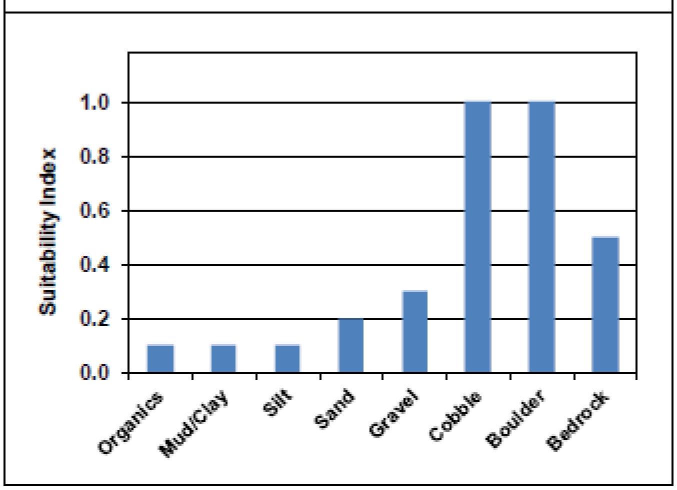
Source:
Groshens and Orth 1994

Velocity (ft/s)	SI
0.00	0.30
0.17	0.66
0.33	0.90
0.50	0.93
0.66	1.00
0.83	1.00
0.98	0.93
1.15	0.87
1.31	0.84
1.47	0.77
1.64	0.70
1.81	0.62
1.98	0.47
2.30	0.27
2.62	0.17
2.95	0.09
3.94	0.03
4.59	0.00



Leonard et al, 1986

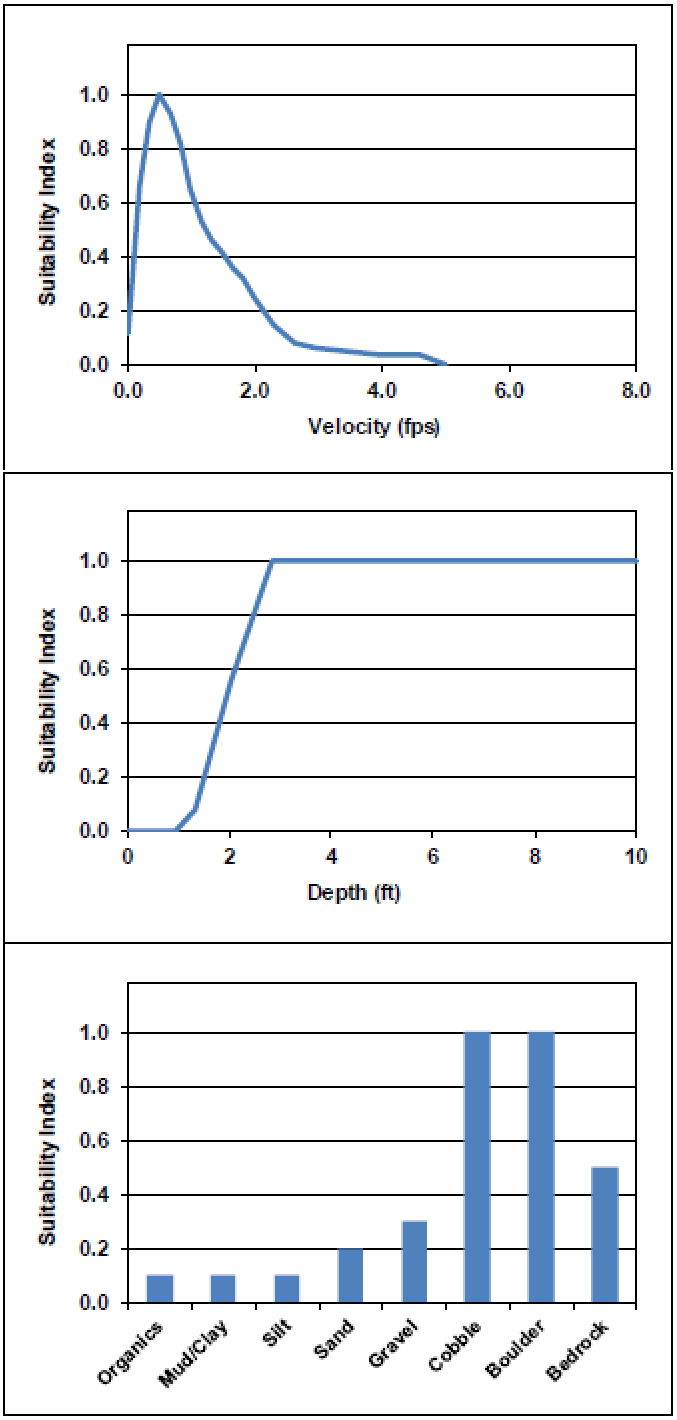
Depth (ft)	SI
0.00	0.00
0.52	0.00
0.67	0.03
2.15	1.00
10.00	1.00



Leonard et al, 1986

Substrate	SI
Organics	0.10
Mud/Clay	0.10
Silt	0.10
Sand	0.20
Gravel	0.30
Cobble	1.00
Boulder	1.00
Bedrock	0.50

Smallmouth Bass Adult



Source:

Groshens and Orth 1994

Velocity (ft/s)	SI
0.00	0.12
0.17	0.66
0.33	0.90
0.50	1.00
0.66	0.93
0.83	0.82
0.98	0.65
1.15	0.53
1.31	0.46
1.47	0.42
1.64	0.36
1.81	0.32
1.98	0.25
2.30	0.15
2.62	0.08
2.95	0.06
3.94	0.04
4.59	0.04
5.00	0.00

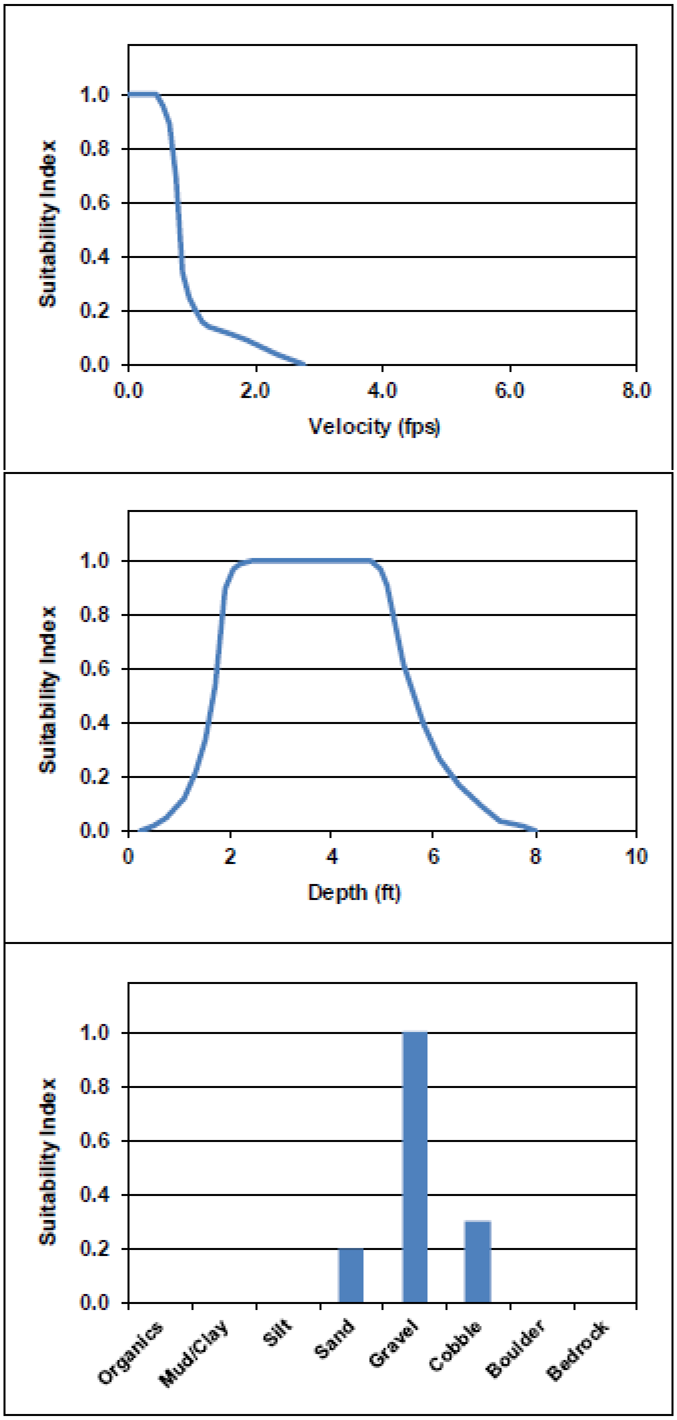
Leonard et al, 1986

Depth (ft)	SI
0.00	0.00
0.92	0.00
1.31	0.08
2.03	0.56
2.82	1.00
6.00	1.00
10.00	1.00

Leonard et al, 1986

Substrate	SI
Organics	0.10
Mud/Clay	0.10
Silt	0.10
Sand	0.20
Gravel	0.30
Cobble	1.00
Boulder	1.00
Bedrock	0.50

Smallmouth Bass Spawning



Source:

Allen, 1996

Velocity (ft/s)	SI
0.00	1.00
0.45	1.00
0.55	0.96
0.65	0.89
0.75	0.69
0.85	0.34
0.95	0.25
1.05	0.20
1.15	0.16
1.25	0.14
1.65	0.11
1.85	0.09
2.35	0.04
2.55	0.02
2.75	0.00

Edwards et al., 1983

Depth (ft)	SI
0.22	0.00
0.50	0.02
0.74	0.05
1.10	0.12
1.32	0.22
1.53	0.34
1.70	0.54
1.90	0.90
2.05	0.97
2.18	0.99
2.40	1.00
4.75	1.00
4.95	0.97
5.10	0.91
5.40	0.62
5.80	0.40
6.10	0.27
6.50	0.17
6.95	0.09
7.30	0.04
7.75	0.02
8.00	0.00

Allen, 1996

Substrate	SI
Organics	0.00
Mud/Clay	0.00
Silt	0.00
Sand	0.20
Gravel	1.00
Cobble	0.30
Boulder	0.00
Bedrock	0.00

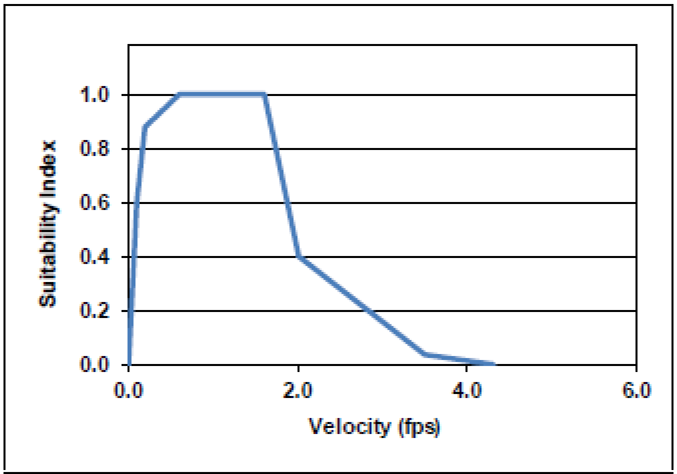
Fallfish Juvenile

Velocity and depth from brook trout fry curves (Deerfield River)

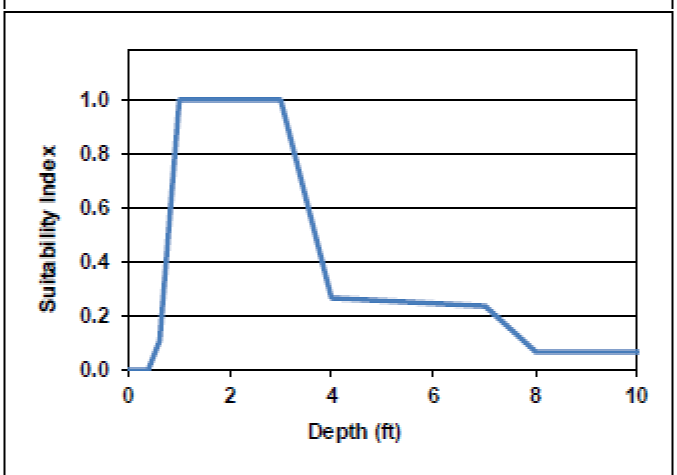
Substrate developed by Charles Ritzi

Source:

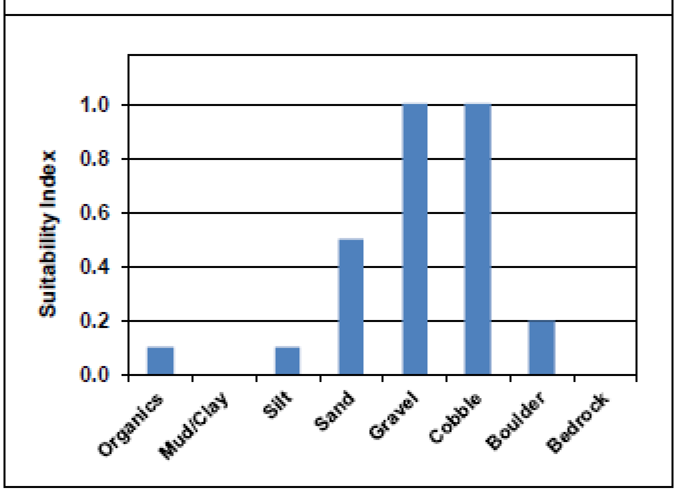
Gomez and Sullivan, 2007



Velocity (ft/s)	SI
0.00	0.00
0.10	0.60
0.20	0.88
0.60	1.00
1.60	1.00
2.00	0.40
3.50	0.04
4.30	0.00



Depth (ft)	SI
0.00	0.00
0.40	0.00
0.60	0.11
1.00	1.00
3.00	1.00
4.00	0.27
7.00	0.24
8.00	0.07
20.00	0.07
100.00	0.07

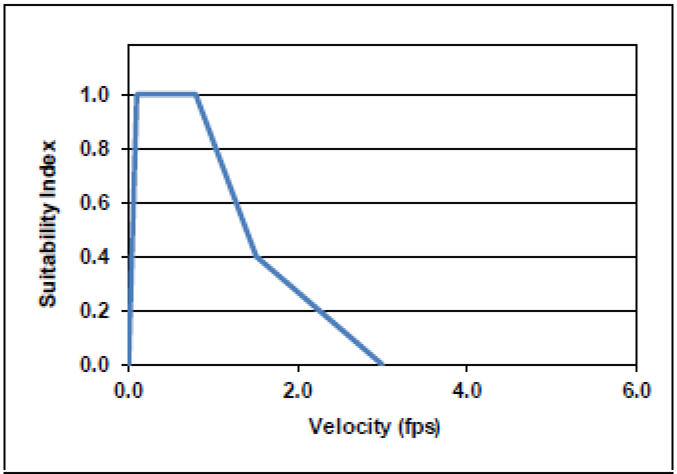


Substrate	SI
Organics	0.10
Mud/Clay	0.00
Silt	0.10
Sand	0.50
Gravel	1.00
Cobble	1.00
Boulder	0.20
Bedrock	0.00

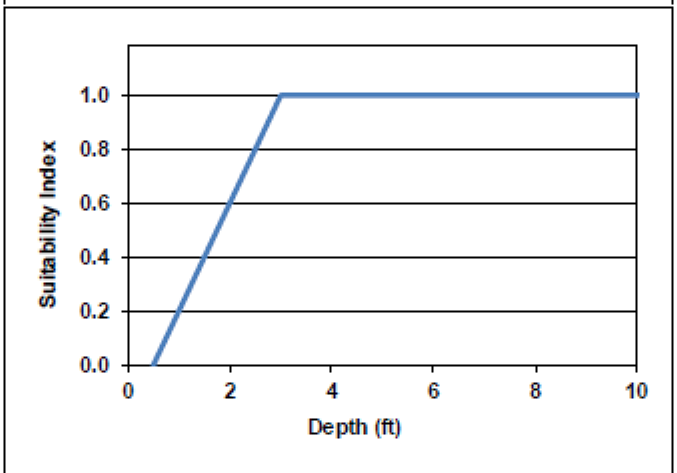
Fallfish Adult

Developed from consultation with NYSDEC
(New York Dept. of Environmental Conservation)

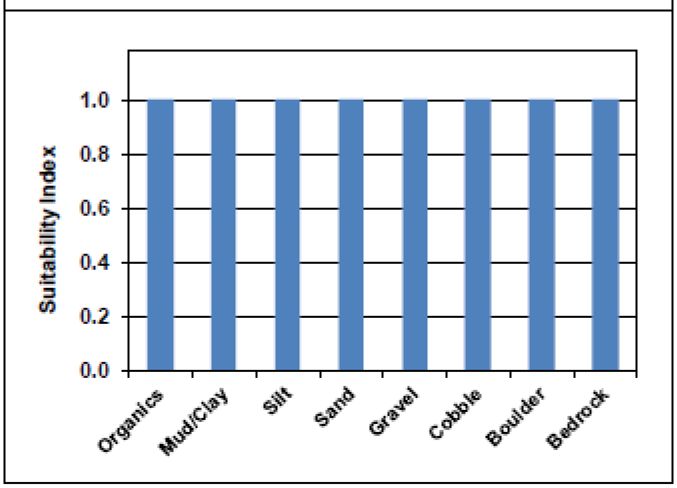
Source:
Gomez and Sullivan, 2007



Velocity (ft/s)	SI
0.00	0.00
0.10	1.00
0.80	1.00
1.50	0.40
3.00	0.00



Depth (ft)	SI
0.00	0.00
0.50	0.00
3.00	1.00
100.00	1.00

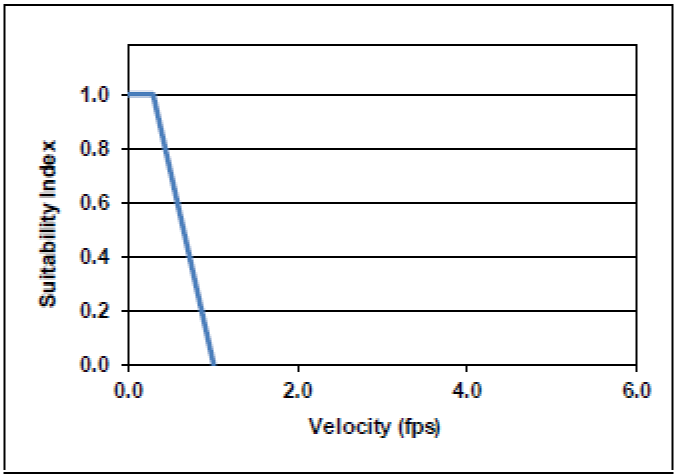


Substrate	SI
Organics	1.00
Mud/Clay	1.00
Silt	1.00
Sand	1.00
Gravel	1.00
Cobble	1.00
Boulder	1.00
Bedrock	1.00

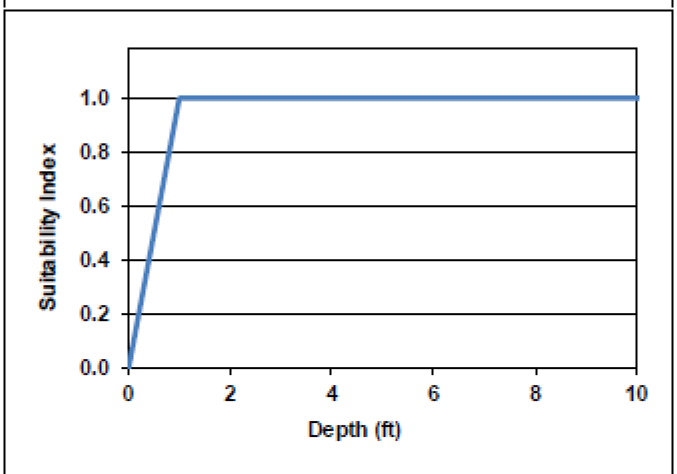
White Sucker Fry

Source:

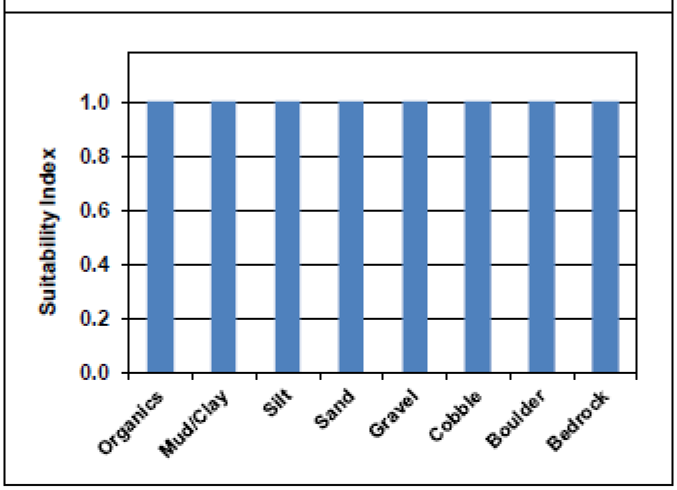
Twomey et al., 1984



Velocity (ft/s)	SI
0.00	1.00
0.30	1.00
1.00	0.00



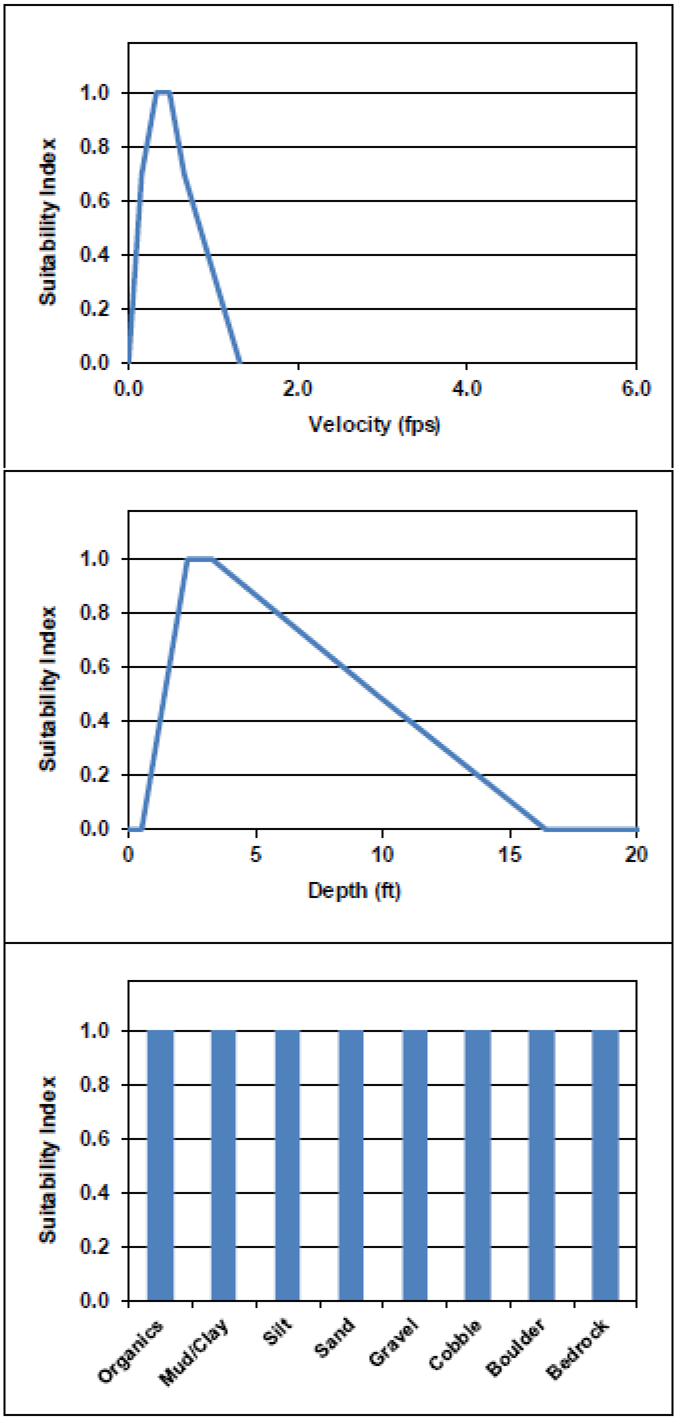
Depth (ft)	SI
0.00	0.00
1.00	1.00
100.00	1.00



Substrate	SI
Organics	1.00
Mud/Clay	1.00
Silt	1.00
Sand	1.00
Gravel	1.00
Cobble	1.00
Boulder	1.00
Bedrock	1.00

White Sucker Adult/Juvenile

Source:
Twomey et al., 1984



Velocity (ft/s)	SI
0.00	0.00
0.16	0.70
0.33	1.00
0.49	1.00
0.66	0.70
1.31	0.00

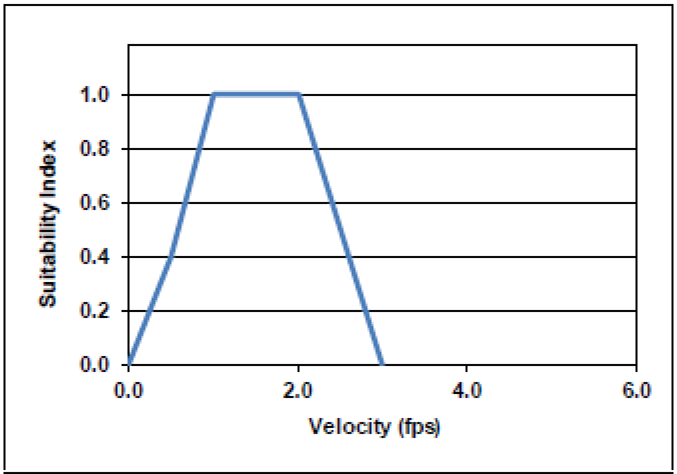
Depth (ft)	SI
0.00	0.00
0.50	0.00
2.30	1.00
3.30	1.00
9.80	0.50
16.40	0.00
100.00	0.00

Substrate	SI
Organics	1.00
Mud/Clay	1.00
Silt	1.00
Sand	1.00
Gravel	1.00
Cobble	1.00
Boulder	1.00
Bedrock	1.00

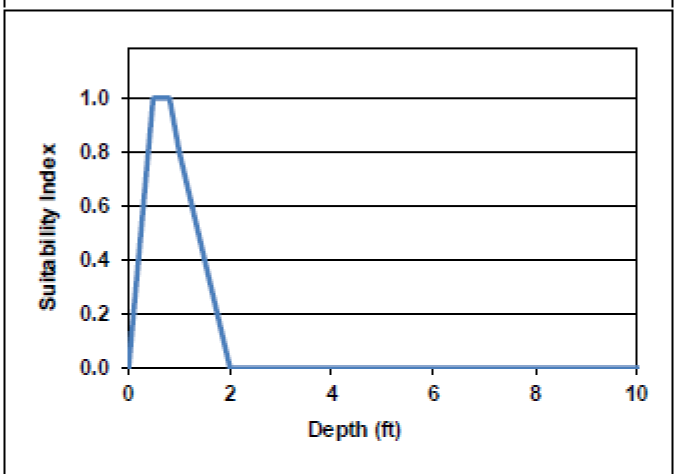
White Sucker Spawning & Incubation

Source:

Twomey et al., 1984

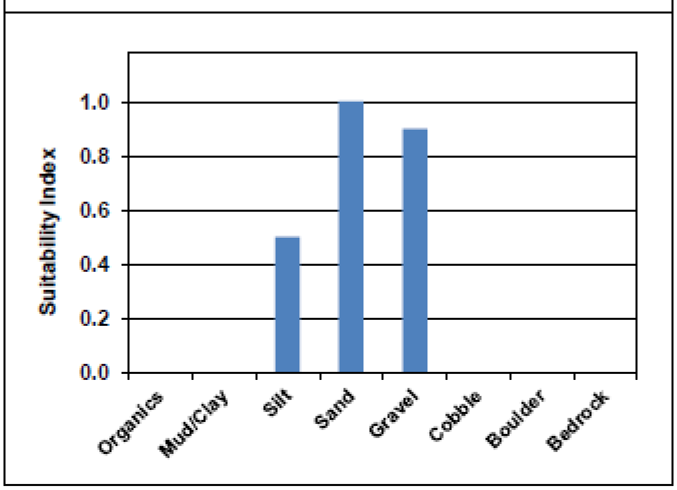


Velocity (ft/s)	SI
0.00	0.00
0.50	0.40
1.00	1.00
2.00	1.00
3.00	0.00



Depth (ft)	SI
0.00	0.00
0.50	1.00
0.80	1.00
1.00	0.80
2.00	0.00
100.00	0.00

Substrate Source:
Gomez and Sullivan, 2007



Substrate	SI
Organics	0.00
Mud/Clay	0.00
Silt	0.50
Sand	1.00
Gravel	0.90
Cobble	0.00
Boulder	0.00
Bedrock	0.00

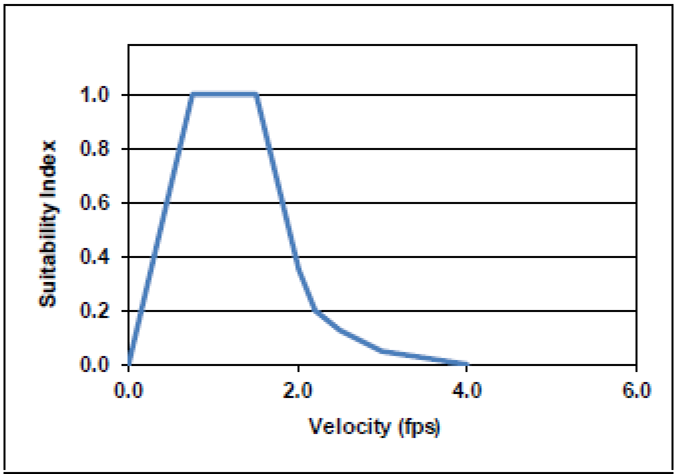
Longnose Dace Juvenile

Original curve identified as from USFWS HSC library

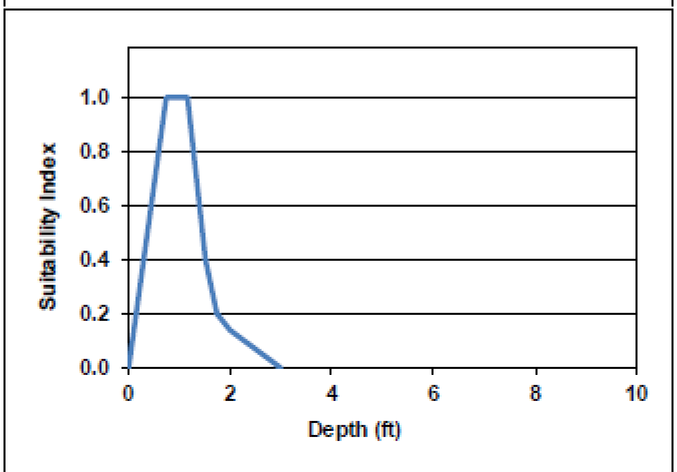
Modified by VDFW for the Lamoille River IFS (Gomez and Sullivan, 2000)

Source:

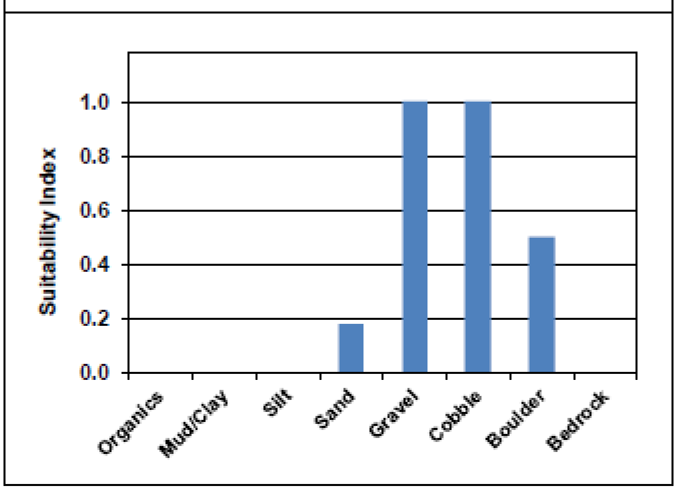
Gomez and Sullivan, 2000



Velocity (ft/s)	SI
0.00	0.00
0.75	1.00
1.50	1.00
2.00	0.35
2.20	0.20
2.50	0.13
3.00	0.05
4.00	0.00



Depth (ft)	SI
0.00	0.00
0.75	1.00
1.15	1.00
1.50	0.40
1.75	0.20
2.00	0.14
3.00	0.00



Substrate	SI
Organics	0.00
Mud/Clay	0.00
Silt	0.00
Sand	0.18
Gravel	1.00
Cobble	1.00
Boulder	0.50
Bedrock	0.00

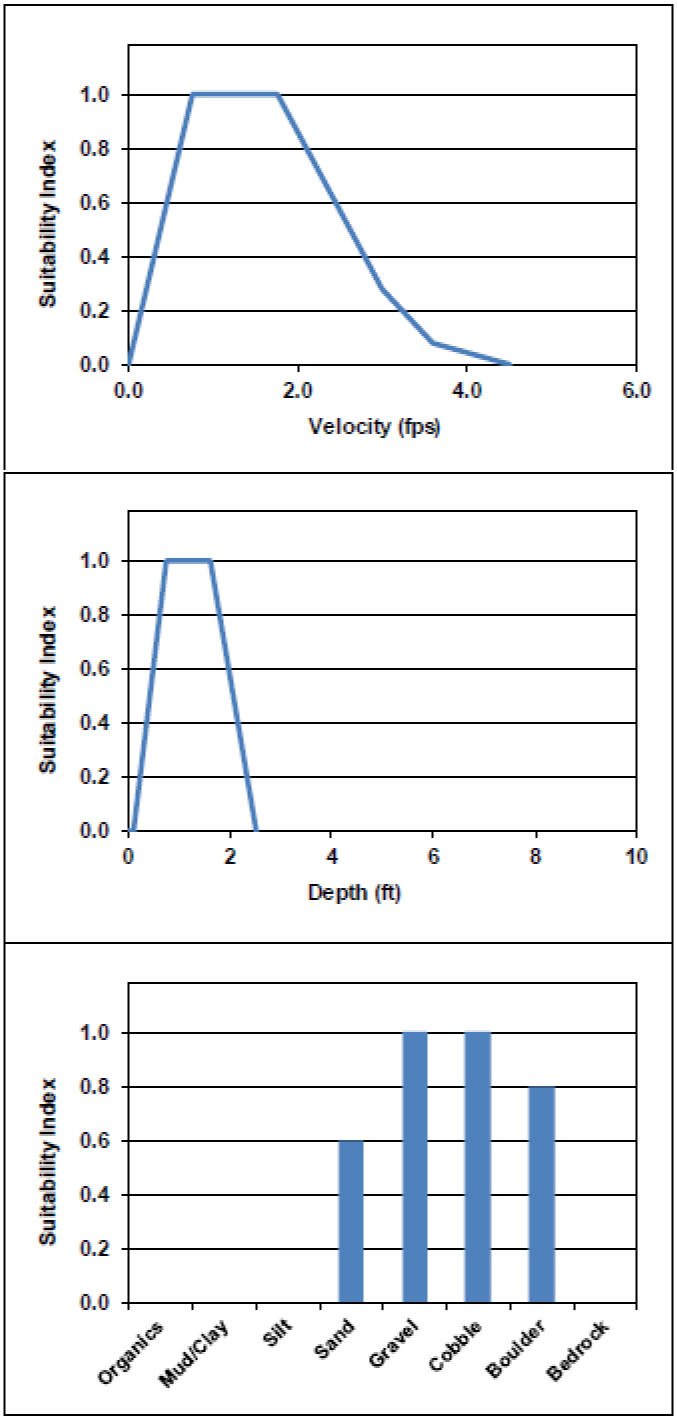
Longnose Dace Adult

Original curve identified as from USGS HSC library

Modified by VDFW for the Lamoille River IFS (Gomez and Sullivan, 2000)

Source:

Gomez and Sullivan, 2000



Velocity (ft/s)	SI
0.00	0.00
0.75	1.00
1.75	1.00
3.00	0.28
3.60	0.08
4.50	0.00

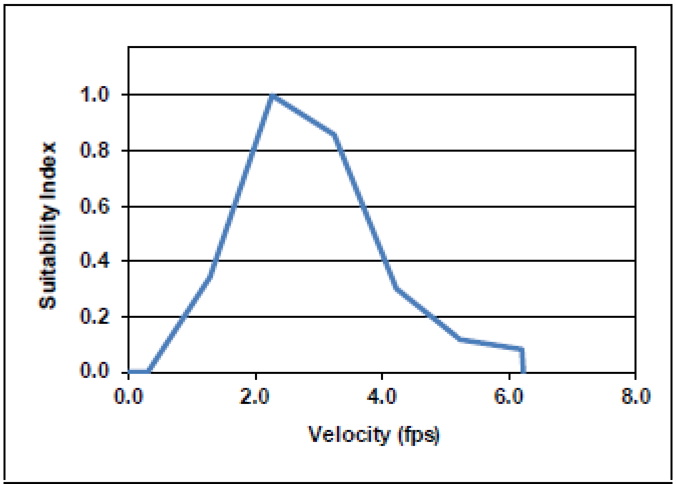
Depth (ft)	SI
0.00	0.00
0.10	0.00
0.75	1.00
1.60	1.00
2.50	0.00

Substrate	SI
Organics	0.00
Mud/Clay	0.00
Silt	0.00
Sand	0.60
Gravel	1.00
Cobble	1.00
Boulder	0.80
Bedrock	0.00

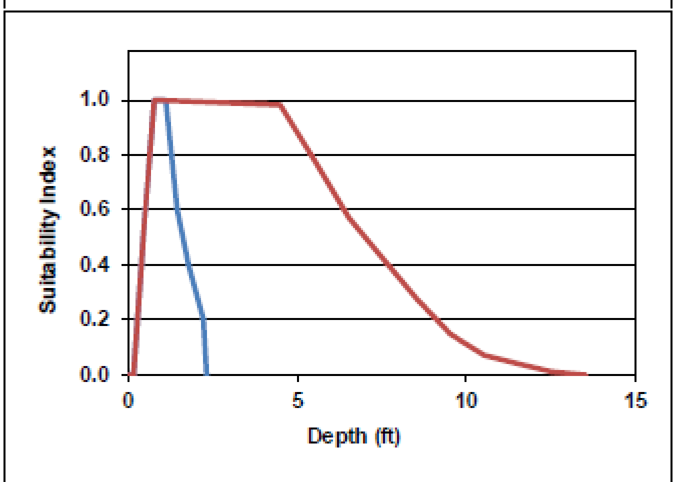
Sea Lamprey Spawning & Incubation

Modified by USFWS (2014) based on Yergeau 1983 (depth and substrate)

Source:
Kynard and Horgan, 2013
Yergeau, 1983



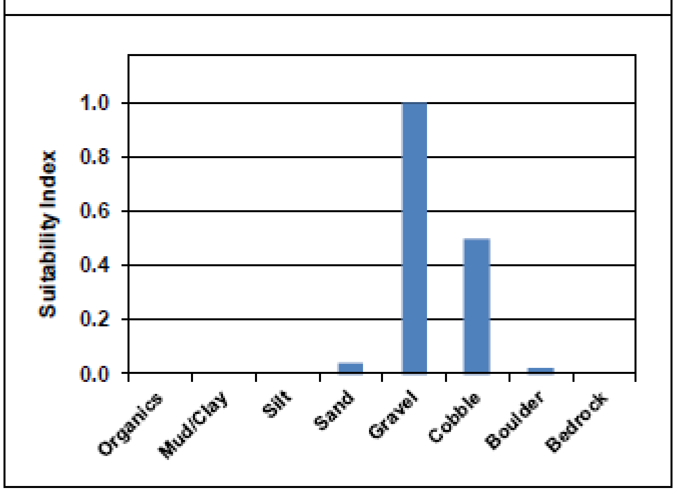
Velocity (ft/s)	SI
0.00	0.00
0.30	0.00
1.28	0.34
2.26	1.00
3.25	0.86
4.23	0.30
5.22	0.12
6.20	0.08
6.23	0.00



Depth (ft)	SI
0.00	0.00
0.13	0.00
0.46	0.50
0.79	1.00
1.12	1.00
1.44	0.60
1.77	0.40
2.20	0.20
2.30	0.00

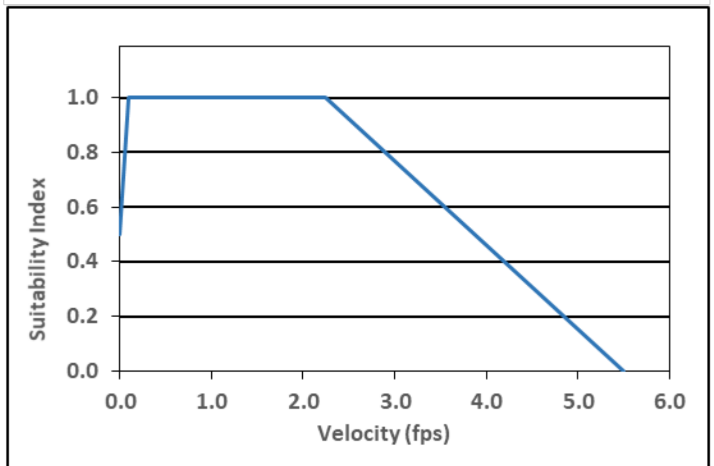
Modified by NAI

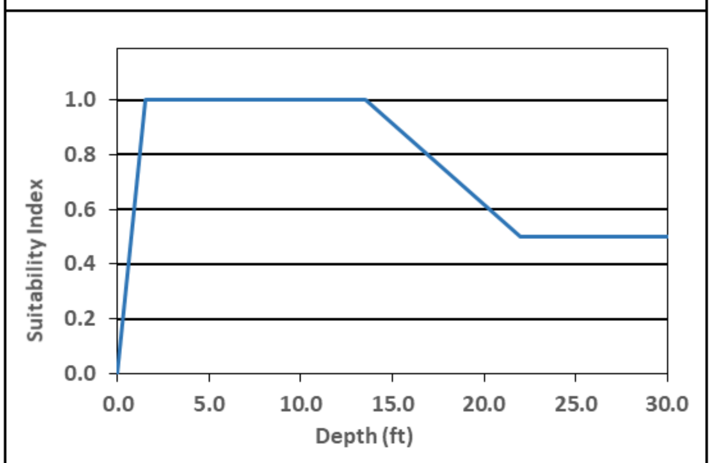
Depth (ft)	SI
0.00	0.00
0.13	0.00
0.46	0.50
0.79	1.00
4.50	0.98
5.50	0.78
6.50	0.57
7.50	0.43
8.50	0.28
9.50	0.15
10.50	0.07
11.50	0.04
12.50	0.01
13.50	0.00

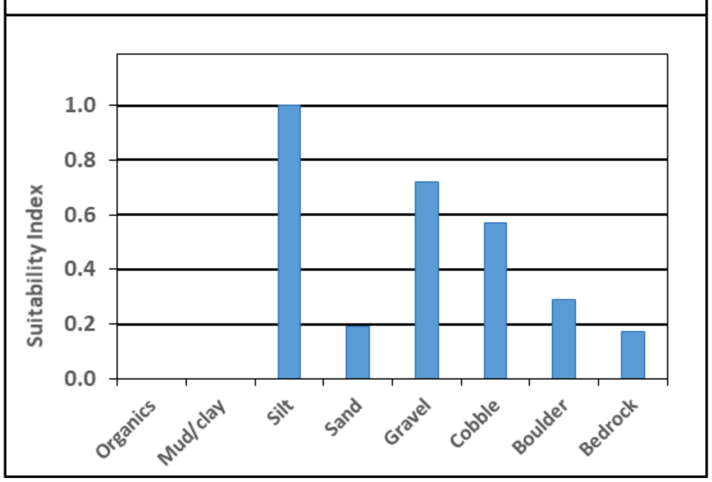


Substrate	SI
Organics	0.00
Mud/Clay	0.00
Silt	0.00
Sand	0.04
Gravel	1.00
Cobble	0.50
Boulder	0.02
Bedrock	0.00

Freshwater Mussels







Freshwater Mussels
Normandeau and Biodrawversity 2017

Freshwater Mussels

MCV (ft/s)	SI
0.00	0.50
0.10	1.00
2.25	1.00
5.50	0.00

Freshwater Mussels

Depth (ft)	SI
0.00	0.00
1.50	1.00
13.50	1.00
22.00	0.50
30.00	0.50
100	0.5

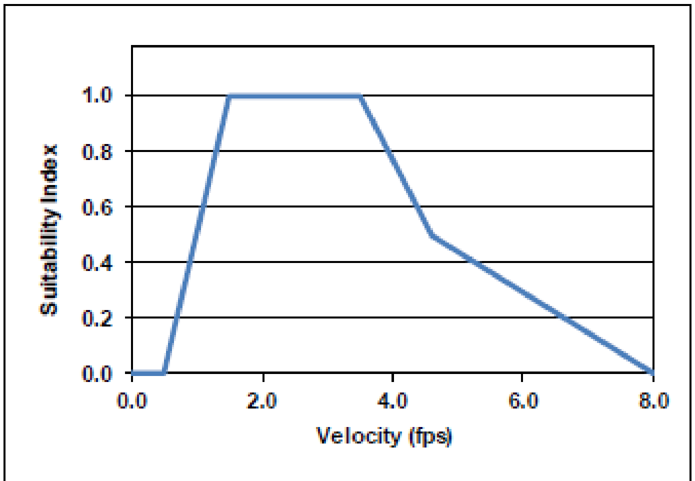
Freshwater Mussels

Substrate	SI
Organics	0.00
Mud/Clay	0.00
Silt	1.00
Sand	0.19
Gravel	0.72
Cobble	0.57
Boulder	0.29
Bedrock	0.17

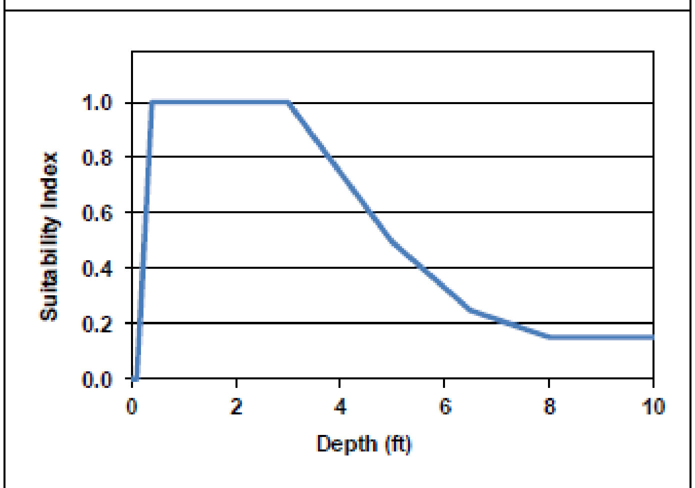
Macroinvertebrates

Source:

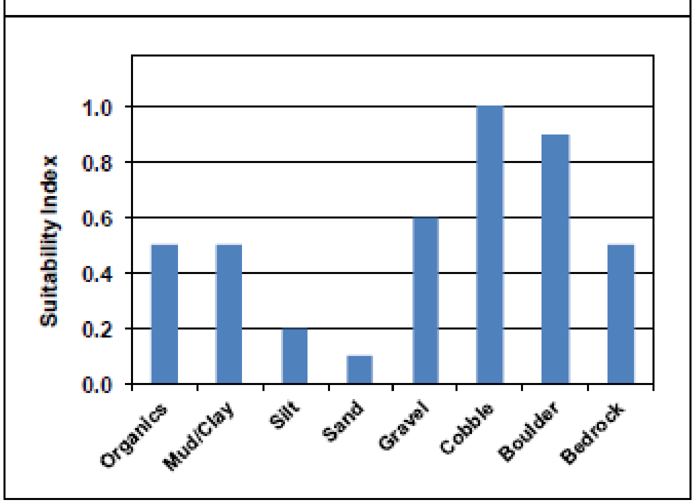
Gomez and Sullivan, 2000



Velocity (ft/s)	SI
0.00	0.00
0.50	0.00
1.50	1.00
3.50	1.00
4.60	0.50
8.00	0.00

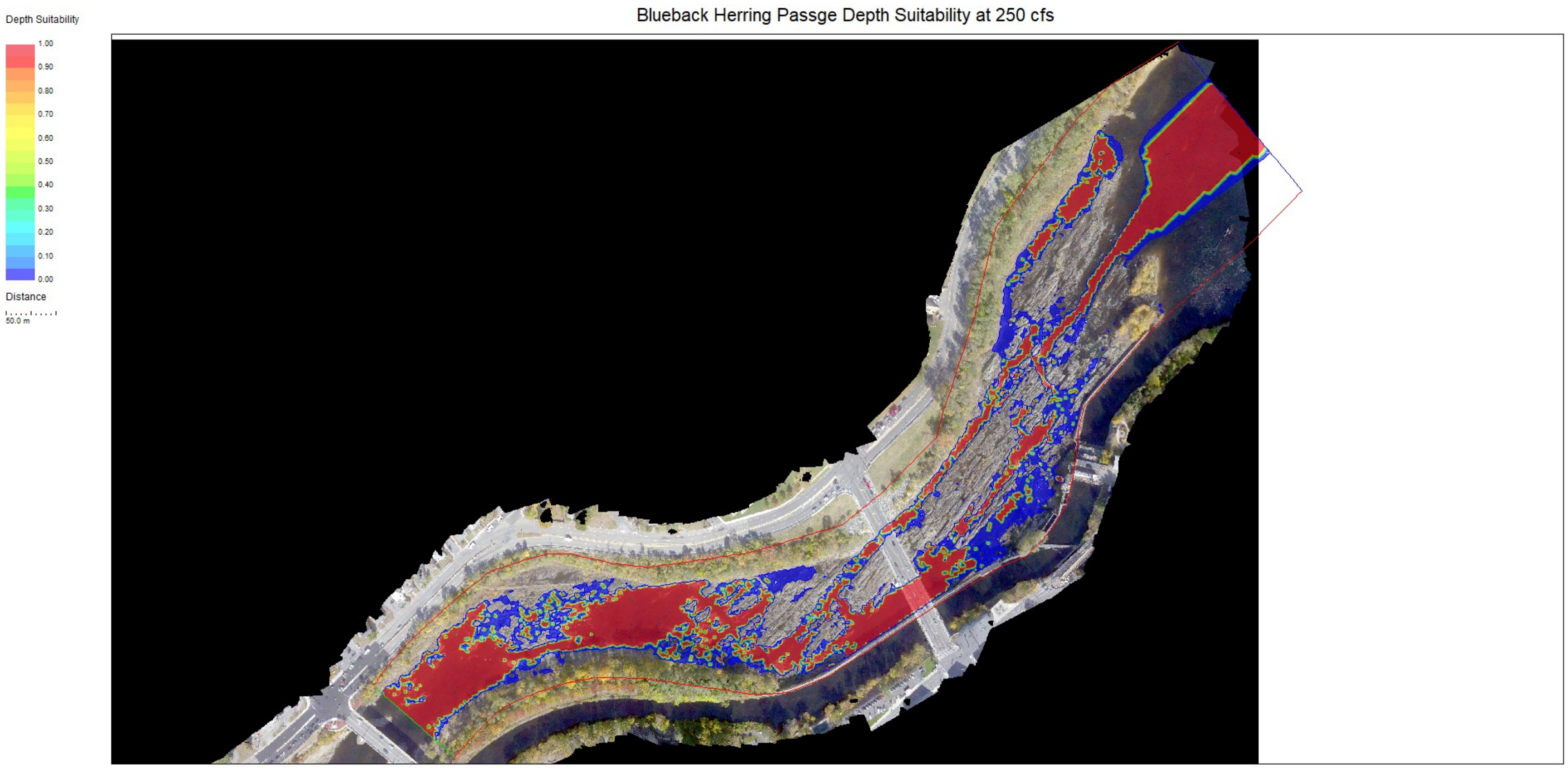


Depth (ft)	SI
0.00	0.00
0.10	0.00
0.40	1.00
3.00	1.00
5.00	0.50
6.50	0.25
8.00	0.15
10.00	0.15
100.00	0.00

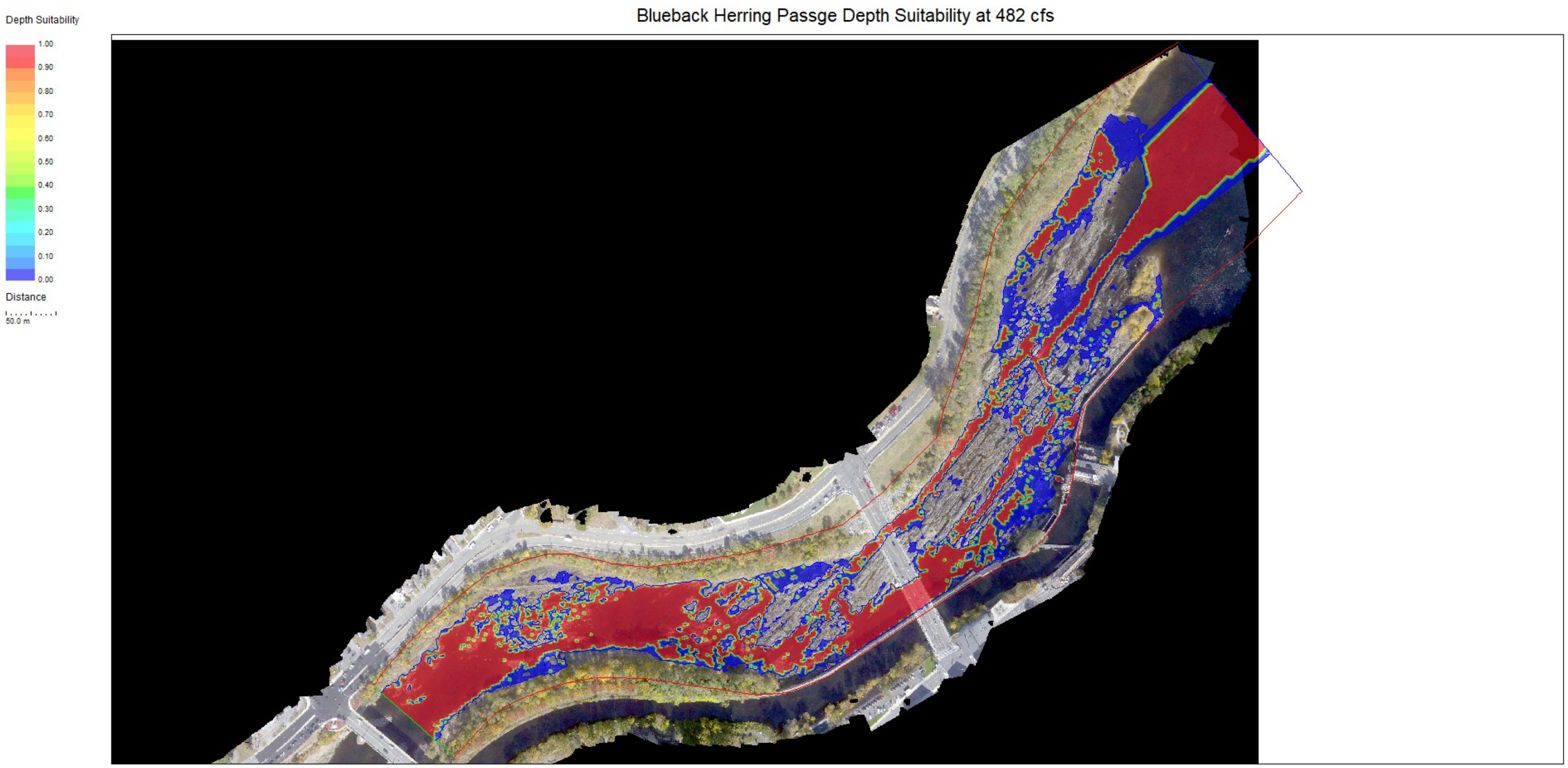


Substrate	SI
Organics	0.50
Mud/Clay	0.50
Silt	0.20
Sand	0.10
Gravel	0.60
Cobble	1.00
Boulder	0.90
Bedrock	0.50

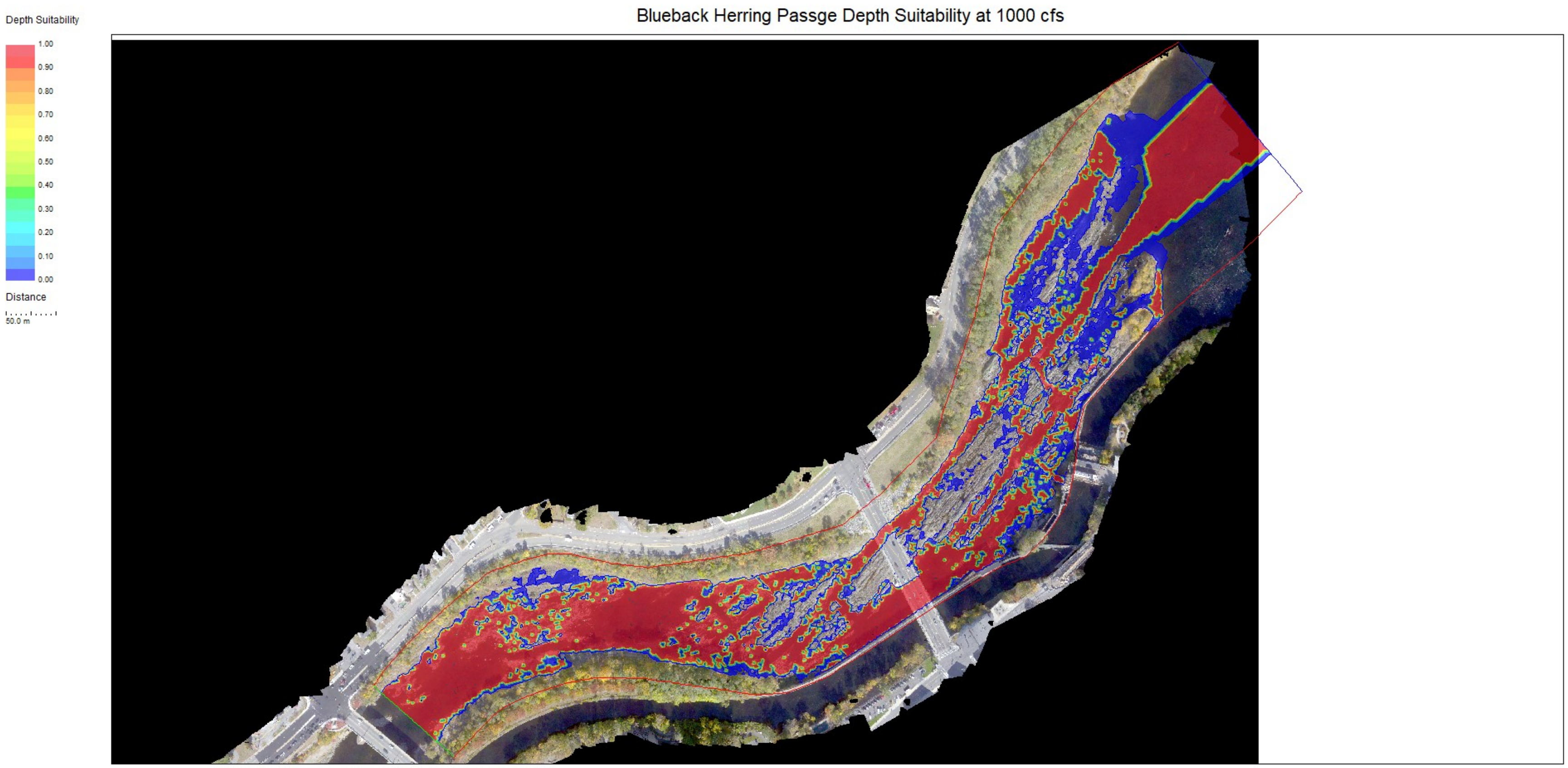
Appendix B. Zone of passage conditions for adult river herring and American shad – depth, velocity, and depth x velocity.



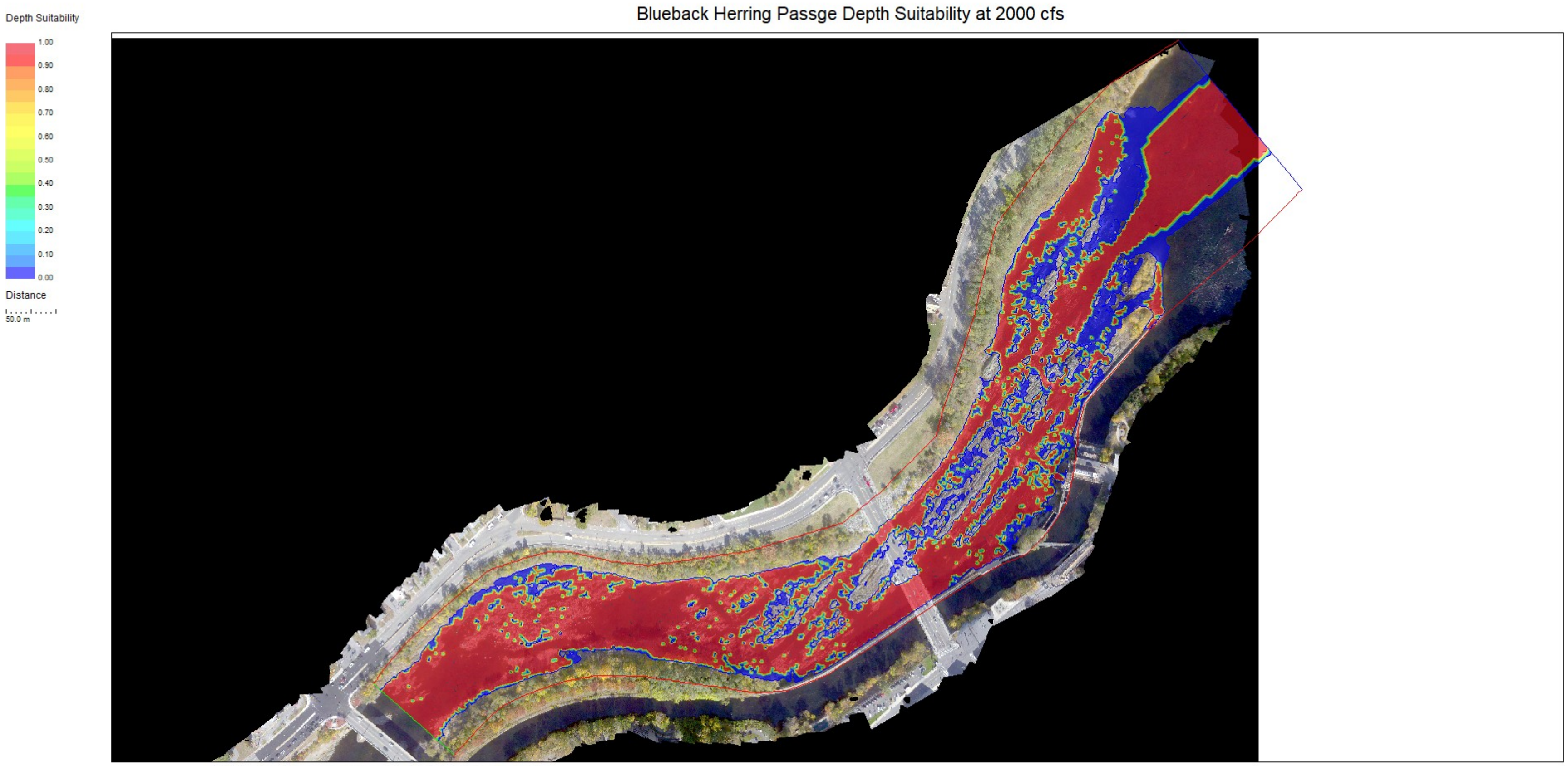
Note: Depth criteria = 1.0 ft. Same criteria for blueback herring and alewife. Map also represents passage for American shad using 1.0 ft depth criteria.



Note: Depth criteria = 1.0 ft. Same criteria for blueback herring and alewife. Map also represents passage for American shad using 1.0 ft depth criteria.

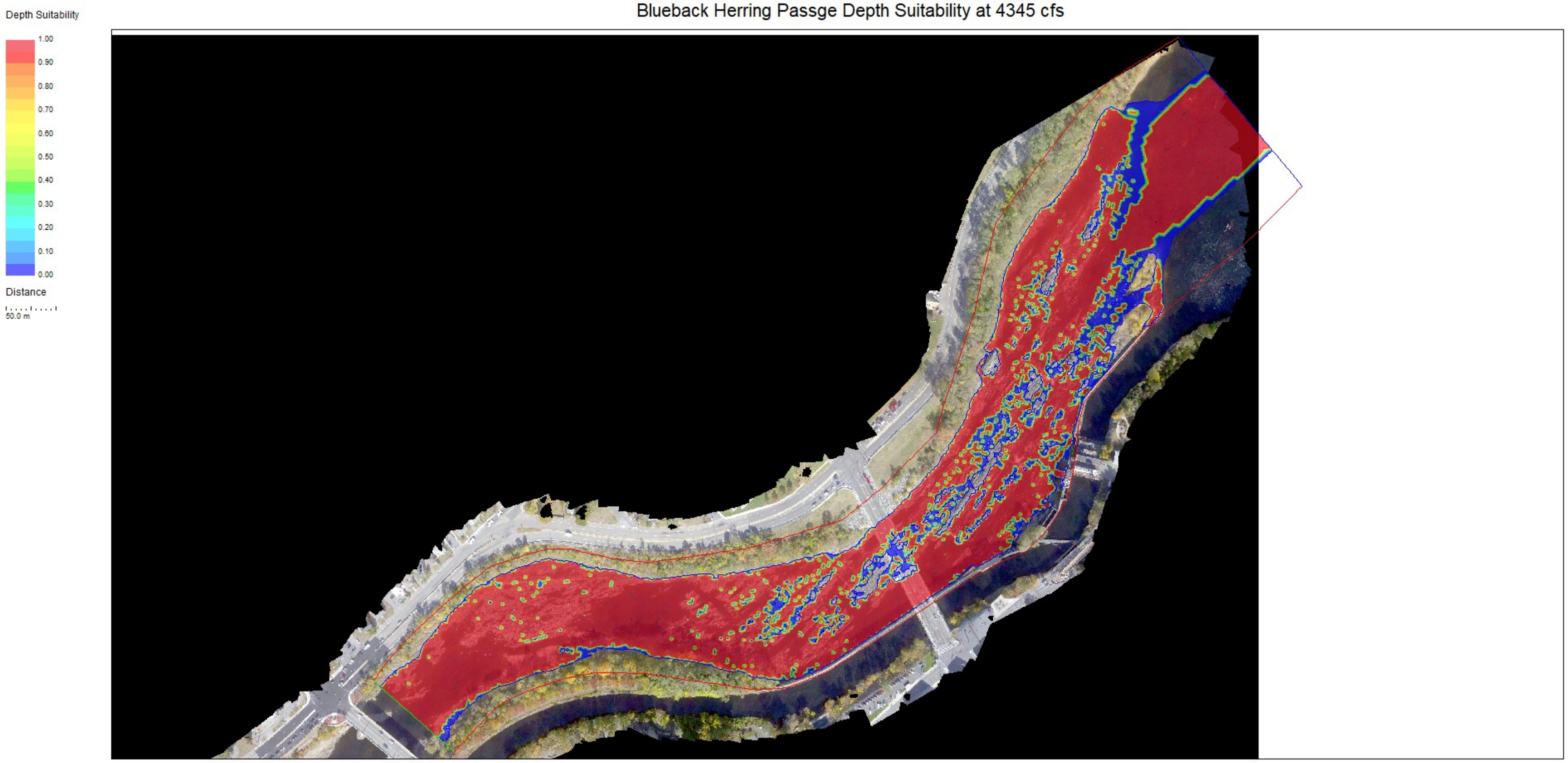


Note: Depth criteria = 1.0 ft. Same criteria for blueback herring and alewife. Map also represents passage for American shad using 1.0 ft depth criteria.

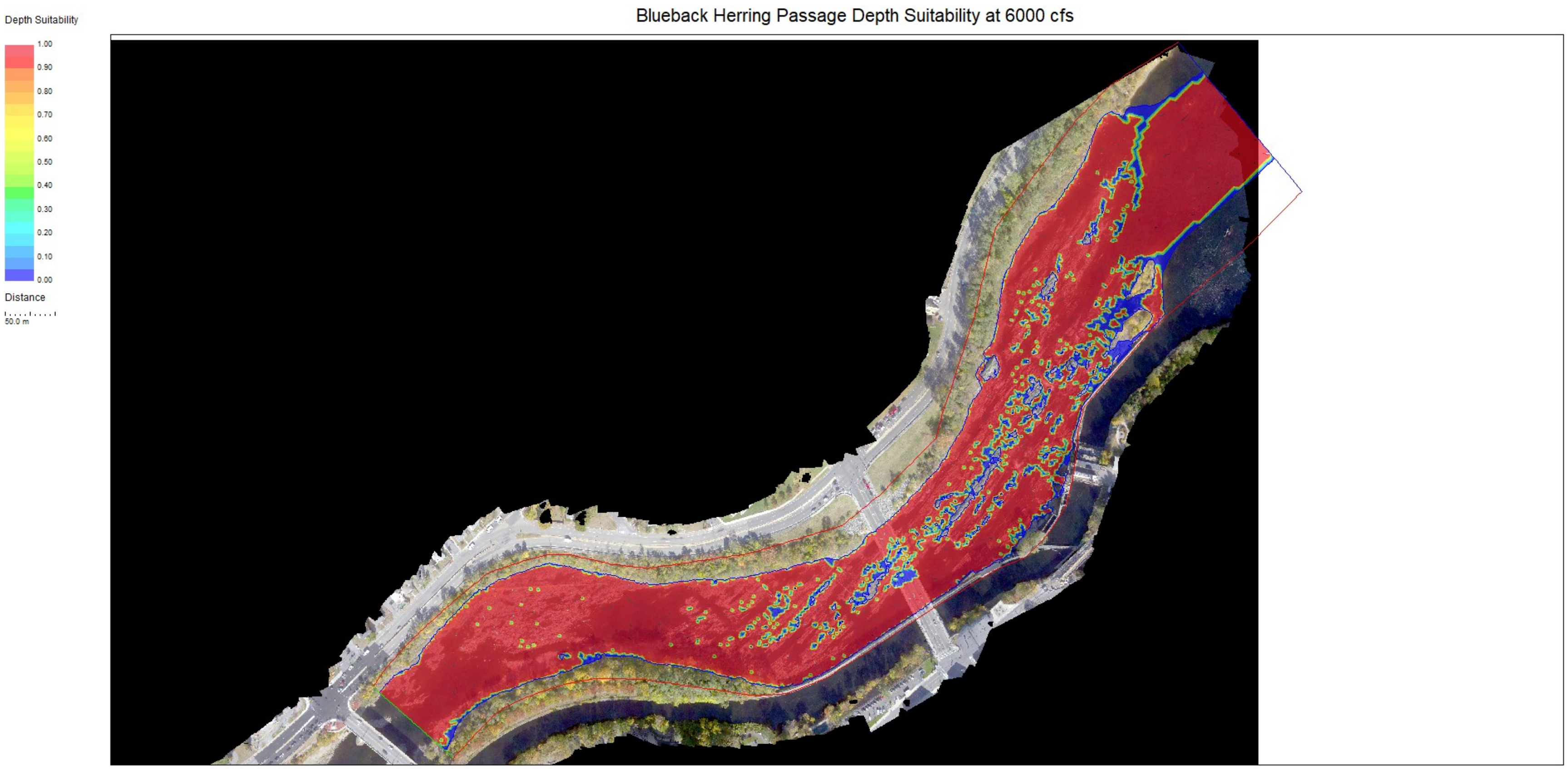


Note: Depth criteria = 1.0 ft. Same criteria for blueback herring and alewife. Map also represents passage for American shad using 1.0 ft depth criteria.

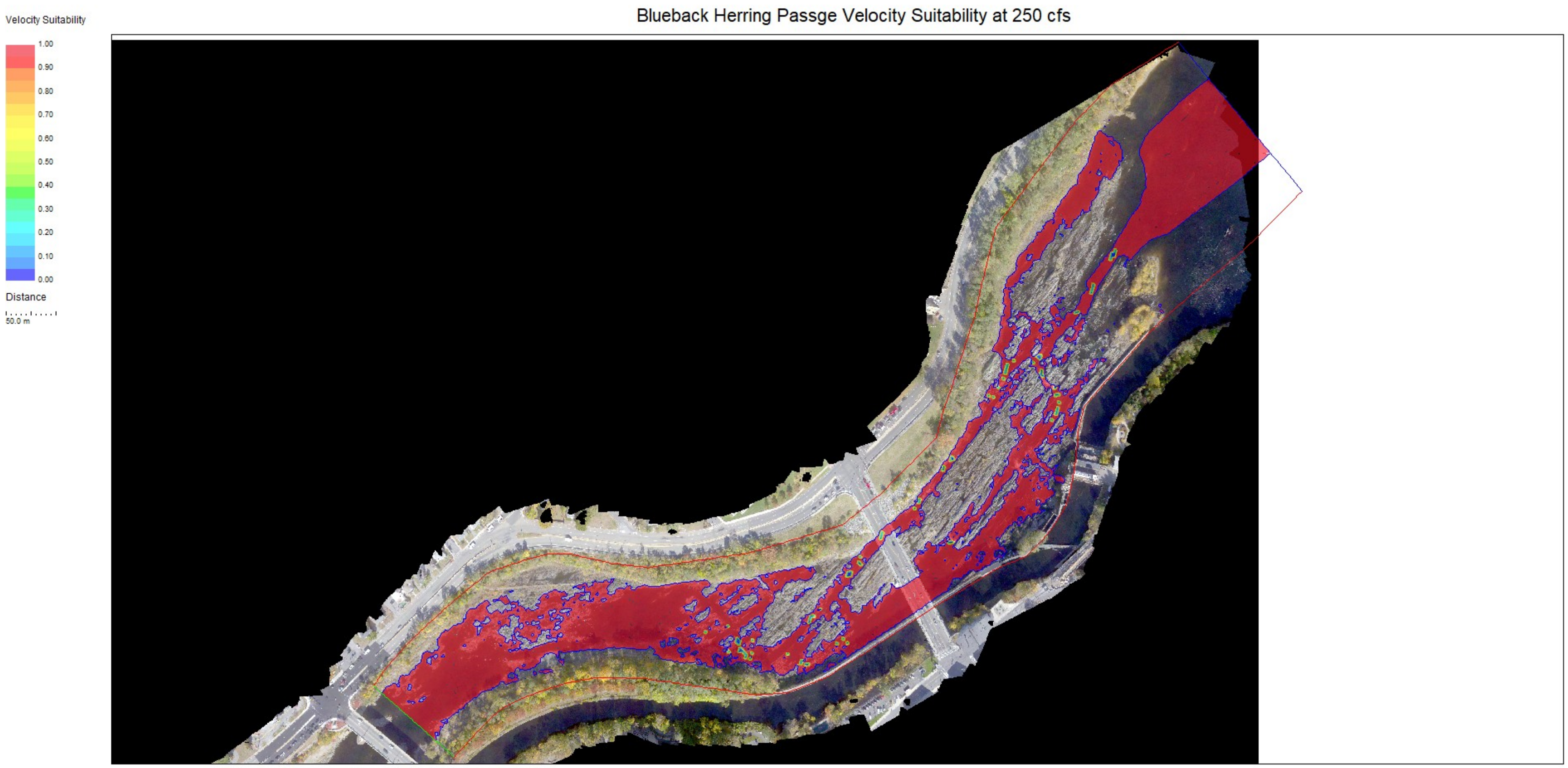
Blueback Herring Passge Depth Suitability at 4345 cfs



Note: Depth criteria = 1.0 ft. Same criteria for blueback herring and alewife. Map also represents passage for American shad using 1.0 ft depth criteria.

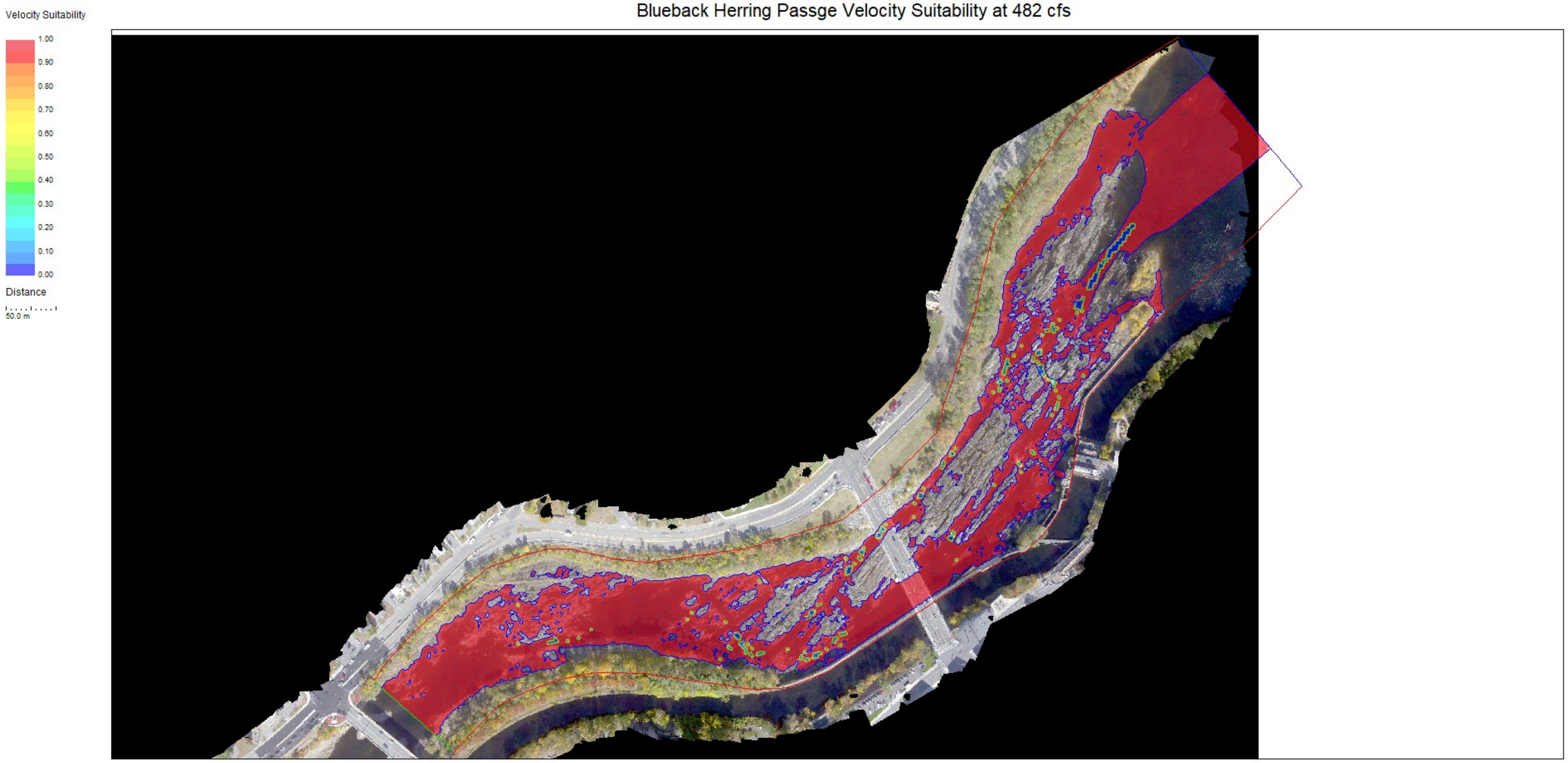


Note: Depth criteria = 1.0 ft. Same criteria for blueback herring and alewife. Map also represents passage for American shad using 1.0 ft depth criteria.

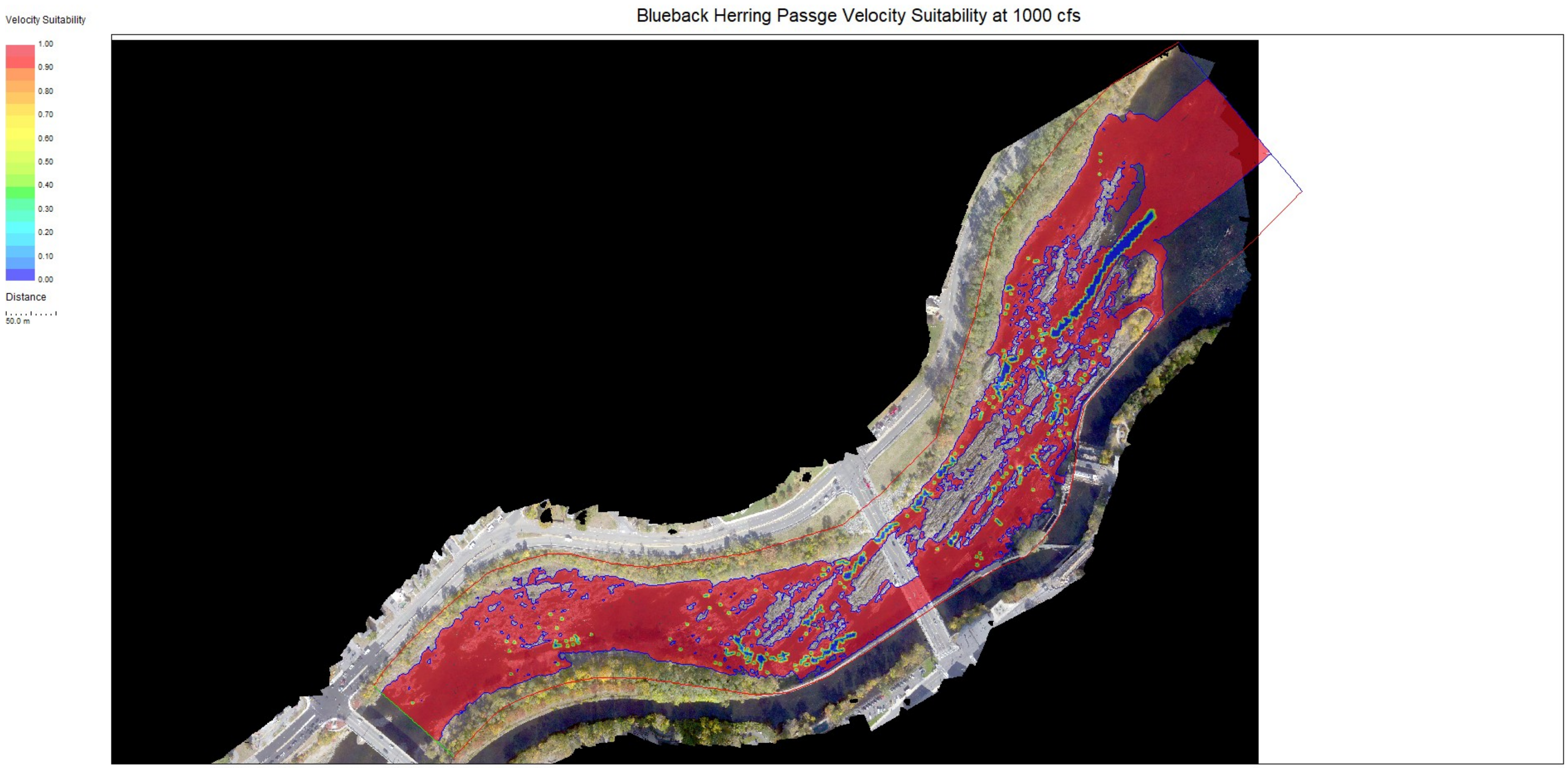


Note: Velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.

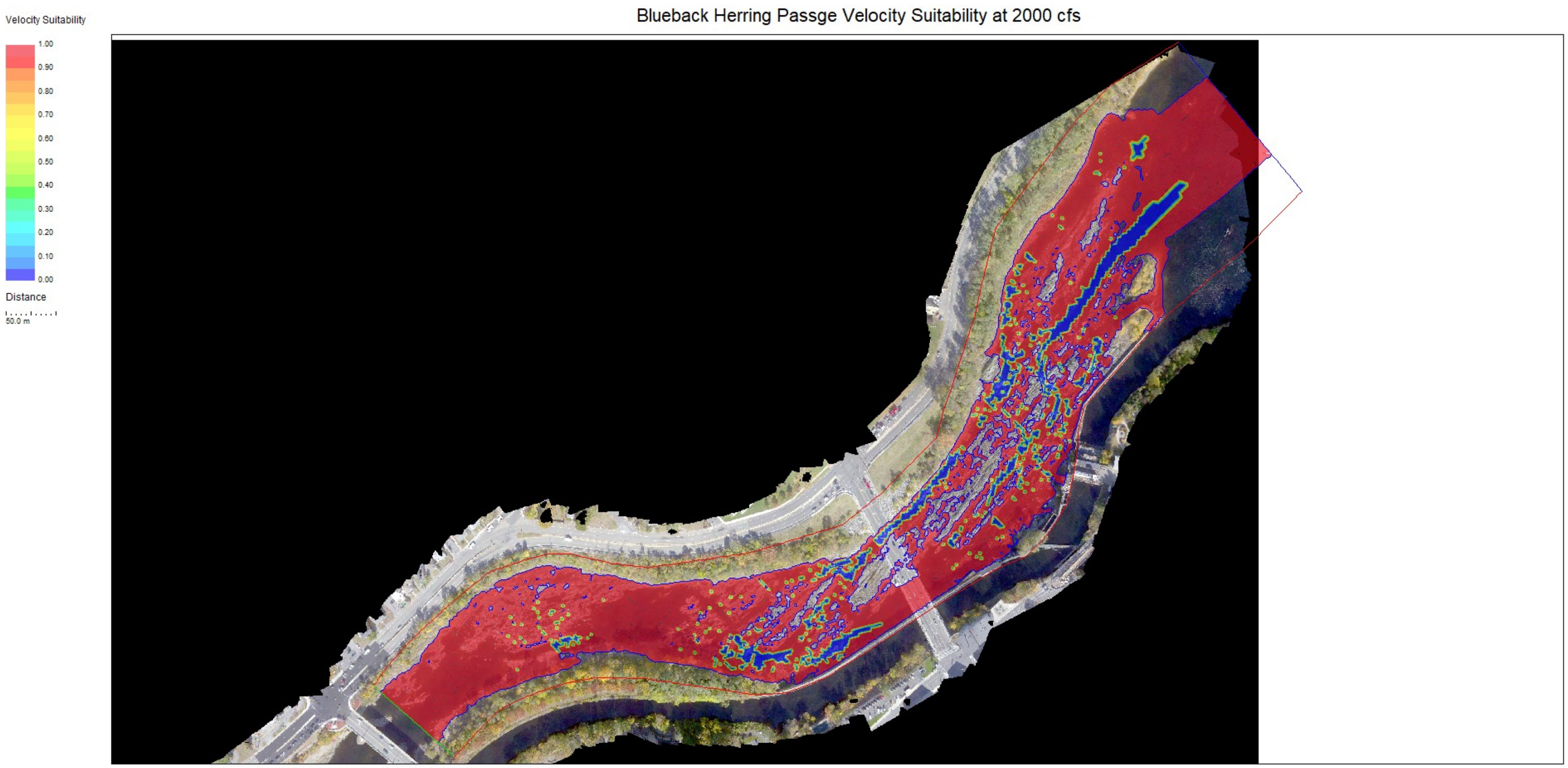
Blueback Herring Passge Velocity Suitability at 482 cfs



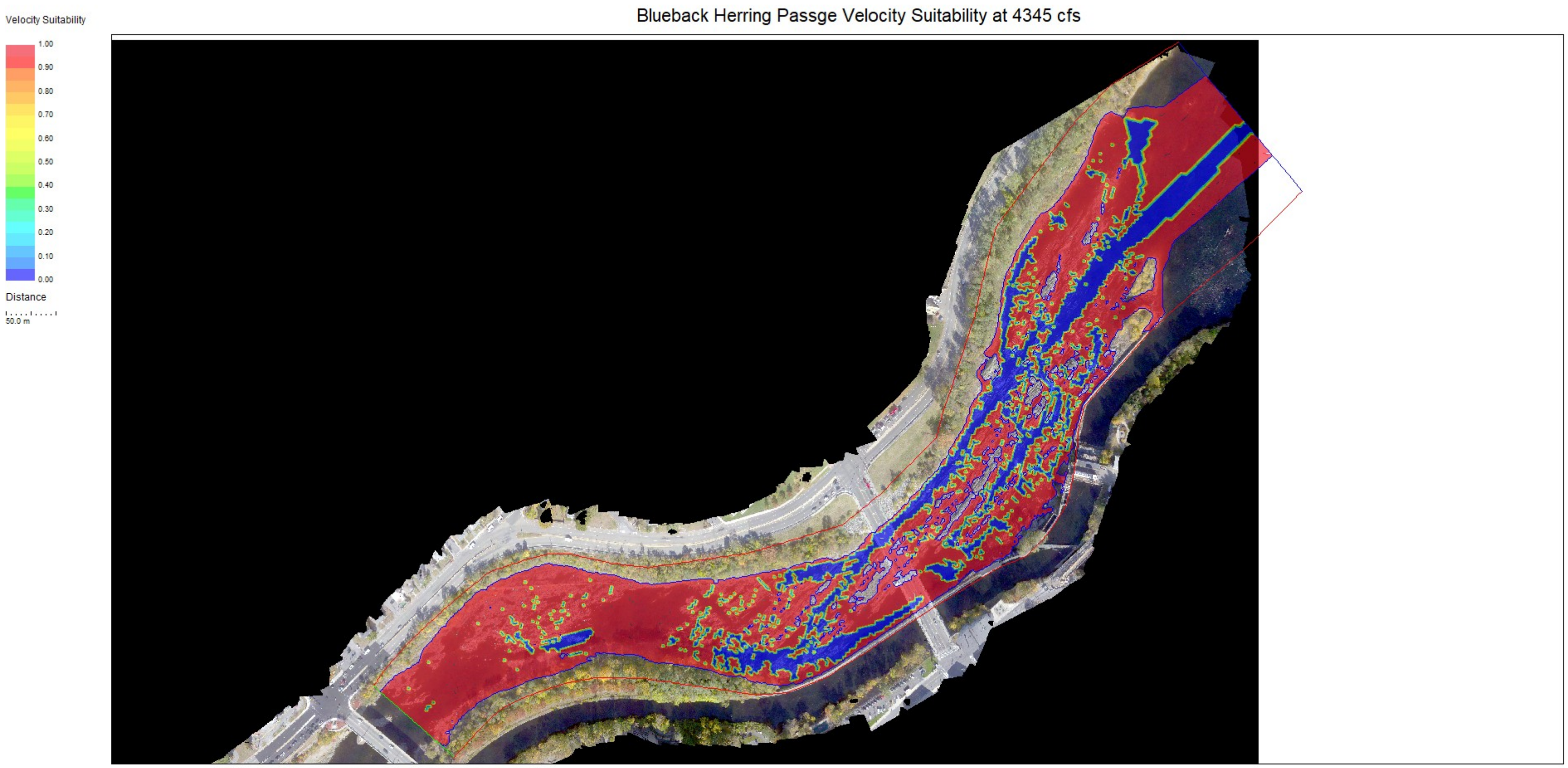
Note: Velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.



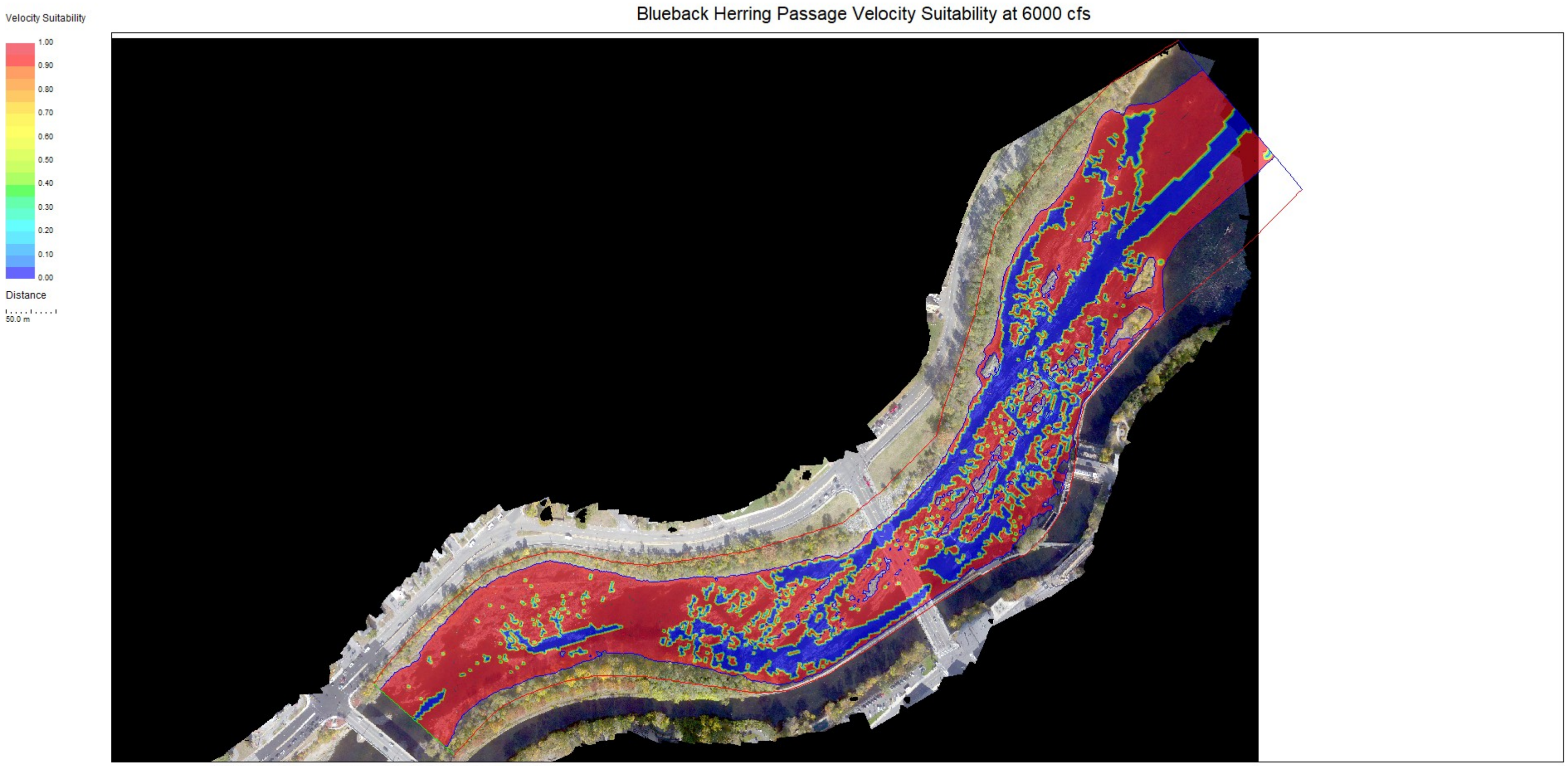
Note: Velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.



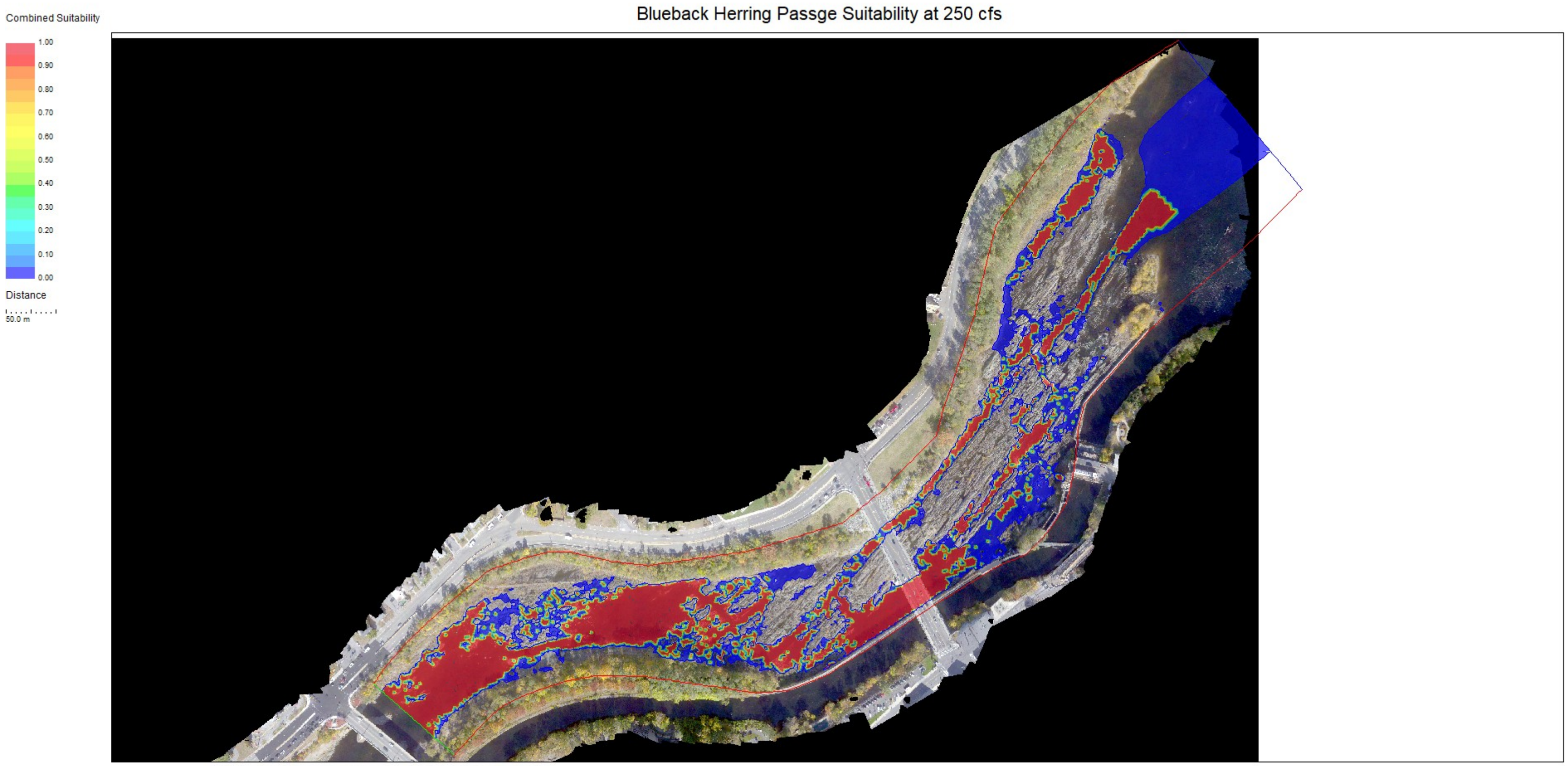
Note: Velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.



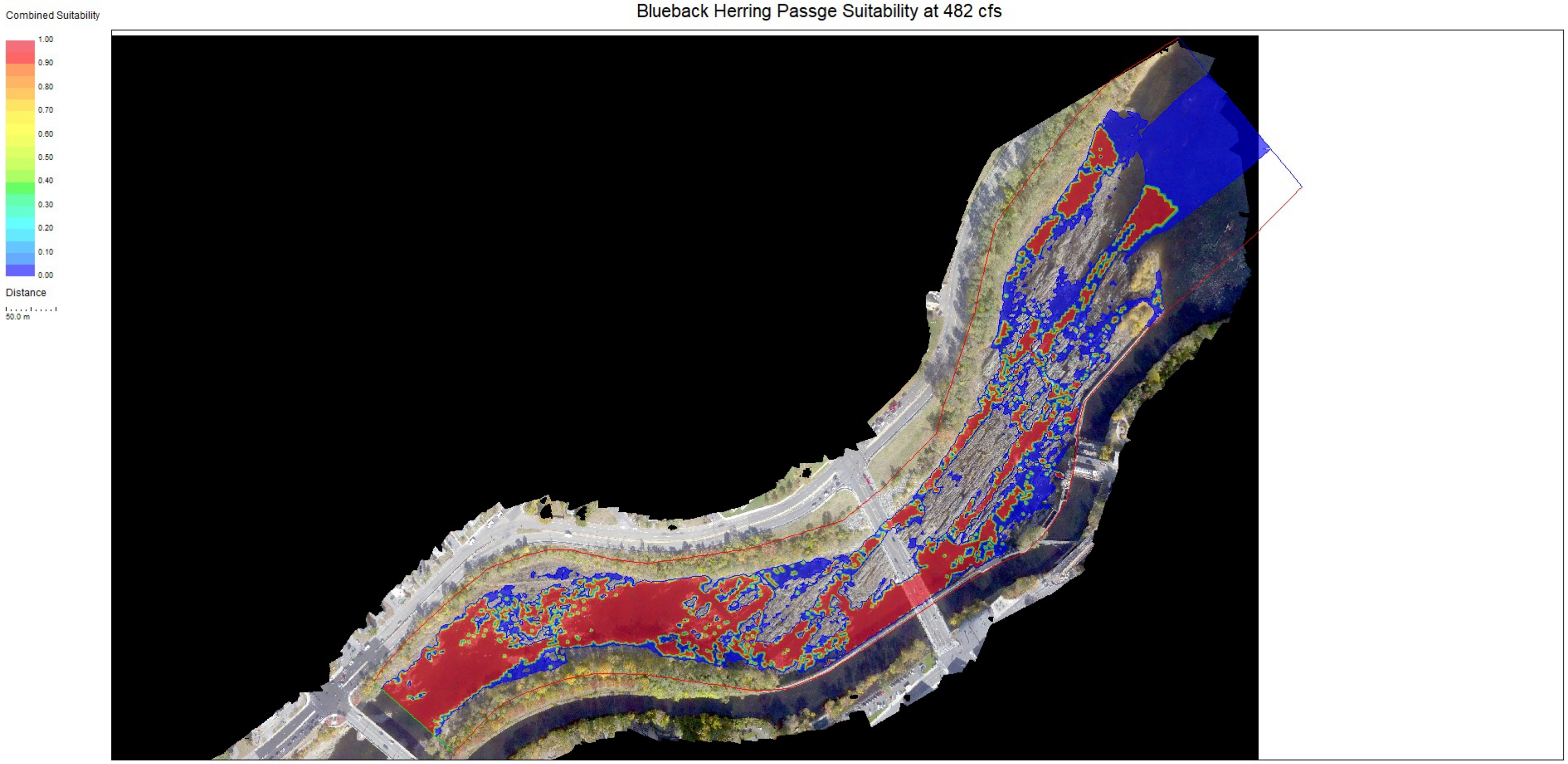
Note: Velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.



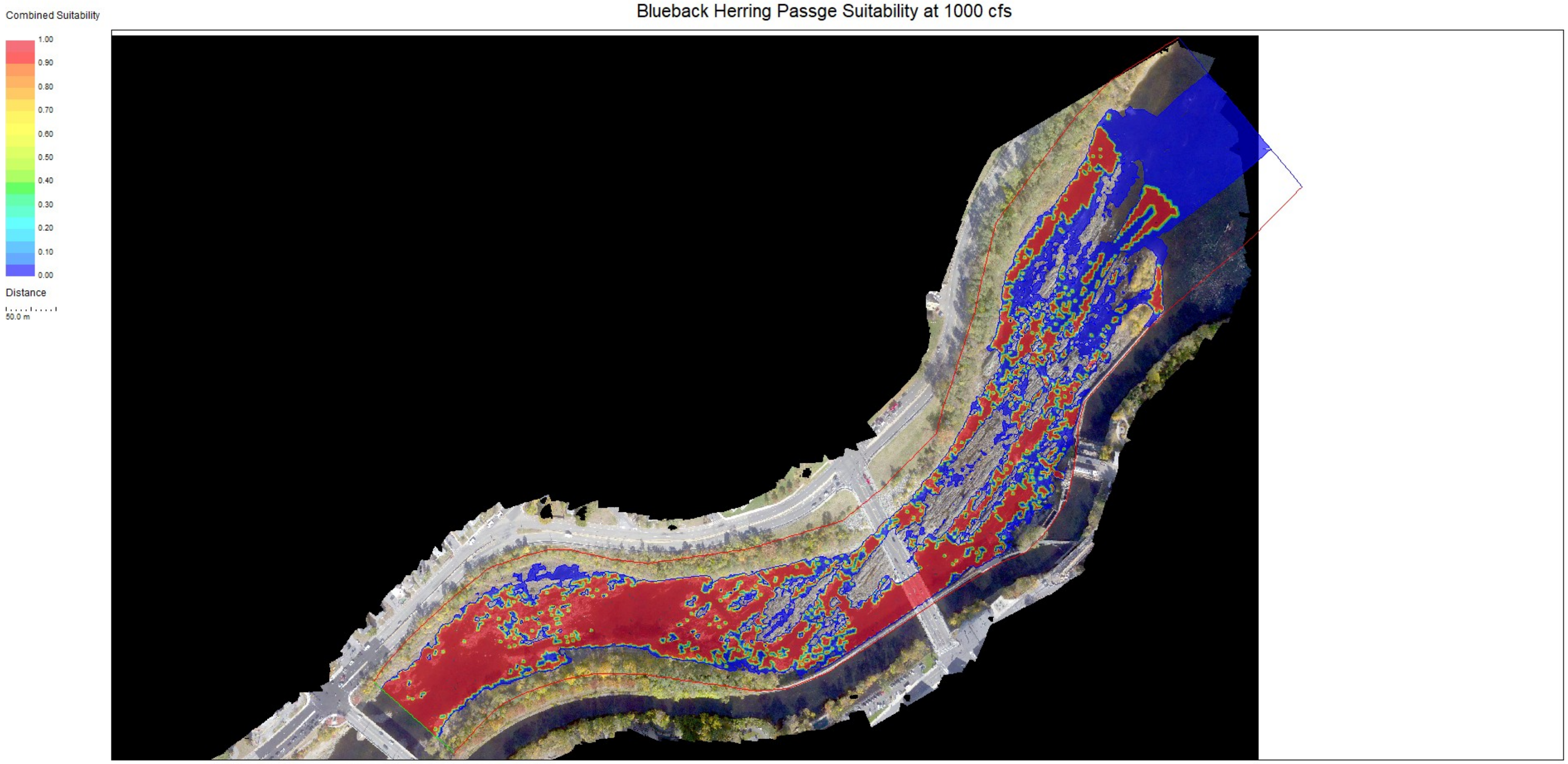
Note: Velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.



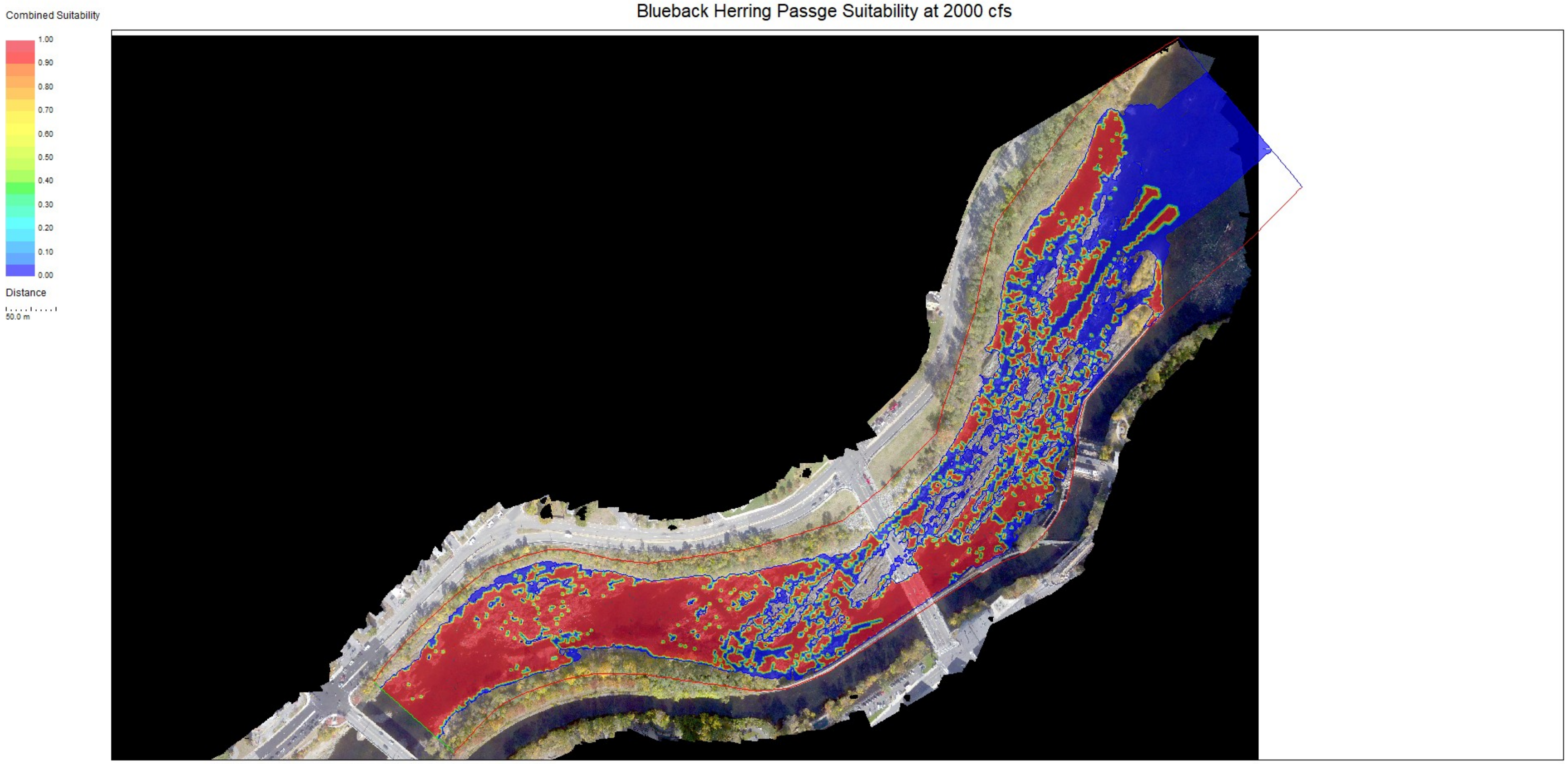
Note: Depth criteria = 1.0 ft, velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.



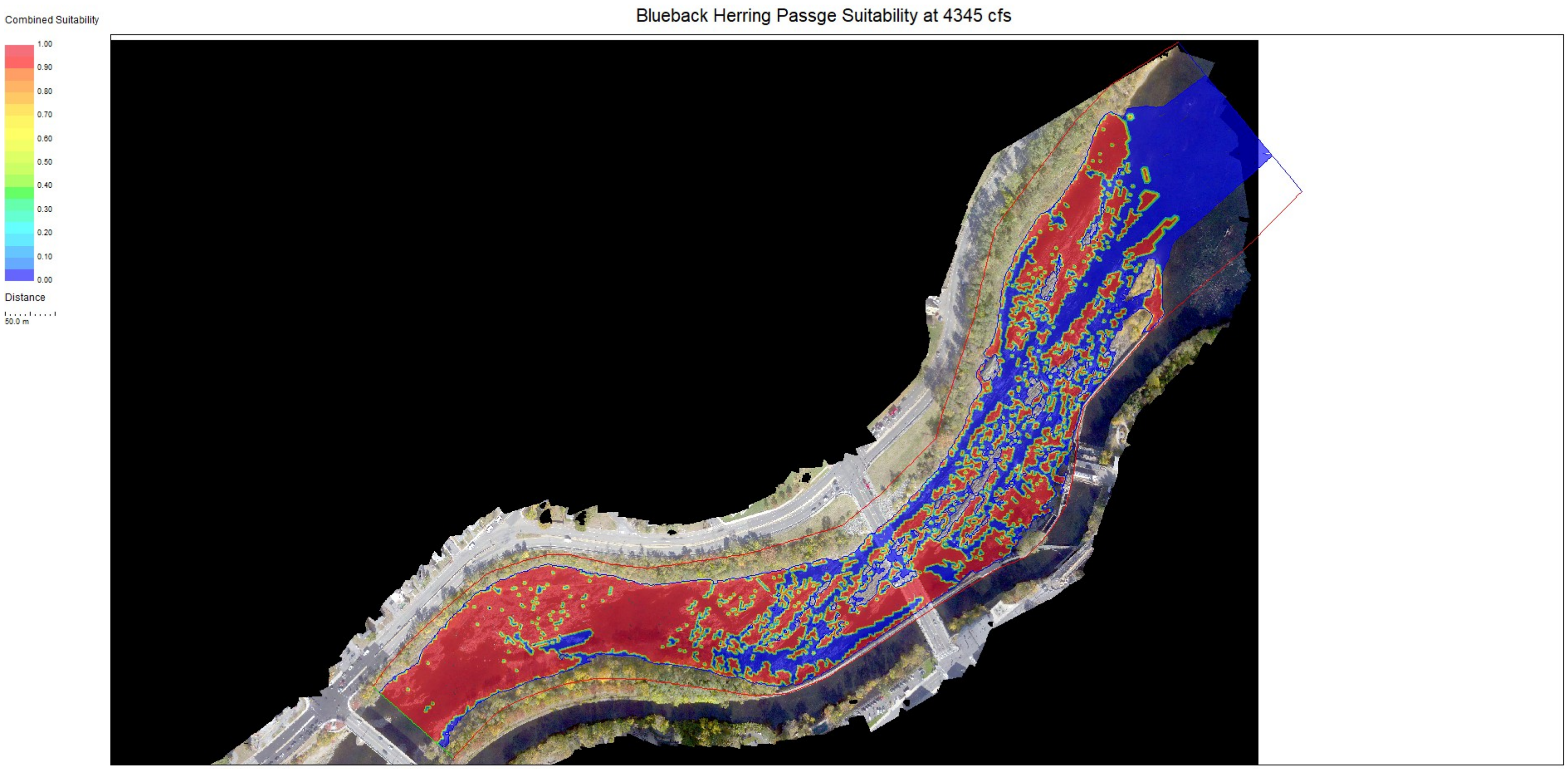
Note: Depth criteria = 1.0 ft, velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.



Note: Depth criteria = 1.0 ft, velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.

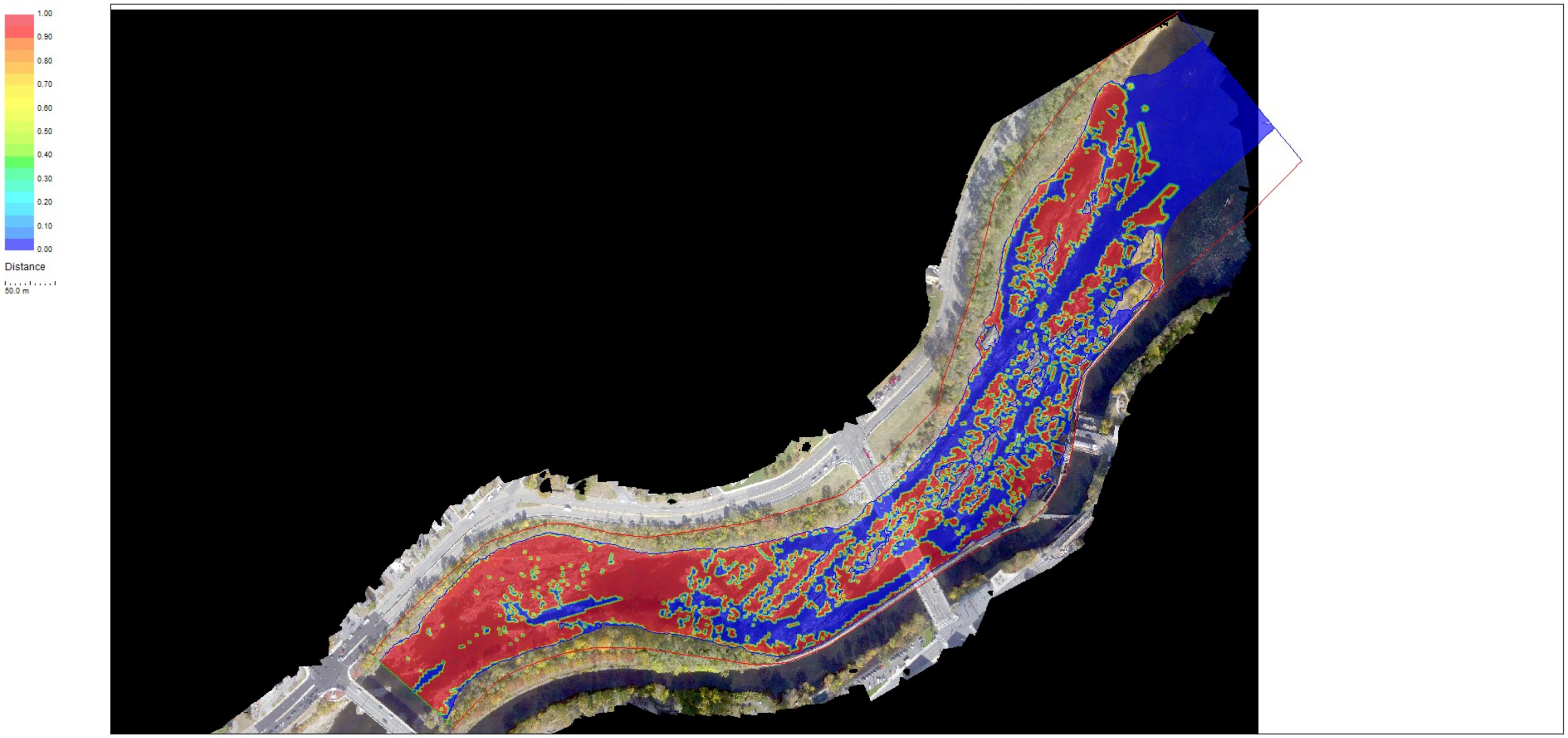


Note: Depth criteria = 1.0 ft, velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.

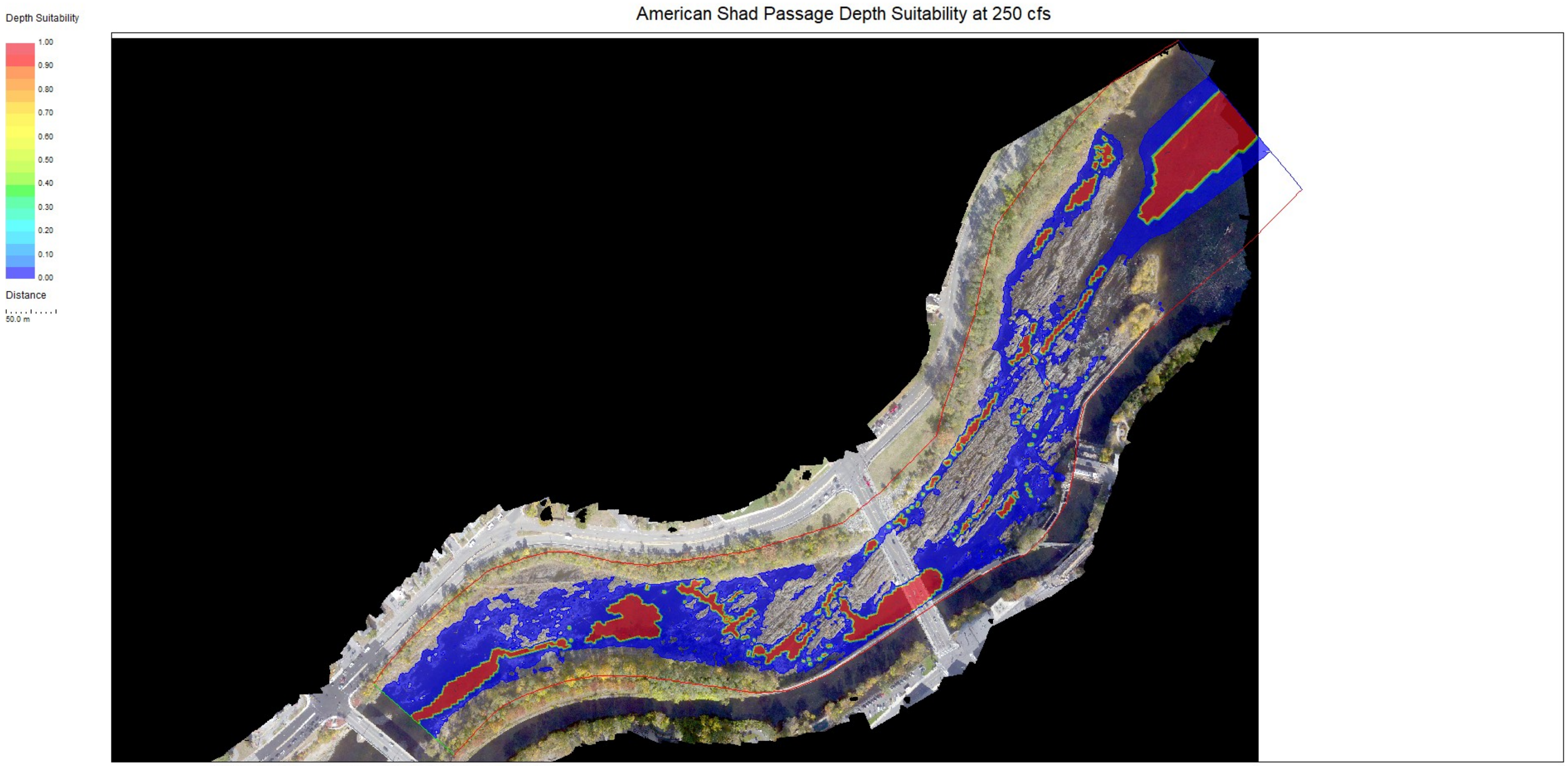


Note: Depth criteria = 1.0 ft, velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.

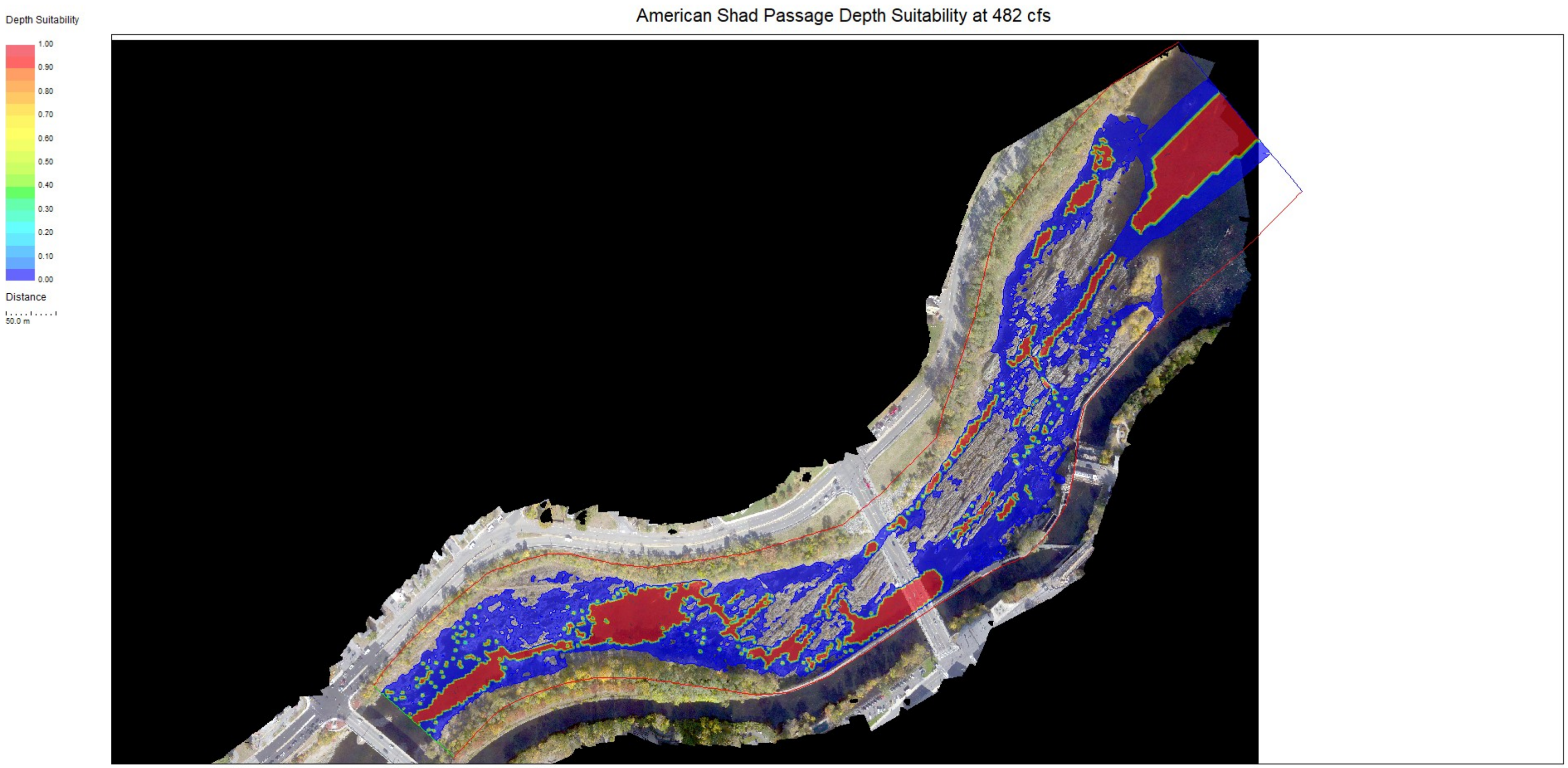
Blueback Herring Passage Suitability at 6000 cfs



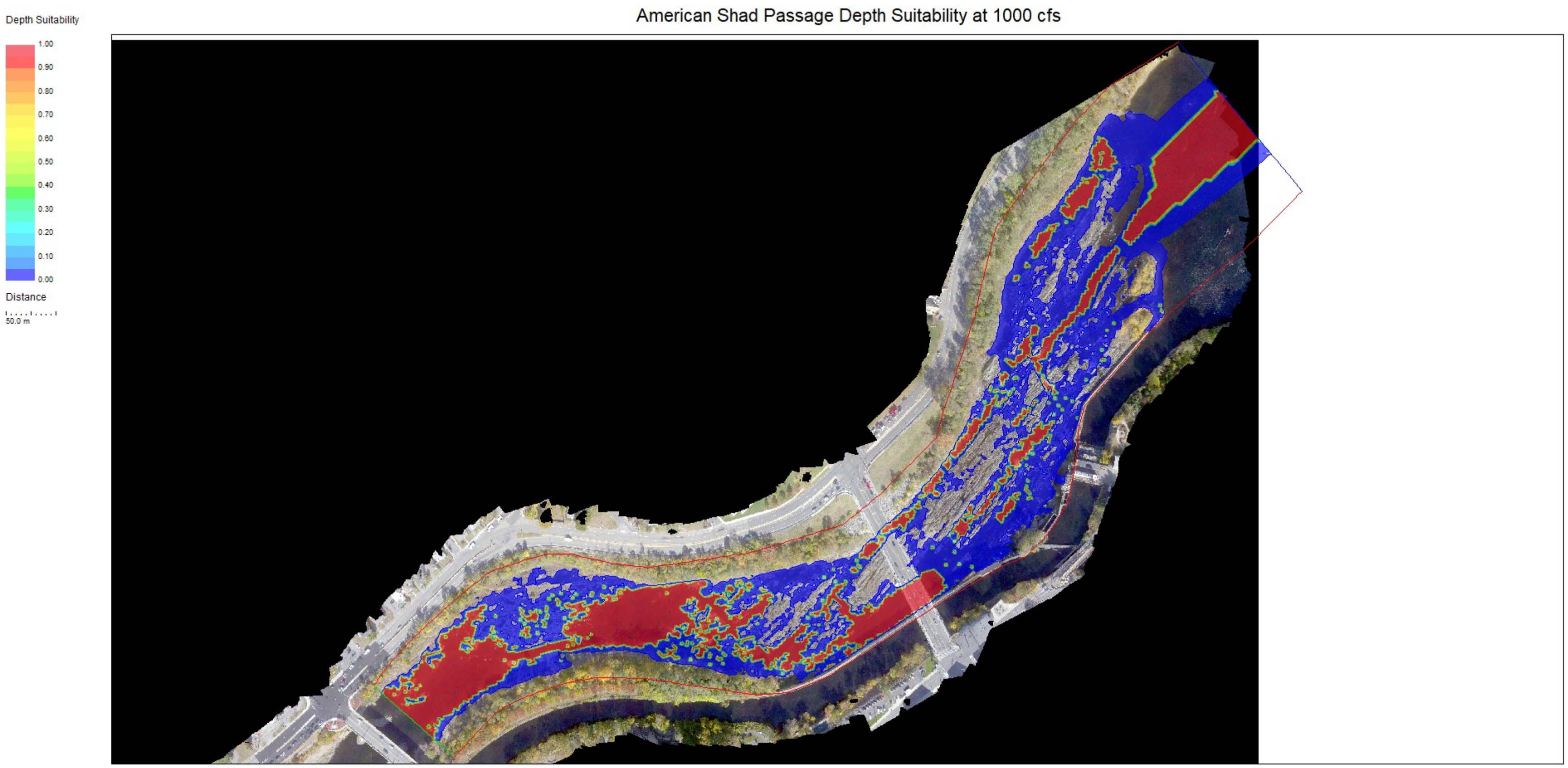
Note: Depth criteria = 1.0 ft, velocity criteria = 6.0 fps. Same criteria for blueback herring and alewife.



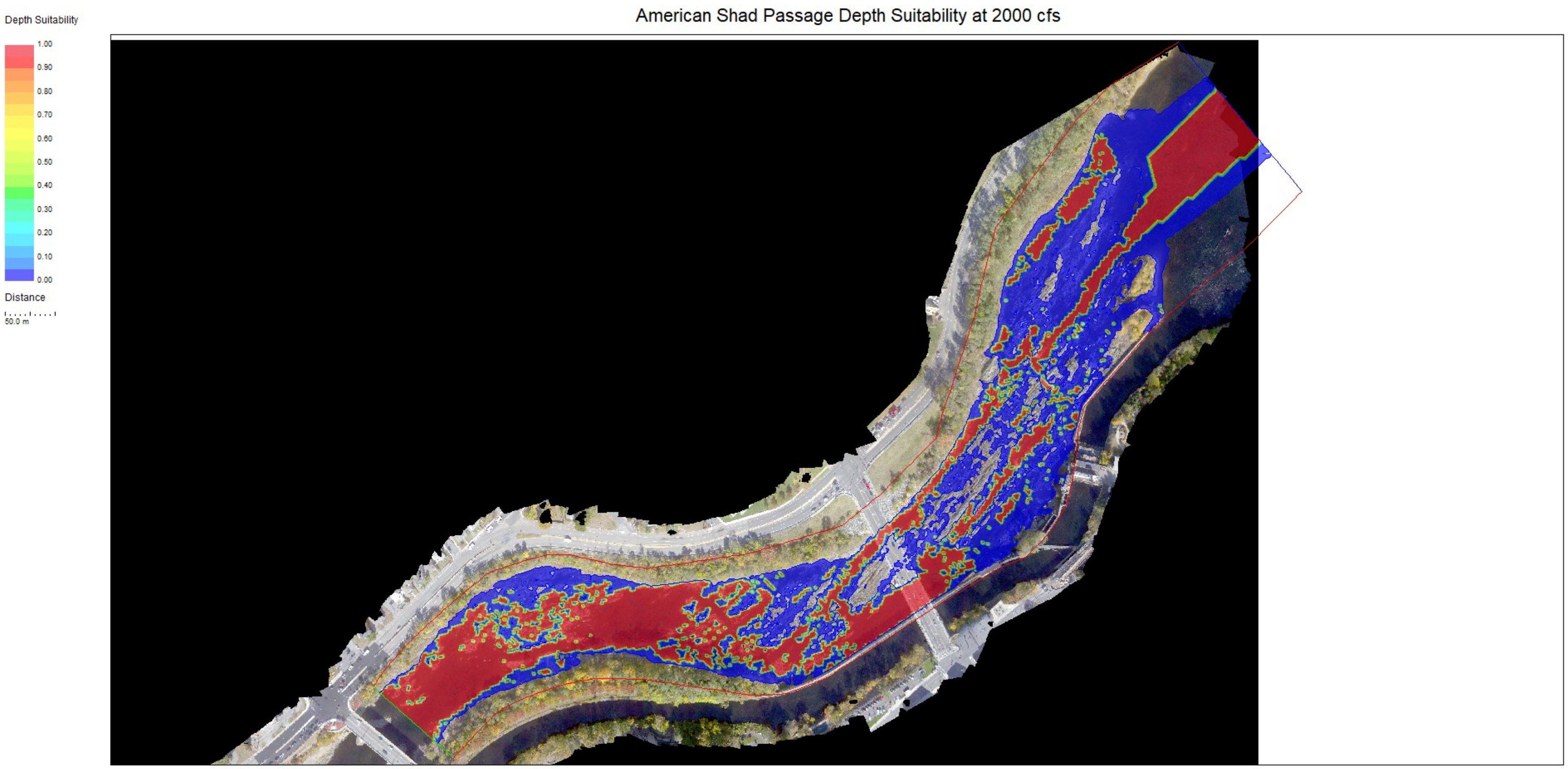
Note: Depth criteria = 2.25 ft. See the herring depth maps for shad passage using a 1.0 ft depth criteria.



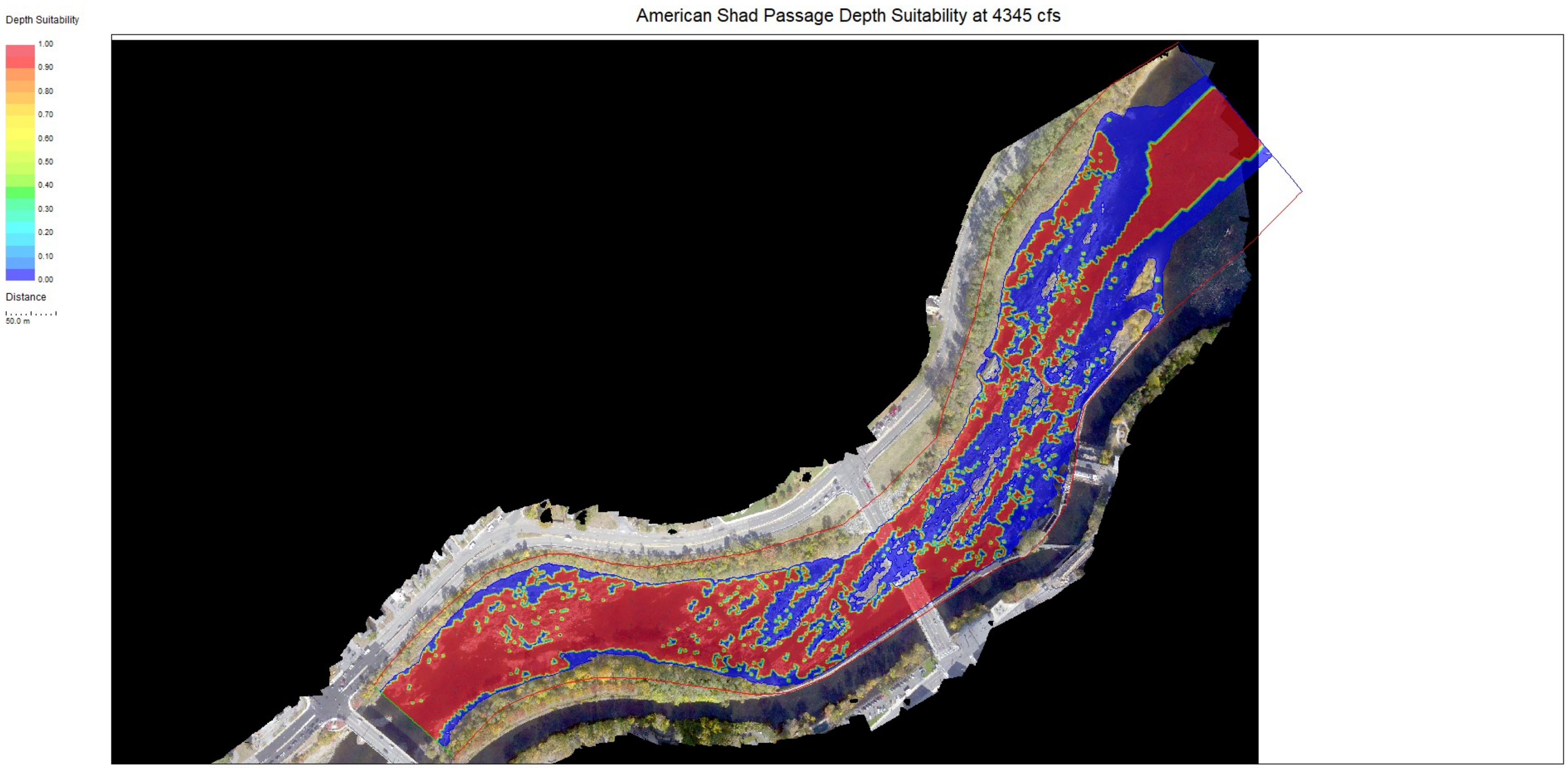
Note: Depth criteria = 2.25 ft. See the herring depth maps for shad passage using a 1.0 ft depth criteria.



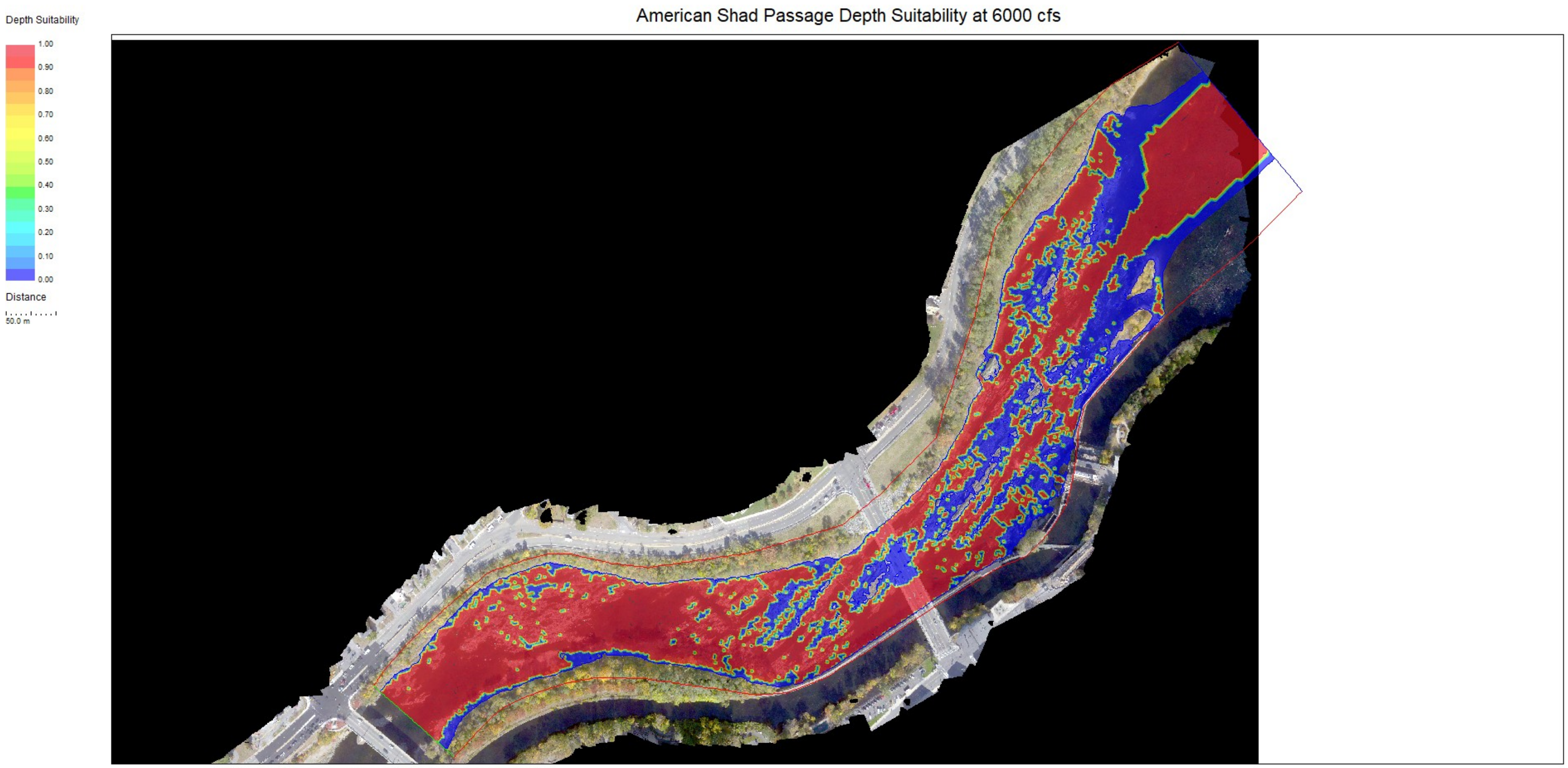
Note: Depth criteria = 2.25 ft. See the herring depth maps for shad passage using a 1.0 ft depth criteria.



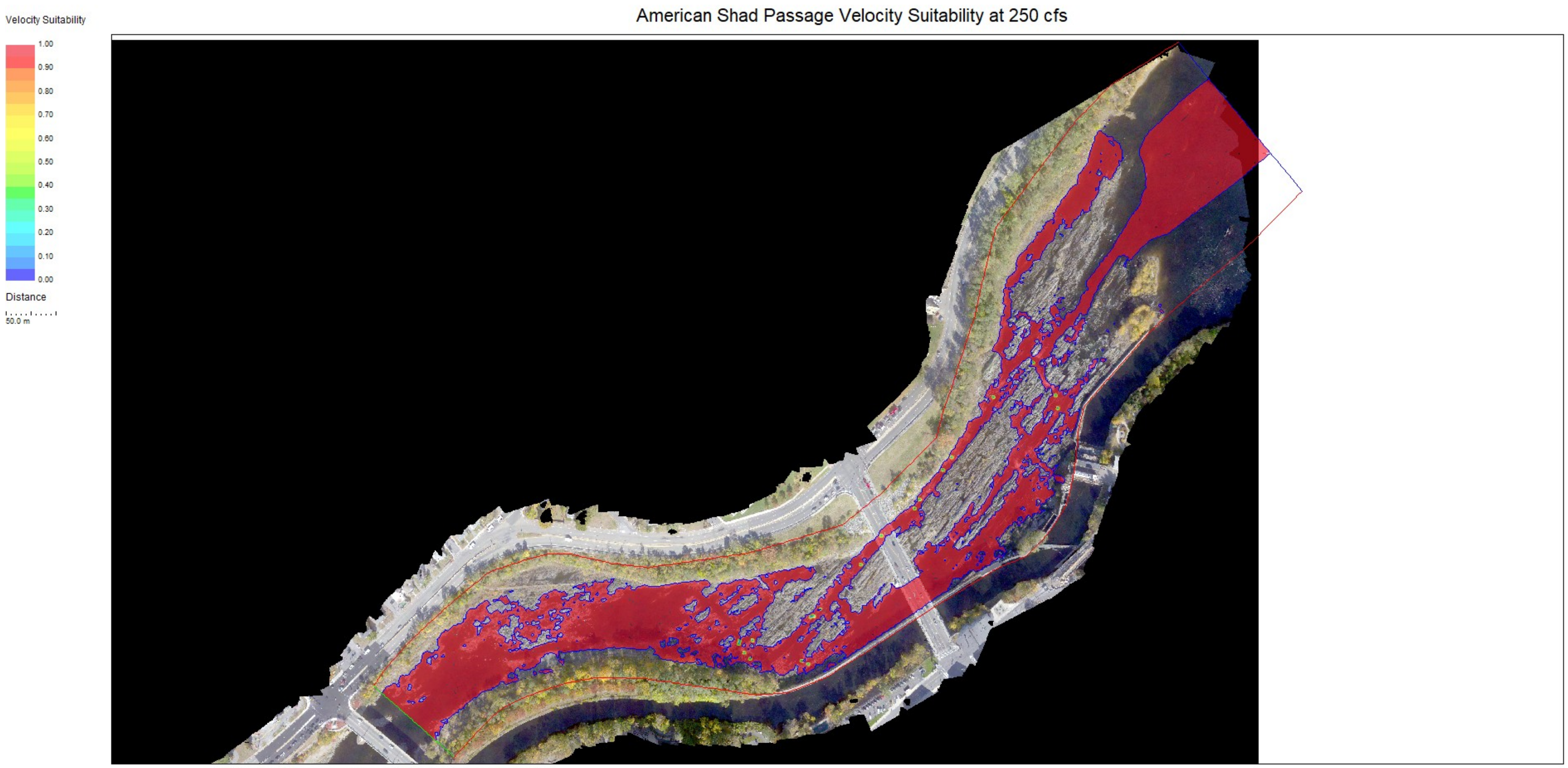
Note: Depth criteria = 2.25 ft. See the herring depth maps for shad passage using a 1.0 ft depth criteria.



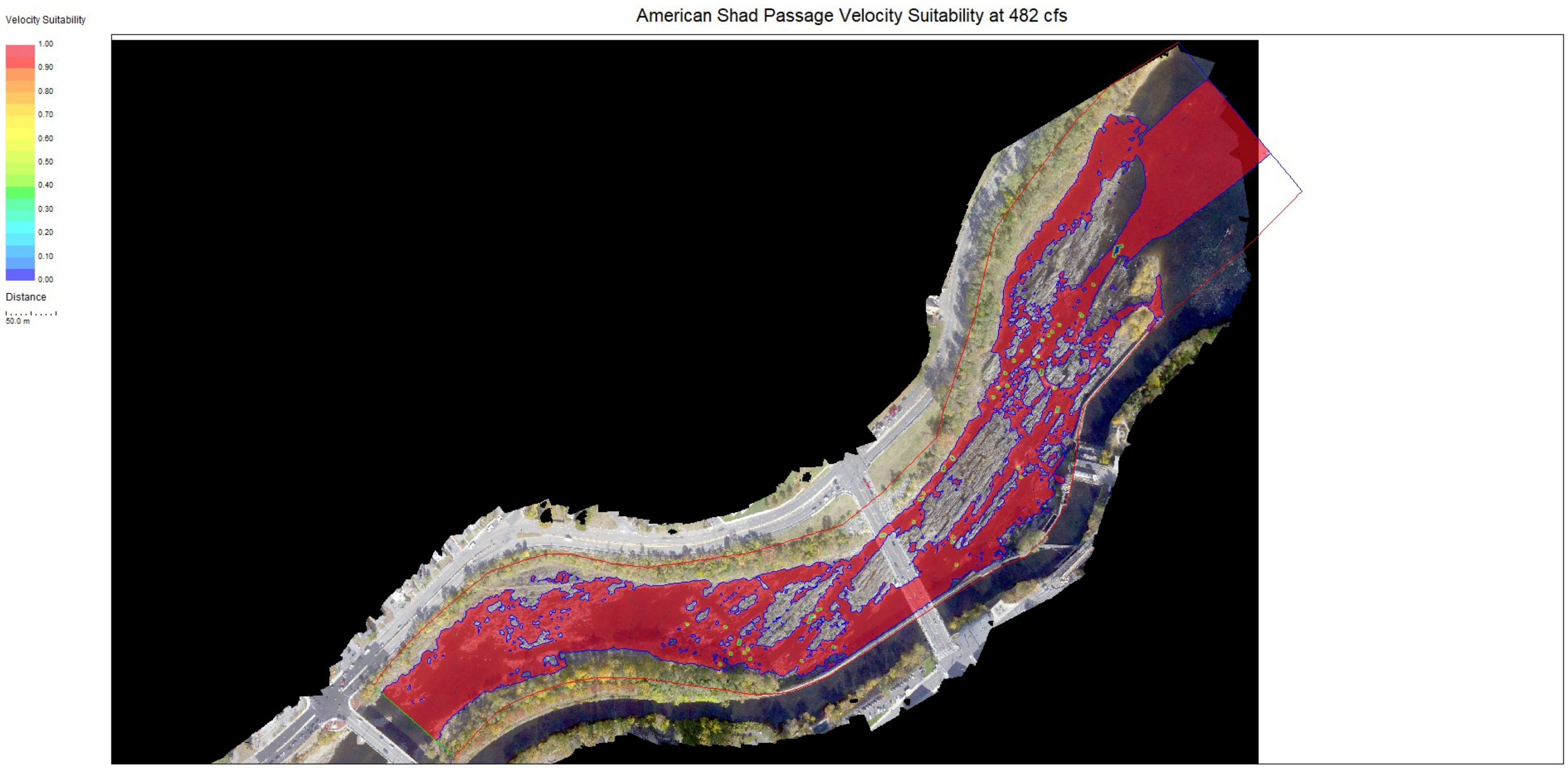
Note: Depth criteria = 2.25 ft. See the herring depth maps for shad passage using a 1.0 ft depth criteria.



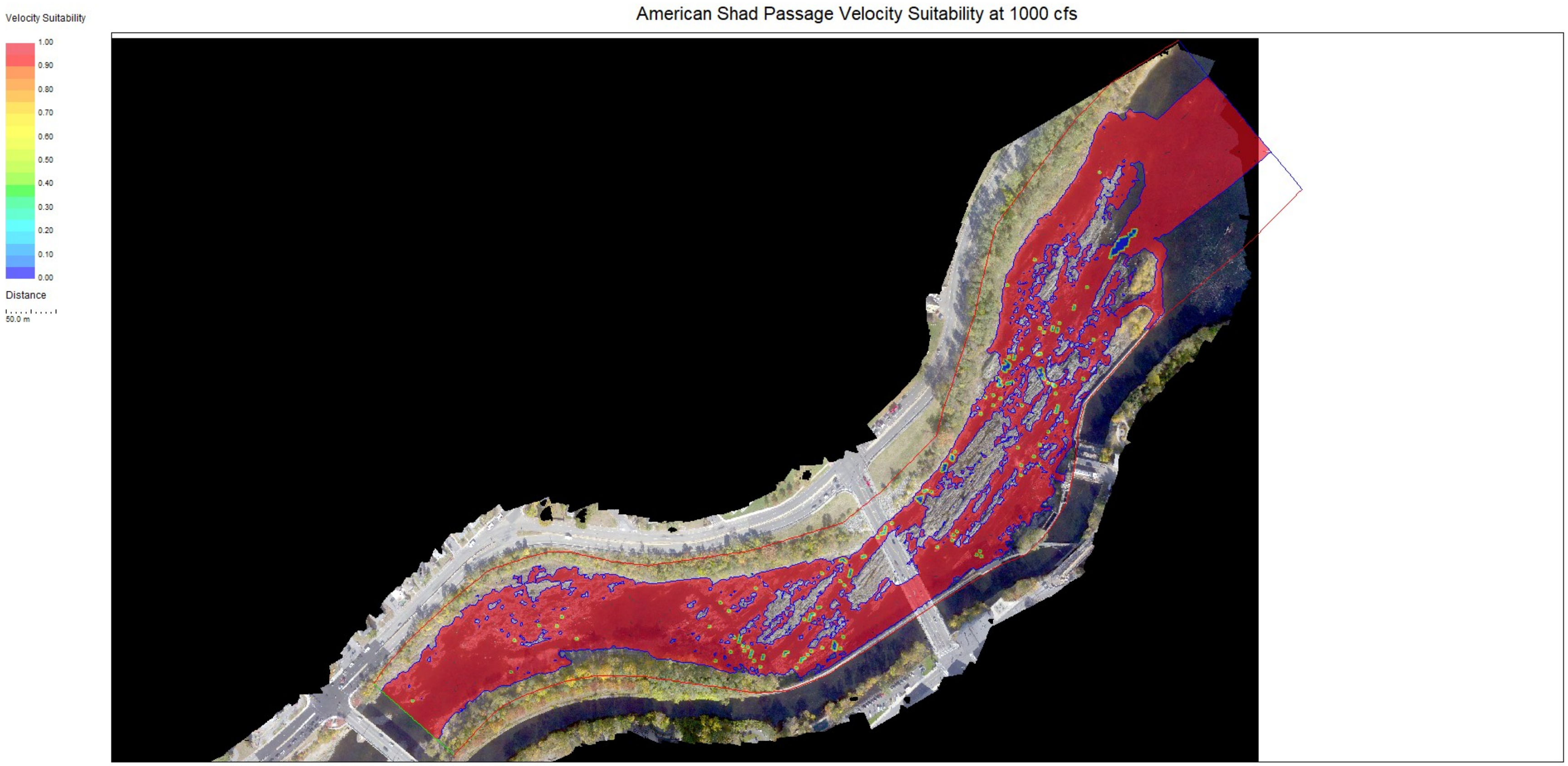
Note: Depth criteria = 2.25 ft. See the herring depth maps for shad passage using a 1.0 ft depth criteria.



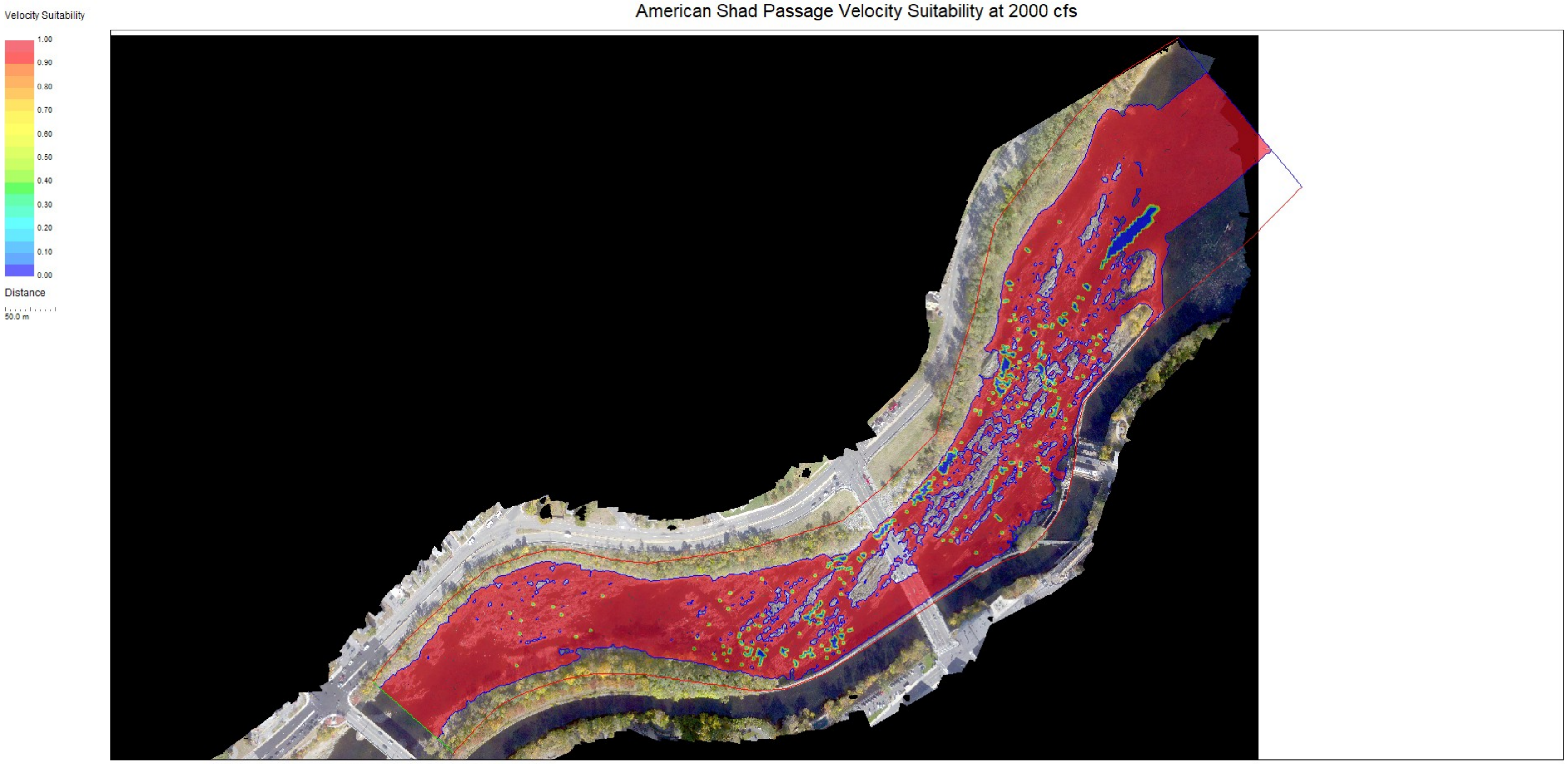
Note: Velocity criteria = 8.25 fps.



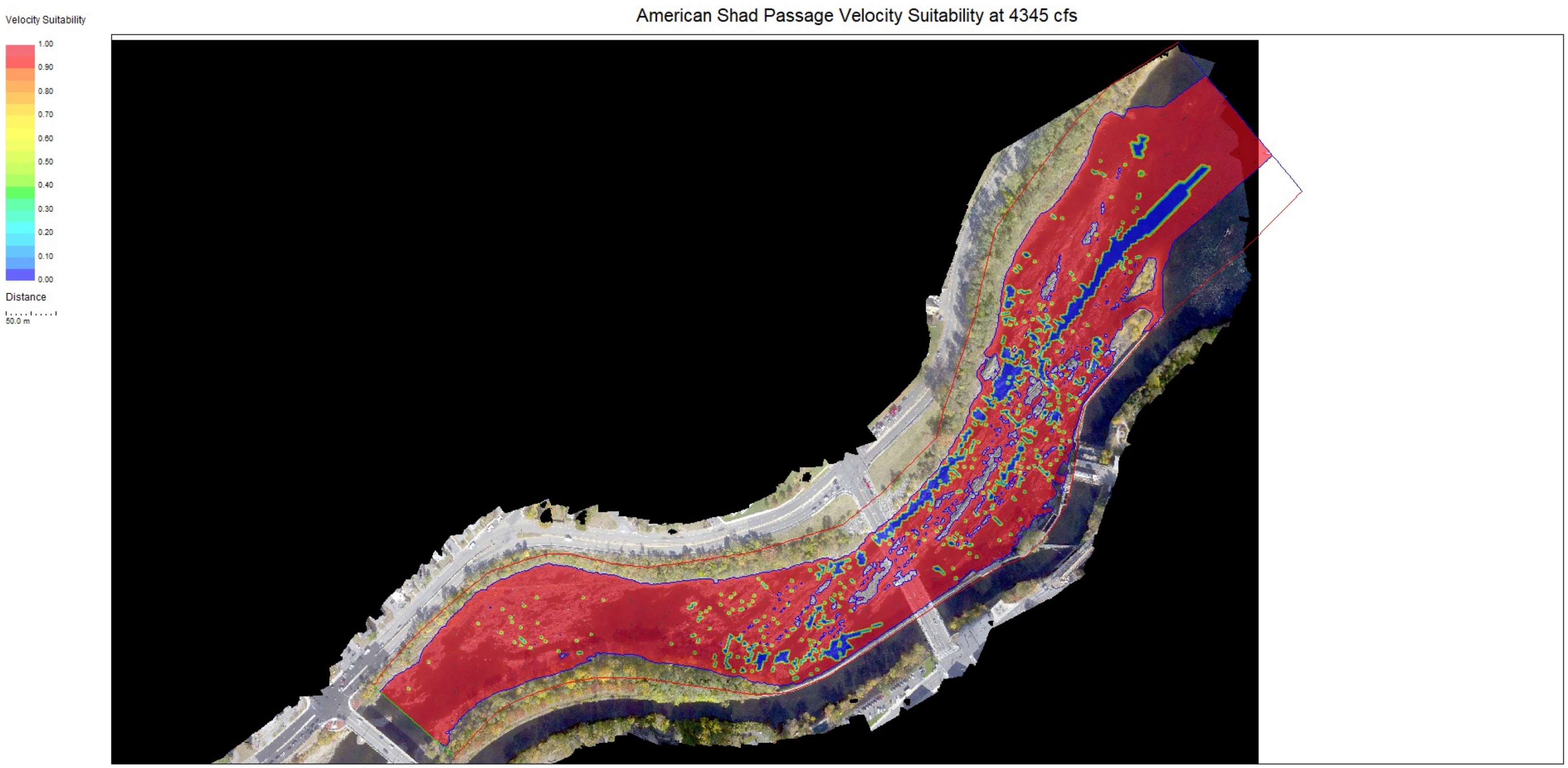
Note: Velocity criteria = 8.25 fps.



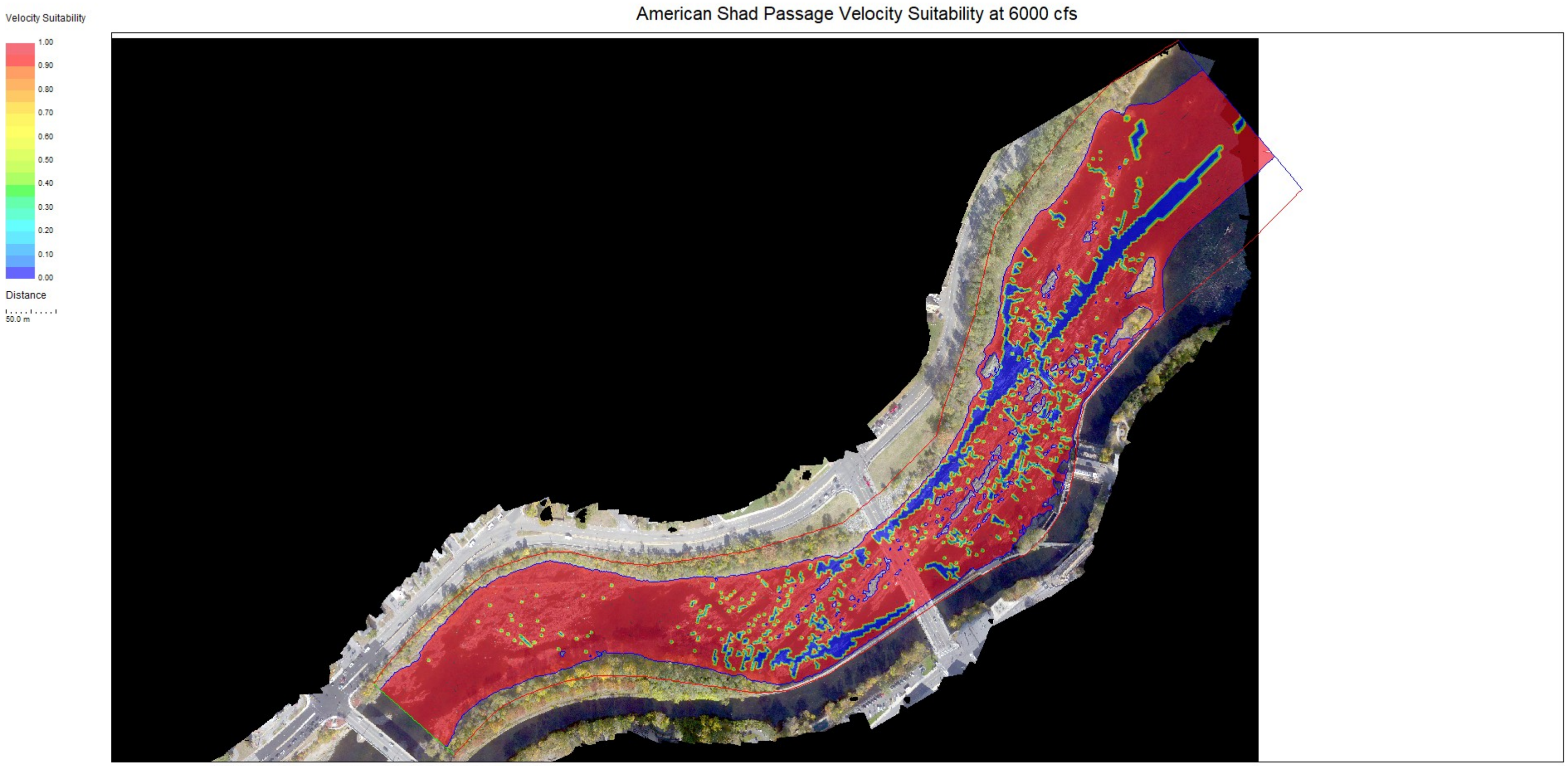
Note: Velocity criteria = 8.25 fps.



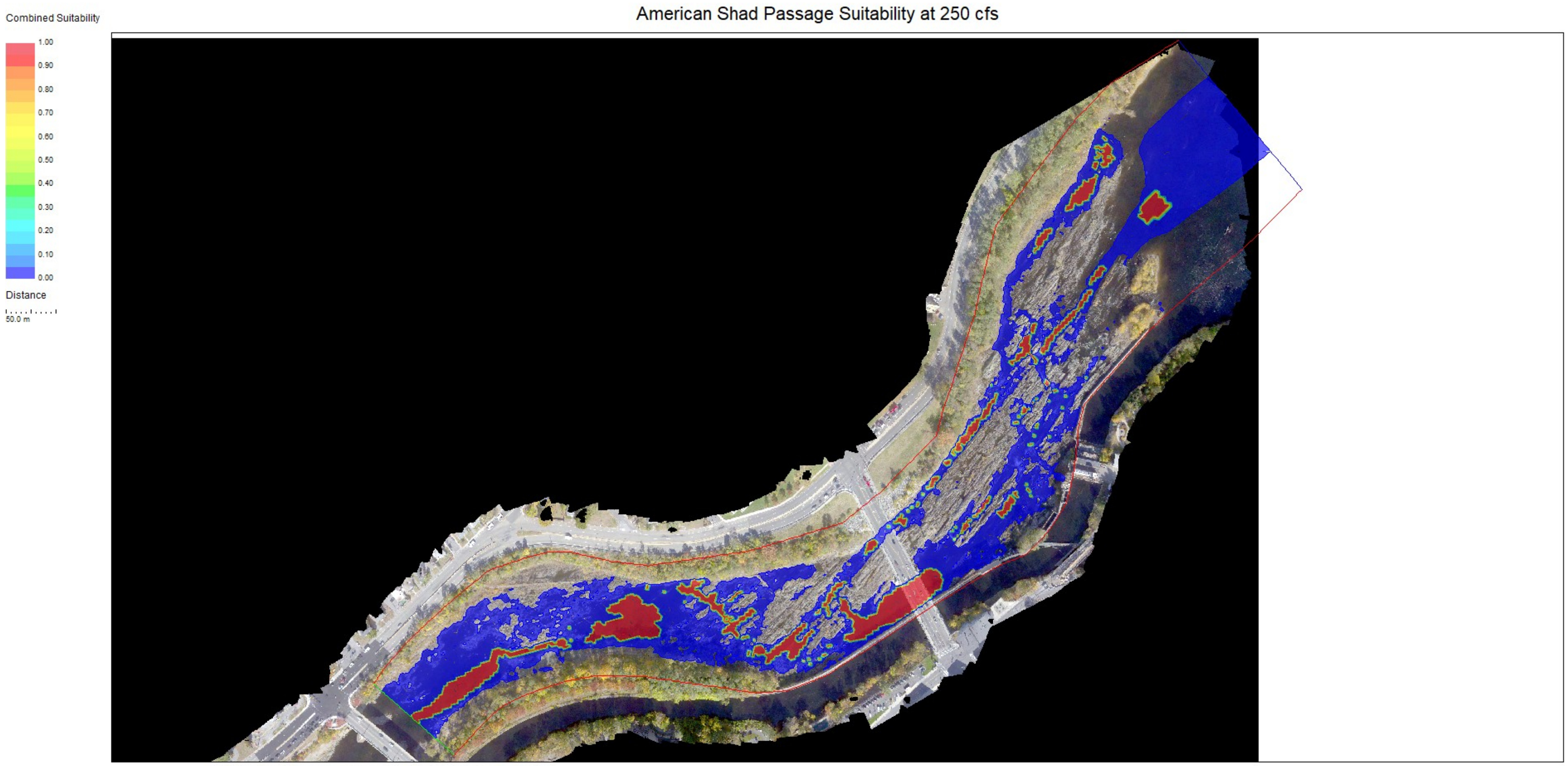
Note: Velocity criteria = 8.25 fps.



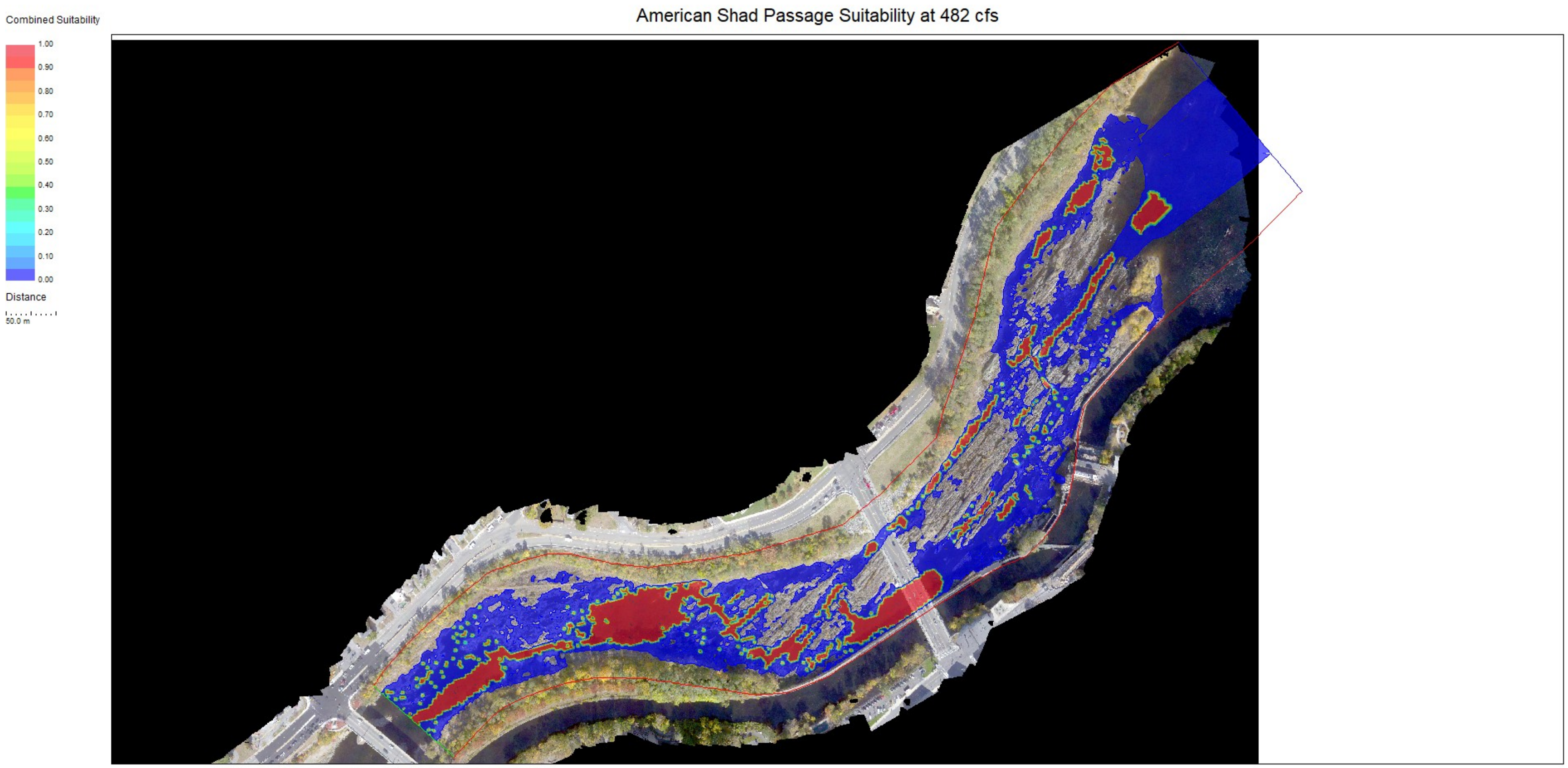
Note: Velocity criteria = 8.25 fps.



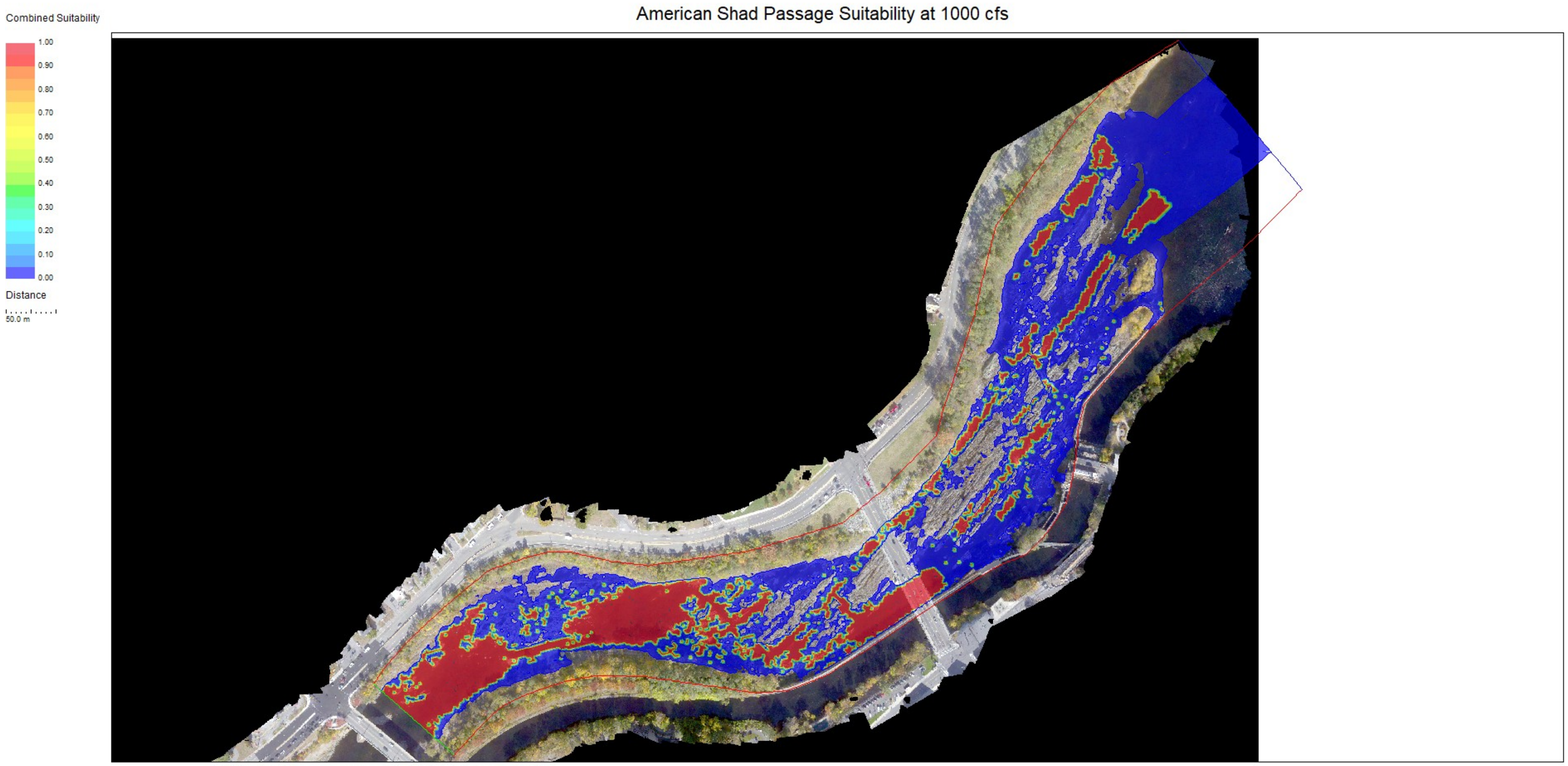
Note: Velocity criteria = 8.25 fps.



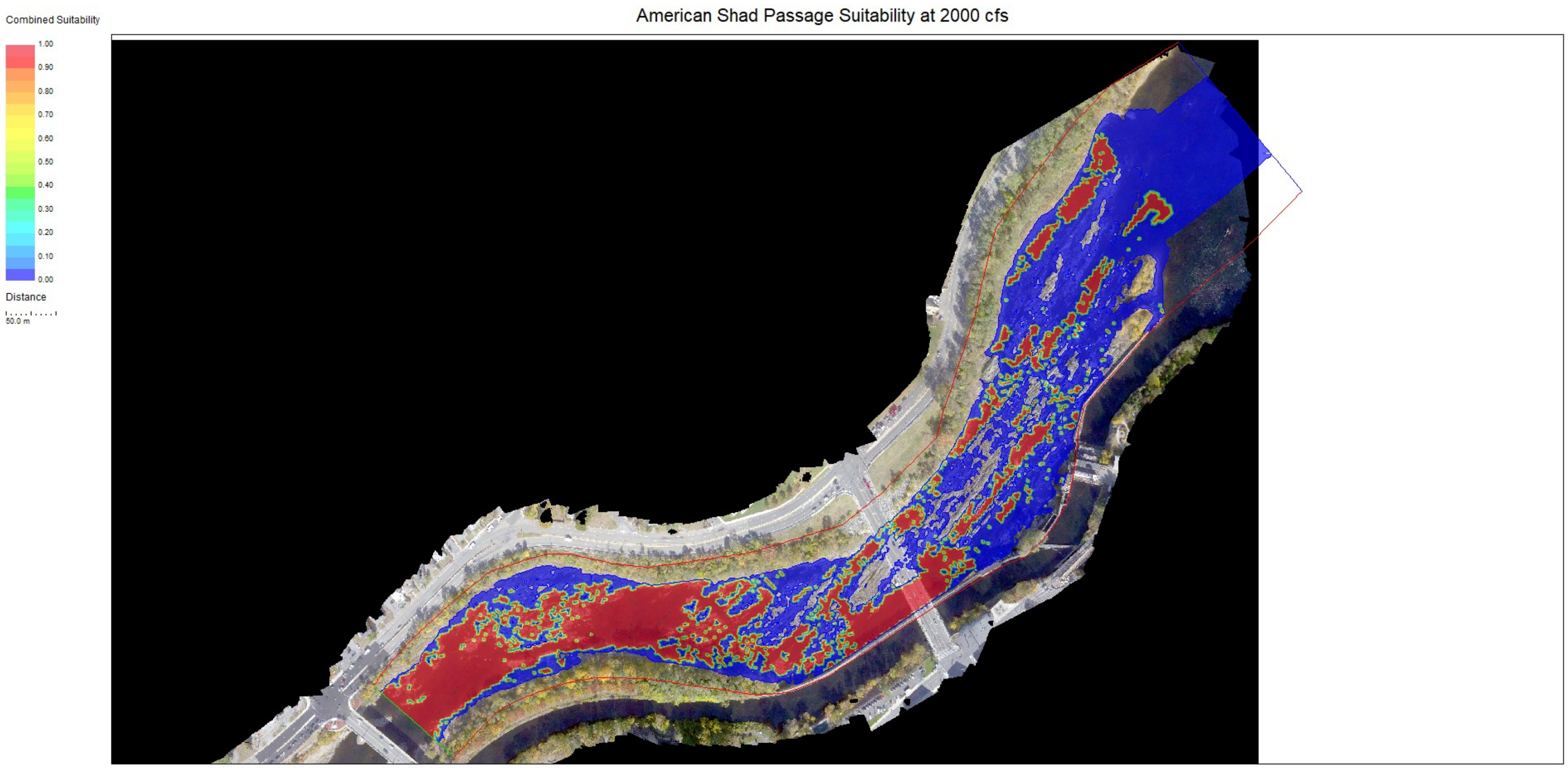
Note: Depth criteria = 2.25 ft, velocity criteria = 8.25 fps.



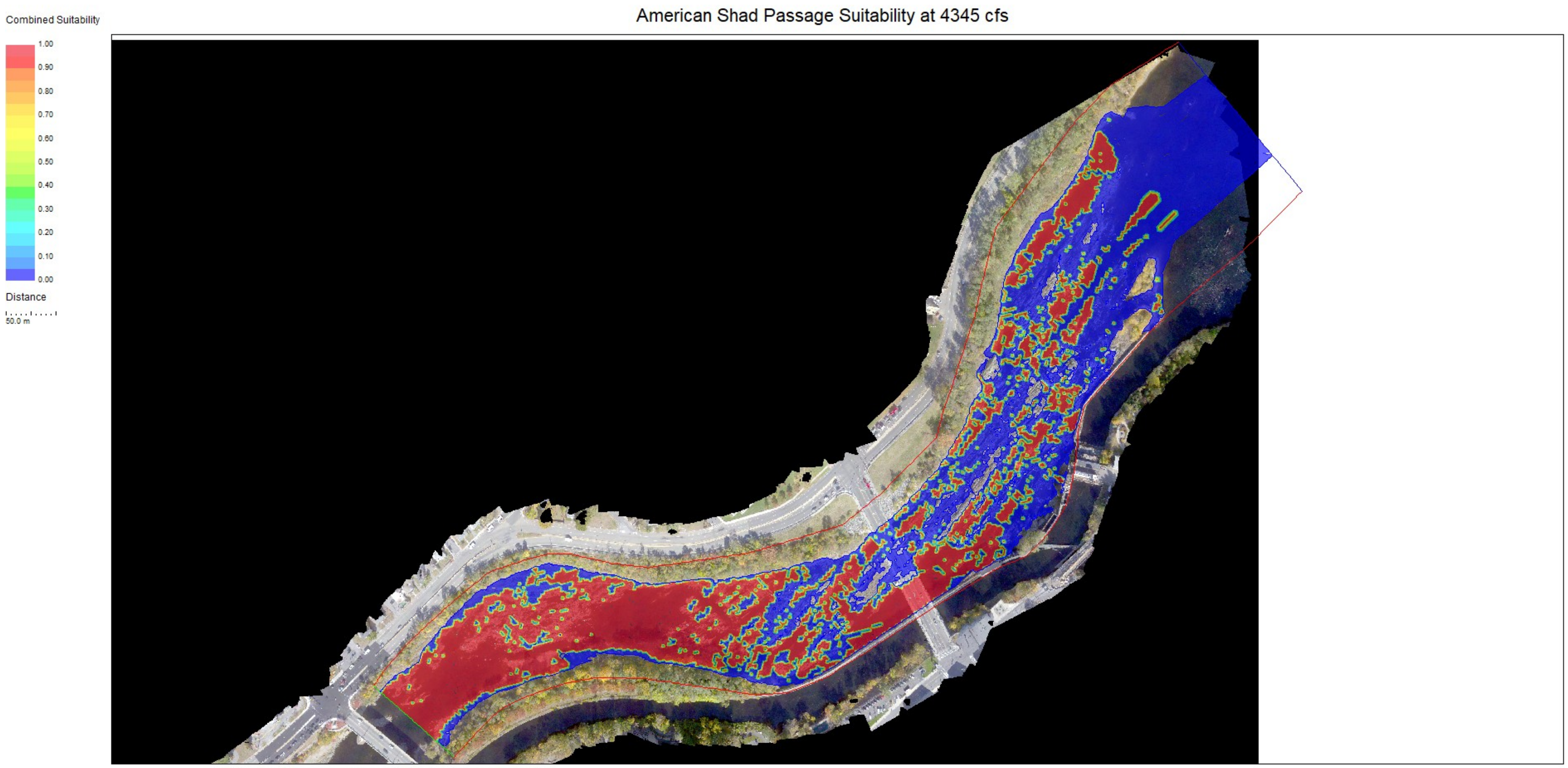
Note: Depth criteria = 2.25 ft, velocity criteria = 8.25 fps.



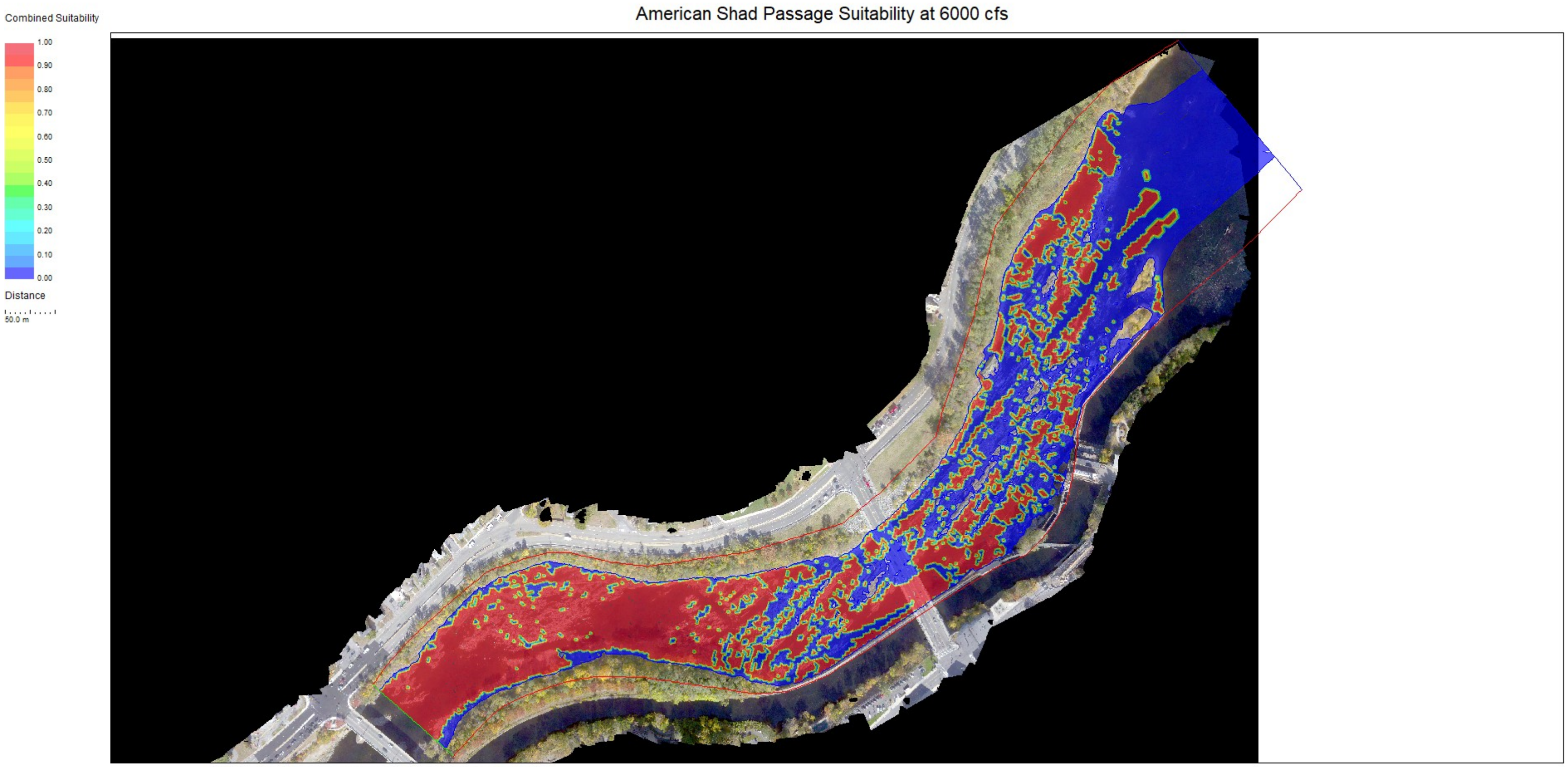
Note: Depth criteria = 2.25 ft, velocity criteria = 8.25 fps.



Note: Depth criteria = 2.25 ft, velocity criteria = 8.25 fps.

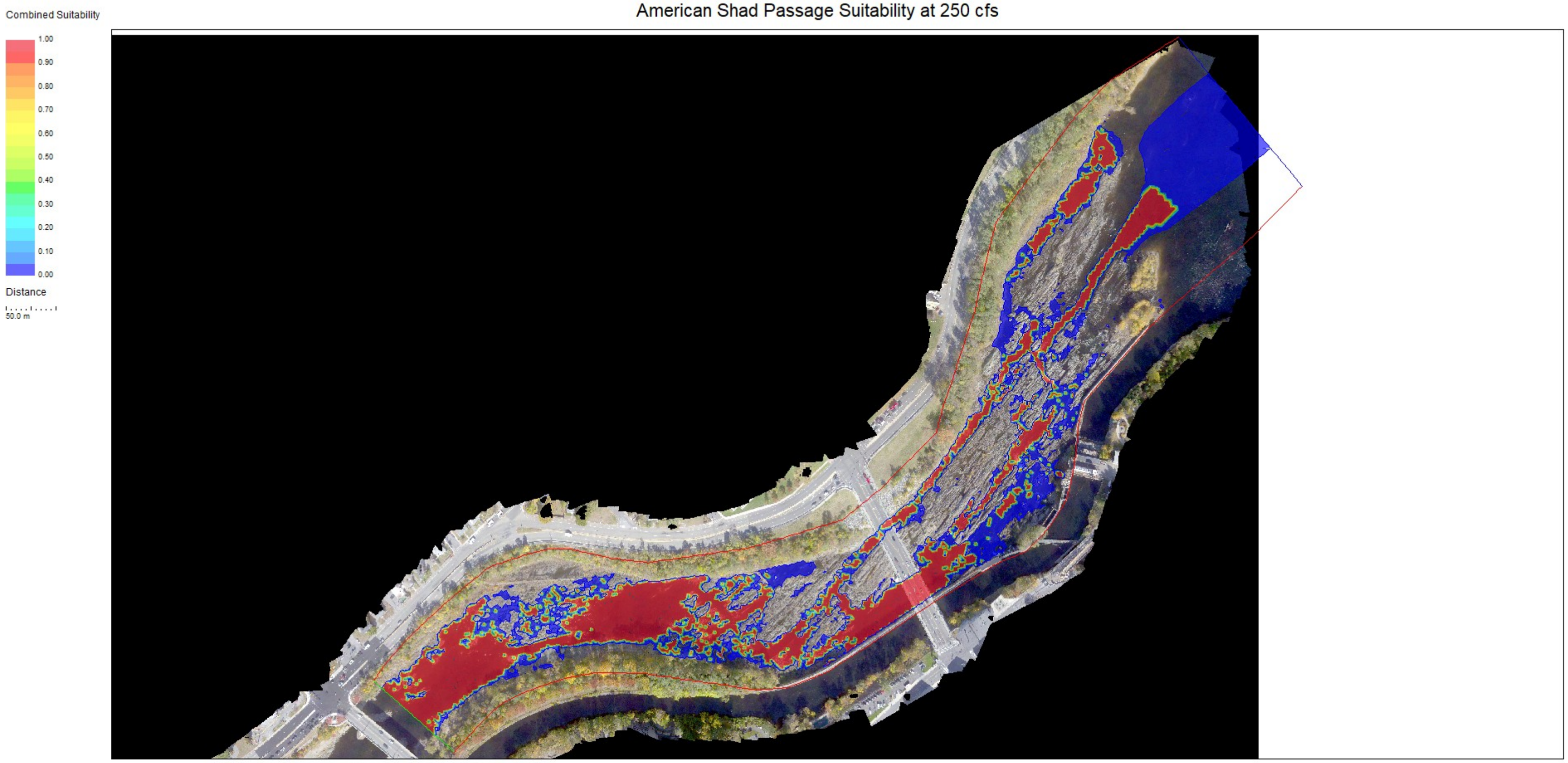


Note: Depth criteria = 2.25 ft, velocity criteria = 8.25 fps.

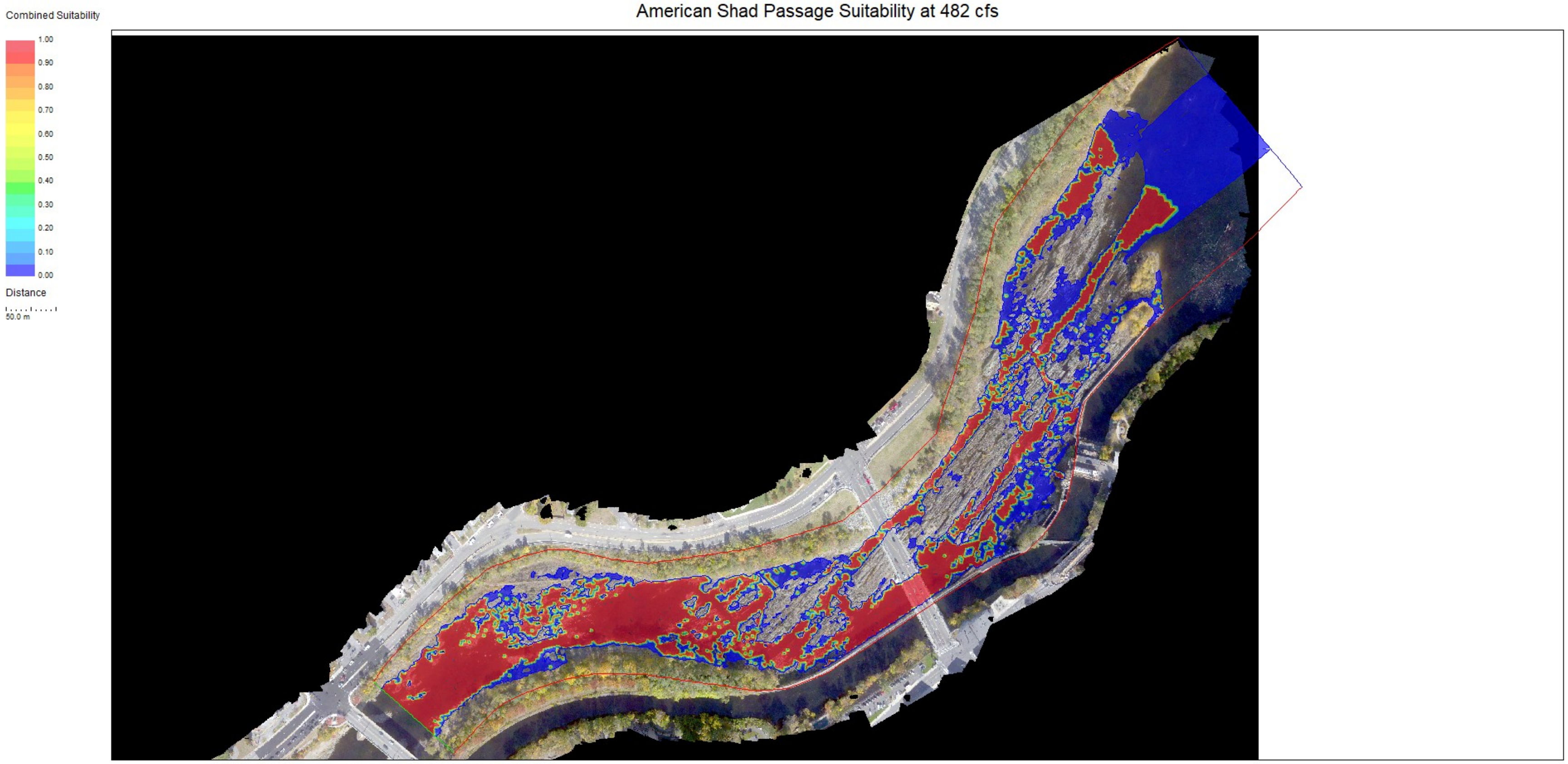


Note: Depth criteria = 2.25 ft, velocity criteria = 8.25 fps.

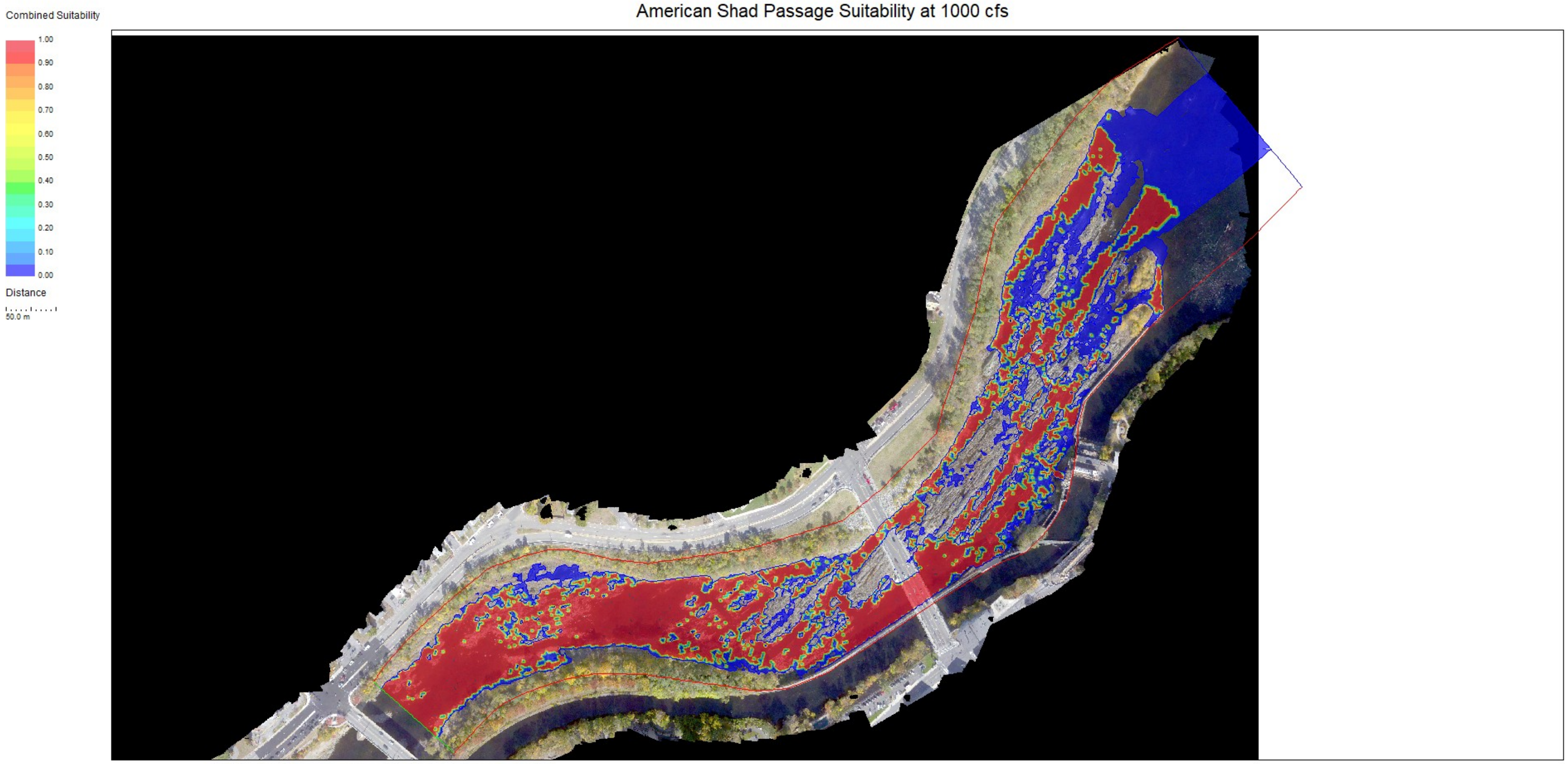
American Shad Passage Suitability at 250 cfs



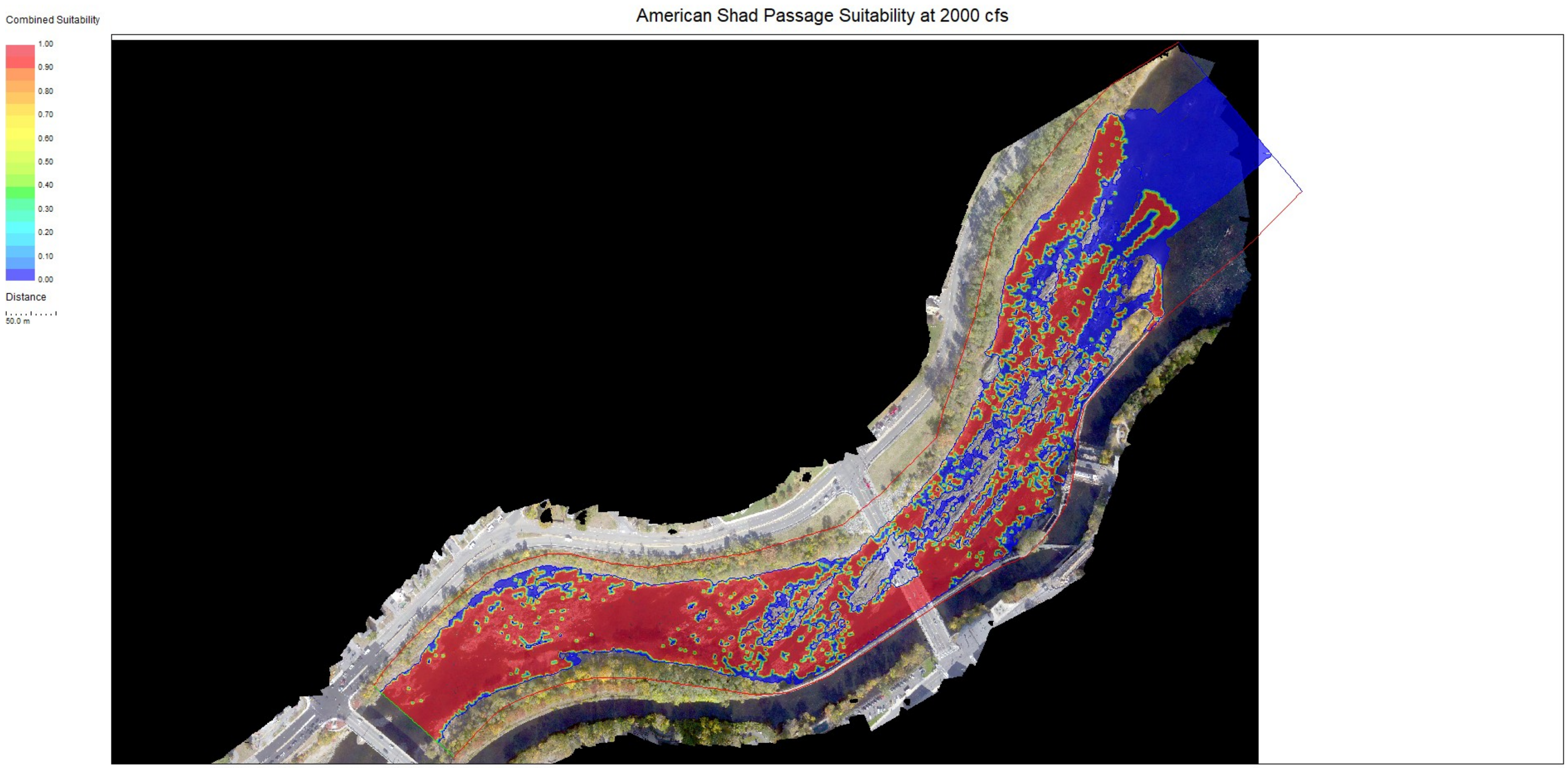
Note: Depth criteria = 1.0 ft, velocity criteria = 8.25 fps. See herring map for depth-only suitability (using 1.0 ft) and the previous maps for shad velocity-only passage.



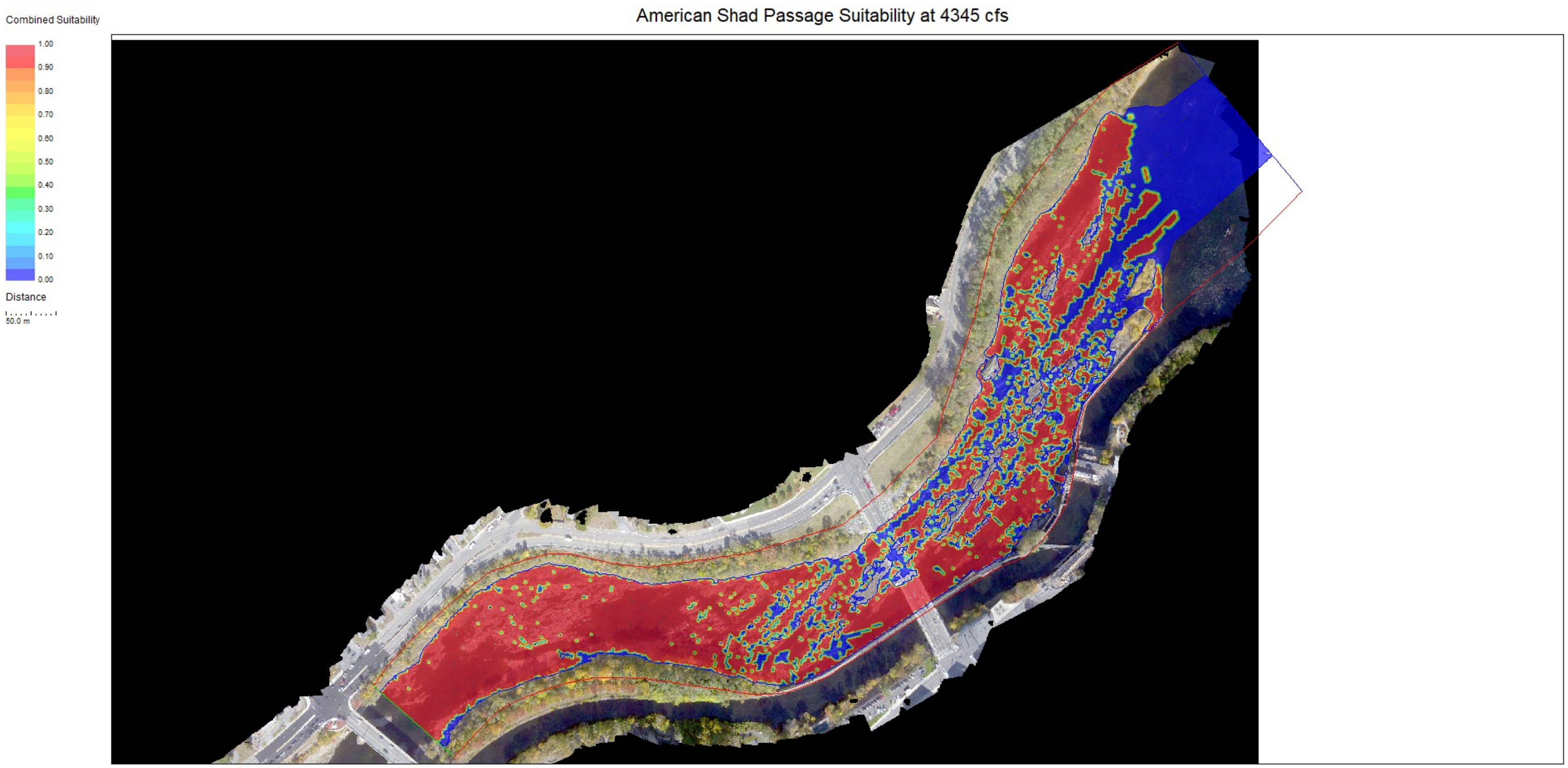
Note: Depth criteria = 1.0 ft, velocity criteria = 8.25 fps. See herring map for depth-only suitability (using 1.0 ft) and the previous maps for shad velocity-only passage.



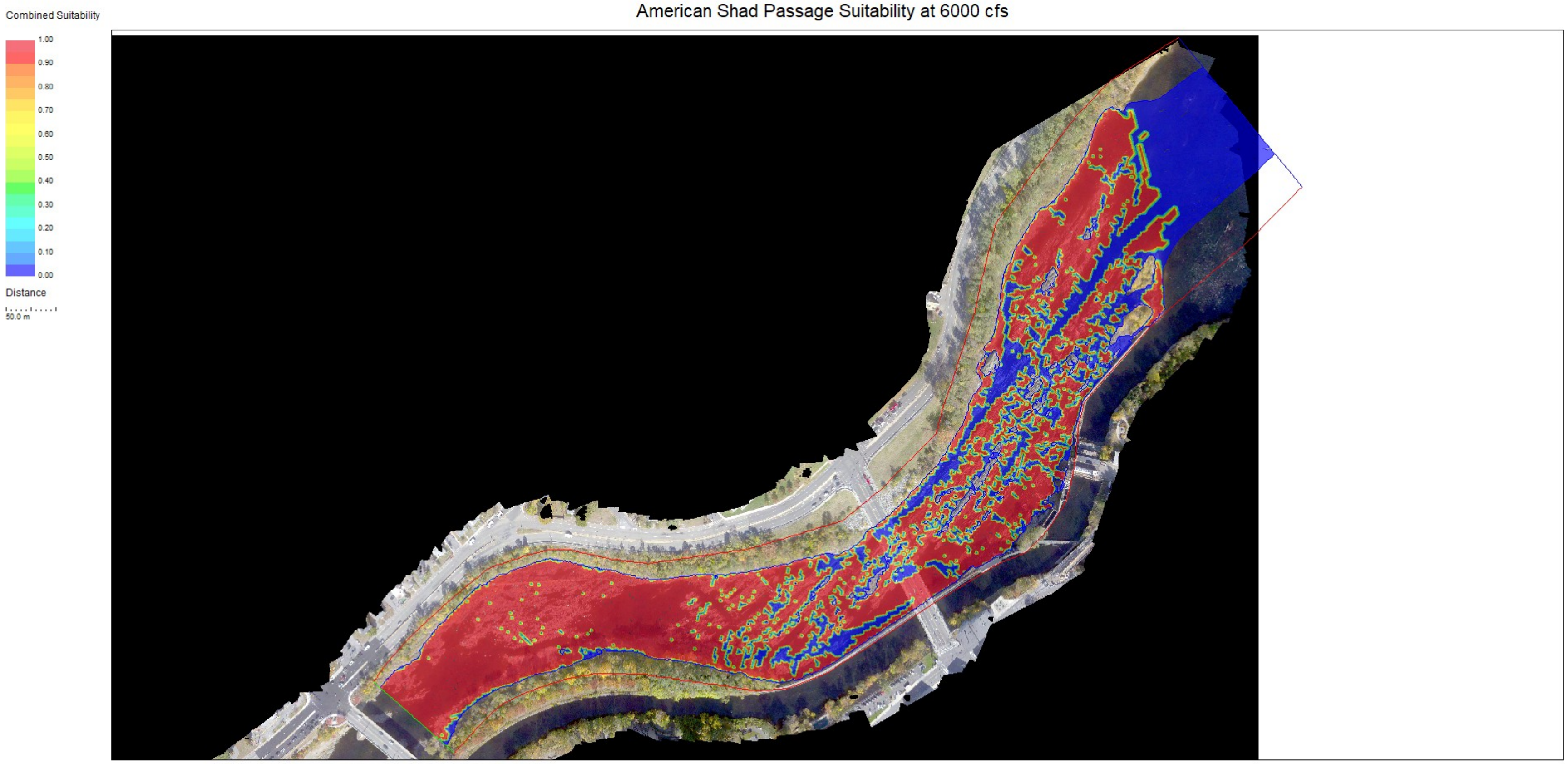
Note: Depth criteria = 1.0 ft, velocity criteria = 8.25 fps. See herring map for depth-only suitability (using 1.0 ft) and the previous maps for shad velocity-only passage.



Note: Depth criteria = 1.0 ft, velocity criteria = 8.25 fps. See herring map for depth-only suitability (using 1.0 ft) and the previous maps for shad velocity-only passage.



Note: Depth criteria = 1.0 ft, velocity criteria = 8.25 fps. See herring map for depth-only suitability (using 1.0 ft) and the previous maps for shad velocity-only passage.



Note: Depth criteria = 1.0 ft, velocity criteria = 8.25 fps. See herring map for depth-only suitability (using 1.0 ft) and the previous maps for shad velocity-only passage.