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APPENDIX E: 1-DIMENSIONAL HYDRAULIC MODEL PREPERATION, CALIBRATION, AND STREAMFLOW–HABITAT RELATIONSHIPS FOR THE UPPER SOUTH FORK SPROUL CREEK STUDY REACH – DRAFT

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1 INTRODUCTION

This memorandum is an appendix to the *Sproul Creek Site Specific Instream Flow Study*, and describes the 1-dimensional (1-D) hydraulic model, SEFA (System for Environmental Flow Analysis), which was used to develop streamflow–habitat relationships for the Upper South Fork Sproul Creek, a tributary to the South Fork Eel River located in northern California. This appendix includes (1) model background, (2) methodology for site selection and hydraulic and structural data collection for model input, (3) selection of habitat suitability indices, and (4) model development and calibration to be used in the modeling of streamflow–habitat relationships for specific life history stages of steelhead (*Oncorhynchus mykiss*), Coho Salmon (*O. kisutch)*, and Chinook Salmon (*O. tshawytscha,* spawning habitat only*)*, and for productive habitat for benthic macroinvertebrates (BMI). Development of the model was an iterative process in association with Thomas Payne (Normandeau Associates and co-author of SEFA), who provided quality checks during model setup and calibration to assure robust model results. Final streamflow–habitat relationships are presented in weighted usable area (WUA, ft^2) of river as a function of streamflow. The relationships between WUA and streamflow that are developed in the SEFA model were used to aid in the establishment of bypass flow criteria for targeted species and life stages in Sproul Creek that maximize habitat availability for anadromous salmonids at critical life history times.

1.1 Targeted Species and Life Stages

The goal of the *Sproul Creek Site Specific Instream Flow Study* is to develop instream flow criteria for priority species and life stages of salmonids in the Sproul Creek watershed using empirical and modeling methods recommended by California state agencies. Flow criteria are developed for four primary freshwater life history stages: (1) adult and juvenile passage; (2) adult spawning habitat; (3) juvenile rearing and foraging habitat; and (4) benthic macro-invertebrate (BMI) production from riffle habitat. The 1-D model uses streamflow–habitat rating curves to aid in the development of flow criteria for the target species.

Coho Salmon, Chinook Salmon, and steelhead were selected as target species because they utilize the South Fork Sproul Creek at all freshwater life stages throughout the year (Figure E-1). While juvenile Chinook Salmon may occasionally over-summer in Sproul Creek, most migrate to the Pacific Ocean by mid to late spring and therefore juvenile life history needs for Chinook Salmon were not included. Target life history stages include fry rearing, juvenile rearing for Coho Salmon and steelhead, and adult spawning for all salmonid species (Figure E-1, Table E-1). For steelhead, juvenile rearing habitat is modeled for both large and small size catergories (Holmes and Cowan 2014; Holmes et al. 2014). To model food availability for fish, productive BMI habitat was also modeled.

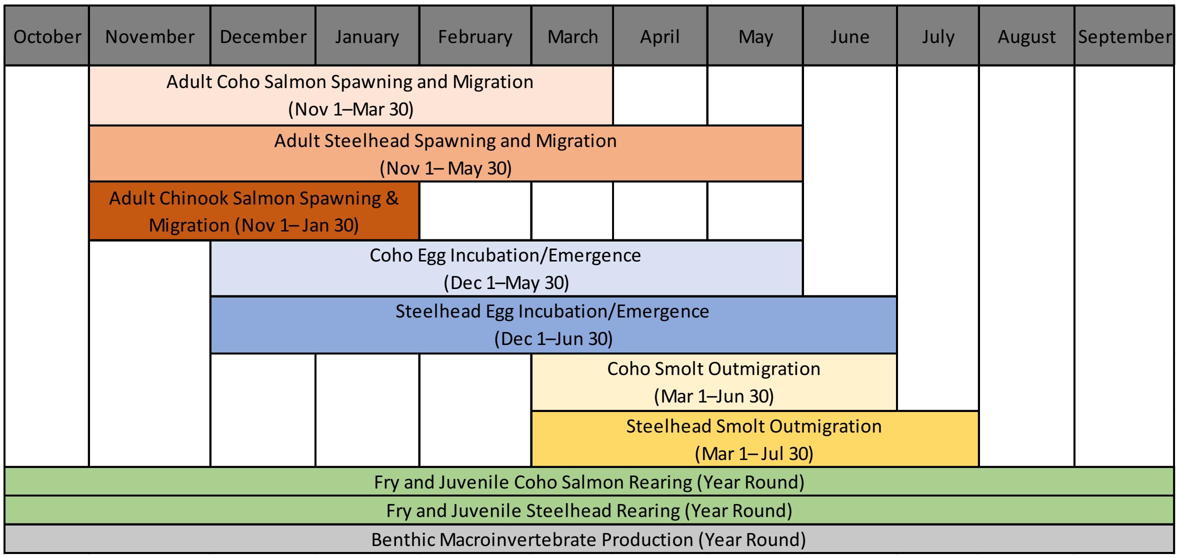

Figure E-1. Timing and duration of target species and life stages in the South Fork Sproul Creek. Timing and duration of life histories was derived from Eel River-specific literature (Brown 1990, Brown et al. 1994).

Table E-1. Target species and life history stages along habitat needs for the South Fork Sproul Creek.

Target Species and Life Stages	**Habitat Needs**
Adult Coho Salmon Spawning	Depth, Velocity, Substrate
Fry Coho Salmon Rearing	Depth, Velocity, Distance to Cover
Juvenile Coho Salmon Rearing	Depth, Velocity, Distance to Cover
Adult Steelhead Spawning	Depth, Velocity, Substrate
Fry Steelhead Rearing	Depth, Velocity, Distance to Cover
Juvenile Steelhead (small and large) Rearing	Depth, Velocity, Distance to Cover
Adult Chinook Salmon Spawning	Depth, Velocity, Substrate
Benthic Macroinvertebrate (BMI) Production	Depth, Velocity, Substrate

1.2 Study Area Description

Sproul Creek is a tributary to the South Fork Eel River which enters 2.3 miles downstream from Benbow Dam, near Garberville, CA. The watershed has a mixed ownership. Boyle Forests LLP and Wagner Corporation, two large timber landowners, own more than 67% of the watershed. Medium-sized ranches and residential parcels comprise the remaining area. Sproul Creek has a history of timber harvest and impacts from the 1955 and 1964 floods. During the past several decades, sustainable forest management and a low rate of harvest have allowed the watershed to recover and sustain high quality salmonid habitat. The Sproul Creek watershed (24.0 mi^2) has approximately 21 linear miles of salmonid habitat, and supports stable runs of Chinook and Coho salmon, and steelhead. The CDFW Coastal Monitoring Program began conducting adult spawner surveys in Sproul Creek in 2011.

The 1-D modeling reach (Figure E-2) is located on the Upper South Fork (USF) Sproul Creek, below the confluence of Cox Creek. Selection of this study reach is described in Appendix C. The reach is 1,893 ft long and composed primarily of riffle and pool habitat. Specific habitat types of the model sites and cross sections located within the reach are described in Section 3.1 and in the *Sproul Creek Site Specific Instream Flow Study*.

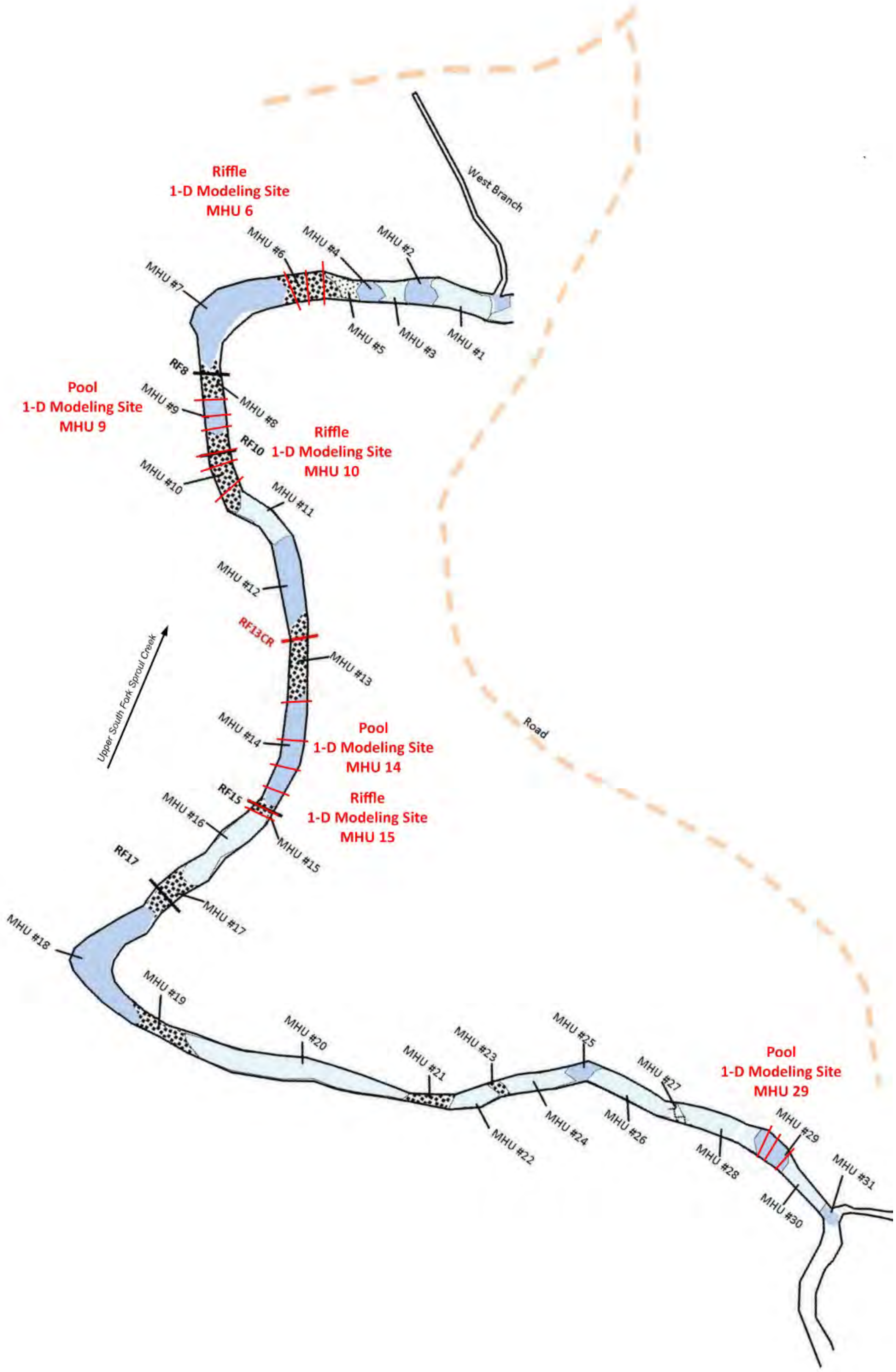

Figure E-2. Upper South Fork Sproul Creek mesohabitat map showing location of 1-D modeling reach, cross sections, mesohabitat.

2 MODEL BACKGROUND

The Instream Flow Incremental Methodology (IFIM) was developed as a decision-making framework for assessing the impacts of water development projects on regulated river systems (Bovee et al. 1998). One approach that is commonly used within the IFIM is to quantify stream habitat (water depth and velocity), and then use computer models to predict those variables over a range of streamflows. Next, those stream habitat variables are linked to habitat suitability indices for fish (commonly salmonids) to create a modeled index of usable habitat at different streamflows, called weighted usable area (WUA). The first version of this Physical Habitat Simulation model (PHABSIM; Milhous and Waddle 2012) has been adapted into several different versions, such as RHABSIM (Riverine Habitat Simulation, Thomas Payne), and RHYHABSIM (River Hydraulics and Habitat Simulation, Ian Jowett). The System for Environmental Flow Analysis (SEFA; Jowett et al. 2016) is an updated version of habitat simulation models that is more user friendly and operates on newer operating systems (Windows 7 and newer).

SEFA provides users several pathways for analysis, including modules for habitat simulation, time-series analysis, sediment modeling, temperature modeling, and dissolved oxygen modeling. The work presented in this appendix used the model exclusively for habitat modeling, and our description focuses on the habitat modeling portion of SEFA for the remainder of this appendix.

The SEFA 1-D hydraulic models are based on surveyed cross sections of the river channel profile that are randomly placed in the most prevalent mesohabitat units, and are weighted based on the respective contribution of habitat type to the entire reach. The model then predicts water surface elevations (WSEL) and velocities using the hydraulic equations developed either in previous model versions (PHABSIM) or specifically for SEFA. To model WSEL at each cross section at varying streamflows, SEFA uses a log stage–log discharge rating relationship. The user can choose to fit the curve through only the survey flow (initial measurement) and the stage at zero flow (SEFA default) or to use the IFG4 method from PHABSIM to fit the rating curve through all stage–discharge pairs collected. The latter method is preferred if bed elevations rather than water depths were surveyed. To model velocity at each cross section at varying streamflows, SEFA provides the option for a newly developed LogD method, which is based on Manning's *n* roughness values and velocity distribution factors from conveyance. Alternatively, the user can select the IFG4 method again, where Manning's *n* values are calculated from depth and assumed slope. For more detailed descriptions of the equations used within the model, refer to Milhous and Waddle (2012) for IFG4 equations and Jowett et al. (2016) for new SEFA equations.

Lastly, SEFA uses user-specified Habitat Suitability Indices for each species and life history stage to relate water depth, velocity and other user-specific variables (i.e., substrate size, distance to cover, cover type, etc.) to usable habitat. Habitat suitability is calculated for each point that is input to the model, which is the product of the values of water depth, velocity and other suitability criteria. Values from each point are then summed and weighted according to the user-specified weighting of each cross section. Finally, a relationship between streamflow and usable fish habitat is modeled. SEFA terms this "average weighted suitability" (AWS), which was previously called "weighted usable area" (WUA). For the remainder of this appendix, we use the term "WUA" to be consistent with other modeling approaches used in the *Sproul Creek Site Specific Instream Flow Study*, specifically Appendix F (2-D modeling). SEFA reports WUA as square feet of habitat per foot of river. To calculate total WUA in square feet, we multiplied by modeled reach length.

3 DATA COLLECTION FOR MODEL INPUT

Project objectives and target species and life stages determine the level of effort needed to collect model input data. Sites must be selected that represent a range of habitats and topographies within the channel. Topographic surveys, combined with water depth, velocity, channel bed substrate, and escape cover for salmonids, are required to estimate habitat availability over a range of streamflows. Below we describe methods for the location of sample sites and cross sections, determination of sample flows, and hydraulic and structural data collection (bed profile, streamflow measurement, water depth and velocity, cover, and substrate). Lastly, the selection of habitat suitability indices (HSI) is described.

3.1 Sample Site Selection

The rationale for selection of the Upper South Fork 1-D modeling reach is described in Appendix C. Sample sites within the Upper South Fork 1-D study reach were selected using methods similar to Holmes and Cowan (2014). Mesohabitat mapping conducted as part of the study informed site selection (Appendix C). After mesohabitat mapping was conducted, sample sites were randomly selected from the most prevelant mesohabitat types in the reach, which were defined as any mesohabitat type that made up greater than 10% of the total reach (Appendix C). For the South Fork Sproul Creek, dominant mesohabitat types included run (27%), mid-channel pool (22%), high-gradient riffle (11%), and low-gradient riffle (18%; Table E-2). Scour pool (8%) was also used in the site selection process due to its importance in juvenile rearing habitat (Table E-2). Individual non-dominant (< 5%) mesohabit unit types (cascade, confluence pool, run/pool, plunge pool and step run) were not included in the model. Total length from dominant mesohabitat types was 1,639 ft, and the relative contribution of each dominant mesohabitat type is shown in Table E-3. For modeling, run, mid-channel pool, and scour pool were all grouped together and were termed "pool habitat," due to their similar habitat features. Low-gradient riffle was termed "riffle habitat." While high-gradient riffle was a dominant mesohabitat type, it was only just above the 10% threshold and would provide little salmonid habitat; thus, it was not included in the model. Therefore, the modeled dominant mesohabitat types accounted for 75% of the total mapped mesohabitat types.

Three habitat units of each grouped mesohabitat type (i.e., pool and riffle) were randomly selected from the entire reach. In most cases, three cross sections were placed using a stratified random design within each habitat unit and were randomly placed into the upper third, middle third, and lower third of the habitat unit (Holmes and Cowan 2014). This ensured adequate representation of the various habitats within a MHU (e.g., pool tail for spawning, deep water for juvenile rearing). In one of the larger pool habitats, four cross sections were placed, while in one of the shorter riffle habitat units, only two cross sections were placed. This resulted in a total of 18 cross sections (10 in pool habitat and 8 in riffle habitat). Photographs are provided for each modeled habitat unit (Figure E-3 through Figure E-8). The randomly selected mesohabitat units were (MHU) 6, 9, 10, 14, 15, and 29, from downstream to upstream (Figure E-2). For labeling of each cross section, we first label MHU number, then cross section within the MHU, starting at the downstream end of the unit. For example, MHU14XS3 would be MHU14, and the third cross section, counted from downstream to upstream.

Table E-2. All mesohabitat units in the Upper South Fork Sproul Creek 1-D study reach.

All Mesohabitat Types										
Mesohabitat type	**Run**	**Mid-Channel Pool**	**Low-Gradient Riffle**	**High-Gradient Riffle**	**Scour Pool**	**Plunge Pool**	**Run/Pool**	**Cascade**	**Confluence Pool**	**Step Run**
# of Units	7	6	5	6	2	1	1	1	1	1
Total Length (ft)	508	415	346	212	158	31.5	70.5	18	65	69
% of Total	27%	22%	18%	11%	8%	2%	4%	1%	3%	4%

Table E-3. Percent contribution of dominant mesohabitat units mapped in the South Fork Sproul Creek 1-D modeling reach.

Dominant Mesohabitat Types					
Mesohabitat Type	Run	Mid-channel Pool	Scour Pool	High-gradient Riffle	Low-gradient Riffle
# of Units	7	6	2	6	5
Total Length (ft)	508	415	158	212	346
% of Total	31%	25%	10%	13%	21%
Modeled Pools and Riffles					
Mesohabitat Type	Pools*		Riffles**		Total
# of Units	15		5		20
Total Length (ft)	1081		346		1427
% of Total	76%		24%		100%
# of Cross Sections	10		8		18

* Includes run, mid-channel pool, and scour pool.

**Low-gradient riffles only, high-gradient riffles were not included in model runs.

Figure E-3.MHU6, a low-gradient riffle, with two of the three cross sections shown with the measuring tape stretched across the channel. Picture is taken from left bank and flow is moving right to left, streamflow = 1 cfs.

Figure E-4.MHU9, a mid-channel pool, with one of the three cross sections shown with the measuring tape stretched across the channel. Picture is taken from left bank and flow is moving right to left, streamflow = 1 cfs.

Figure E-5. MHU10, a low-gradient riffle. Picture is taken from left bank and flow is moving right to left, streamflow = 1 cfs.

Figure E-6. MHU14, a scour pool, with one of four cross sections shown with measuring tapes strung across the channel. Picture is taken from left bank and flow is moving right to left, streamflow = 1 cfs.

Figure E-7. MHU15, a Low-gradient riffle. Picture is taken from left bank and flow is moving right to left, streamflow = 1 cfs.

Figure E-8. MHU29, a pool, with two of the three cross sections shown by a measuring tape stretched across the channel. Picture is taken from left bank and flow is moving right to left, streamflow = 1 cfs.

3.2 Identification of Target Flows

Target flows for sampling water depth, velocity, and water surface elevations to be used in SEFA modeling were identified as above 20%, near 50%, and less than 80% exceedance probability (Table E-4). The percent exceedance between 20% and 80% reflects the most commonly observed flows in the system, while flows outside of that range reflect the lower and higher bounds in the system. The 20%, 50%, and 80% target flows were selected in accordance with previous studies (Holmes and Cowan 2014), and to represent low flow, moderate flow, and high flows, respectively. The exceedance probabilities were determined using the estimated unimpaired hydrology for South Fork Sproul Creek (Figure E-9), described in Appendix A.

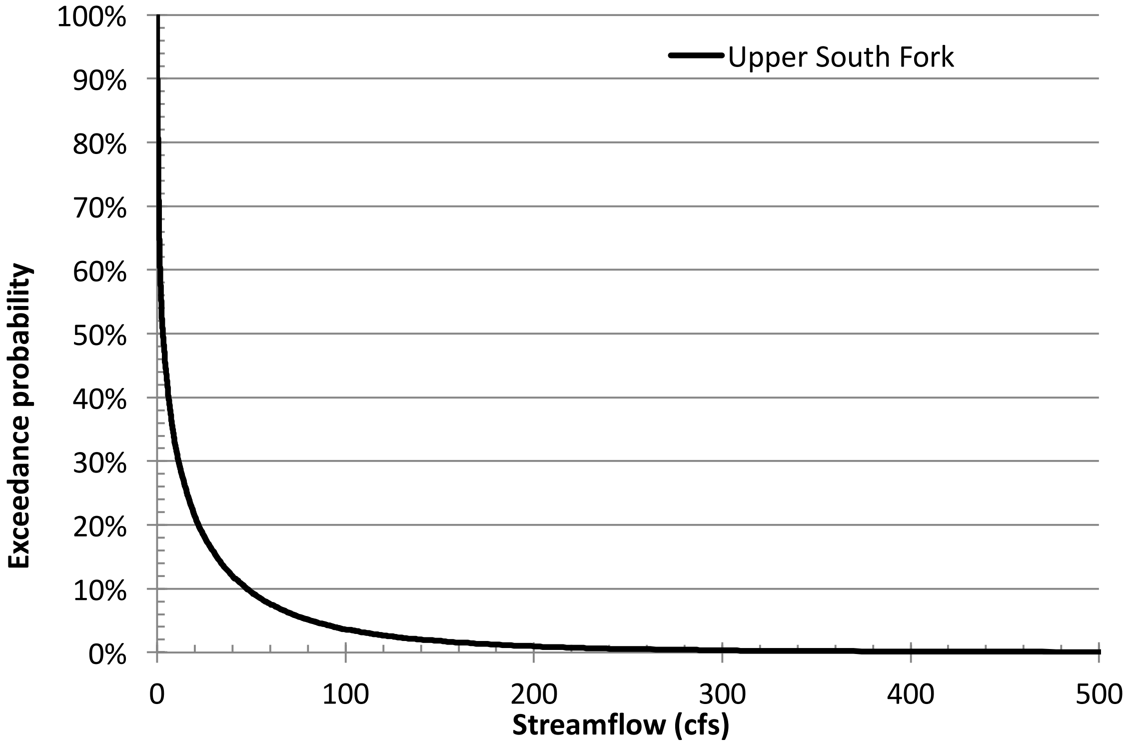

Figure E-9. Exceedance probability curves from the Upper South Fork Sproul Creek 1-D modeling reach.

3.3 Hydraulic and Structural Data Collection

Hydraulic and structural data are the key components used in the SEFA 1-D model. Hydraulic and structural data required by the model include bed depth profiles, water surface elevations, streamflow measurements, substrate size classes, and distance to cover. We collected data for 18 cross sections at 6 mesohabitat units to be used in the model development (Table E-4).

3.3.1 Topography Survey

Channel geometry of each cross section was surveyed using a stadia rod and an auto level in April 2016 during cross section installation. A survey tape (ft) was strung from left bank to right bank along the cross section perpendicular to flow, and topographic breaks associated with survey tape stationing were surveyed to best describe the topography (Harrelson et al. 1995). Elevations were referenced to an arbitrary datum of 100 ft for MHU6, 200 ft for MHU9 and MHU10, 300 ft for MHU14 and MHU15, and 400 ft for MHU29.

3.3.2 Water Surface Elevations

Water surface elevations (WSEL's) were measured to the nearest 0.01 ft at each cross section between April 21, 2016, and November 2, 2016, at 20%, 50% and 80% exceedance streamflows (Table E-4) using a stadia rod and an auto level. A survey tape (ft) was strung from left bank to right bank along the cross section and the stadia rod was held at the water surface at each wetted edge of the channel (left bank, right bank and any medial bar wetted edges) and at the middle of the wetted channel. WSEL measurements were averaged and used with paired discharge measurements for rating curve development. In addition to WSEL, the stage-at-zero flow (SZF) was determined by subtracting the WSEL from the depth at the riffle control point of each pool unit.

Table E-4. Cross sections with dates of discharge measurements for 1-D modeling reach on the South Fork Sproul Creek. Water depth, velocity and WSEL were also collected at these times.

Cross Section	20% Exceedance			50% Exceedance			80% Exceedance		
	Date	Flow (cfs)	Exceed-ance Value (%)	Date	Flow (cfs)	Exceed-ance Value (%)	Date	Flow (cfs)	Exceed-ance Value (%)
MHU6XS1	11/2/2016	32	14.8	4/21/2016	3.6	47.7	6/10/2016	0.99	66.5
MHU6XS2	11/2/2016	32	14.8	4/21/2016	3.6	47.7	6/10/2016	0.99	66.5
MHU6XS3	11/2/2016	32	14.8	4/21/2016	3.6	47.7	6/10/2016	0.99	66.5
MHU9XS1	11/2/2016	32	14.8	4/21/2016	3.6	47.7	6/10/2016	0.99	66.5
MHU9XS2	11/2/2016	32	14.8	4/21/2016	3.6	47.7	6/10/2016	0.99	66.5
MHU9XS3	11/2/2016	32	14.8	4/21/2016	3.6	47.7	6/10/2016	0.99	66.5
MHU10XS1	11/2/2016	32	14.8	4/21/2016	3.6	47.7	6/10/2016	0.99	66.5
MHU10XS2	11/2/2016	32	14.8	4/21/2016	3.6	47.7	6/10/2016	0.99	66.5
MHU10XS3	11/2/2016	32	14.8	4/21/2016	3.6	47.7	6/10/2016	0.99	66.5
MHU14XS1	4/22/2016	18	23.0	4/27/2016	4.5	44.5	6/10/2016	0.99	66.5
MHU14XS2	4/22/2016	18	23.0	4/27/2016	4.5	44.5	6/10/2016	0.99	66.5
MHU14XS3	4/22/2016	18	23.0	4/27/2016	4.5	44.5	6/10/2016	0.99	66.5
MHU14XS4	4/22/2016	18	23.0	4/27/2016	4.5	44.5	6/10/2016	0.99	66.5
MHU15XS1	4/22/2016	18	23.0	4/27/2016	4.5	44.5	6/10/2016	0.99	66.5
MHU15XS2	4/22/2016	18	23.0	4/27/2016	4.5	44.5	6/10/2016	0.99	66.5
MHU29XS1	4/22/2016	18	23.0	4/27/2016	4.5	44.5	6/10/2016	0.99	66.5
MHU20XS2	4/22/2016	18	23.0	4/27/2016	4.5	44.5	6/10/2016	0.99	66.5
MHU29XS3	4/22/2016	18	23.0	4/27/2016	4.5	44.5	6/10/2016	0.99	66.5

3.3.3 Streamflow Measurements

Streamflow was measured at a good gaging site, i.e., where velocity and depth were relatively homogenous across the channel width, at a station within the study reach (Table E-4) for each date that WSEL was collected, to build rating curves that could be used in the 1-D model. We followed standard U.S. Geological Survey (USGS) protocol to take discharge measurements (Buchanan and Somers 1969). Streamflow measurements were collected by stringing a nylon tape from left bank to right bank and using a Pygmy meter to collect velocity and depth at stations along the cross section. An Aquacalc was used to record current meter data and compute preliminary streamflow measurements, and streamflow data were reviewed and finalized by a qualified hydrologist. Each final streamflow measurement was paired with the WSEL collected at each cross section and input to the SEFA 1-D model to build a rating curve for each cross section in the model.

3.3.4 Depth and Velocity at Each Cross Section

Water depth and velocity measurements were collected at each cross section at the 20%, 50%, and 80% exceedance streamflows (Table E-4). A survey tape (ft) was strung from left bank to right bank along the cross section, and depths (±0.01 ft) were measured in the wetted channel using a stadia rod at maximum 1 ft increments along the tape. Velocities (ft/sec) were measured using a Marsh-McBirney flow meter at the same stations where water depths were measured.

3.3.5 Substrate and Cover

Substrate and cover were collected in spring 2016, during site installation. Cover was visually estimated using categories from the PHABSIM manual (Milhous and Waddle 2001). Substrate for spawning habitat and BMI habitat was collected using four size classes (bedrock, boulder > 0.83ft, gravel/cobble 0.006–0.83ft, and silt/sand <0.006 ft), and five cover classes (small woody debris, large woody debris, undercut bank, overhanging vegetation, and aquatic vegetation).

The substrate and cover data collected in the spring of 2016 were categorized to meet HSI needs for PHABSIM modeling (Milhous and Waddle 2001). However, these substrate and cover data collected were coarser than the HSI suggested during QA/QC procedures with Thomas Payne (Normandeau Associates). Thus, an additional set of substrate and distance to cover data were collected in spring 2017 at each of the cross sections to refine the distance to cover and substrate size classes. The substrate size classes collected in spring 2017 used the D_{50} categories from Dettman and Kelly (1986) for spawning and BMI categories from Gore et al. (2001). At 1 ft increments along each cross section, the distance to escape cover was measured to the nearest 0.25 ft with a maximum distance of 10 ft. Escape cover was considered any large substrate (boulder > 264 mm), structural or vegetative component, or feature located within or out of the water, but within 18 inches of the water surface. While it is preferable to have all field data collected at the same time, in the case of distance to cover and substrate it may be acceptable to use data from consecutive years if mesohabitat units remain intact between water years. In this case, mesohabitat units had not changed between WY 2016 and WY 2017, maintaining the representativeness of each cross section within each of the six mesohabitat units. In addition, the 2016 substrate categories reevaluated during the 2017 data collection effort were observed to be intact. Photographs of each site from spring 2016 and spring 2017 showed little to no movement of bed material, cobbles, and boulders, or large wood. Thus, we feel that using the spring 2017 distance to cover and substrate data is adequate and representative of stream conditions when depth, velocity, bed profile, and rating curves were developed.

3.4 Habitat Suitability Indices

Habitat suitability indices (HSI) are used to describe the relative appropriateness of habitat attributes for targeted species and life stages (Bovee 1986). They are used in creating streamflow–habitat relationships by weighting the suitability of modeled water depth and velocity results, and cover and substrate values measured in the 1-D modeling site at a specific flow. While they are ideally developed for each study system, the development of these curves is logistically and financially exhaustive, and was not in the scope of this project. Thus, HSI were gathered for each target species and life stage based on a review of relevant literature, recommendations from California Department of Fish and Wildlife (CDFW), and our professional experience (Table E-5, Figure E-10 through Figure E-30; Holmes et al. 2014, Hampton et al. 1997, Gore et al. 2001, Dettman and Kelly 1986).

Table E-5. Source of water depth, velocity, substrate, and cover HSI curves used for calculating Coho Salmon, Chinook Salmon and steelhead spawning habitat, fry and juvenile rearing habitat (Coho Salmon and steelhead only), and productive BMI habitat WUA curves from 1-D model outputs (calculated in System for Environmental Flow Analysis).

Species	Life Stage	Hydraulic (Depth and Velocity)	Cover	Substrate
Coho Salmon	Spawning	Hampton et al. (1997) Figure E-10 & Figure E-11	N/A	Dettman and Kelley (1986) Figure E-29
	fry Rearing	Hampton et al. (1997) Figure E-12 & Figure E-13	Holmes et al. (2014) Figure E-28	N/A
	Juvenile Rearing	Hampton et al. (1997) Figure E-14 & Figure E-15	Holmes et al. (2014) Figure E-28	N/A
Steelhead	Spawning	Hampton et al. (1997) Figure E-16 & Figure E-17	N/A	Dettman and Kelley (1986) Figure E-29
	fry Rearing	Holmes et al. (2014) Figure E-18 & Figure E-19	Holmes et al. (2014) Figure E-28	N/A
	Small Juvenile Rearing	Holmes et al. (2014) Figure E-20 & Figure E-21	Holmes et al. (2014) Figure E-28	N/A
	Large Juvenile Rearing	Holmes et al. (2014) Figure E-22 & Figure E-23	Holmes et al. (2014) Figure E-28	N/A
Chinook Salmon	Spawning	Hampton et al. (1997) Figure E-24 & Figure E-25	N/A	Dettman and Kelley (1986) Figure E-29
BMI	Larval	Gore et al. (2001) Figure E-26 & Figure E-27**Error! Reference source not found.**	N/A	Gore et al. (2001) Figure E-30

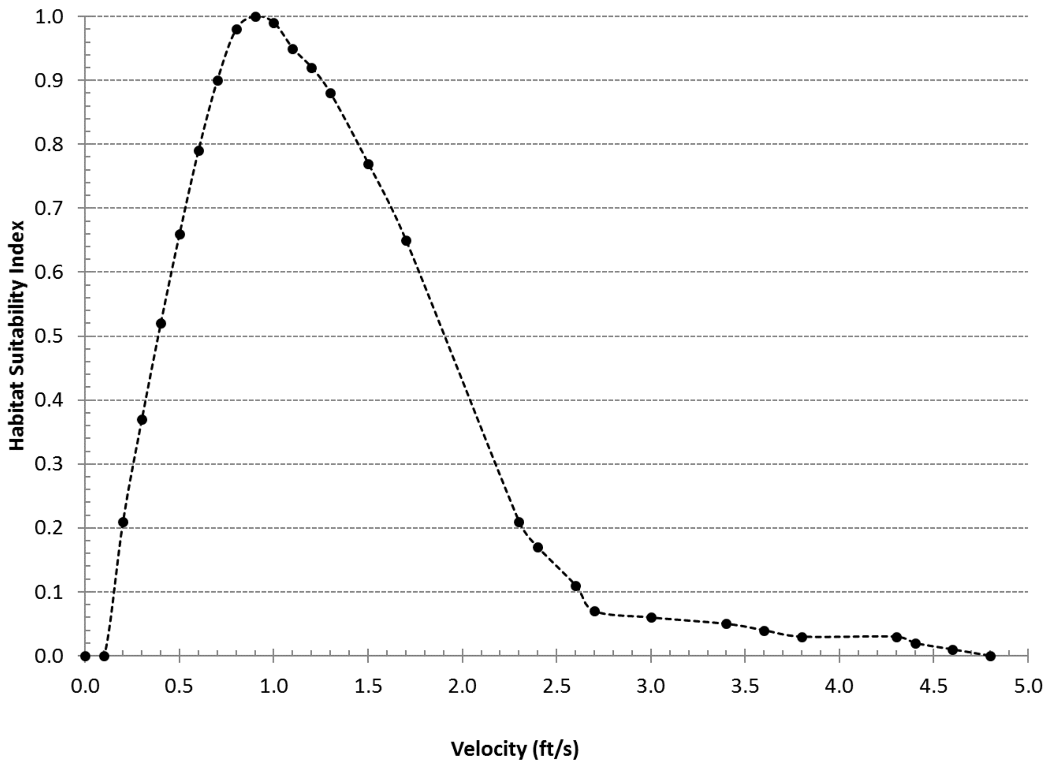

Figure E-10. Velocity HSI for Coho Salmon spawning habitat. Adapated from Hampton et al. (1997)

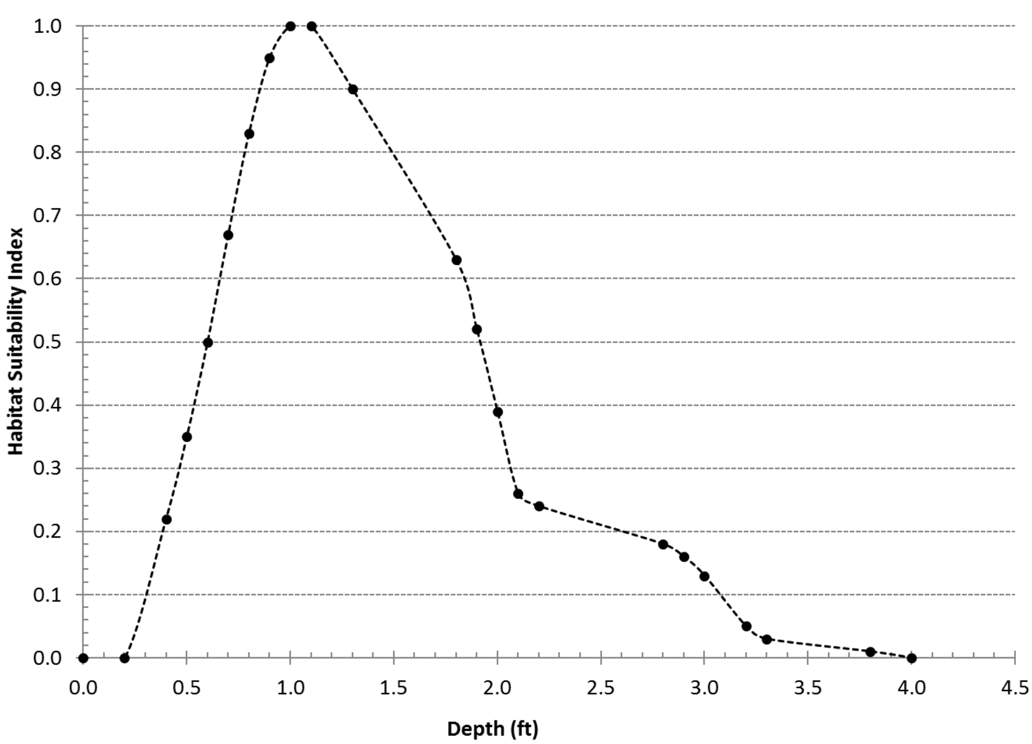

Figure E-11. Depth HSI for Coho Salmon spawning habitat. Adapted from Hampton et al. (1997).

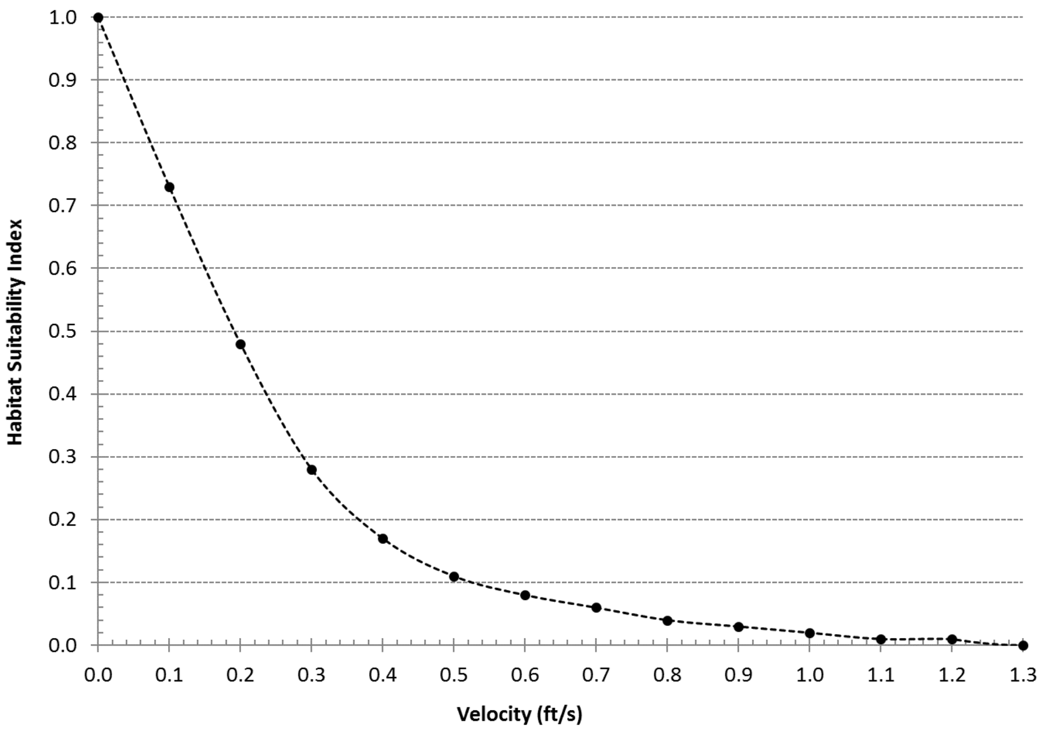

Figure E-12. Velocity HSI for Coho Salmon fry rearing habitat. Adapted from Hampton et al. (1997).

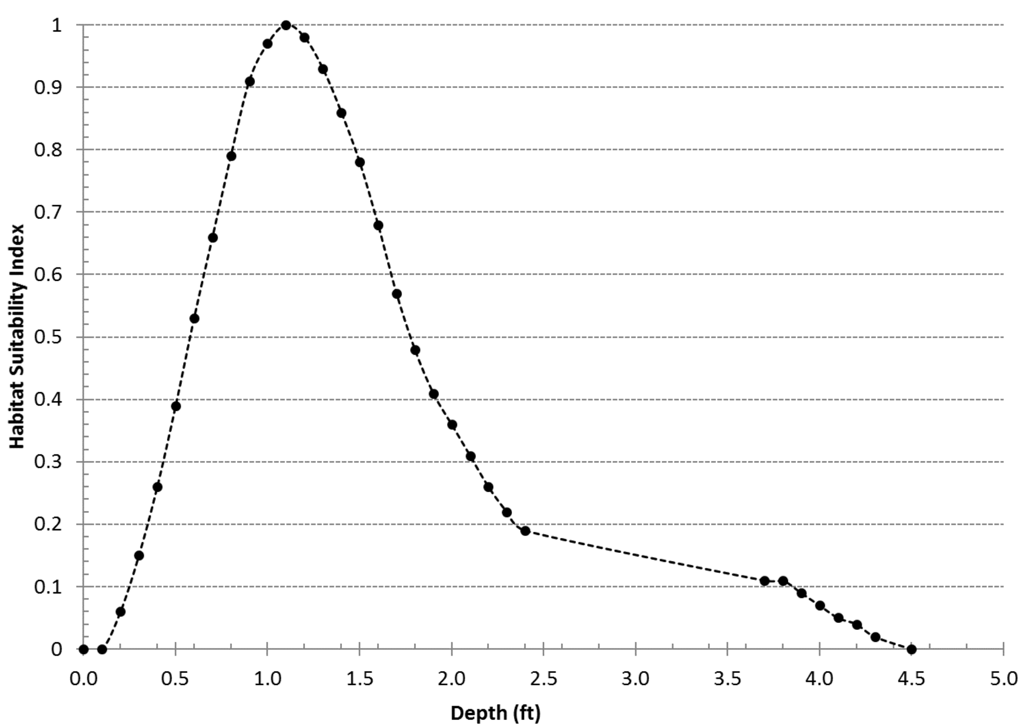

Figure E-13. Depth HSI for Coho Salmon fry rearing habitat. Adapted from Hampton et al. (1997).

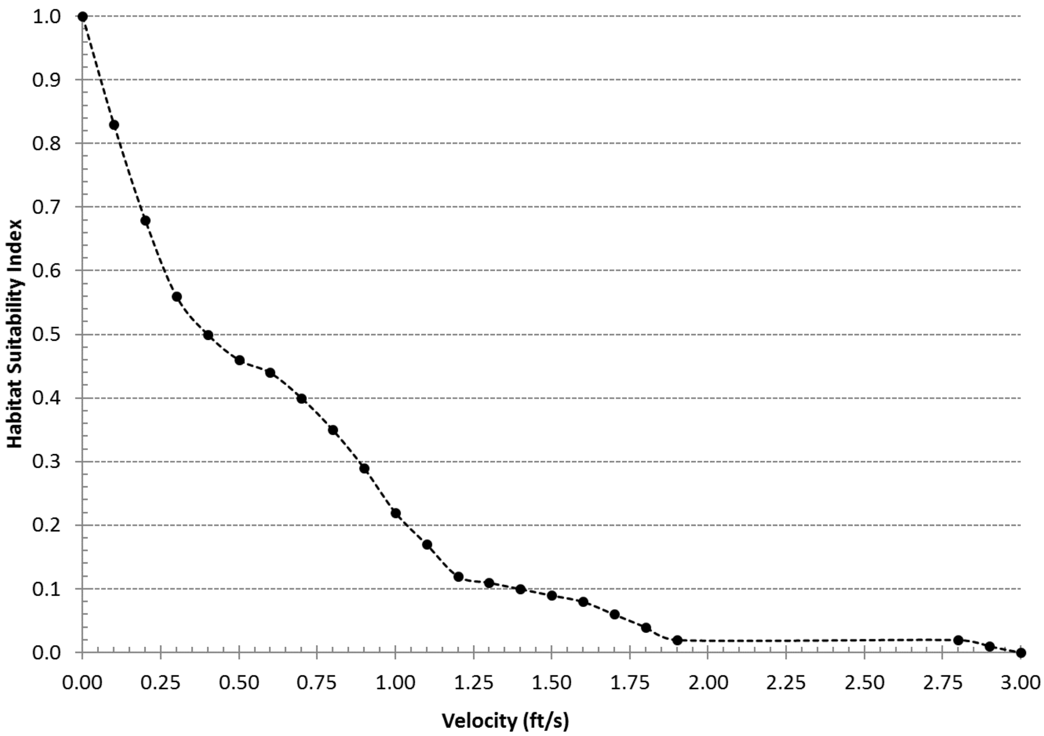

Figure E-14. Velocity HSI for Coho Salmon juvenile rearing habitat. Adapted from Hampton et al. (1997).

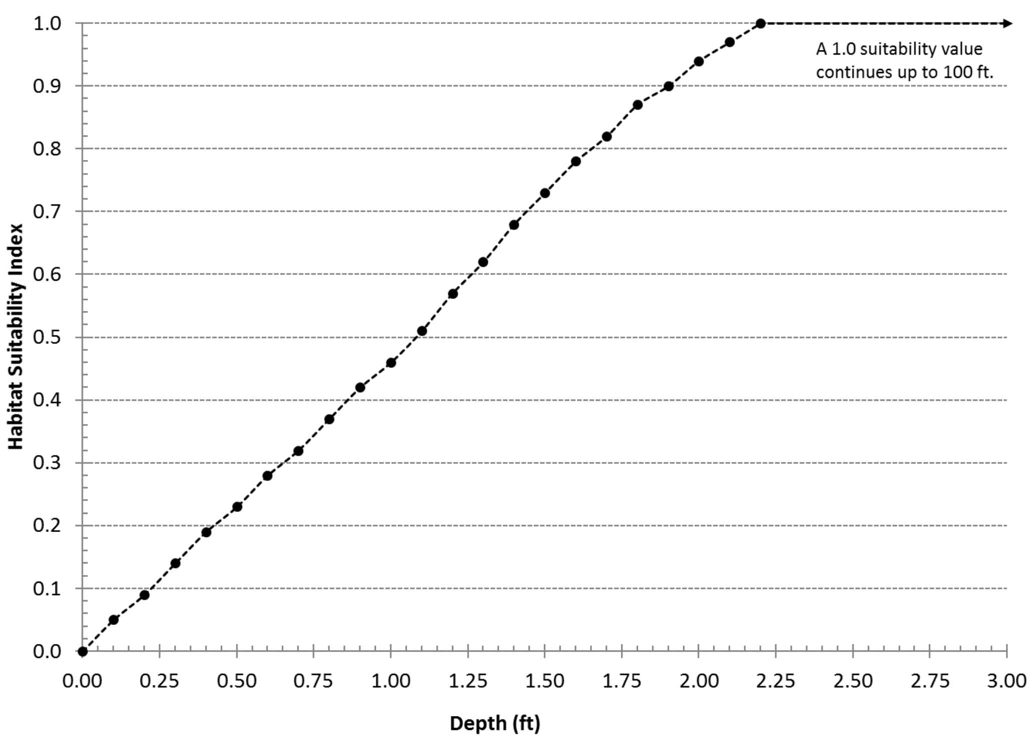

Figure E-15. Depth HSI for Coho Salmon juvenile rearing habitat. Adapted from Hampton et al. (1997).

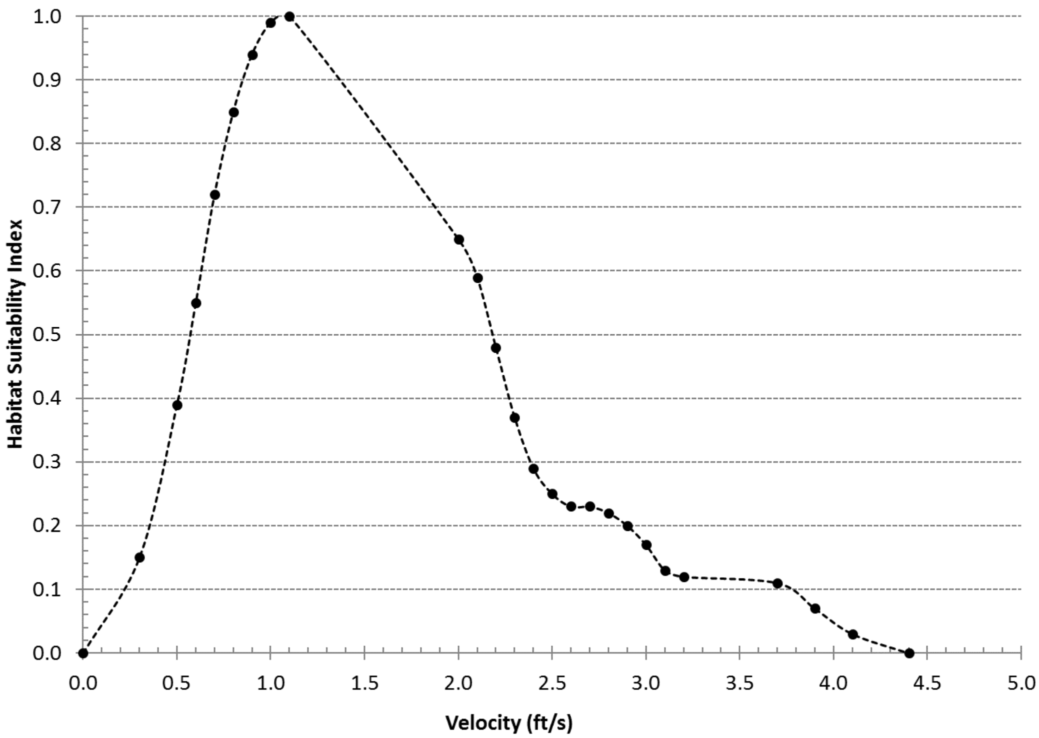

Figure E-16. Velocity HSI for steelhead spawning habitat. Adapted from Hampton et al. (1997).

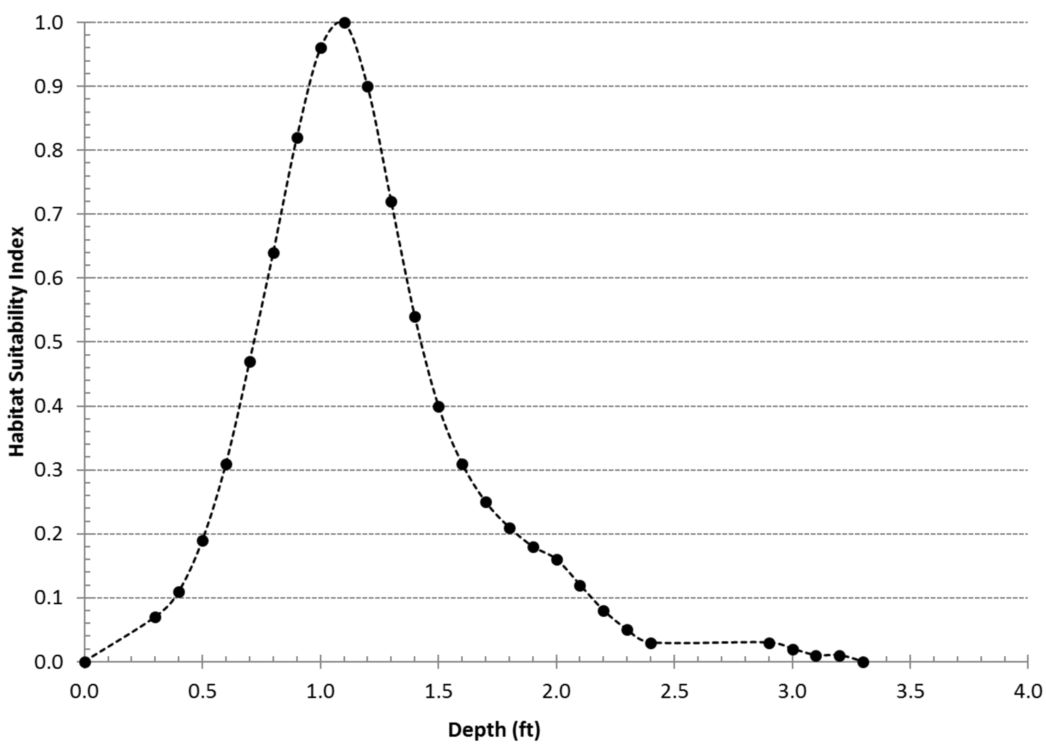

Figure E-17. Depth HSI for steelhead spawning habitat. Adapted from Hampton et al. (1997).

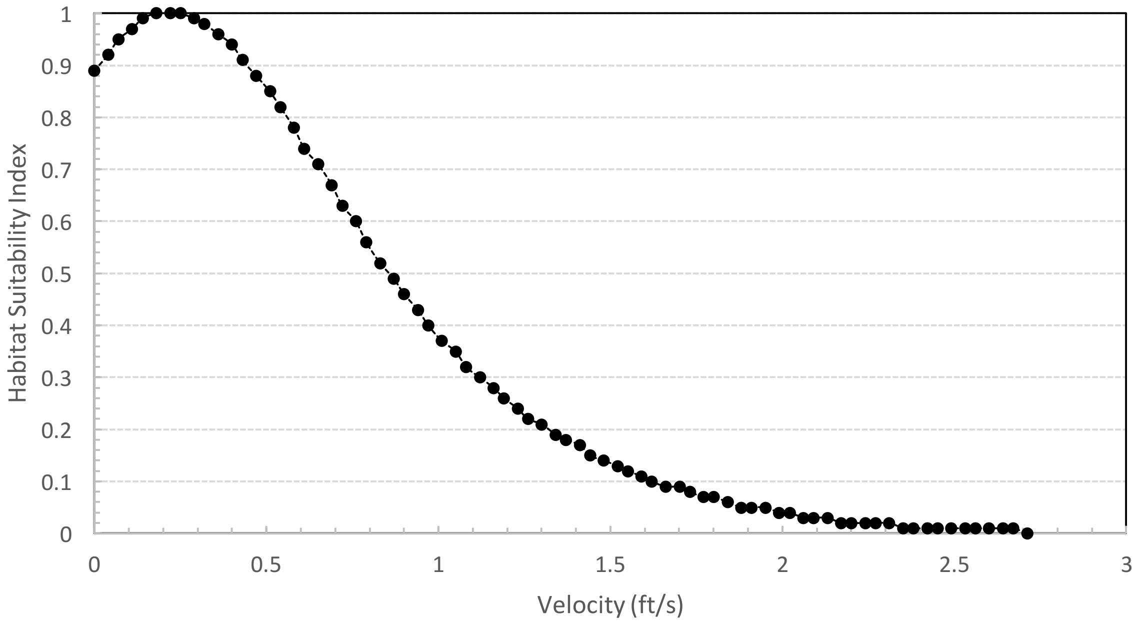

Figure E-18. Velocity HSI for steelhead fry rearing habitat. Adapted from Holmes et al (2014).

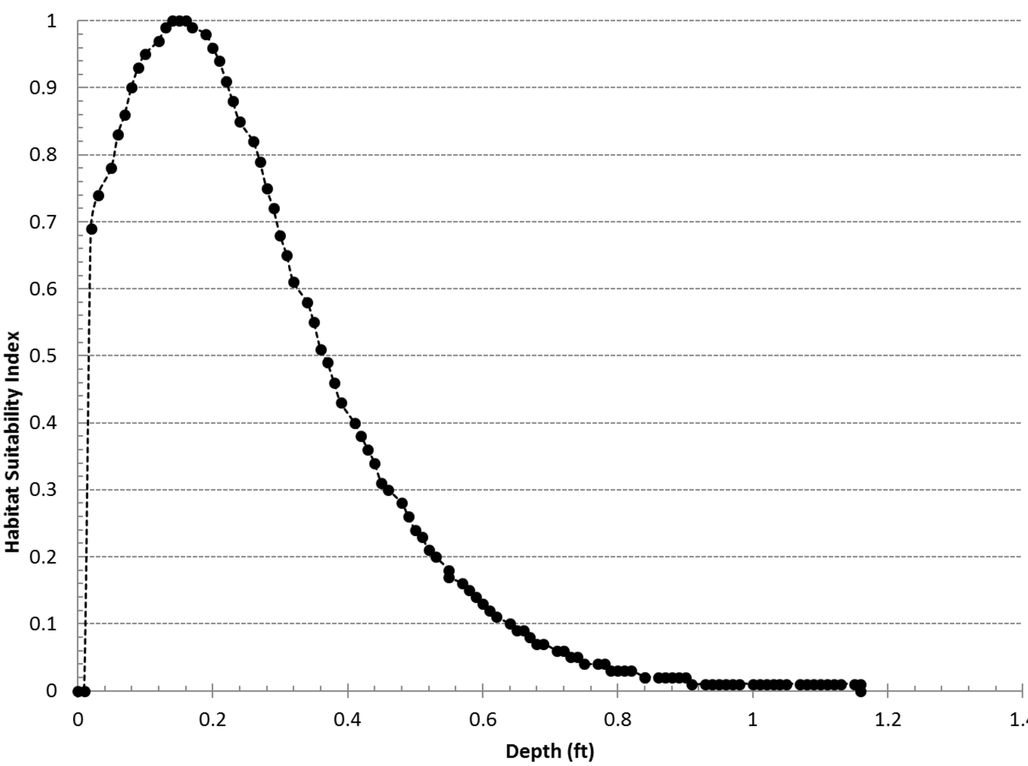

Figure E-19. Depth HSI for steelhead fry rearing habitat. Adapted from Holmes et al (2014).

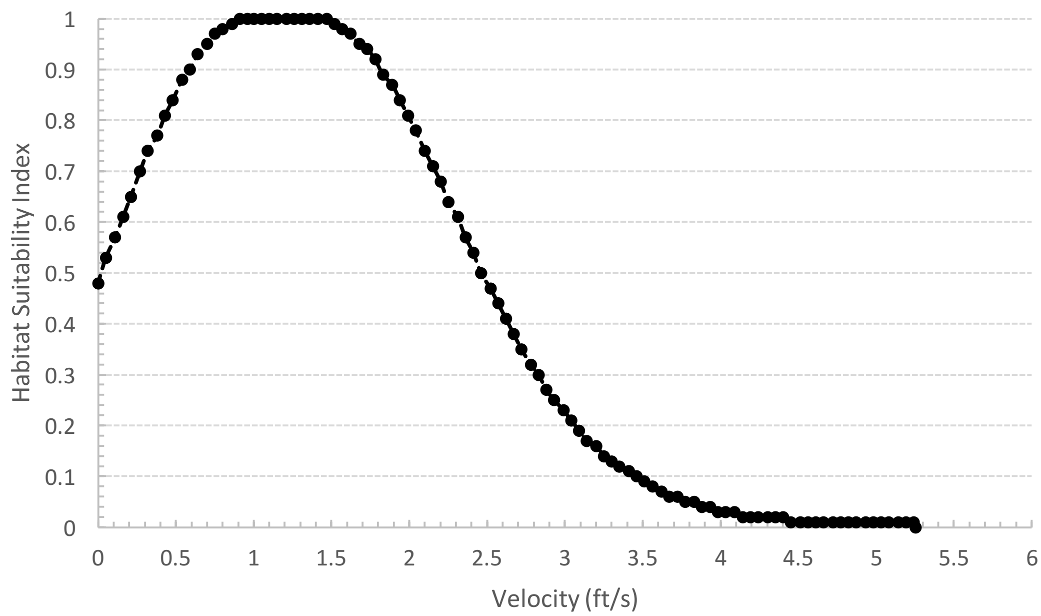

Figure E-20. Velocity HSI for steelhead juvenile (small) rearing habitat. Adapted from Holmes et al (2014).

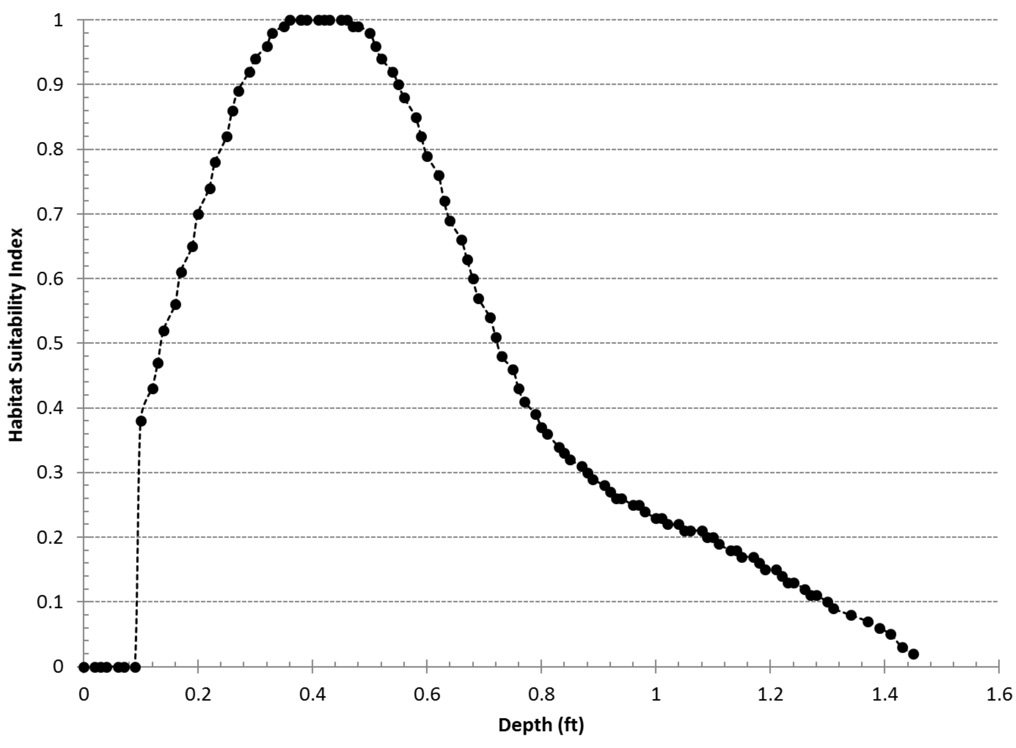

Figure E-21. Depth HSI for steelhead juvenile (small) rearing habitat. Adapted from Holmes et al (2014).

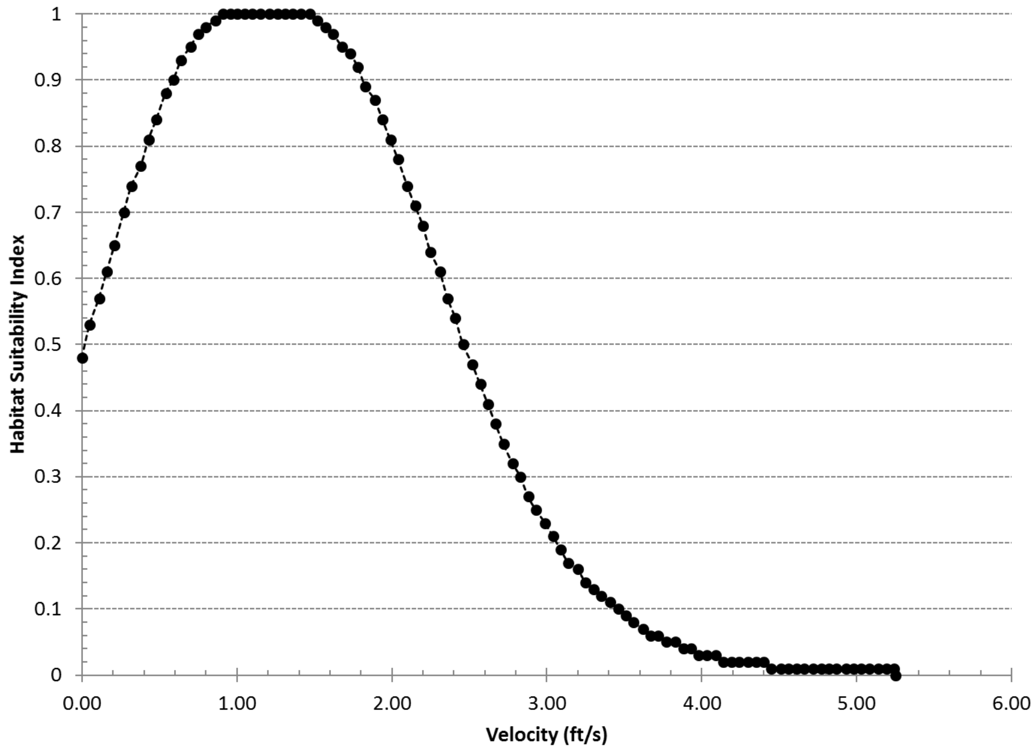

Figure E-22. Velocity HSI for steelhead juvenile (large) rearing habitat. Adapted from Holmes et al (2014).

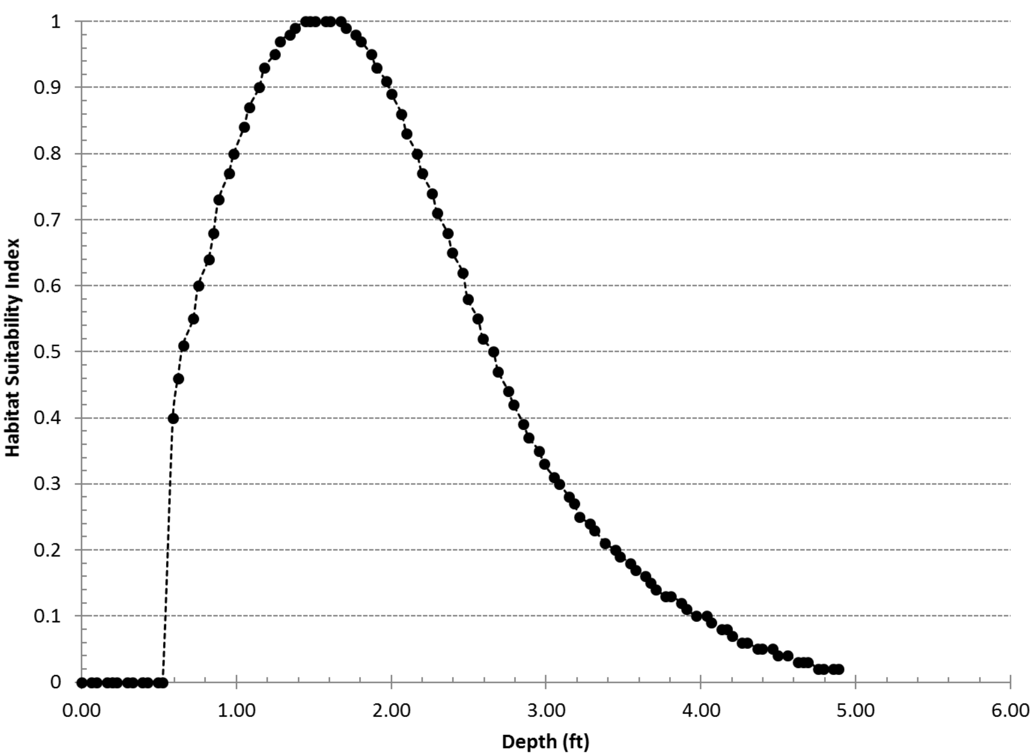

Figure E-23. Depth HSI for steelhead juvenile (large) rearing habitat. Adapted from Holmes et al (2014).

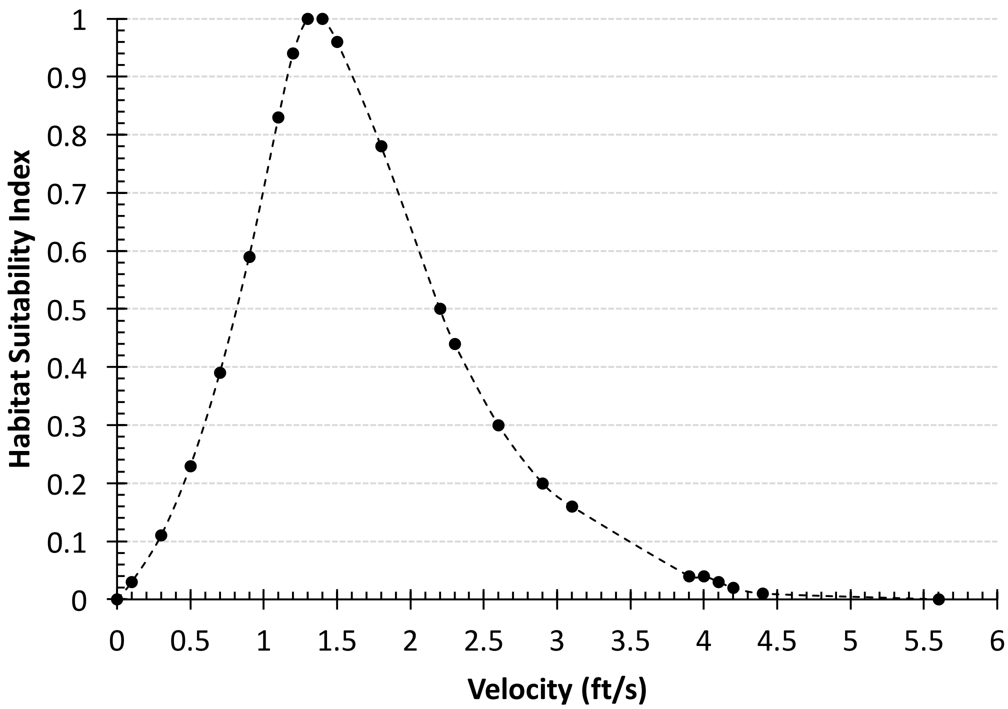

Figure E-24. Velocity HSI for adult Chinook Salmon spawning habitat. Adapted from Hampton (1997).

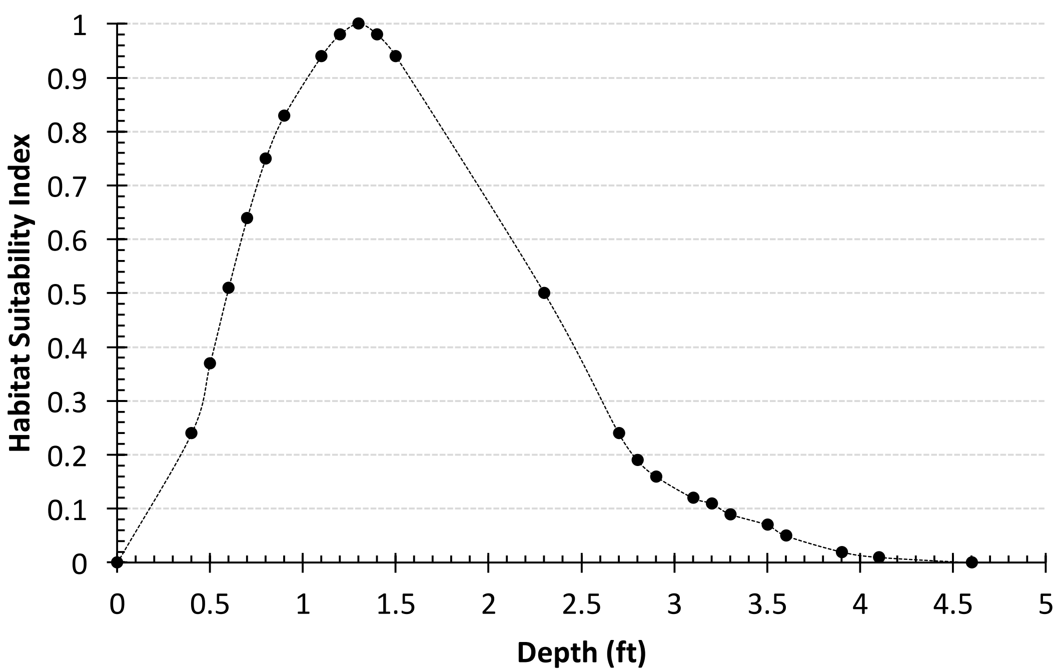

Figure E-25. Depth HSI for adult Chinook Salmon spanwing habitat. Adapted from Hampton (1997).

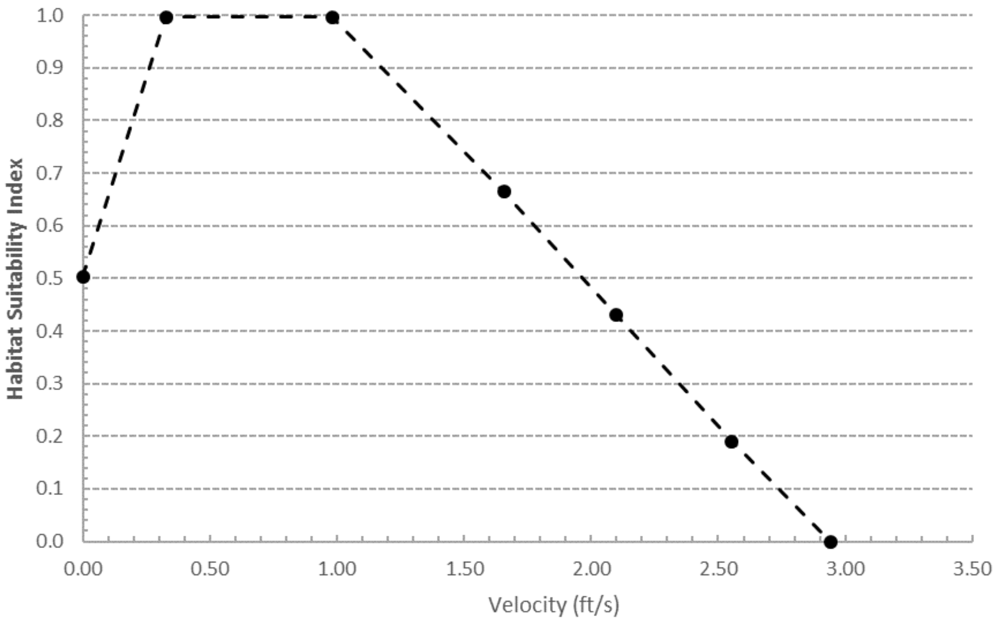

Figure E-26. Velocity HSI for productive BMI habitat. Adapted from Gore et al. (2001).

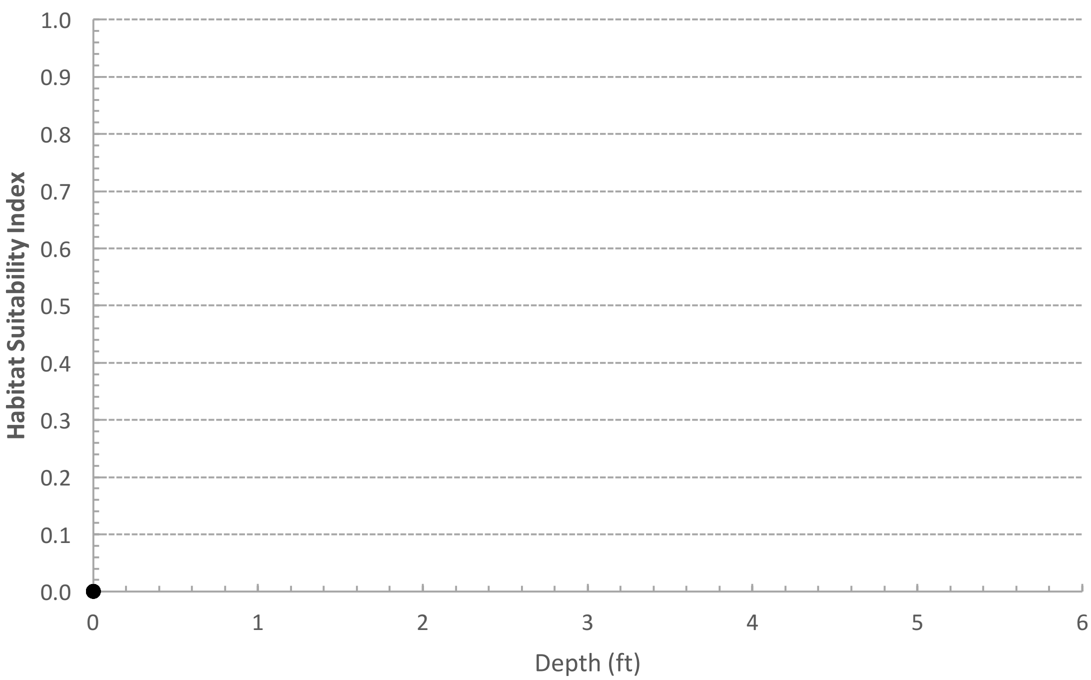

Figure E-27. Depth HSI for productive BMI habitat. Adapted from Gore et al. (2001).

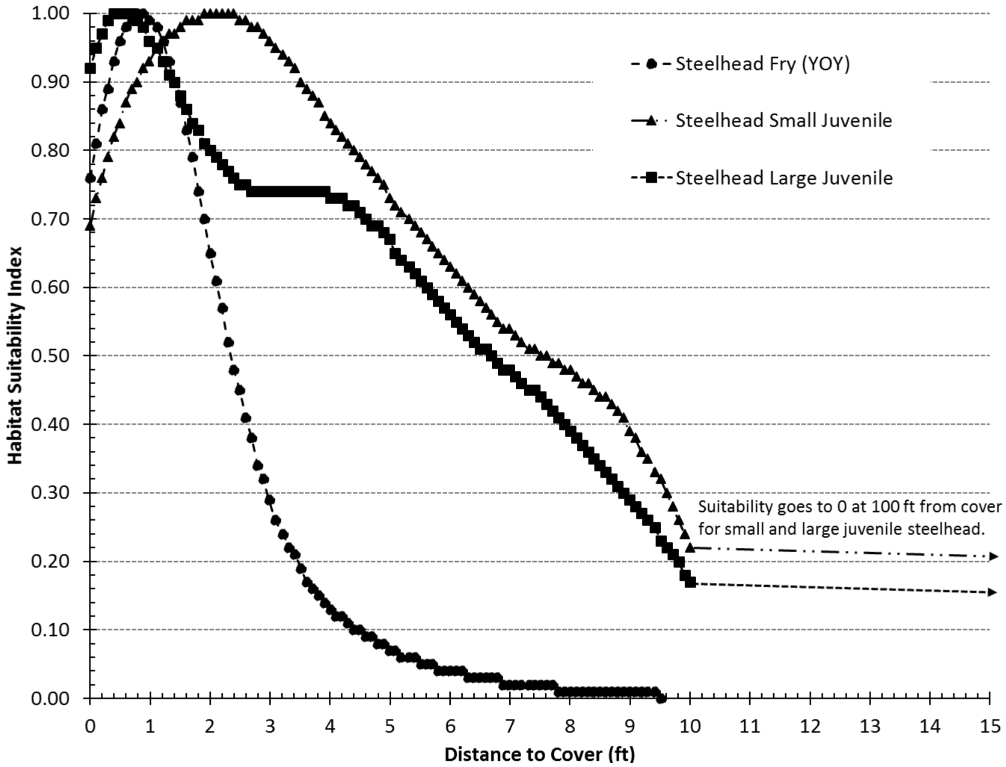

Figure E-28. Distance to cover HSI for steelhead fry, small and large juveinle steelhead. Adapated from Holmes et al. (2014). Distance to cover HSI for steelhead was also used for fry and juvenile Coho Salmon.

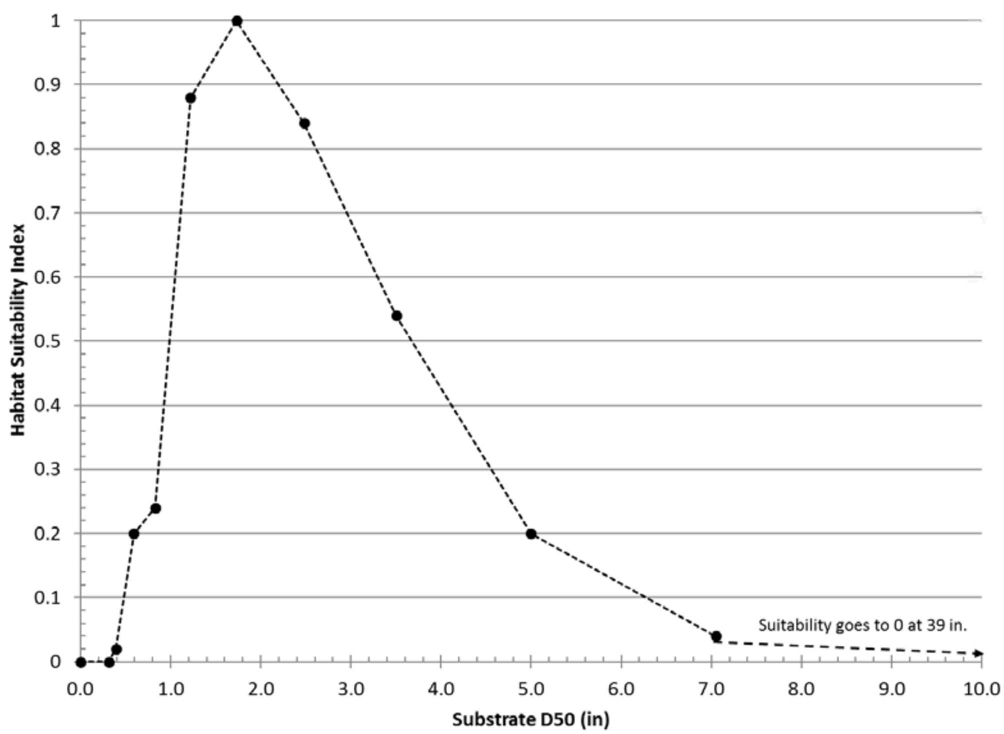

Figure E-29. Substrate HSI for Coho Salmon, Chinook Salmon, and steelhead spawning. Adapated from Dettman and Kelly (1986).

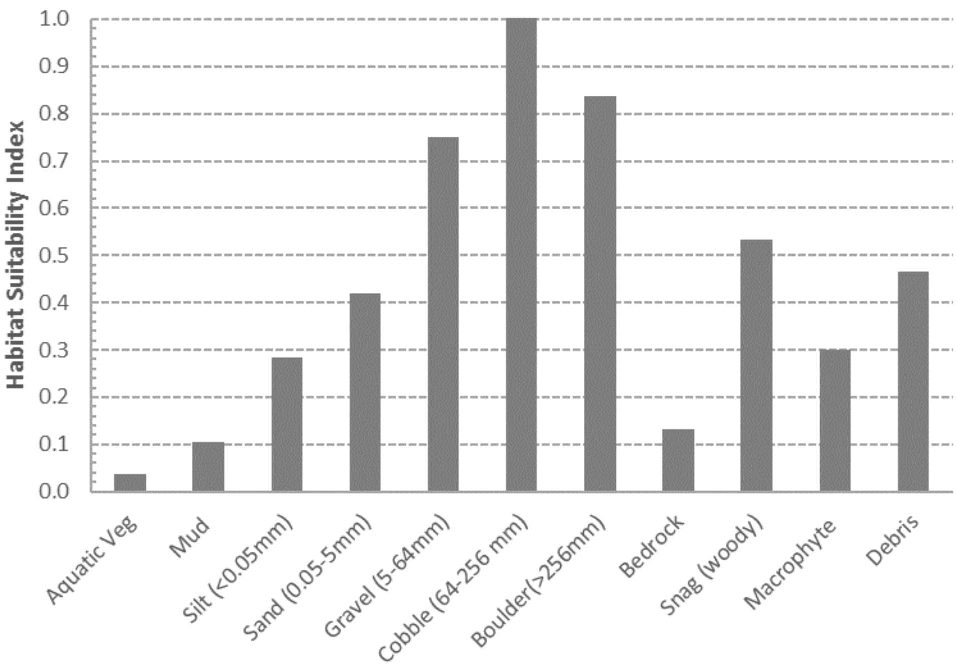

Figure E-30. Substrate and cover HSI for productive BMI habitat. Adapated from Gore et al. (2001).

4 1-D MODEL DEVELOPMENT, CALIBRATION AND QA/QC

This section describes the process of the SEFA model development, model calibration, and model QA/QC. The SEFA model is developed by first inputting data, including bed depth profiles, paired WSEL and streamflows, velocity, and cover and substrate codes from a formatted excel workbook. The hydraulic model is then calibrated using four criteria comparing predicted and measured values. The final step in developing the model is a QA/QC procedure. As described previously, part of the QA/QC procedure used in developing the 1-D SEFA model on the South Fork Sproul Creek involved input and guidance from Thomas Payne (Normandeau Associates) to ensure high quality model output. Each step is described in more detail in the following sections.

4.1 Model Development

The first step in model development is to format data into an excel workbook which can then be read into the SEFA model graphical user interface (GUI). The data in the excel worksheet included paired WSEL and streamflows, a bed depth profile paired with velocity, distance to cover, and substrate for each cross section. Once the hydraulic, structural, and habitat data are entered, specific calculation preferences are selected for modeling WSEL and velocity (Figure E-31). Then the model is run for a variety of streamflows, and calibration criteria are applied (Section 4.2). If calibration criteria are not met, the model is modified and rerun until calibration is complete. Throughout the set up and calibration process, QA/QC procedures are used to assess data quality.

The SEFA 1-D model was initiated with data collected during approximately 20% exceedance streamflows (~18 cfs for MHU14, MHU15, and MHU29; and 31 cfs for MHU6, MHU9 and MHU10) at the recommendation of the user manual (Jowett et al. 2016). Each hydraulic variable (depth and velocity) and habitat (WUA) was simulated from 0–70 cfs in 1 cfs increments. Because the model reach included two main mesohabitat types, we built a single SEFA model for the entire reach (including all mesohabitat types) and for riffle and pool mesohabitat types separately. This allows model reviewers to evaluate the whole reach, and/or focus on changes in usable habitat by mesohabitat type. For each run of the SEFA model, we developed cross section weighting factors to ensure representativeness of available habitats (Table E-6). Calibration was first performed on the reach-wide model and then exported into separate pool and riffle habitats. Thus, calibration, velocity, and WSEL for the reach-wide model are the same as those used in the riffle only and pool only model results.

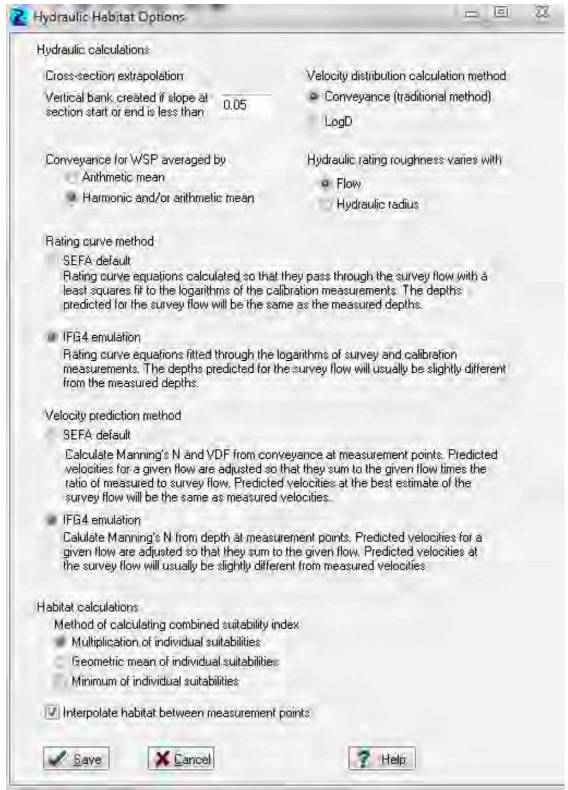

Figure E-31. SEFA calculation preferences from the graphical user interface. For each model run, we used IFG4 emulation methods (from PHABSIM model) for both rating curve development and velocity simulations.

Table E-6. Weighting factors used in SEFA model for cross section and each model run. Weighting factors are developed from only those mesohabitat unit types which were included in the model.

Mesohabitat Type	Pools*	Riffles**	Total
# of Units	15	5	20
Total Length (ft)	1,081	346	1,427
% of Total Length	76%	24%	100%
# of Cross Section	10	8	18
Whole Reach			
% Weight per Cross Section	7.6%	3.0%	100%
Riffles Only			
% Weight per Cross Section		12.5%	100%
Pools Only			
% Weight per Cross Section	10%		100%

*Pool habitat has 10 cross sections that are weighted at 10% each.

**Riffle habitat has 8 cross sections weighted at 12.5% each.

4.1.1 Rating Curves and Water Surface Elevations

Rating curves within the SEFA model are developed using paired discharge and stage height measurements for each cross section. Water surface elevations at three different streamflows, and stage-at-zero flow (SZF), at each cross section, paired with a measured discharge were used to develop rating curves using log stage–log streamflow relationships. SEFA provides two options for simulating WSEL from the developed rating curves: the SEFA default method (Figure E-31, Jowett et al. 2016) or IFG4 (PHABSIM) method. The IFG4 method was used because bed elevations were collected instead of water depths.

4.1.2 Velocities

SEFA provides two options for simulating velocity over a range of streamflows (Figure E-31). The SEFA default is to use a new algorithm (LogD, Jowett et al. 2016) or use conveyance at each measurement point, similar to PHABSIM and RHABSIM. After QA/QC procedures of our model (reviewed by Thomas Payne), we determined that conveyance methods were more appropriate for our data set. Velocity distribution factors were inspected and manually calibrated by viewing their distribution in the stream channel per the recommendation of the user manual. In addition, the beta constant was set to −0.3, which assumes that roughness increases with increasing depths. Minor calibration adjustments included changing negative to positive velocity values in cases where measured negative velocities were not realistic or within the error of the velocity meter (i.e. −0.02 ft/s, was rounded to 0 ft/s); realistic negative velocities (i.e., eddys) were not adjusted. Calibrations that were made typically occurred in edge cells or where negative or angular velocities are caused by upstream objects. These adjustments have little effect on streamflow–habitat relationships because absolute values of velocities are used for habitat calculations (Gast et al. 2004).

4.1.3 Streamflow–habitat Relationship Curve Development

Streamflow–habitat relationship curves are developed in SEFA from water depth, velocity, and other user specified attributes (substrate or cover) that are input as HSI. To calculate habitat, the combined suitability index (CSI) of each point in each cross section is determined from the product of each HSI. The habitat variables used were water depth, water velocity, and cover (juvenile and fry rearing) or substrate (spawning habitat and BMI habitat).

$$CSI_i = HSI_1 \times HSI_2 \ldots \times HSI_n$$

CSI values for each point are then multiplied by the area it represents (see Milhous and Waddle (1989) and Jowett et al. (2016) for detailed descriptions on area of each cell) and summed for each cross section and weighted based on the weighting factors in Table E-6.

$$AWS = \sum_{i=1}^{n} CSI_i$$

SEFA uses the specified HSI to create average weighted suitability (AWS) in ft^2/ft. AWS is the same as weighted usable habitat (WUA) but was renamed to be clearer in what the index meant (see Jowett et al. 2016 for a detailed description). We chose to be more consistent with previous reports (Holmes and Cowan 2014) and the 2-D model approach in Appendix F, and therefore use WUA (total square ft). To arrive at WUA, we multiplied the AWS by the length of the reach represented in the model (Table E-6).

4.2 Calibration Procedures

The model was calibrated and validated using the following criteria (Milhous and Waddle 2001; Holmes and Cowan 2014):

1. The mean error of predicted versus measured discharge does not exceed 10%
2. The maximum variance of any one predicted discharge compared to a measured discharge does not exceed 25%
3. Difference between measured and predicted WSELs does not exceed 0.1 ft at a given calibration flow.
4. Velocity adjustment factors are within tolerances of recommended guidelines (0.5–1.5).

4.3 QA/QC Procedures

QA/QC procedures were done in three ways. First, we used the “check” function within SEFA to verify all data were imported appropriately and the model was reading data accurately. Next, we used SEFA’s visual graphics to view each cross section’s depth and velocity data to look for unrealistic values or errors. Lastly, we conducted three QA/QC iterations with Thomas Payne (model co-author). We forwarded exact model files, then walked through each step with him at three different times during model development to ensure accuracy of model results.

5 1-D MODELING RESULTS AND STREAMFLOW–HABITAT RELATIONSHIPS

This section describes hydraulic model outputs, calibrations results, and streamflow–habitat relationships. Streamflow–habitat relationships are the main output of the 1-D SEFA model and are used in developing the flow criteria in the time series analysis (Appendix G).

5.1 Rating Curves and Water Surface Elevations

SZF rating curves were successfully developed using the log stage–log streamflow relationship for each cross section (Table E-7, Figure E-32). One mean error (%) of predicted vs measured streamflow for cross section MHU9XS2 was 10.1%, which is outside of the recommended value for calibration (10%). However, our evaluation suggested that it did not have any impacts on the model performance and was accepted in our QA/QC procedure.

WSEL was simulated at all cross sections (Figure E-33) from 0–70 cfs in 1 cfs increments, with a mean difference of 0.01 ft between modeled and measured values (Figure E-34). This procedure was done by modeling WSEL with data collected at 20% exceedance and comparing it to the WSEL measured at 50% and 80% exceedance streamflows. Our value of 0.01 ft was an order of magnitude lower than the recommended maximum value (0.10 ft) from Milhous and Waddle (2001).

Table E-7. Stage-at-zero flow (SZF) rating curves and mean error (%) for each cross section in the South Fork Sproul Creek 1-D SEFA hydraulic model. The mean error (%) and coefficient of determination (R^2) show the goodness of fit of the rating to curve for each location. The mean error is the average percentage error in predicted and rating calibration discharges as a % of the rating calibration streamflows.

Section	**SZF rating, Flow = A × (Water Level − SZF)^{exp}**				
	exp	**A**	**SZF**	**R^2**	**Mean error (%)**
MHU6XS1	2.92	43.35	5.70	0.999	5.4
MHU6XS2	2.86	39.61	5.73	0.998	7.0
MHU6XS3	2.89	39.16	5.75	0.999	6.7
MHU9XS1	2.39	29.76	7.45	0.998	7.5
MHU9XS2	2.36	29.24	7.48	0.997	10.1
MHU9XS3	2.46	30.97	7.51	1	2.4
MHU10XS1	2.74	39.98	7.64	0.999	5.4
MHU10XS2	2.52	34.01	8.28	0.998	7.4
MHU10XS3	2.68	35.21	8.73	0.998	8.7
MHU14XS1	2.27	43.90	9.68	1	2.6
MHU14XS2	2.25	42.28	9.69	0.999	3.3
MHU14XS3	2.19	40.07	9.70	1	1.0
MHU14XS4	2.19	40.07	9.70	1	1.0
MHU15XS1	2.15	47.37	10.00	1	0.6
MHU15XS2	2.17	49.28	10.12	1	1.4
MHU29XS1	2.13	43.74	12.10	0.994	8.8
MHU29XS2	2.13	43.74	12.10	0.994	8.8
MHU29XS3	2.20	46.824	12.11	0.997	6.7

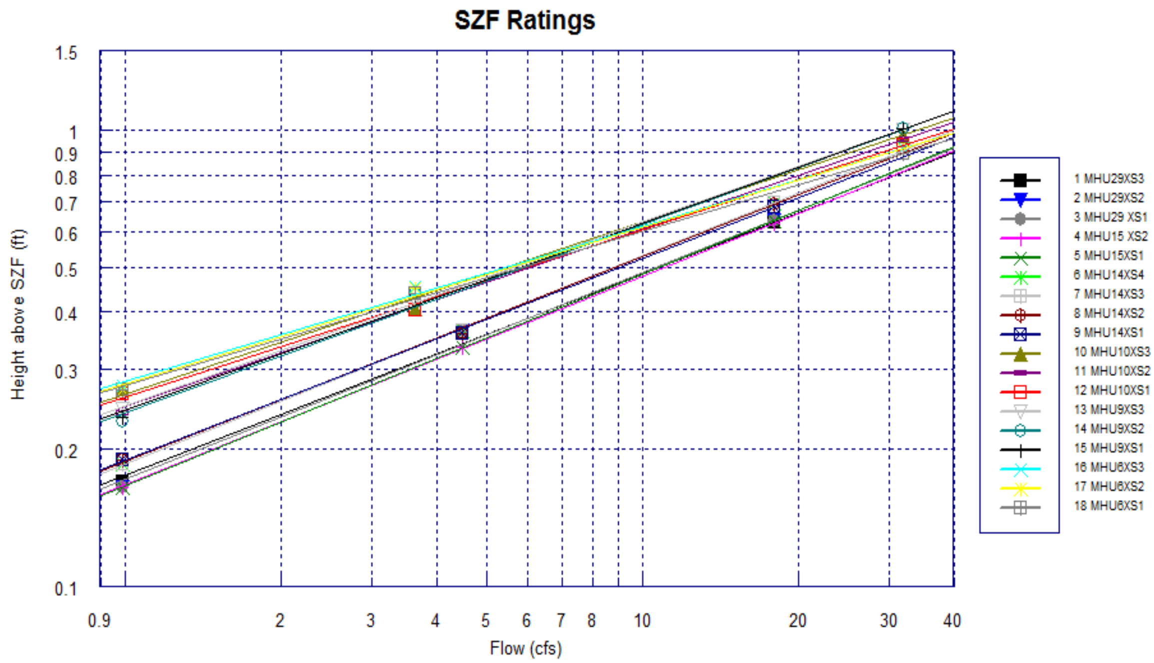

Figure E-32. Stage-at-zero flow (SZF) log stage–log streamflow rating curves for each cross section in the 1-D SEFA model for the South Fork Sproul Creek.

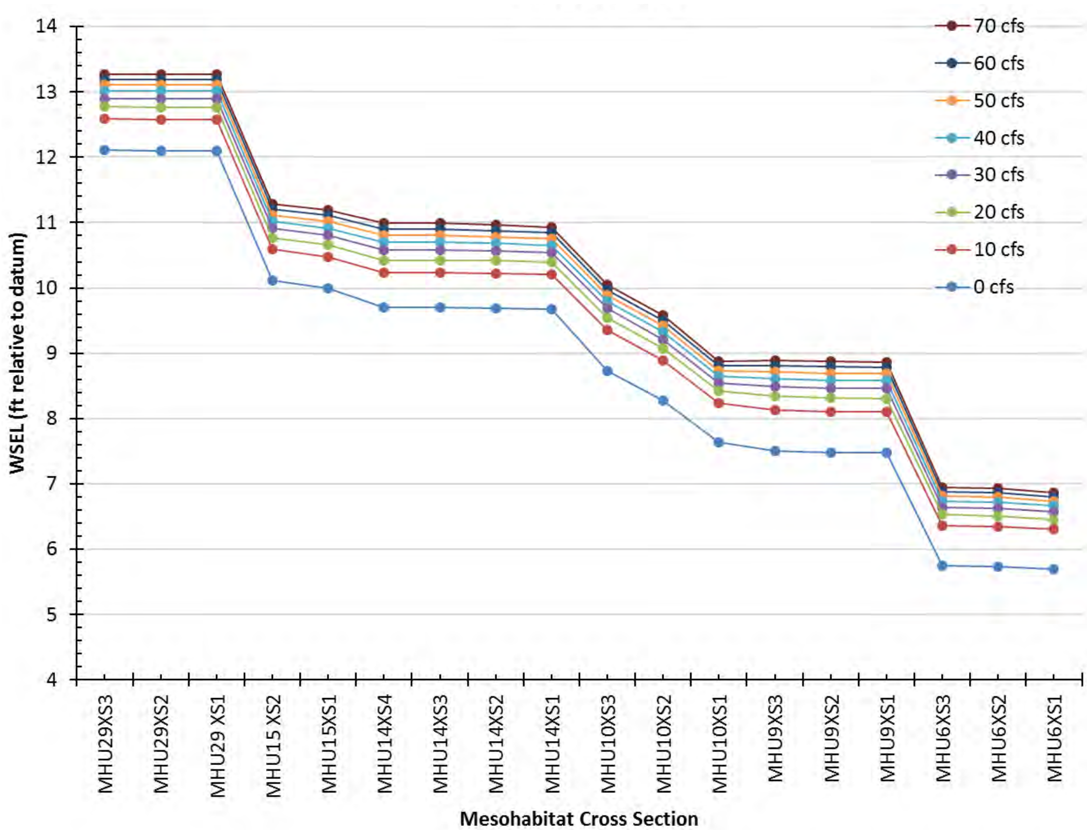

Figure E-33. Simulated WSEL from the 1-D SEFA hydraulic model for the Upper South Fork Sproul Creek study reach. Cross sections are in order from upstream to downstream (left to right). The model output simulated WSEL at 1 cfs increments; here we present data in 10 cfs increments for visualization purposes.

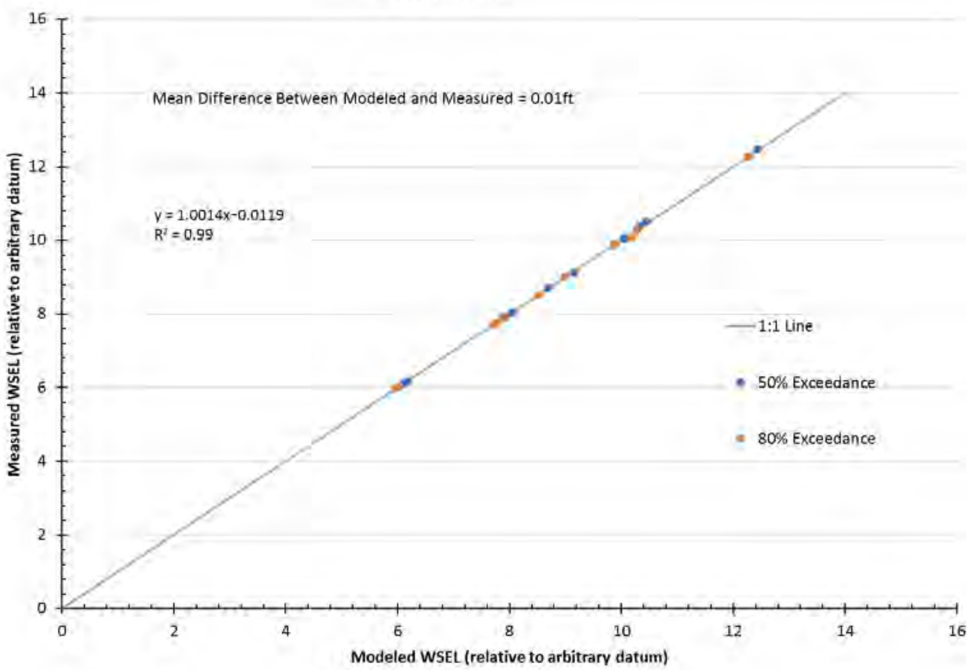

Figure E-34. Validation of modeled WSEL to measured WSEL. Modeled data was performed using data from 20% exceedance flows, and measured data were collected at 50% and 80% exceedance flows. Each data point from each streamflow category represents a different cross section.

5.2 Velocities

Velocities were successfully modeled for flows from 0–70 cfs at 1 cfs increments at each cross section (Figure E-35 through Figure E-52). Modeled velocities were visually inspected, in consultation with Thomas Payne, for irregularities or unreasonable modeled values. Comparing the field-measured streamflows (first streamflow in the legends of Figure E-35 through Figure E-52) to the modeled streamflows provided one check of model accuracy. Few (< 10) irregularities were found, and were typically areas where high negative flow values were modeled.

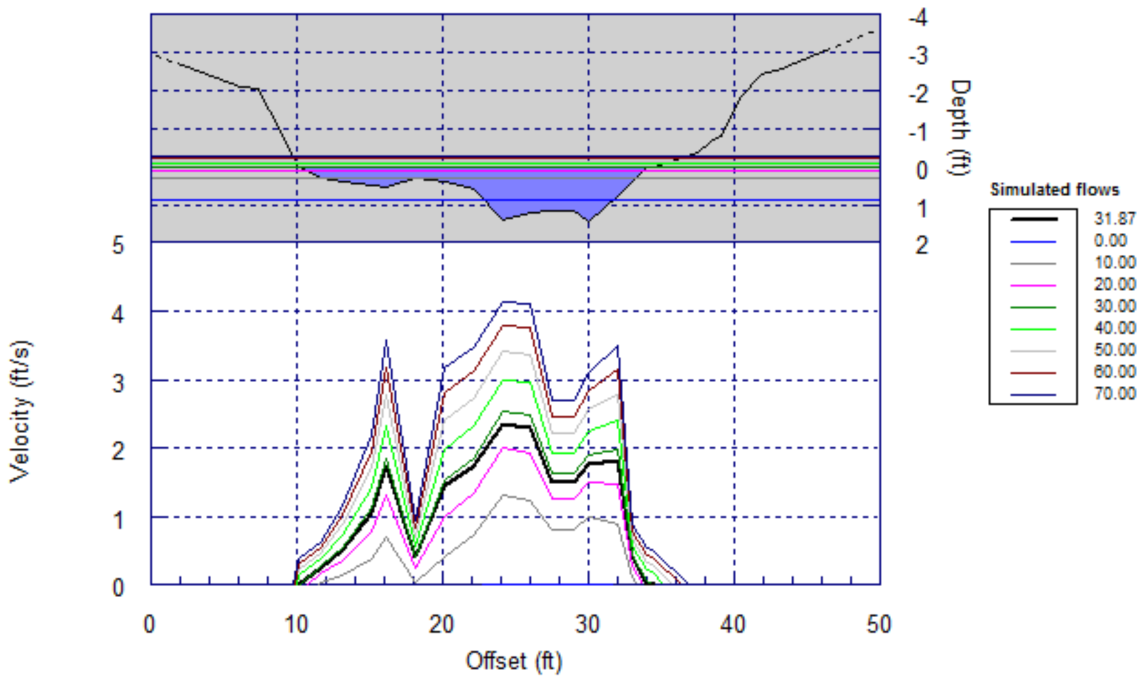

Figure E-35. Modeled velocities, WSEL's, and bed depth profile for MHU6XS1 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

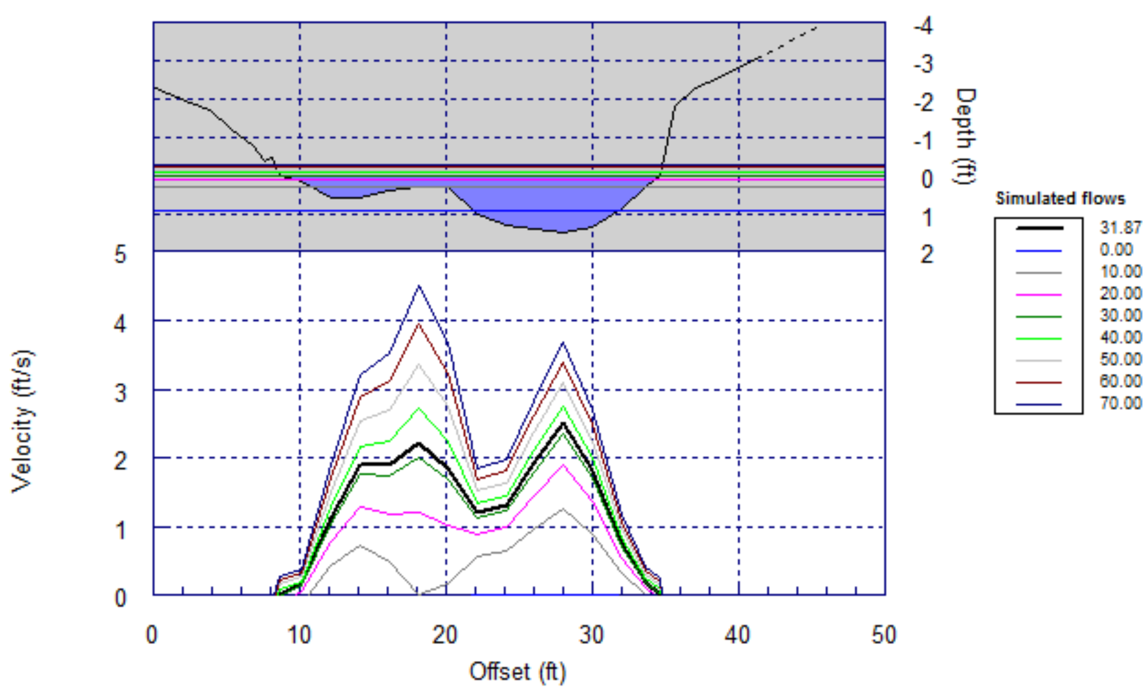

Figure E-36. Modeled velocities, WSEL's, and bed depth profile for MHU6XS2 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

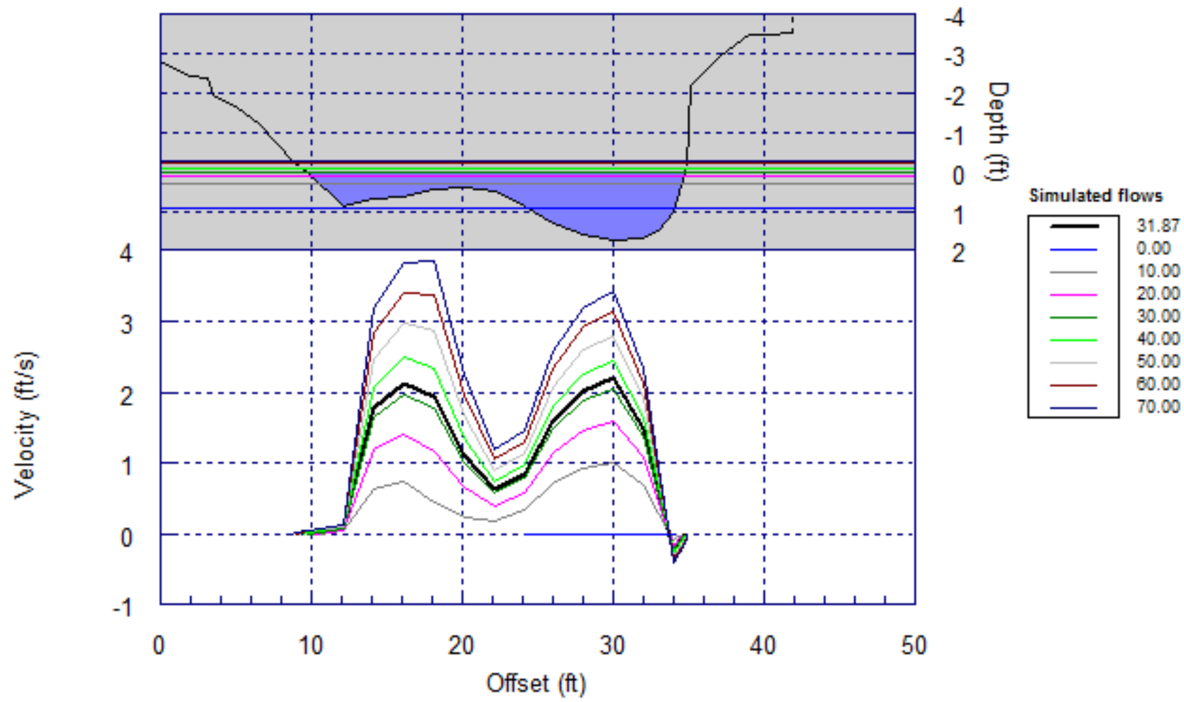

Figure E-37. Modeled velocities, WSEL's, and bed depth profile for MHU6XS3 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

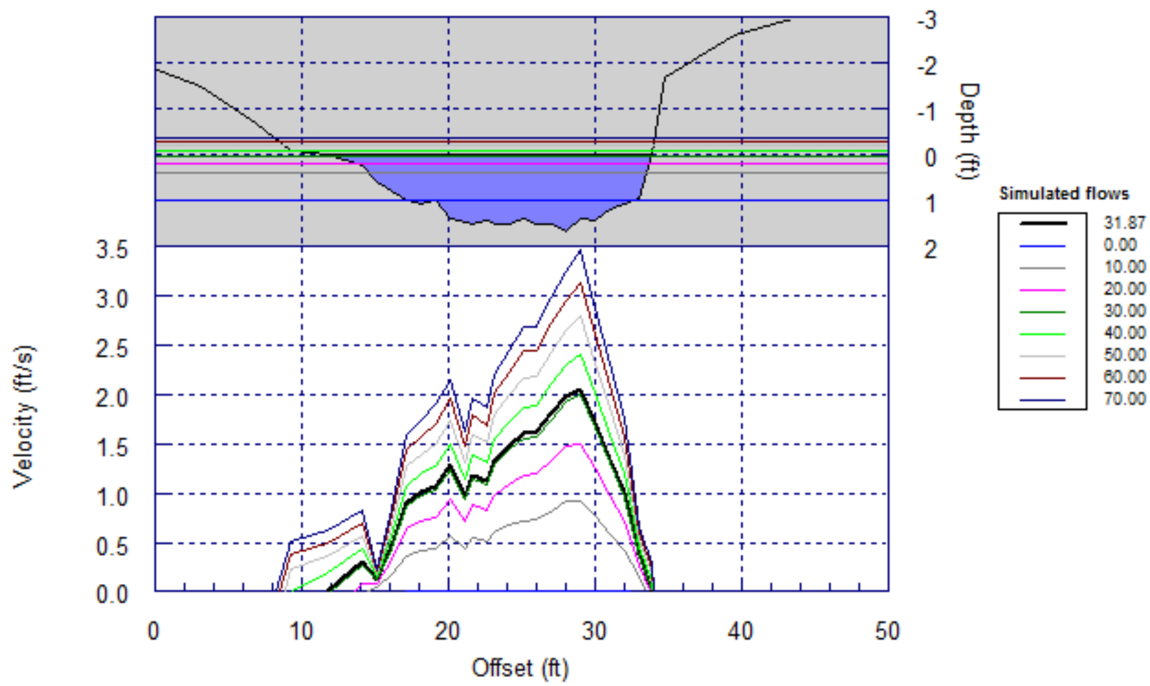

Figure E-38. Modeled velocities, WSEL's, and bed depth profile for MHU9XS1 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

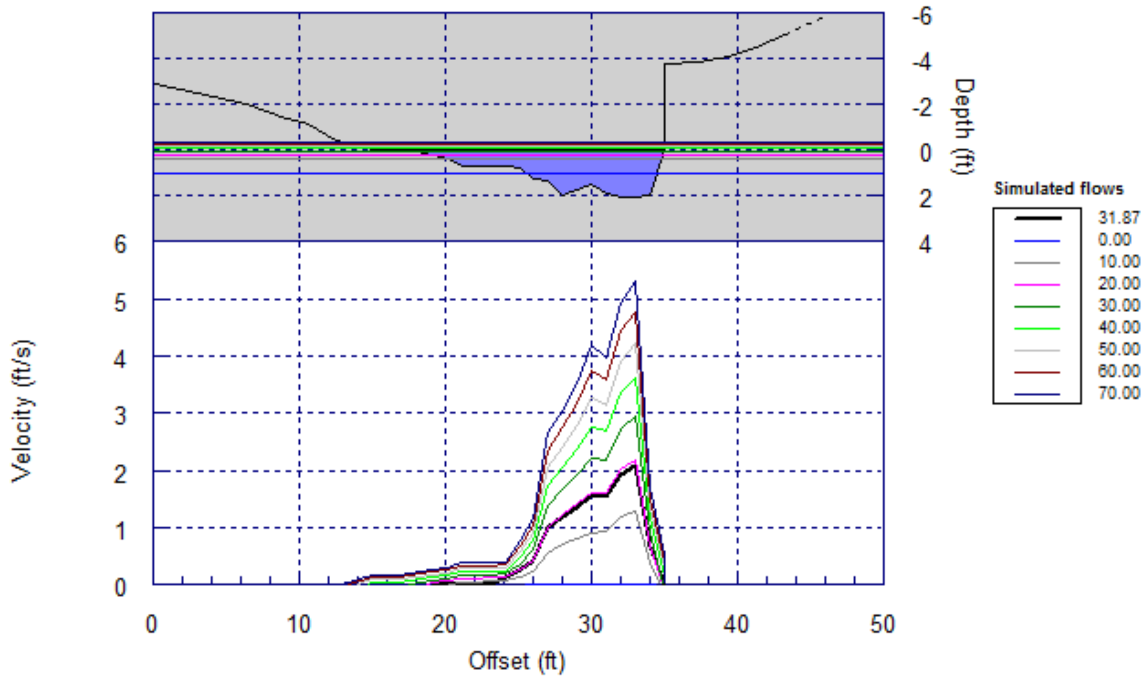

Figure E-39. Modeled velocities, WSEL's, and bed depth profile for MHU9XS2 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

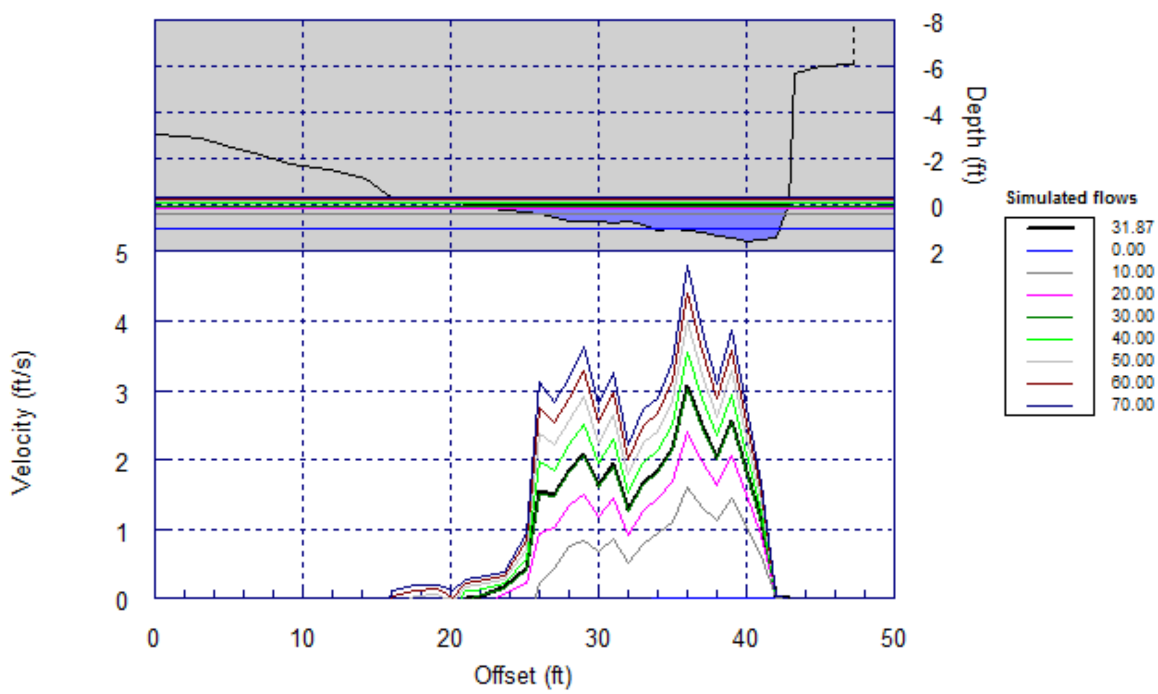

Figure E-40. Modeled velocities, WSEL's, and bed depth profile for MHU9XS3 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

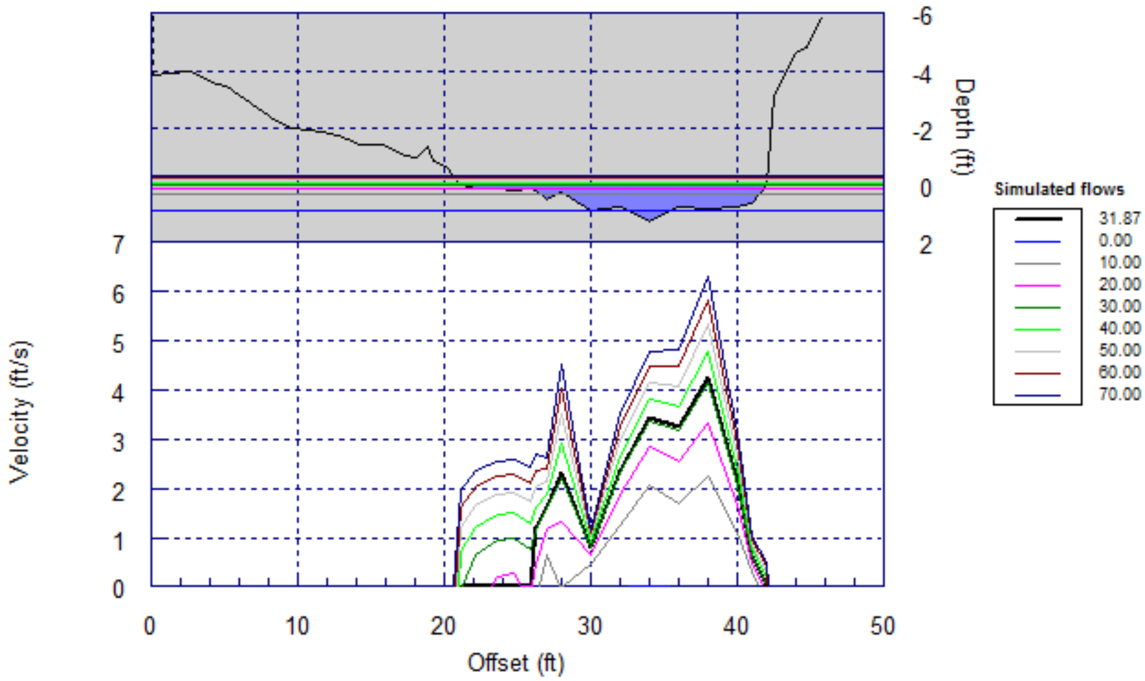

Figure E-41. Modeled velocities, WSEL's, and bed depth profile for MHU10XS1 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

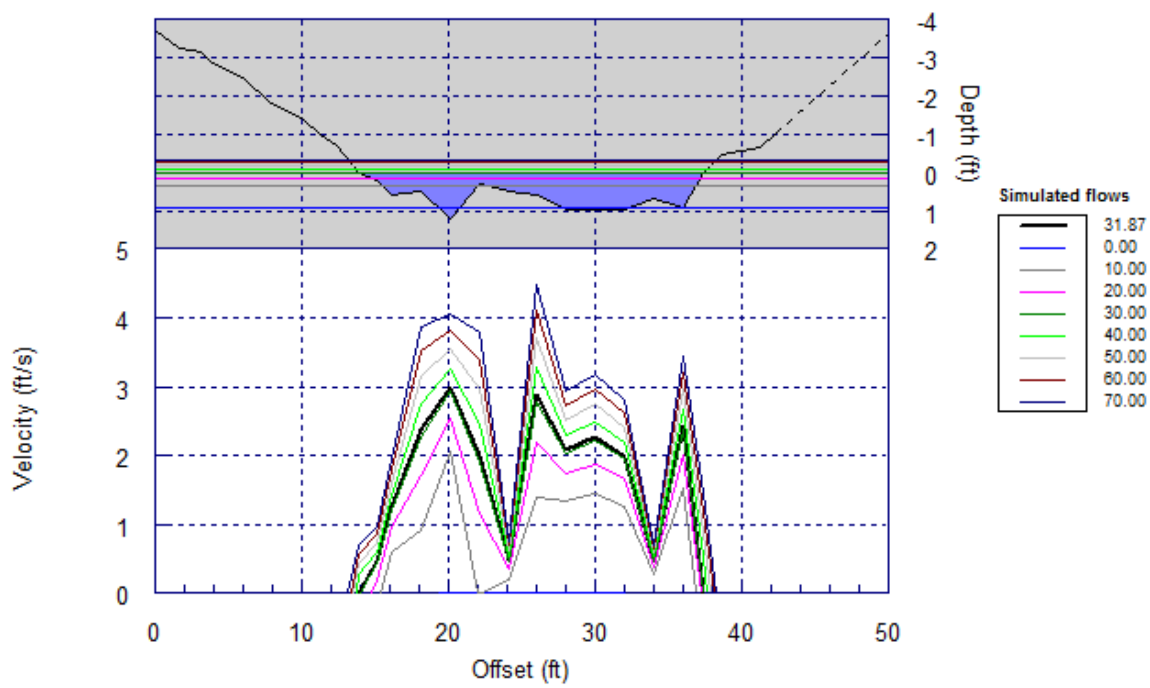

Figure E-42. Modeled velocities, WSEL's, and bed depth profile for MHU10XS2 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

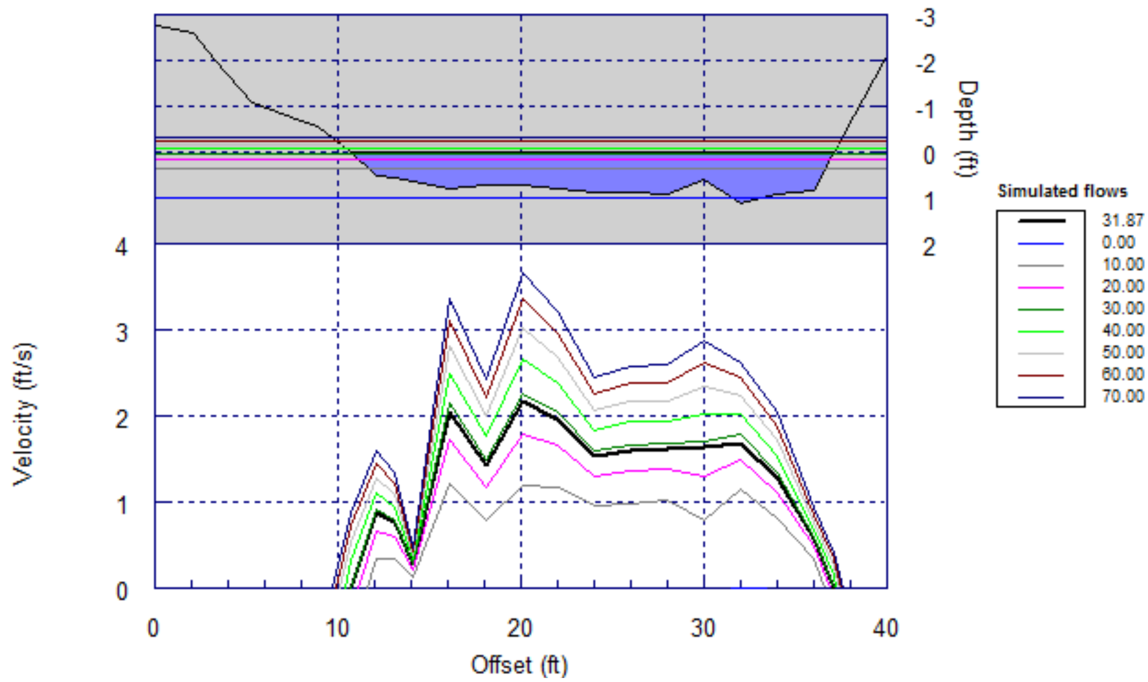

Figure E-43. Modeled velocities, WSEL's, and bed depth profile for MHU10XS3 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

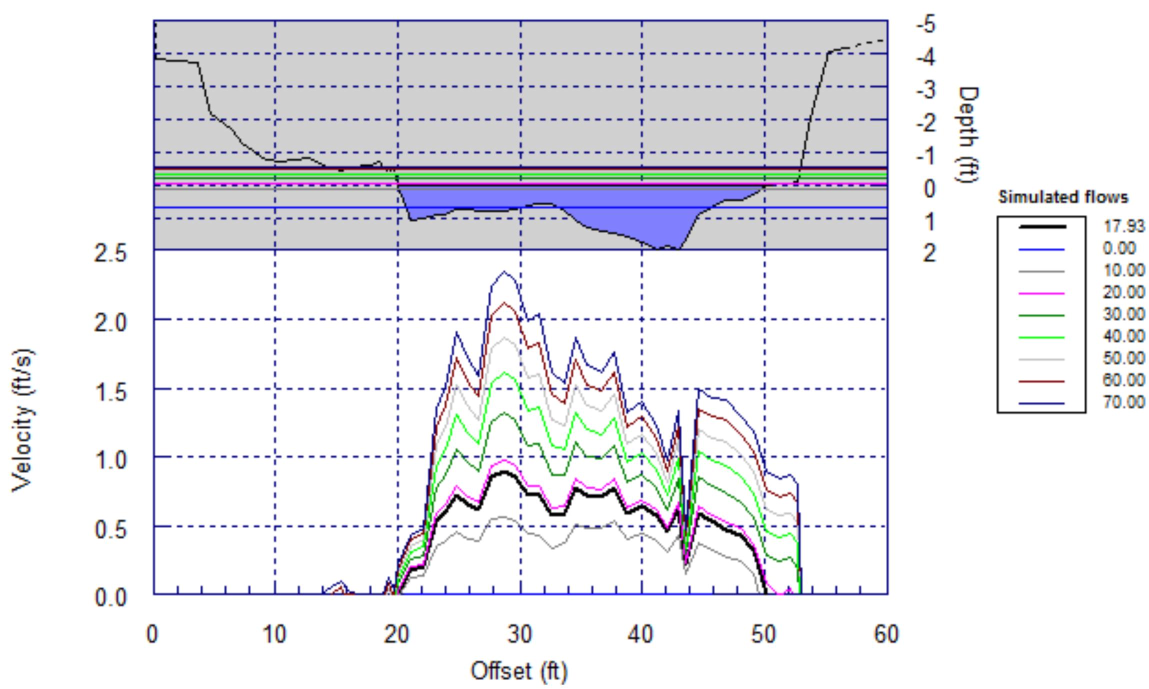

Figure E-44. Modeled velocities, WSEL's, and bed depth profile for MHU14XS1 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

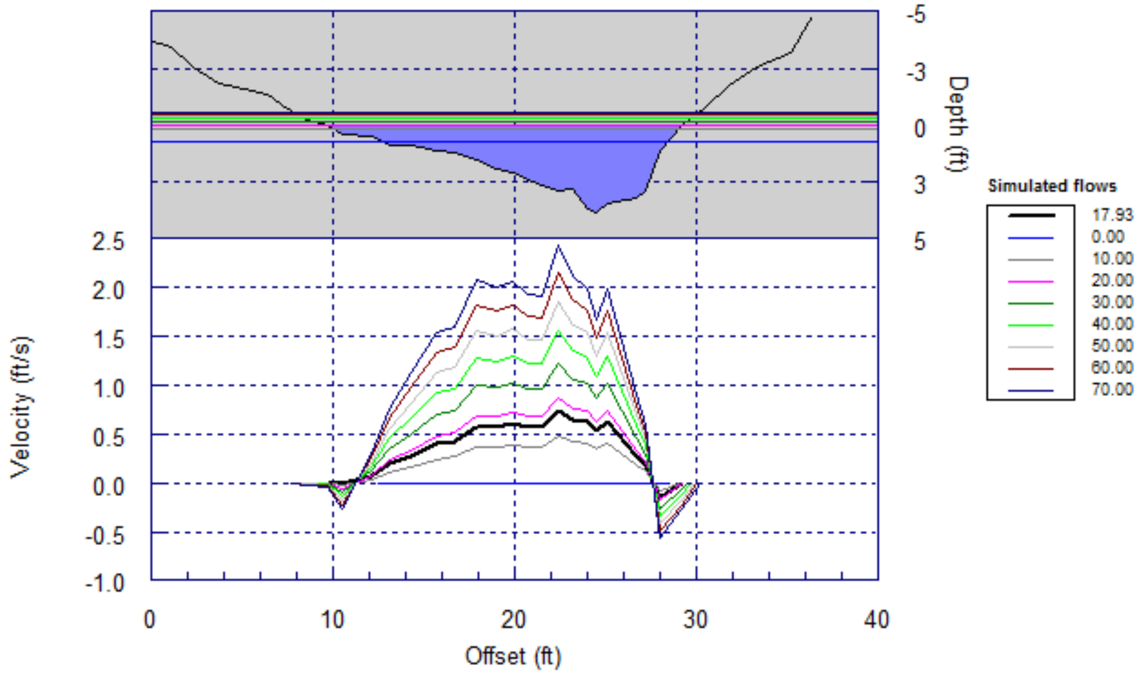

Figure E-45. Modeled velocities, WSEL's, and bed depth profile for MHU14XS2 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

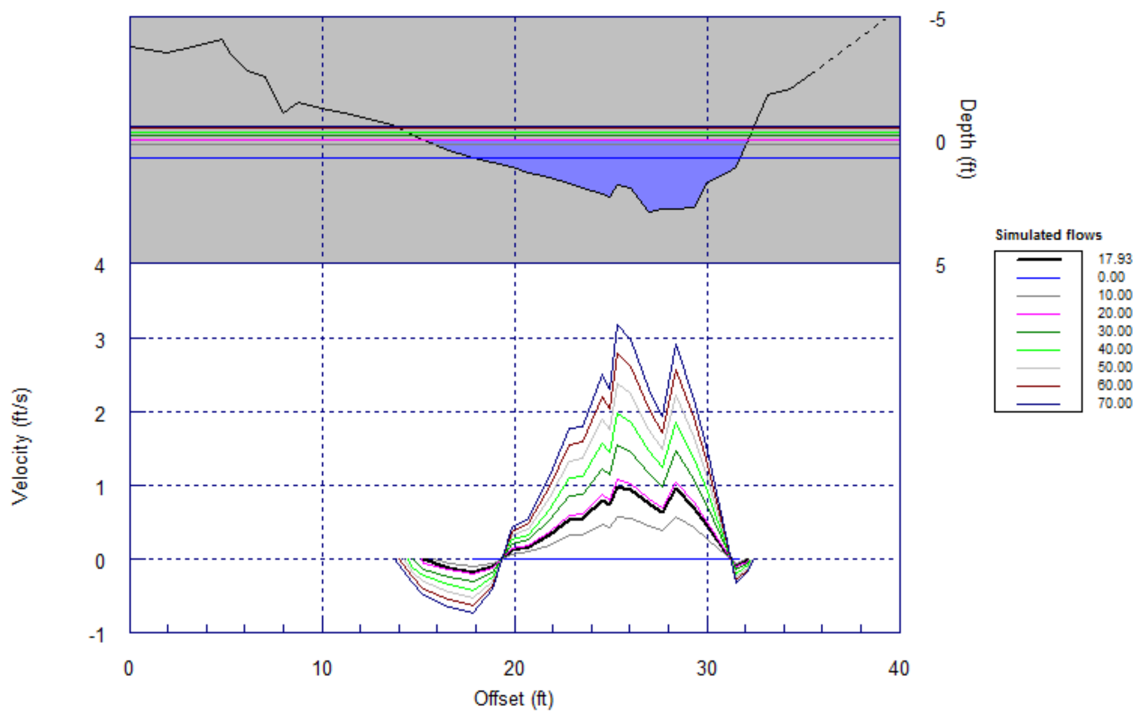

Figure E-46. Modeled velocities, WSEL's, and bed depth profile for MHU14XS3 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

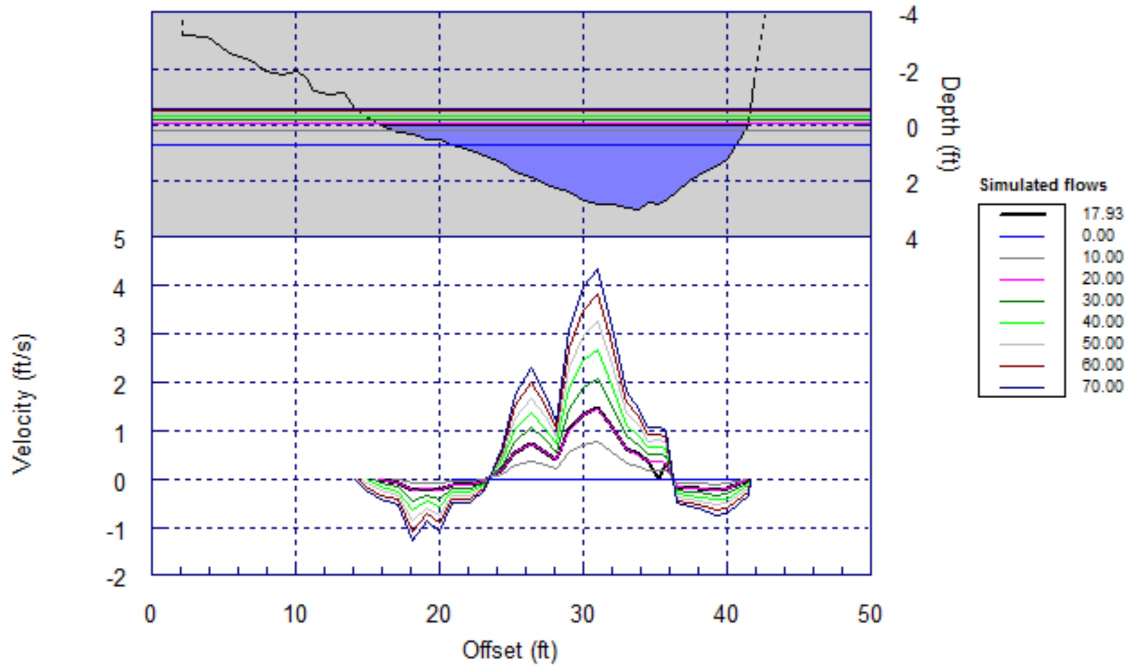

Figure E-47. Modeled velocities, WSEL's, and bed depth profile for MHU14XS4 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

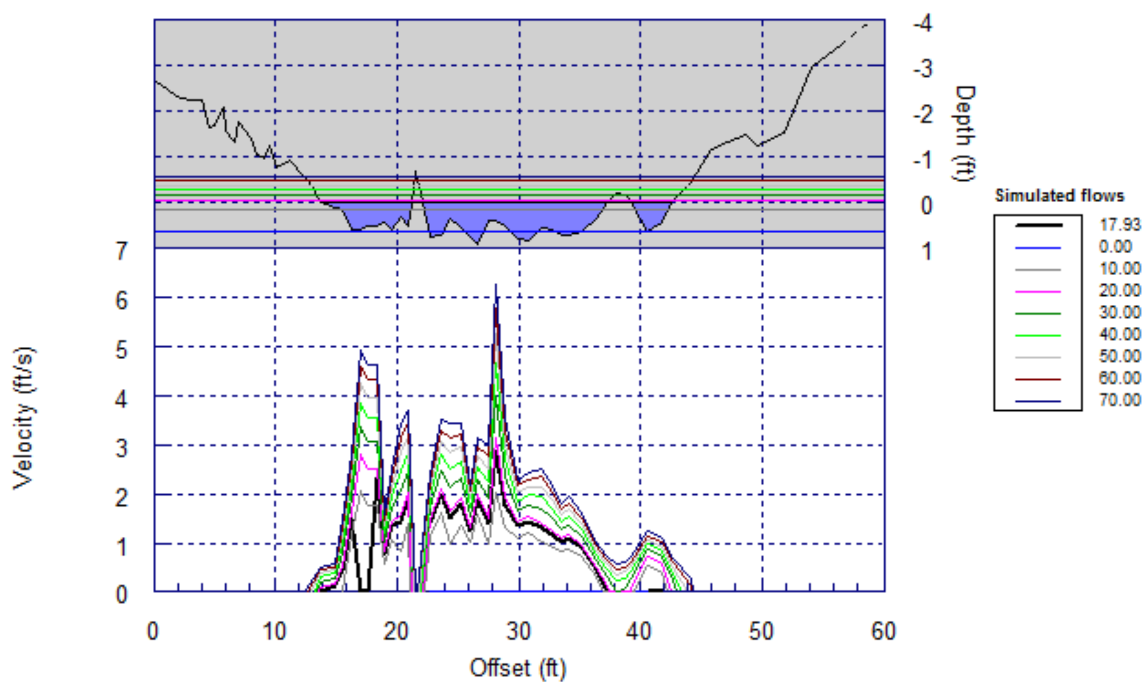

Figure E-48. Modeled velocities, WSEL's, and bed depth profile for MHU15XS1 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

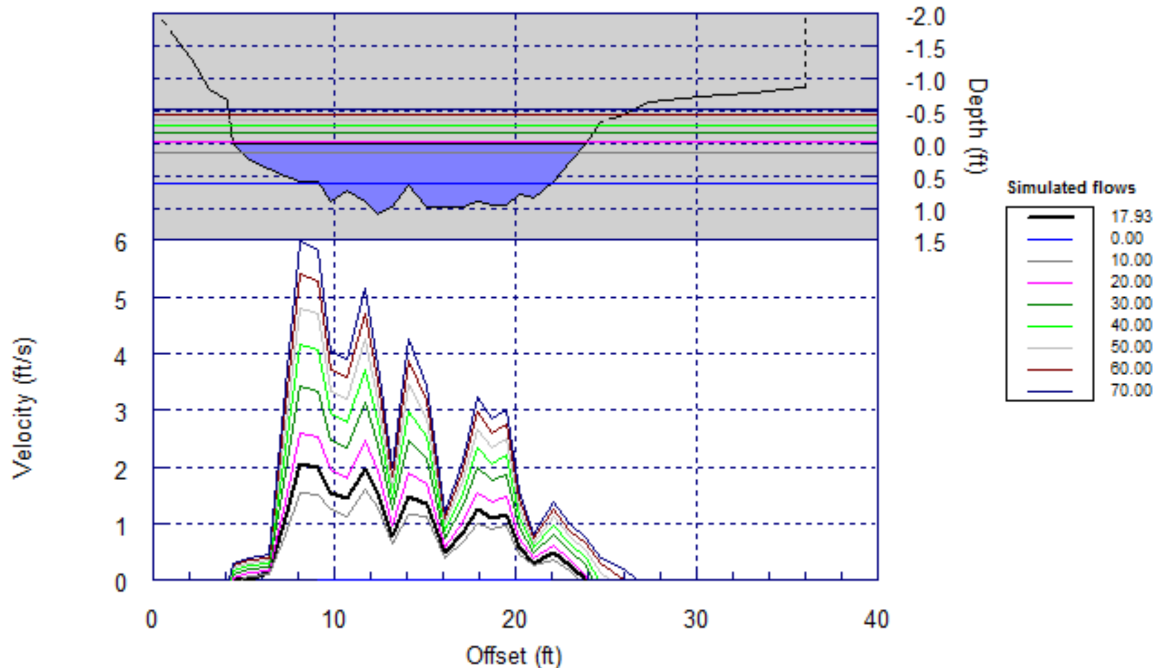

Figure E-49. Modeled velocities, WSEL's, and bed depth profile for MHU15XS2 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

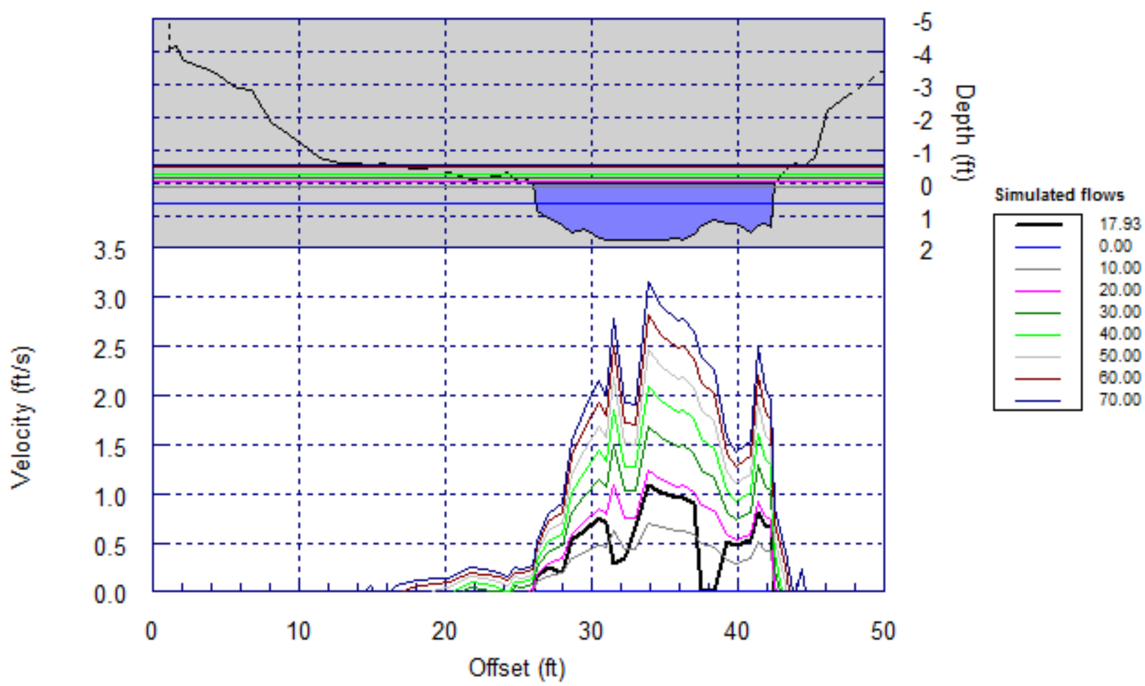

Figure E-50. Modeled velocities, WSEL's, and bed depth profile for MHU29XS1 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

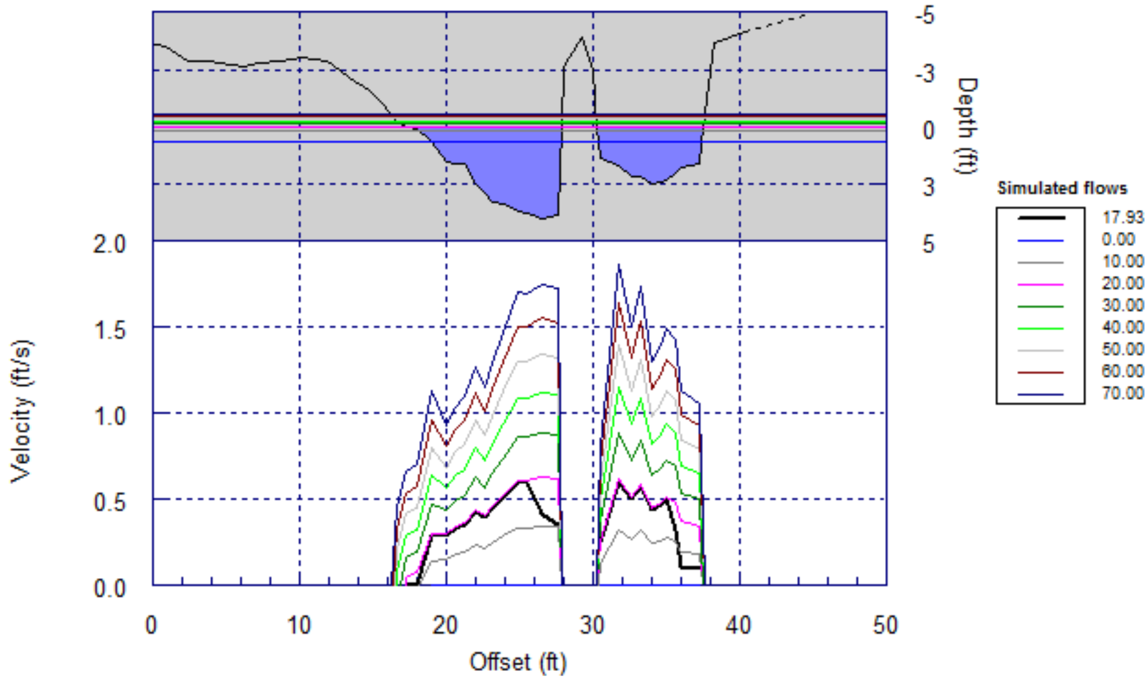

Figure E-51. Modeled velocities, WSEL's, and bed depth profile for MHU29XS2 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

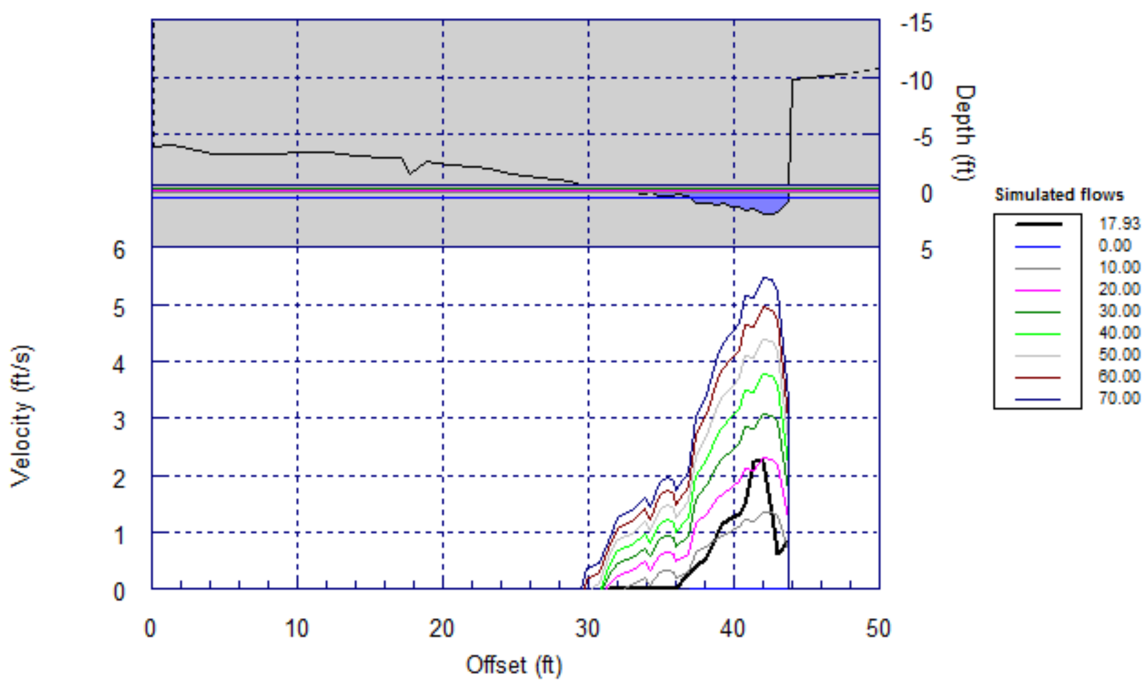

Figure E-52. Modeled velocities, WSEL's, and bed depth profile for MHU29XS3 at the South Fork Sproul Creek 1-D modeling reach. Velocity and WSEL were modeled at 1 cfs increments from 0–70 cfs for habitat modeling and presented in 10 cfs increments here for clarity. Offset is the distance (ft) from left bank pin of the cross section.

Velocity was calibrated within SEFA via the use of the velocity distribution factor editor. Seven cross sections had velocity adjustment factors (VAF) outside of the recommended range (0.5–1.5, Figure E-53) at higher flow rates. However, all the velocities modeled in these cross sections were realistic values, and the higher VAF's were driven by habitat complexity that caused negative velocities during the survey. For example, in MHU14XS2 through MHU14XS4, there was an eddy formed on either side of the channel that created negative values, which resulted in higher VAF's for those cross sections. However, modeled velocities for those cross sections are in realistic ranges, and further adjustments to the VDF's would result in unrealistic velocity values (i.e. −7 ft/s). Similarly, in MHU29XS2 and MHU29XS3, a large woody debris snag caused large eddies, resulting in high VAF's.

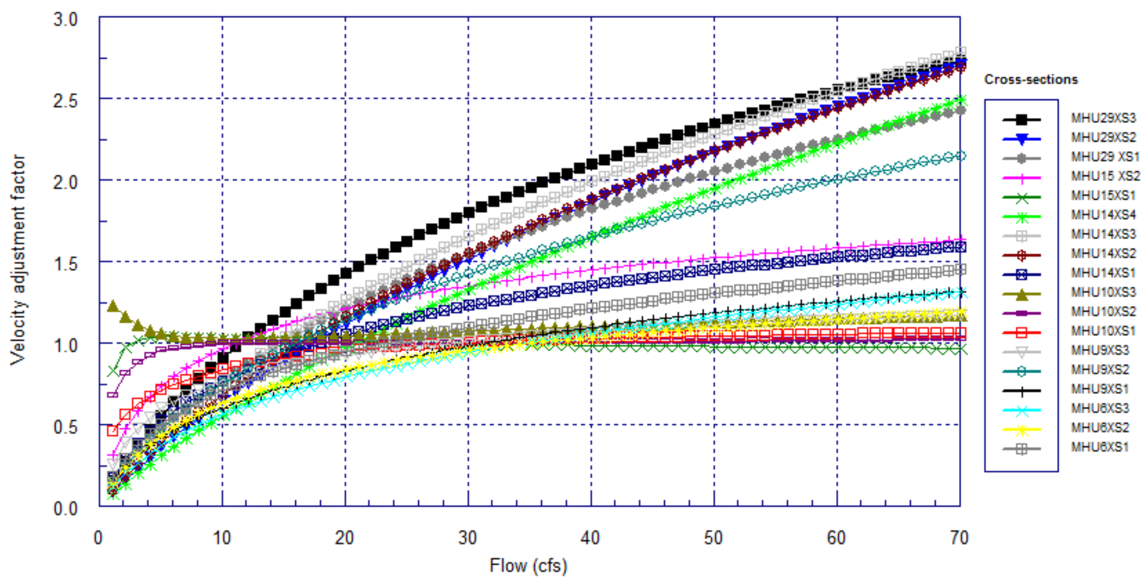

Figure E-53. Velocity adjustment factors for each cross section at the 1-D SEFA model reach.

5.3 Streamflow–habitat Relationships

Weighted usable area was modeled at 1 cfs increments from 0–70 cfs for the entire reach and for riffles and pools separately. Reach-wide WUA for steelhead spawning increased from 0 cfs to 30 cfs then decreased (Figure E-54). Similar curves for Coho Salmon and Chinook Salmon spawning habitat was observed, but with a maximum habitat value at 23 cfs and 38 cfs, respectively (Figure E-54). Juvenile steelhead had the highest absolute WUA values, which increased from 0 cfs to 35 cfs for large juveniles and 31 cfs for small juveniles. Juvenile Coho Salmon WUA increased briefly from 0 to 1 cfs, then decreased for the remainder of the modeled streamflows (Figure E-54). Steelhead fry WUA also increased sharply from 0 cfs until it was maximized at 4 cfs and slowly decreased until 50 cfs, where it remained stable for the remainder of the modeled flows. Coho fry WUA followed a similar pattern to that of steelhead, but it was maximized at 1 cfs, and decreased much faster and reached a stable value from 30–70 cfs. Modeled productive BMI WUA was similar to the pattern of WUA for juvenile steelhead, but was maximized at a lower stream flow (17 cfs).

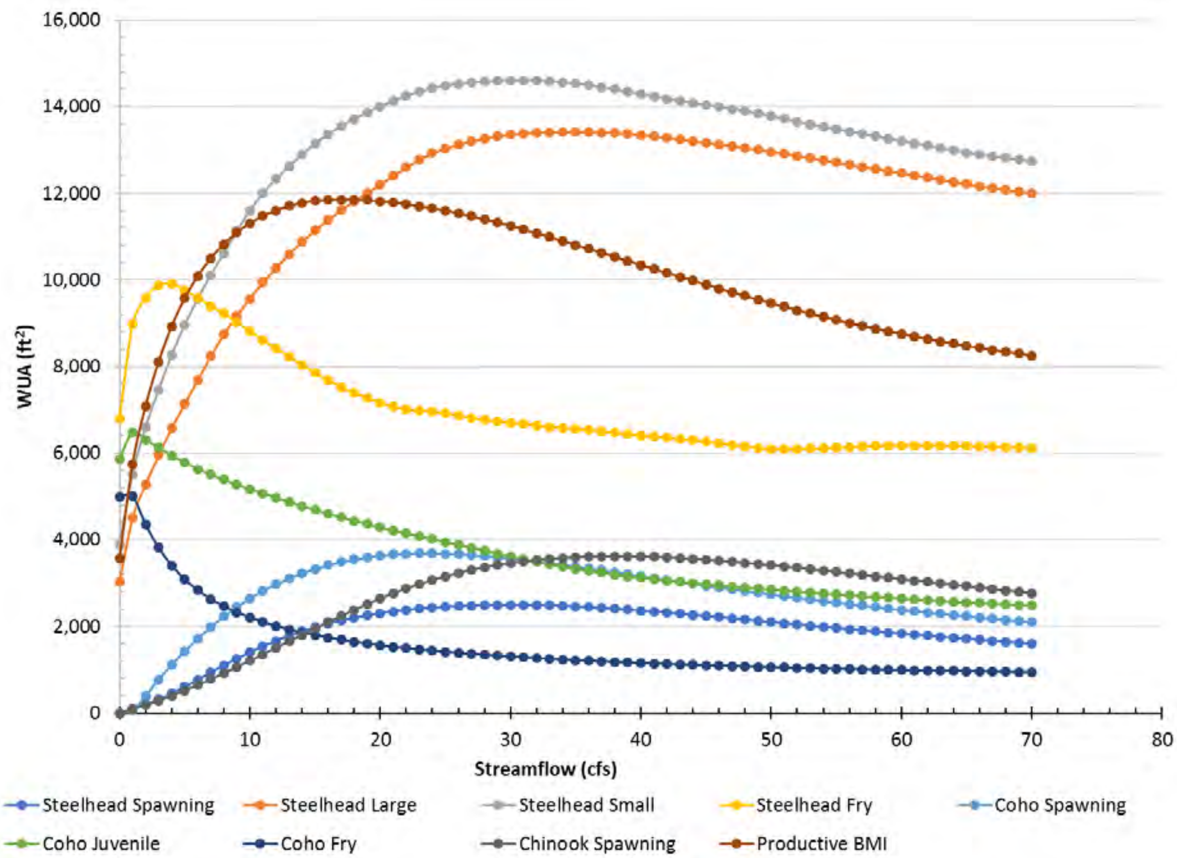

Figure E-54. Reach-wide modeled WUA for freshwater life history stages of steelhead, Coho Salmon, Chinook Salmon (spawning only), and BMI in the South Fork Sproul Creek.

WUA for riffle habitat was modeled and is presented in Figure E-55. Modeled adult spawning habitat for steelhead increased from 0 cfs to 32 cfs, from 0 to 23 cfs for Coho Salmon, and from 0 to 30 cfs for Chinook Salmon. WUA for both species then declined for the remainder of modeled streamflows. Juvenile steelhead habitat (large and small) had the highest absolute WUA in riffle habitat, and habitat was maximized at 37 and 32 cfs, respectively. Juvenile Coho Salmon WUA increased slightly from 0–5 cfs, then decreased for the remainder of modeled streamflows. Modeled WUA for steelhead fry increased from 0–3 cfs, then decreased. Coho Salmon fry modeled habitat was maximized at 1 cfs (similar to reach-wide) and then decreased for the remainder of modeled streamflow. BMI WUA increased from 0–17 cfs and then decreased for higher modeled streamflows.

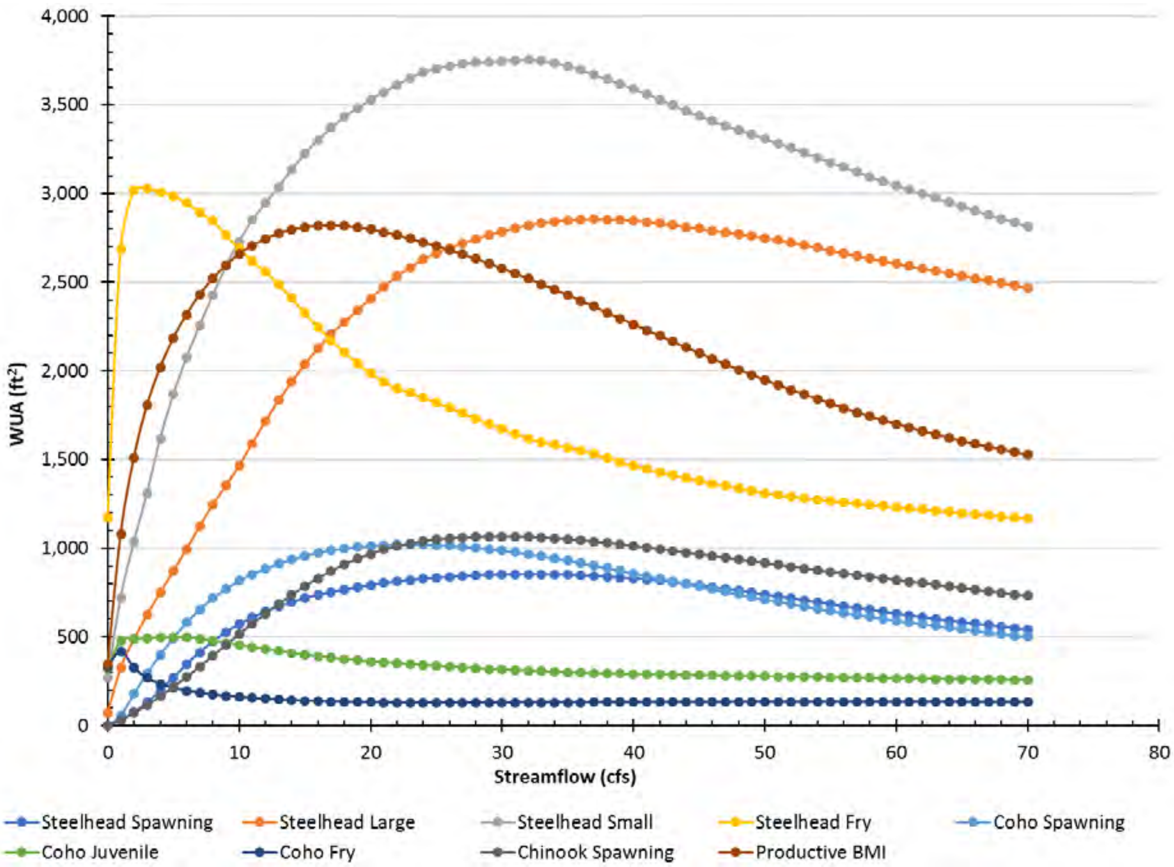

Figure E-55. Riffle habitat modeled WUA for freshwater life history stages of steelhead, Coho Salmon, Chinook Salmon (spawning only), and BMI in the South Fork Sproul Creek.

Modeled pool habitat had higher absolute values than those in riffles, but the shape of curves for each species and life history stage were similar (Figure E-56). Spawning habitat for all species was similar to reach-wide and riffle habitats, and was maximized at 30 cfs for steelhead, 23 cfs for Coho Salmon, and 40 cfs for Chinook Salmon. Juvenile steelhead habitat was maximized at 32 cfs for large juveniles and 30 cfs for small juveniles, while modeled juvenile Coho Salmon WUA was maximized at 1 cfs. Fry habitat for steelhead was maximized at 5 cfs while Coho Salmon fry habitat was highest at the lowest streamflow (0 cfs). BMI WUA was similar to that modeled for the entire reach and for riffles, and was maximized at 17 cfs.

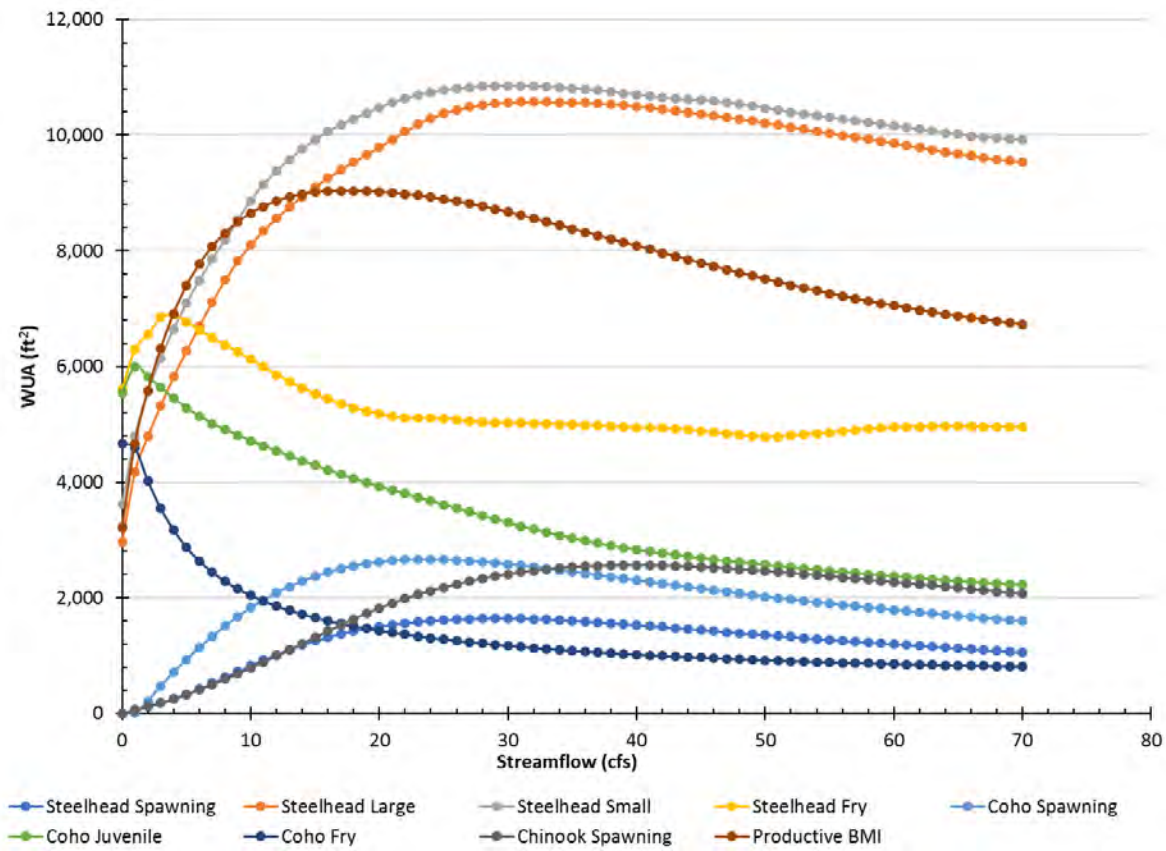

Figure E-56. Pool habitat modeled WUA for freshwater life history stages of steelhead, Coho Salmon, Chinook Salmon (spawning only), and BMI in the South Fork Sproul Creek.

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