CALIFORNIA TROUT

APPENDIX D: RIFFLE CREST THALWEG RATING CURVES for UPPER SOUTH FORK and UPPER MAINSTEM SPROUL CREEK STUDY REACHES

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SEPTEMBER 1, 2017

Introduction: The riffle-pool hydraulic unit

The majority of California's coastal watersheds that support anadromous salmonid populations exhibit relatively similar hydrological and geomorphic characteristics:

- a Mediterranean climate characterized by distinctly seasonal precipitation with winter rainstorms of moderate intensity and a prolonged dry season;
- stream channels dominated by a step-pool (>5% gradient) or a riffle-pool (<5%) channel morphology, moderately confined channels, substrate of bedrock and coarse-grained alluvium, and frequent large wood influence;
- a wide variation from year to year in mean annual precipitation;
- stream channels in a prolonged state of recovery from the sediment impairment legacy of the 1955 and 1964 floods.

This uniformity in physical habitat across the region offers a key attribute for quantifying the hydraulic performance of streams, and protecting freshwater life-stages of salmonid species.

A single riffle-pool unit, which we refer to as a hydraulic unit (Figure D-1), is also a basic morphological and salmonid habitat unit ubiquitous of streams in California's coastal watersheds (Langbein and Leopold 1968; Lisle 1979, 1982, 1987; Richards 1982; Trush et al. 2000). Lisle (1982) states that "riffle-pool sequences are often created by [point] bars extending over the full channel width. …At low to moderate flows, the submerged bar crest forms the control section for the pool upstream and often forms the downstream riffle crest." According to Clifford et al. (2002): "In current conservation literature, the most important bedform assemblage in gravel and mixed-load rivers is the riffle-pool sequence. Riffle-pool features are quasi-regular undulations in bed topography, associated with fast, shallow flow over riffles, and slower, ponded flow in pools, at low to moderate flows." And Leopold et al. (1964) stated:

> *"The alternating pool and riffle is present in practically all perennial channels in which the bed material is larger than coarse sand, but it appears to be most characteristic of gravel-bed streams."*

Hydraulic units manifest distinctive hydraulic patterns of water depths and velocities, which in turn create and sustain salmonid microhabitats. Riffles provide higher velocity, well-mixed water and sustain abundant, productive algal communities that support a rich benthic-invertebrate community. Pools provide juvenile salmonid rearing habitat resulting from bio-energetically favorable velocity shear zones created by velocity 'cores' extending into pool slack-water and delivering food resources. Deep pools offer juvenile refugia and adult holding areas. Pool tails provide well-sorted gravels, hyporheic flow, and accelerating water velocities favored for spawning. Nueman and Newcombe (1977) described typical habitat features within hydraulic units in this way:

> *"A riffle-pool sequence is the basic requirement of the productive salmon stream…. Juvenile rearing habitat is perhaps the most vulnerable phase of the salmonid life-cycle and rearing requirements are the most difficult to understand. …Rearing fish require an easily exploitable food source and living space in streams. Food production, in the form of benthic invertebrates, occurs mainly in riffles and fish inhabit pools (and to a lesser extent, riffles) where they feed on drifting insects."*

Hydraulic units link streamflow hydraulics to salmonid microhabitats utilized by individual fish (Trush et al. 2000). The idealized hydraulic unit is rarely found in nature, because naturally occurring features (e.g., bedrock exposures, large wood 'jams', etc.) perturb the idealized channel form shown in Figure D-1 (Trush et al. 2000). In addition, variability between hydraulic units is a key concept that is addressed in both stream ecology and instream flow management. The relationship between streamflow and salmonid spawning or rearing habitat is a function of sediment size, gradient, and channel morphology (Bovee 1978, Sullivan et al. 1987; Everest et al. 1987; Sebastian et al. 1991; Kondolf and Wolman 1993; Buffington and Montgomery 2001; Buffington et al. 2004, Carling at al. 1994, Emery et al. 2003. The effect of channel morphology on the relationship between streamflow and rearing habitat is particularly relevant to spring and summer diversions as coarser, narrow channels may provide suitable rearing habitat at lower flows than wider, fine grained channels (Sullivan et al 1987; Lisle 1986).

<u>The riffle crest as a natural weir and hydraulic control</u>

In the moderate-to-low baseflows, the stability of hydraulic patterns within a riffle-pool sequence stems from the hydraulic 'control' exerted at the riffle crest (Clifford et al. 2002). The riffle crest controls the water surface elevation, depth, and velocities of the upstream pool or run, and marks the boundary of the downstream riffle (Figure D-1). The active channel cross section at the riffle crest hydraulically controls the magnitude and shape of habitat rating curves used in most instream flow investigations. At moderate streamflows a decelerating velocity core extends into and through the pool body, creating eddies, backwaters, and shear zones, then accelerates as the pool ramps to the pool tail. As streamflow recedes to zero, hydraulic connectivity is lost between consecutive pools, exposing the channelbed and riffle between them.

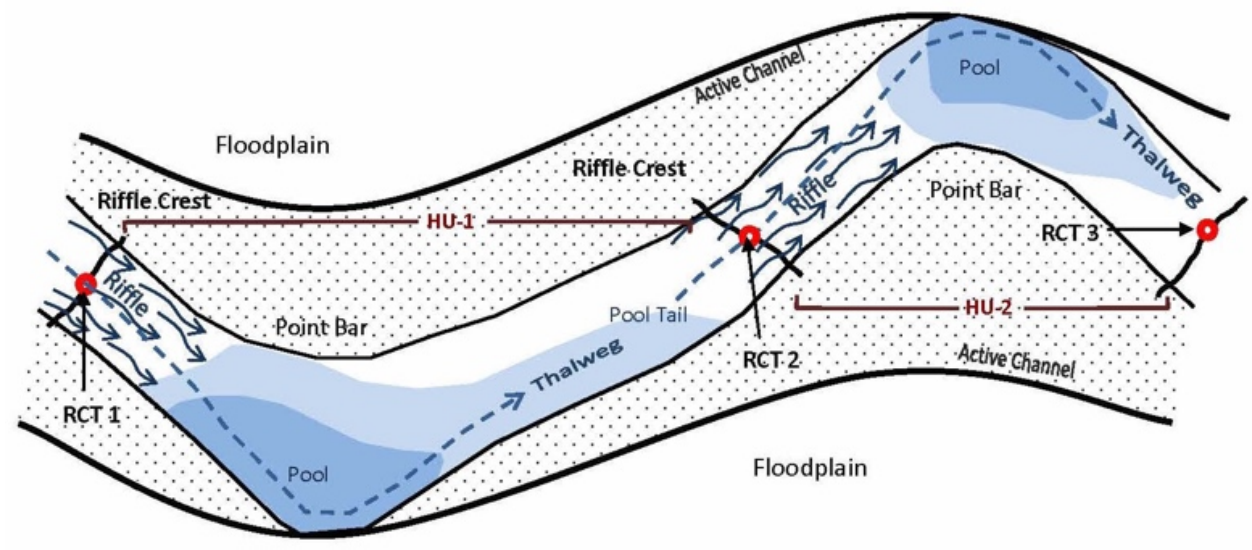


Figure D-1. Plan-view of two pool-riffle sequences (or 'hydraulic units'), showing the pathway of the thalweg through the pool and crossing over into the downstream riffle. HU=Hydraulic Unit; RCT=Riffle Crest Thalweg. Figure adapted from Dietrich (1987) Figure 8.1c.

The lowest channelbed elevation along a stream cross-section surveyed at the top of a riffle is the **riffle crest thalweg (RCT)** (Figure D-2). The RCT is typically located at the channel cross-over, where the thalweg pathway transitions from one bank toward the opposite bank, and is the highest thalweg elevation within the hydraulic unit (Figure D-3). If streamflow was entirely cut-off, the resultant elevation of the pool water surface would coincide with the RCT channelbed elevation (i.e., RCT depth would be zero ft deep, and identified as the 'point-of-zero flow' by hydrographers). The riffle crest thalweg is singularly the most identifiable physical location for measuring a stream's depth. It also serves as the benchmark for measuring residual pool depths (Bathurst 1981; Lisle 1987; Hilton and Lisle 1993). The RCT has been greatly under-utilized as a critical linkage between stream channel hydraulics and habitat characteristics of the stream, but is nevertheless an ideal independent variable for quantifying hydraulic habitat.

Figure D-2. A typical riffle crest from Sproul Creek, with accelerating water velocity directed toward the riffle crest thalweg (indicated by "x").

Riffle crest cross-sections bear a strong resemblance to engineered weirs. Their similarity in shape extends to their similarity in function. This commonality was observed by Seddon in the early 1900's (from Richards 1976). Based on this resemblance, in assessing instream habitat and developing diversion protocols, the best location to measure a reference stream depth is at the thalweg of riffle crests (Figure D-3) i.e., the depth of the weir.

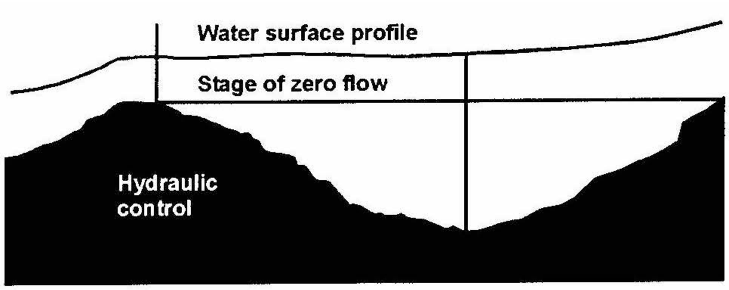


Figure D-3. Figure 4-27 from Bovee et al. (1988), illustrating the typical channel bedform exhibited by a pool-riffle morphology, the hydraulic control exerted by the riffle crest, and the stage of zero streamflow corresponding to the thalweg of the riffle crest.

Understanding how weirs function hydraulically helps explain how riffle crests function. Engineered weirs come in two basic shapes: rectangular and triangular (Figure D-4). Others combine both shapes, generally a rectangular weir stacked on top a triangular weir, which is considered a 'compound weir.' Both basic weir shapes behave hydraulically as power functions:

Rectangular Weir: $Q = c_d\, L\, h^{3/2}$

Triangular V-Notched Weir: $Q = c_d \tan(\text{Ø}/2)\, h^{5/2}$

where Q is streamflow (discharge). These power functions share two common independent variables, h and c_d. The coefficient c_d is the calibration coefficient that groups many contributing physical factors into a single value derived empirically (i.e., that balances the equation, similar to 'Manning's n'). The other common independent variable, h or 'head,' is similar to the empirically measured RCT depth. L is the width of the rectangular weir. Ø is the angle of a V-notch weir.

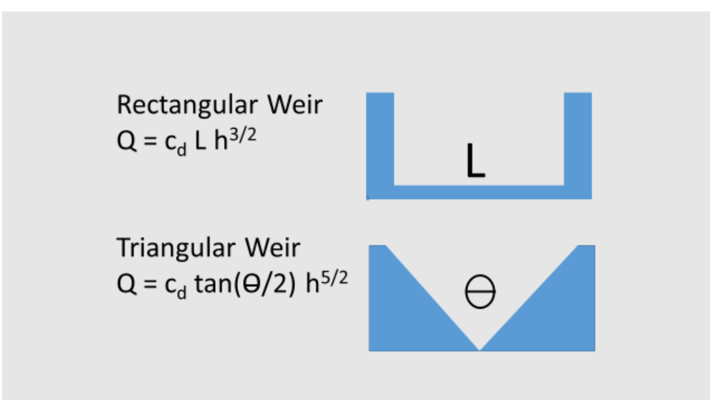


Figure D-4. Two basic engineered weir shapes.

Riffle Crest Thalweg Measurements in Sproul Creek

Three steps are required to consistently measure RCT depth in the field, using a stadia rod (i.e., not using an engineer's level):

1. Locate the riffle crest.
2. Trace the thalweg through the riffle-pool unit.
3. Locate the intersection of the thalweg and the riffle crest.

In Sproul Creek, the RCT in each hydraulic unit was thus located by identifying the highest channelbed elevation where the thalweg pathway exited an upstream pool or run and entered the downstream riffle (i.e., the thalweg located at the very crest of the riffle) (Figure 5). Water depth was measured by setting the bottom of the stadia rod at the "average" bed elevation, not forcing the stadia rod into the deepest, hydraulically dead rock crevices.

In Sproul Creek, we selected two primary study reaches for measuring RCT depths: a 2,626 ft long Upper Mainstem Sproul (UMS) reach; and a 1,961 ft long Upper South Fork Sproul Creek (USF) reach. Mesohabitat units were mapped on April 9 and 13, 2016, at the USF reach and UMS reach, respectively, following methods described in Flosi et al. (2004). Mesohabitats were then assigned hydraulic units (Tables D-1 and D-2). Thirteen hydraulic units were identified in the USF reach; and 13 hydraulic units were identified in the UMS reach (Tables 1 and 2). Both reaches had consistent hydraulic units with relatively homogenous gradients.

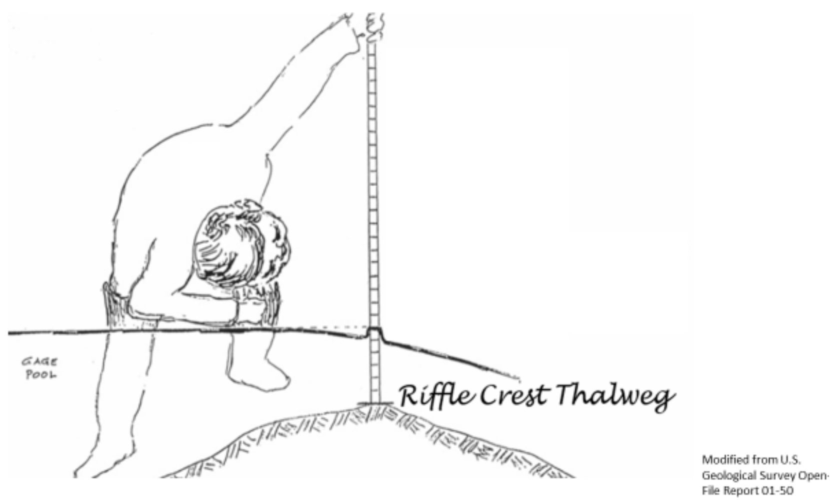


Figure D-5. Measuring riffle crest thalweg depth in a small stream. Streamflow is from left to right. Figure modified from USGS Open File Report 2001-50. Note the RCT has the highest bed elevation.

Table D-1. Mesohabitat and hydraulic units mapped on Upper Mainstem Sproul Creek.

Hydraulic Unit	Mesohabitat Unit	Habitat Unit Type	Unit Length (ft)	Cum Length (ft)
1	2-	Mid Channel Pool (Lg Stump)	130	130
	1-	Low Gradient Trans Riffle	24	154
	0	Run	66	220
2	1	Mid Channel Pool	75	295
	2	Low Gradient Riffle	15	310
3	3	Corner Scour Pool	280	590
	4	Low Gradient Riffle	45	635
4	5	Mid Channel Pool	127	762
	6	High Gradient Riffle	22	784
5	7	Mid Channel Pool (Log Structures)	209	993
	8	High Gradient Trans Riffle	41	1034
6	9	Mid Channel Pool	237	1271
	10	Low Gradient Riffle	10	1281
7	11	Run	50	1331
	12	Low Gradient Riffle	63	1394
8	13	Mid Channel Pool	184	1578
	14	Low Gradient Riffle	21	1599
9	15	Mid Channel Pool	130	1729
	16	Low Gradient Riffle	10	1739
10	17	Run	102	1841
	18	High Gradient Riffle	44	1885
11	19	Corner Scour Pool	200	2085
	20	Low Gradient Riffle	95	2180
12	21	Step Run	145	2325
	22	High Gradient Riffle	80	2405
13	23	Dry Trib Confluence Pool	145	2550
	24	Run	61	2611
	25	Low Gradient Riffle	15	2626

Table D-2. Mesohabitat and hydraulic units mapped on Upper South Fork Sproul Creek.

Hydraulic Unit	Mesohabitat Unit	Habitat Unit Type	Unit Length (ft)	Cum Length (ft)
	1	Run	73	73
	2	Bedrock Plunge Pool	31.5	104.5
1	3	Run	53	157.5
	4	Mid Channel Pool	30.5	188
	5	High Gradient Riffle	21.5	209.5
2	6	Low Gradient Riffle	42	251.5
	7a	Mid Channel Corner Pool	75.5	327
	7b		32	359
	7c		19.5	378.5
3	8	High Gradient Riffle	42.5	421
	9	Mid Channel Pool	58.5	479.5
4	10	Low Gradient Riffle	94.5	574
	11	Run with Notched Log Weir	64.5	638.5
	12	Mid Channel Pool	71.5	710
5	13	Low Gradient Riffle	62.5	772.5
	14	Scour Pool	93	865.5
6	15	Low Gradient Riffle	22	887.5
	16	Run/pool	70.5	958
7	17	High Gradient Riffle	58	1016
	18	Mid Channel Log Pool	137	1153
8	19	High Gradient Riffle	42	1195
	20	Run/pool	154	1349
9	21	High Gradient Riffle	33	1382
	22	Run	46.5	1428.5
10	23	High Gradient Riffle	15	1443.5
	24	Run	63	1506.5
	25	Mid Channel Pool	42	1548.5
	26	Low Gradient Riffle	125	1673.5
11	27	Cascade	18	1691.5
	28	Run	70.5	1762
12	29	Scour Pool	65	1827
	30	Step Run	69	1896
13	31	Cox Creek Confluence Pool	65	1961

A 12 inch steel nail was hammered into the channelbed, positioning the nail head flush with the surrounding bed elevation. Nails were left in-place for the duration of the study to provide a consistent location and bed elevation for measuring RCT water depths at any given streamflow. Between April and November 2016, RCT water depths were measured at 13 to 15 streamflows ranging from 0.3 cfs to 120 cfs on the UMS reach and 0.2 cfs to 32 cfs on the USF reach (Tables D-3 and D-4).

RCT-Q rating curve for the 2016 study season were constructed for all hydraulic units Figures D-13-35. These rating curves were similar to stage-discharge rating curves used for streamflow gaging. An example RCT-Q rating curve from the Upper Mainstem (UMS) 2-D hydraulic model site is shown in Figure D-6. Power functions were fit to each rating curve, and presented as a 'family' of RCT curves (Figures D-7 and D-8). Data points redundant for a given stream stage were omitted. Anomalous 'outlier' RCT data points were screened for sampling error in streamflow measurement, changes in streamflow during an RCT depth survey (especially at higher streamflows that could change rapidly in magnitude), and backwater effects from the accumulation of leaf litter at very low baseflows.

For each streamflow-RCT monitored, surveyed RCT depths were ranked from deepest to shallowest. For the X-axis, the ranks were converted to exceedence probabilities (Figures D-9 and D-10). The 10-Percentile, 50-Percentile, and 90-Percentile RCT-Q rating curves (RCT10, RCT50, RCT90) were computed for each study reach (Figures D-11 and D-12). These curves provided quantitative, repeatable baseline RCT rating curves for both study reaches.

We compiled regression equations for each power function and developed spreadsheet functions to compute streamflow from a known RCT depth, and RCT depth from a known streamflow, for each rating curve, as well as for the RCT10, RCT50, and RCT90 (Tables D-5 and D-6). The power function exponent (PFE) is synonymous with the exponent from the rectangular and triangular weir equations in Figure D-4 above; the PFE generally range between 1.5 and 3.5. The PFE is a good indicator of the riffle crest morphology: riffle crests in steeper reaches with coarser substrates will approximate triangular weir shapes, and have higher PFE values approaching 3.5, whereas riffle crests in flatter alluvial reaches with smaller particle sizes will approximate rectangular or compound weir shapes, and thus have lower PFE values approaching 1.5.

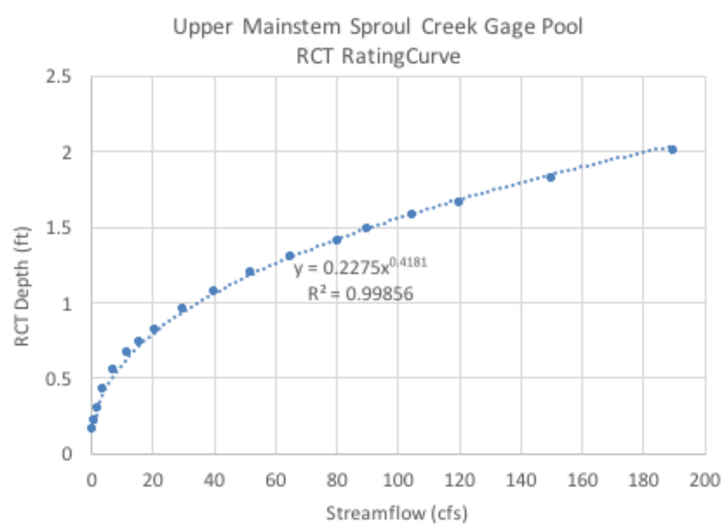


Figure D-6. Example of an RCT-Q rating curve developed from the Upper Mainstem Sproul Creek 2D hydraulic model for the gaging station in upper mainstem Sproul Creek (UMS).

Table D-3. Riffle Crest data collected in 2016 at the Upper Mainstem Sproul Creek study site. Data points highlighted in gray-scale were omitted from the RCT-Q rating curves due to anomalies with streamflow estimates, or were a poor fit to rating curves.

Upper Mainstem Sproul (UMS) Riffle Crest Data (2016)											
		HU-1	**HU-2**	**HU-3**	**HU-4**	**HU-5**	**HU-6**	**HU-8**	**HU-9**	**HU-11**	**HU-13**
		big stump pool	stump pool	corner pool	lower 2d pool	upper 2d pool	along road	along road	Q section pool	brk corner pool	DryTrib pool
Date	**Streamflow (cfs)**	**RCT # (-2)**	**RCT #1**	**RCT #3**	**RCT #5**	**RCT #7**	**RCT #9**	**RCT #13**	**RCT #15**	**RCT #19**	**RCT #23**
14-Apr-16	21.4	No Pin	NA	0.95	1.12	1.3	0.92	1	1.1	1.2	0.81
29-Apr-16	13.22	No Pin	0.62	0.9	0.92	1.2	0.86	0.92	0.94	1.26	0.74
5-May-16	10.27	No Pin	0.49	0.72	0.76	1.03	0.67	0.73	0.76	1.16	0.6
25-May-16	6.52	0.61	0.41	0.6	0.67	0.88	0.55	0.6	0.67	0.93	0.53
15-Jun-16	3.31		0.36	0.43	0.49	0.71	0.45	0.47	0.54	0.83	0.43
6-Jul-16	1.69		0.25	0.36	0.38	0.56	0.35	0.35	0.44	0.61	0.35
27-Jul-16	0.29		0.22	0.27	0.26	0.41	0.22	0.21	0.35	0.43	0.3
20-Oct-16	5.24	0.85	0.4	0.52	0.58	0.83	0.53	0.53	0.6	0.81	0.49
28-Oct-16	58	1.4	0.89	1.2	1.21	1.57	1.13	1.23	1.2	1.38	0.99
2-Nov-16	120.11	1.61	1.12	1.5	1.56	1.81	1.29	1.71	1.66	1.61	1.26
3-Nov-16	69.43	1.5	0.96	1.27	1.31	1.63	1.19	1.49	1.4	1.46	1.07
4-Nov-16	47.3	1.35	0.86	1.13	1.15	1.53	1.06	1.31	1.22	1.36	0.91
22-Nov-16	101.91	1.56	1.07	1.4	1.55	1.79	1.3	1.63	1.53	1.61	1.18

Table D-4. Riffle Crest data collected in 2016 at the Upper South Fork Sproul Creek study site. Data points highlighted in gray-scale were omitted from the RCT-Q rating curves due to anomalies with streamflow estimates, or were a poor fit to rating curves.

Upper South Fork Sproul Riffle Crest Data (2016)														
		HU-0	**HU-1**	**HU-2**	**HU-3**	**HU-4**	**HU-5**	**HU-6**	**HU-7**	**HU-8**	**HU-9**	**HU-11**	**HU-12**	**HU-13**
		abv WBSF	bedrock sill	1D site	rip-rap pool	1D site	log weir	CRA site	run-pool	LWD pool	run-pool	pool	rootwad pool	Cox Creek
	Streamflow	RCT #1	RCT #2	RCT #4	RCT #7	RCT #9	RCT #11	RCT #14	RCT #16	RCT #18	RCT #20	RCT #25	RCT #29	RCT #31
14-Apr-16	6.71			0.44		0.76	0.42	0.52	0.72	0.75	0.63	0.6	0.5	0.61
21-Apr-16	3.49		0.78	0.44	0.65	0.42	0.36	0.43	0.66	0.67	0.52	0.52	0.42	0.52
29-Apr-16	5	0.81	0.6	0.77	0.42	0.71	0.38	0.47	0.68	0.69	0.58	0.56	0.42	0.57
6-May-16	2.85	0.67	0.47	0.64	0.33	0.56	0.23	0.33	0.54	0.55	0.46	0.43	0.32	0.42
24-May-16	1.66	0.61	0.42	0.58	0.26	lamprey redd	0.23	0.26	0.44	0.465	0.37	0.38	0.25	0.31
15-Jun-16	0.851	0.5	0.34	0.46	0.21	0.42	0.2	0.19	0.36	0.37	0.35	0.3	0.21	0.26
7-Jul-16	0.27	0.41	0.25	0.39	0.16	0.32	0.11	0.14	0.29	0.26	0.26	0.21	0.16	0.18
28-Jul-16	0.033	0.32	0.12	0.3	missed data	0.28	0.09	0.09	0.2	0.19	0.17	0.15	0.09	0.12
28-Oct-16	19.84	1.05	0.75	1.06	0.62	0.98	0.42	0.72	0.87	0.96	0.8	0.79	0.69	0.8
2-Nov-16	31.87	1.32	1	1.4	0.8	1.22	0.63	0.97	1.1	1.23	1.01	1.1	1.03	1.12
3-Nov-16	22.7	1.15	0.84	1.23	0.65	1.11	0.47	0.79	1.1	1.03	0.88	0.9	0.72	0.89
4-Nov-16	13	1.03	0.79	1.1	0.55	1.01	0.45	0.69	0.89	0.94	0.76	0.8	0.7	0.78

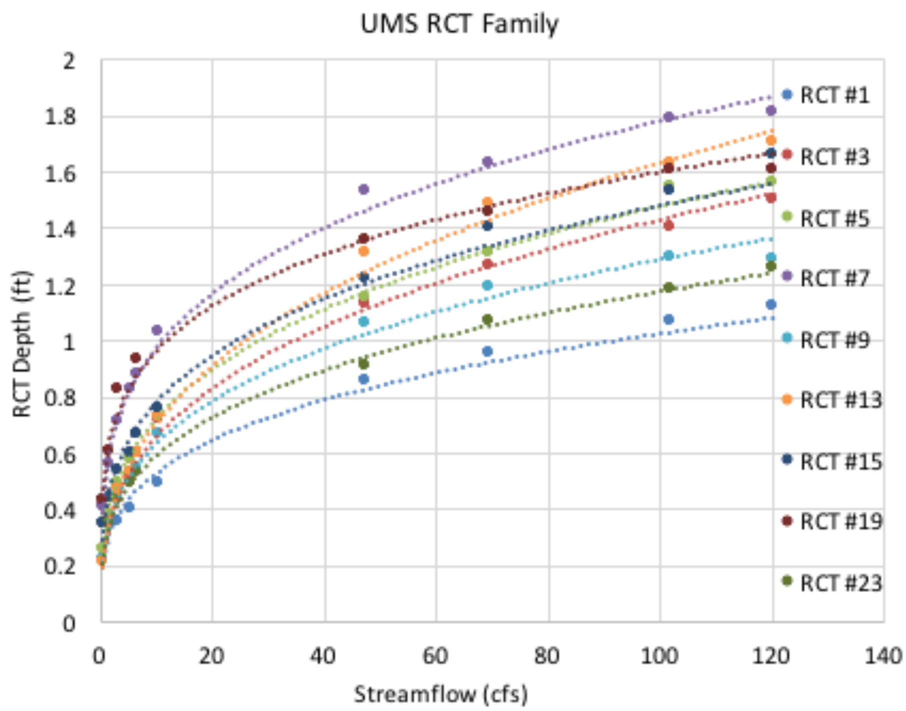


Figure D-7. RCT-Q rating curve "family" for the Upper Mainstem Sproul Creek study reach.

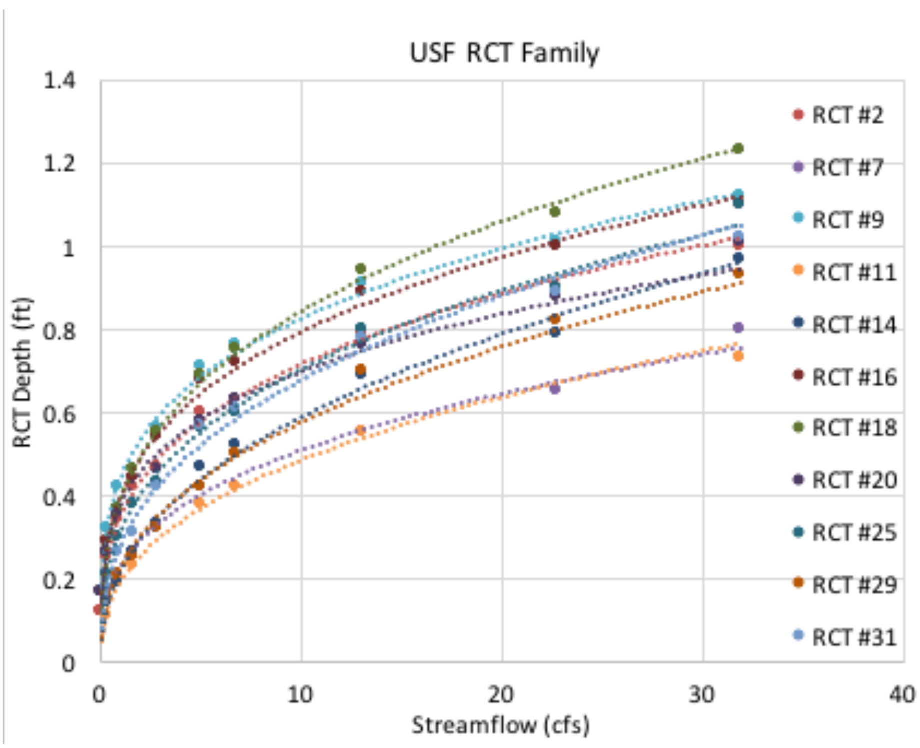


Figure D-8. RCT-Q rating curve "family" for the Upper South Fork Sproul Creek study reach.

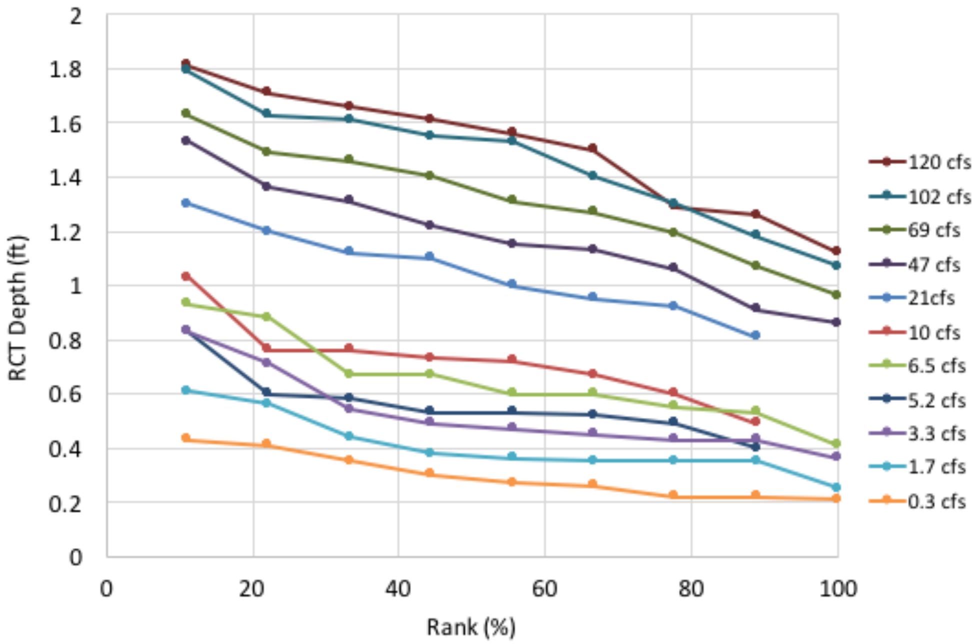


Figure D-9. Eleven RCT depth surveys (ranked plots) for the Upper Mainstem Sproul Creek study reach, collected in WY2016.

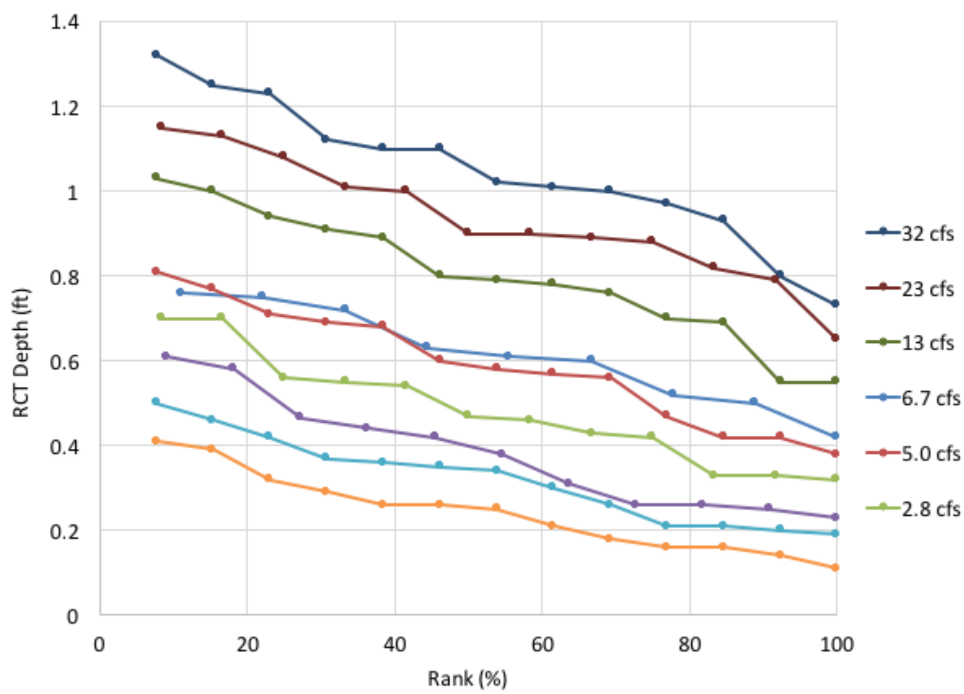


Figure D-10. Nine RCT depth surveys (ranked plots) for the Upper South Fork Sproul Creek study reach, collected in WY 2016.

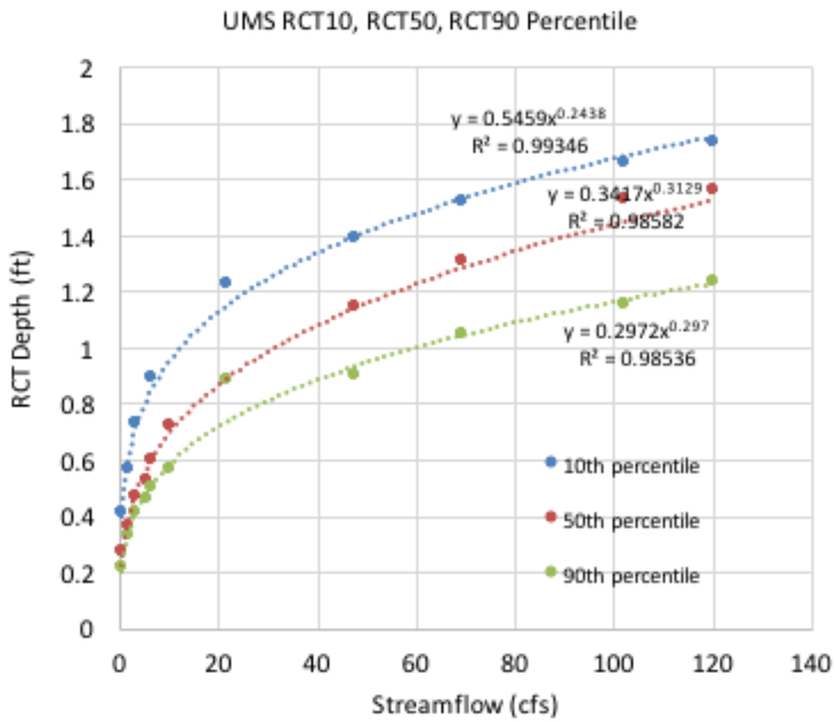


Figure D-11. Upper Mainstem Sproul Creek 10-percentile, 50-percentile, and 90-percentile RCT-Q rating curves (RCT10, RCT50, RCT90) computed from the 13 RCT-Q rating curves from 2016 monitoring.

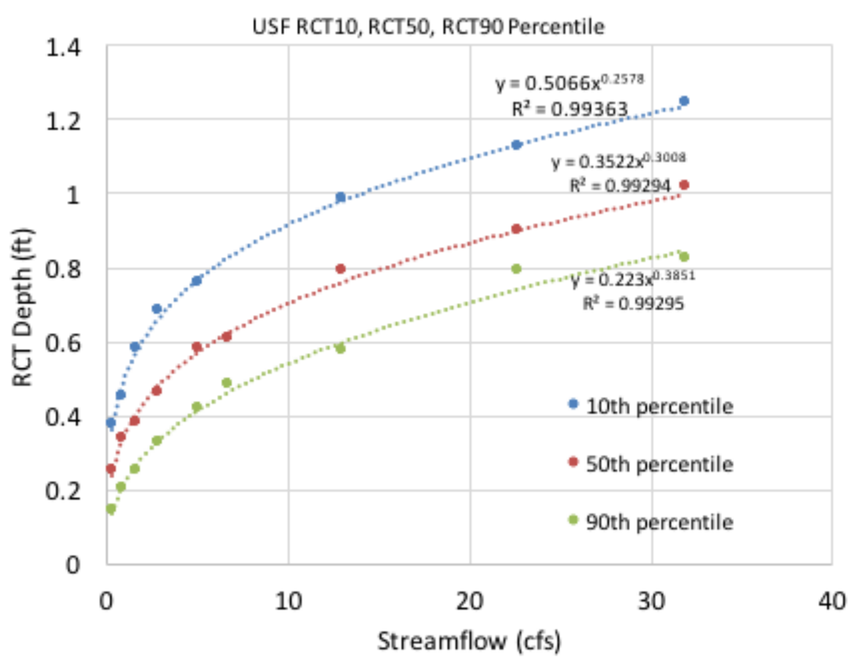


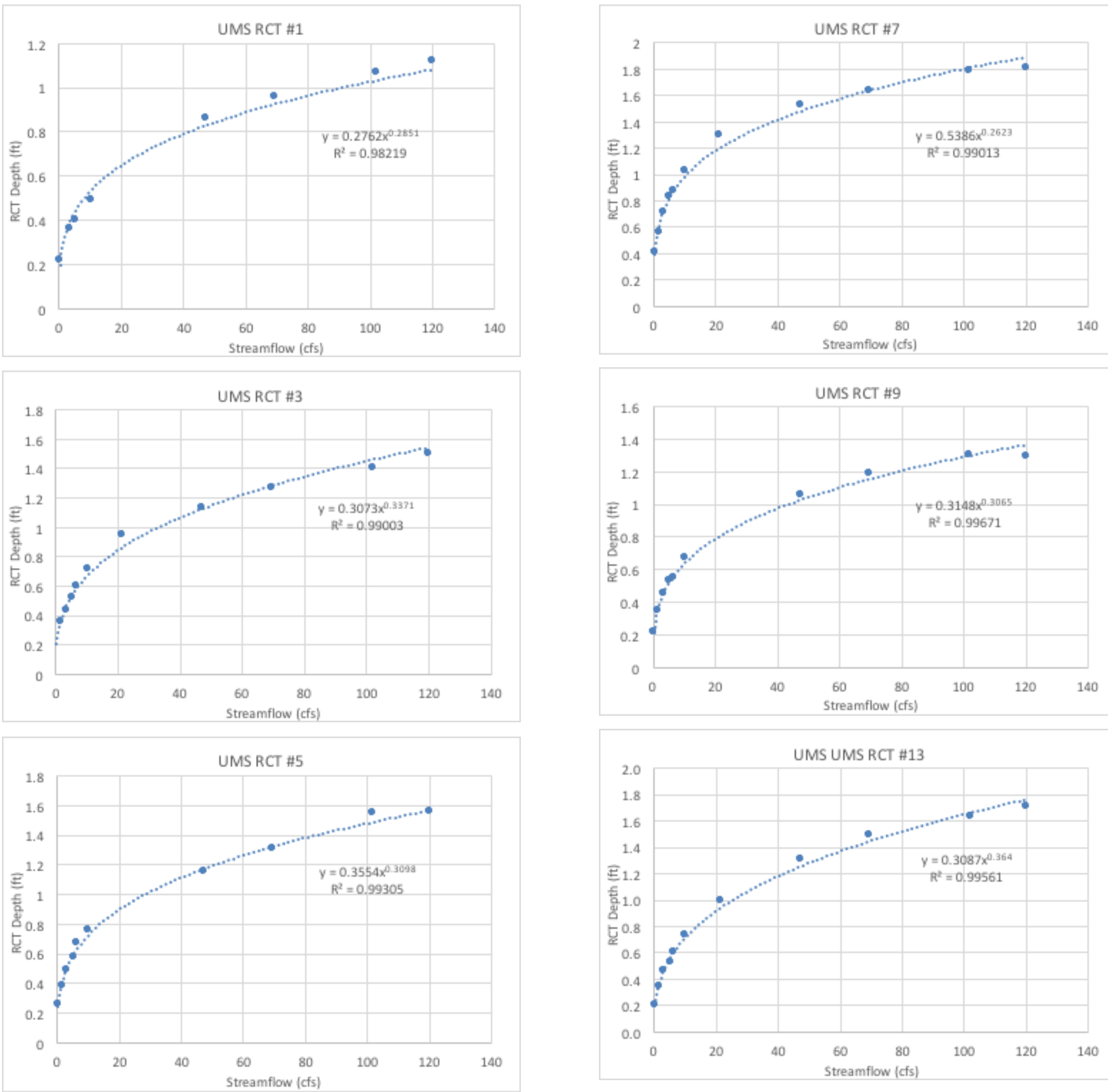
Figure D-12. Upper Mainstem Sproul Creek 10-percentile, 50-percentile, and 90-percentile RCT-Q rating curves (RCT10, RCT50, RCT90) computed from the 13 RCT-Q rating curves from 2016 monitoring.

Table D-5. Power function equations from RCT-Q rating curves, and the RCT10, RCT50, and RCT90, for the Upper Mainstem Sproul study reach.

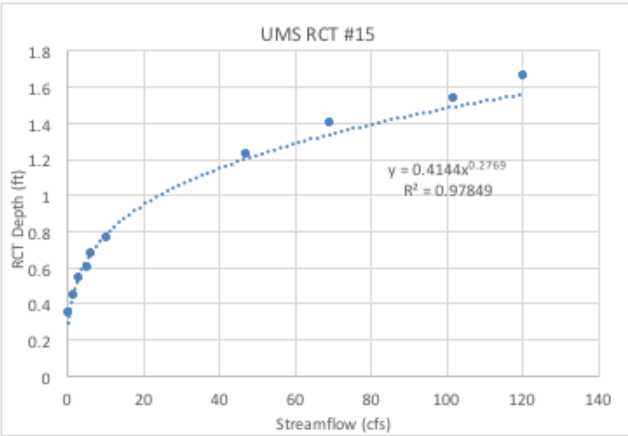
RCT	R2	m	^	coefficient	PFE
1	0.9822	0.2762	0.2851	91.1866	3.51
3	0.9900	0.3073	0.3371	33.1234	2.97
5	0.9931	0.3544	0.3098	28.4567	3.23
7	0.9901	0.5386	0.2623	10.5810	3.81
9	0.9967	0.3148	0.3065	43.4244	3.26
13	0.9956	0.3087	0.364	25.2564	2.75
15	0.9785	0.4144	0.2769	24.0799	3.61
19	0.9890	0.5825	0.2197	11.7029	4.55
23	0.9692	0.3422	0.26	61.8345	3.85
23 (rev)	0.9956	0.3027	0.2971	55.8271	3.37
RCT10	0.9936	0.5459	0.2438	11.9754	4.10
RCT50	0.9858	0.3417	0.3129	30.9334	3.20
RCT90	0.9854	0.2972	0.297	59.4629	3.37

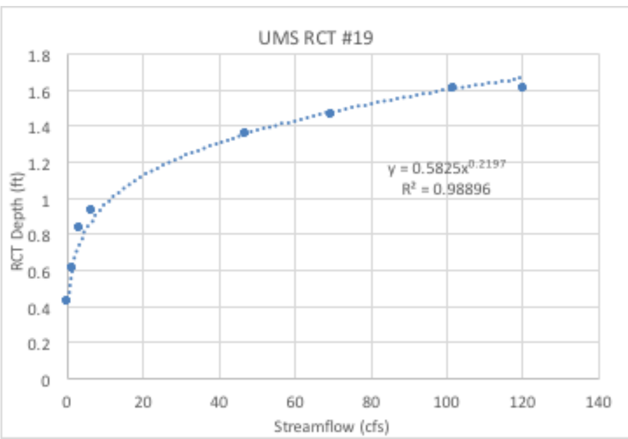
Table D-6. Power function equations from RCT-Q rating curves, and the RCT10, RCT50, and RCT90, for the Upper South Fork Sproul study reach.

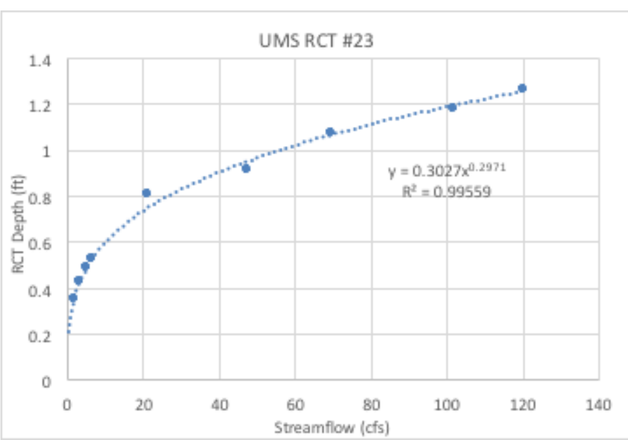
RCT	r2	m	^	coefficient	PFE
1	0.9955	0.5434	0.2471	11.8020	4.05
2	0.9977	0.3547	0.3055	29.7474	3.27
4	0.9722	0.551	0.2187	15.2608	4.57
7	0.9922	0.233	0.3398	72.7467	2.94
9	0.9954	0.4465	0.2677	20.3283	3.74
11	0.9937	0.1957	0.3944	62.5416	2.54
14	0.9905	0.223	0.4219	35.0483	2.37
16	0.9908	0.4021	0.2956	21.8031	3.38
18	0.9988	0.3964	0.3285	16.7239	3.04
20	0.9916	0.3822	0.2618	39.4029	3.82
25	0.9955	0.3187	0.3445	27.6415	2.90
29	0.9813	0.2321	0.3953	40.2408	2.53
31	0.9905	0.2844	0.3776	27.9358	2.65
RCT10	0.9936	0.5066	0.2578	13.9829	3.88
RCT50	0.9929	0.3522	0.3008	32.1133	3.32
RCT90	0.9930	0.223	0.3851	49.2351	2.60

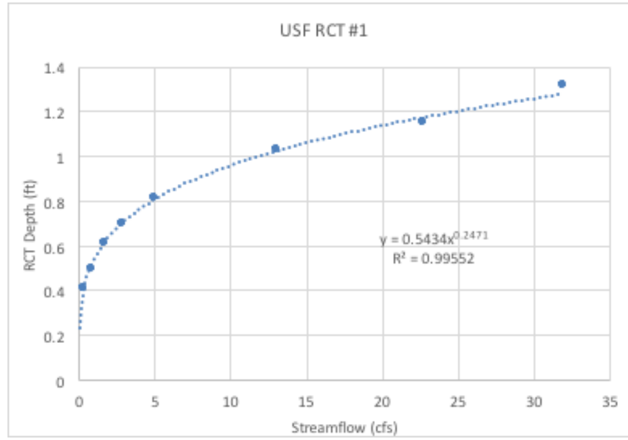


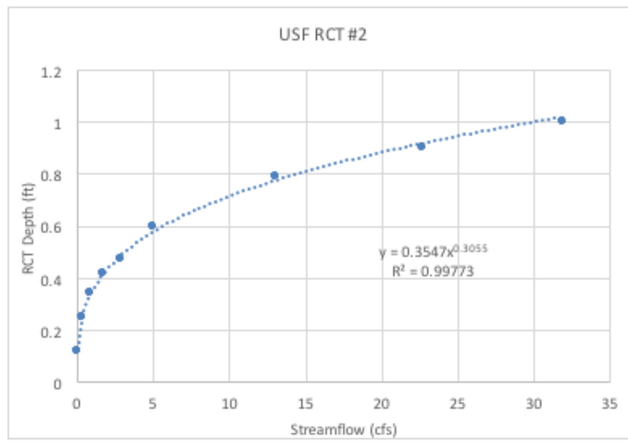
Figures D-13-18. RCT-Q rating curves for Upper Mainstem Sproul Creek.

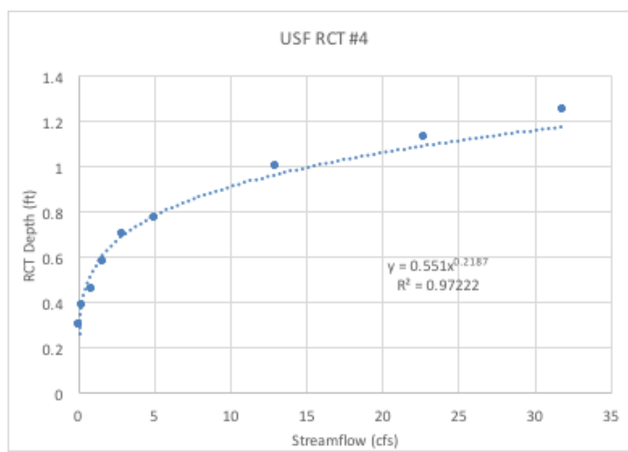




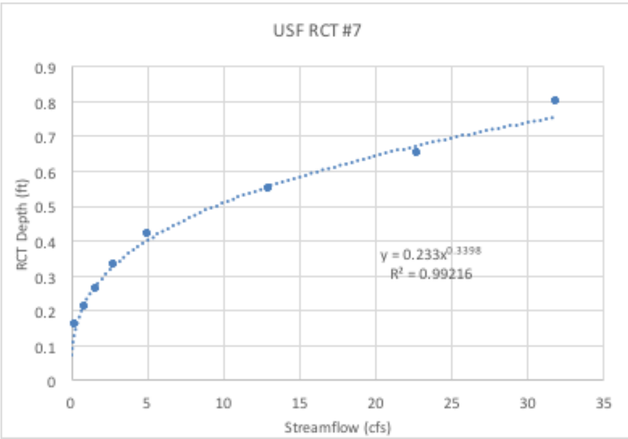


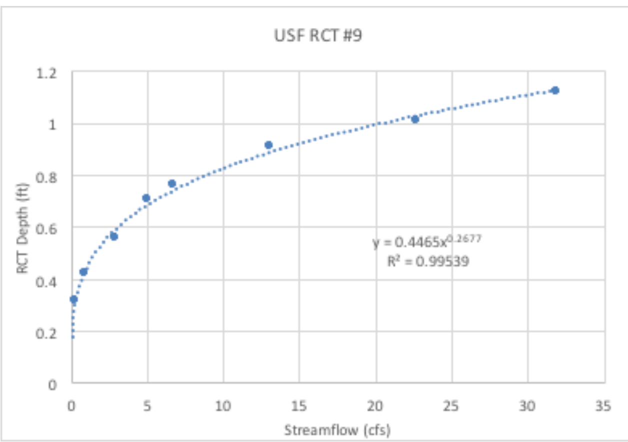


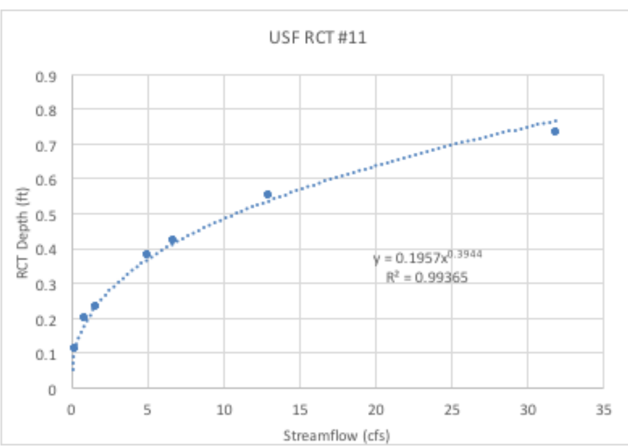


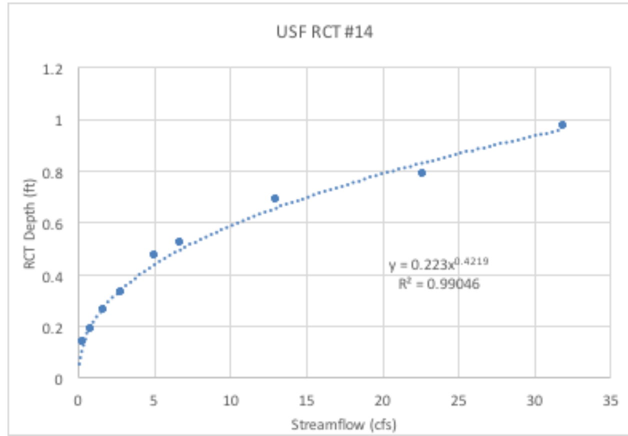


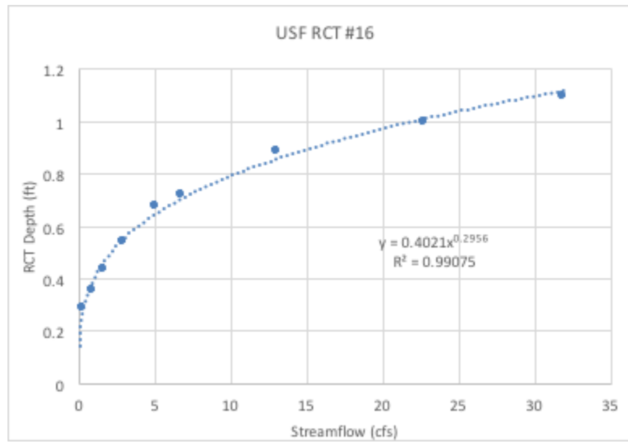
Figures D-19-24. RCT-Q rating curves for Upper Mainstem and Upper South Fork Sproul Creek.

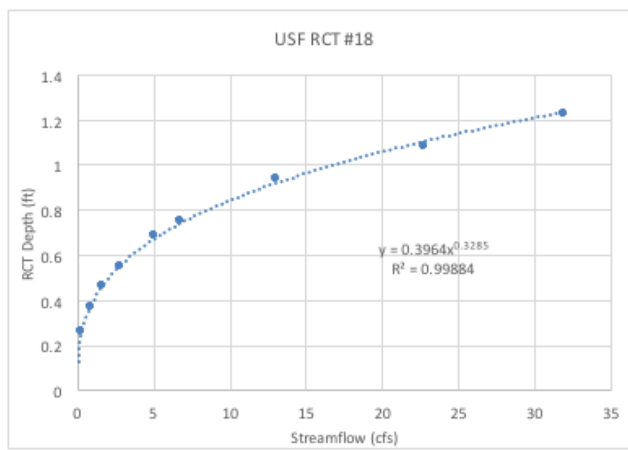




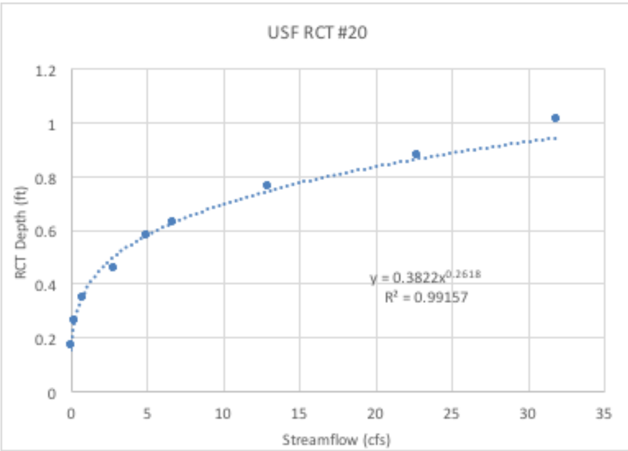


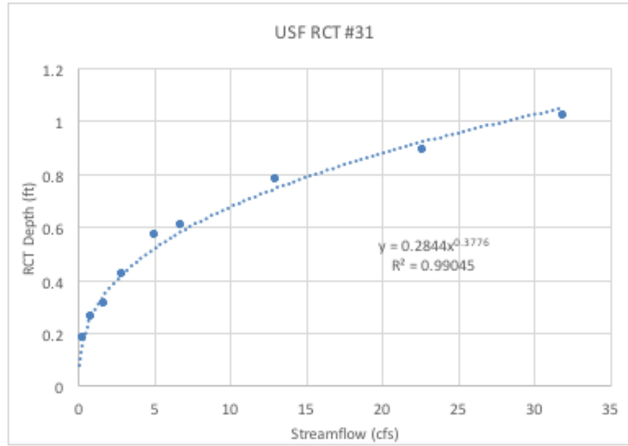


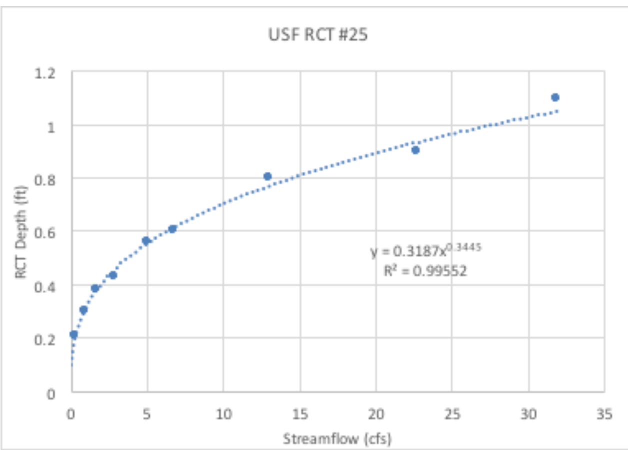


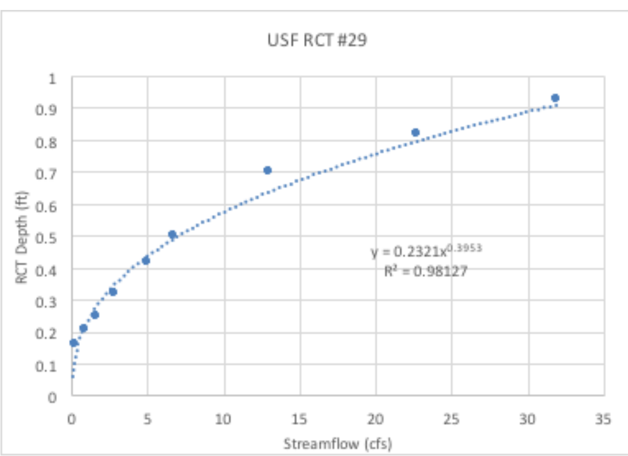


Figures D:25-30. RCT-Q rating curves for Upper South Fork Sproul Creek.









Figures D-31-35.

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