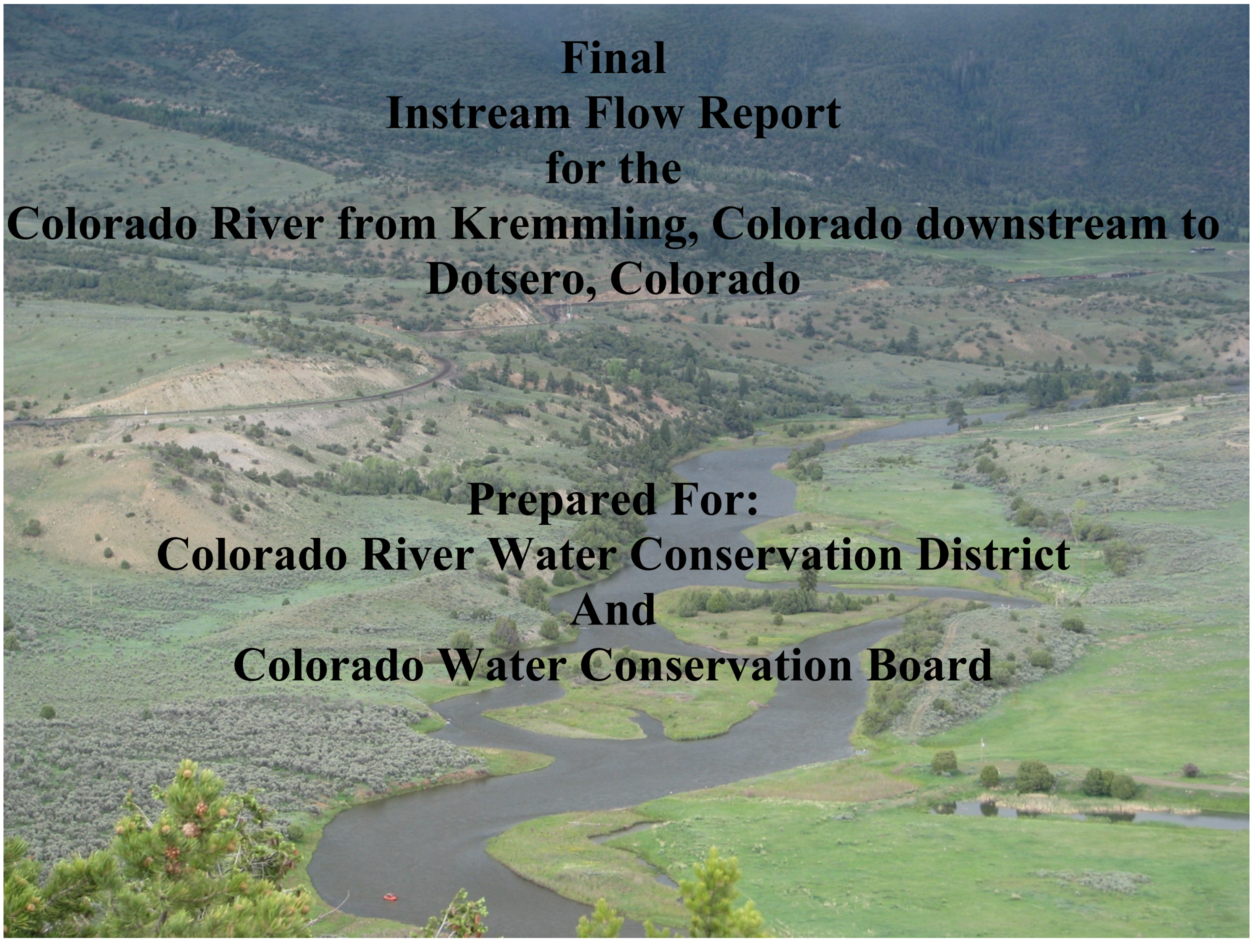

Final
Instream Flow Report
for the
Colorado River from Kremmling, Colorado downstream to Dotsero, Colorado

Prepared For:
Colorado River Water Conservation District
And
Colorado Water Conservation Board

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Acknowledgements

The Colorado Water Conservation Board through the Colorado River Water Conservation District and the Colorado River Basin Roundtable funded this project. We wish to acknowledge those entities for the funding and the many individuals in those organizations that participated during the course of the study. In addition, the Colorado Division of Wildlife provided valuable input and comments that improved the study and final report.

Executive Summary

The study area is the Colorado River from the Blue River confluence to the Eagle River confluence (approximately from Kremmling to Dotsero). Colorado River Water Conservation District (CRWCD), Colorado Water Conservation Board (CWCB) and Colorado Division of Wildlife (CDOW) are interested in the fish habitat response to flows in the Colorado River between Kremmling and Dotsero, Colorado. CDOW may use the data contained in this report to evaluate management opportunities and to determine how changes within the watershed might impact CDOW's ability to meet management objectives. There are several fish species that inhabit this reach, but for the purposes of this project, the primary interest is in determining the needs for rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), mountain whitefish (*Prosopium williamsoni*), and flannelmouth sucker (*Catostomus latipinnis*). The species of interest were selected by CDOW personnel and represent a range of species including native non-game fish.

CWCB and CDOW requested the application of a current state-of-the-art River2D study for the analysis. River2D is a two-dimensional hydrodynamic model that uses an irregular triangulated mesh to cover the entire river channel. The mesh is developed from a river channel topographic survey. River2D is a fine-scale approximation of habitat and river topography. River2D is the approach that is currently used by USGS for its evaluations of river habitat in similar studies.

The River2D application consists of establishing geo-referenced benchmarks, surveying river topography with either a Total Station or Survey Grade GPS, and measuring water surface, depths, and velocities at three different flows and constructing the River2D model. The River2D model simulates a continuous river reach. The habitat is simulated by combining River2D hydraulic data with habitat suitability criteria using GIS habitat analysis tools or within River2D.

The objectives of this study were as follows: 1) Determine the current state of the physical habitat available for the identified species in this section of the Colorado River—this includes physical/geomorphic, hydrologic, riparian, and instream aquatic habitat characteristics. 2) Determine the expected changes to physical habitat as a result of natural and man made hydrologic change—expected changes include geomorphic, riparian, and aquatic habitat changes.

Sites were initially selected based on topographic and hydrologic characteristic and finalized during a site visit in June 2009. The hydraulic properties of Gore Canyon (essentially a series of rapids) excluded this reach from further consideration. It was decided that three sites were necessary to represent the varying slope of the Colorado River downstream of Gore Canyon to the confluence with the Eagle River. Pumphouse was chosen to represent the river from downstream of Gore Canyon to Radium. Rancho del Rio was chosen to represent the river from Radium to Rancho del Rio. Finally, Lyons Gulch represents the river from Rancho del Rio to Dotsero.

The state-of-the-art model used for instream flow studies is the two-dimensional hydraulic model River2D. The information presented in this report includes an analytical model that combines

two-dimensional hydraulics, a GIS habitat model, and hydrologic data into a habitat time series. This approach follows the concepts of the Instream Flow Incremental Methodology (IFIM).

Two-dimensional hydraulic modeling requires channel geometry data, multiple water-surface elevation data sets, and multiple velocity data sets. The specific hydraulic data that were collected at each site included stream bed elevations, mean column velocity at selected locations (multiple collections at each habitat type), water-surface elevations, and visual estimates of dominant and subdominant substrate size.

The two-dimensional hydraulic simulations use a mesh to depict the stream channel. This mesh is configured to best represent each simulated flow. The result is multiple model meshes to represent the range of flow conditions. Unlike a one-dimensional hydraulic simulation that uses multiple cross sections that remain fixed for the full range of simulation flows, each of the two-dimensional meshes can have a different number of nodes and therefore a different surface area. The hydraulic simulation data sets contain the horizontal and vertical reference locations for each node in the model mesh. In addition, the node locations have depth (Figure E-1) and velocity (Figure E-2) data for each flow. These georeferenced data sets were combined with the habitat suitability functions. The result of the analysis is a georeferenced map of usable habitat for each species and life stage (Figure E-3). A summation file for the usable habitat for each flow is used to develop the habitat–discharge relationship for the flows simulated at each site for each species and life stage (Figure E-4).

The habitat versus discharge relationships combined with hydrology data for each river reach calculate habitat on a daily basis (Figure E-5). These data can be used to determine times when flows may be limiting to a particular species or life stage. These data also can be used to determine a preferred flow regime based on the range of hydrologic conditions needed for ecological function and fish habitat.

The Colorado River from the Blue River confluence downstream to the confluence of the Eagle River contains both canyon-bound and meandering river sections. The river is confined by canyon or steep topography in approximately 60 percent of this reach. There are sections with more open topography at the upper end of the reach and in certain locations near the middle of the reach.

The canyon-bound and confined reaches have steeper gradients and larger bed material on the river bottom than the lower gradient meandering reaches. Islands are present in all sections of the river from the Blue River downstream to the Eagle River with the exception of Gore Canyon. Larger islands are present in the lower portion of the study area.

Vegetation varies with gradient and topography. In the steeper canyon-bound sections, juniper and coniferous trees are the dominant vegetation. In the lower gradient, more open reaches, sagebrush is dominant in upland areas with willows dominant in the near-shore riparian areas. Cottonwoods are present throughout the reach but are most abundant in the lower portion of the river from Burns to Dotsero.

Hydrology in the reach is typical of snowmelt-dominated rivers. Peak flows occur during May and June. The upper sections of the reach have peak flows that on average exceed 2000 cfs. The peak flow in the lower reach is nearly twice the peak flow of the upper reach due to additional watershed area and tributary inflow. Bankfull flows occur at approximately 2500 cfs and approximately 4000 cfs in the upper and lower river, respectively. Peak flows are most important for habitat creation and maintenance. Peak flows of bankfull and higher are required at regular frequency for proper ecosystem functions.

The habitat-flow relationships for most life stages of each species are similar in shape at each site with the exception of mountain whitefish at the Lyons Gulch site. Habitat for most species and lifestages is most abundant at flows between 500 and 1500 cfs, however, the habitat quality is generally higher at mid to lower flows. Habitat abundance for most species and life stages decreases rapidly at flows less than 500 cfs.

Based on the available hydrology and the habitat-discharge functions, base flows of 500 cfs or higher would maintain habitat during fall, winter, and early spring at the current levels. Average peak flows that exceed 2000 cfs upstream of State Bridge and 4000 cfs near Dotsero should create and maintain habitat in its current state. Higher peak flows (double the average peak) with recurrence intervals of one to two times every ten years should continue to create habitat and riparian areas as they now function. Ascending and descending limbs of the hydrograph should follow the current shape to provide higher habitat quantity and quality in late spring and summer than during fall and winter base flows.

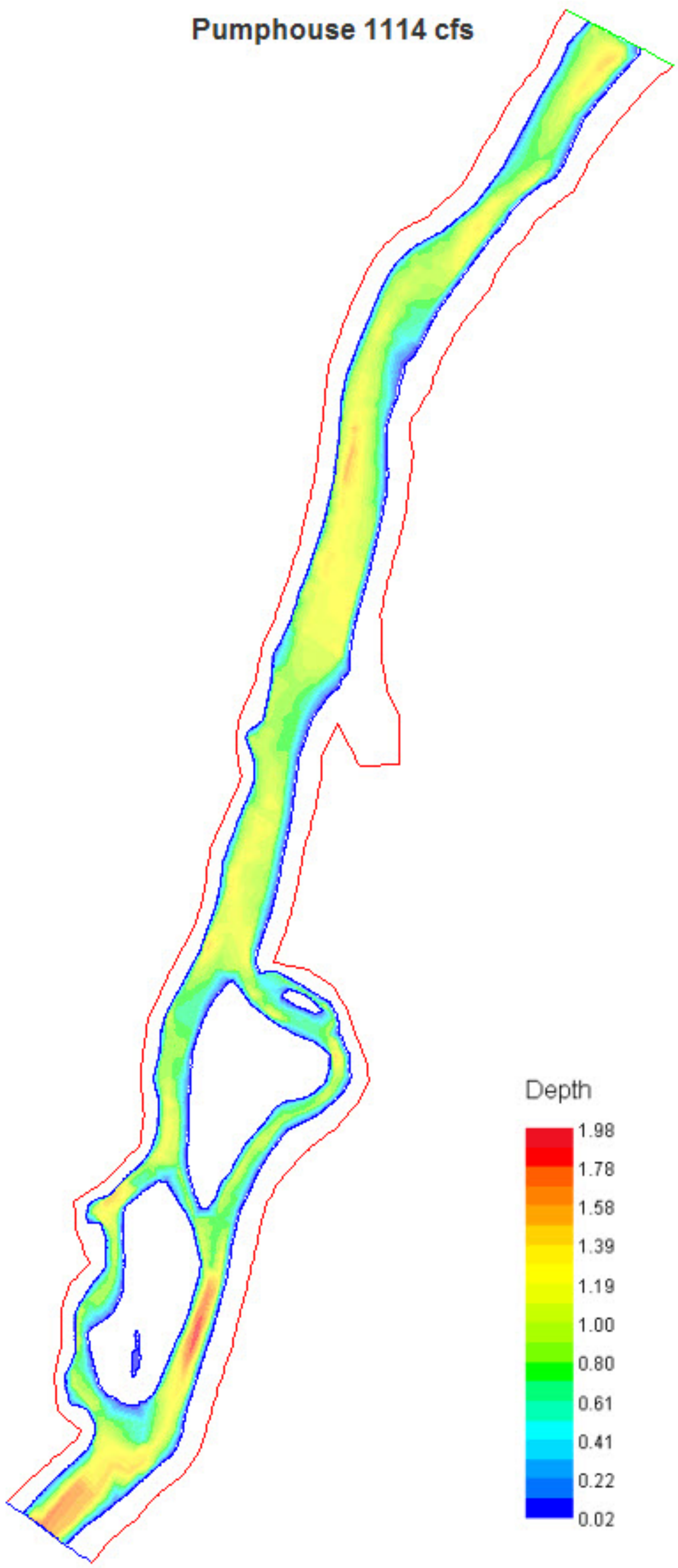

Figure E-1. Example of depth simulation in River2D. Depth is in meters, river flows from top of page to bottom, red line is model boundary.

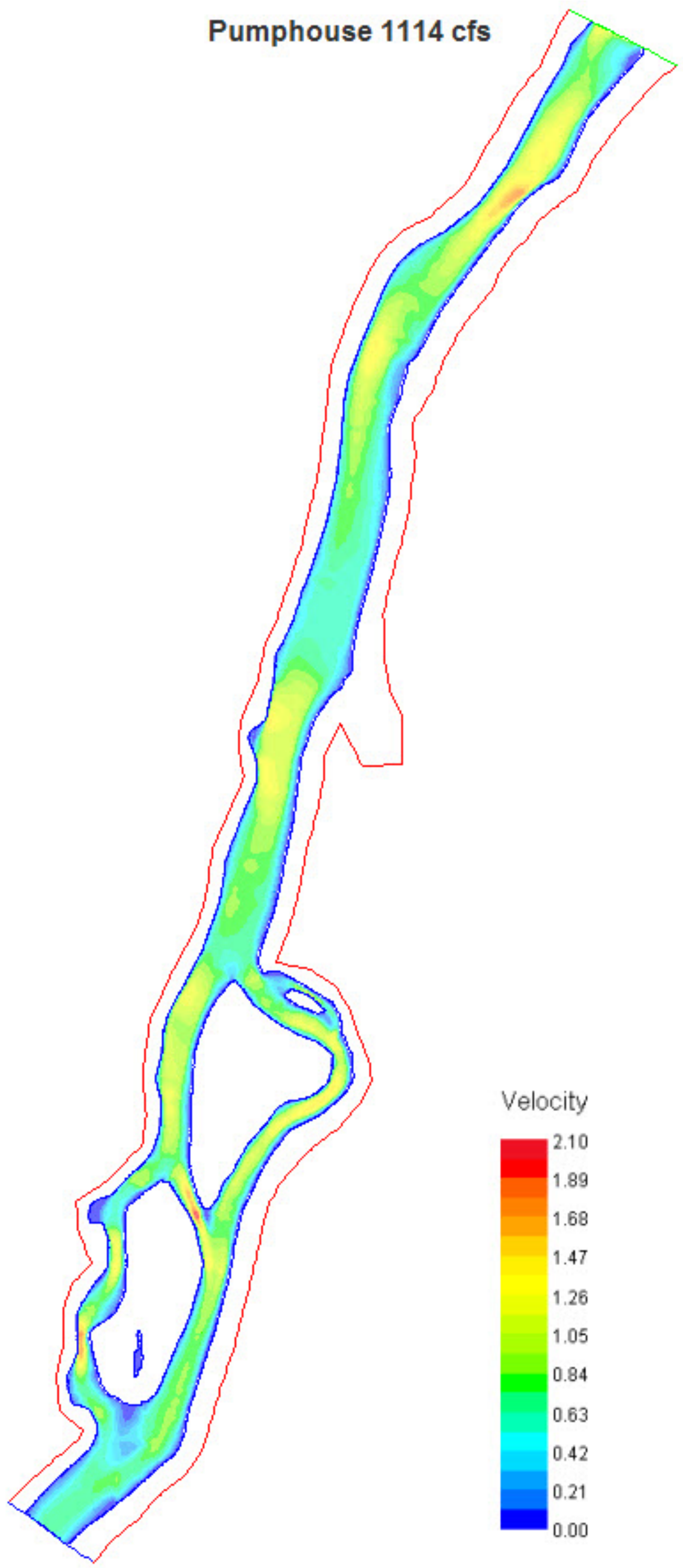

Figure E-2. Example of velocity simulation in River2D. Velocity is in meters per second.

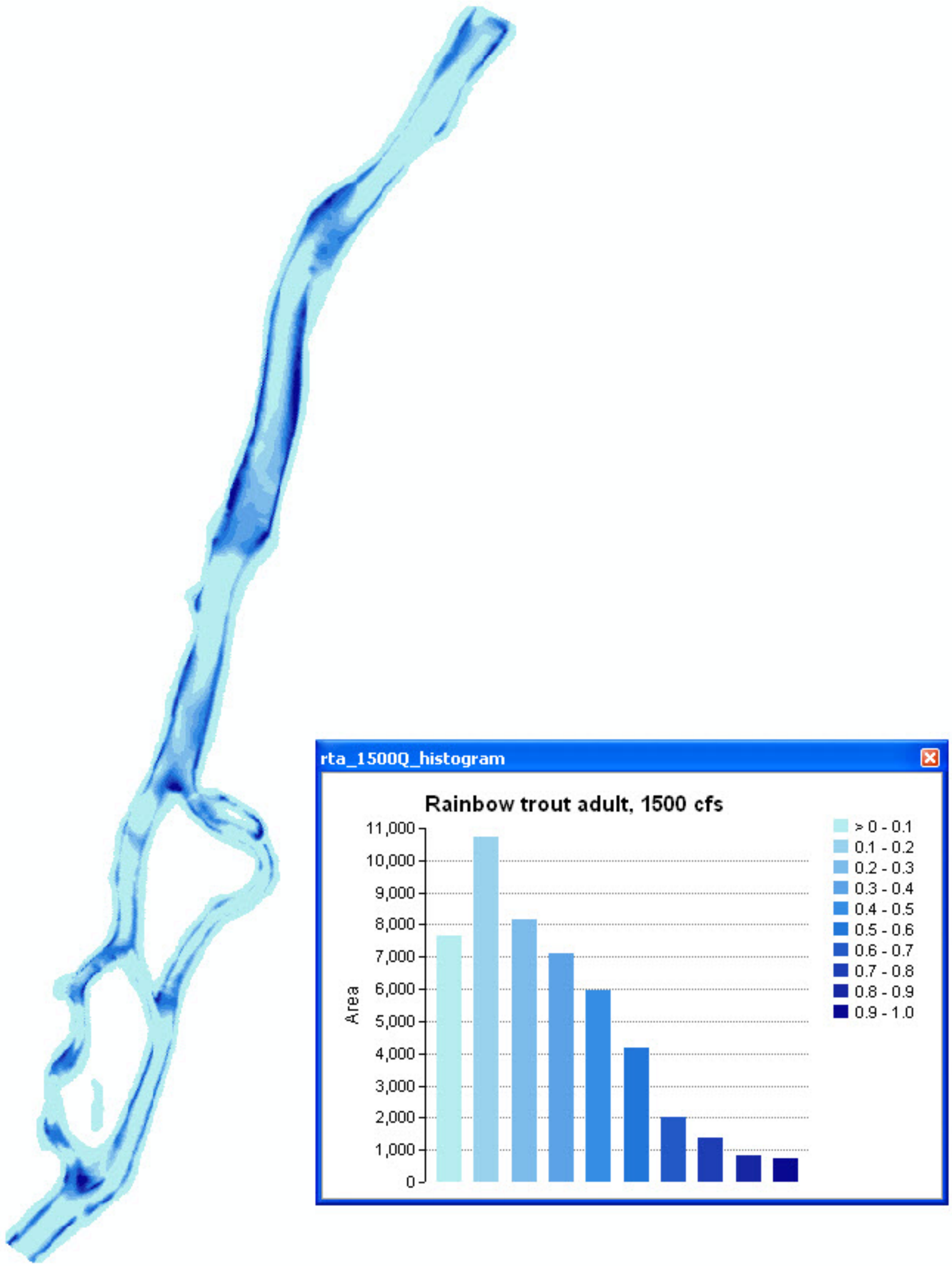

Figure E-3. Example of habitat map (square meters habitat) produced by River2D and GIS analysis (darker area depicts higher quality habitat).

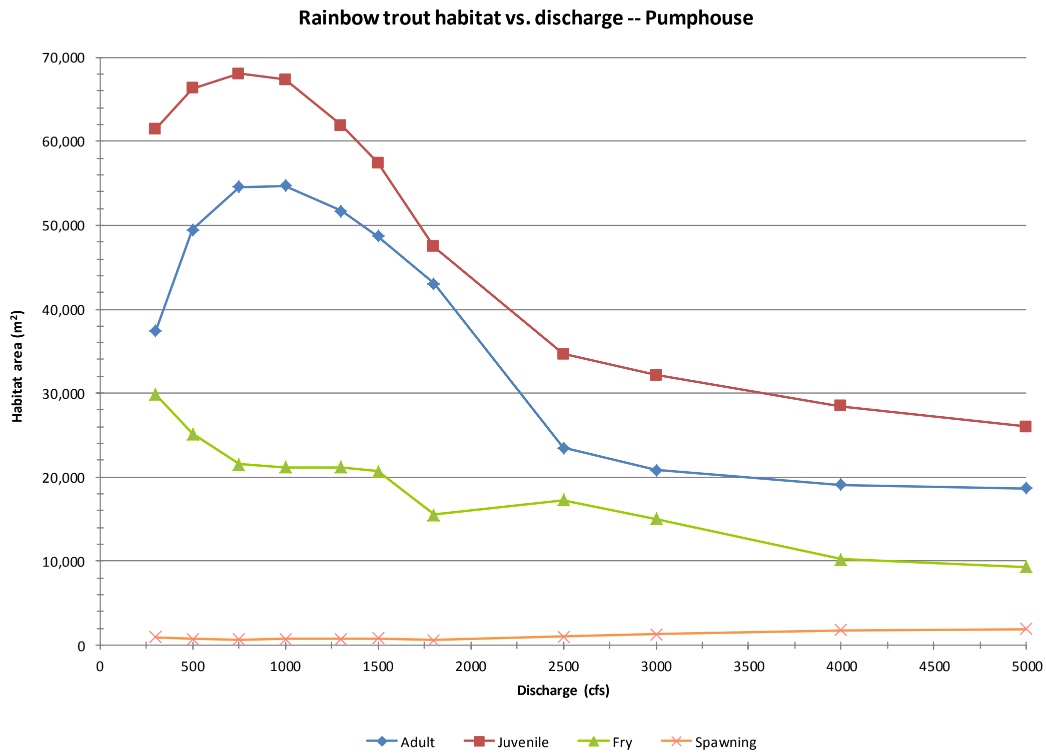

Figure E-4. Example of habitat versus discharge function developed from River2D output.

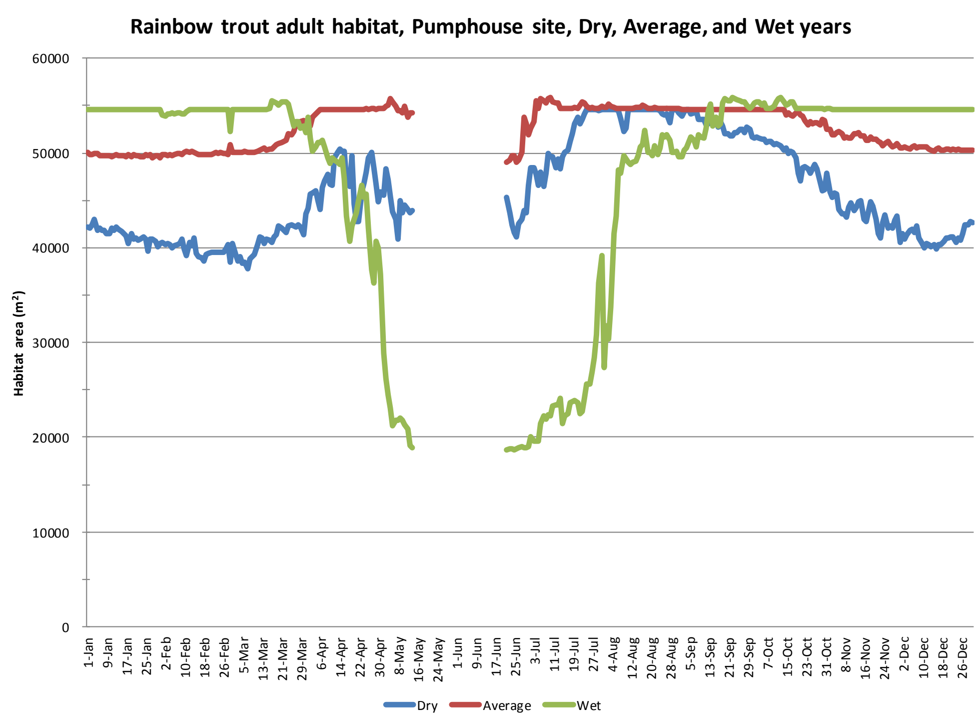

Figure E-5. Example of habitat time series analysis.

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INTRODUCTION

Colorado River Water Conservation District (CRWCD), Colorado Water Conservation Board (CWCB), and Colorado Division of Wildlife (CDOW) are interested in the fish habitat response to flows in the Colorado River between Kremmling and Dotsero, Colorado. CDOW may use the data contained in this report to evaluate management opportunities and to determine howchanges within the watershed impact CDOW's ability to meet those management objectives. There are several fish species that inhabit this reach, but for the purposes of this project, the primary interest is in determining the needs for rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), mountain whitefish (*Prosopium williamsoni*), and flannelmouth sucker (*Catostomus latipinnis*). The species of interest were selected by CDOW personnel and represent a range of species including native non-game fish.

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Objectives

The objectives of this study were as follows: 1) Determine the current state of the physical habitat available for the identified species in this section of the Colorado River—this includes physical/geomorphic, hydrologic, riparian, and instream aquatic habitat characteristics. 2) Determine the expected changes to the physical habitat as a result of natural and manmade hydrologic change —expected changes include geomorphic, riparian, and aquatic habitat changes.

Study Area and Site Selection

The study area is the Colorado River from the Blue River confluence to the Eagle River confluence (approximately from Kremmling to Dotsero). Site selection began by developing river length and slope information from topographic maps. From this information, the river was broken into six reaches (Figure 1, Table 1).

A site visit took place on June 1, 2009. This visit was a reconnaissance-level effort to familiarize the team with the project area and finalize plans for the initial inventory of field data. The group stopped at multiple locations between Dotsero and Pumphouse to view potential site locations. The hydraulic properties of Gore Canyon (essentially a series of rapids) excluded this reach from further consideration. It was decided that three sites were necessary to represent the varying slope of the Colorado River downstream of Gore Canyon to the confluence with the Eagle River. Pumphouse was chosen to represent the river from downstream of Gore Canyon to Radium (Figure 2, Figure 3). Rancho del Rio was chosen to represent the river from Radium to Rancho del Rio (Figure 2, Figure 4). Finally, Lyons Gulch represents the river from Rancho del Rio to Dotsero (Figure 2, Figure 5). Once the sites were chosen, several benchmarks were placed and surveyed at each site. The benchmarks were surveyed using a survey-grade GPS unit to acquire UTM coordinates (Table 2). Site lengths and average widths were calculated for each site (Table 3).

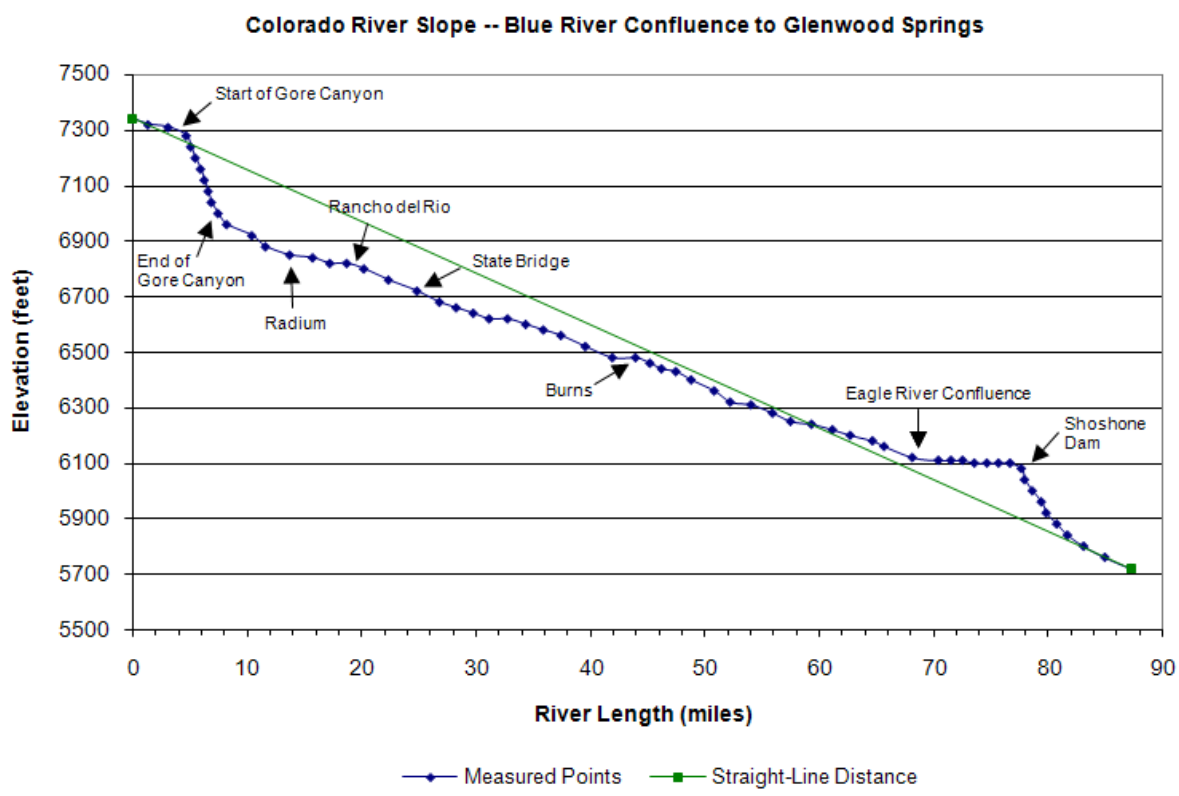


Figure 1. Graph of the slope of the Colorado River from the Blue River confluence to Glenwood Springs.

Table 1. Colorado River slope and habitat characteristics by reach from the Blue River downstream to Dotsero, Colorado.

			% of Habitat Type		
Reach	Length (miles)	Slope (feet/feet)	Riffle	Run	Island
Blue River confluence to Gore Canyon	3.79	0.0020	0%	83.40%	16.60%
Gore Canyon	3.67	0.0155	100%	0%	0%
Gore Canyon to Radium	6.27	0.0045	27.33%	50.39%	22.27%
Radium to Rancho del Rio	6.08	0.0009	30.97%	42.39%	26.64%
Rancho del Rio to Burns	23.43	0.0027	39.72%	47.31%	12.97%
Burns to Dotsero/Eagle River confluence	25.20	0.0027	27.94%	63.18%	8.88%
Blue River confluence to Eagle River confluence	68.44	0.0035	30.87%	55.59%	13.54%

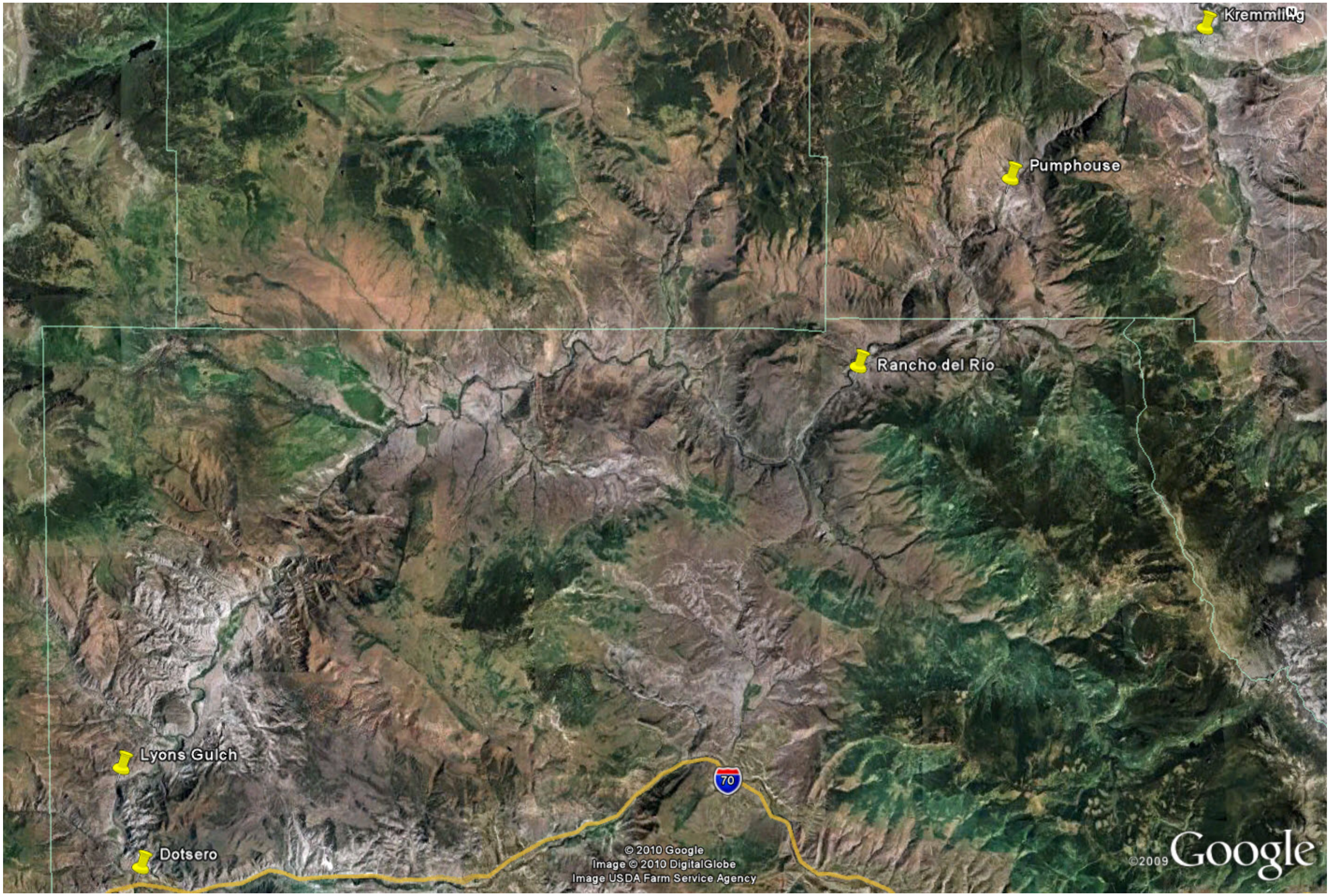


Figure 2. Colorado River from Kremmling to Dotsero and the three sites chosen for instream flow studies.

Figure 3. Pumphouse site. Benchmark locations are shown in red.

Figure 4. Rancho del Rio site. Benchmark locations are shown in red.

Figure 5. Lyons Gulch site. Benchmark locations are shown in red.

Table 2. Locations of benchmarks at the Lyons Gulch, Rancho del Rio, and Pumphouse sites.

	Northing (meters)	Easting (meters)	Elevation (meters)
Lyons Gulch			
BM1	4396155.737	322276.768	1878.149
BM2	4396531.566	322551.206	1885.002
BM3	4396556.084	322777.275	1883.931
BM4	4396602.476	322917.063	1890.509
BM5	4396360.485	322359.177	1875.790
Rancho del Rio			
BM1	4417802.863	362270.713	2072.137
BM2	4417825.887	362301.832	2081.419
BM3	4418002.344	362519.665	2072.726
BM4	4418274.187	362581.307	2062.445
BM5	4417747.528	362296.026	2065.965
Pumphouse			
BM1	4426389.888	370600.915	2114.184
BM2	4426671.116	370624.517	2104.967
BM3	4427065.996	370817.787	2118.068
BM4	4427373.114	370906.916	2109.101

Table 3. Site lengths, average widths, and length of site in terms of stream widths.

Site	Length (m)	Length (ft)	Avg. Width (m)	Avg. Width (ft)	Stream Lengths
Lyons Gulch	939	3080	41	133	23
Rancho del Rio	1143	3749	44	146	26
Pumphouse	1453	4766	51	167	28

Initial Inventory

In addition to calculations of river length and slope, an initial inventory was conducted to assemble any existing physical and biological data for the Colorado River from Kremmling to Dotsero. The data collection effort was sufficient to qualitatively describe the existing environment within this reach of the river.

Aquatic Habitat: Distinct aquatic habitat reaches exist within this stretch of river: a canyon-bound reach and a meandering reach. General characteristics of these habitat reaches were described using data from topographic maps, aerial photography (Google Earth Pro), and field site visits of the river (Table 1, Table 4). The river was characterized as confined or unconfined. Confined sections were defined as river sections with a limited ability for the channel to migrate laterally, usually caused by steep upland topography or canyon walls. More than half of the linear distance from the Blue River downstream to the Eagle River confluence is confined channel (Table 4).

Table 4. Percent of river channel that is confined, Colorado River from the Blue River to Dotsero, Colorado.

	% of Confined Channel	
Reach	**Left Bank**	**Right Bank**
Blue River confluence to Gore Canyon	8.60	19.98
Gore Canyon	100	100
Gore Canyon to Radium	65.79	81.51
Radium to Rancho del Rio	64.59	35.41
Rancho del Rio to Burns	68.67	51.61
Burns to Dotsero/Eagle River confluence	60.66	57.87
Blue River confluence to Eagle River confluence	63.45	56.06

Hydrology: Hydrology data for the Colorado River were obtained from USGS gages for descriptive information regarding seasonal flow variation. Daily data were averaged over several years. Peak flows are fed by snowmelt and occur primarily in June, although flow can vary considerably (Figure 6, Figure 7, Figure 8, Figure 9). Three year types were selected for the analysis of daily habitat: dry (90% of the time exceeded), median (50% of time exceeded), and wet (10% of time exceeded). These year types show the range of conditions that can occur at each site. They differ from the daily peak and minimum flows shown in Figure 7 since the exceedence flows are based on a statistical distribution for many daily values (e.g. 1962-2008) and the daily flows (Figure 7) are the highest or lowest flow for a single day.

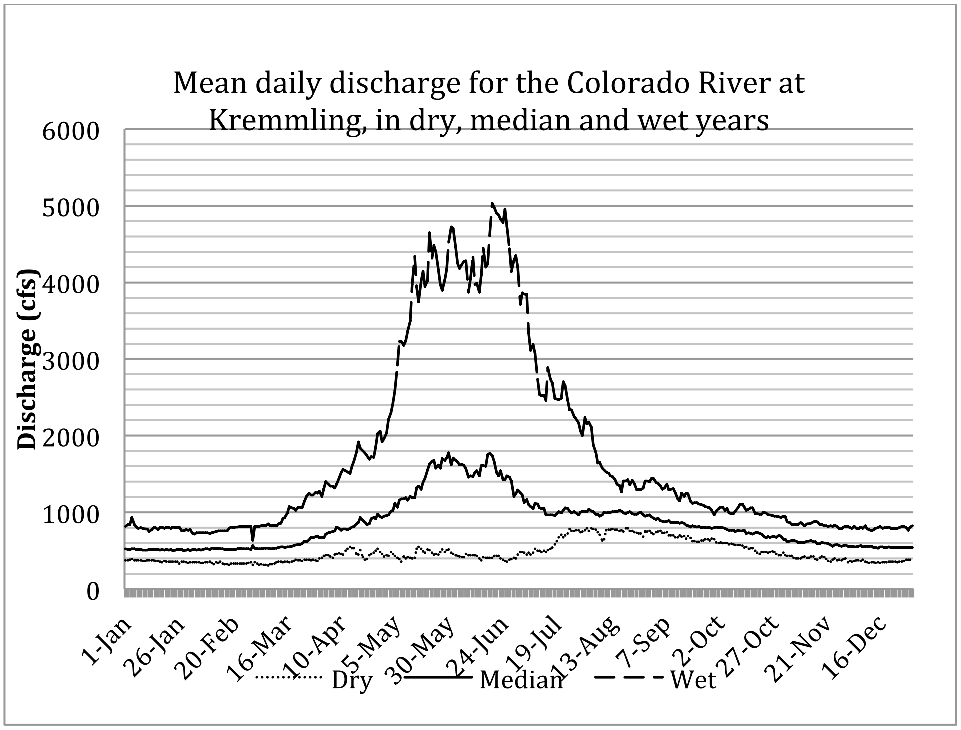


Figure 6. Daily discharge for the Colorado River at Kremmling for dry (90 % of time exceeded), median (50% of time exceeded) and wet (10% of time exceeded) years.

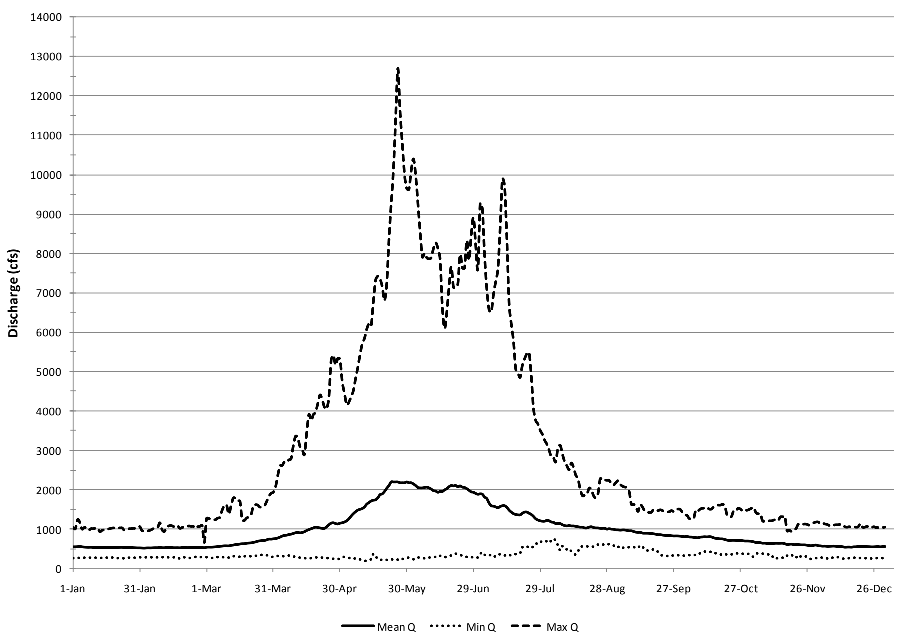


Figure 7. Hydrograph of the Colorado River from USGS gage 09058000, near Kremmling. For the period of record 1962 to 2008. This hydrograph is representative of maximum daily, mean daily and minimum daily flows that occur at the Pumphouse and Rancho del Rio sites.

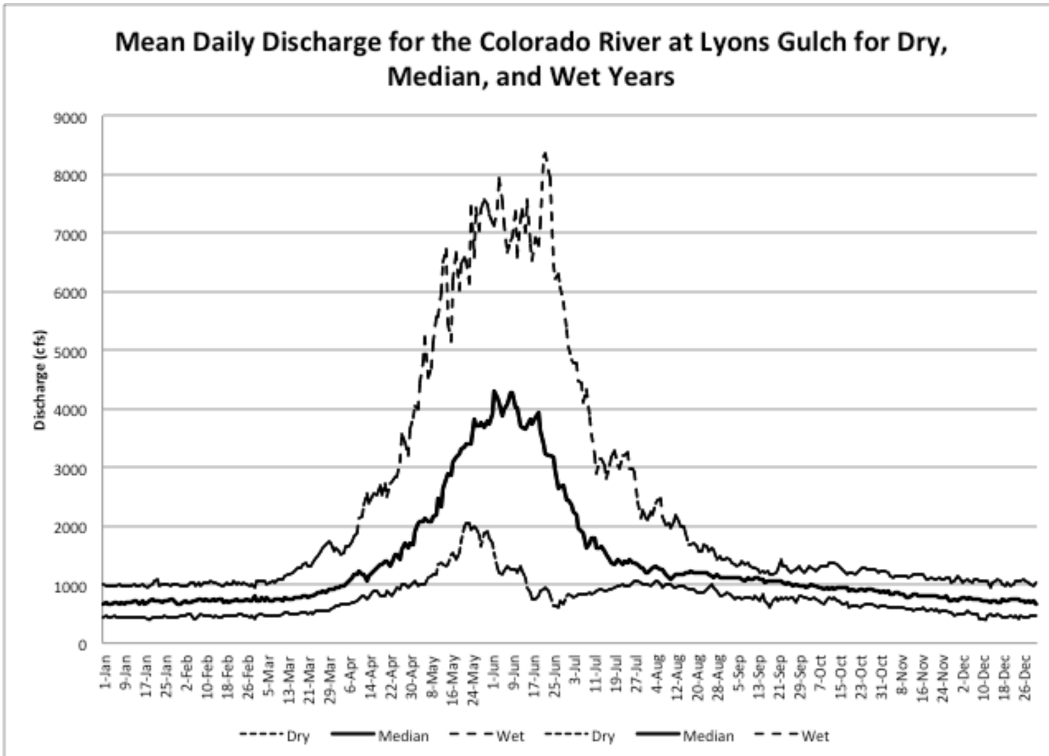


Figure 8. Mean daily discharge for the Colorado River at Lyons Gulch for dry (90 % of time exceeded), median (50% of time exceeded) and wet (10% of time exceeded) years.

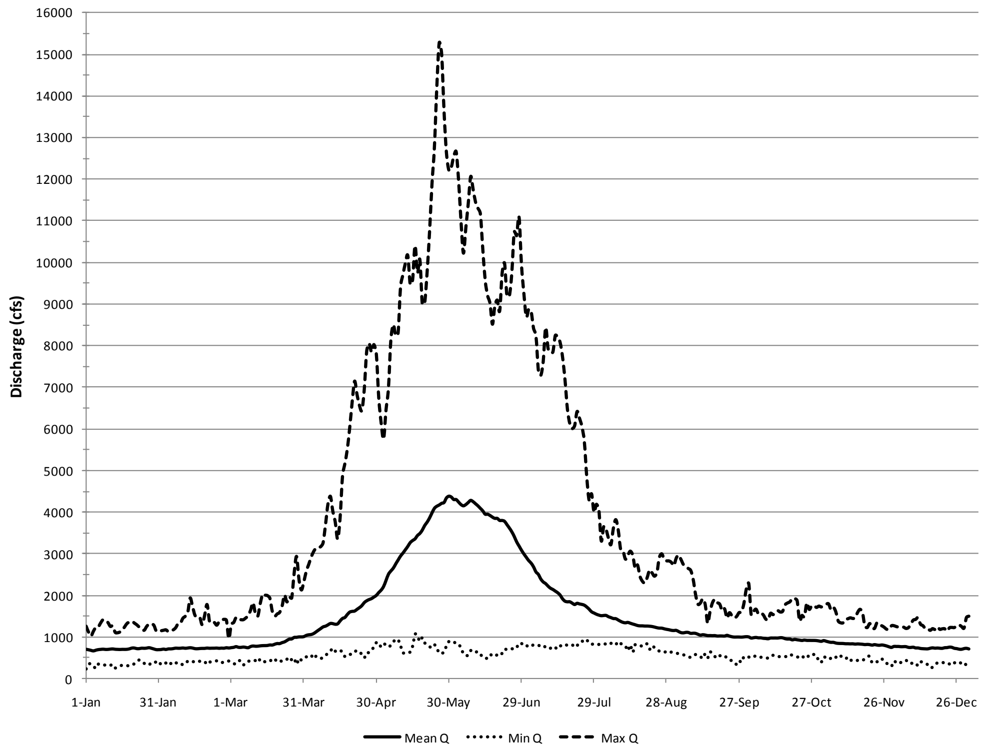


Figure 9. Hydrograph of the Colorado River upstream of Dotsero. Data were obtained by subtracting data from USGS gage 09070000 (Eagle River below Gypsum) from USGS gage 09070500 (Colorado River near Dotsero). Data are averaged from 1947 to 2008 for gage 09070000 and 1941-2008 for gage 09070500. This hydrograph is representative of maximum daily, mean daily, and minimum daily flows that occur at the Lyons Gulch site.

Hydrologic and Biological Processes

Recently, research has focused on comprehensive ecologically-based hydrology regimes management of riverine systems to provide function for both instream aquatic biota as well as near-stream riparian areas (Bunn and Arthington 2002, Chapin et al. 2002,Lytle and Merritt 2004, Lytle and Poff 2004, Richter et al. 2003). Natural flow regimes, with both floods and droughts, occurred for many years prior to any river regulation. The biota in these ecosystems have adapted to that flow regime. That adaptation is the response to changes in the physical environment with floods as well as the biological adaptation to withstand floods or prolonged droughts in those systems (Lytle and Poff, 2004). Lytle and Merritt (2004) in their study of riparian forests concluded that a natural flow regime was the best prescription for maintaining near-stream cottonwood riparian areas.

In addition to instream flows, research has focused on river conservation and restoration (Trush et al. 2000). The study of river ecosystems includes all of the riverine components listed by the

Instream Flow Council in the context of a functioning system that provides the components necessary for restoring and maintaining a diverse ecosystem similar to natural conditions (Annear et al. 2004).

The dynamic character of river systems has been stated as one of the important features in maintaining ecological integrity (Poff et al. 1997). The natural variability within riverine systems needs to be considered as part of restoration and flow manipulation efforts. Any specified instream flow management should include a strategy for incorporating this natural variability and also the potential uncertainty involved with that in restoration of river systems (Wissmar and Bisson, 2003).

Clipperton et al. (2003) incorporated four ecosystem components into a Instream Flow Needs Determination for the South Saskatchewan River Basin. The four components were: 1) fish habitat; 2) water quality; 3) riparian vegetation; and 4) channel maintenance. The objective of their determination was to provide a high level of protection for the riverine ecosystem that could be achieved by instream flows alone. Further, they wanted to provide for protection of aquatic habitats in the short term while protecting processes that maintained aquatic habitat in the long term.

Physical components of riverine systems that affect the biota both in the riparian and instream areas include hydrology, geomorphology, and water quality. Hydrology within riverine systems, especially in systems with snowmelt-driven hydrographs, usually have spring or early summer peak flows with base flows occurring in fall through winter. The magnitude and duration of the peak flows are variable and dependent on annual snowpack and also rainfall events that occur after snowpack has subsided. These flows affect the stream morphology. Specific flow magnitude and duration are required to move sediment, initiate channel migration, create and maintain habitat, and incorporate organic material in the form of woody debris into the system.

Research has shown that the geomorphic changes occur with peak flows of various return intervals. Hill et al. (1991) discussed the need for large flow events for channel migration and valley form influences. These events are generally large events that occur approximately 1 in 25 years or greater. More frequent flooding occurs on nearly an annual basis. These flows occur at a bankfull or slightly higher than bankfull level and are shown to rework channel features without a lot of channel migration. In general, these flows occur every 1.5 to 2 years in most stream systems. Research has shown that flows that occur during the annual peaks do most of the in-channel reworking of bars and instream habitat to create habitat for the base flow period of the year.

By considering various physical processes that occur in river systems, particularly in alluvial systems with cobble and gravel bedforms, flow regimes can be specified that will modify channel morphology. These modifications can move from a present day condition which may be a detached floodplain and incised channel to a more connected floodplain with a less incised channel which provides function for both instream and near-channel riparian habitat (Trush et al. 2000). Riparian corridors also include terrestrial species of plants and animals that depend on instream flows. High flows during runoff inundate riparian which promotes new vegetation growth, maintains existing vegetation, and carry organic material into the stream channel.

The ecological flows should have a recurrence interval for overbank flooding that is approximately 1.5 to 2 years between flow events, to maintain connectivity with the riparian areas and maintain longevity of riparian forests. In addition the specified bankfull flows, to maintain instream channel habitat and create new habitats, should occur at a frequency that is generally found in the natural system and is suitable for present channel conditions. Habitat flow relationships for baseflow conditions and other seasons of the year can be determined from stream cross-sectional data for riffles, which is an indicator of benthic invertebrates' productivity.

Riparian: The initial riparian inventory used both aerial photography and ground truthing (where access was available) to describe the existing riparian conditions, notes on vegetative species composition, general locations of native riparian corridor, and ranchland. A 200-foot-wide vegetation corridor was estimated and both riparian and upland vegetation were characterized by length of reach occupied (**Table 5**). While the dominant vegetation was noted, many other unidentified species were also present. Additionally, some of the dominant vegetation types were likely present in small amounts but were not directly observed or detectable from aerial photographs. For example, willows are likely found in the Blue River to Gore Canyon reach but were not readily discernible from aerial photos and access through this reach was limited.

Table 5. Vegetation characteristics for the Colorado River from the Blue River downstream to Dotsero, Colorado (expressed as percent of linear distance in the reach).

	Reach						
% Vegetation Type	Blue River confluence to Gore Canyon	Gore Canyon	Gore Canyon to Radium	Radium to Rancho del Rio	Rancho del Rio to Burns	Burns to Dotsero/ Eagle River confluence	Blue River confluence to Eagle River confluence
Sagebrush	51.06	4.87	37.00	63.70	74.11	66.56	62.01
Willow	x	x	20.59	76.30	56.01	61.26	50.40
Grass	57.46	4.87	25.46	9.97	10.84	18.60	17.22
Juniper	6.07	89.98	60.44	49.81	48.79	29.93	42.85
Pine	6.07	89.98	36.03	x	16.07	8.36	17.04
Cottonwood	8.73	x	1.71	x	6.16	16.58	8.86
Oak	x	x	x	x	x	3.84	1.41
Other Large Trees	0.91	x	6.28	24.19	6.31	14.79	5.80
Unidentified Shrub	24.07	x	x	x	1.20	2.43	2.64
Bare	0.63	38.87	15.46	1.30	1.26	0.52	4.27

Geology: A geologic map of Colorado was downloaded from the U.S. Geological Survey's National Geologic Map Database and used to characterize the geology surrounding the river (Figure 10). A general description of the geology of the six reaches follows.

Blue River confluence to Gore Canyon: This stretch of the river consists primarily of alluvium deposits (gravel, sand, silt, and clay). The surrounding hills consist of shale, limestone, and landslide deposits.

Gore Canyon: The head of Gore Canyon consists of sandstone, shale, limestone, and claystone. The majority of the canyon is metamorphic biotite gneiss, schist, and migmatite and these were derived principally from sedimentary rocks.

Gore Canyon to Radium: This stretch of the river contains a variety of sedimentary rocks: sandstone, shale, claystone, mudstone, siltstone, limestone, and conglomerate from several formations are present. Lower Gore Canyon is composed of granitic rocks.

Radium to Rancho del Rio: This stretch of the Colorado River contains the same sedimentary rocks as the previous section. Similar to Lower Gore Canyon, Red Gorge is composed of granitic rocks. Rancho del Rio is located on landslide deposits.

Rancho del Rio to Burns: Landslide deposits continue at the beginning of this section on the left side of the river. The right side contains shale and limestone. Close to State Bridge, basalt flows and associated tuff, breccia, and conglomerate are present. Sedimentary sandstone, siltstone, conglomerate, limestone, shale, claystone, and mudstone from various formations comprise the bulk of this section. Near Bond, a small outcrop of dolomite and quartzite combined with shale, sandstone, and limestone is present. Another landslide deposit occurs northeast of Dell.

Burns to Dotsero: From Burns to Dotsero, the geology is again primarily sedimentary. Sandstone, claystone, mudstone, limestone, siltstone, conglomerate, shale, and gypsum are present. A small outcrop of rhyolitic rock occurs about seven miles downstream of Burns on the left side of the river. Alluvium occurs at the Eagle River confluence.

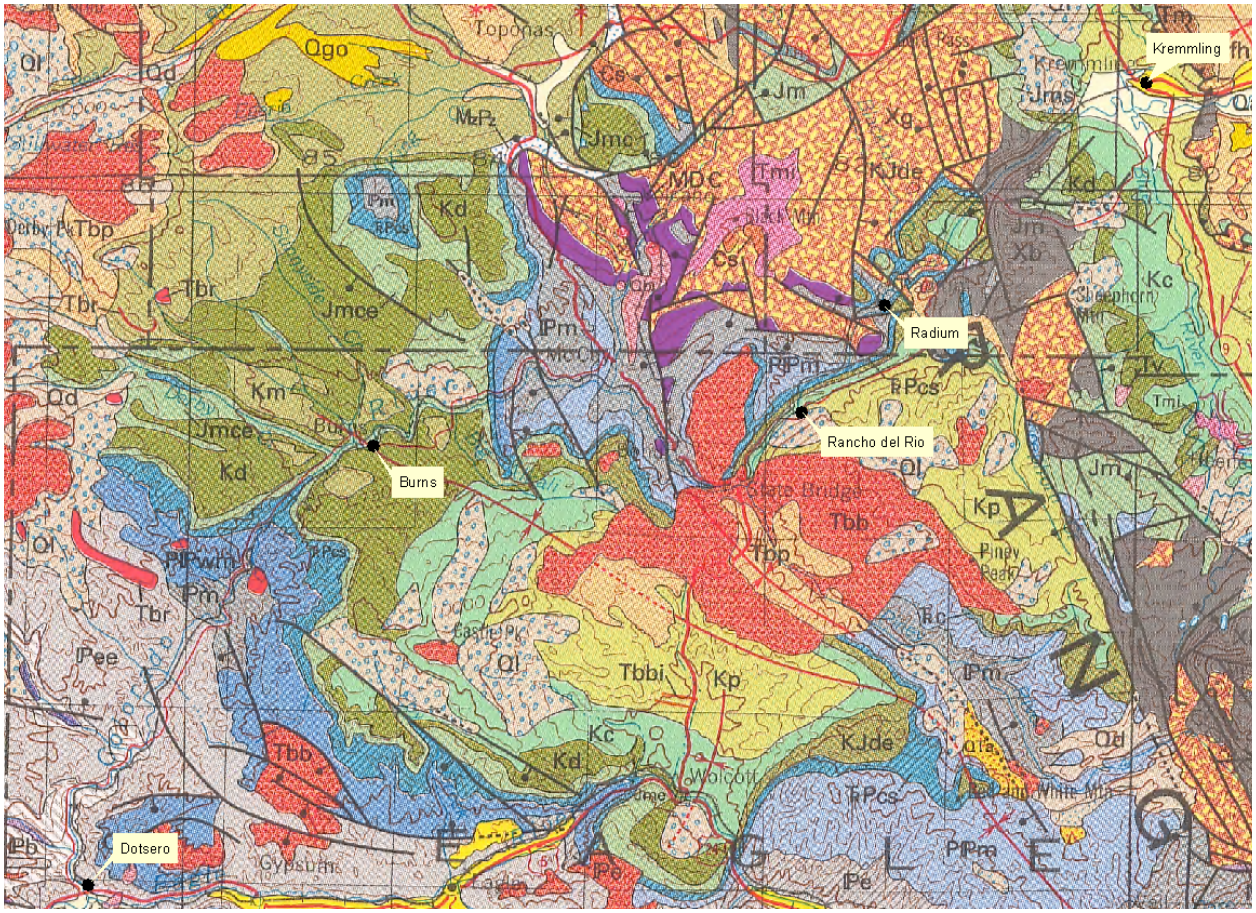


Figure 10. Geologic map of Colorado showing the section of the Colorado River from Kremmling to Dotsero. Source: Tweto, Ogden. 1979. Geologic Map of Colorado. U.S. Geological Survey. Downloaded from the USGS National Geologic Map Database: http://ngmdb.usgs.gov/

METHODS

Two-Dimensional Hydraulic and Habitat Modeling—General Approach

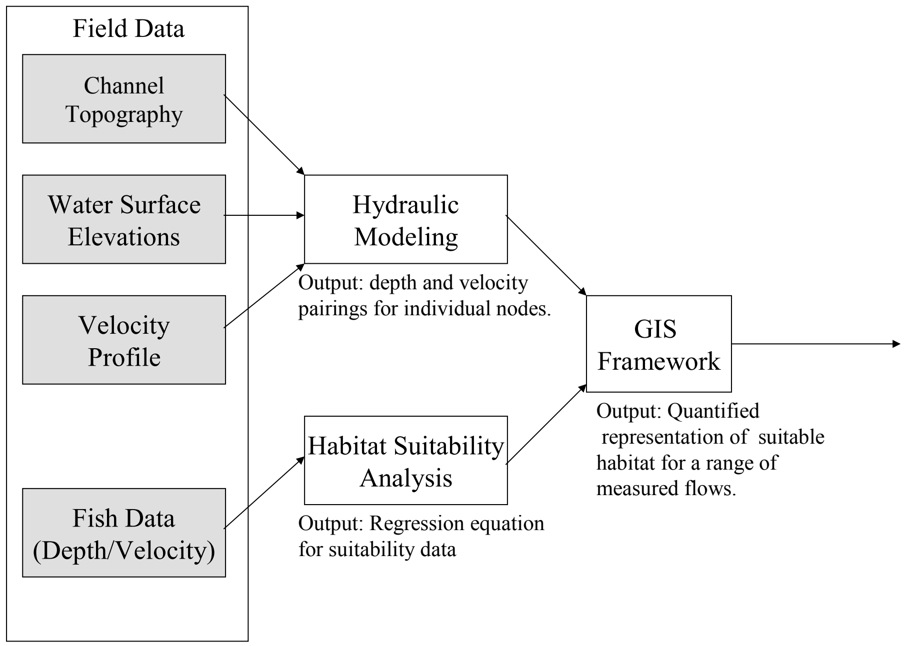
The state-of-the-art model used for instream flow studies is the two-dimensional hydraulic model River2D. The information presented in this report includes an analytical model that combines two-dimensional hydraulics, a GIS habitat model, and hydrologic data into a habitat time series. This approach follows the concepts of the Instream Flow Incremental Methodology (IFIM) (Bovee 1982, Bovee et al. 1998). IFIM is an analysis framework that combines stream hydraulics, habitat use criteria, and hydrology data to predict fish habitat as a function of stream flow. Stream hydraulics were measured in the field and modeled with the two-dimensional hydraulic simulations. Existing habitat suitability data from the Colorado Division of Wildlife were used for the target fish species (CDOW unpublished data). These habitat criteria were combined with the hydraulic simulations in a GIS habitat model to calculate habitat versus discharge relationships. The habitat versus discharge relationships were input to a computer spreadsheet and combined with hydrology data to calculate habitat over time. Generally, the time series analysis is the primary output from IFIM, which indicates the changes in habitat for a duration of time (Figure 11).

The IFIM assumes that physical habitat is a function of stream flow level in the streams being studied (Bovee 1982). Part of the scoping process for application of IFIM involves determining the factors that may be limiting to fish populations. The factors evaluated include channel geometry, water temperature, water quality, food sources (such as benthic macroinvertebrates), and management factors affecting fish populations. Existing records (e.g. USGS, CDOW) were reviewed to complete the limiting-factor analysis. Based on this review no factors were determined to be limiting.

Topographic Data Collection

Two-dimensional hydraulic modeling began with construction of a digital terrain map of the study area. Data points were obtained to construct a detailed topography map (or grid) of the channel and adjacent floodplains and terraces. A survey-grade GPS unit was used to collect data points. Within the river channel, data points were closely spaced to define channel geometry in both plan form and cross section. Other channel geometry points, such as toe of bank, top of bank, and even beyond the typical high-water mark, were collected so that various flow regimes can be modeled. Each point's coordinates were in the UTM coordinate system, zone 13N, and elevation recorded in meters. Substrate composition was visually estimated for all in-channel locations. The following categories were used to denote substrate type: Aquatic vegetation, Silt, Sand, Small gravel (0.25 – 1.0 inch), Large gravel (>1.0 – 3.0 inches), Cobble (>3.0 – 10.0 inches), Boulder (>10.0 inches), and Bedrock. Substrate was categorized by dominant and subdominant size class. Vegetation type was also recorded for those points outside of the river channel and general reference photos were taken.

An Acoustic Doppler Current Profiler (ADCP) (StreamPro model, Teledyne RD Instruments, Inc.) was used to collect stream bed elevation points. An ADCP transmits a pulse of energy (a ping) into the water, which is reflected off suspended particles in the water. It measures the change in frequency (Doppler shift) of the reflected energy and computes the velocity of the water relative to the ADCP (Teledyne RD Instruments 2009). An ADCP is typically used to measure discharge but it can also be used to measure velocity and depth for a given point. Via a Bluetooth connection, data from the ADCP were transmitted to a laptop computer running WinRiver II software (Teledyne RD Instruments, Inc.), which stores all measurements from the ADCP (Figure 12). To get an exact location for each data point, the GPS rover unit was connected to the laptop via a NMEA cable (Figure 13). In this way, each streambed point has an exact location in space as well as water velocity and depth information. The advantage of using an ADCP is that several hundred data points can be collected over a short period of time.



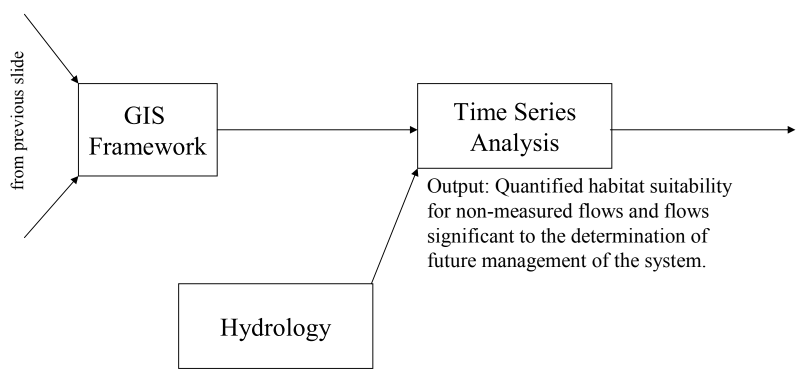


Figure 11. Flow chart of data analysis for the Colorado River hydraulic and habitat modeling.

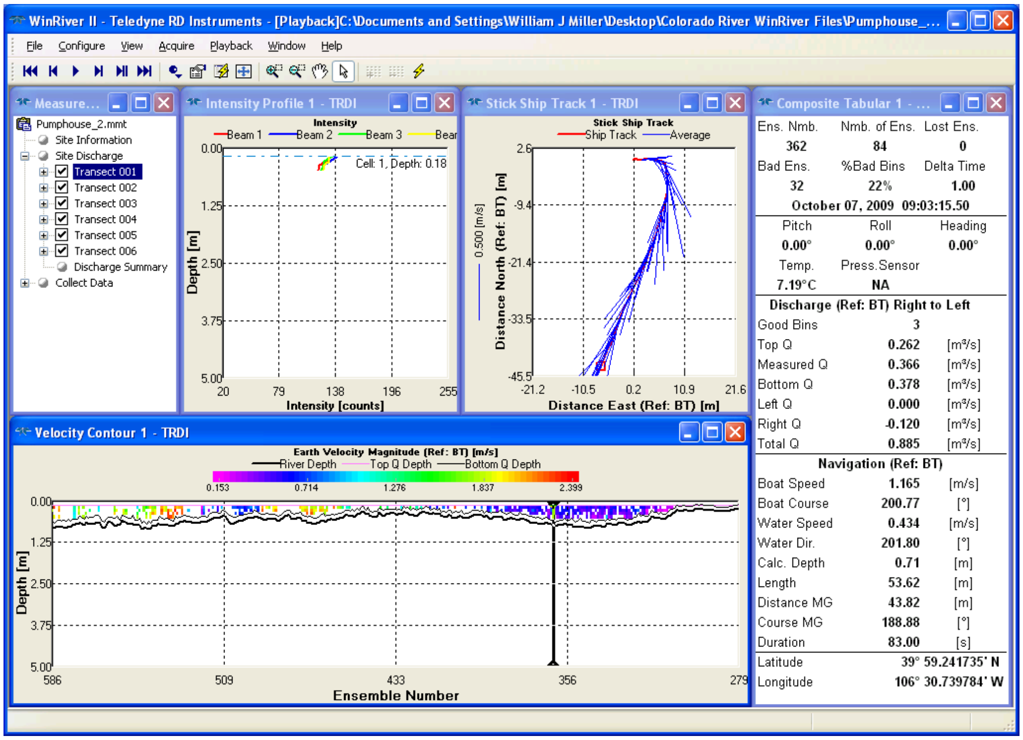


Figure 12. WinRiver II software program, which collects data from an ADCP.

Figure 13. Setup of the ADCP, GPS rover unit, and laptop computer on a raft so that bed elevations and velocities can be measured.

To collect bed elevation and velocity data the ADCP, GPS rover unit, and laptop computer were mounted on a raft and floated downstream (Figure 14). Five longitudinal transects were floated at Pumphouse (Figure 15), five at Rancho del Rio, and seven at Lyons Gulch. Additional points were collected with a top-set wading rod or GPS survey rod where water depth was too shallow to float.

Hydraulic Data Collection

Two-dimensional hydraulic modeling requires channel geometry data, multiple water-surface elevation data sets, and multiple velocity data sets. The specific hydraulic data that were collected at each site included stream bed elevations, mean column velocity at selected locations (multiple collections at each habitat type), water-surface elevations, and visual estimates of dominant and subdominant substrate size. An ADCP and survey-grade GPS were used to collect stream bed elevations as described above. Velocities were measured either with the ADCP or a Marsh-McBirney Flo-Mate portable velocity meter attached to a top-set wading rod.

Figure 14. Floating a longitudinal transect at Pumphouse to collect streambed elevation, velocity, and depth information.

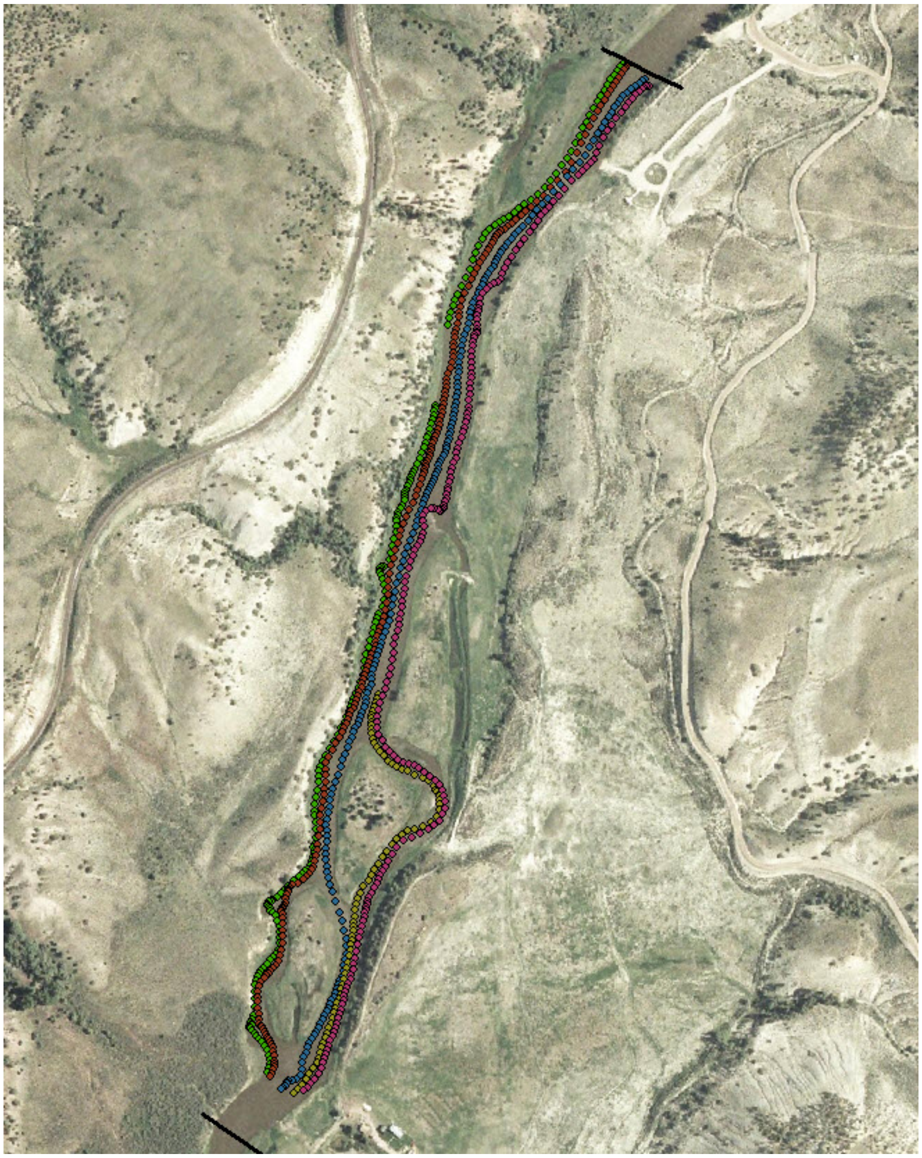


Figure 15. Longitudinal transects that collected bed elevation and velocity data at the Pumphouse site. Each color represents a different transect.

To calibrate the hydraulic model, repeat measurements of water-surface elevations and velocities were taken from three different discharge levels. Each time water-surface elevations were surveyed, discharge was measured either with the ADCP or it was estimated from USGS gage data. These stage-discharge measurements provided the necessary data for model calibration and for extending the range of hydraulic simulations.

Two-Dimensional Hydraulic Modeling

Two-dimensional hydraulic modeling was accomplished using River2D hydrodynamic modeling software (Steffler and Blackburn 2002). The model was developed to simulate two-dimensional velocity vectors in river systems, and can simulate element (i.e., grid cell) wetting and drying as flows are increased or decreased. Data inputs included site topography, substrate, and flow impediments (e.g.riffles, eddies, islands); a stage-discharge relationship at the downstream end of the site; and calibration and validation data throughout the site. Model calibration and validation data consist of depth, velocity, and water-surface elevation measurements taken at known discharges. This model operates on an irregular triangulated grid developed from the digital terrain model for each site. The grid system represents the stream geometry as a mesh. For Pumphouse and Lyons Gulch mesh size was approximately 1.25 meters; for Rancho del Rio mesh size was approximately 2.5 meters. This mesh was combined with the hydraulic data to simulate water depths and velocities for a range of flow conditions.

Habitat Suitability Curves

Species habitat suitability criteria were required for the habitat analysis. The recommended approach is to develop site-specific criteria for each species and life stage of interest. An alternative to this is to use existing curves and literature to develop suitability criteria for species of interest. Habitat suitability criteria that accurately reflect the habitat requirements of the species of interest are essential to conducting meaningful and defensible instream flow analyses. The curves used in this study fit that criterion.

Development of habitat suitability curves requires precise information on water depths, velocities, substrates, and cover types utilized by each life stage of the target species. Calculation of habitat suitability criteria for a two-dimensional hydraulic model can include use of a bivariate analysis of depth-velocity paired data to calculate fish preference for depth and velocity in the stream reach. Data from CDOW were used to develop habitat suitability criteria for adult and juvenile brown trout and rainbow trout. Habitat suitability for trout fry was developed by CDOW researchers. Trout spawning habitat suitability was developed from Raleigh et al. (1984, 1986). Mountain whitefish habitat suitability is from Bovee (1978). Flannelmouth sucker habitat use data was developed from Colorado River radio telemetry studies (Rees & Miller 2001).

A bivariate statistical analysis was used to develop habitat suitability criteria for brown and rainbow trout adult and juvenile lifestages (Miller 2001). This analysis first plotted bivariate histograms, then converted those to a three-dimensional surface, and finally computed a polynomial expression that replicates the three-dimensional surface to predict suitability values. A multivariate exponential polynomial equation was developed to fit the three-dimensional surface. The peak of the surface shape represents optimal depth and velocity for the life stage of interest (Figure 16).

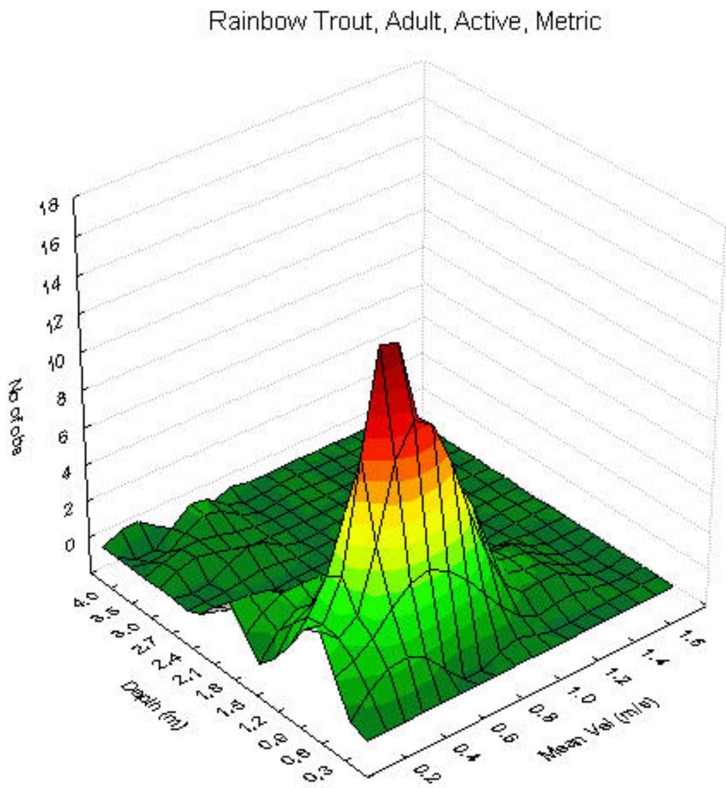


Figure 16. Example of a three-dimensional surface used to generate a habitat suitability equation for adult rainbow trout.

Habitat Modeling

The habitat modeling for this analysis followed the concepts of IFIM and the computer simulation steps of the Physical Habitat Simulation System (PHABSIM). IFIM requires hydraulic data and simulations, habitat use data expressed as habitat suitability criteria, and hydrology data for a range of stream discharge conditions. The hydraulic analysis and simulations were described above.

Habitat suitability modeling for each species of interest was accomplished in an ArcView GIS analysis (Miller and Geise 2003). The ArcView instream habitat model relies on inputs from both the two-dimensional hydraulic modeling and the habitat suitability criteria described above. These inputs are provided in the form of data layers within the GIS and parameters for spatial queries. Data layers corresponding to flow depths and velocities provided by the two-dimensional hydraulic modeling were developed for each discharge and overlain with data layers for substrate and cover within the study site. Specific habitat criteria developed from the suitability analyses described above were then used to conduct GIS queries. In this way, the amount of area within the study site that matches a particular species' habitat preference was determined for a specified discharge. Multiple layers of usable habitat were generated, corresponding to each species, life stage, and flow of interest. The analysis was output as a two-dimensional map for a visual presentation of the results. Summation of total habitat for each species and simulated flow resulted in a habitat-flow relationship by species and life stage that became input for the habitat-time series analysis. The usable habitat area for each species of interest was the result of combining the hydraulic simulations for each flow with the habitat suitability function for each species and life stage. The general sequence of habitat modeling was as follows.

The two-dimensional hydraulic simulations use a mesh to depict the stream channel. This mesh is configured to best represent each simulated flow. The result is multiple model meshes to represent the range of flow conditions. Unlike a one-dimensional hydraulic simulation that uses multiple cross sections that remain fixed for the full range of simulation flows, each of the two-dimensional meshes can have a different number of nodes and therefore a different surface area. The hydraulic simulation data sets contain the horizontal and vertical reference locations for each node in the model mesh. In addition, the node locations have depth, velocity and substrate data for each flow. These georeferenced data sets were combined with the habitat suitability functions in ArcView. The result of the GIS analysis is a georeferenced map of usable habitat for each species and life stage. The GIS model created a summation file for the usable habitat for each flow. The habitat–discharge relationship for the flows simulated at each site was developed for each species and life stage.

The habitat–discharge relationships are a set of theoretical functions based on channel shape and hydraulics. The actual habitat realized by the species is a function of the discharge at the site over time. The combination of the habitat–discharge function and hydrology data is the habitat time series.

Habitat Time Series

The actual habitat experienced by the fish in any river depends on the flow regime of the river. The relative abundance of habitat conditions over a period of time is an integral part of the comparison of flow regimes. Generally, the habitat time series is the comparative analysis used for the decision point in IFIM. Habitat time series produces the data needed to compare a range of flow conditions over time and to compare different flow scenarios. The habitat-discharge relationships for each study site were used as input data for the habitat time series. This analysis allowed a comparison between the existing flow regime and alternate flow regimes to determine available habitat with each time series.

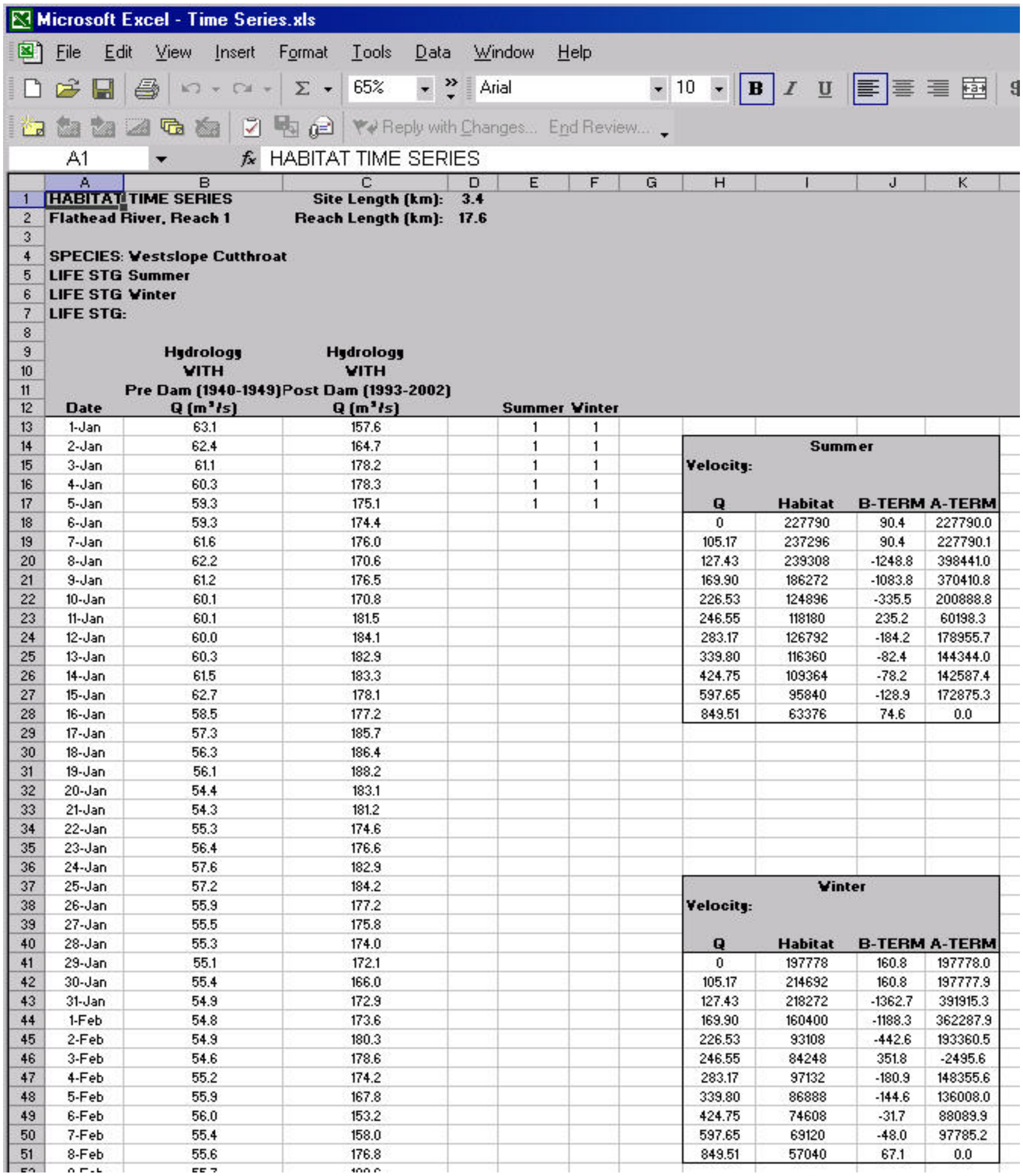
MEC conducted time series evaluations on several different flow regimes. For each flow regime assessed, we conducted both hydrology and habitat time series analysis to calculate both flow- and habitat statistics. These values allowed a direct comparison of the changes that occur in both flow and habitat under a range of conditions. These tabular data can be displayed for each flow scenario to represent the spatial habitat distributions.

Habitat time series uses a spreadsheet format with data arranged in columns and rows that combines the hydrology over time with the habitat use as a function of discharge. These values are converted to area of habitat for the study site and then area of habitat for the reach. Comparisons of change in habitat over time for each flow of interest are possible with this spreadsheet setup. The steps to use the spreadsheet for analysis are as follows:

The habitat time series spreadsheet is arranged with data in column format. Cell A1 contains the title. Cell A2 contains the name of the river. Cells A4 through A6 are titles for species and life stage. The species names and life stages are typed into Cells B4, B5, and B6 (Figure 17).

The hydrology data is placed in columns A, B and C. Rows 10 through 12 of those columns contain header information. Column A contains the Date, and Columns B and C contain the hydrology data. Column B contains the baseline hydrology titled “Pre-dam”. Column C contains the hydrology for the “Post-dam” alternative.

To the right of the hydrology columns are a look-up table with regression coefficients and functions for the weighted usable area for juvenile and adults of the species. The headers denote discharge (Q), habitat, and the A and B terms for the functions. The cells contain the formulas that calculate the A and B terms. The discharge and habitat values are generated in the GIS Base habitat model and copied or typed into the cells. The data for the blocks should start in cells of the time series spreadsheet contained in the distribution CD. The habitat for the site for each flow is analyzed by date and flow regime. The rows must be identical for the correct analysis. The habitat calculations are based on a Vlookup formula contained in cells R12, S12 and higher (Figure **18**).



Microsoft Excel - Time Series.xls

A1 HABITAT TIME SERIES

HABITAT TIME SERIES Site Length (km): 3.4
Flathead River, Reach 1 Reach Length (km): 17.6

SPECIES: Westslope Cutthroat
LIFE STG Summer
LIFE STG Winter
LIFE STG:

Date	Hydrology WITH Pre Dam (1940-1949) Q (m³/s)	Hydrology WITH Post Dam (1993-2002) Q (m³/s)	Summer	Winter
1-Jan	63.1	157.6	1	1
2-Jan	62.4	164.7	1	1
3-Jan	61.1	178.2	1	1
4-Jan	60.3	178.3	1	1
5-Jan	59.3	175.1	1	1
6-Jan	59.3	174.4		
7-Jan	61.6	176.0		
8-Jan	62.2	170.6		
9-Jan	61.2	176.5		
10-Jan	60.1	170.8		
11-Jan	60.1	181.5		
12-Jan	60.0	184.1		
13-Jan	60.3	182.9		
14-Jan	61.5	183.3		
15-Jan	62.7	178.1		
16-Jan	58.5	177.2		
17-Jan	57.3	185.7		
18-Jan	56.3	186.4		
19-Jan	56.1	188.2		
20-Jan	54.4	183.1		
21-Jan	54.3	181.2		
22-Jan	55.3	174.6		
23-Jan	56.4	176.6		
24-Jan	57.6	182.9		
25-Jan	57.2	184.2		
26-Jan	55.9	177.2		
27-Jan	55.5	175.8		
28-Jan	55.3	174.0		
29-Jan	55.1	172.1		
30-Jan	55.4	166.0		
31-Jan	54.9	172.9		
1-Feb	54.8	173.6		
2-Feb	54.9	180.3		
3-Feb	54.6	178.6		
4-Feb	55.2	174.2		
5-Feb	55.9	167.8		
6-Feb	56.0	153.2		
7-Feb	55.4	158.0		
8-Feb	55.6	176.8		

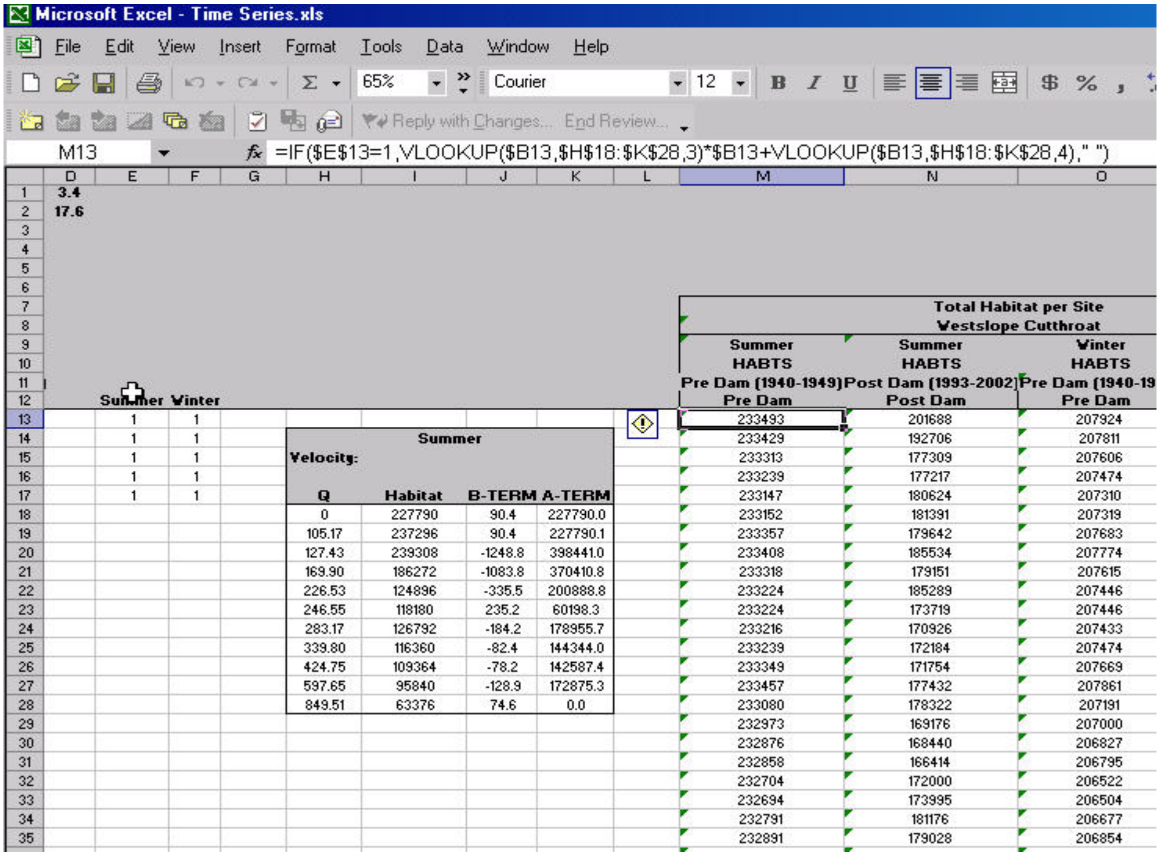
Summer
Velocity:

Q	Habitat	B-TERM	A-TERM
0	227790	90.4	227790.0
105.17	237296	90.4	227790.1
127.43	239308	-1248.8	398441.0
169.90	186272	-1083.8	370410.8
226.53	124896	-335.5	200888.8
246.55	118180	235.2	60198.3
283.17	126792	-184.2	178955.7
339.80	116360	-82.4	144344.0
424.75	109364	-78.2	142587.4
597.65	95840	-128.9	172875.3
849.51	63376	74.6	0.0

Winter
Velocity:

Q	Habitat	B-TERM	A-TERM
0	197778	160.8	197778.0
105.17	214692	160.8	197777.9
127.43	218272	-1362.7	391915.3
169.90	160400	-1188.3	362287.9
226.53	93108	-442.6	193360.5
246.55	84248	351.8	-2495.6
283.17	97132	-180.9	148355.6
339.80	86888	-144.6	136008.0
424.75	74608	-31.7	88089.9
597.65	69120	-48.0	97785.2
849.51	57040	67.1	0.0

Figure 17. Spreadsheet template for habitat time series.



	D	E	F
1	3.4		
2	17.6		
12		Summer	Winter
13		1	1
14		1	1
15		1	1
16		1	1
17		1	1

Summer			
Velocity:			
Q	Habitat	B-TERM	A-TERM
0	227790	90.4	227790.0
105.17	237296	90.4	227790.1
127.43	239308	-1248.8	398441.0
169.90	186272	-1083.8	370410.8
226.53	124896	-335.5	200888.8
246.55	118180	235.2	60198.3
283.17	126792	-184.2	178955.7
339.80	116360	-82.4	144344.0
424.75	109364	-78.2	142587.4
597.65	95840	-128.9	172875.3
849.51	63376	74.6	0.0

	Total Habitat per Site Vestslope Cutthroat		
	Summer HABTS Pre Dam (1940-1949) Pre Dam	Summer HABTS Post Dam (1993-2002) Post Dam	Vinter HABTS Pre Dam (1940-19 Pre Dam
13	233493	201688	207924
14	233429	192706	207811
15	233313	177309	207606
16	233239	177217	207474
17	233147	180624	207310
18	233152	181391	207319
19	233357	179642	207683
20	233408	185534	207774
21	233318	179151	207615
22	233224	185289	207446
23	233224	173719	207446
24	233216	170926	207433
25	233239	172184	207474
26	233349	171754	207669
27	233457	177432	207861
28	233080	178322	207191
29	232973	169176	207000
30	232876	168440	206827
31	232858	166414	206795
32	232704	172000	206522
33	232694	173995	206504
34	232791	181176	206677
35	232891	179028	206854

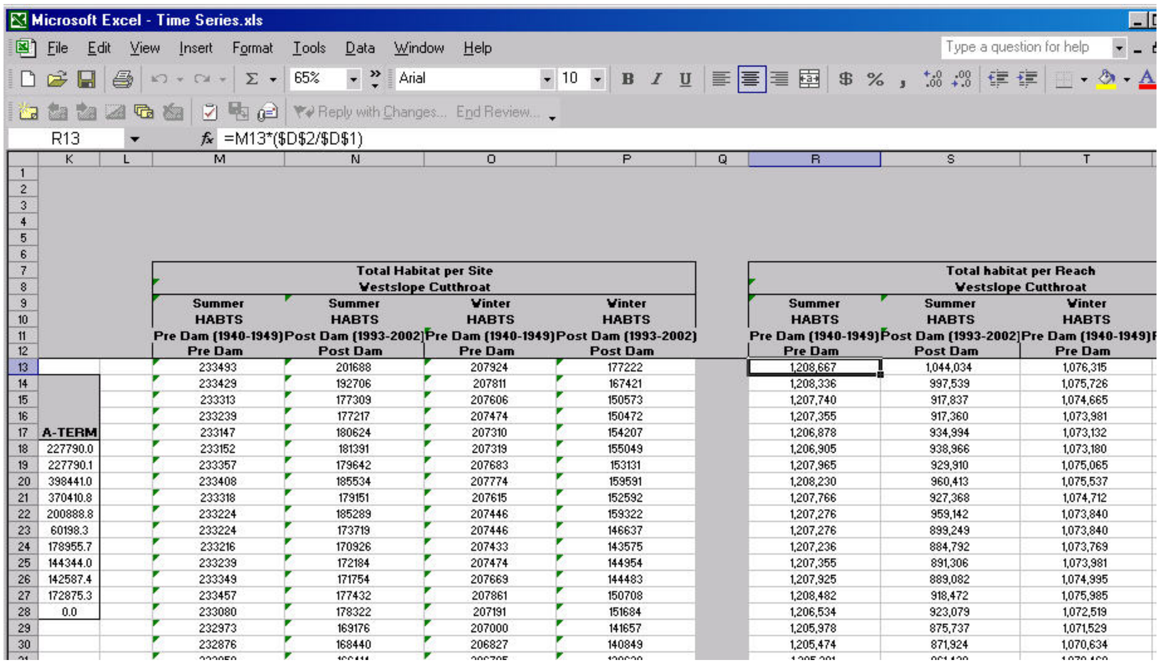
Figure 18. **Example of Vlookup function for time series analysis.**

Calculation of habitat for the site is completed for each life stage. The spreadsheet is set up to calculate habitat for each species and life stage of interest. The analysis requires that the formula be copied into the appropriate number of rows that correspond to every row containing hydrology in Columns B and C.

There are corresponding formulas in columns R, S, T and U to calculate the total habitat for the reach. The amount of habitat for the site is multiplied by the reach distance to compute total habitat for the reach (Figure **19**). Again, the number of rows corresponds to the number of hydrology data points.

This spreadsheet can also be used to graphically display the data to compare habitat over time. This identifies the information visually to give the capability of displaying where changes occur in habitat over time with the proposed flow regimes. Those results are presented in the next section.

The GIS based model calculated habitat from geo referenced hydraulic data and habitat suitability indices. The resulting values calculate habitat time series using the included spreadsheet. The habitat time series relies on formulas in specific cells to calculate habitat values over time. The user is cautioned to keep the data in the same cells as those in the example sheet. An experienced spreadsheet user can customize the example sheet for any number of species and dates for hydrology. In our experience it is best to limit each spreadsheet to no more than four hydrology data sets and four life stages.



Microsoft Excel - Time Series.xls

R13 =M13*($D$2/$D$1)

Row	K	M	N	O	P	R	S	T
7–8		Total Habitat per Site Vestslope Cutthroat				Total habitat per Reach Vestslope Cutthroat		
9–10		Summer HABTS	Summer HABTS	Vinter HABTS	Vinter HABTS	Summer HABTS	Summer HABTS	Vinter HABTS
11		Pre Dam (1940-1949)	Post Dam (1993-2002)	Pre Dam (1940-1949)	Post Dam (1993-2002)	Pre Dam (1940-1949)	Post Dam (1993-2002)	Pre Dam (1940-1949)
12		Pre Dam	Post Dam	Pre Dam	Post Dam	Pre Dam	Post Dam	Pre Dam
13		233493	201688	207924	177222	1,208,667	1,044,034	1,076,315
14		233429	192706	207811	167421	1,208,336	997,539	1,075,726
15		233313	177309	207606	150573	1,207,740	917,837	1,074,665
16		233239	177217	207474	150472	1,207,355	917,360	1,073,981
17	A-TERM	233147	180624	207310	154207	1,206,878	934,994	1,073,132
18	227790.0	233152	181391	207319	155049	1,206,905	938,966	1,073,180
19	227790.1	233357	179642	207683	153131	1,207,965	929,910	1,075,065
20	398441.0	233408	185534	207774	159591	1,208,230	960,413	1,075,537
21	370410.8	233318	179151	207615	152592	1,207,766	927,368	1,074,712
22	200888.8	233224	185289	207446	159322	1,207,276	959,142	1,073,840
23	60198.3	233224	173719	207446	146637	1,207,276	899,249	1,073,840
24	178955.7	233216	170926	207433	143575	1,207,236	884,792	1,073,769
25	144344.0	233239	172184	207474	144954	1,207,355	891,306	1,073,981
26	142587.4	233349	171754	207669	144483	1,207,925	889,082	1,074,995
27	172875.3	233457	177432	207861	150708	1,208,482	918,472	1,075,985
28	0.0	233080	178322	207191	151684	1,206,534	923,079	1,072,519
29		232973	169176	207000	141657	1,205,978	875,737	1,071,529
30		232876	168440	206827	140849	1,205,474	871,924	1,070,634

Figure 19. **Habitat time series example for the site and reach.**

The daily hydrology for dry, median, and wet year types and habitat data were imported into the computer spreadsheet for the time series analysis. The spreadsheet was set up to analyze the effect of changing hydrology over time on aquatic habitat as described above. Any combination of flow scenarios can be analyzed with this approach.

RESULTS

Topographic and Hydraulic Data

High-flow measurements were collected on June 10 and 11, 2009. Discharge was 3040 cfs at Pumphouse, 3200 cfs at Rancho del Rio, and 4850 cfs at Lyons Gulch. All discharges were estimated from USGS gages. Gage 0905800, Colorado River near Kremmling, was used to estimate discharge for Pumphouse and Rancho del Rio. For Lyons Gulch, data from gage 09070000 (Eagle River below Gypsum) was subtracted from gage 09070500 (Colorado River near Dotsero) in order to estimate discharge. Only water-surface elevation data were collected for high flows; depth and velocity data were not collected.

Mid-flow measurements were collected on July 21-23, 2009. Discharge was 1590 cfs at Pumphouse, 1337 cfs at Rancho del Rio, and 1642 cfs at Lyons Gulch. Discharge at Lyons

Gulch was estimated from USGS gage data due to an equipment malfunction on the ADCP; the ADCP was used to estimate discharge for Rancho del Rio and Pumphouse. Depth and velocity data were collected using a Marsh-McBirney Flo-Mate portable velocity meter attached to a top-set wading rod.

Low-flow measurements were collected on September 22-24, 2009. Discharge was 1114 cfs at Pumphouse, 1063 cfs at Rancho del Rio, and 1044 cfs at Lyons Gulch. All discharges were estimated with the ADCP. The ADCP was also used to collect depth and velocity data.

Topographic data collection occurred on September 22-24 and October 7-8, 2009. A sufficient number of points were surveyed to enable construction of a digital terrain model (Table 6, Figure 20, Figure 21, Figure 22). The River2D model uses field data points (survey points) in the construction of a computational mesh. The triangles that comprise mesh are referred to as elements and the vertices of the triangles are the computational nodes (Steffler and Blackburn 2002). The hydraulic computations occur at the model nodes.

Table 6. Summary of survey points, model nodes and model elements for study sites.

Site	Survey Points	River2D nodes	River2D elements
Pumphouse	1493	40,352	79,895
Rancho del Rio	647	15,839	31,085
Lyons Gulch	704	23,983	47,426

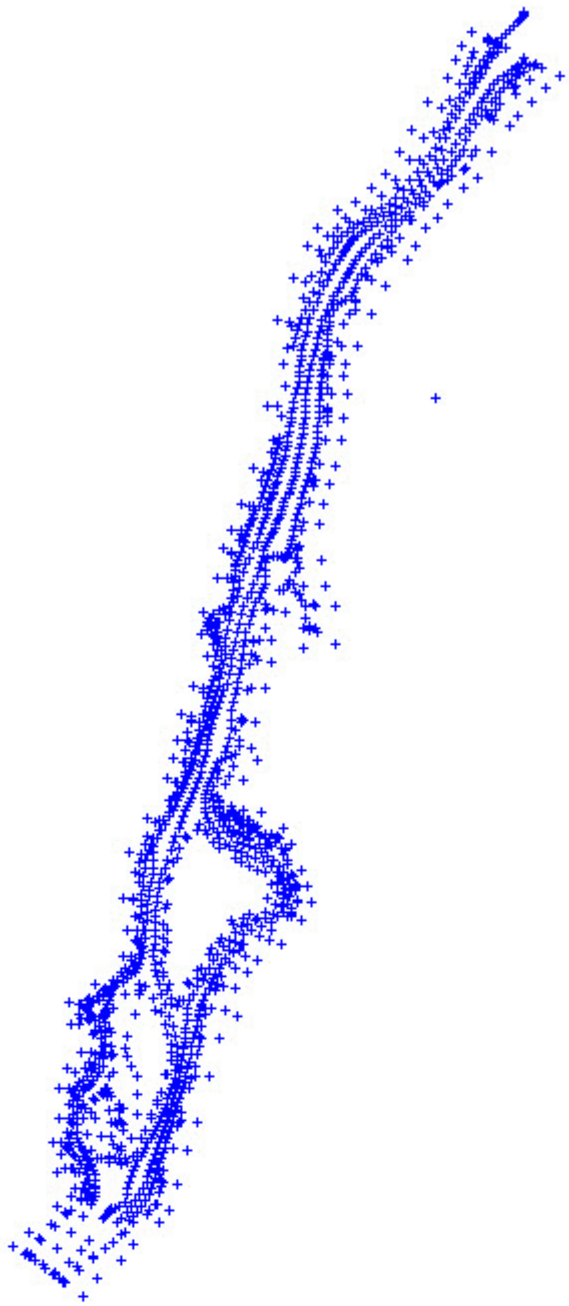


Figure 20. Topography survey locations at Pumphouse.

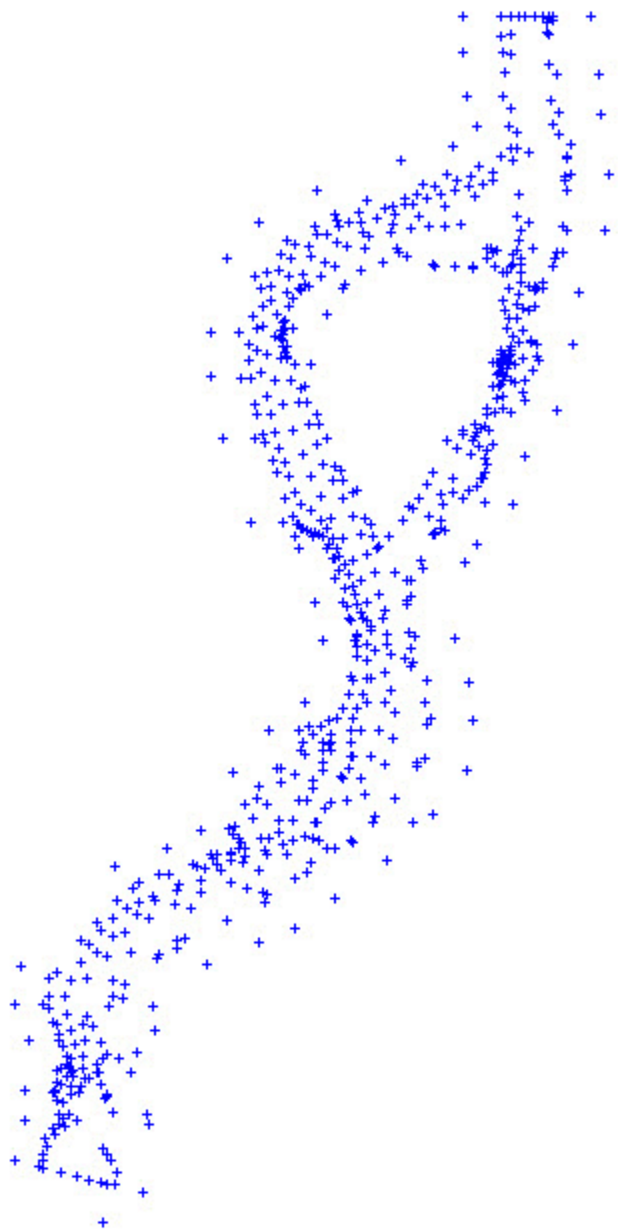


Figure 21. Topography survey locations at Rancho del Rio.

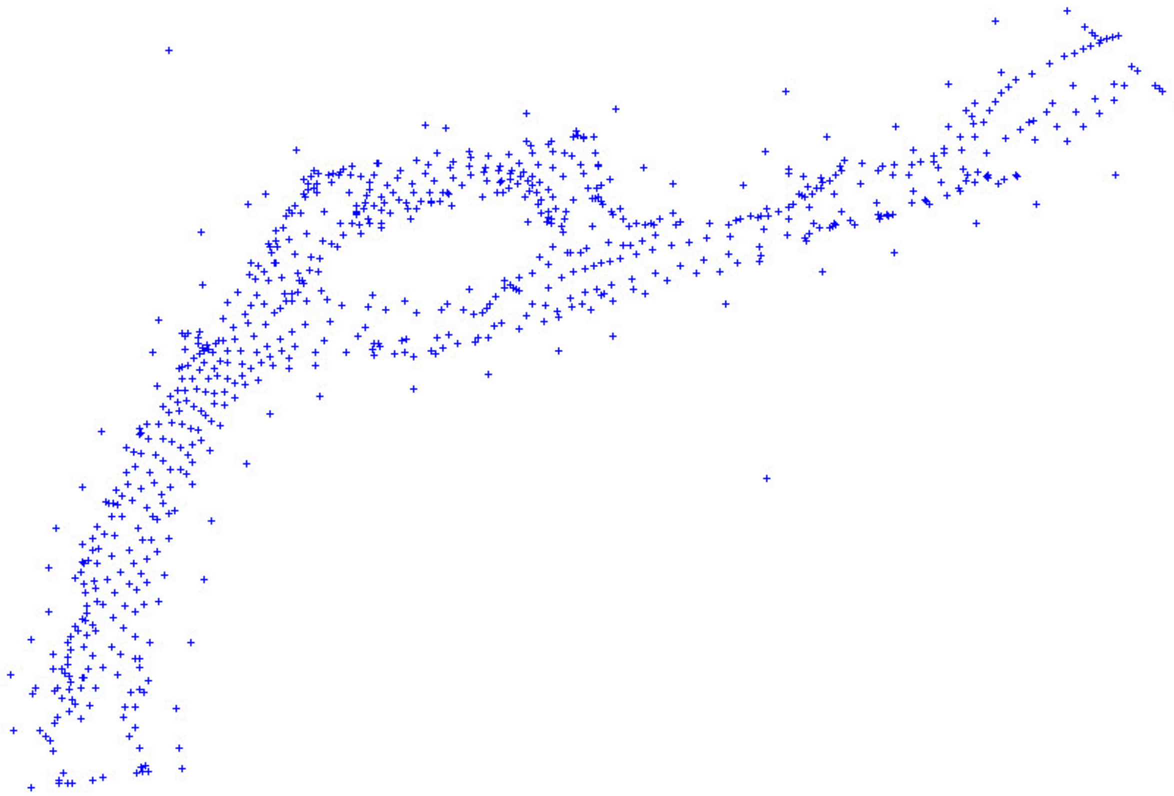


Figure 22. Topography survey locations at Lyons Gulch.

River2D Hydraulic Model Calibration

The River2D hydraulic models were calibrated from the low, mid, and high flows at each site. For each site and flow, several models were run with varying bed roughnesses and transmissivities. The measured water-surface elevation, depth, and velocity data were compared to simulated data at the same flow to determine model calibrations. Models were considered calibrated when the simulated water-surface elevations, depths, and velocities generally matched the observed values (Figure 23). These calibrated models for each site were then used for the model simulations for a range of discharges from low to high (Table 7).

Habitat Suitability Criteria

The species modeled at each site were determined in consultation with CDOW biologists. The habitat suitability criteria for brown and rainbow trout were derived from Colorado Division of Wildlife data collected in the South Platte and Cache La Poudre rivers. These data were collected by direct observation by life stage. The data for adult and juvenile trout were transformed to habitat suitability criteria using a bivariate analysis to develop a multivariate exponential equation. The data for trout fry were a univariate function derived from CDOW data. The data for flannelmouth sucker were collected from radio telemetry studies in the Colorado River near Grand Junction (Rees & Miller 2001. These suitability functions were used to transform the hydraulic model output into habitat values for each study site using GIS.

Mountain whitefish habitat was calculated using the habitat model within River2D using standard univariate criteria for adult (Figure 24), Juvenile (Figure 25), Fry (Figure 26), and spawning (Figure 27), lifestages (Bovee 1978).

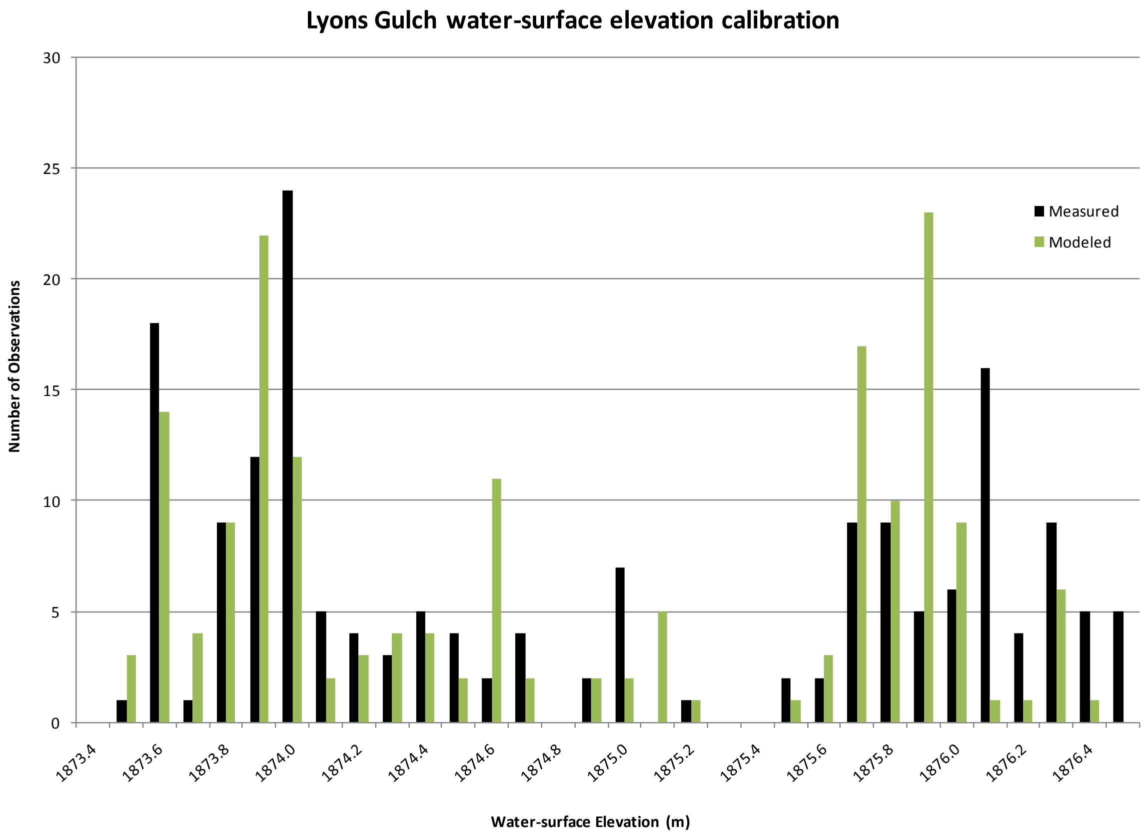


Figure 23. Example of measured versus modeled water-surface elevations for low flow at Lyons Gulch.

Table 7. Calibration and simulation flows for each site.

Site	Calibration Discharges (cfs)	Simulation Discharges (cfs)
Pumphouse	1114, 1590, 3040	300, 500, 750, 1000, 1300, 1500, 1800, 2000, 2250, 2500, 3000, 4000, 5000
Rancho del Rio	1063, 1337, 3200	300, 500, 750, 1100, 1500, 1650, 1800, 2000, 2250, 2500, 3000, 4000, 5000
Lyons Gulch	1044, 1642, 4850	300, 500, 750, 1000, 1100, 1300, 1500, 1800, 2000, 2250, 2500, 3000, 4000, 5200, 6500, 8000

Normalized Suitability Equations: (Note: units for depth are meters, units for velocity are meters per second) used to determine the habitat suitability for each point in the hydraulic files.

Brown Trout-Juvenile

$Z=(1/31.64259495)*(exp(-((3.905144)+(-69.092*Dep)+(41.6398*Vel)+(-5.22811*Dep*Vel)+(188.0895*Dep^2)+(-205.393*Vel^2)+(-227.543*Dep^3)+(423.2293*Vel^3)+(131.2333*Dep^4)+(-378.955*Vel^4)+(-27.5451*Dep^5)+(124.5627*Vel^5))$

Where:
Dep = Depth (m)
Vel = Velocity (m/s)

Brown Trout-Adult

$Z=(1/8.984860564)*(exp(-((33.61703)+(-148.355*Dep)+(-89.8087*Vel)+(-77.5644*Dep*Vel)+(384.7402*Dep^2)+(273.4011*Vel^2)+(-366.375*Dep^3)+(-225.051*Vel^3)+(136.2446*Dep^4)+(77.94253*Vel^4))$

Rainbow Trout-Juvenile

$Z=(1/21.10178982)*(exp(-((4.340354)+(-61.9731*Dep)+(19.46745*Vel)+(-7.67705*Dep*Vel)+(155.9402*Dep^2)+(-85.5221*Vel^2)+(-164.439*Dep^3)+(185.1374*Vel^3)+(77.34849*Dep^4)+(-173.877*Vel^4)+(-11.8636*Dep^5)+(61.66031*Vel^5))$

Rainbow Trout-Adult

$Z=(1/11.08667378)*(exp(-((0.087184)+(11.36193*Dep)+(56.9357*Vel)+(3.539872*Dep*Vel)+(-51.7545*Dep^2)+(-309.223*Vel^2)+(55.63995*Dep^3)+(626.7088*Vel^3)+(-23.3391*Dep^4)+(-559.162*Vel^4)+(3.403427*Dep^5)+(184.4437*Vel^5))$

2-4 week trout fry

$Z=(((-85.2*Vel^3)+(56.454*Vel^2)-(12.388*Vel)+0.9248)*((-18153*Dep^5)+(14008*Dep^4)-(3451.2*Dep^3)+(229.84*Dep^2)+(10.575*Dep)-0.0063))$

Trout spawning

$Z=(((-2.6353*Vel^5)+(14.929*Vel^4)-(27.642*Vel^3)+(18.323*Vel^2)-(2.3518*Vel)+0.0053)*((0.0543*Dep^3)-(0.6838*Dep^2)+(1.5715*Dep))*((-0.101*CI^3)+(0.7676*CI^2)-(0.7654*CI)-1.807*CI))$

Where:
CI = Channel Index (substrate for spawning)

Flannelmouth sucker adult suitability equation (Metric values)

$$Z=(1/63.008095)*\exp(-(24.05885+(-72.9041*Dep)+(-81.2860*Vel)+(-5056615*Dep*Vel)+94.56186*Dep^2+333.3527*Vel^2+(-48.0601*Dep^3)+(-488.737*Vel^3)+8.532339*Dep^4+239.6474*Vel^4+0.65574*Dep^3*Vel^3))$$

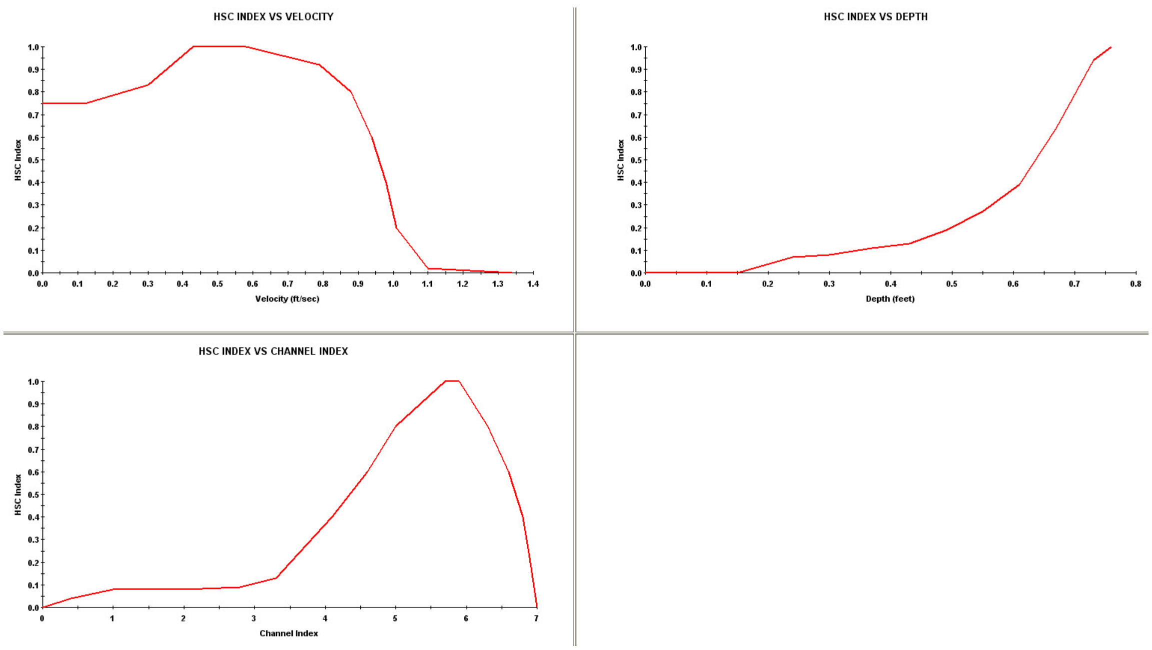


Figure 24. Mountain whitefish adult HSI

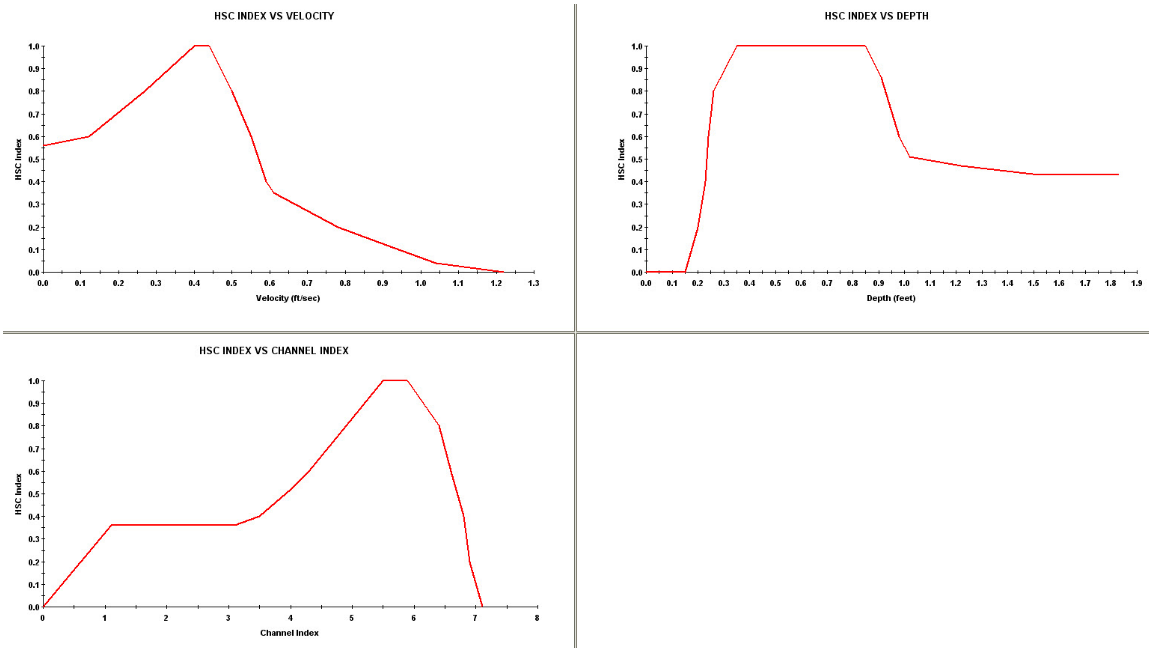


Figure 25, Mountain whitefish juvenile HSI

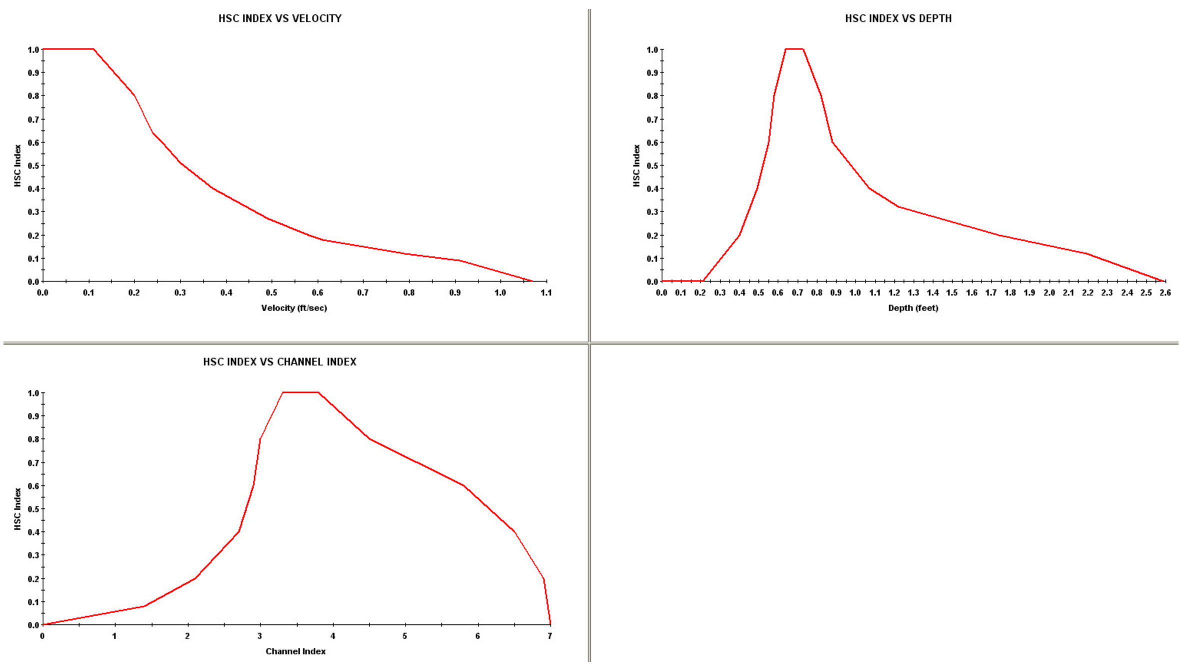


Figure 26. Mountain whitefish fry HSI

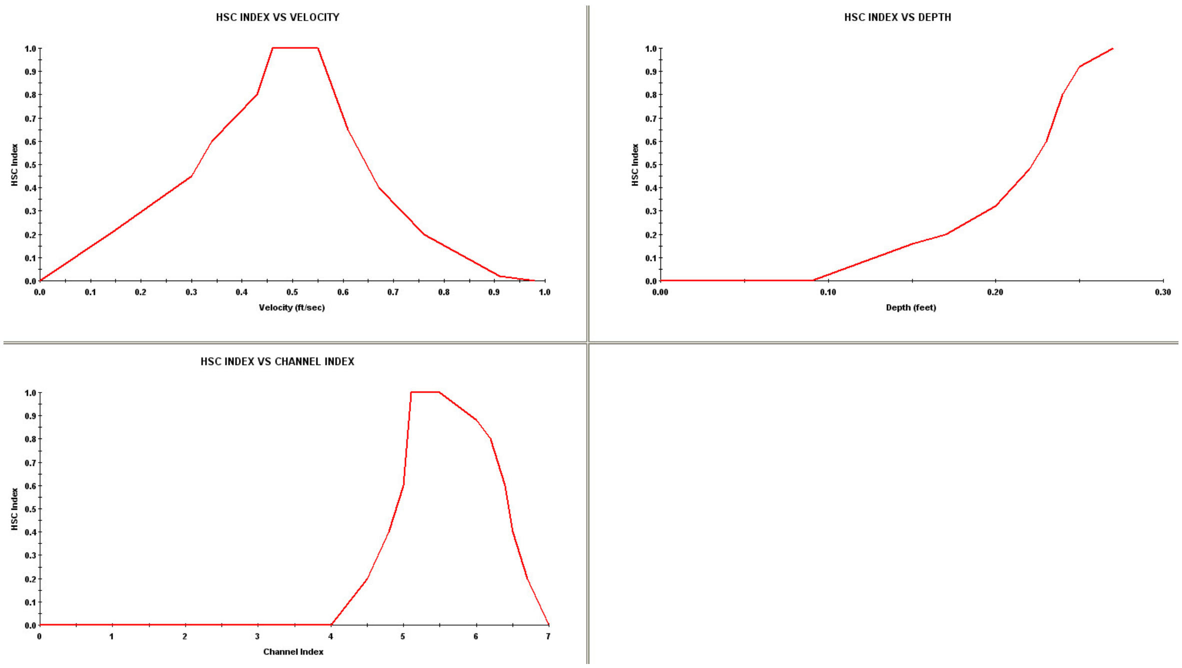


Figure 27. Mountain whitefish spawning HSI

Hydraulic Modeling

Pumphouse

The first half of the Pumphouse site consists primarily of run habitat (Figure 28), although a few small riffles are present within this section (Figure 29). The downstream half of the site contains two large islands (Figure 30) and one small island; more riffle habitat is present in this section and velocities are higher (Figure 31, Figure 32, Figure 33). At the approximate mid-point of the site, a former diversion channel is present on the left bank and partially fills at higher flows (Figure 34). The diversion channel slows down streamflow, yet the effect is less pronounced at higher flows. Substrate within the channel is primarily cobble, although small areas of sand and gravel are present (Figure 35).

Figure 28. Pumphouse from mid-site looking upstream, low flow.

Figure 29. Upstream end of the Pumphouse site looking downstream, mid flow.

Figure 30. View of downstream end and islands of the Pumphouse site, high flow.

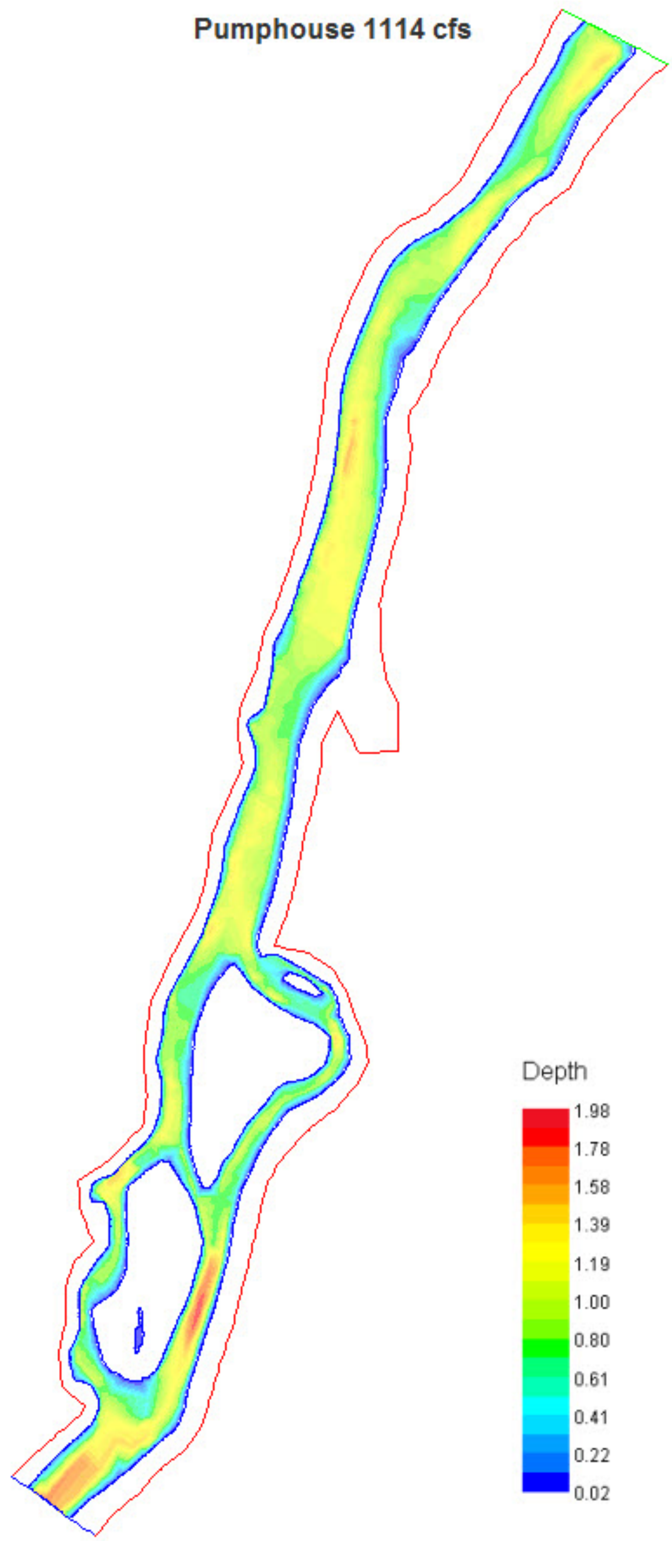


Figure 31. Pumphouse simulated water depth (m) at 1114 cfs (low flow). Flow moves from top to bottom.

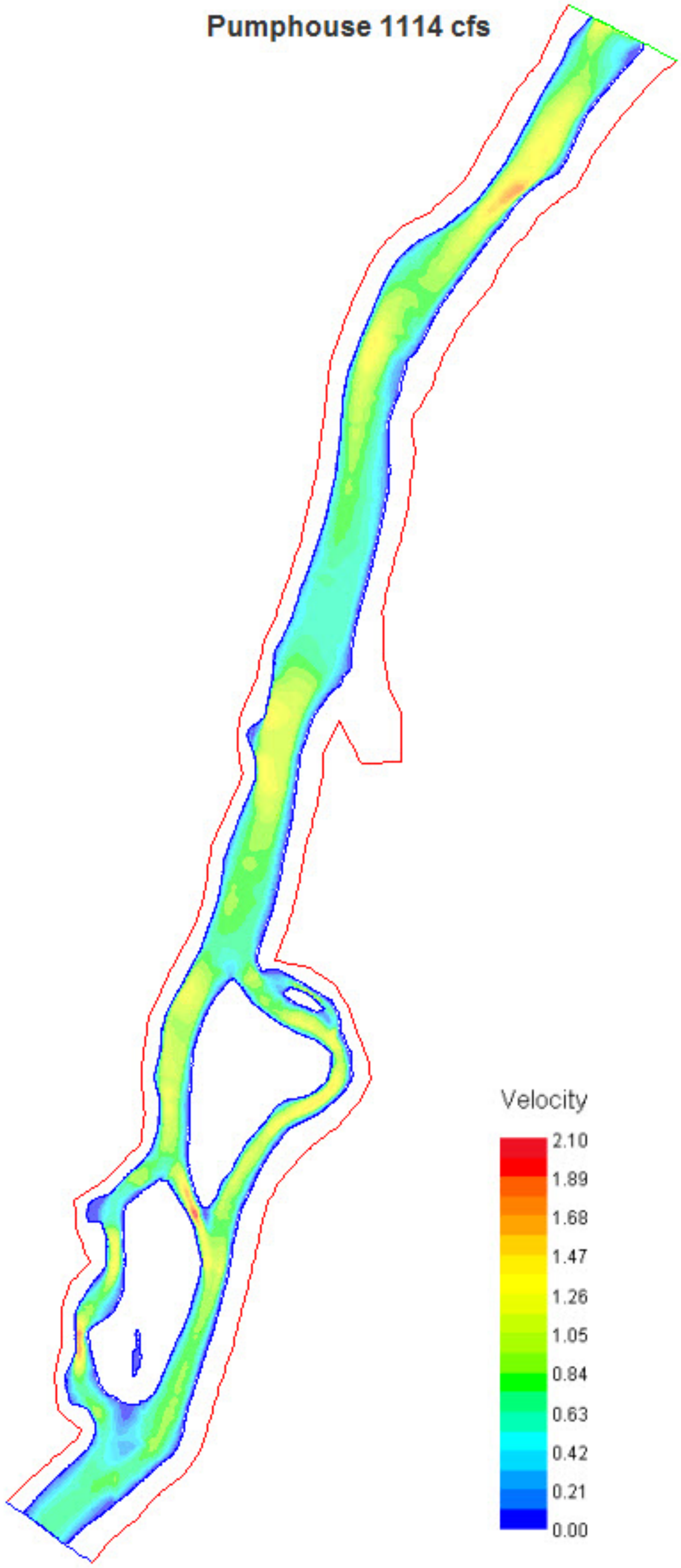


Figure 32. Pumphouse simulated water velocity (m/s) at 1114 cfs (low flow). Flow moves from top to bottom.

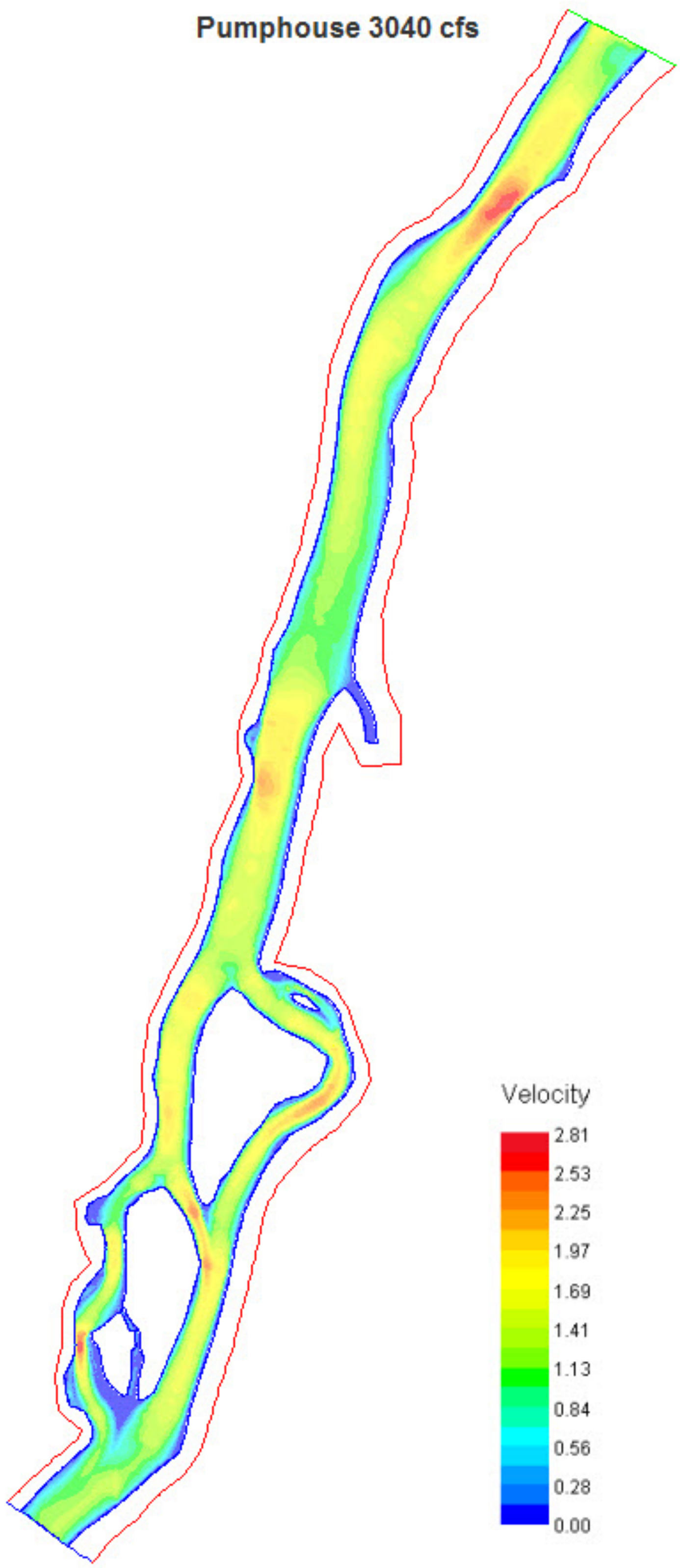


Figure 33. Pumphouse simulated water velocity (m/s) at 3040 cfs (high flow). Flow moves from top to bottom.

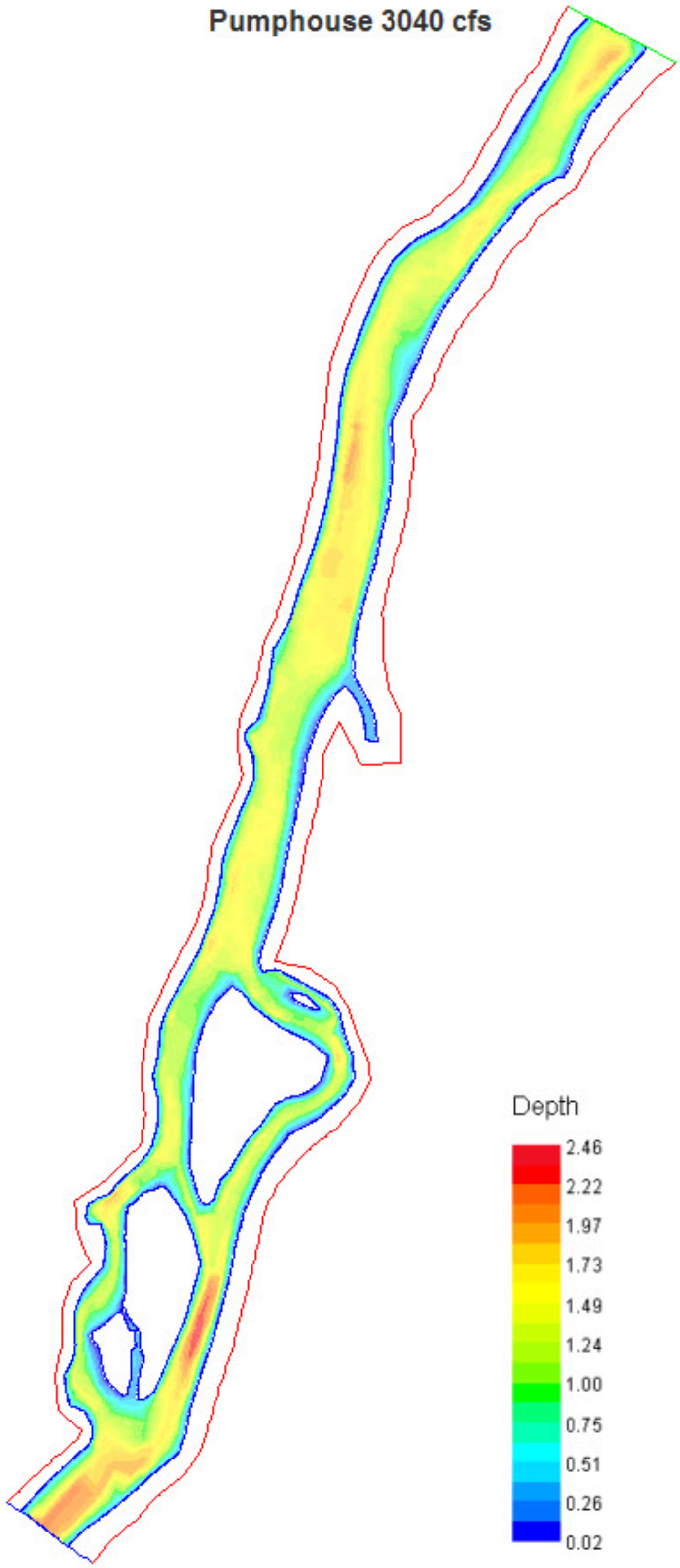


Figure 34. Pumphouse simulated water depth (m) at 3040 cfs (high flow). Flow moves from top to bottom.

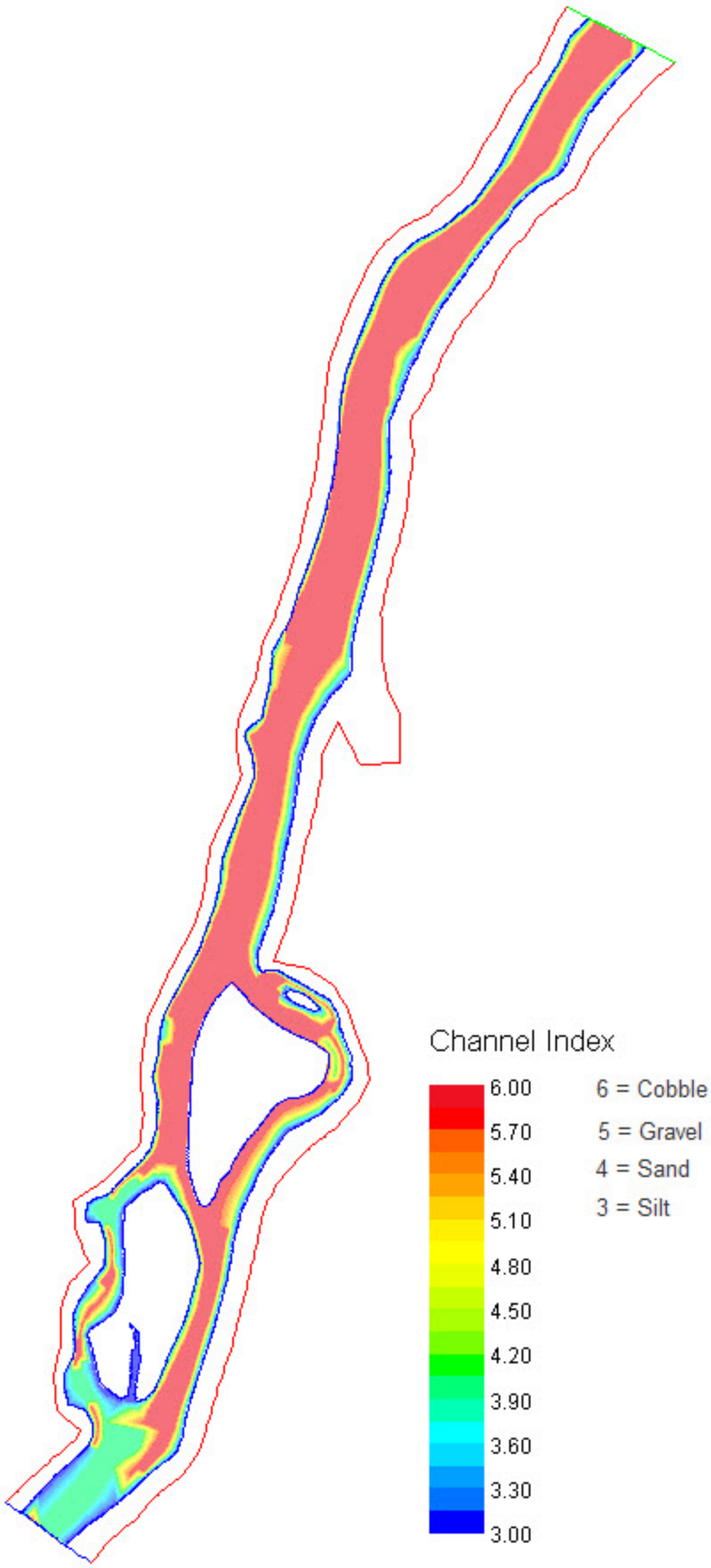


Figure 35. Bed substrate at the Pumphouse site.

Rancho del Rio

The Rancho del Rio site begins with a riffle (Figure 36); at low flows this riffle consists of several standing waves. Downstream of the riffle, a large island splits the streamflow into two channels. The right channel is run habitat while the left channel is more riffle-like. Once the channels merge, run habitat is present until near the end of the site. At high flows, a smaller island occurs approximately two-thirds of the way down the site along the right bank (Figure 37); at mid to low flows, the island becomes part of the right stream bank (Figure 38). At the end of the site the channel deepens and a small cliff constricts the channel; deep backwater eddies form after the constriction point (Figure 39). The highest velocities occur at the uppermost riffle (Figure 40, Figure 41). Depth is greatest at the downstream end of the site (Figure 42, Figure 43). Substrate within the channel is a mixture of cobble and gravel in the upper half of the site; the lower half consists of gravel (Figure 44).

Figure 36. View of the uppermost riffle at Rancho del Rio, high flow.

Figure 37. Rancho del Rio from benchmark 2 looking upstream, high flow.

Figure 38. Rancho del Rio from benchmark 2 looking upstream, mid flow. Note the former island in the center of the photo.

Figure 39. Rancho del Rio from benchmark 1 looking downstream at the end of the site, mid flow.

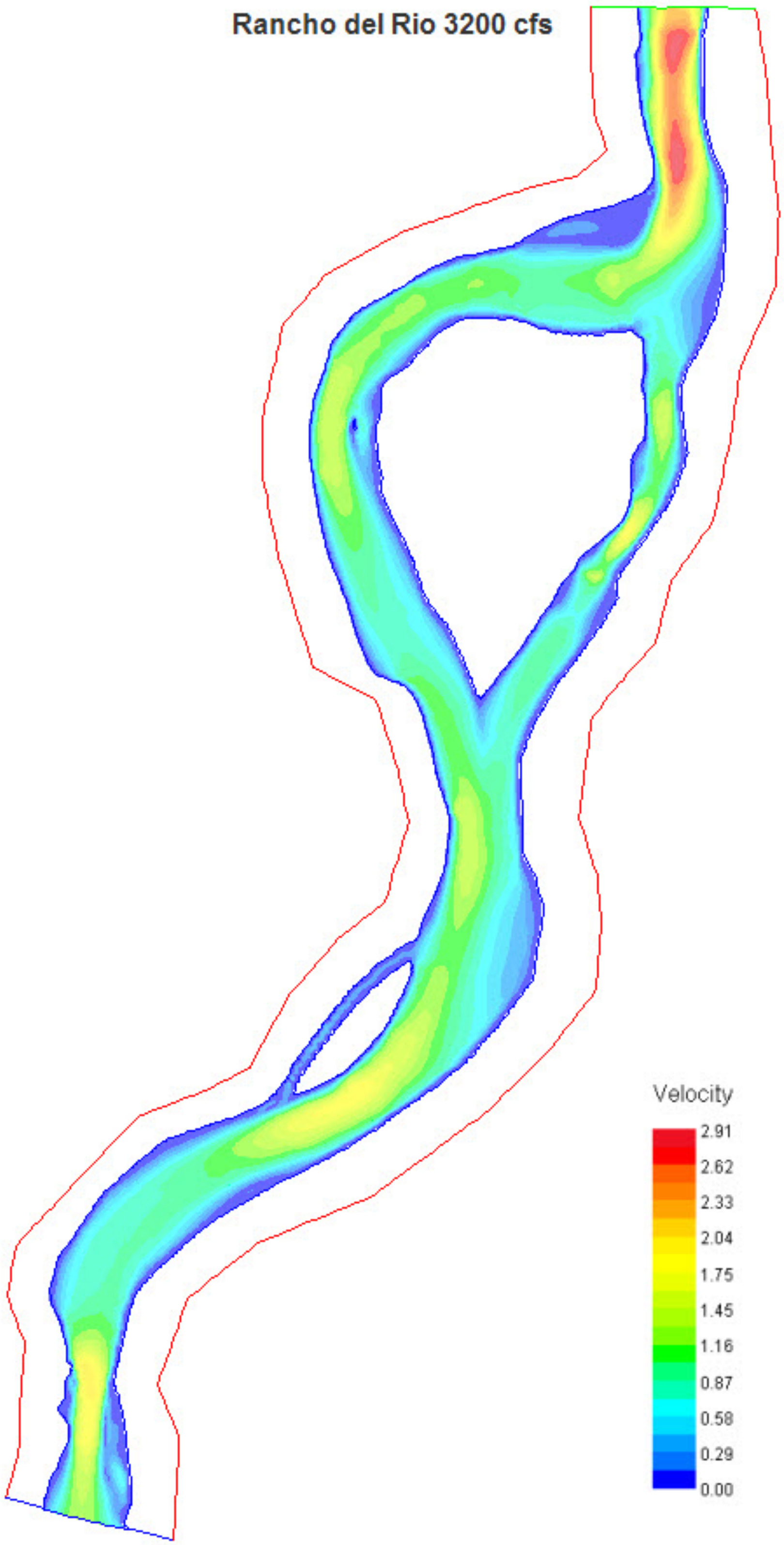


Figure 40. Rancho del Rio simulated water velocity (m/s) at 3200 cfs (high flow). Flow moves from top to bottom.

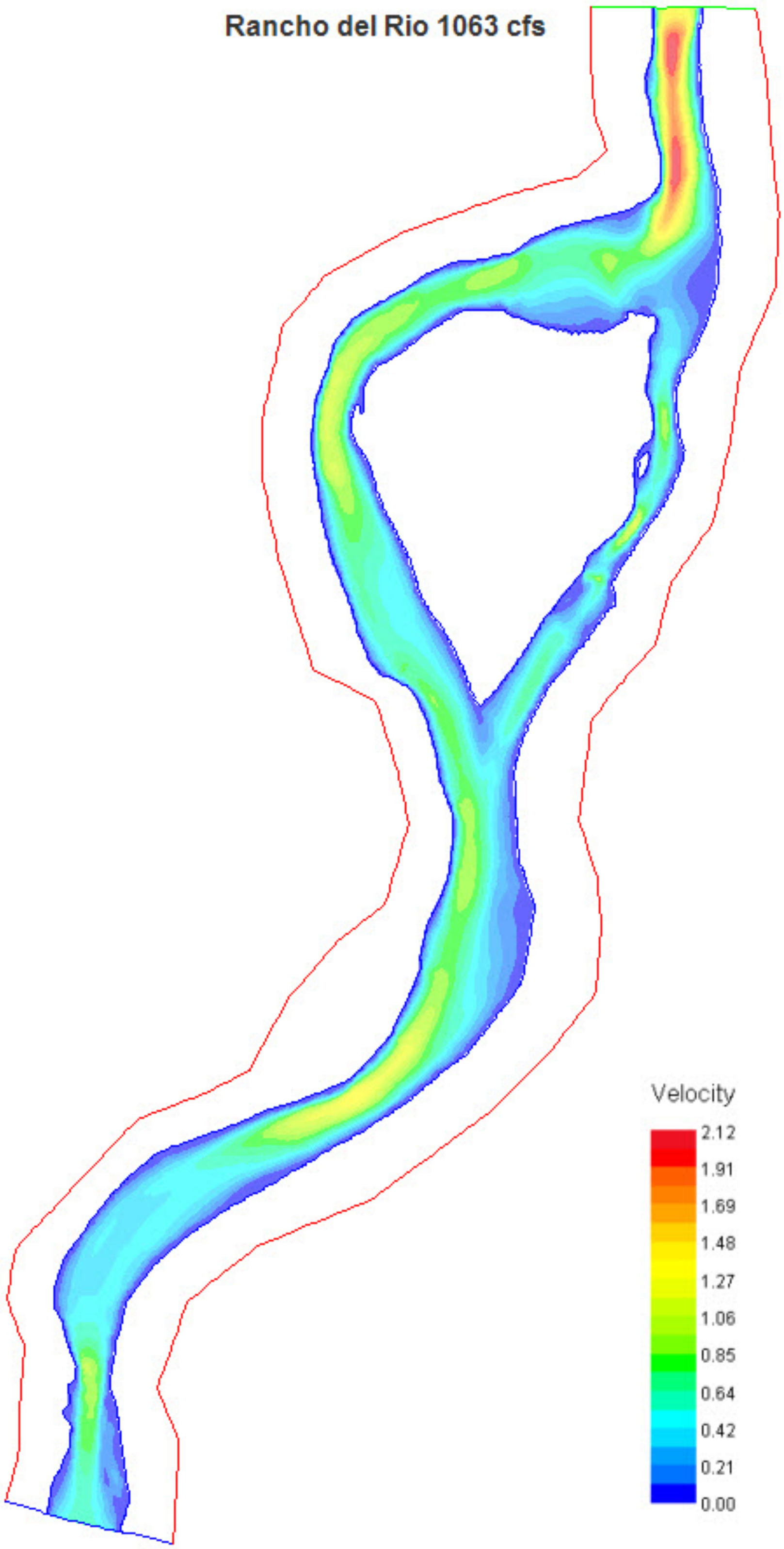


Figure 41. Rancho del Rio simulated water velocity (m/s) at 1063 cfs (low flow). Flow moves from top to bottom.

Figure 42. Rancho del Rio simulated water depth (m) at 3200 cfs (high flow). Flow moves from top to bottom.

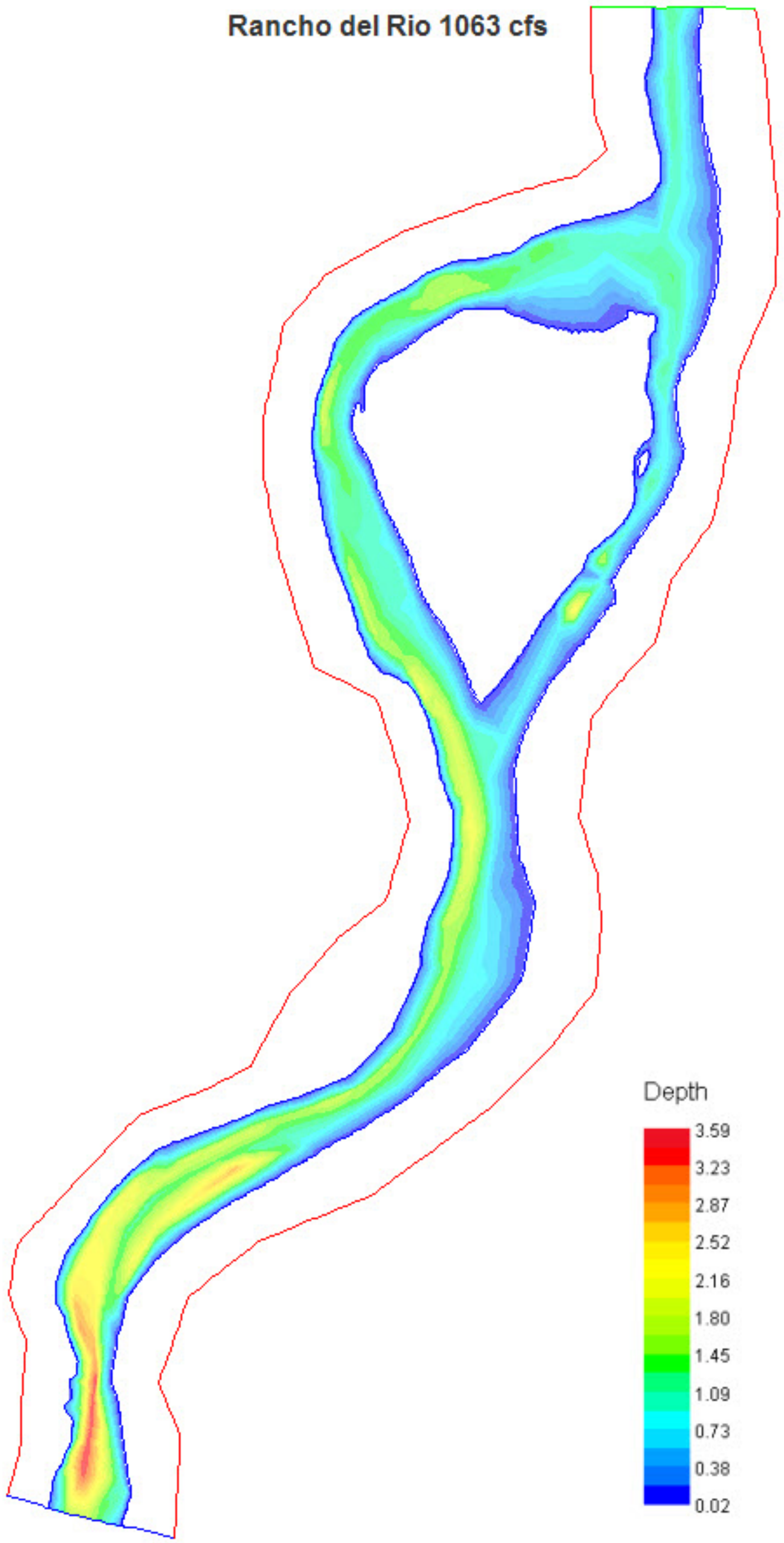


Figure 43. Rancho del Rio simulated water depth (m) at 1063 cfs (low flow). Flow moves from top to bottom.

Figure 44. Bed substrate at the Rancho del Rio site.

Lyons Gulch

The Lyons Gulch site begins with run habitat. Approximately 115 meters downstream the channel narrows, forming a riffle. The river then splits into two channels around a large island. The left channel is riffle habitat of high velocity. The right channel transitions from riffle habitat to run habitat (Figure 45) and several cobble/gravel bars are exposed at mid to low flows (Figure 46). The remainder of the site is run habitat with a few deep pools. Water velocities are highest at the first riffle and the left channel around the island (Figure 47, Figure 48). The greatest depths occur at the beginning of the site and in the pools within the downstream-most run (Figure 49, Figure 50). Due to the constriction at the first riffle, the first run has lower velocities and consists of silt, sand, and gravel. The rest of the site consists of cobble with occasional areas of gravel and sand (Figure 51).

Figure 45. Lyons Gulch from benchmark 2 looking upstream, mid flow. The large island is at the right side of the photo.

Figure 46. Lyons Gulch from benchmark 2 looking downstream, mid flow. The large island is at the left side of the photo.

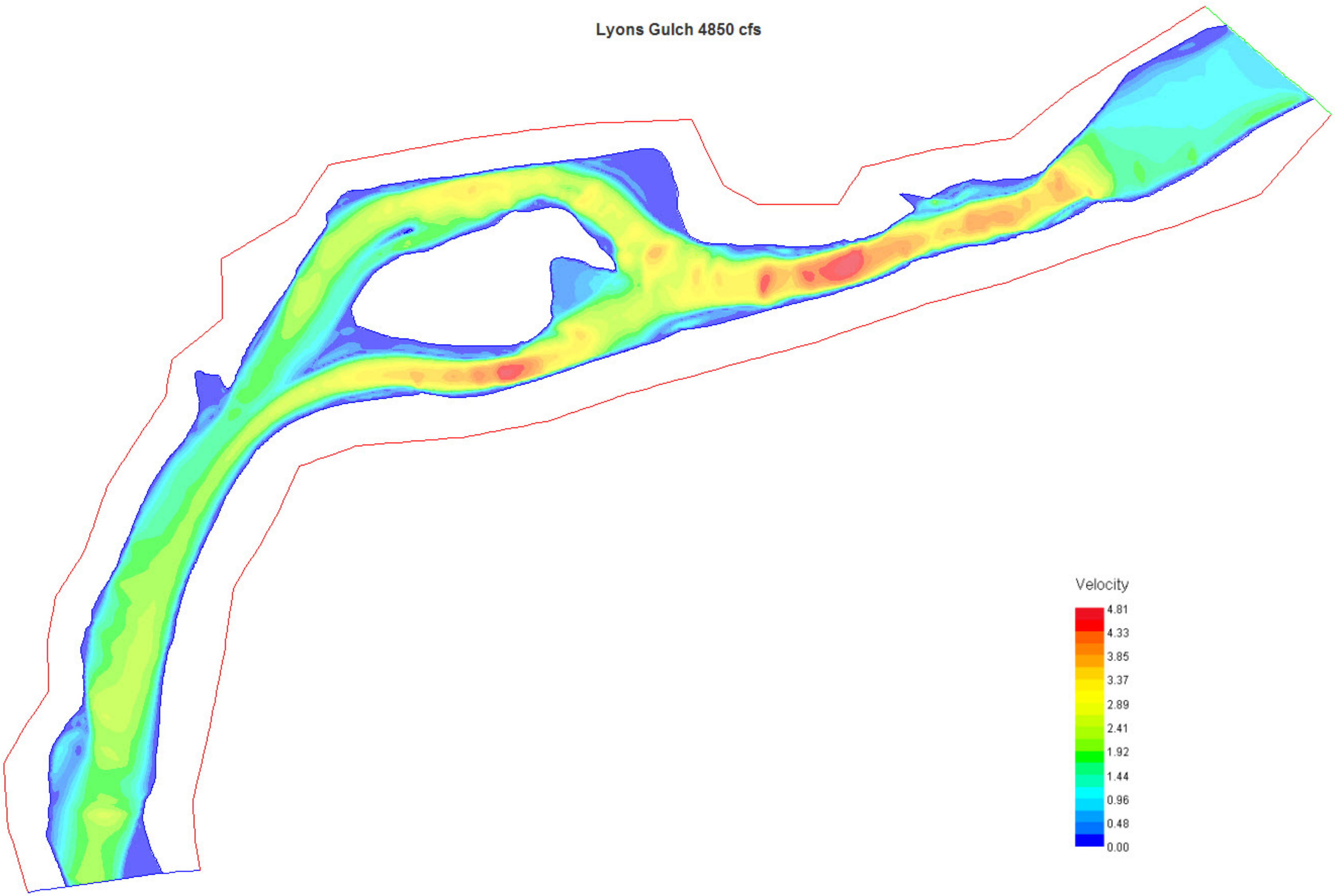


Figure 47. Lyons Gulch simulated water velocity (m/s) at 4850 cfs (high flow). Flow moves from right to left.

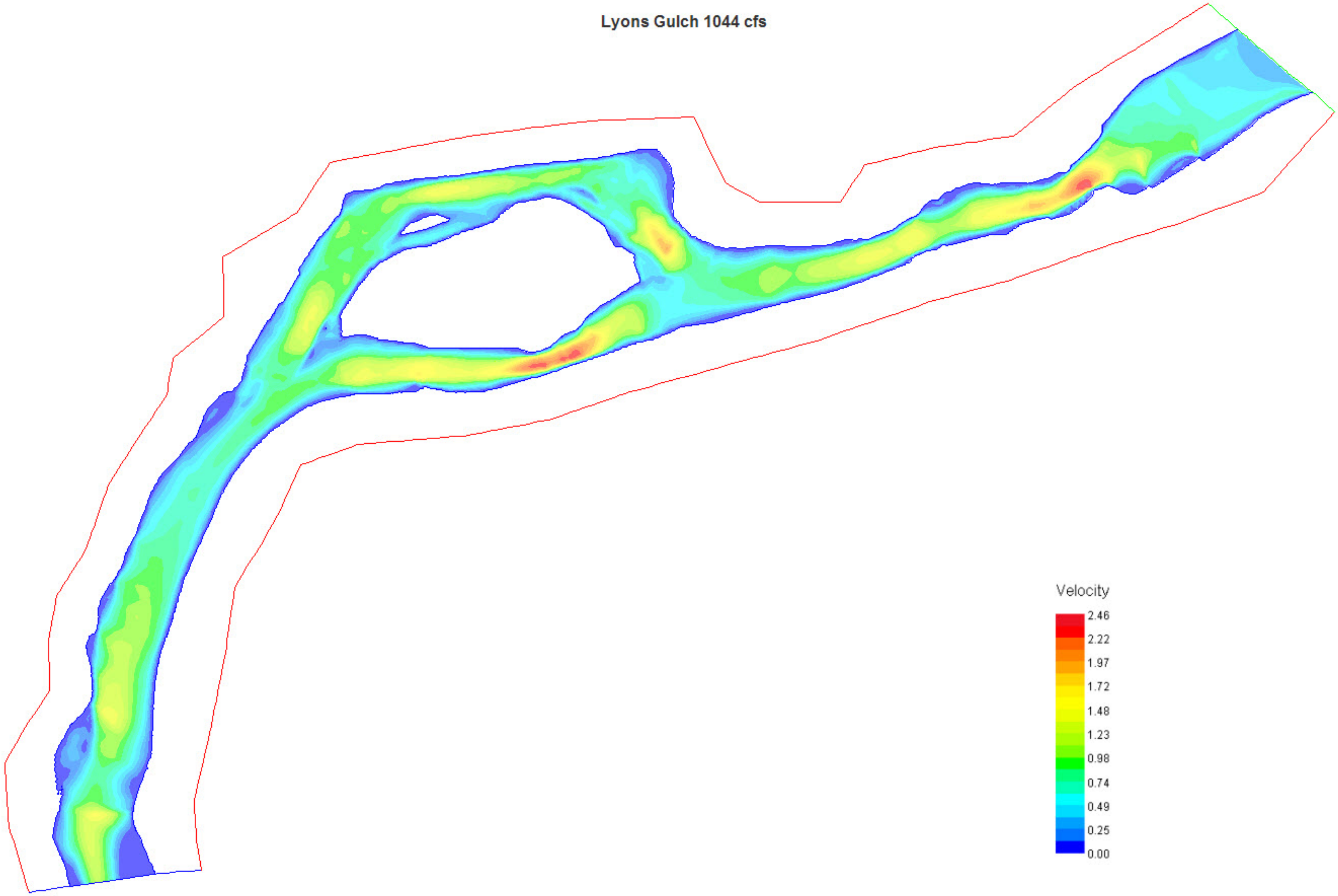


Figure 48. Lyons Gulch simulated water velocity (m/s) at 1044 cfs (low flow). Flow moves from right to left.

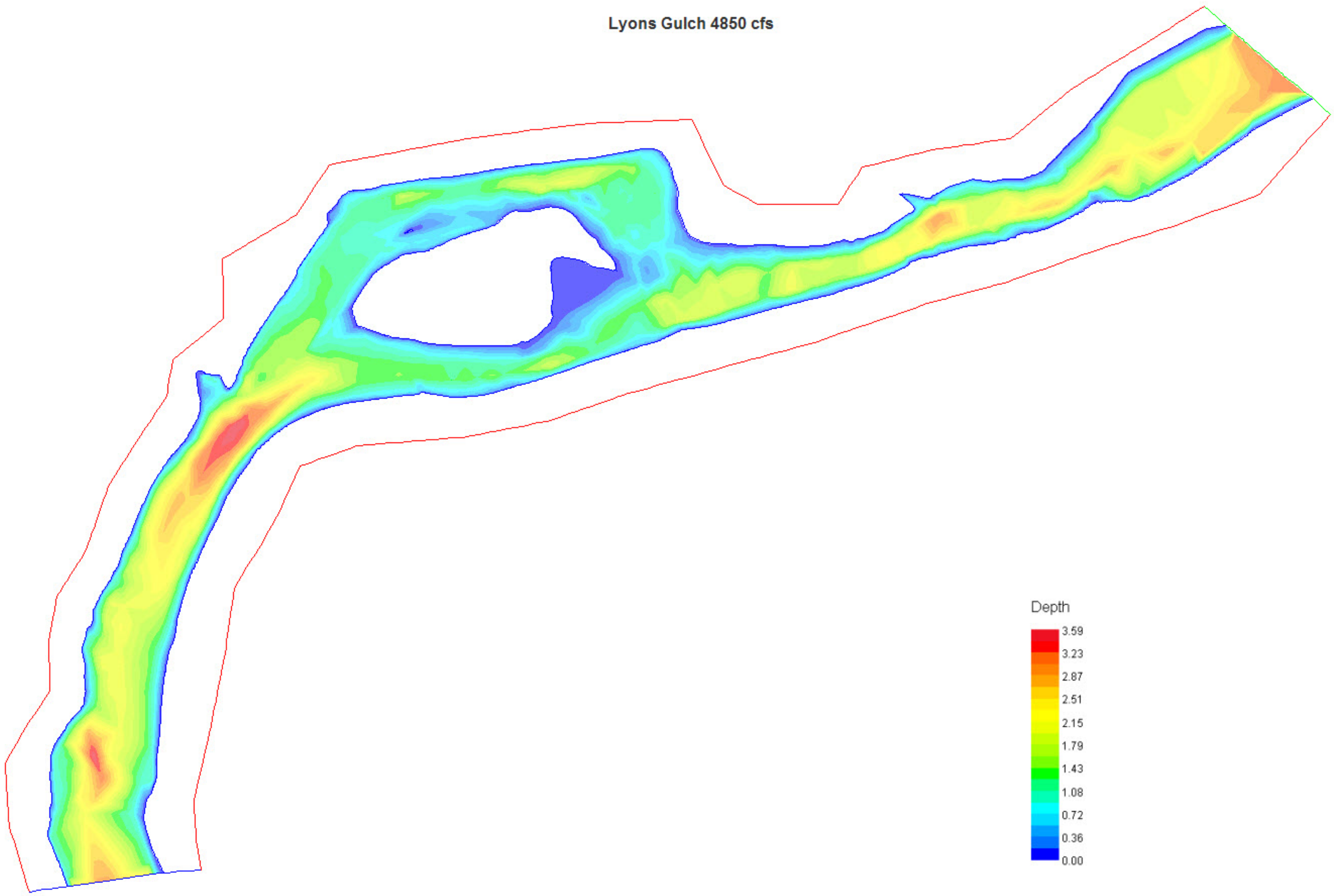


Figure 49. Lyons Gulch simulated water depth (m) at 4850 cfs (high flow). Flow moves from right to left.

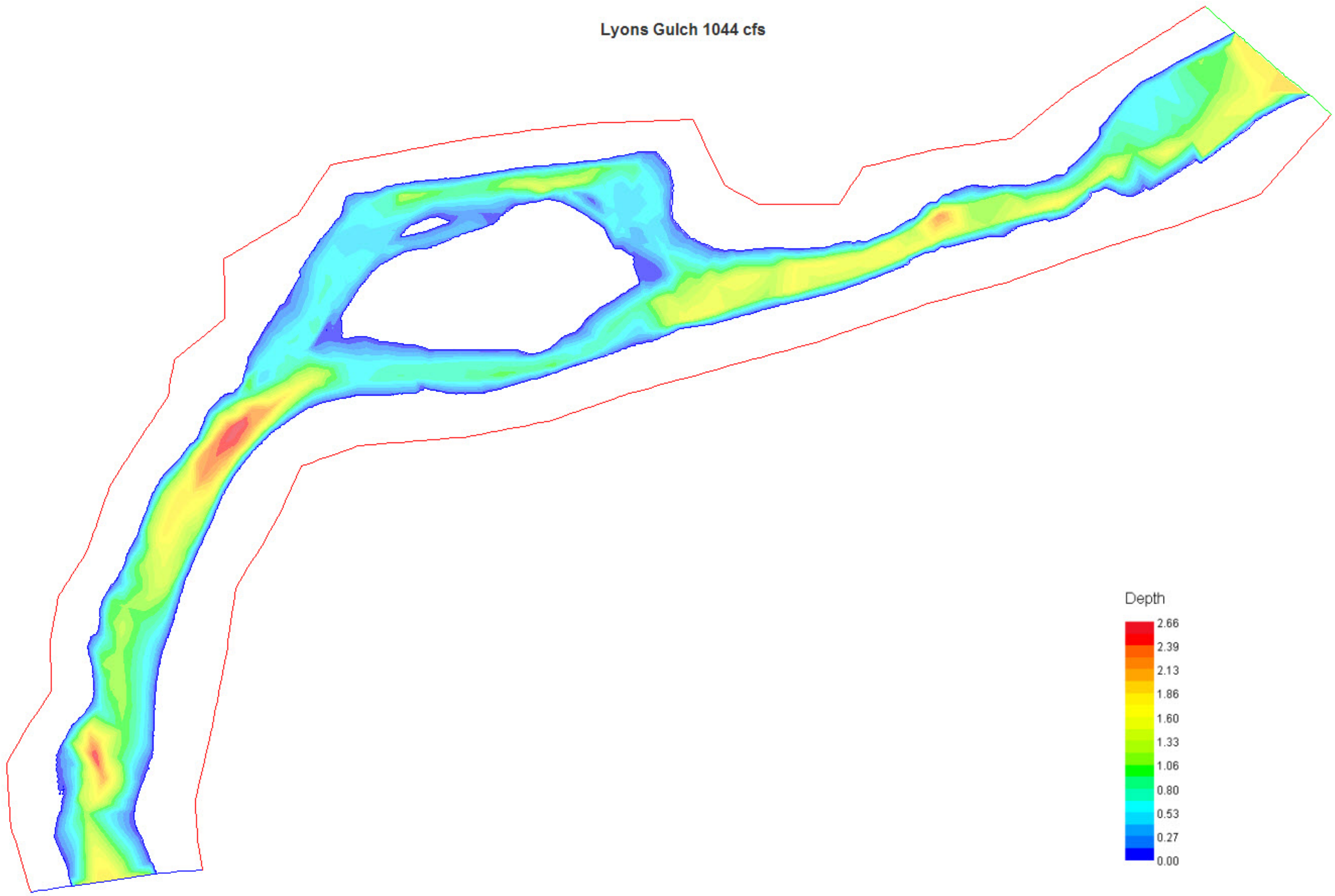


Figure 50. Lyons Gulch simulated water depth (m) at 1044 cfs (low flow). Flow moves from right to left.

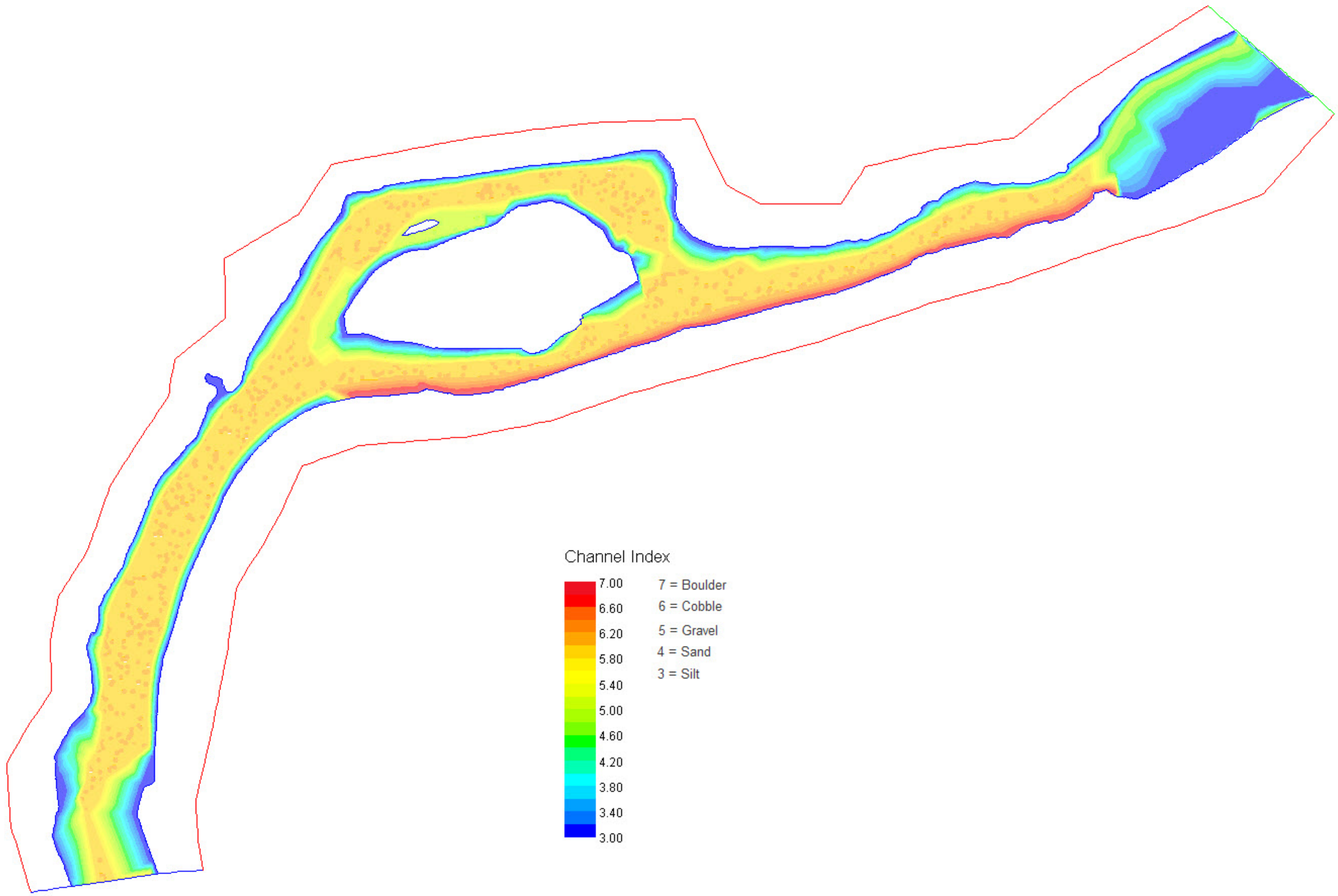


Figure 51. Bed substrate at the Lyons Gulch site

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Habitat Modeling

Habitat for each site and each species is a function of both quantity and quality. Both of these characteristics vary with discharge. For each of the study sites, an example of the change in habitat for selected life stages and species are shown in the text to illustrate these relationships. Detailed graphs of the habitat maps for each study site are presented in Appendix A. The daily variability in habitat location and quantity depends on the daily flows. These variations are shown in the time series plots of habitat in Appendix B. The hydrology used for the time series analysis was taken from USGS gage stations. The data for dry, median, and wet year types were used to display the annual change in habitat for a range of hydrologic conditions.

Pumphouse Site

Habitat versus discharge relationships for rainbow trout show a relatively high amount of habitat between 500 and 1500 cfs (Figure 52). Rainbow trout habitat for spawning fish is low and constant for all discharges. Juvenile habitat is more abundant than other life stages at all discharges. Trout fry habitat is highest at the lowest flows due to their high use of low velocity areas.

Habitat versus discharge relationships for brown trout are similar to rainbow trout (Figure 53). Brown trout fry and spawning habitat use a common suitability with rainbow trout and therefore the relationship is the same as the rainbow trout function. Brown trout juvenile and adult habitats have higher abundance at lower flows in a lower full range than rainbow trout. Brown trout juveniles show a drop in habitat as flows increase over 1000 cfs.

Mountain whitefish habitat versus discharge for all life stages except adult show habitat at its highest at the lowest flows (Figure 54). Adult mountain whitefish habitat is most abundant between flows of 500 and 1500 cfs, which is similar to the response for the adult trout species.

There is a difference in habitat quality over the range of flows. The amount of adult rainbow trout habitat at 500 cfs and 1500 cfs is nearly the same. The habitat maps show that at 500 cfs the habitat has higher quality than the habitat at 1500 cfs. Higher quality is denoted by more areas with suitability values in the range of 0.5 to 1.0. This is illustrated by the habitat maps for 3000 cfs, 1500 cfs, and 500 cfs (Figure 55, Figure 56, Figure 57). Habitat quality for trout fry also shows a change with discharge (Figure 58, Figure 59).

Habitat Time Series

The habitat-discharge functions are combined with hydrology data for the Colorado River to display habitat over time for dry, median, and wet years. Average daily discharge for all flow years show that flows range from slightly under 500 cfs to greater than 5000 cfs in some years (**Figure 60).** Wet flow years have flows greater than 2000 cfs for more than two months. Peak flows in average years are slightly less than 2000 cfs and in dry years the highest flows occur late in the summer likely due to releases from upstream reservoirs. Flows in 2009 during our measurements were typical of wet years during runoff and late summer and more like dry years or average years in the late fall and winter. The flows during high flow measurements were near 3000 cfs and exceeded bankfull conditions. This would suggest that flows in the range of 2500 cfs or greater would inundate near-shore riparian vegetation and maintain riparian health.

Adult habitat time series are displayed for brown trout and rainbow trout and mountain whitefish. This life stage of these species is present year round and the lowest habitat availability of the full year life stages at most flows. Flows that maintain the habitat for these key life stages should maintain the habitat for other life stages as well. The habitat functions for adult brown trout over time is almost a mirror image of the hydrology graphs (**Figure 61**). Wet years have the highest abundance of habitat during winter into early spring and late fall. The lowest habitat occurs during runoff. Median years are intermediate between wet and dry years in the winter, fall and early spring with the highest habitat during the early runoff.

Adult rainbow trout habitat has a similar response over daily flows during the year as brown trout habitat, wet years provide the most habitat during winter with the least amount habitat during runoff (**Figure 62**). There is a wider range of habitat availability between flow years for rainbow trout than was shown for brown trout habitat.

Adult mountain whitefish habitat over time is very similar in function and shape to rainbow trout habitat. There is a wide range of habitat abundance between the flow years in the winter, fall and early spring. Wet years provide the most habitat during the winter and the least amount of habitat during runoff (**Figure 63**). Habitat time series for all species and life stages is presented in Appendix B.

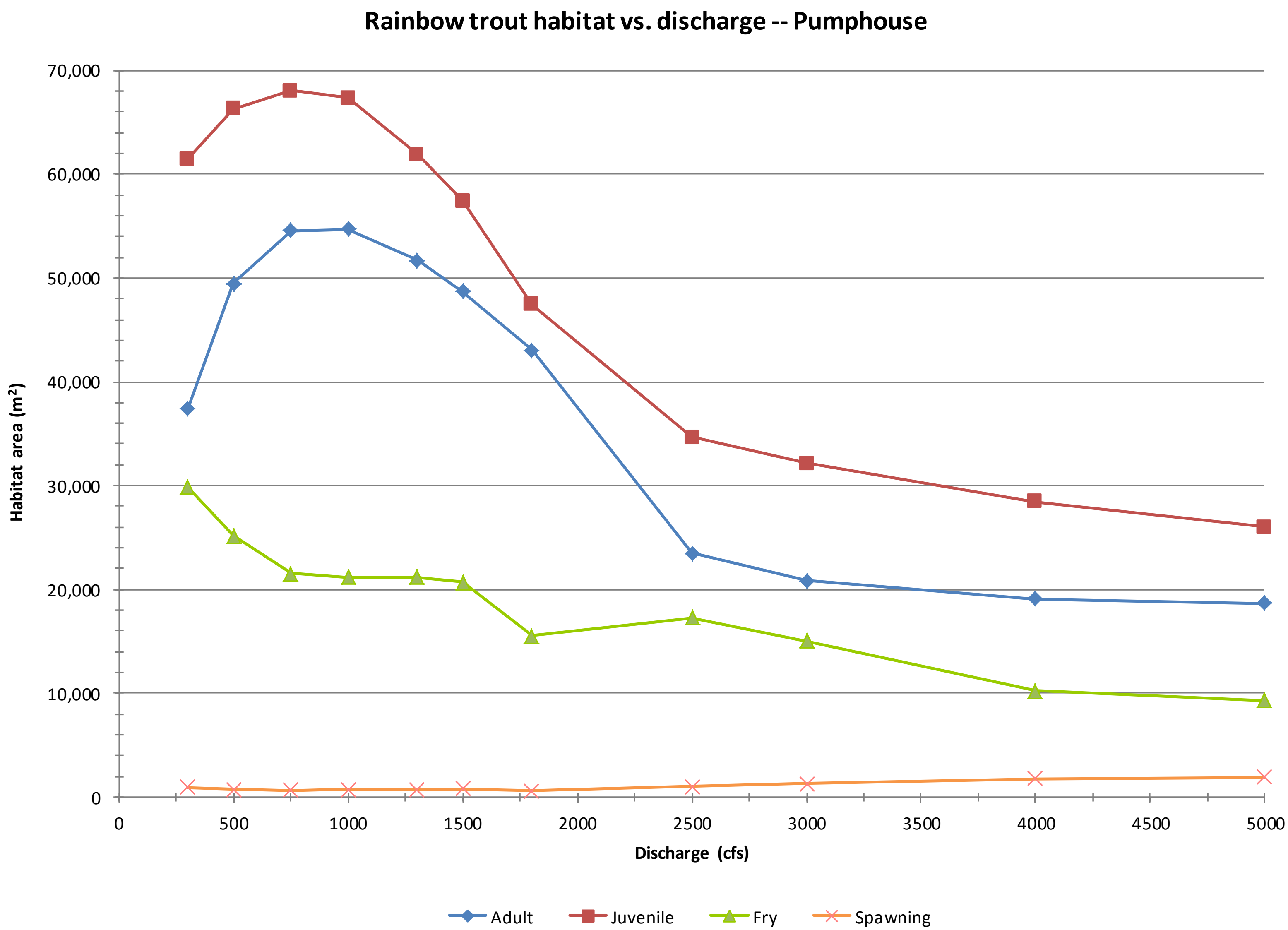


Figure 52. Rainbow trout habitat versus discharge, Pumphouse site.

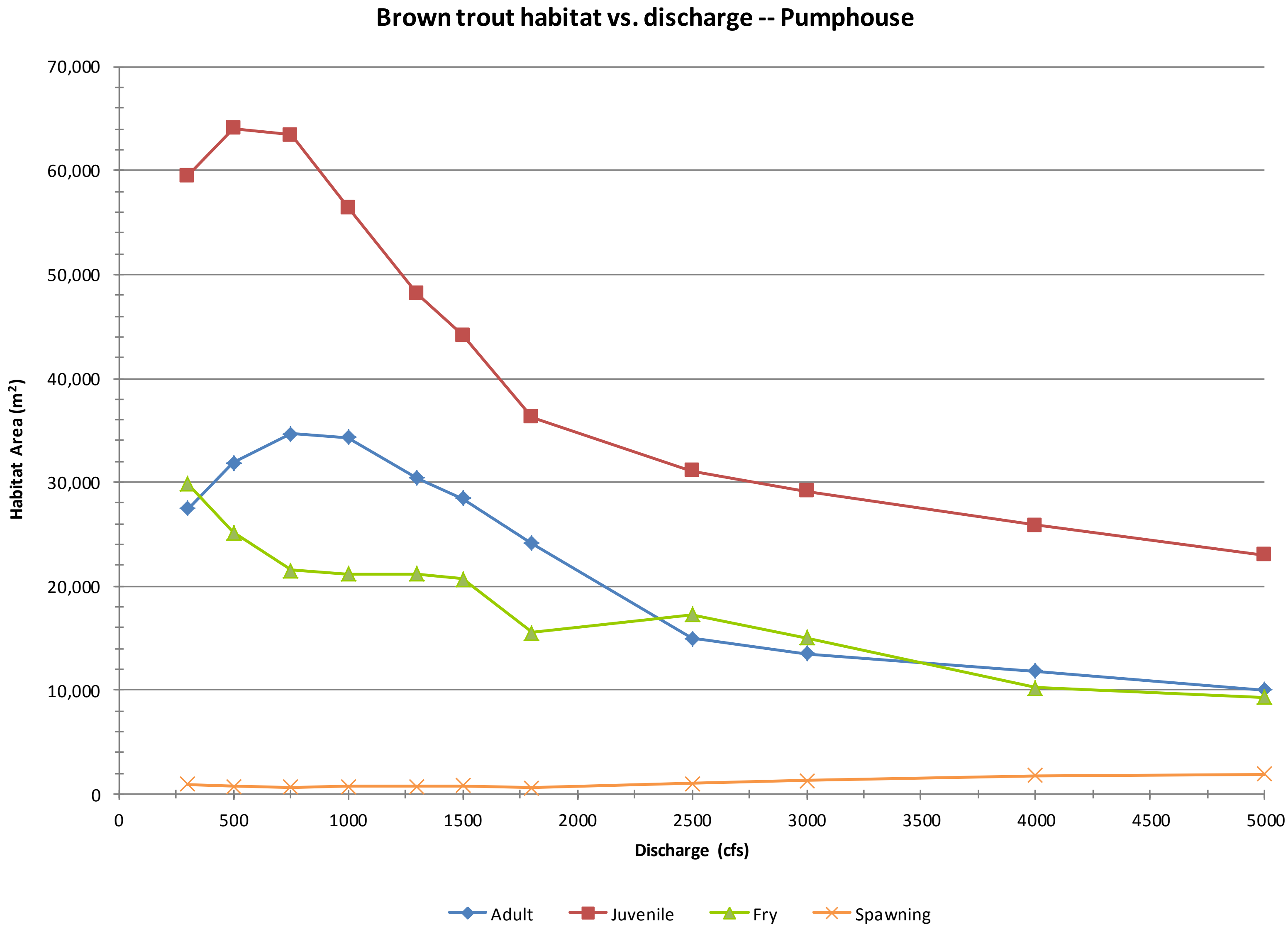


Figure 53. Brown trout habitat versus discharge, Pumphouse site.

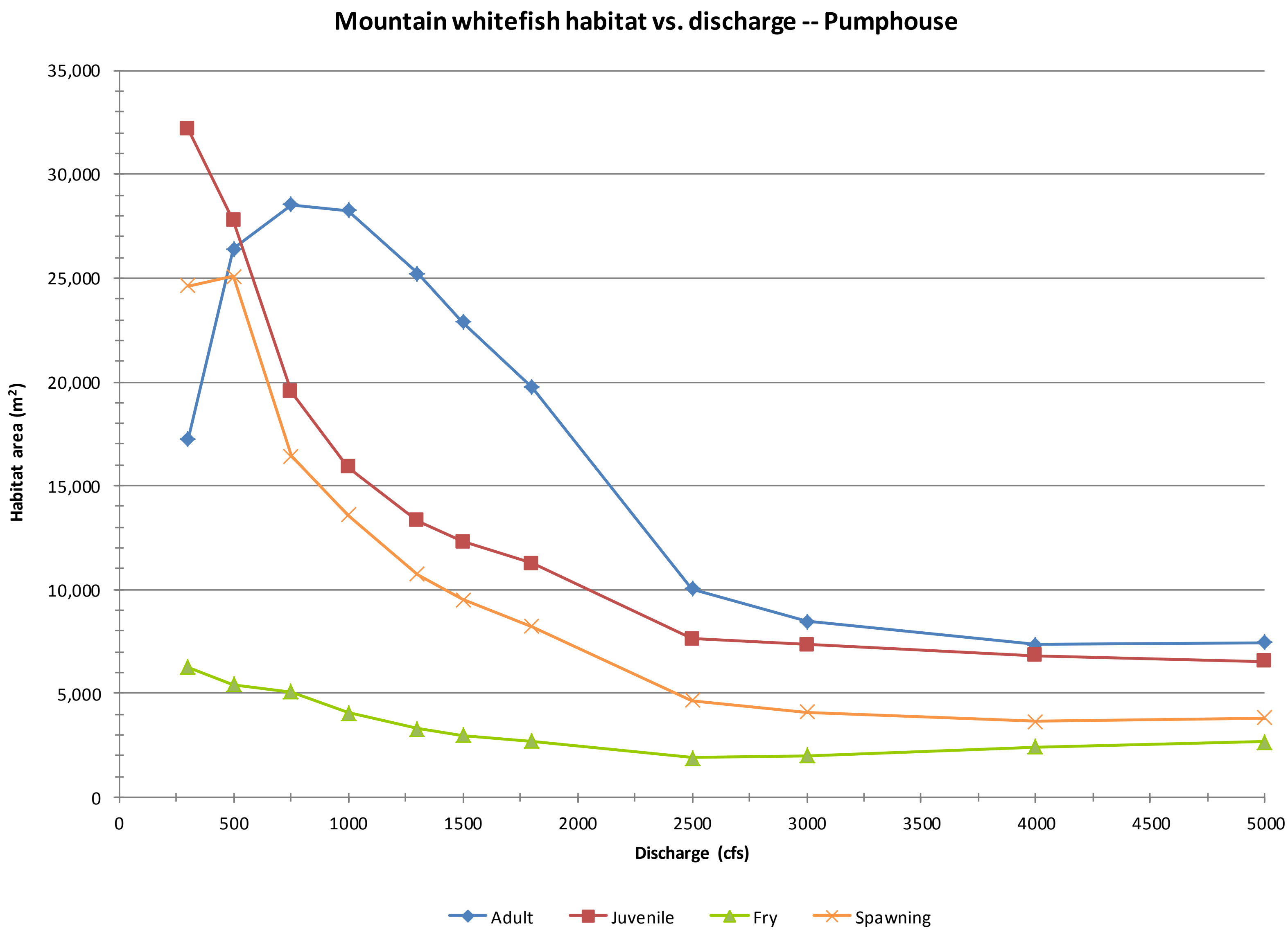
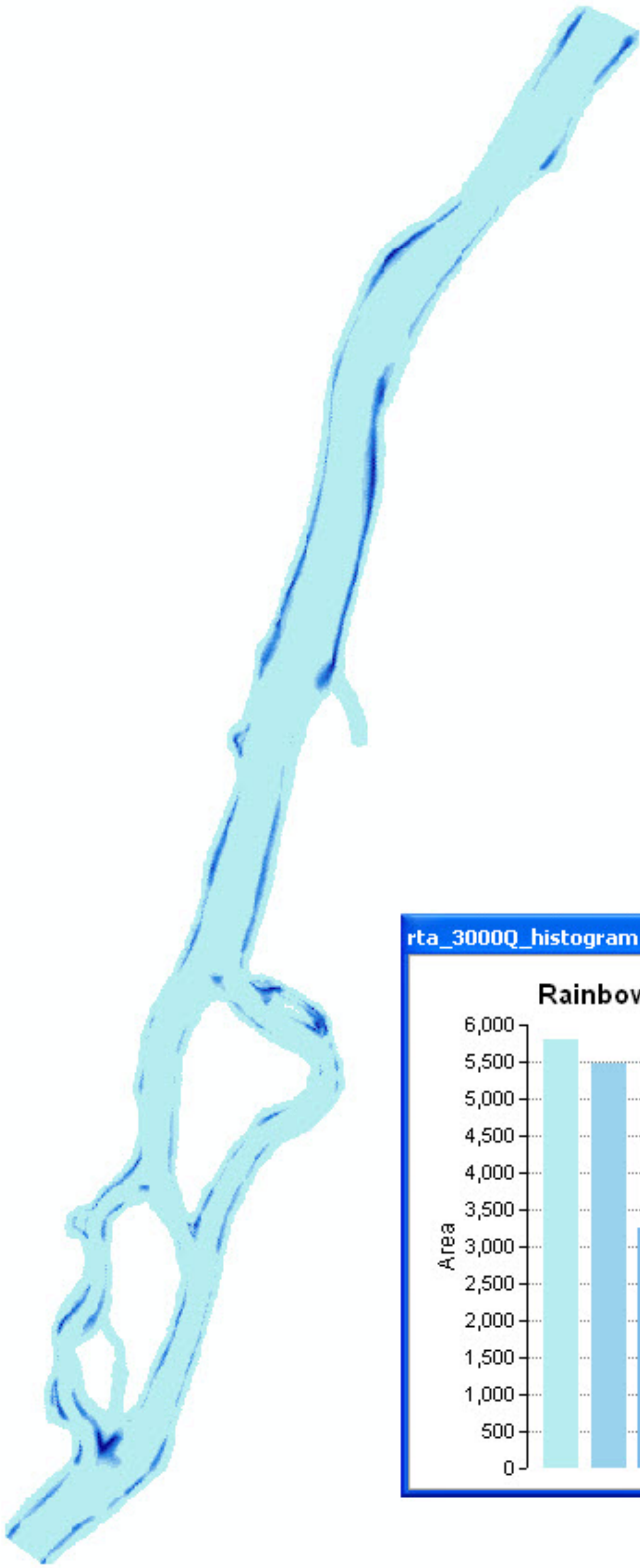


Figure 54. Mountain whitefish habitat versus discharge, Pumphouse site.



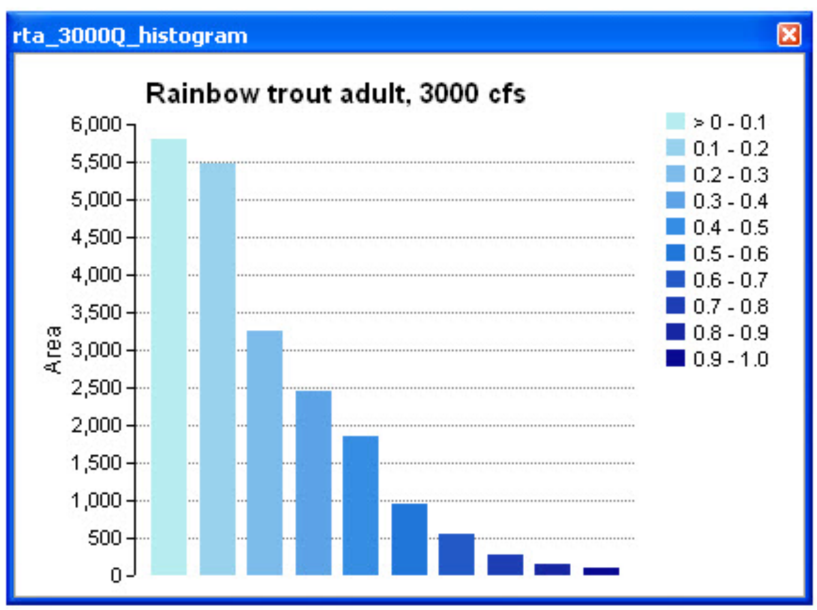


Figure 55. Adult rainbow trout habitat map, 3000 cfs, Pumphouse site.

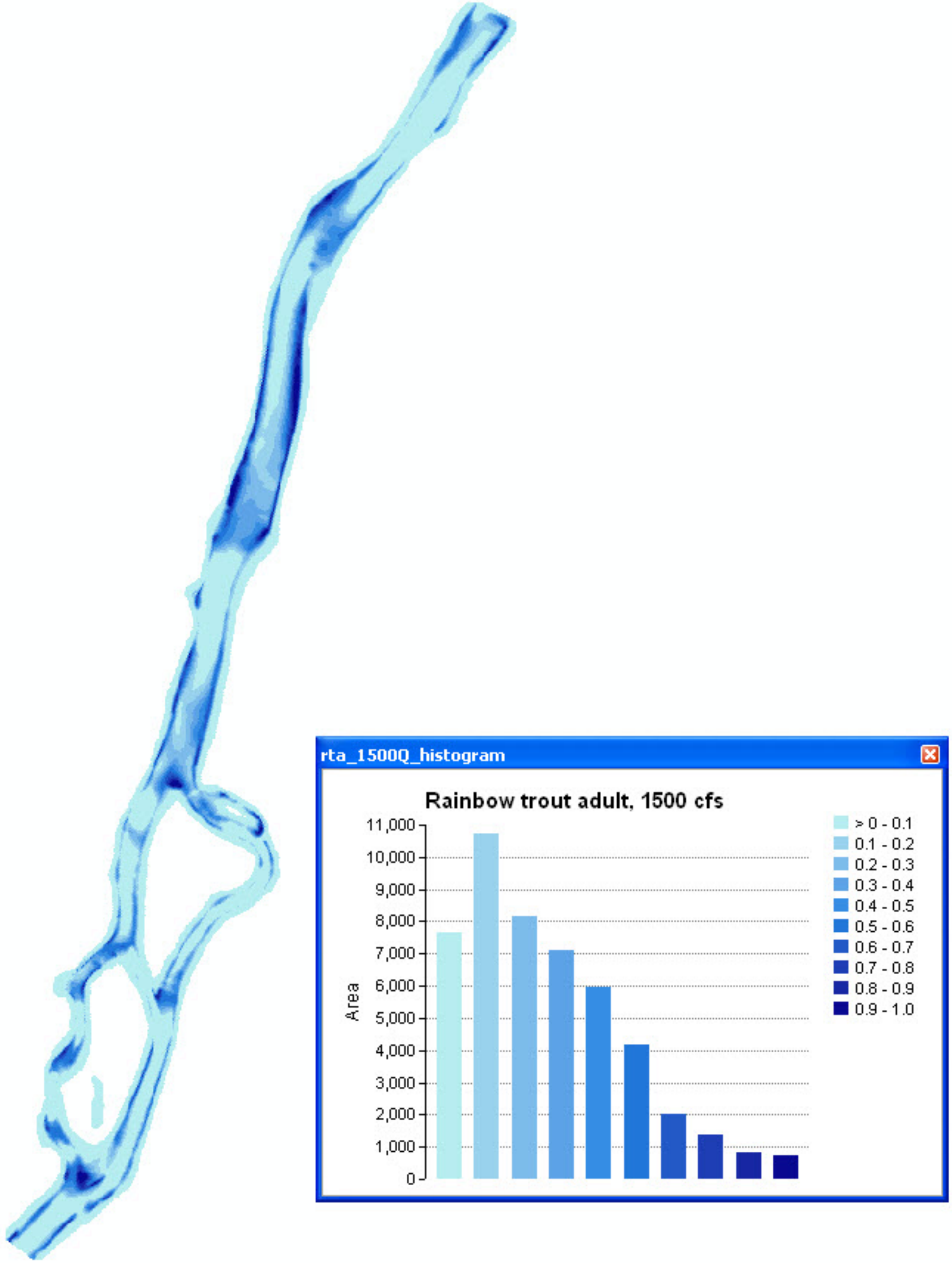


Figure 56. Adult rainbow trout habitat map, 1500 cfs, Pumphouse site.

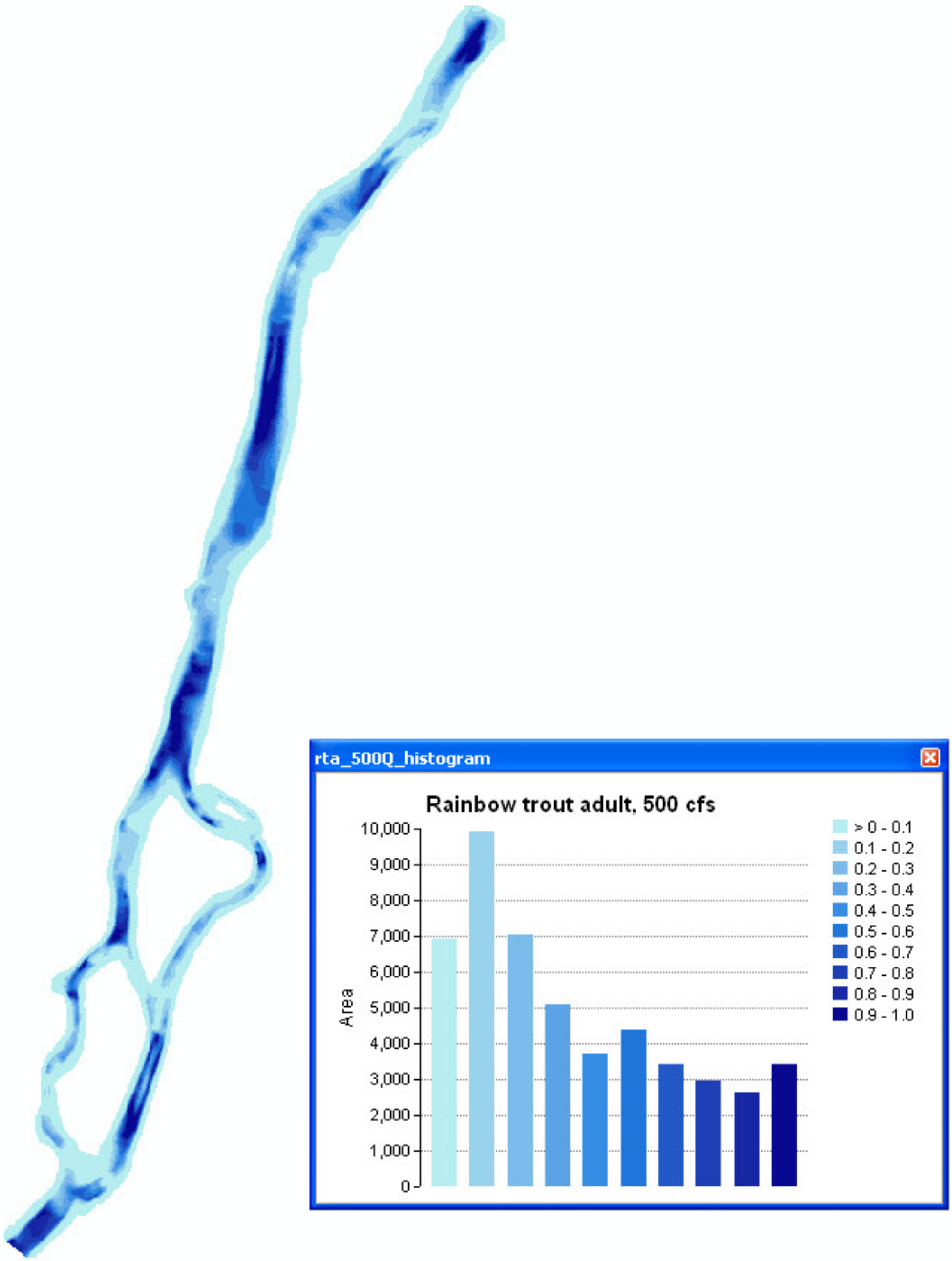


Figure 57. Adult rainbow trout habitat map, 500 cfs, Pumphouse site.

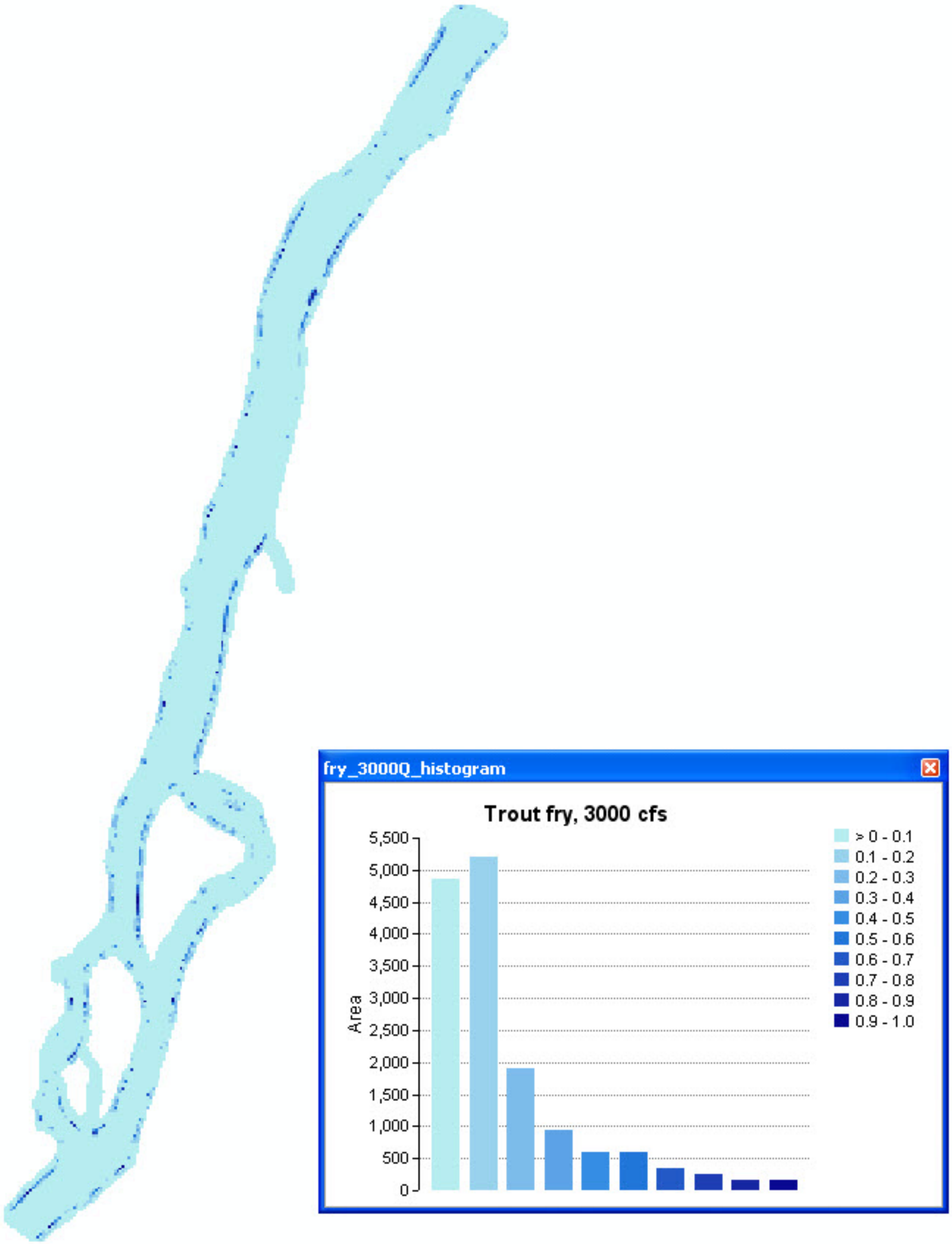


Figure 58. Trout fry habitat map, 3000 cfs, Pumphouse site.

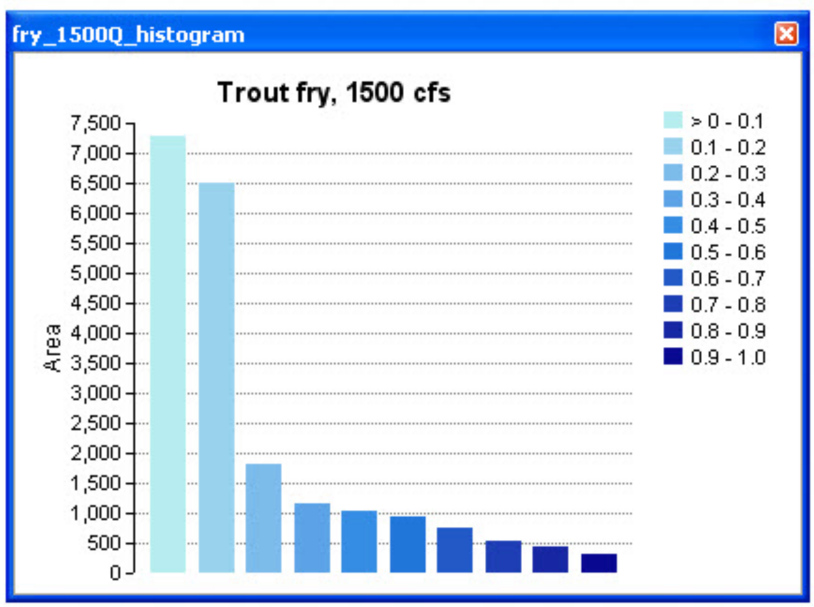


Figure 59. Trout fry habitat map, 1500 cfs, Pumphouse site.

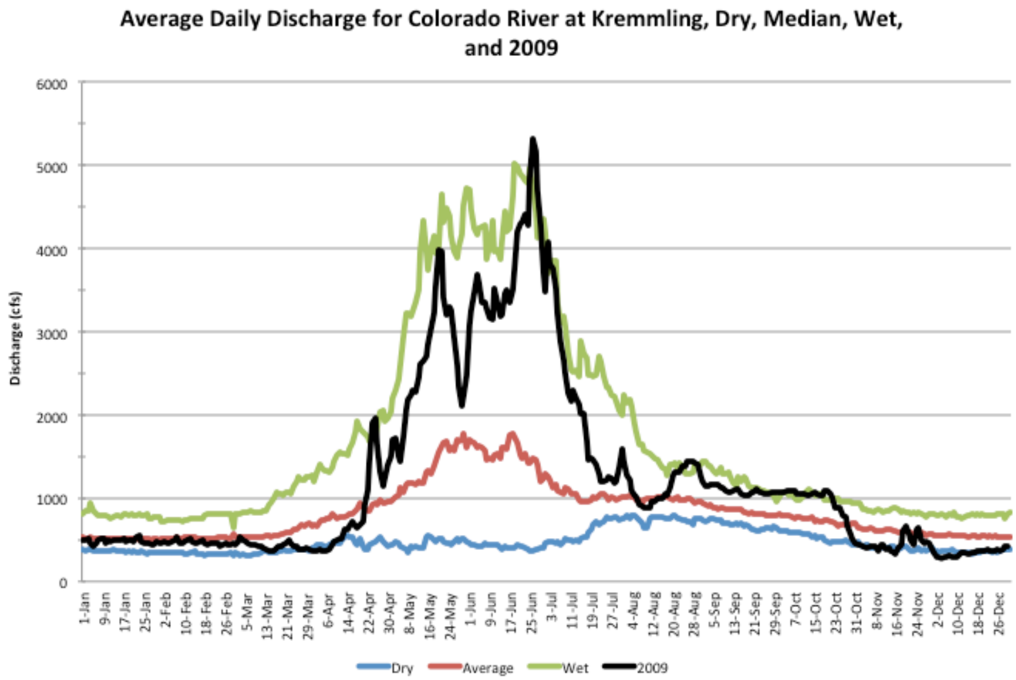


Figure 60. Average daily discharge for the Colorado River at Kremmling in dry, median, wet years, and 2009.

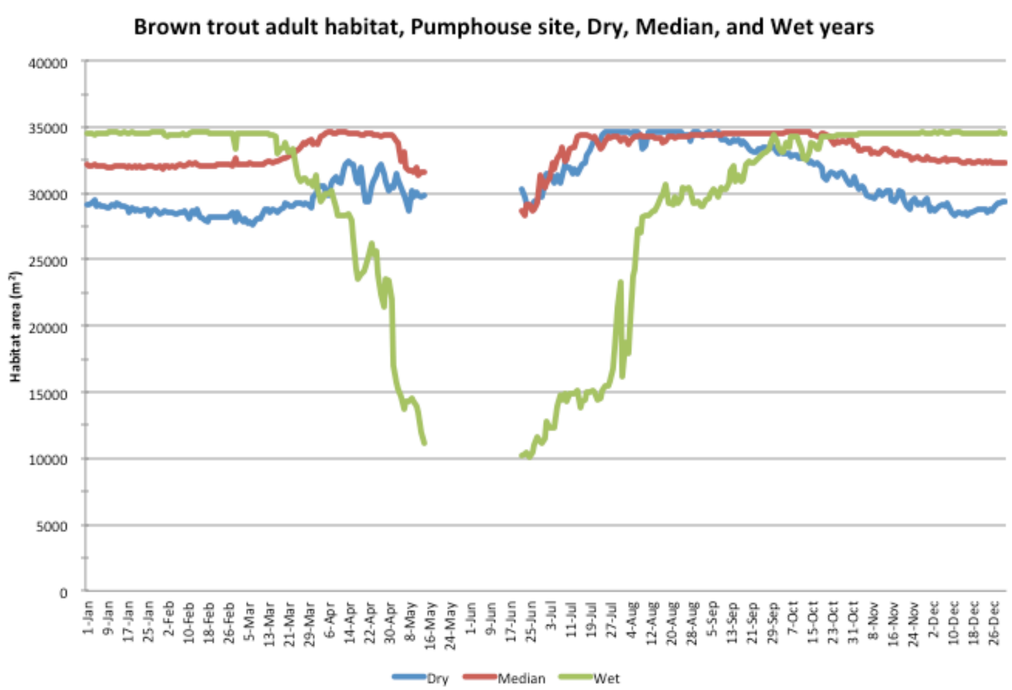


Figure 61. Adult brown trout habitat at the Pumphouse site in dry, median, and wet years.

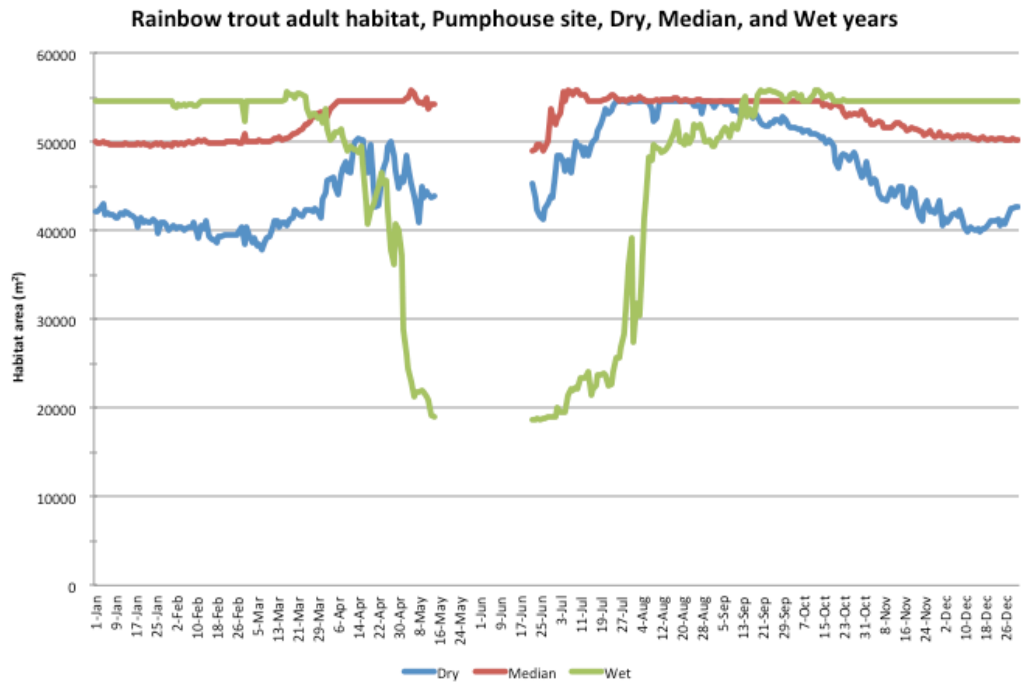


Figure 62. Adult rainbow trout habitat at the Pumphouse site in dry, median, and wet years.

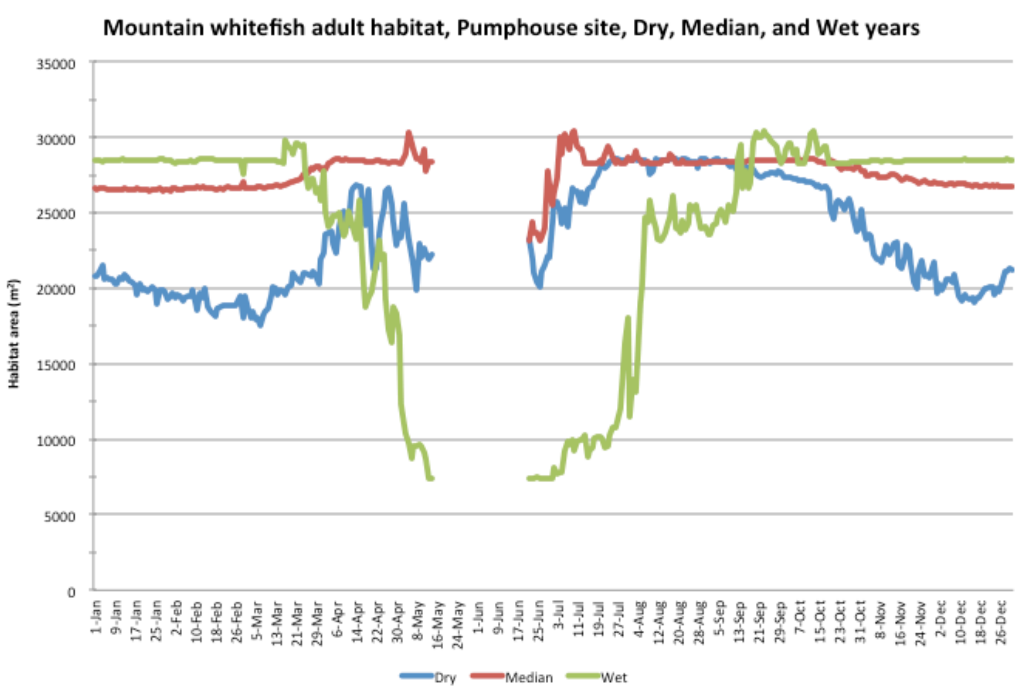


Figure 63. Adult mountain whitefish habitat at the Pumphouse site in dry, median, and wet years.

Rancho del Rio

Habitat versus discharge relationships for rainbow trout show a relatively high amount of habitat between 500 and 2500 cfs (Figure 64). Rainbow trout habitat for spawning fish is low and relatively constant for all discharges. There is more spawning habitat available at this site than was modeled at the Pumphouse site. Habitat is most abundant for juveniles up to 1500 cfs. At flows higher than 1500 cfs adult habitat is most abundant.

Habitat versus discharge relationships for brown trout are similar to rainbow trout (Figure 65). Brown trout fry and spawning habitat use a common suitability with rainbow trout and therefore the relationship is the same as the rainbow trout function. Brown trout juvenile and adult habitat has higher abundance at lower flows than rainbow trout. Brown trout juvenile habitat drops as flows increase over 1000 cfs.

Mountain whitefish habitat versus discharge for fry, juvenile and spawning life stages show habitat is at its highest at flows less than 2500 cfs (Figure 66). Adult mountain whitefish habitat is most abundant between flows of 500 and 2500 cfs, which is similar to the response for the adult trout species.

Adult flannelmouth sucker habitat is most abundant when flows are between 1000 to 3000 cfs (Figure 67). The habitat versus discharge relationship for flannelmouth sucker is very similar in shape to adult mountain whitefish. Habitat area rapidly reduces as flows drop below 750 cfs.

The difference in habitat quality that occurs at different flows is also apparent at the Rancho del Rio site. The habitat area at 3000 cfs is higher than the habitat area at 500 cfs (Figure 64), however, the habitat quality is higher at 500 cfs than at 3000 cfs (Figure 68, Figure 69).

Habitat Time Series

The habitat functions for adult brown trout over time during wet years is almost a mirror image of the hydrology graph. Wet years have the highest abundance of habitat during winter into early spring and late fall with the lowest habitat during runoff. Habitat in median years is intermediate between wet and dry years in the winter, fall and early spring. Adult brown trout habitat is higher during runoff in median years than wet and dry years (**Figure 70**).

Adult rainbow trout habitat has a similar response over daily flows during the year as brown trout habitat where wet years provide the most habitat during winter and the least amount of habitat during summer (**Figure 71**). There is a wider range of habitat availability between flow years for rainbow trout than are shown in the brown trout habitat. There is approximately 25% more habitat in winter in wet years than in dry years.

Adult mountain whitefish habitat over time is very similar in function and shape to rainbow trout habitat during winter. There is a wide range of habitat abundance between the flow years in the winter, fall and early spring. Wet years provide the most habitat during the winter and the least amount of habitat during runoff (**Figure 72**).

The ratio of Adult flannelmouth sucker habitat over time is nearly the same as adult mountain whitefish except during runoff. The lowest amount of adult flannelmouth habitat occurs during dry years (**Figure 73**).

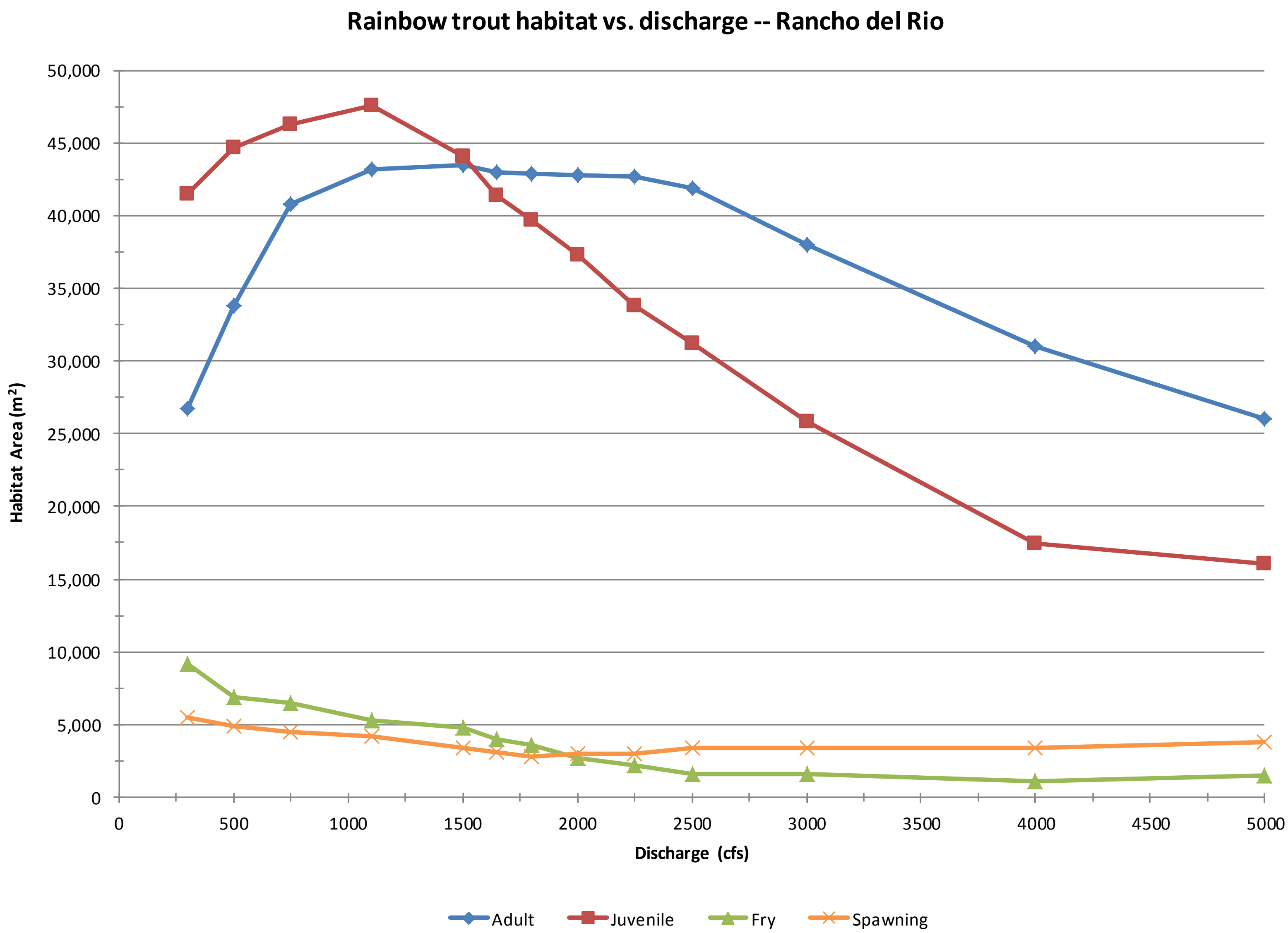


Figure 64. Rainbow trout habitat versus discharge, Rancho del Rio site.

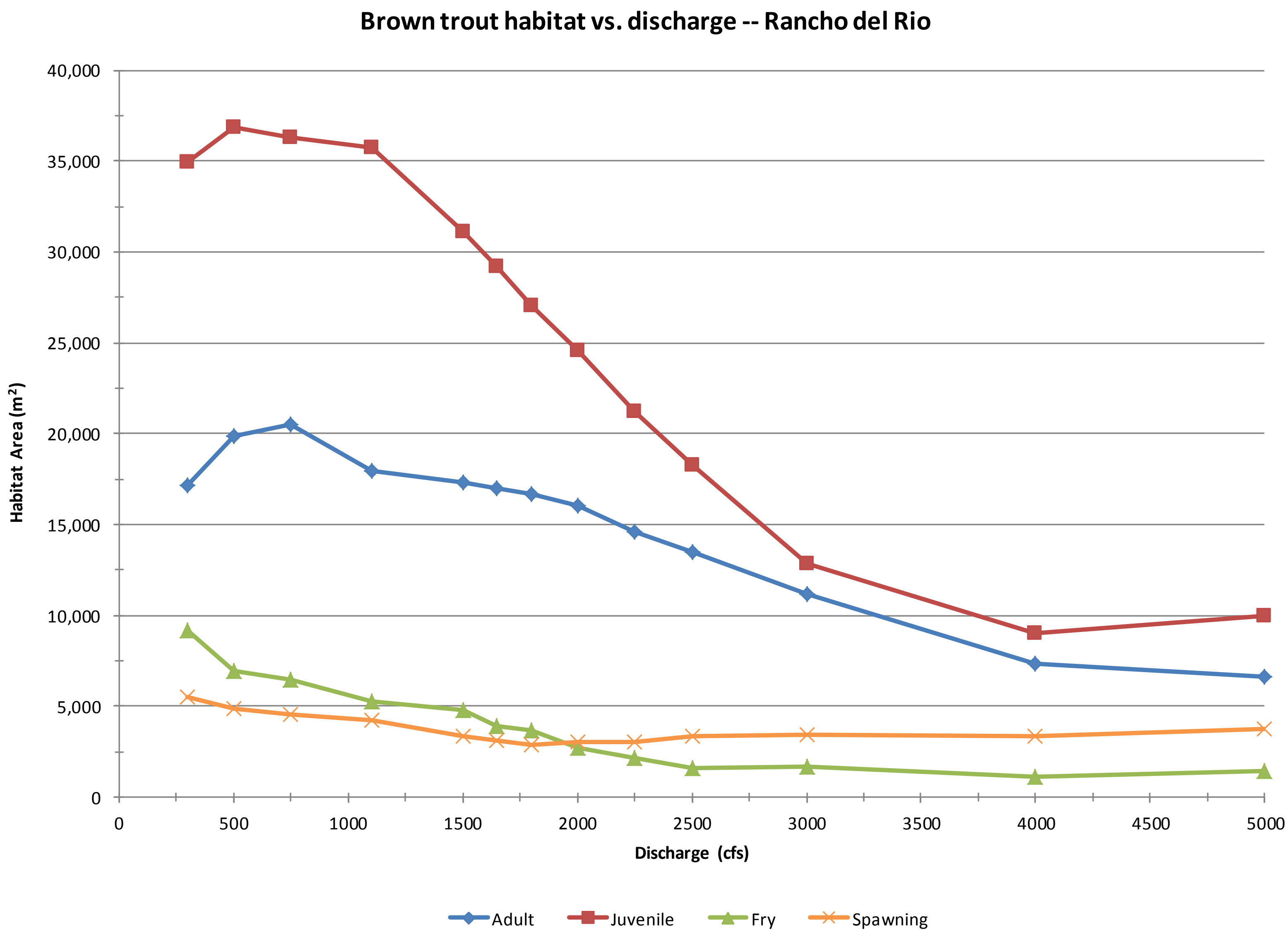


Figure 65. Brown trout habitat versus discharge, Rancho del Rio site.

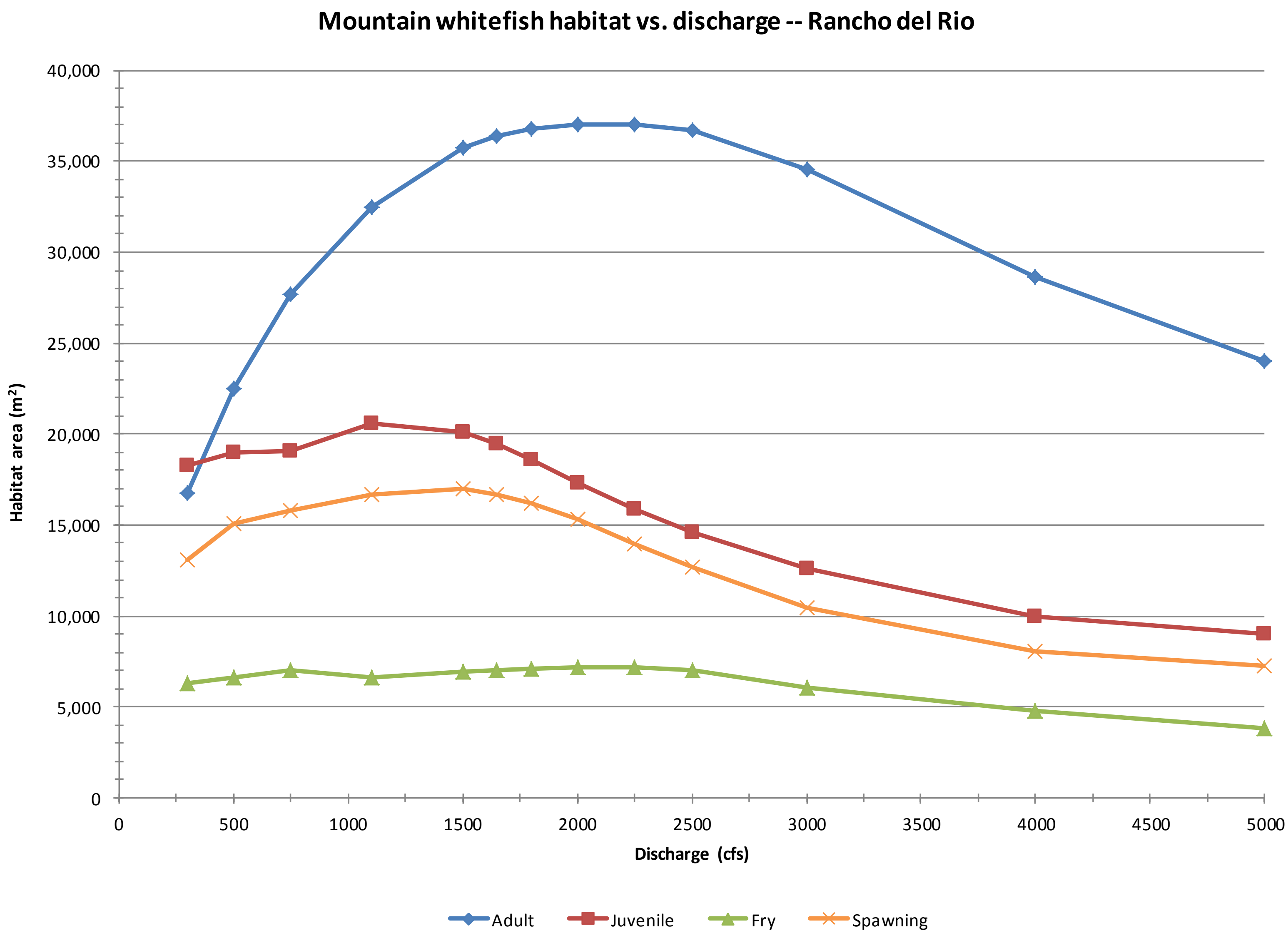


Figure 66. Mountain whitefish habitat versus discharge, Rancho del Rio site.

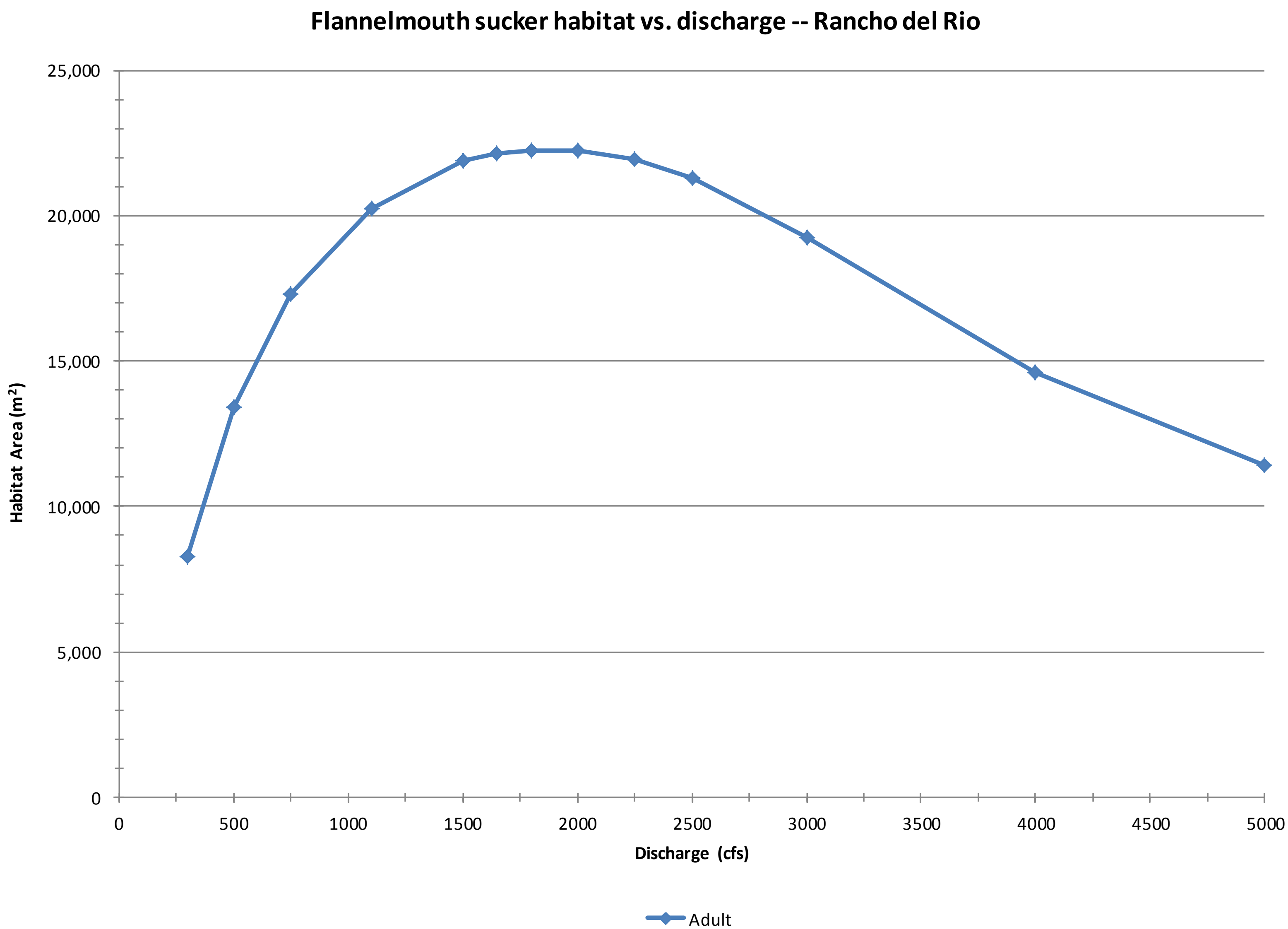


Figure 67. Flannelmouth sucker habitat versus discharge, Rancho del Rio site.

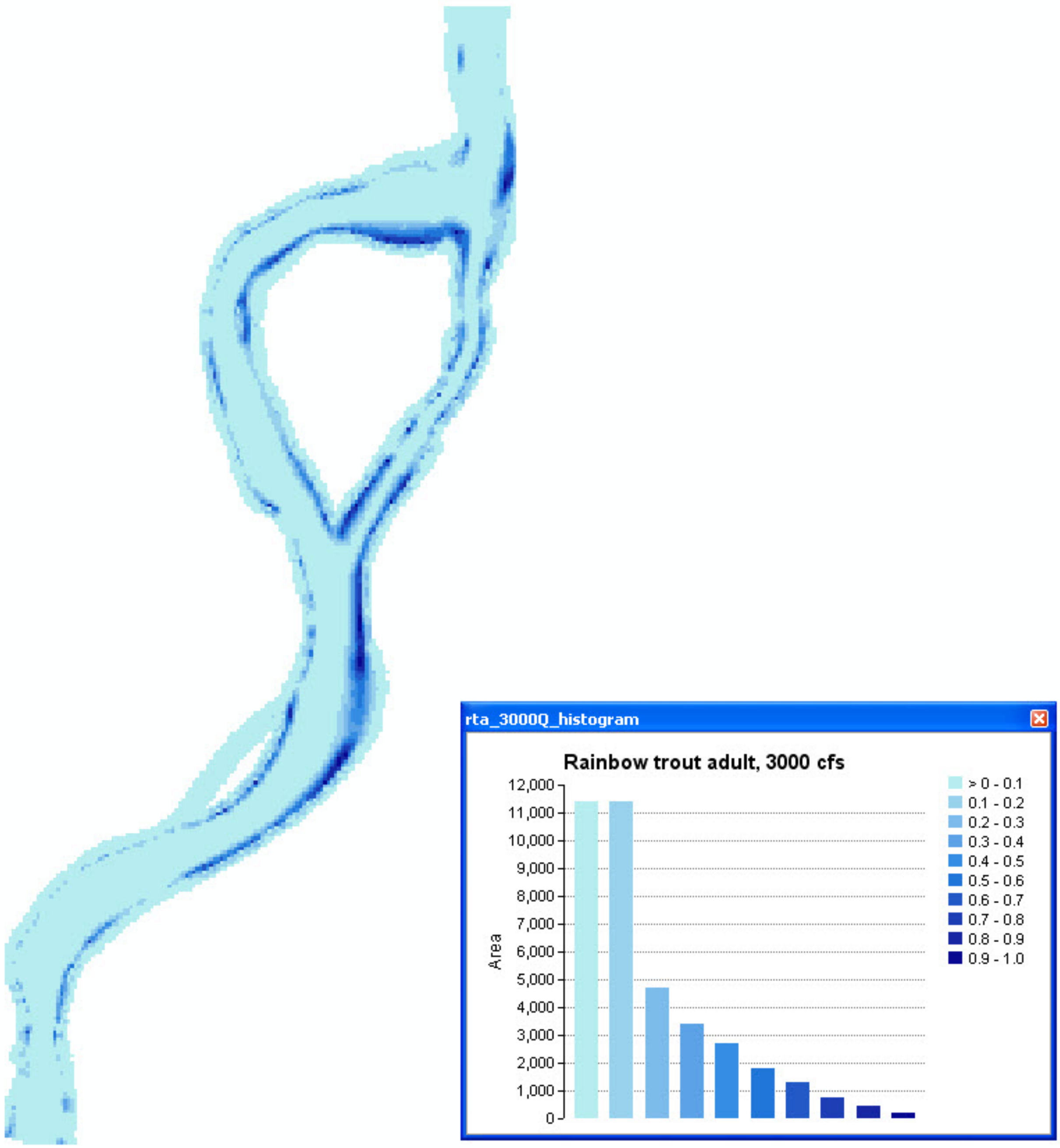


Figure 68. Adult rainbow trout habitat map at 3000 cfs at Rancho del Rio.

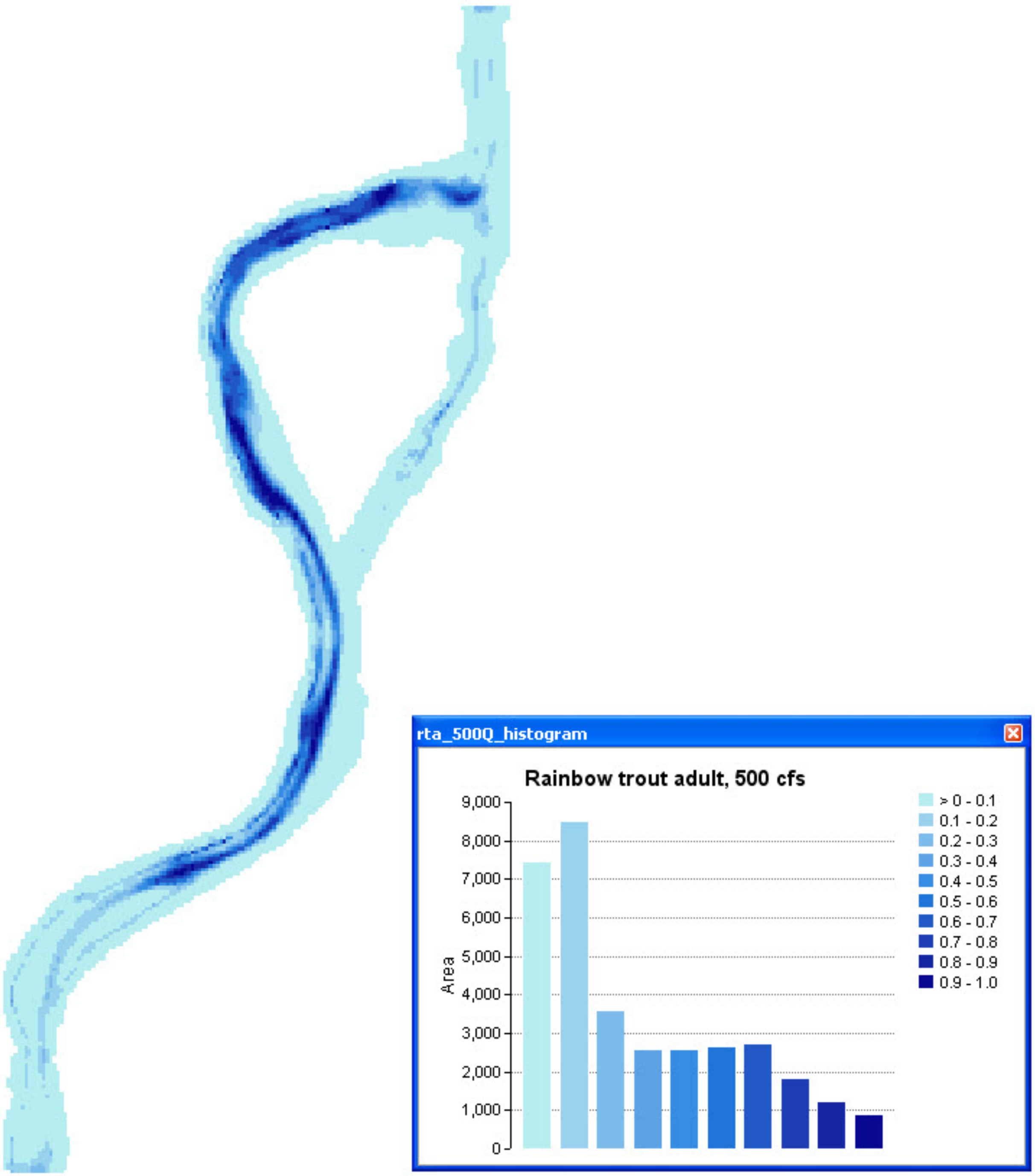


Figure 69. Adult rainbow trout habitat map at 500 cfs at Rancho del Rio.

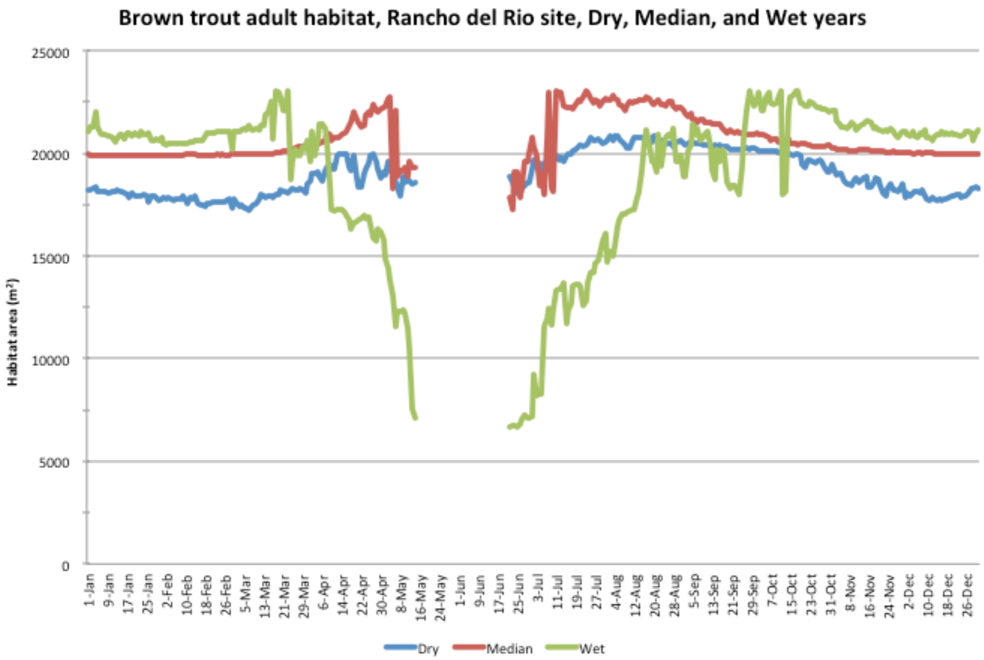


Figure 70. Adult brown trout habitat at Rancho del Rio in dry, median, and wet years.

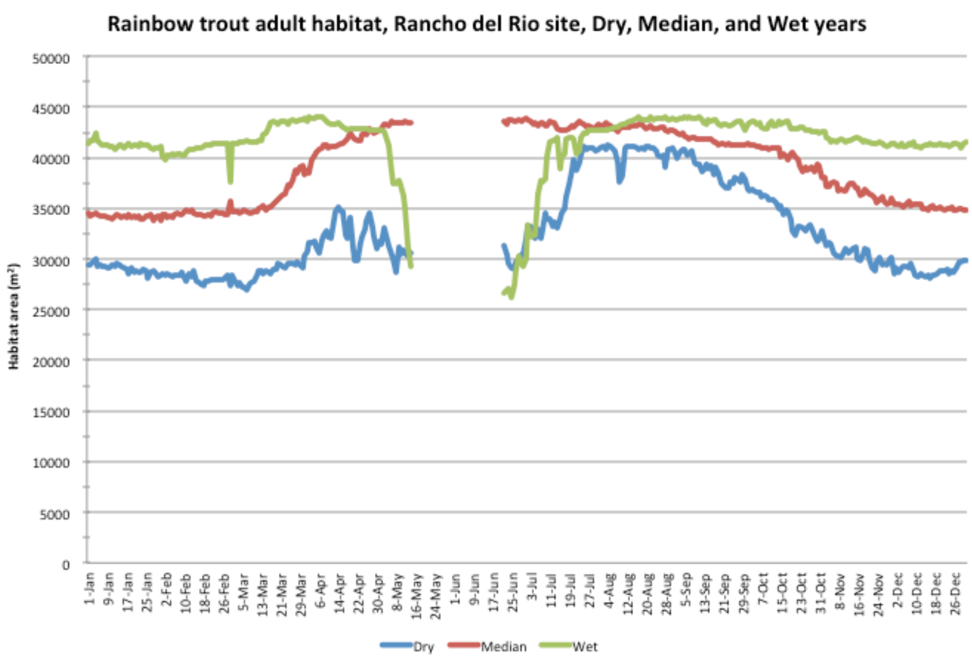


Figure 71. Adult rainbow trout habitat at Rancho del Rio in dry, median, and wet years.

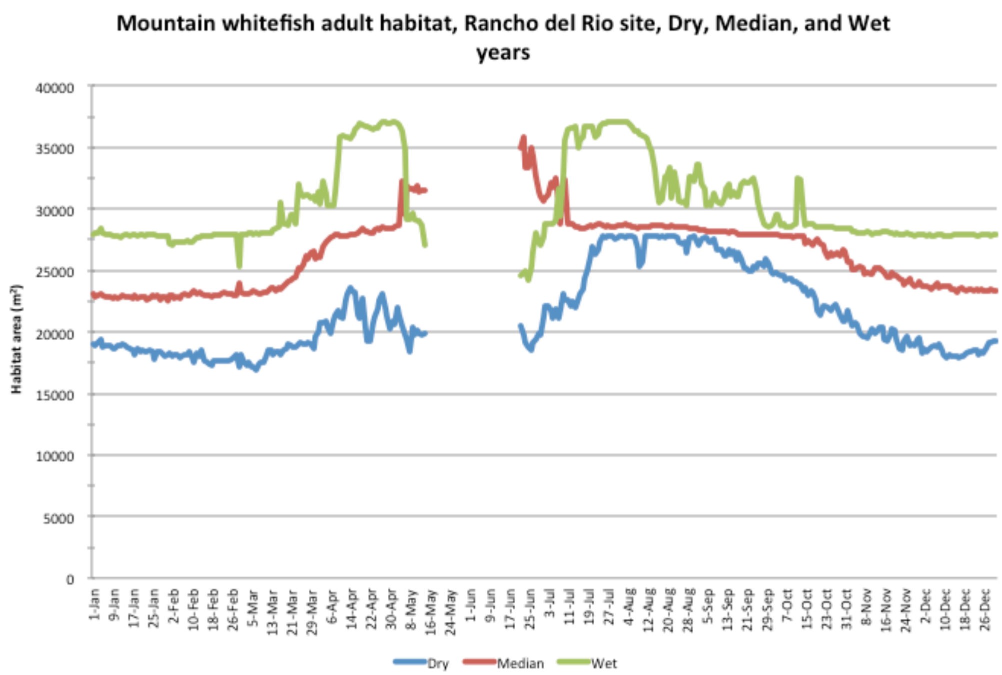


Figure 72. Adult mountain whitefish habitat at Rancho del Rio in dry, median, and wet years.

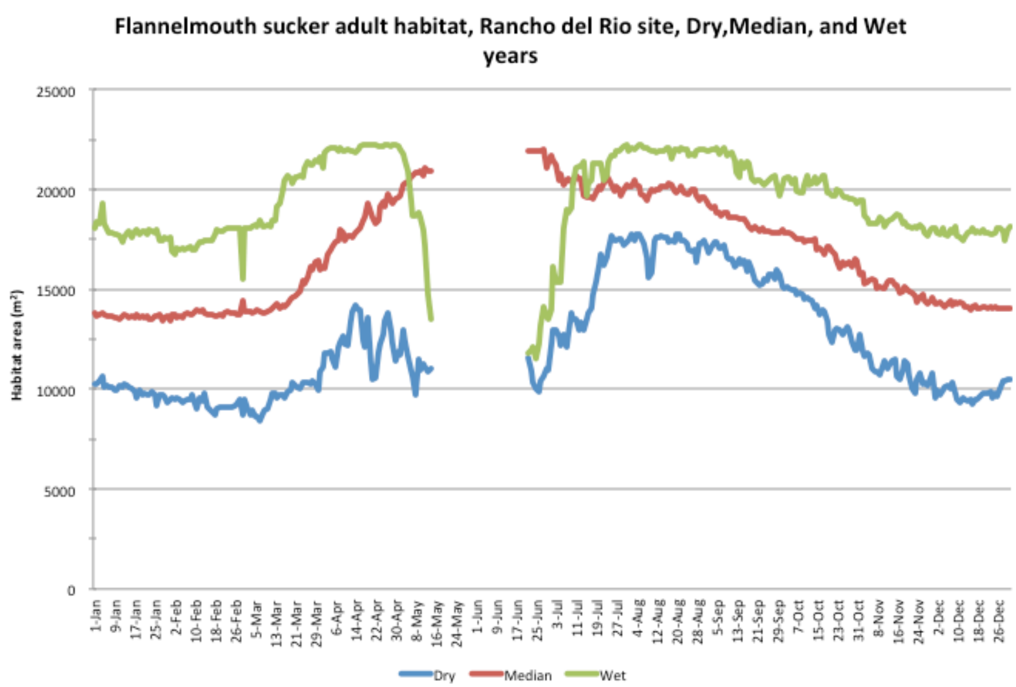


Figure 73. Adult flannelmouth sucker habitat at Rancho del Rio in dry, median, and wet years.

Lyons Gulch

Habitat versus discharge relationships for rainbow trout show a relatively high amount of habitat between 750 and 2000 cfs (Figure 74). Rainbow trout habitat for spawning fish is low and relatively constant for all discharges (Figure 74). The amount of spawning habitat is similar to the amount shown for the Pumphouse site. Juvenile habitat for rainbow trout is more abundant than other life stages at all discharges.

Habitat versus discharge relationships for brown trout are similar to rainbow trout, however, the amount of juvenile and adult brown trout habitat is lower than rainbow trout (Figure 75). Brown trout fry and spawning habitat use a common suitability with rainbow trout and therefore the relationship is the same as the rainbow trout function. Brown trout juveniles show a drop in habitat as flows increase over 1000 cfs.

Mountain whitefish adult habitat versus discharge relationship is similar to the trout species. Flows between 1000 cfs and 1500 cfs provide the most habitat. Spawning habitat is relatively stable over all flow ranges. Juvenile and fry life stage habitats are higher at flows less than 1500 cfs and are stable at flows greater than 2500 cfs. (Figure 76).

Adult flannelmouth sucker habitat is most abundant when flows are between 500 and 2200 cfs (Figure 77). The habitat versus discharge relationship for flannelmouth sucker is very similar in shape to adult mountain whitefish and rainbow trout. Habitat area is rapidly reduced as flows drop below 750 cfs or increase above 2200 cfs.

Habitat Time Series

The habitat-discharge functions are combined with hydrology data for the Colorado River upstream of Dotsero to display habitat over time for dry, median, and wet years. Median daily discharges show that flows range from approximately 500 cfs to more than 8000 cfs in some years (**Figure 78**).

Wet flow years have flows that are over 4000 cfs for more than two months. Peak flows in average years exceed 4000 cfs. Peak flows in dry years are short duration and reach approximately 2000 cfs during runoff. Flows in 2009 during our measurements were typical of wet years during runoff and late summer or more like wet or average years in the late fall and winter. Discharge during high flow measurements in 2009 were approximately 4000 cfs and were inundating the near-shore vegetation. This suggests that flows greater than 4000 cfs are needed during runoff to maintain riparian vegetation.

The habitat functions for adult brown trout over time mirrors the hydrographs during runoff from April through July. Wet and median years produce the most habitat in fall and winter. Brown trout habitat is higher in dry years during runoff and into July than wet or median years (**Figure 79**).

Adult rainbow trout habitat for daily flows is very similar to brown trout habitat except rainbow trout habitat is more abundant. Wet and median years provide the most habitat in winter and fall. Dry year flows provide more habitat during runoff (**Figure 80**).

Adult mountain whitefish habitat over time is very similar to the shape of the hydrograph. The higher flows produce more habitat than the low flows and wet years provide more habitat than dry years (**Figure 81**).

Adult flannelmouth sucker habitat response to daily flows is similar in shape to both brown and rainbow trout. Wet years provide more habitat in winter than either median or dry years (Figure 82). Flannelmouth sucker habitat is approximately 30% less in winter in dry years than in median years.

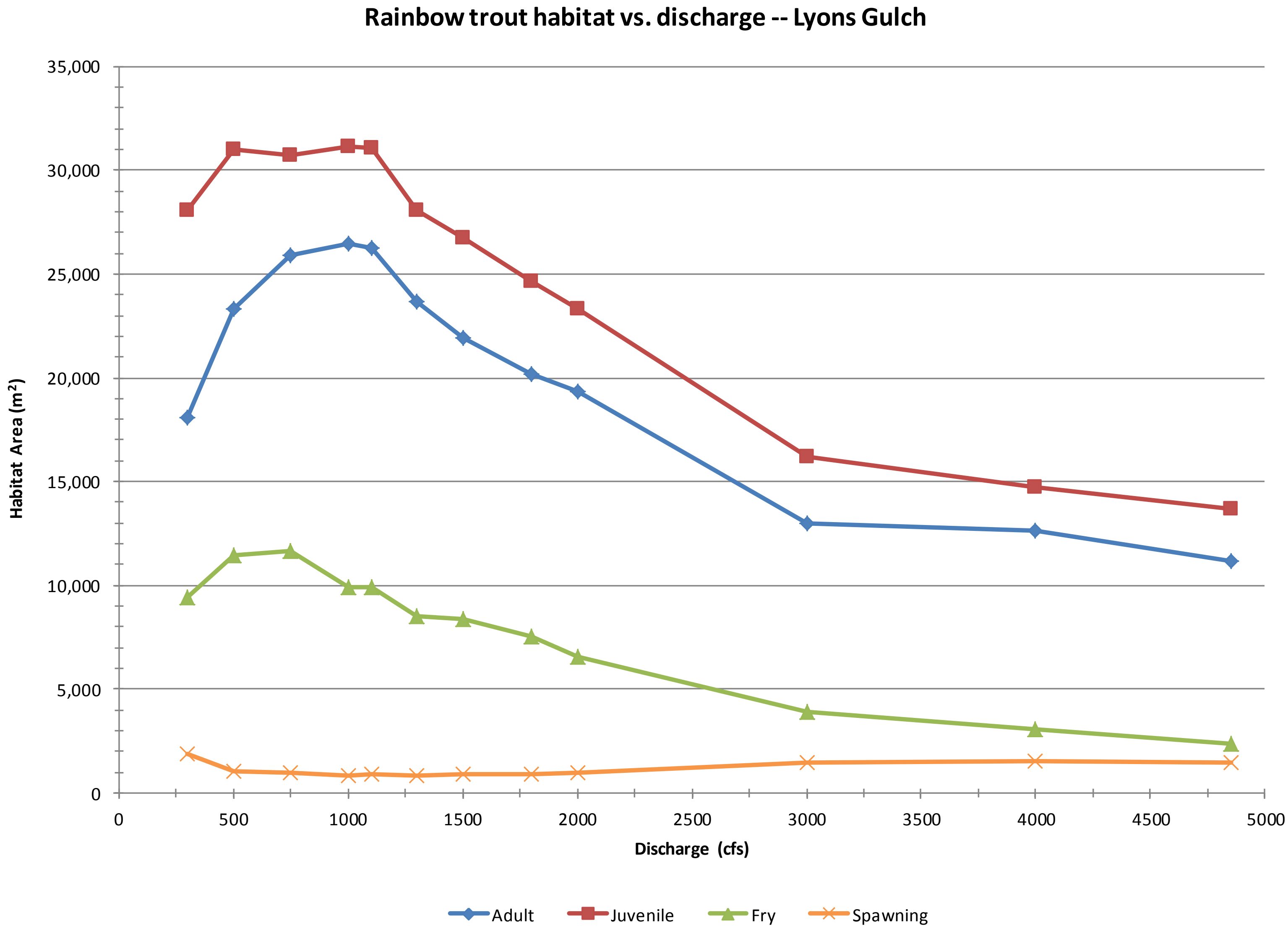


Figure 74. Rainbow trout habitat versus discharge, Lyons Gulch site.

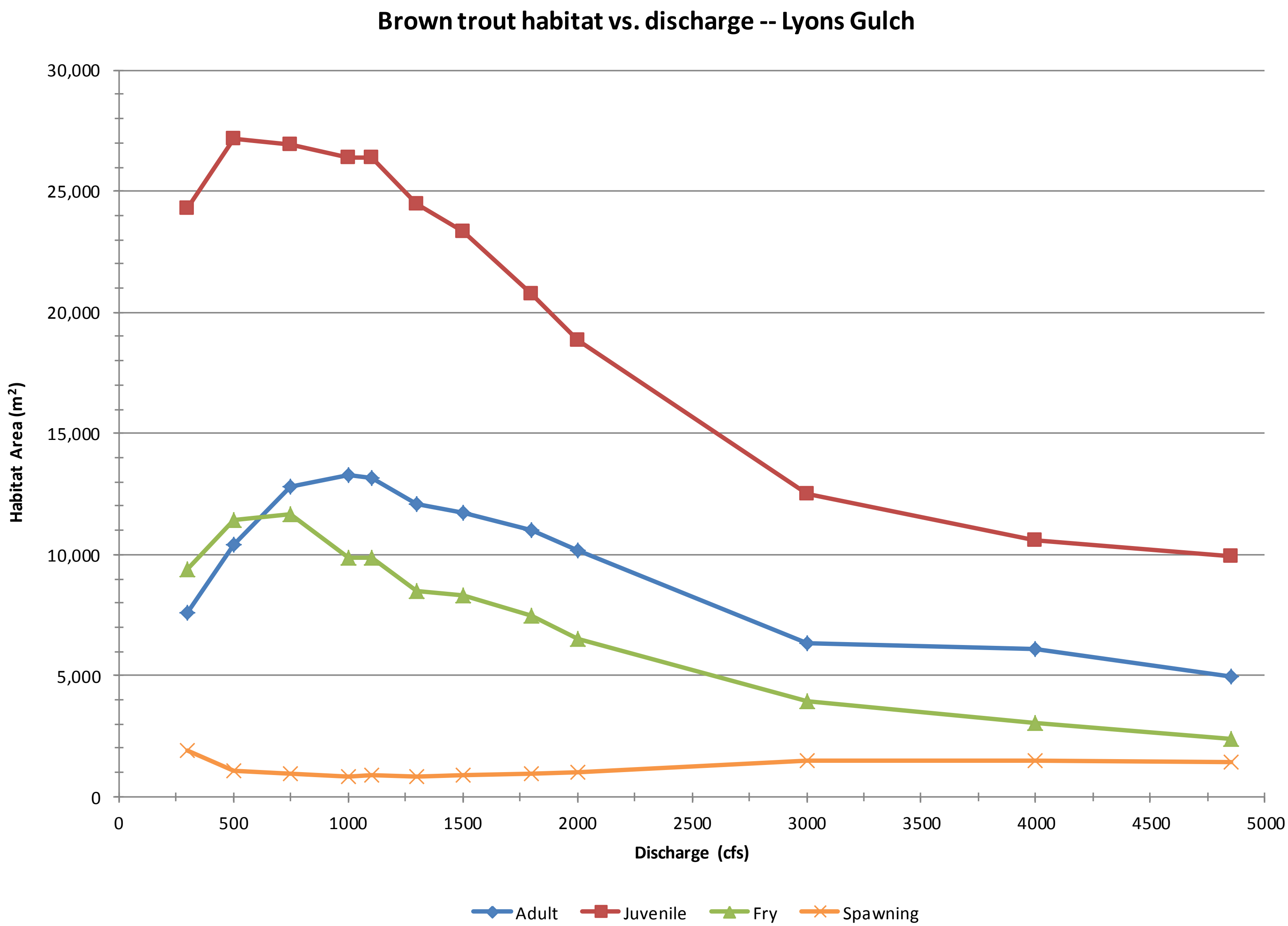


Figure 75. Brown trout habitat versus discharge, Lyons Gulch site.

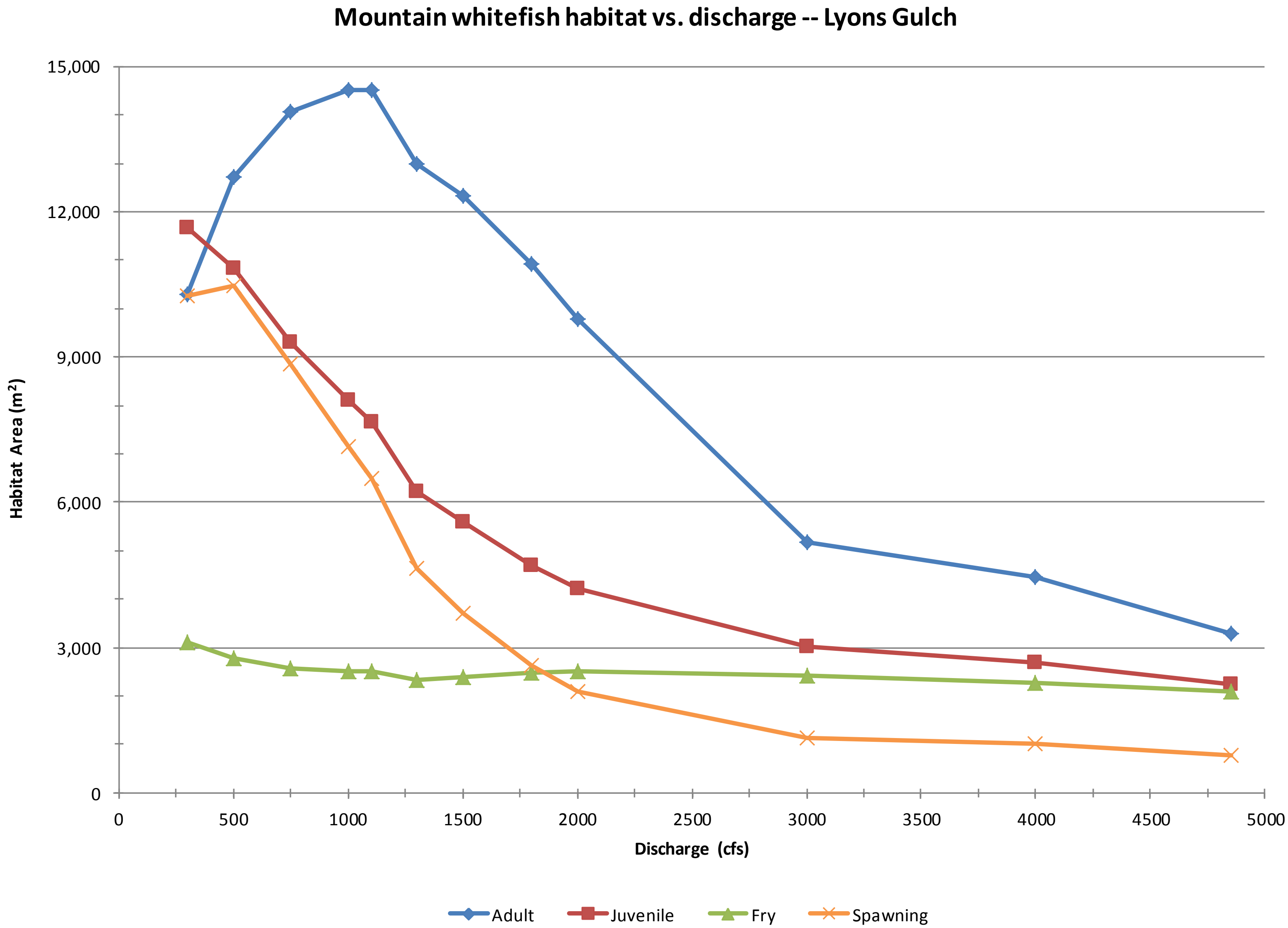


Figure 76. Mountain whitefish habitat versus discharge, Lyons Gulch site.

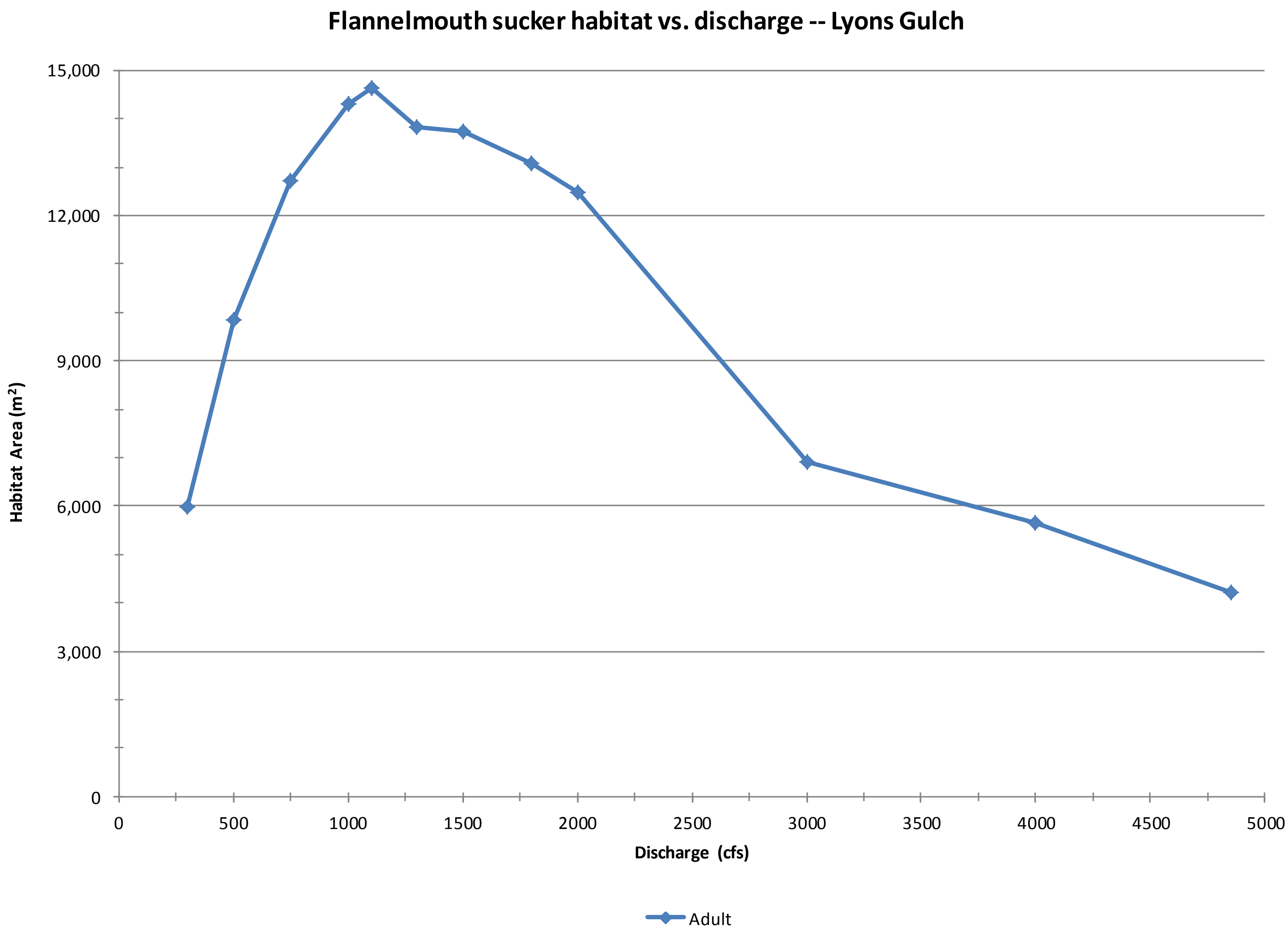


Figure 77. Flannelmouth sucker habitat versus discharge, Lyons Gulch site.

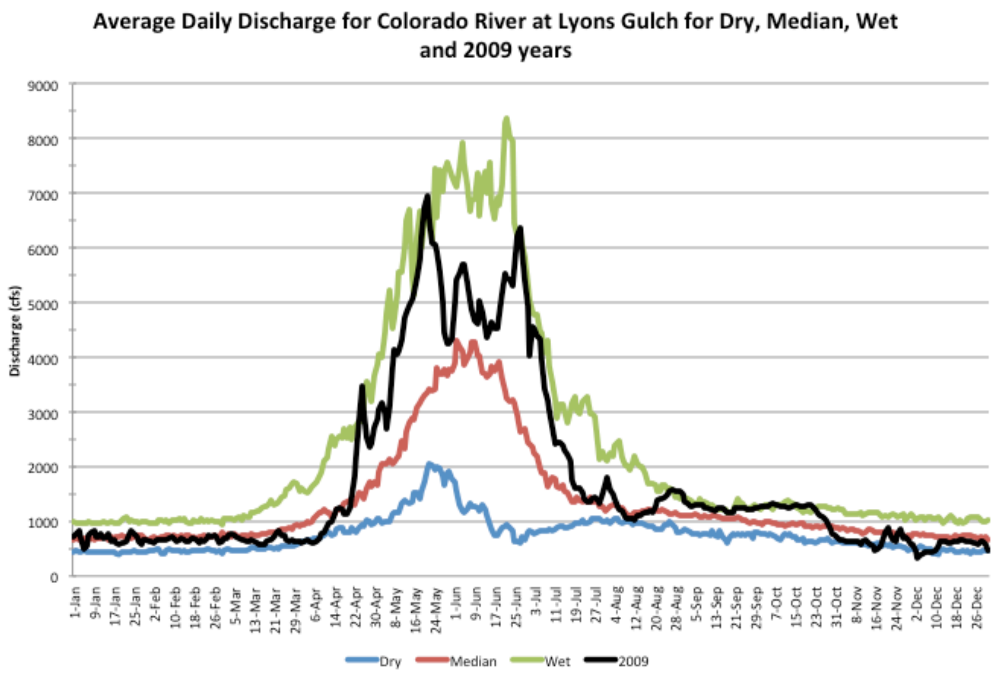


Figure 78. Average daily discharge for the Colorado River at Lyons Gulch in dry, median, and wet years and 2009.

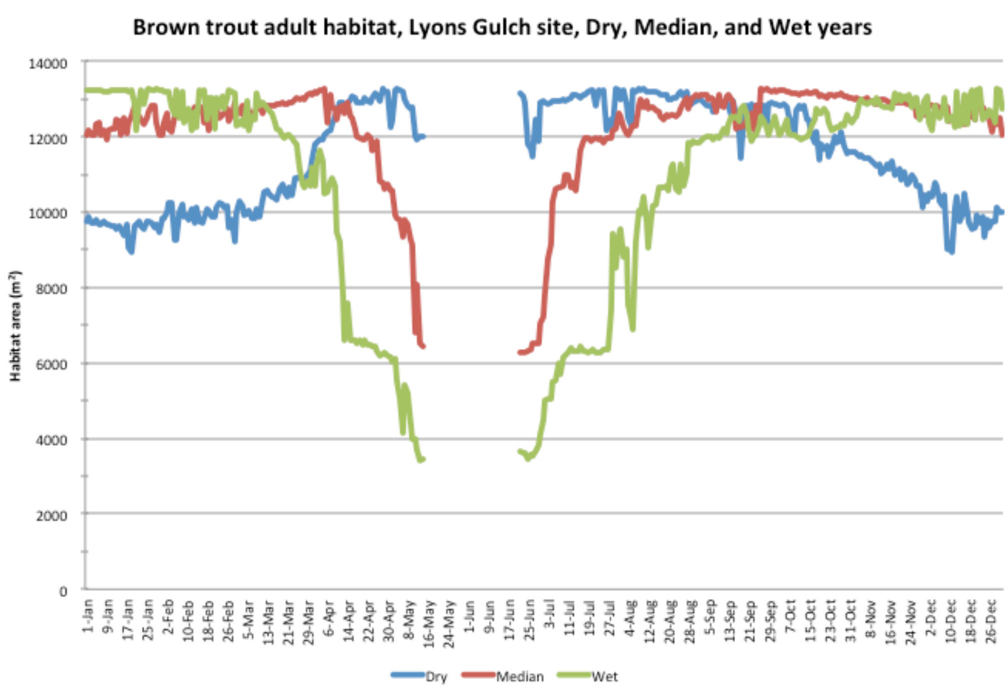


Figure 79. Adult brown trout habitat at Lyons Gulch in dry, median, and wet years.

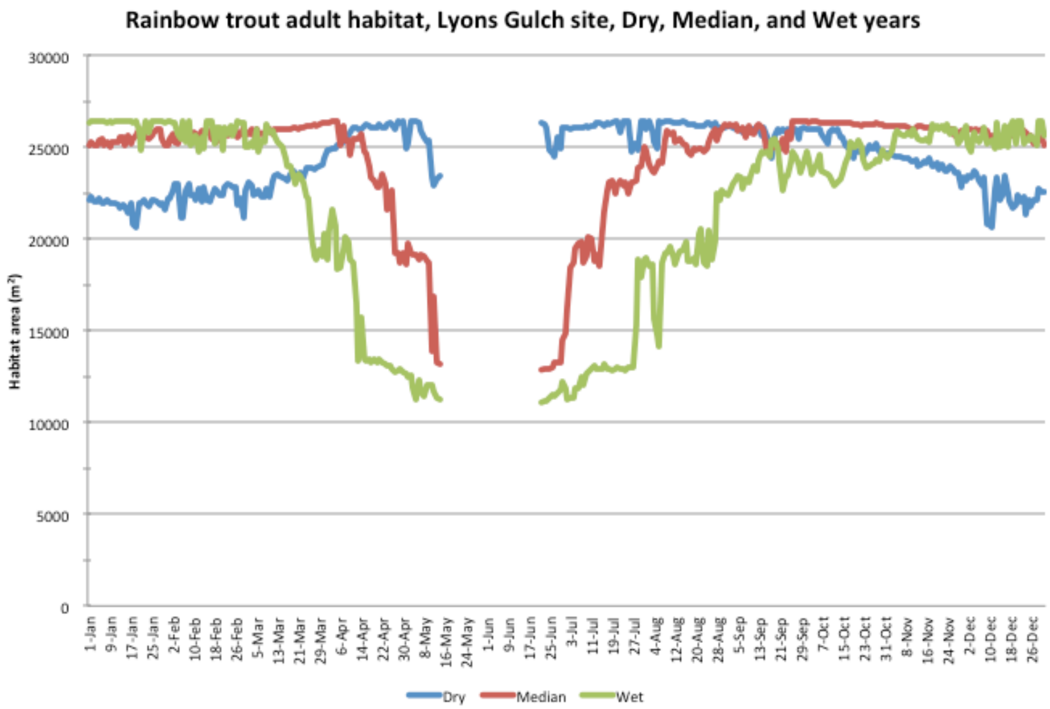


Figure 80. Adult rainbow trout habitat at Lyons Gulch in dry, median, and wet years.

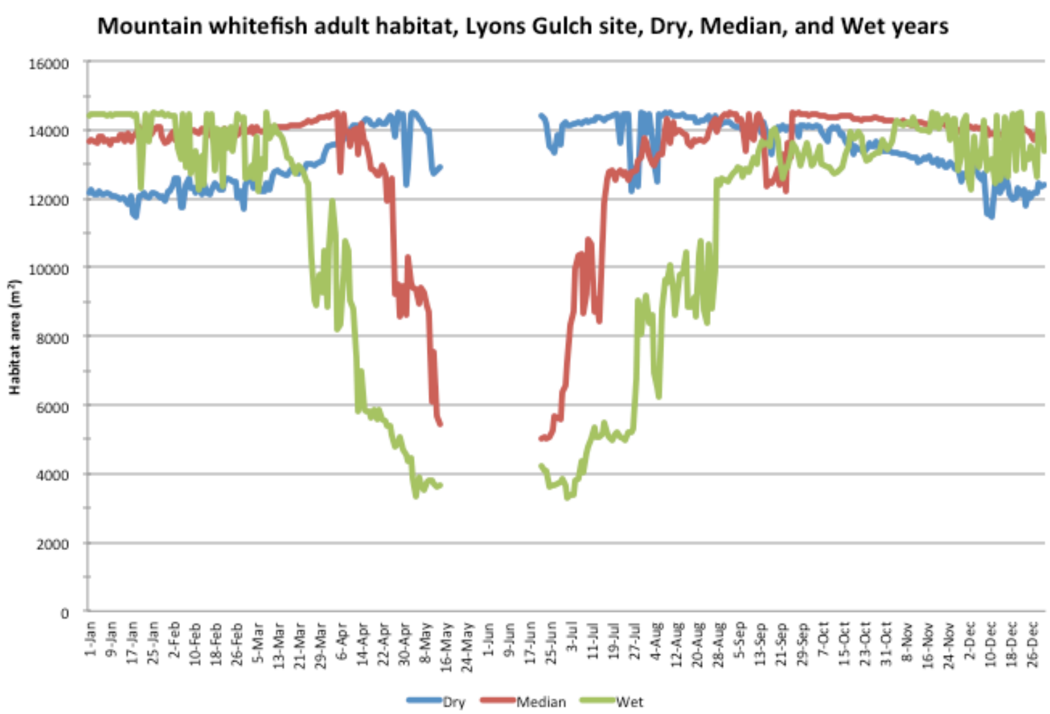


Figure 81. Adult mountain whitefish habitat at Lyons Gulch in dry, median, and wet years.

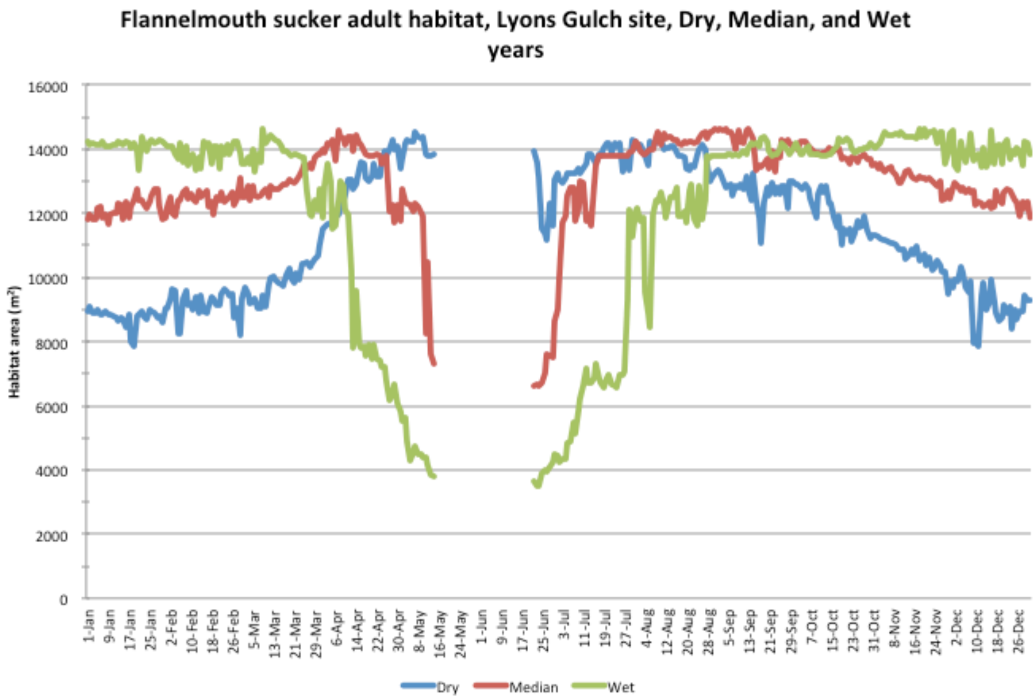


Figure 82. Adult flannelmouth sucker habitat at Lyons Gulch in dry, median, and wet years.

Discussion and Conclusions

The Colorado River from the Blue River confluence downstream to the confluence of the Eagle River contains both canyon-bound and meandering river sections. The river is confined by canyon or steep topography in approximately 60 percent of this reach. There are sections with more open topography at the upper end of the reach and in certain locations near the middle of the reach.

The canyon-bound and confined reaches have steeper gradients and larger bed material on the river bottom than the lower-gradient meandering reaches. Islands are present in all sections of the river from the Blue River downstream to the Eagle River with the exception of Gore Canyon. Larger islands are present in the lower portion of the study area.

Vegetation varies with gradient and topography. In the steeper canyon-bound sections, juniper and coniferous trees are the dominant vegetation. In the lower gradient, more open reaches, sagebrush is dominant in upland areas with willows dominant in the near-shore riparian areas. Cottonwoods are present throughout the reach but are most abundant in the lower portion of the river from Burns to Dotsero.

Hydrology in the reach is typical of snowmelt-dominated rivers. Peak flows occur during May and June. The upper sections of the reach have peak flows that on average exceed 2000 cfs. The peak flow in the lower reach is nearly twice the peak flow of the upper reach due to additional watershed area and tributary inflow. Bankfull flows occur at approximately 2500 cfs and approximately 4000 cfs in the upper and lower river, respectively. Peak flows are most important for habitat creation and maintenance. Peak flows of bankfull and higher are required at regular frequency for proper ecosystem functions.

The habitat-flow relationships for most life stages of each species are similar in shape at each site with the exception of mountain whitefish at the Lyons Gulch site. Habitat for most species and life stages is most abundant at flows between 500 and 1500 cfs, however, the habitat quality is generally higher at mid to lower flows. Habitat abundance for most species and life stages decreases rapidly at flows less than 500 cfs.

Based on the available hydrology and the habitat-discharge functions, base flows of 500 cfs or higher would maintain habitat during fall, winter, and early spring at the current levels. Average peak flows that exceed 2000 cfs upstream of State Bridge and 4000 cfs near Dotsero should create and maintain habitat in its current state. Higher peak flows (double the average peak) with recurrence intervals of one to two times every ten years should continue to create and maintain habitat and riparian areas as they now function. Ascending and descending limbs of the hydrograph should follow the current shape to provide higher habitat quantity and quality in late spring and summer than during fall and winter base flows.

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Appendix A – Habitat Maps for Colorado River Sites

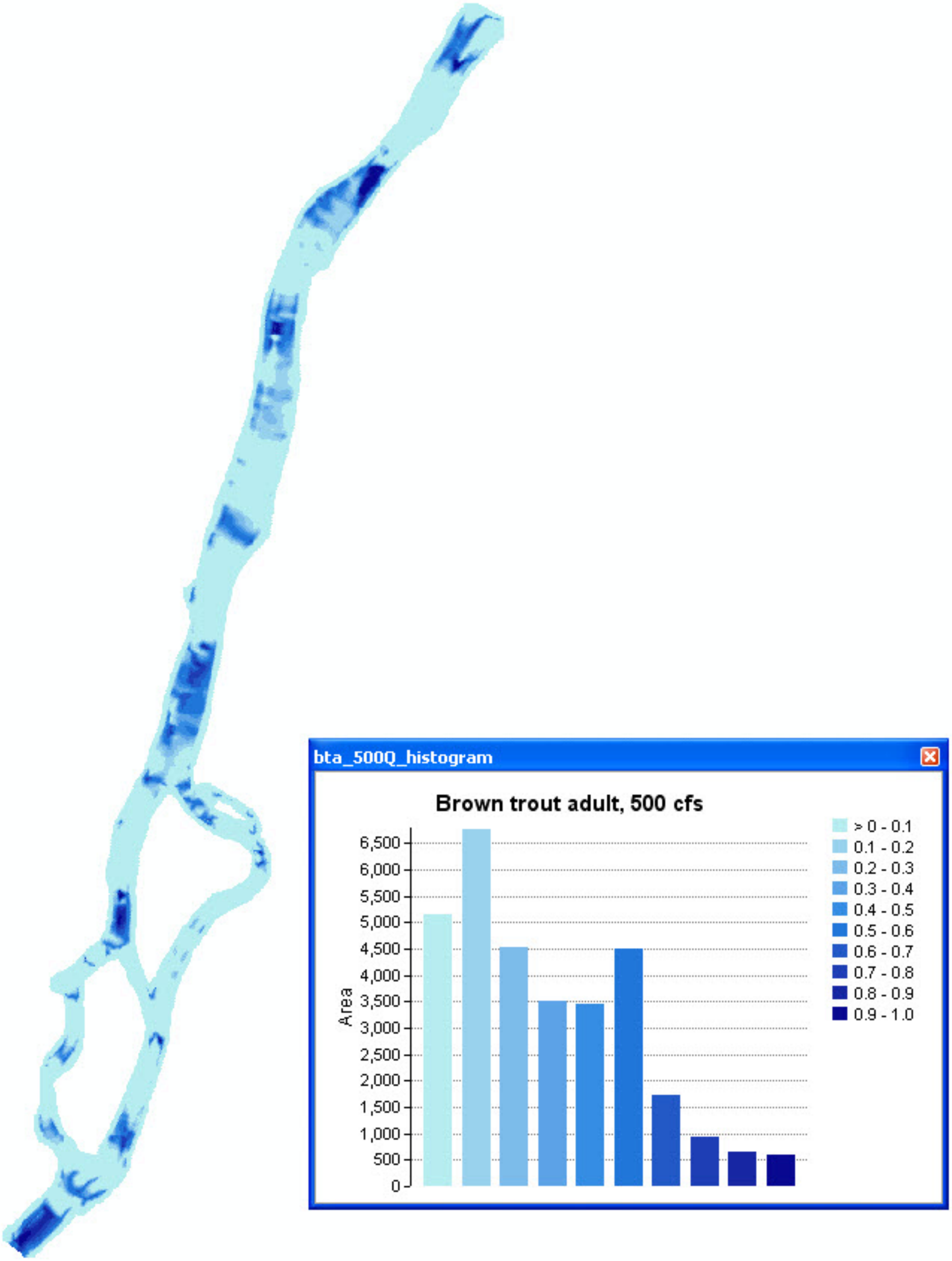


Figure A-1. Adult brown trout habitat map, Pumphouse site, 500 cfs.

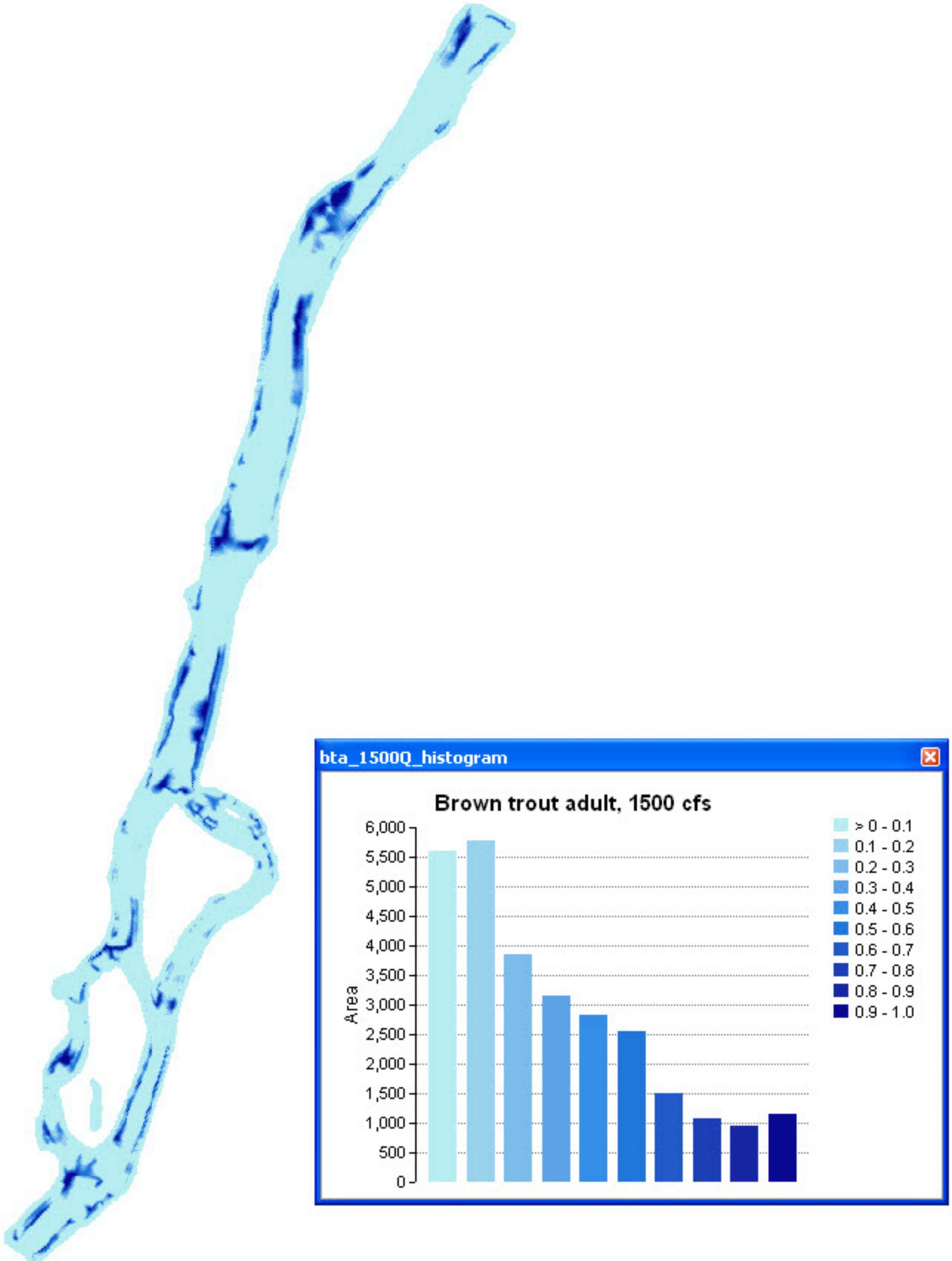
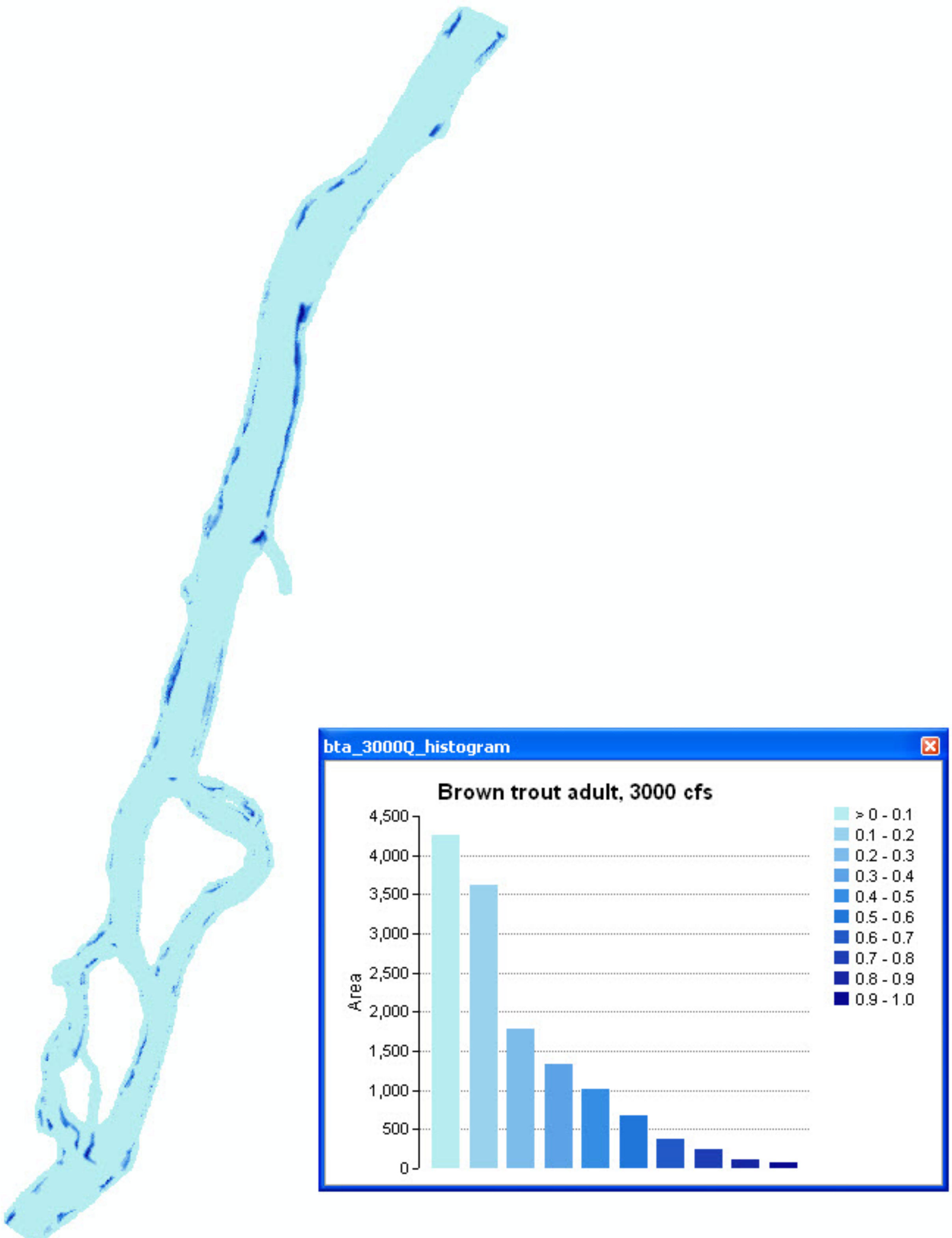


Figure A-2. Adult brown trout habitat map, Pumphouse site, 1500 cfs.



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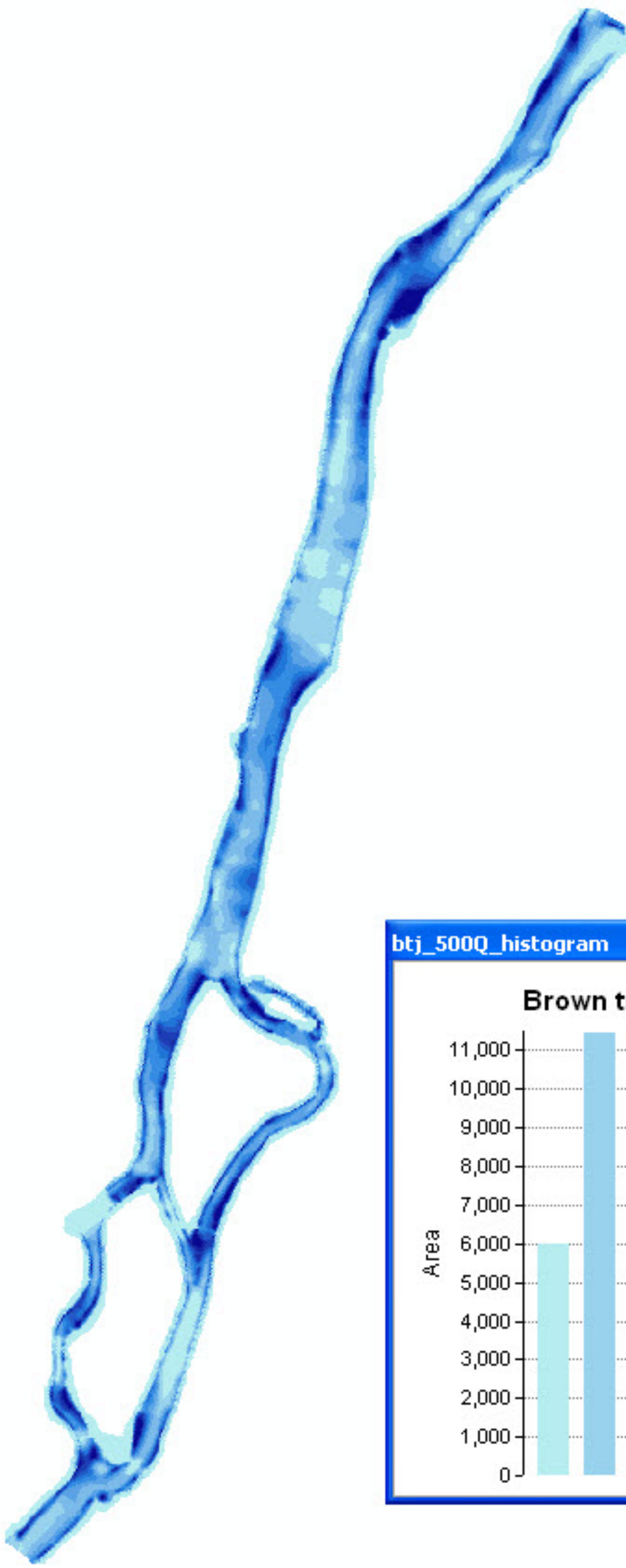


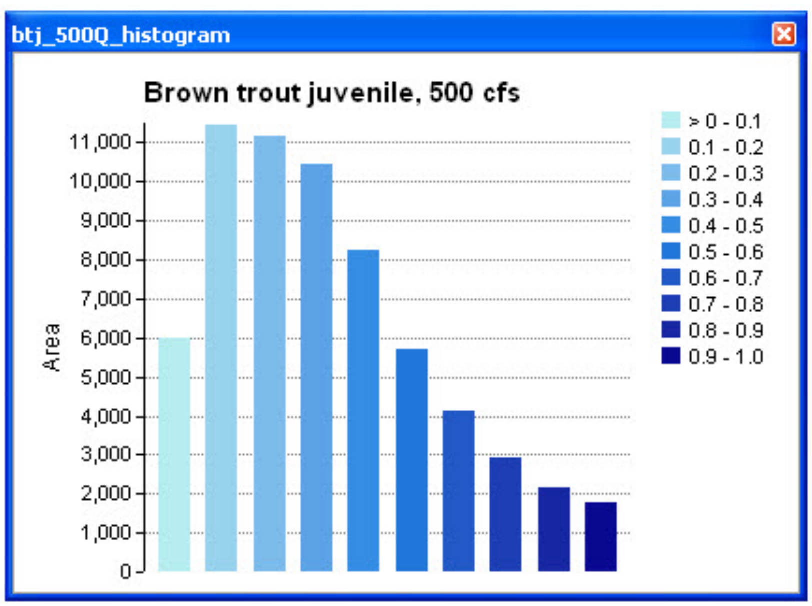
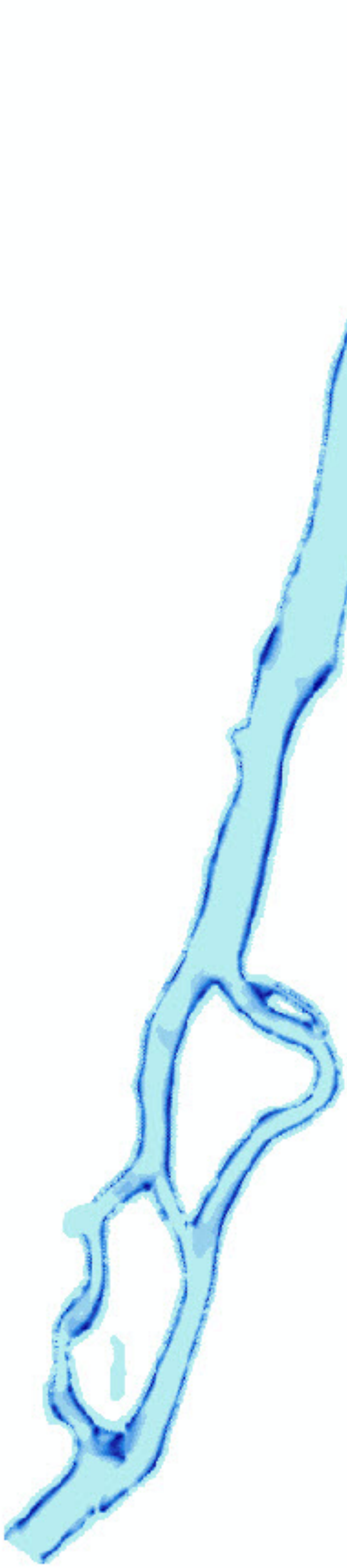
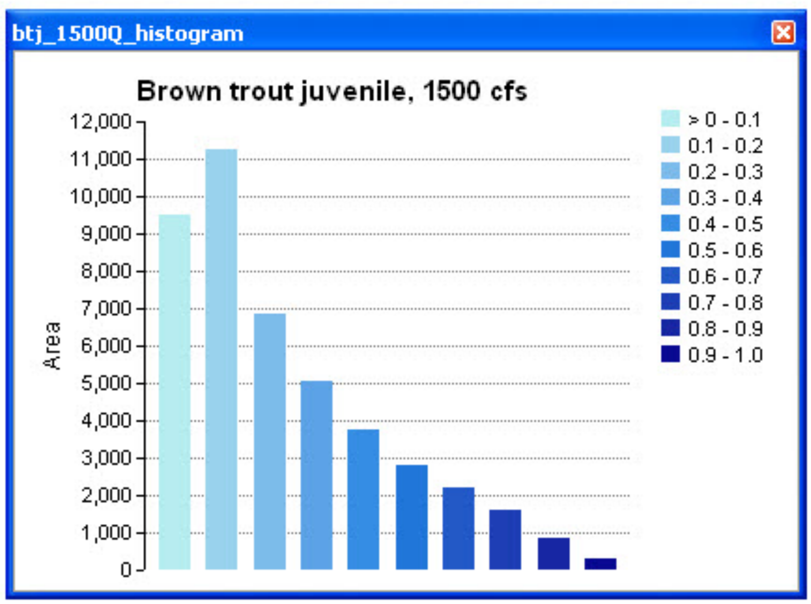


Figure A-4. Juvenile brown trout habitat map, Pumphouse site, 500 cfs.





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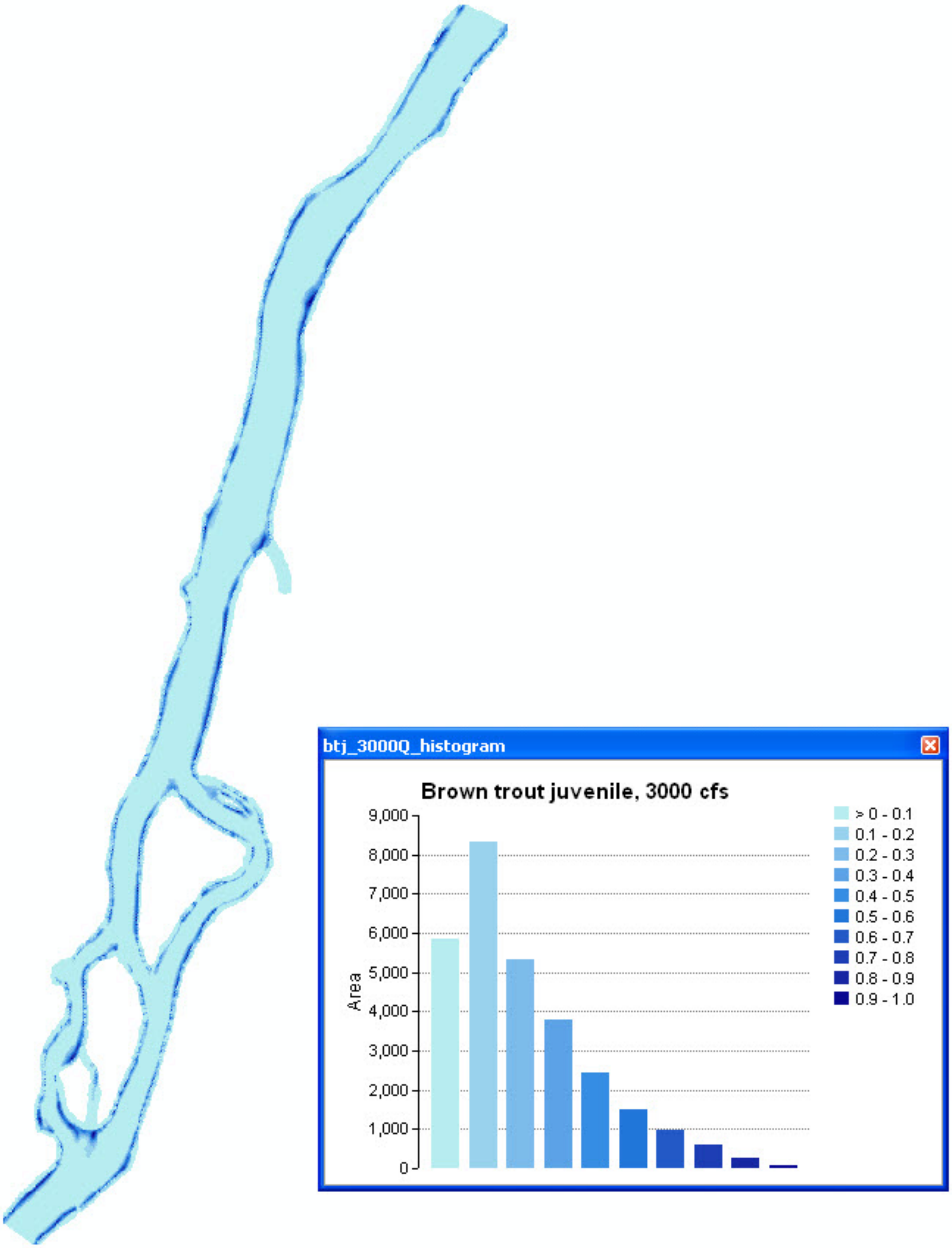
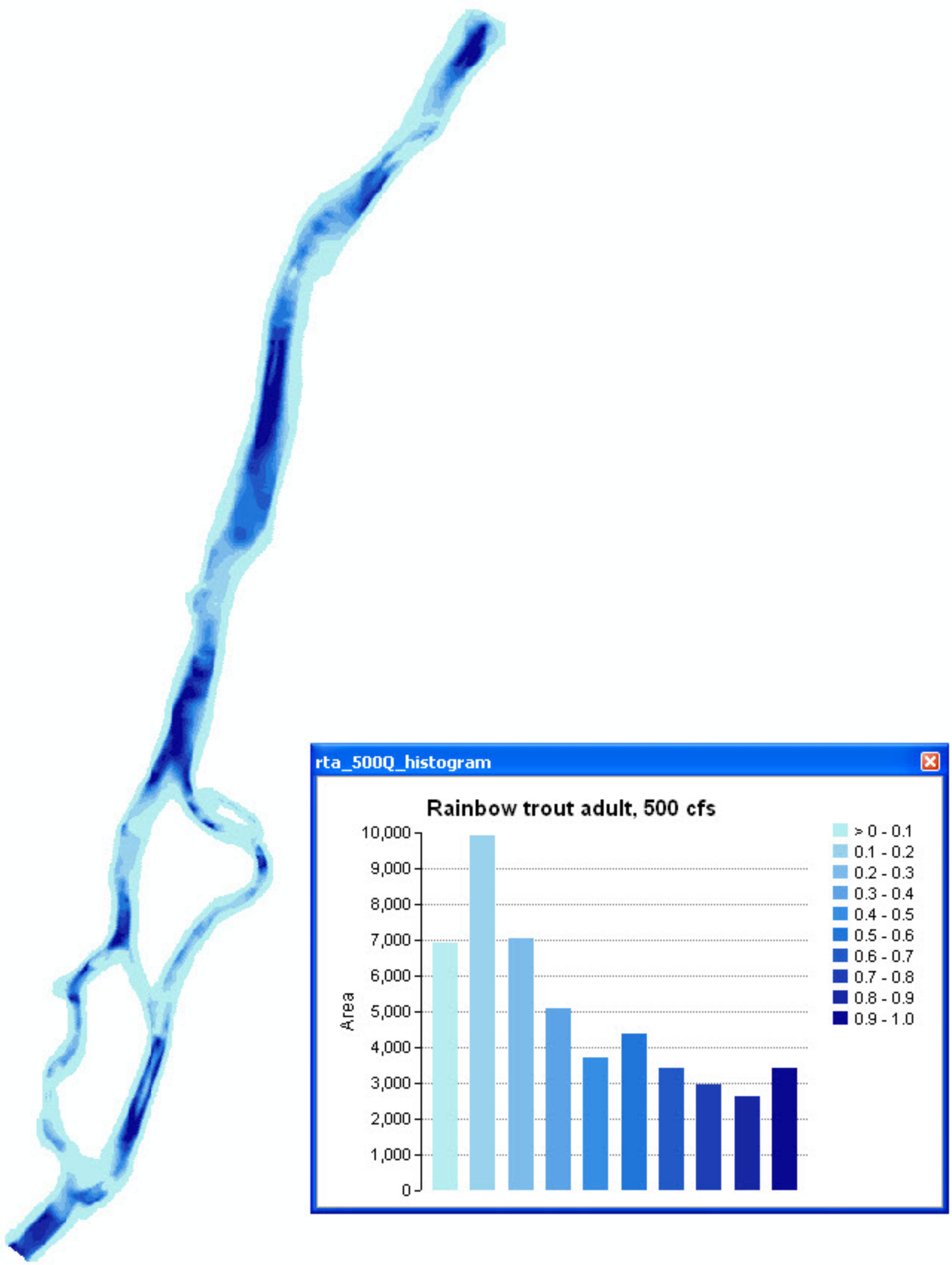


Figure A-6. Juvenile brown trout habitat map, Pumphouse site, 3000 cfs.



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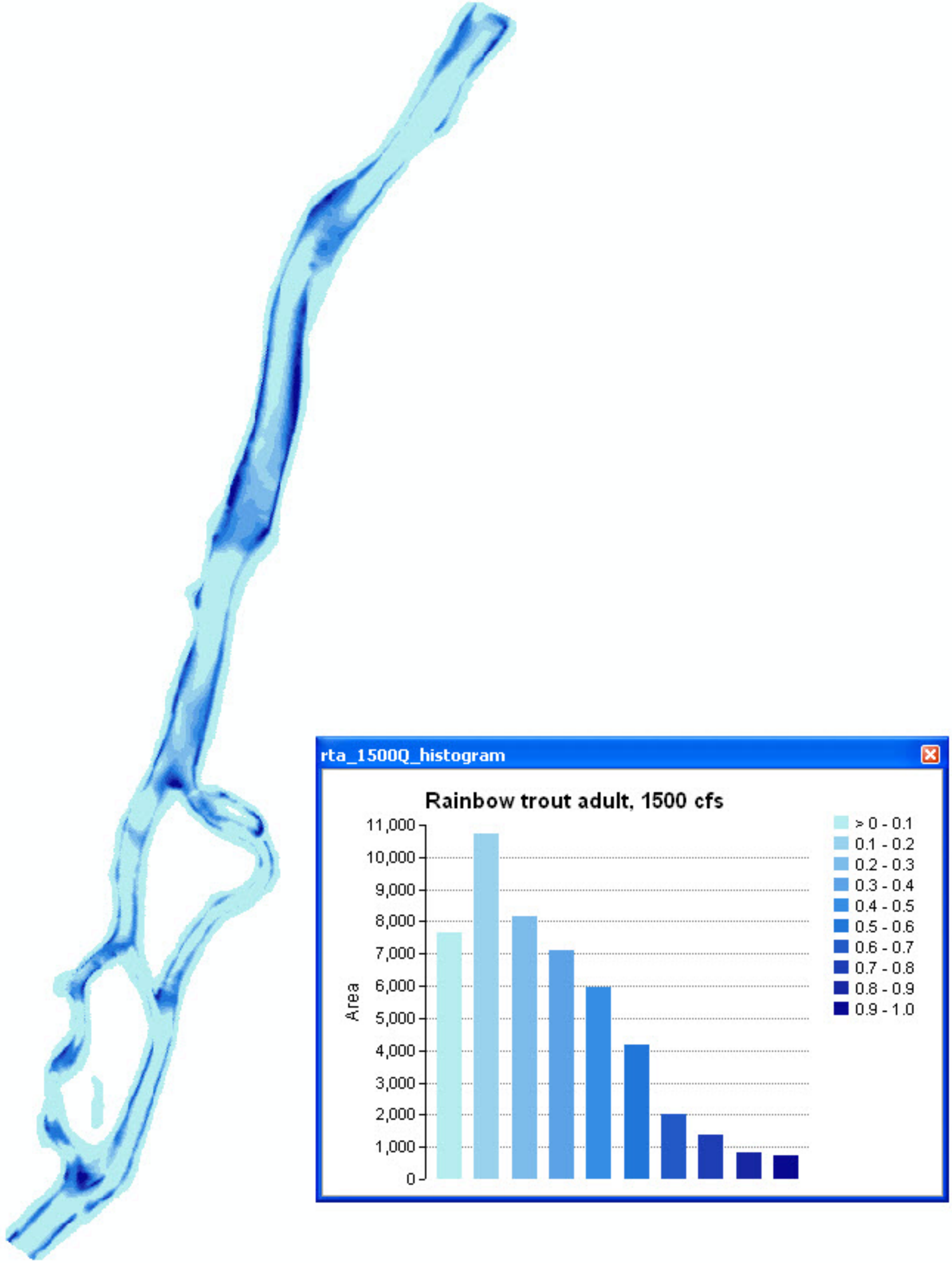

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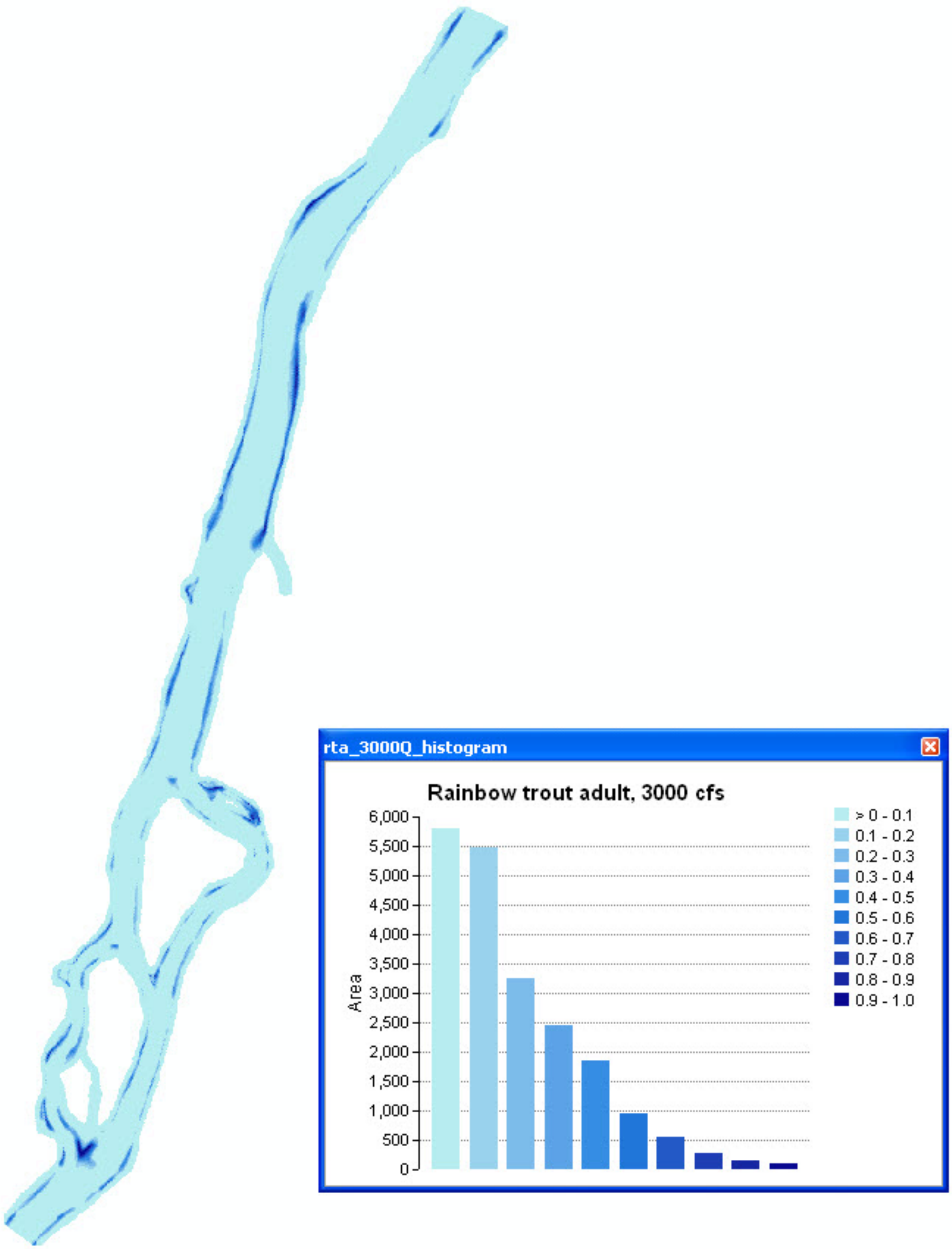

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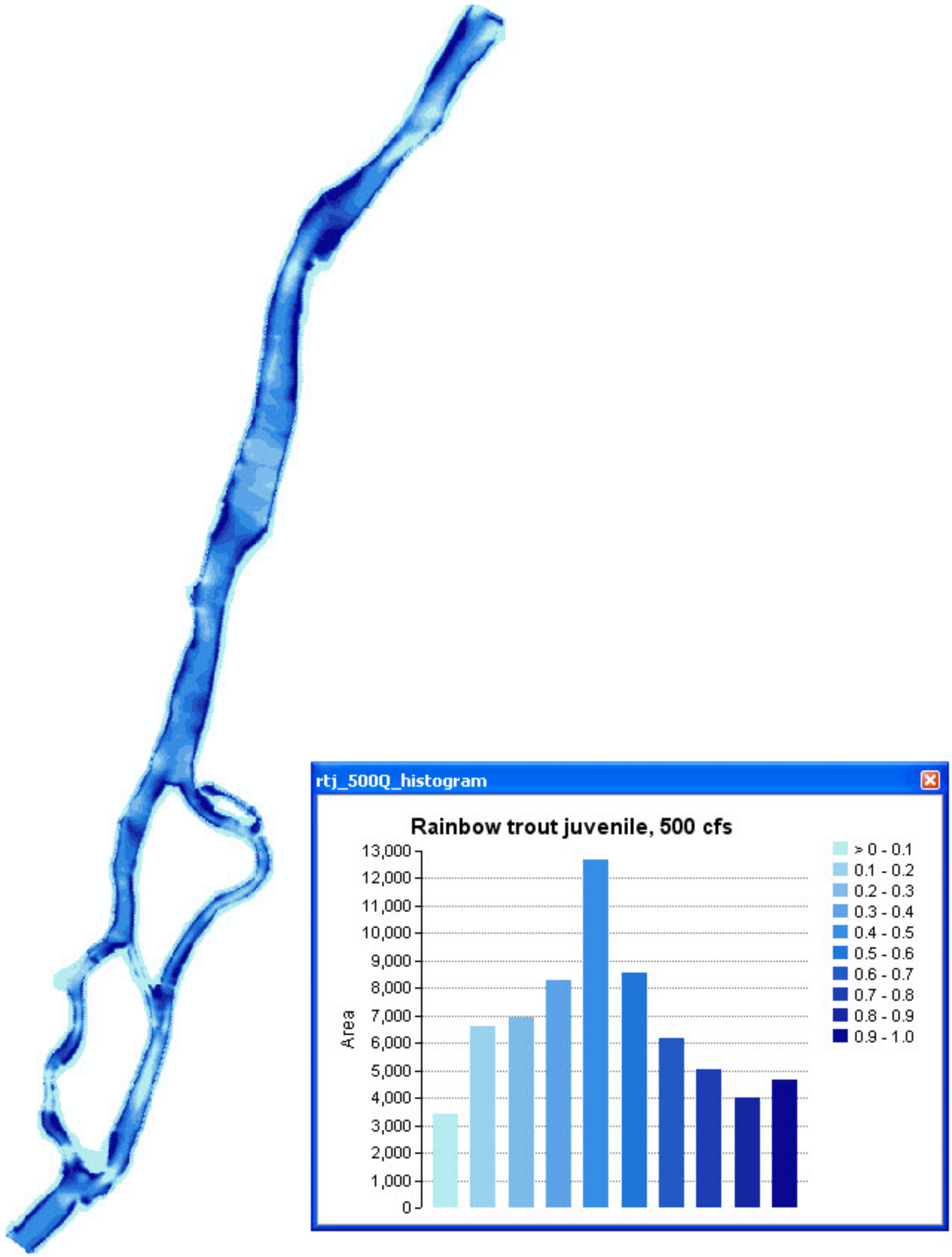

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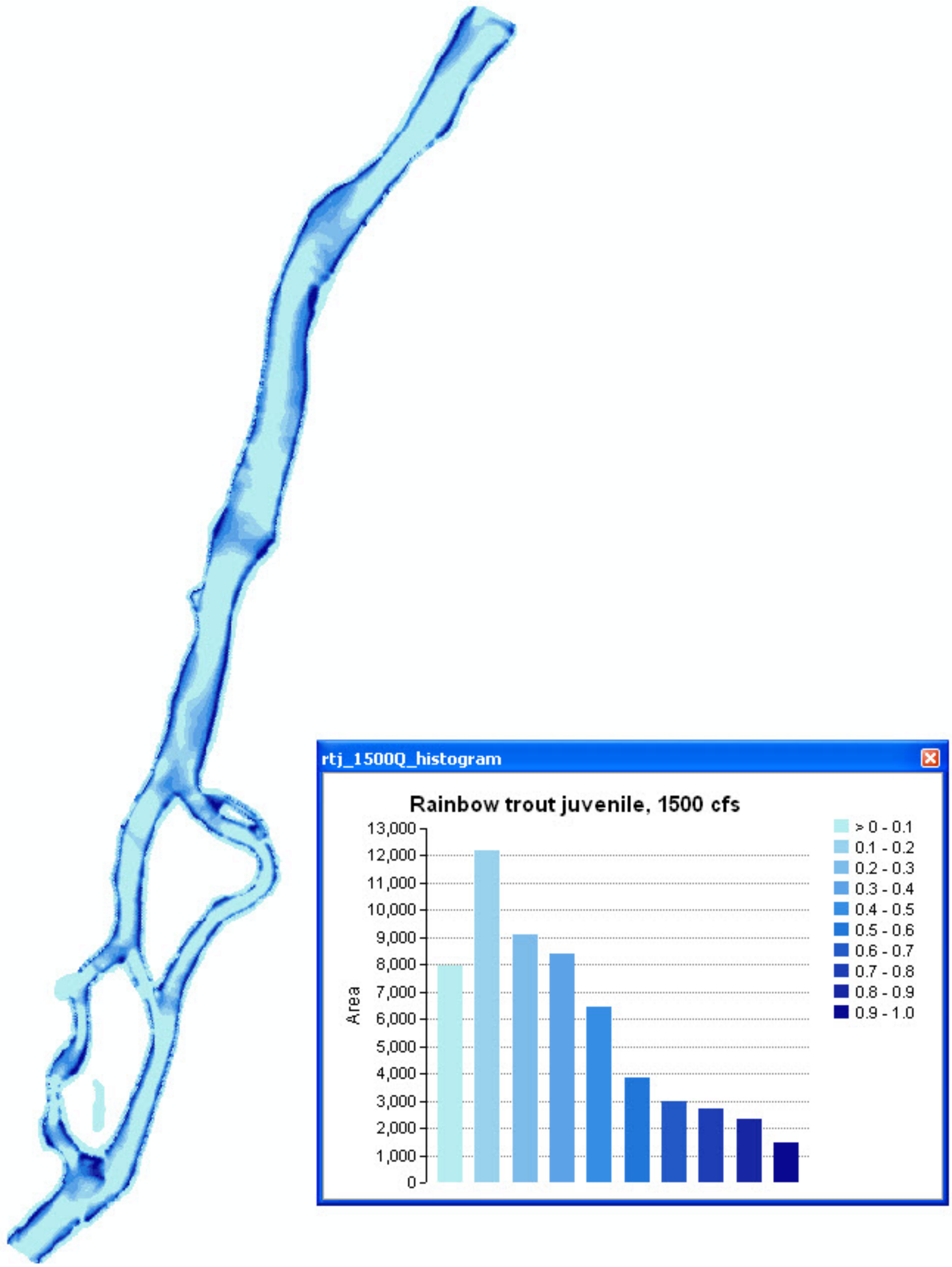

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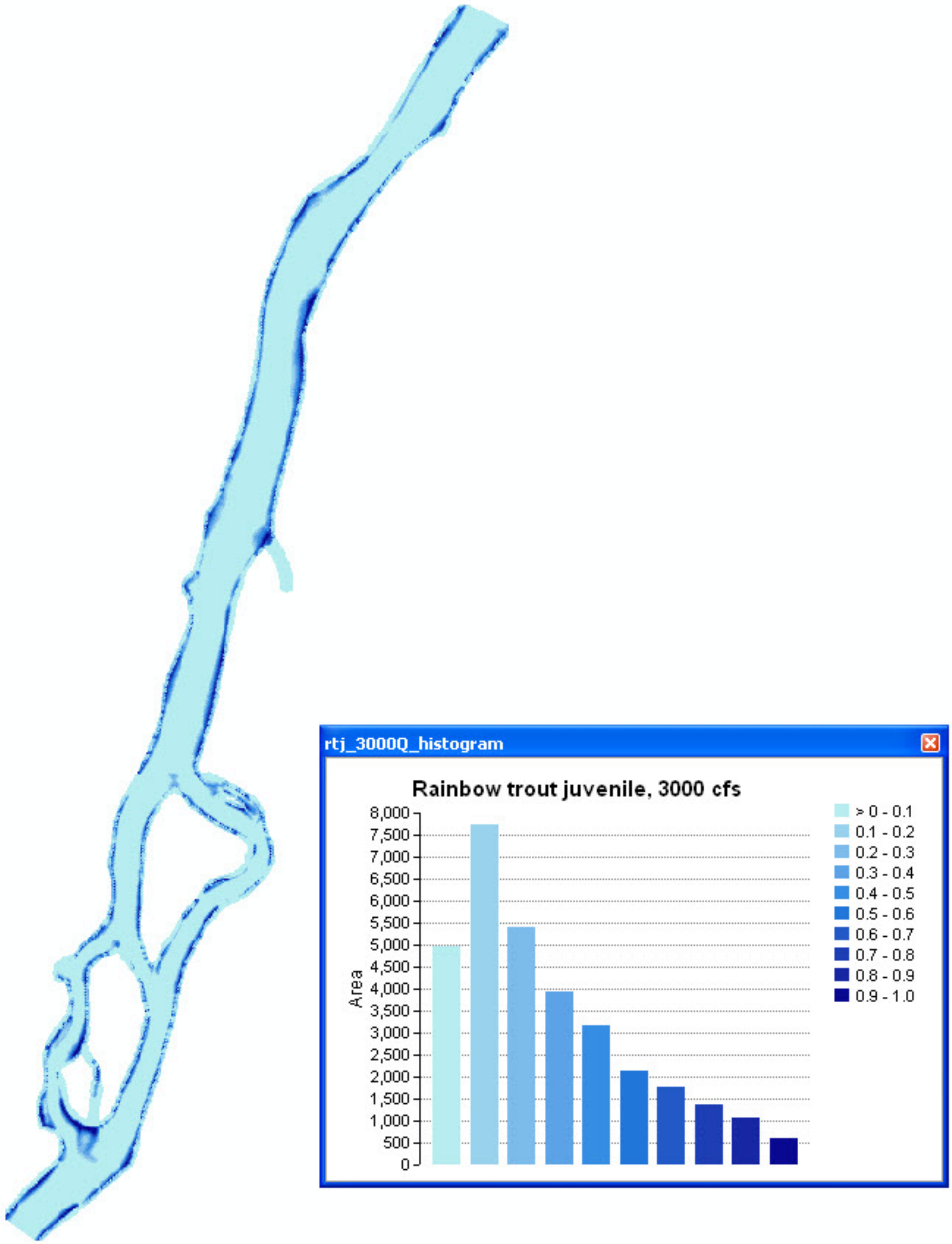

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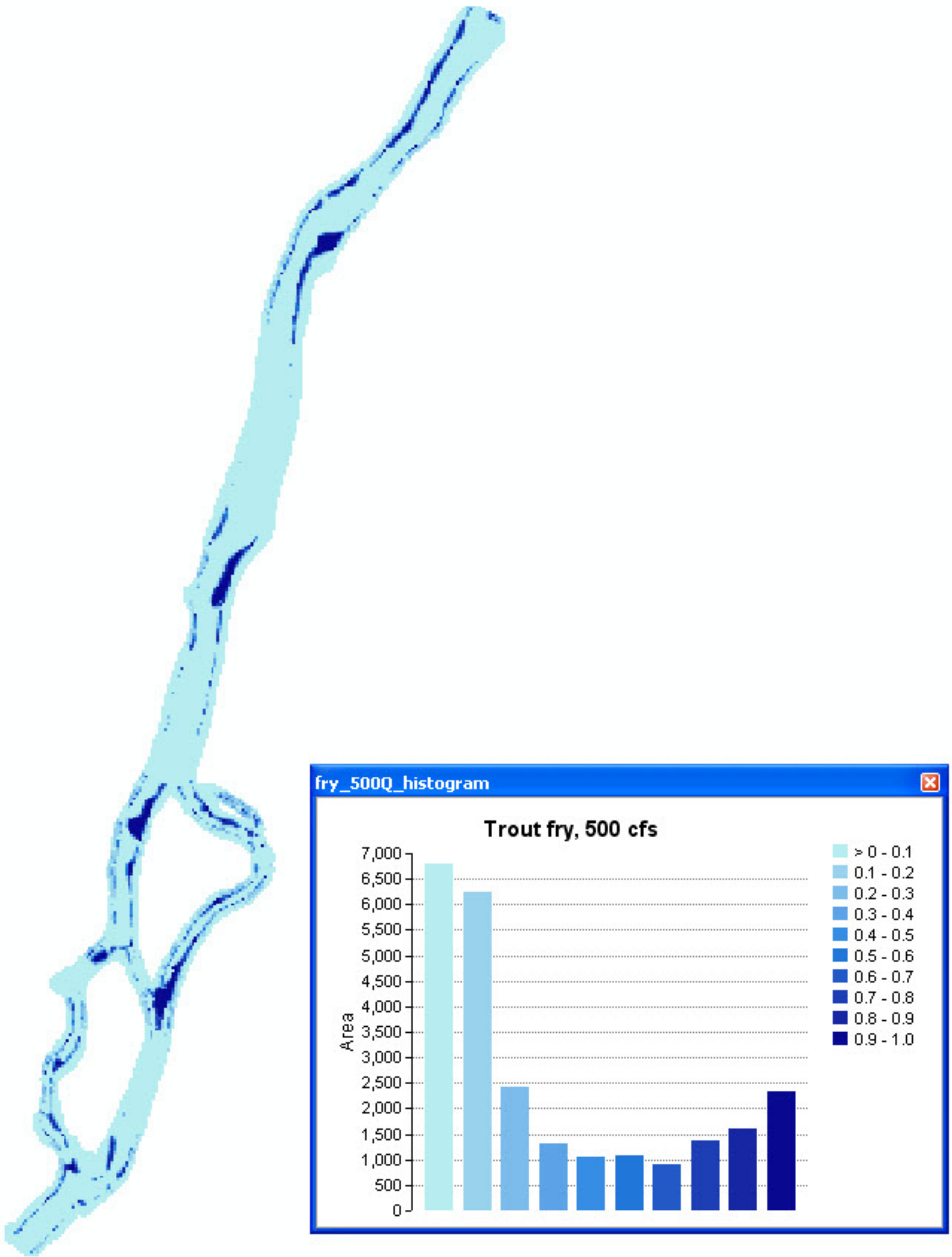
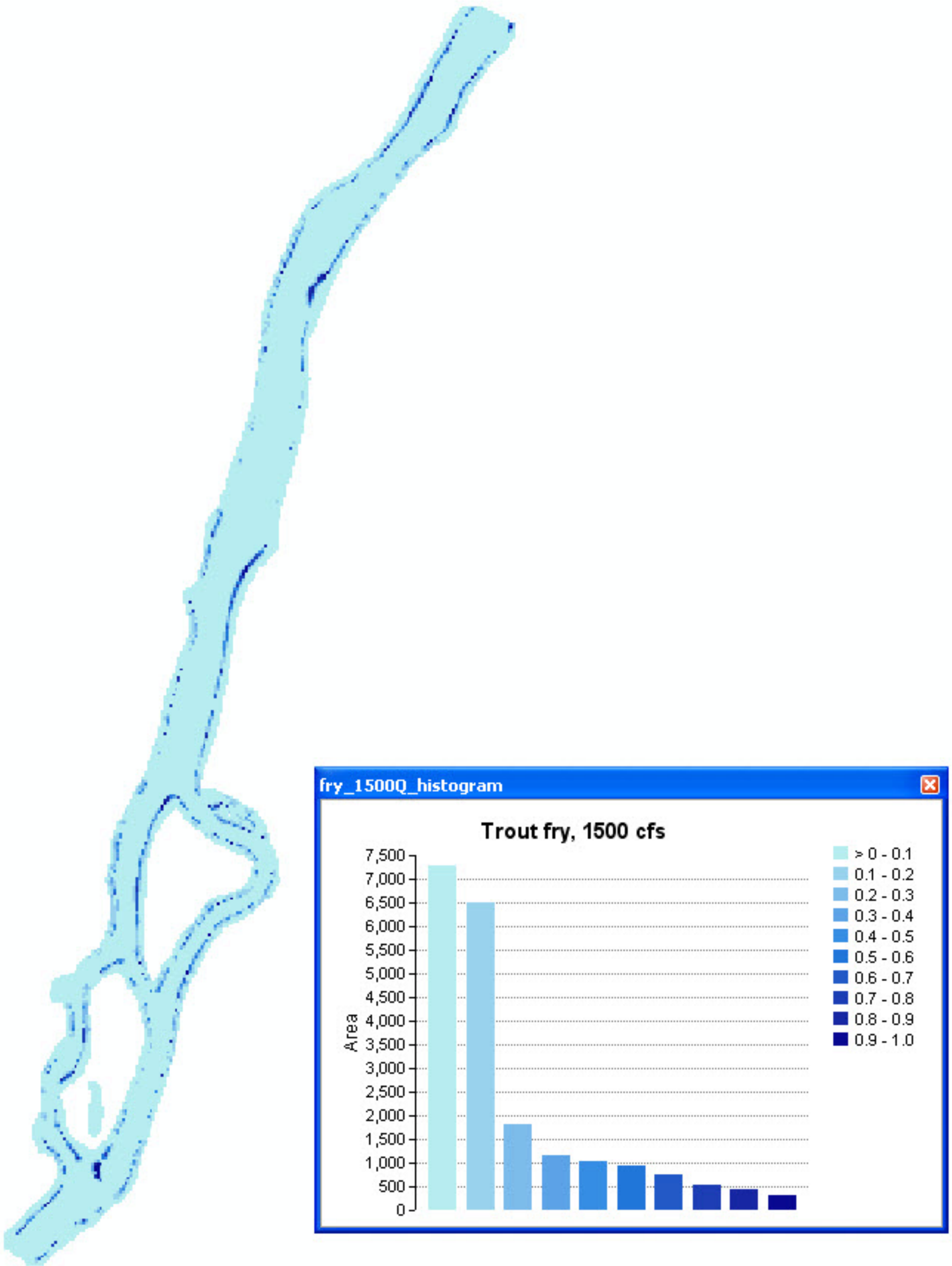


Figure A-13. Trout fry habitat map, Pumphouse site, 500 cfs.



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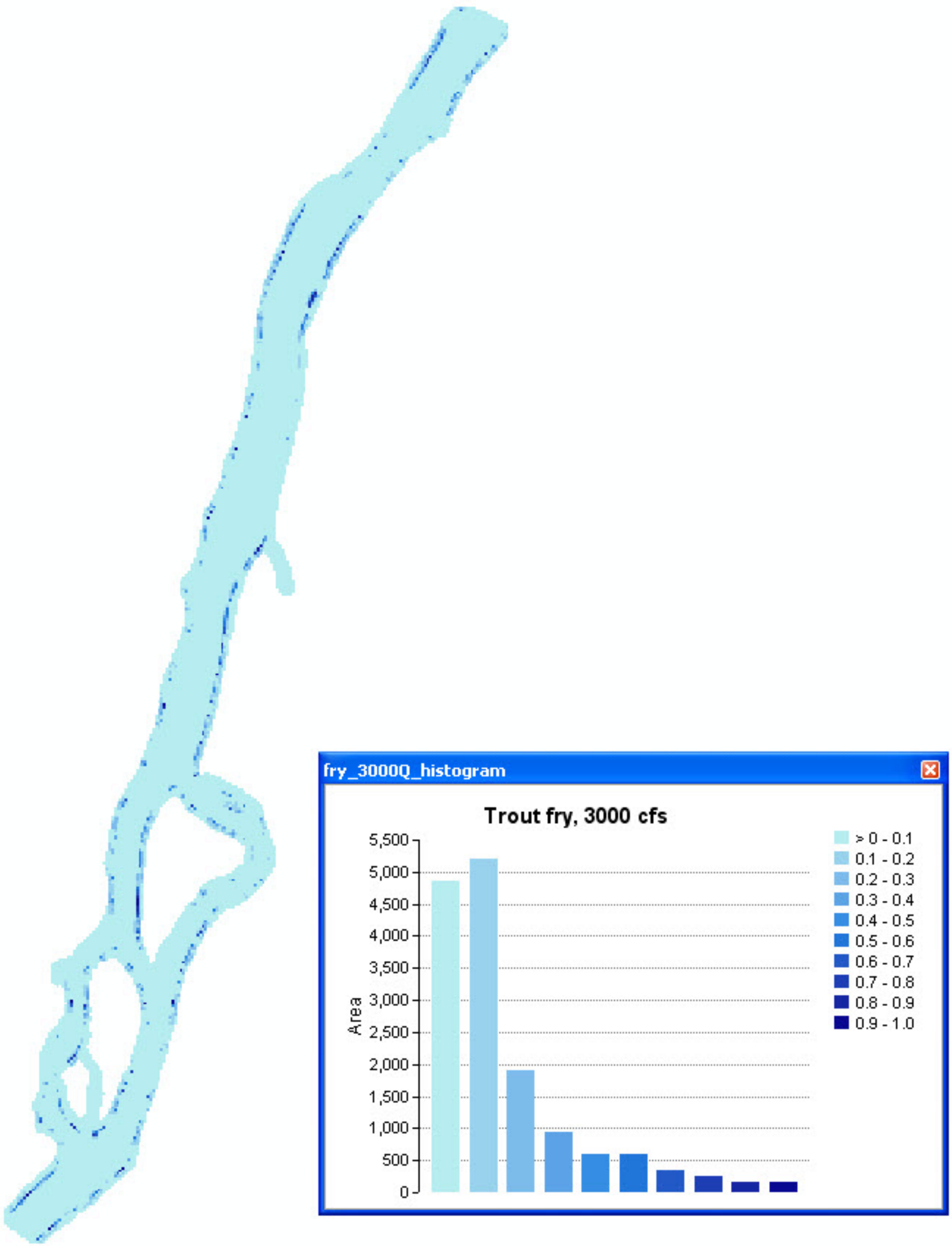

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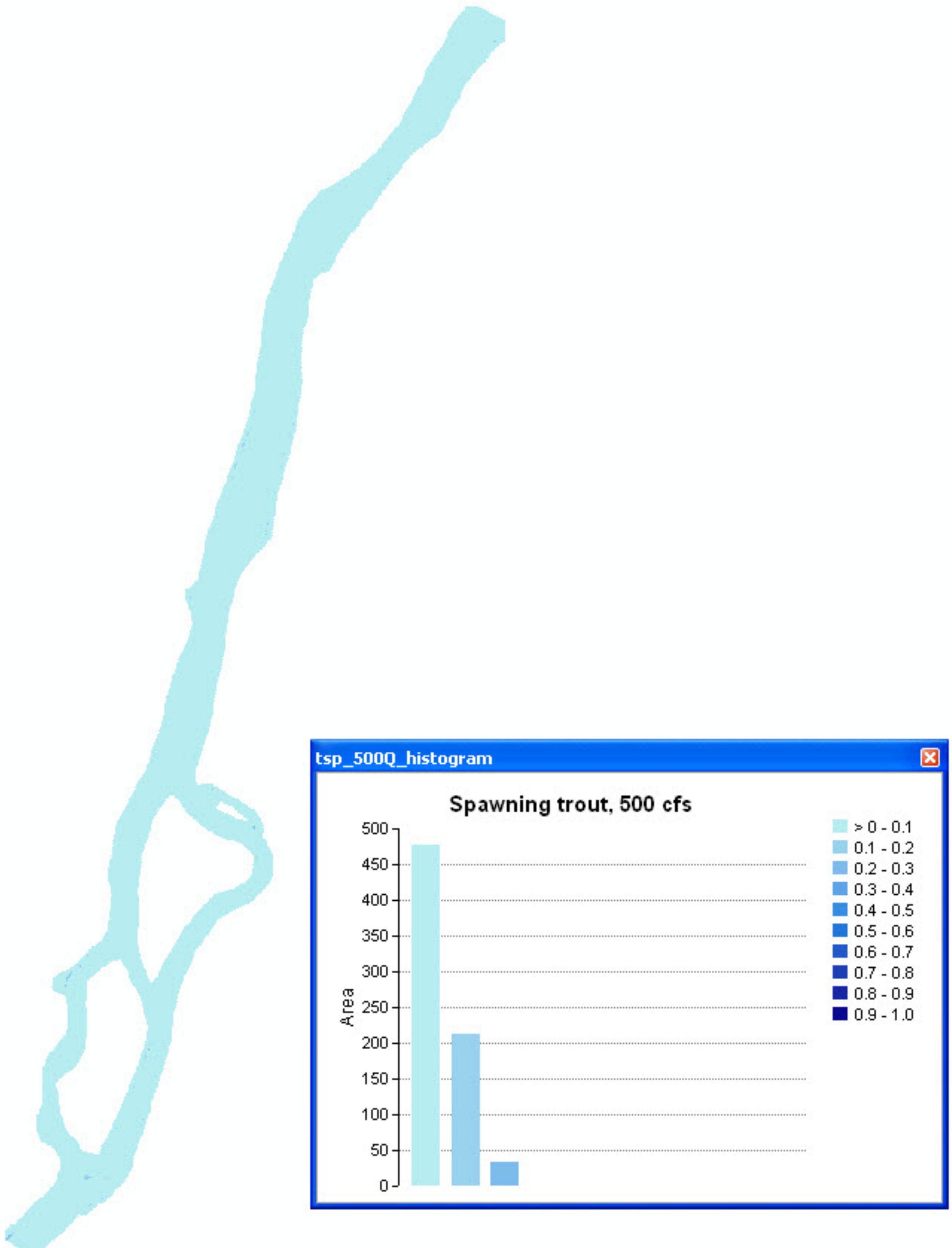
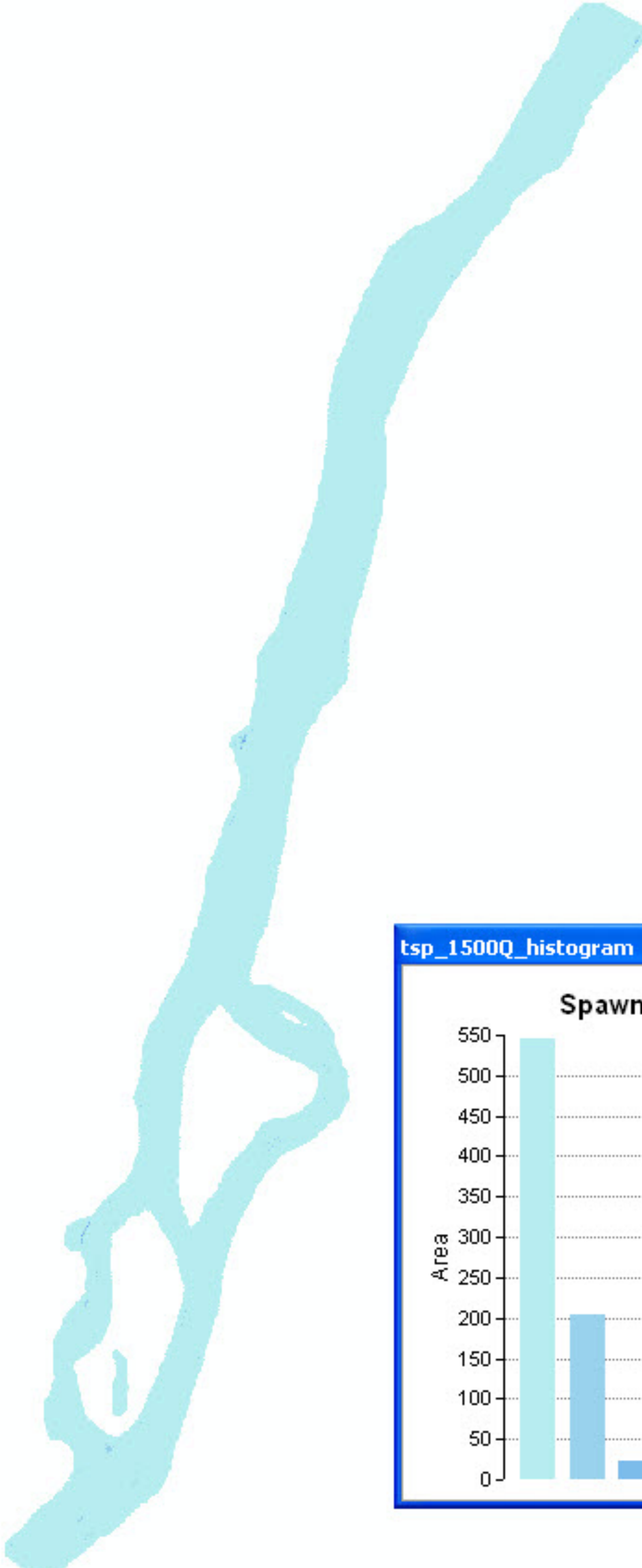
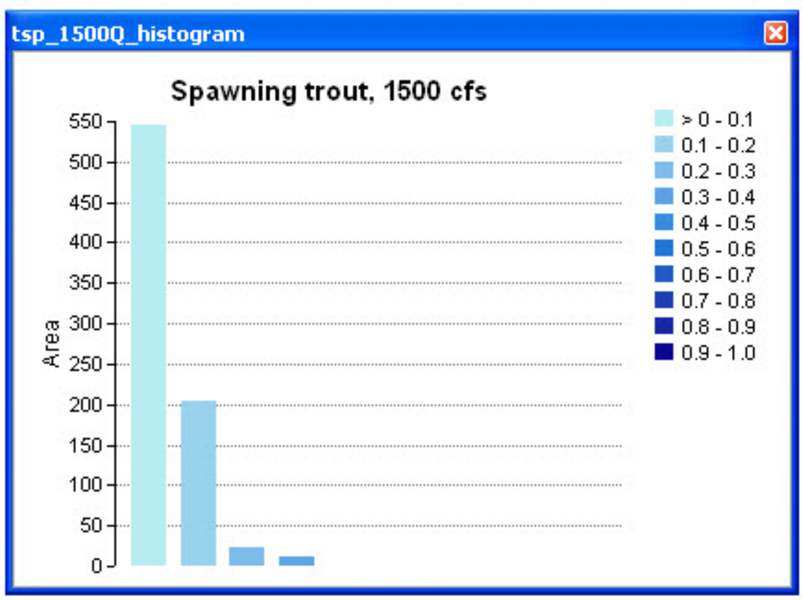


Figure A-16. Trout spawning habitat map, Pumphouse site, 500 cfs.





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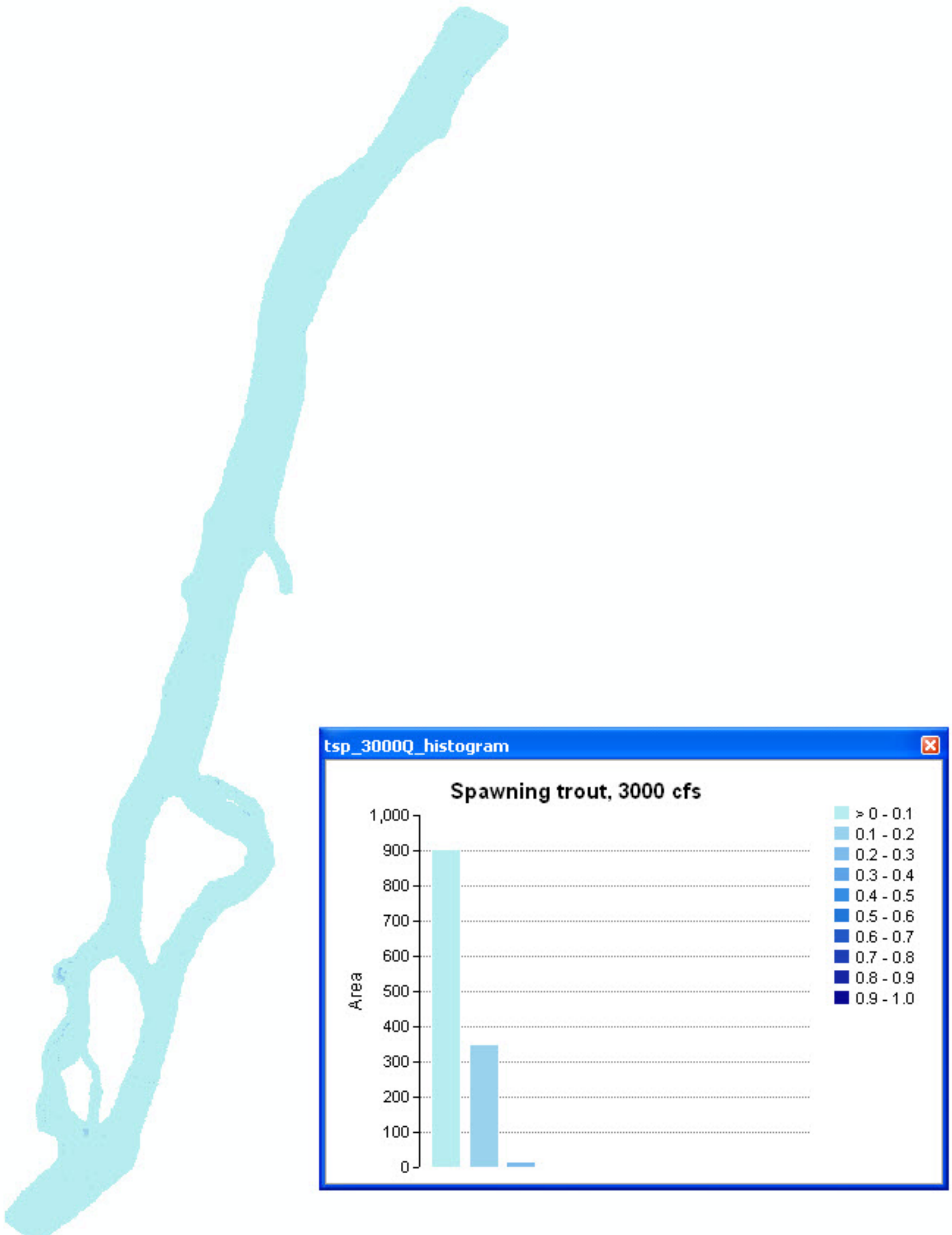

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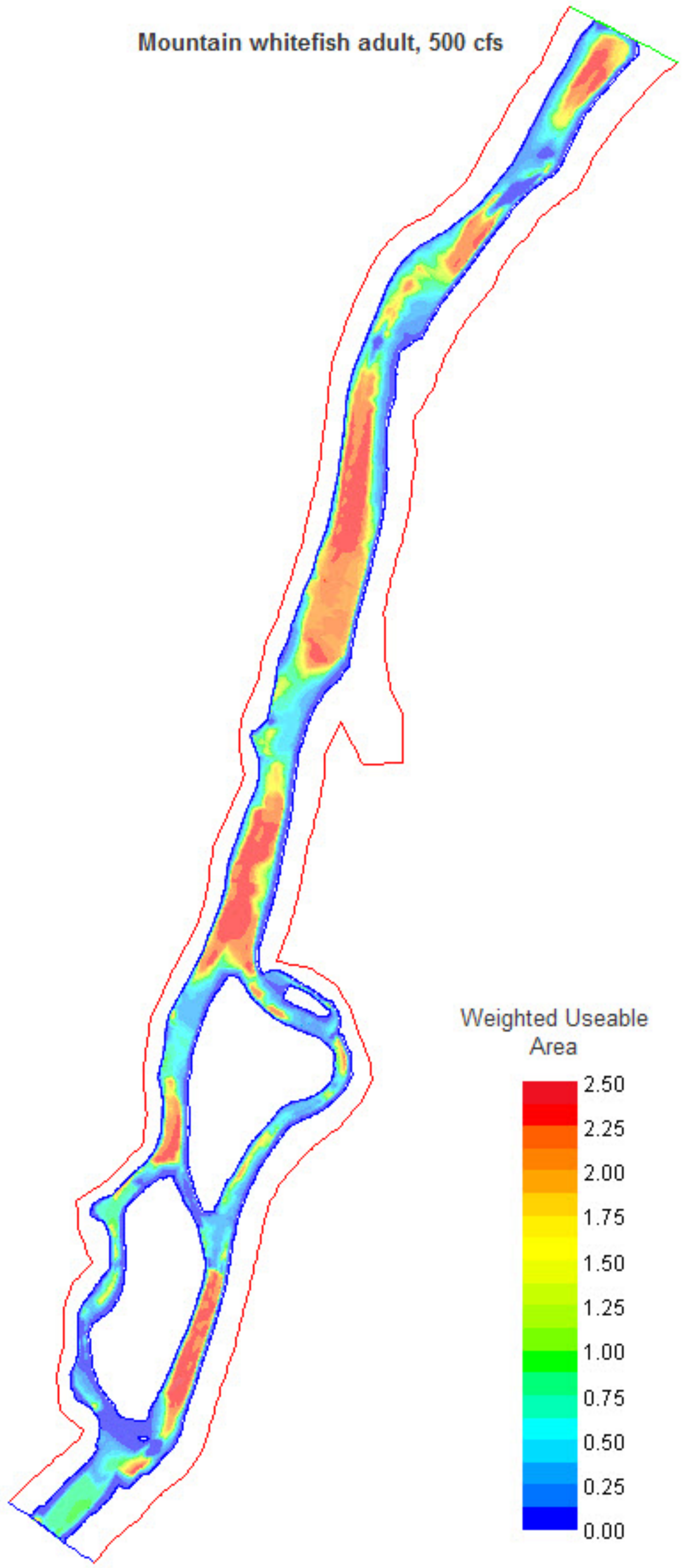
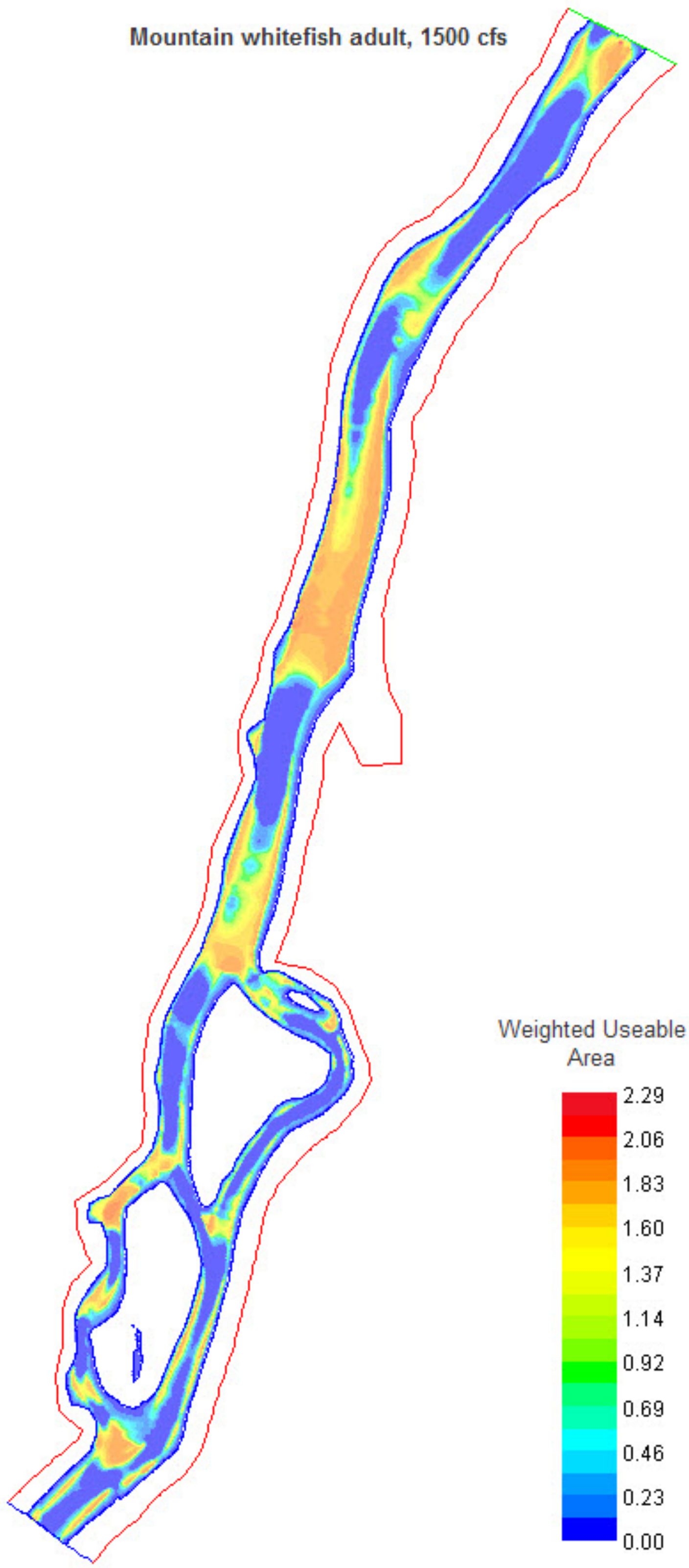


Figure A-19. Adult mountain whitefish habitat map, Pumphouse site, 500 cfs.



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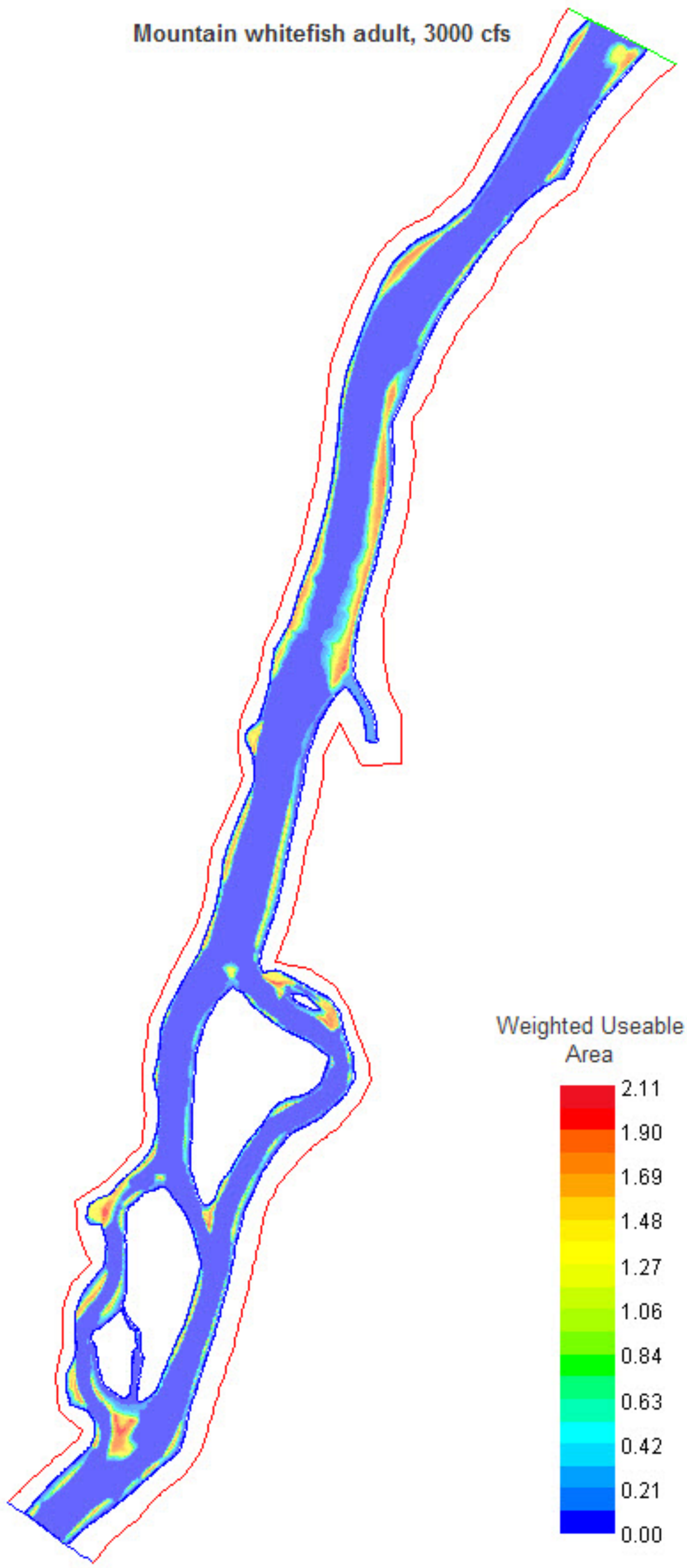

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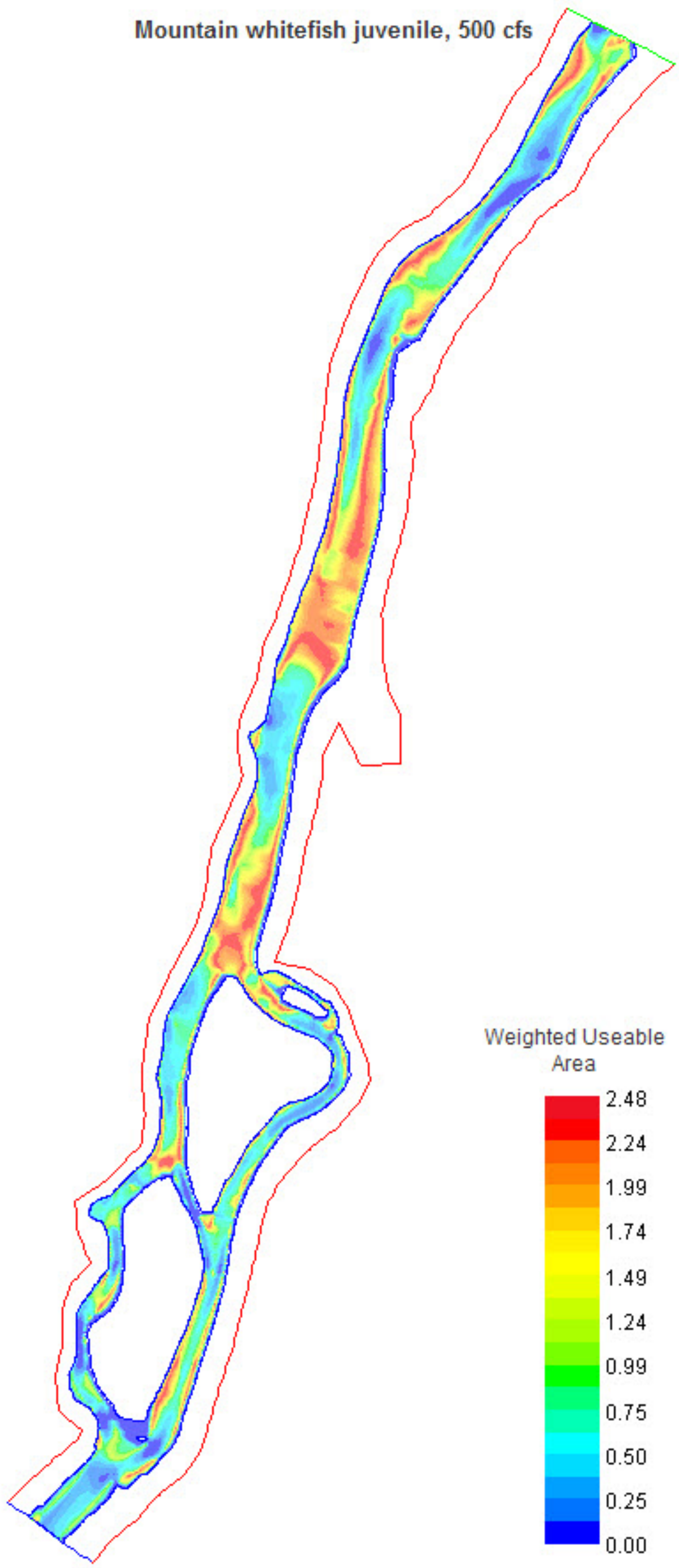

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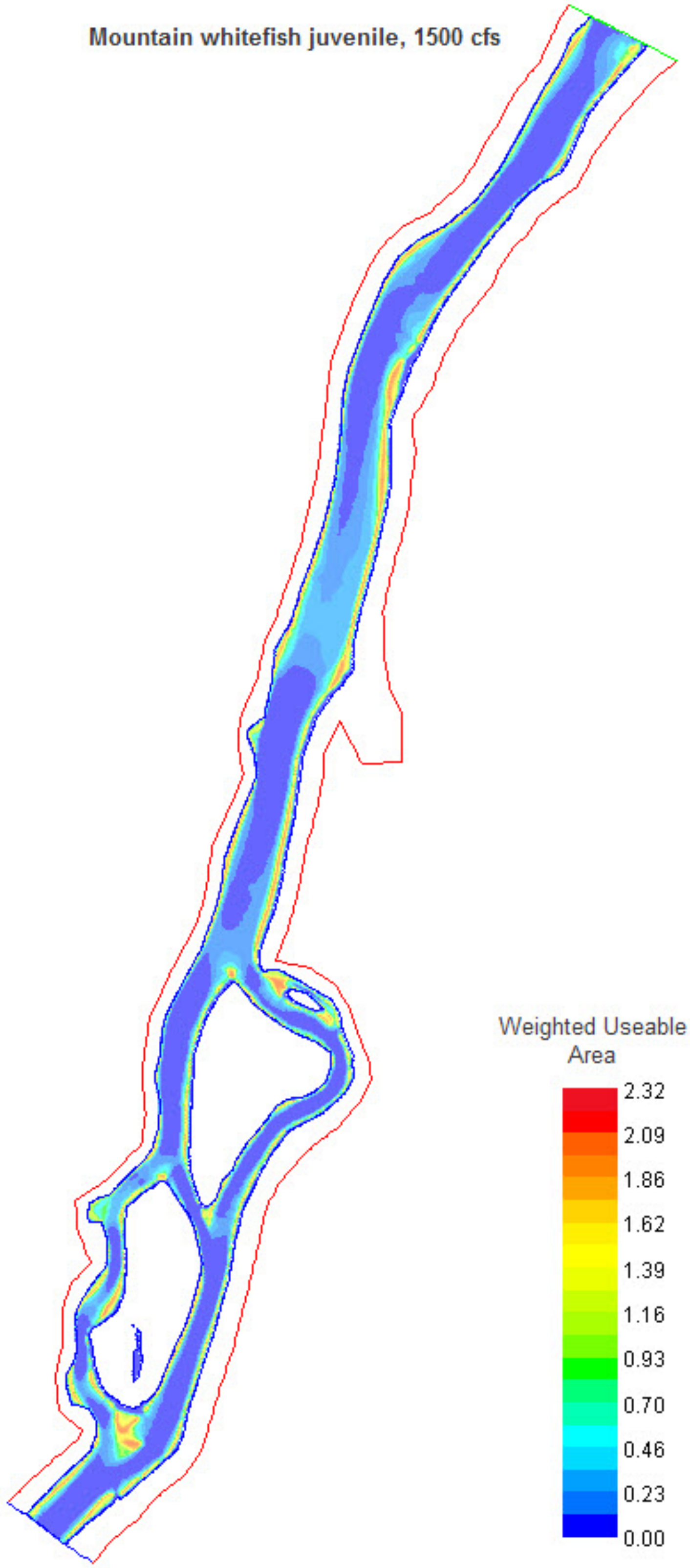


Figure A-23. Juvenile mountain whitefish habitat map, Pumphouse site, 1500 cfs.

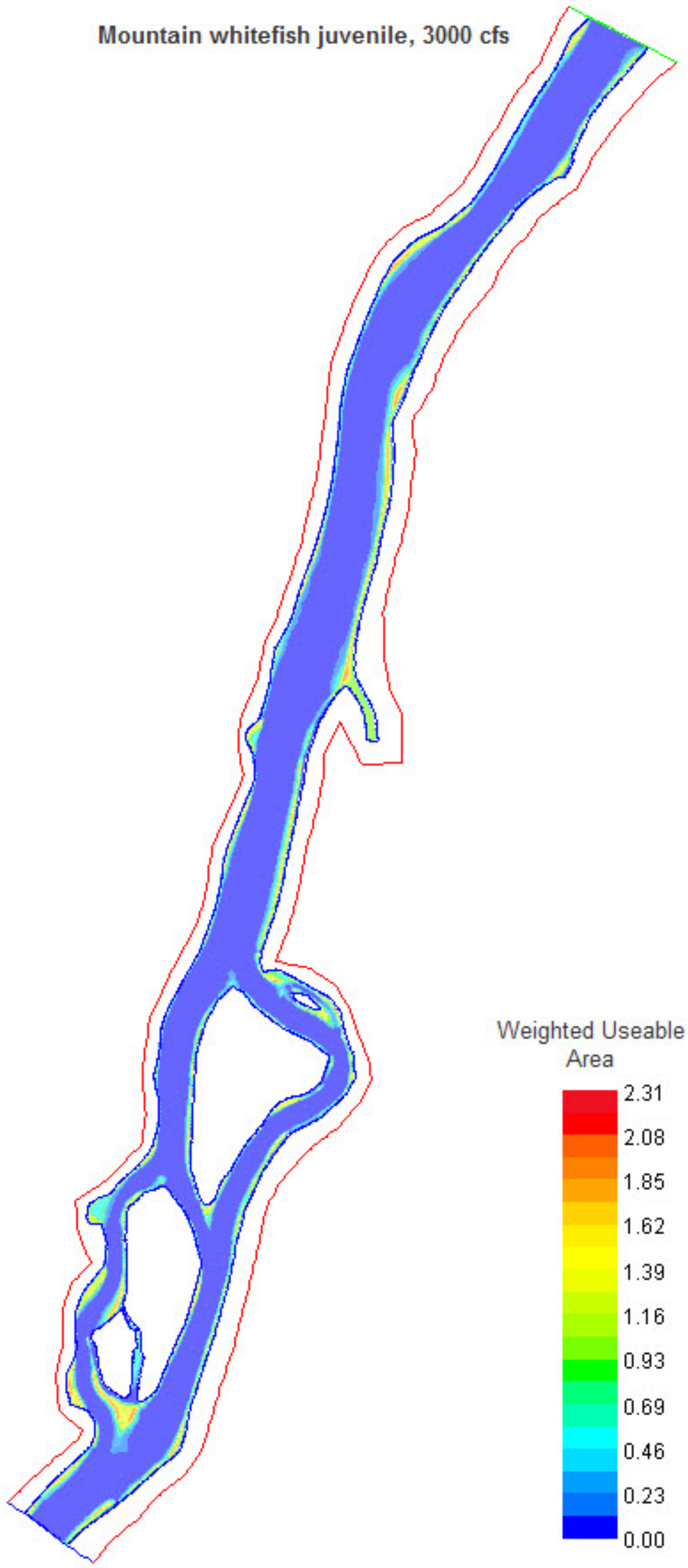


Figure A-24. Juvenile mountain whitefish habitat map, Pumphouse site, 3000 cfs.

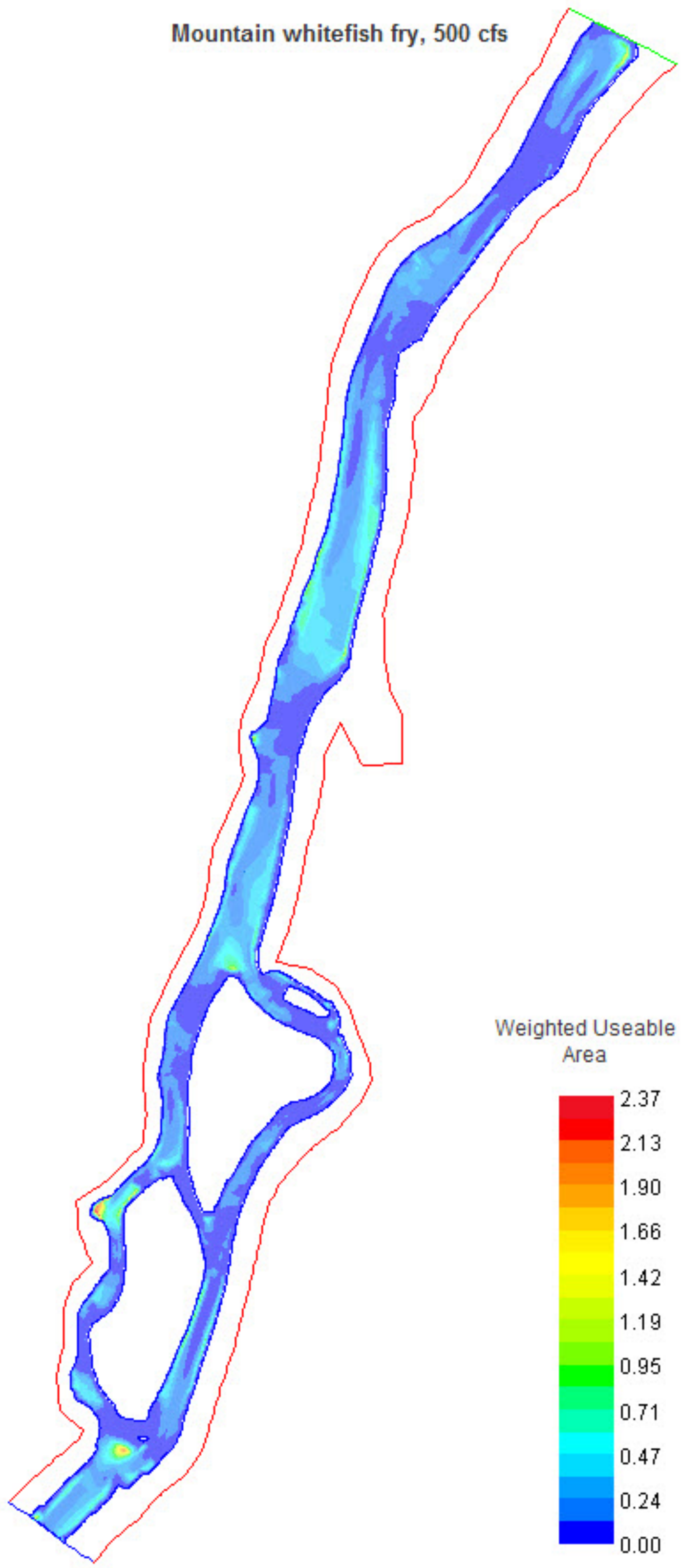


Figure A-25. Mountain whitefish fry habitat map, Pumphouse site, 500 cfs.

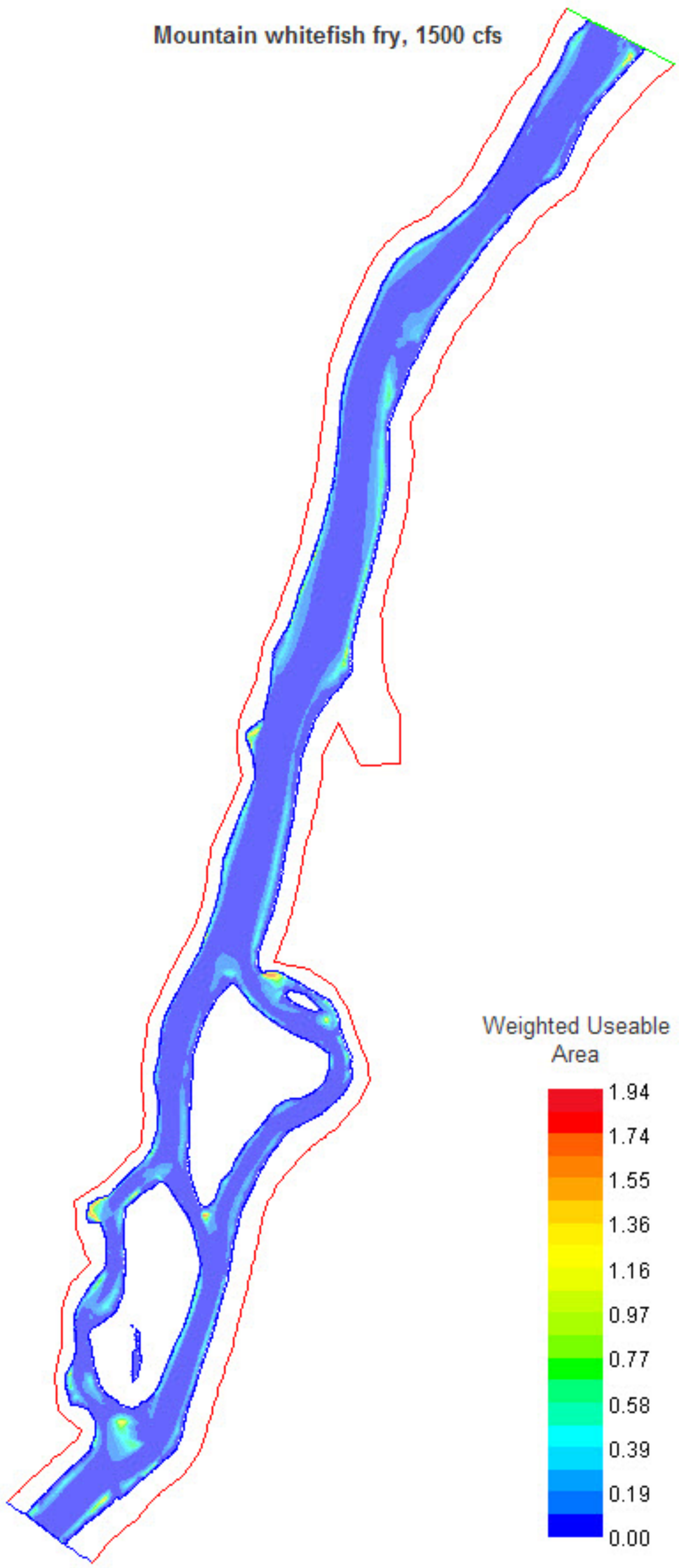


Figure A-26. Mountain whitefish fry habitat map, Pumphouse site, 1500 cfs.

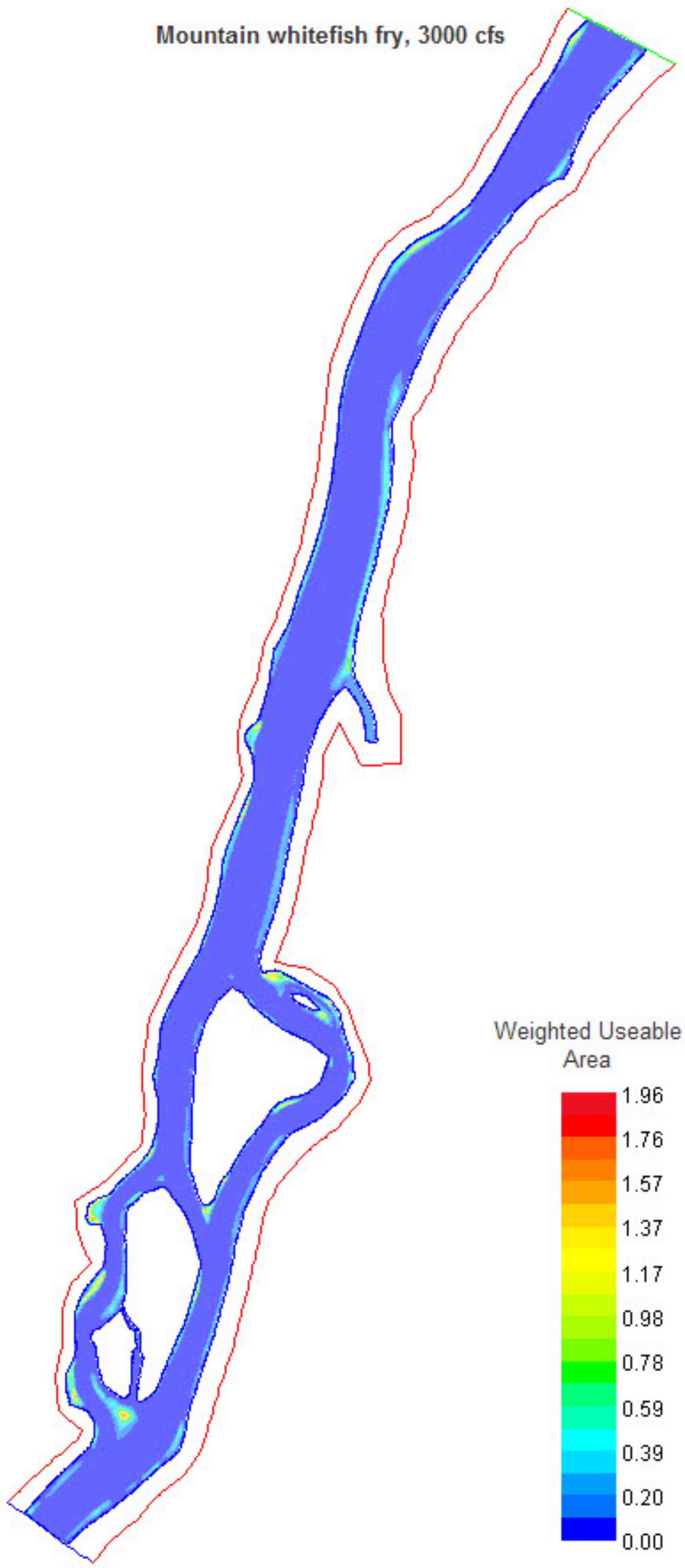


Figure A-26. Mountain whitefish fry habitat map, Pumphouse site, 3000 cfs.

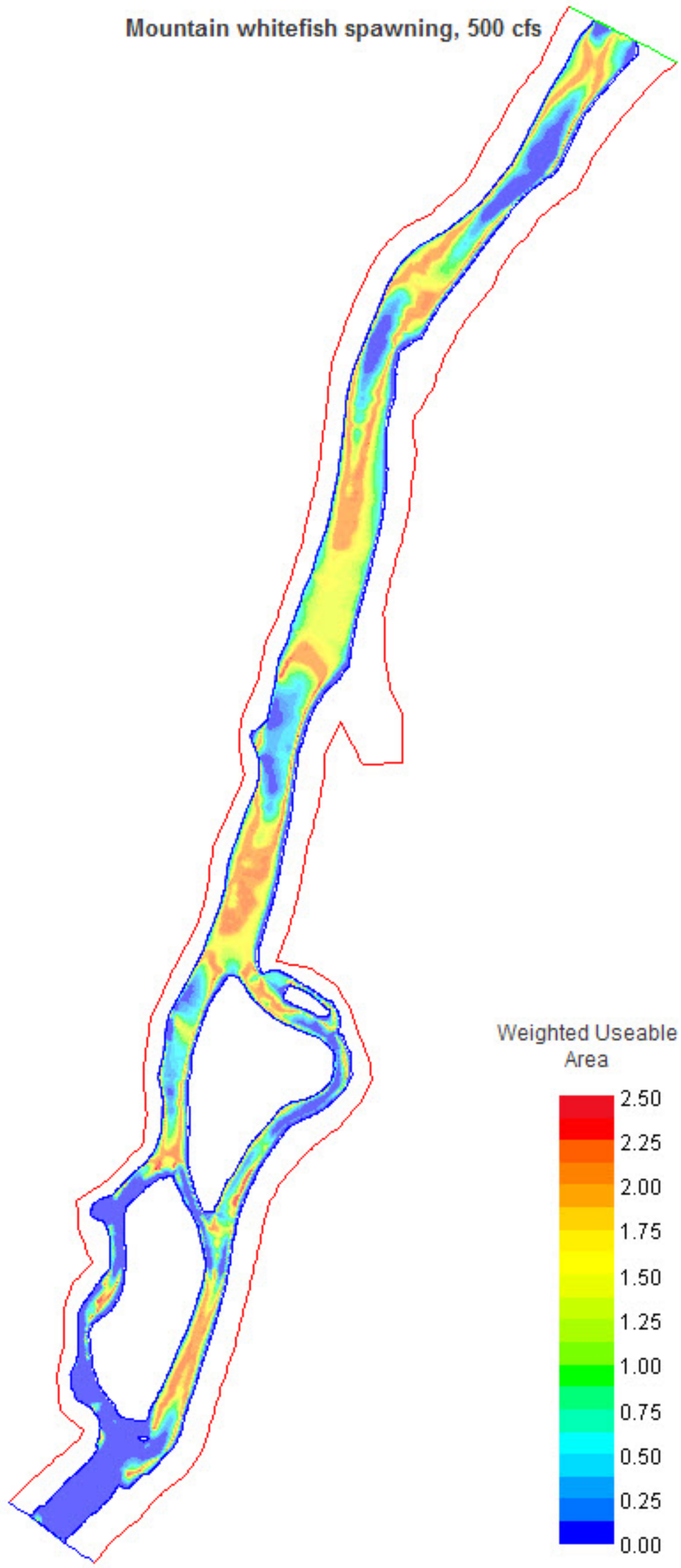


Figure A-27. Mountain whitefish spawning habitat map, Pumphouse site, 500 cfs.

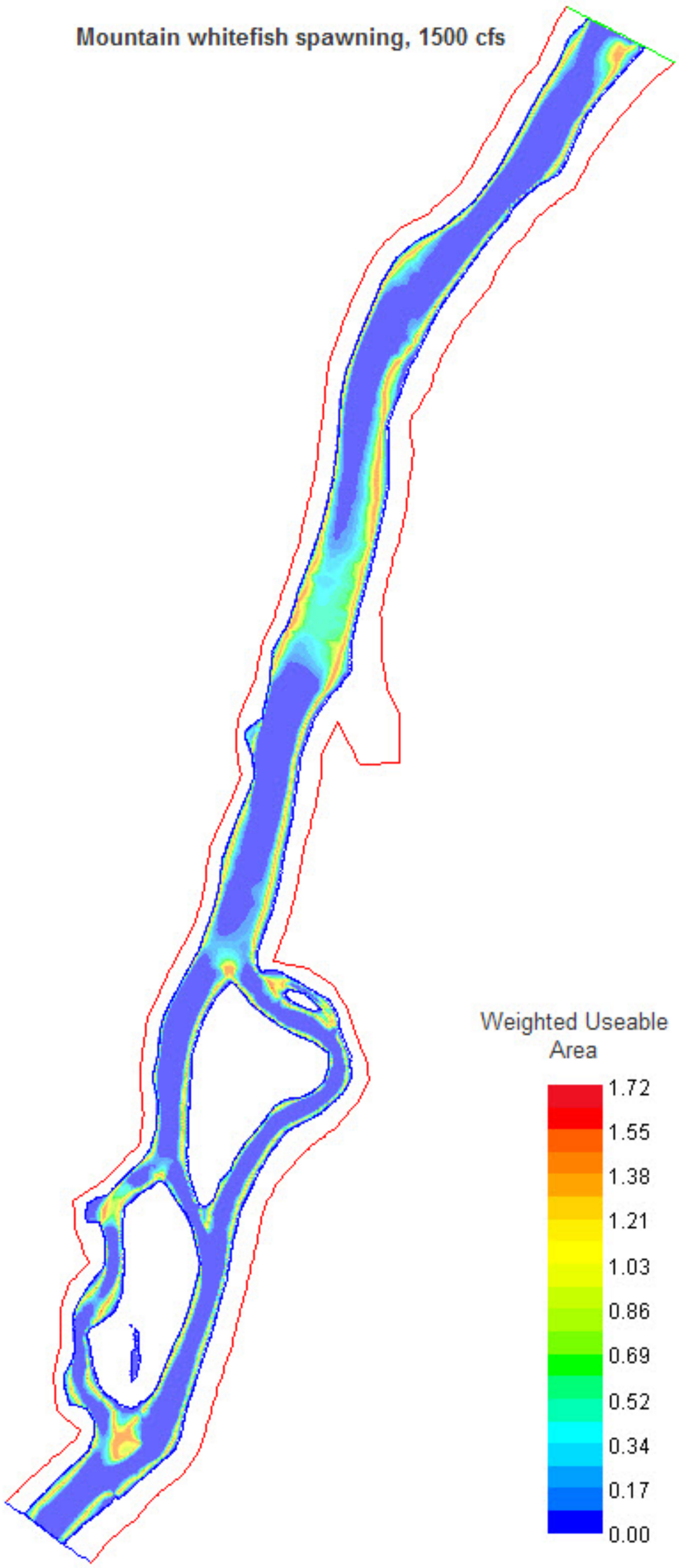


Figure A-28. Mountain whitefish spawning habitat map, Pumphouse site, 1500 cfs.

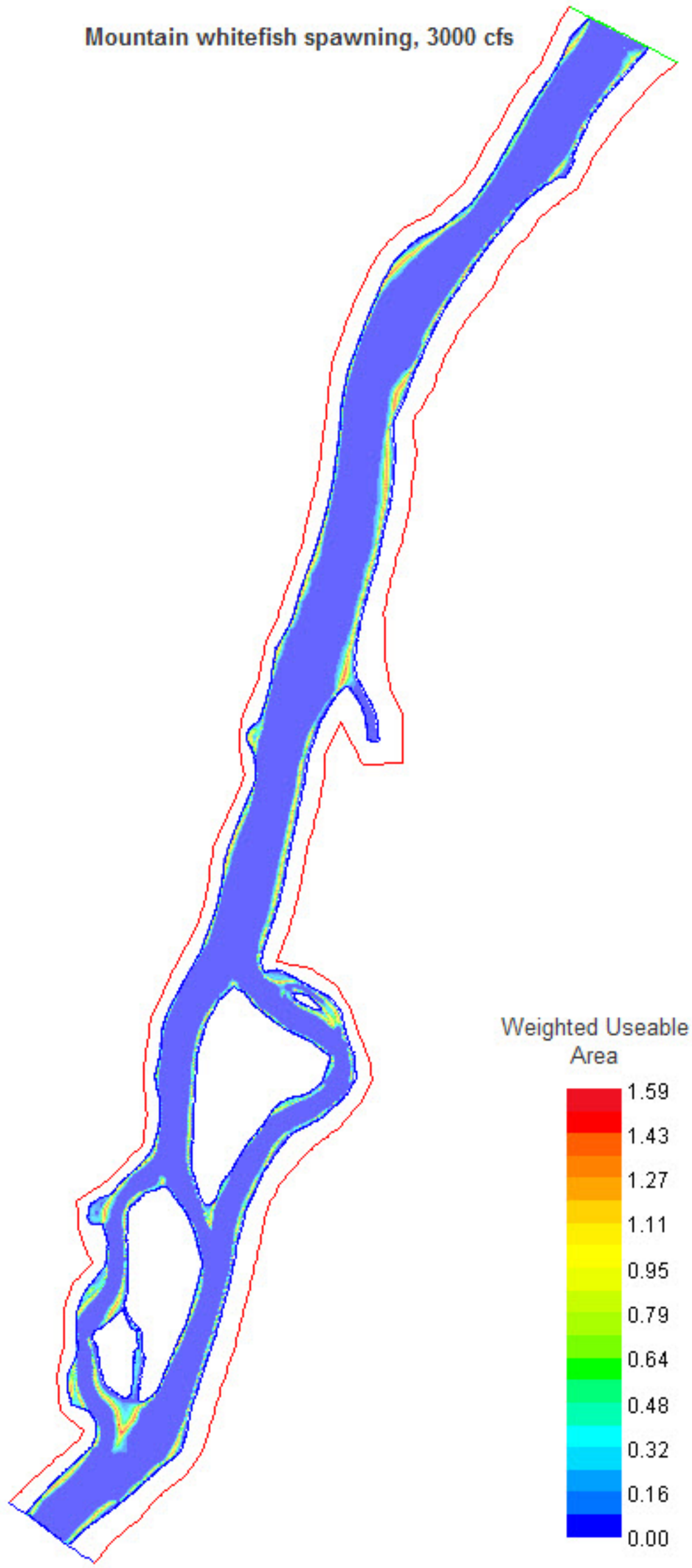
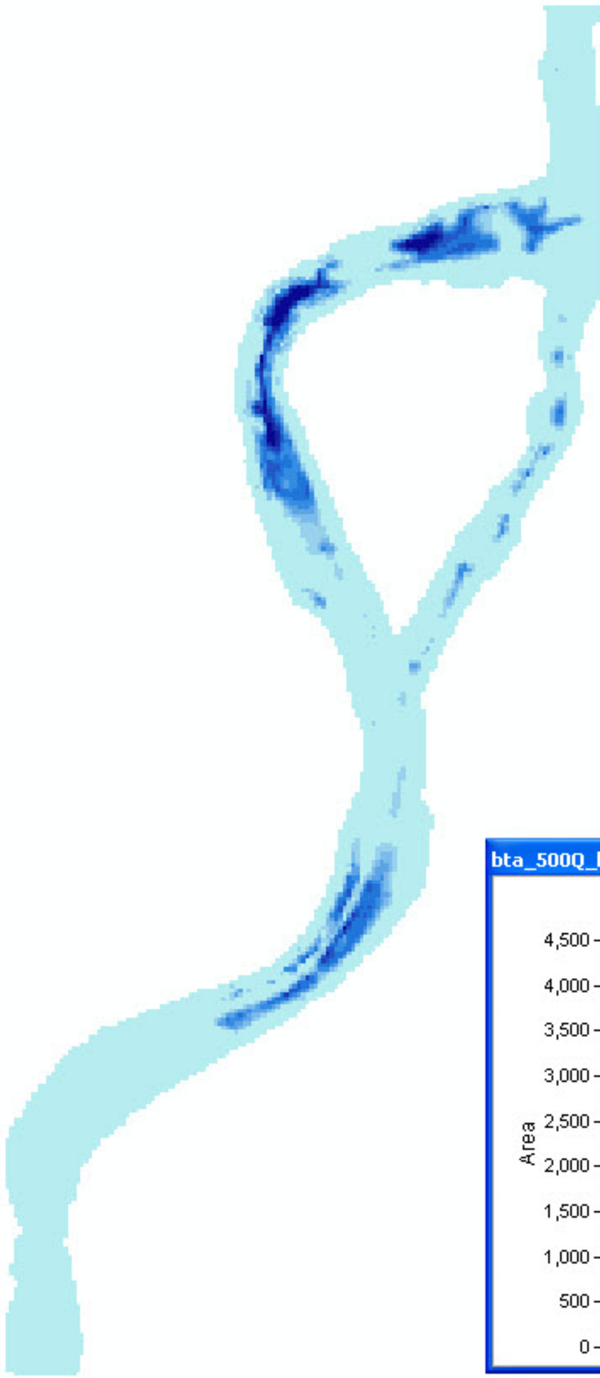


Figure A-29. Mountain whitefish spawning habitat map, Pumphouse site, 3000 cfs



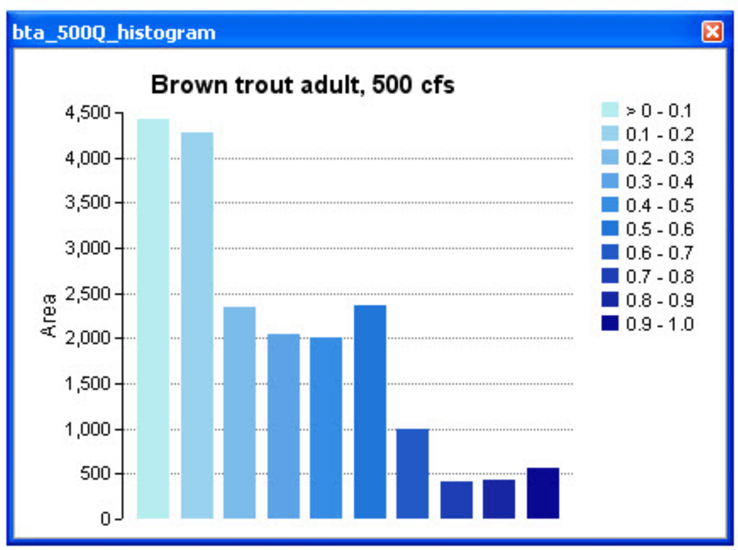


Figure A-30. Adult brown trout habitat map, Rancho del Rio site, 500 cfs.

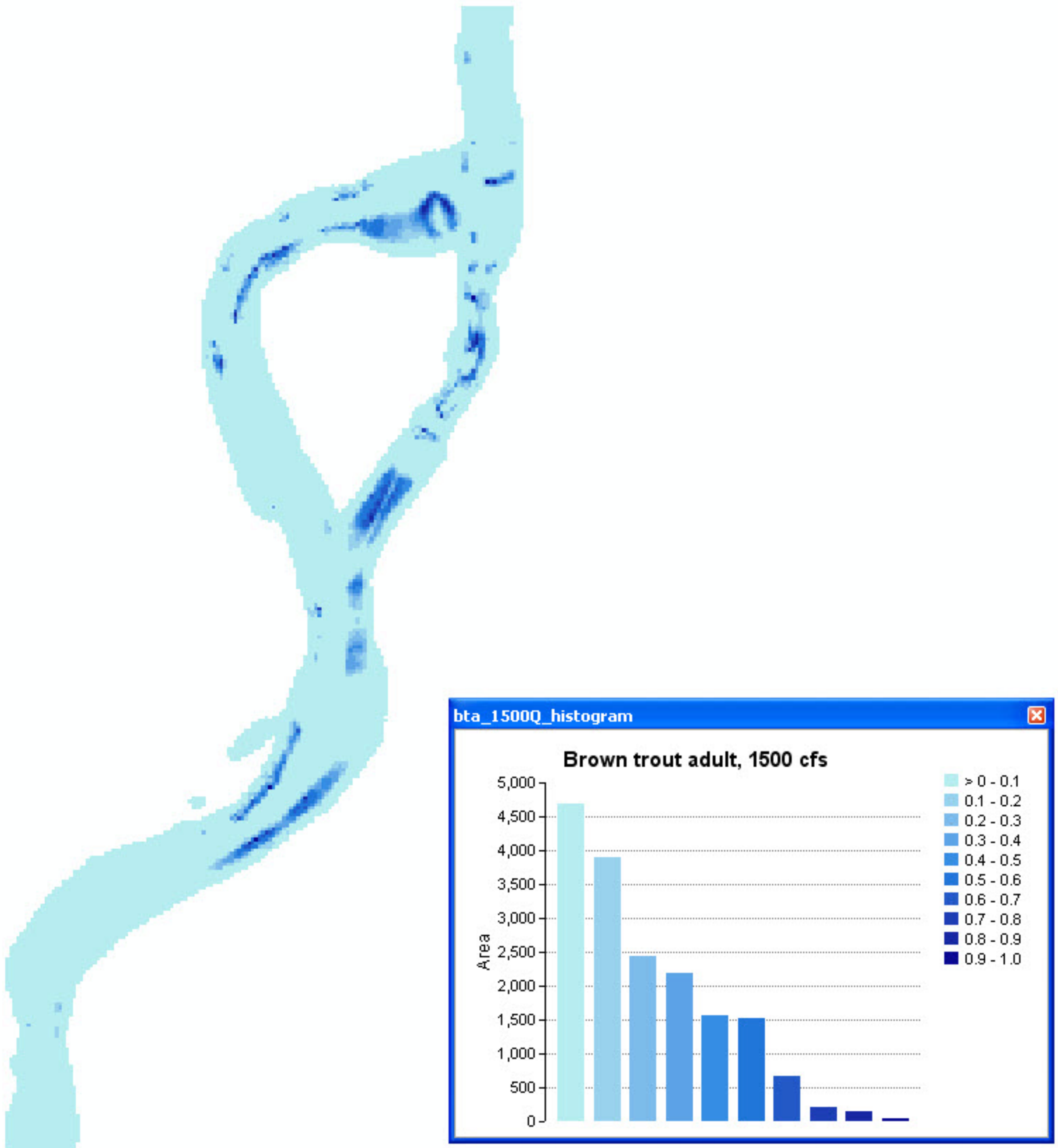


Figure A-31. Adult brown trout habitat map, Rancho del Rio site, 1500 cfs.

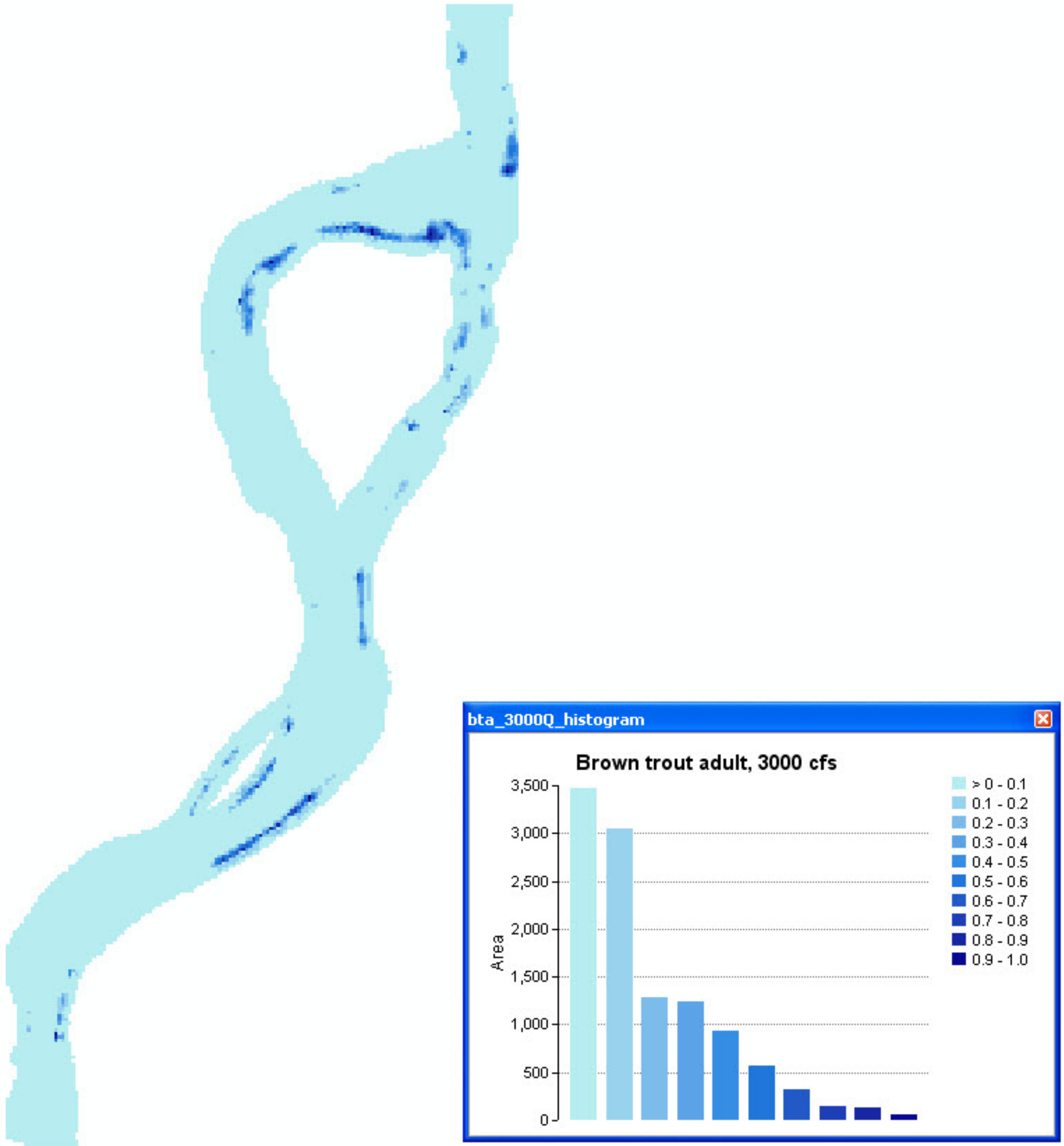


Figure A-32. Adult brown trout habitat map, Rancho del Rio site, 3000 cfs.

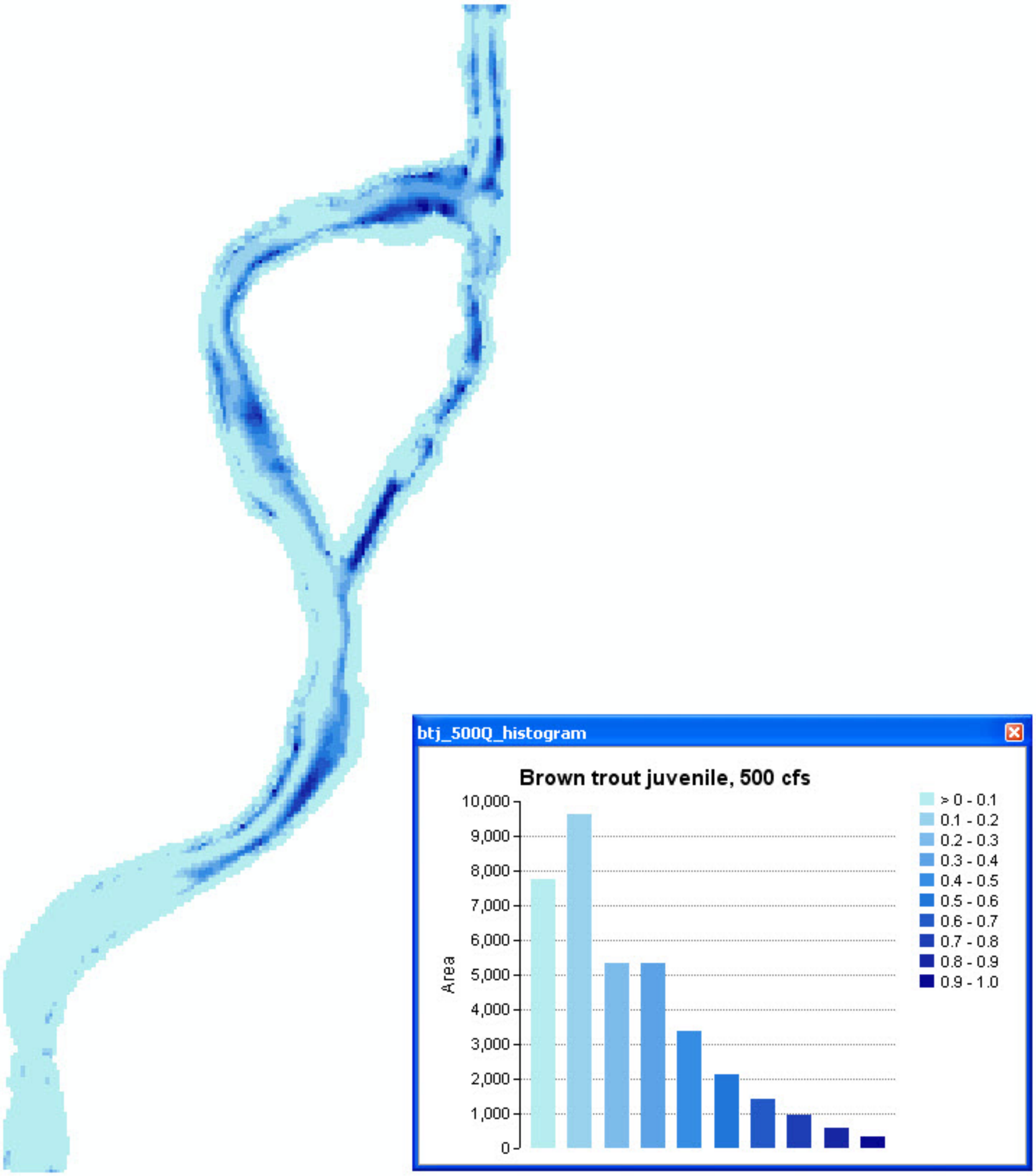


Figure A-33. Juvenile brown trout habitat map, Rancho del Rio site, 500 cfs.

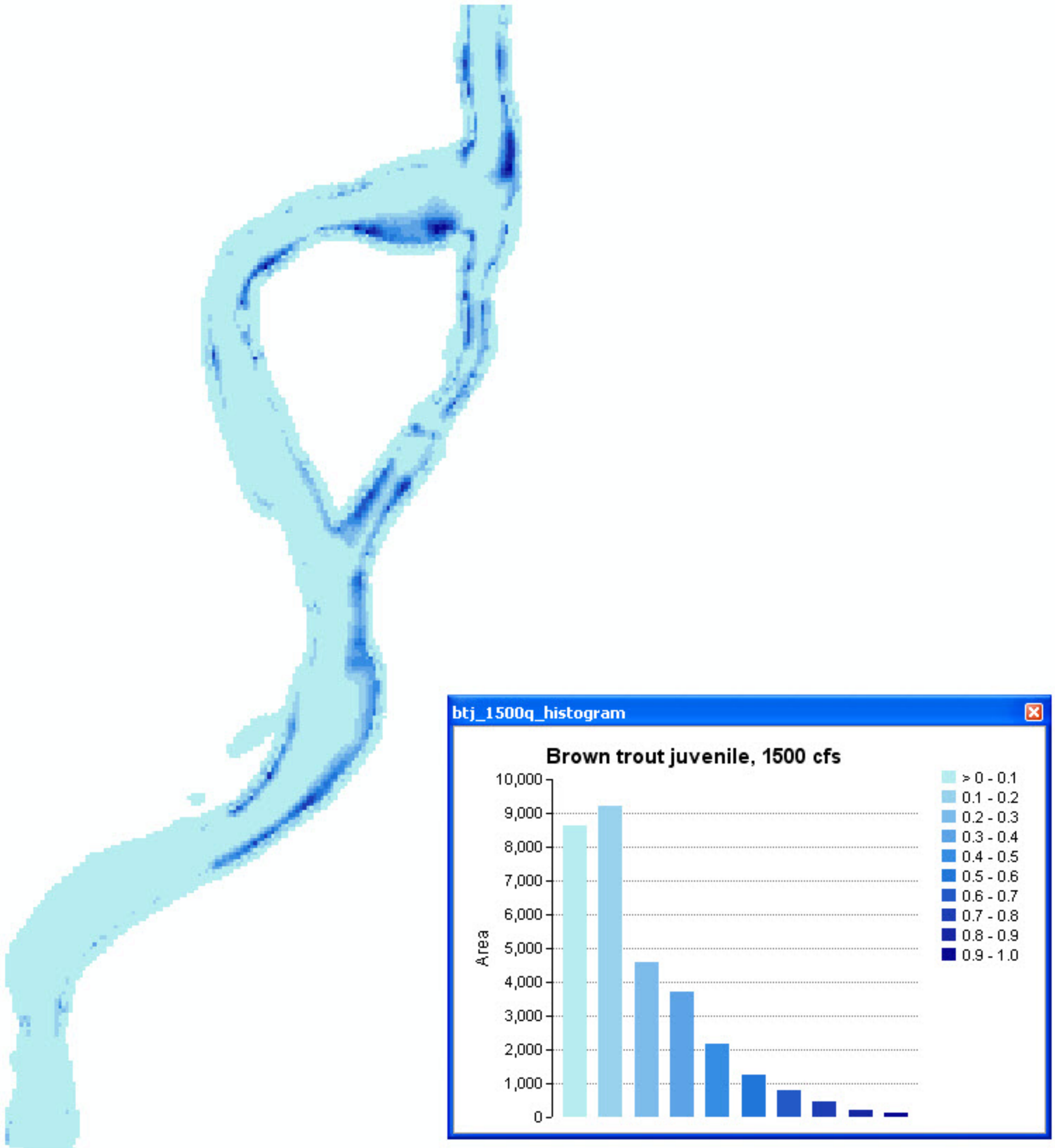


Figure A-34. Juvenile brown trout habitat map, Rancho del Rio site, 1500 cfs.

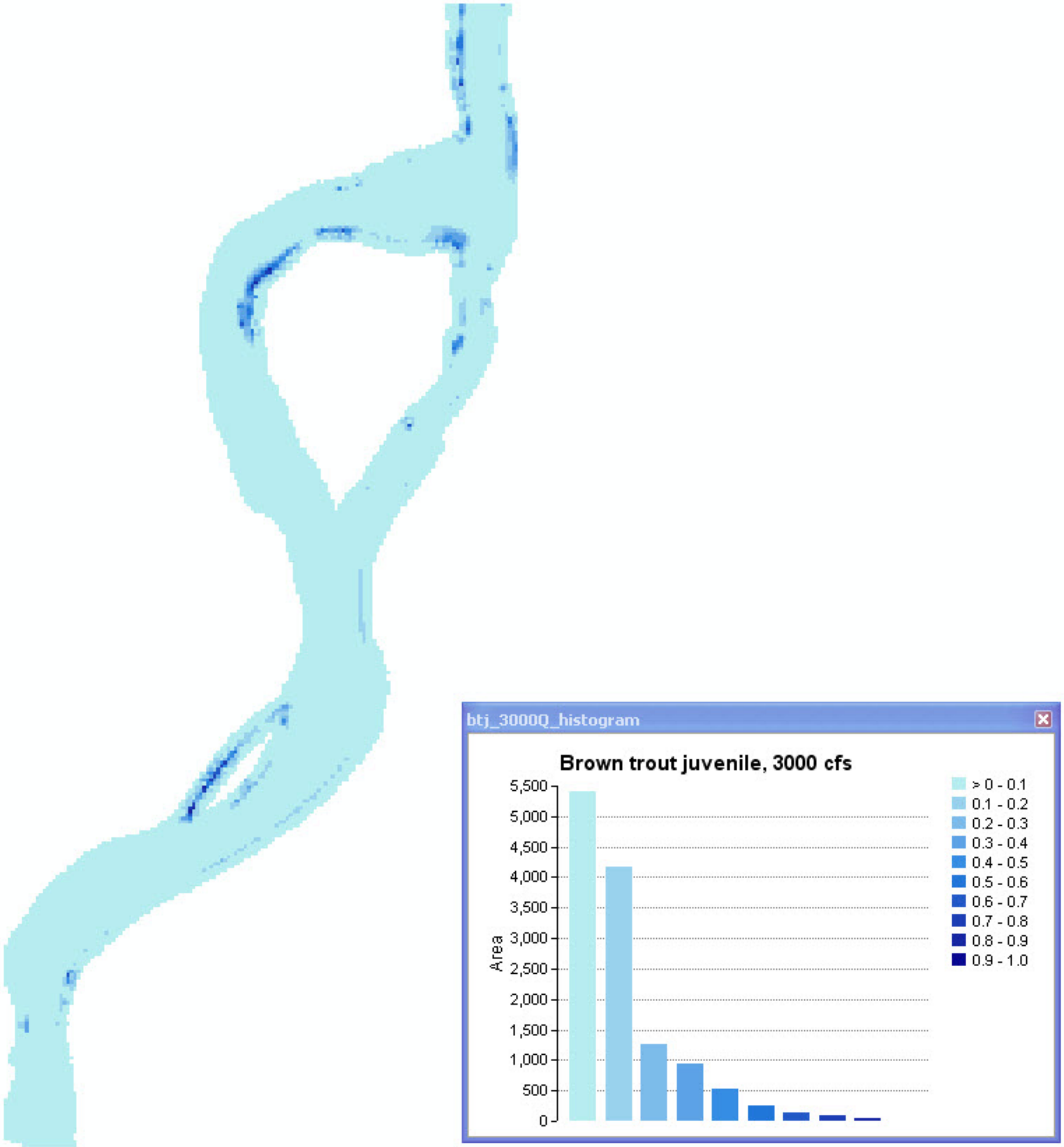


Figure A-35. Juvenile brown trout habitat map, Rancho del Rio site, 3000 cfs.

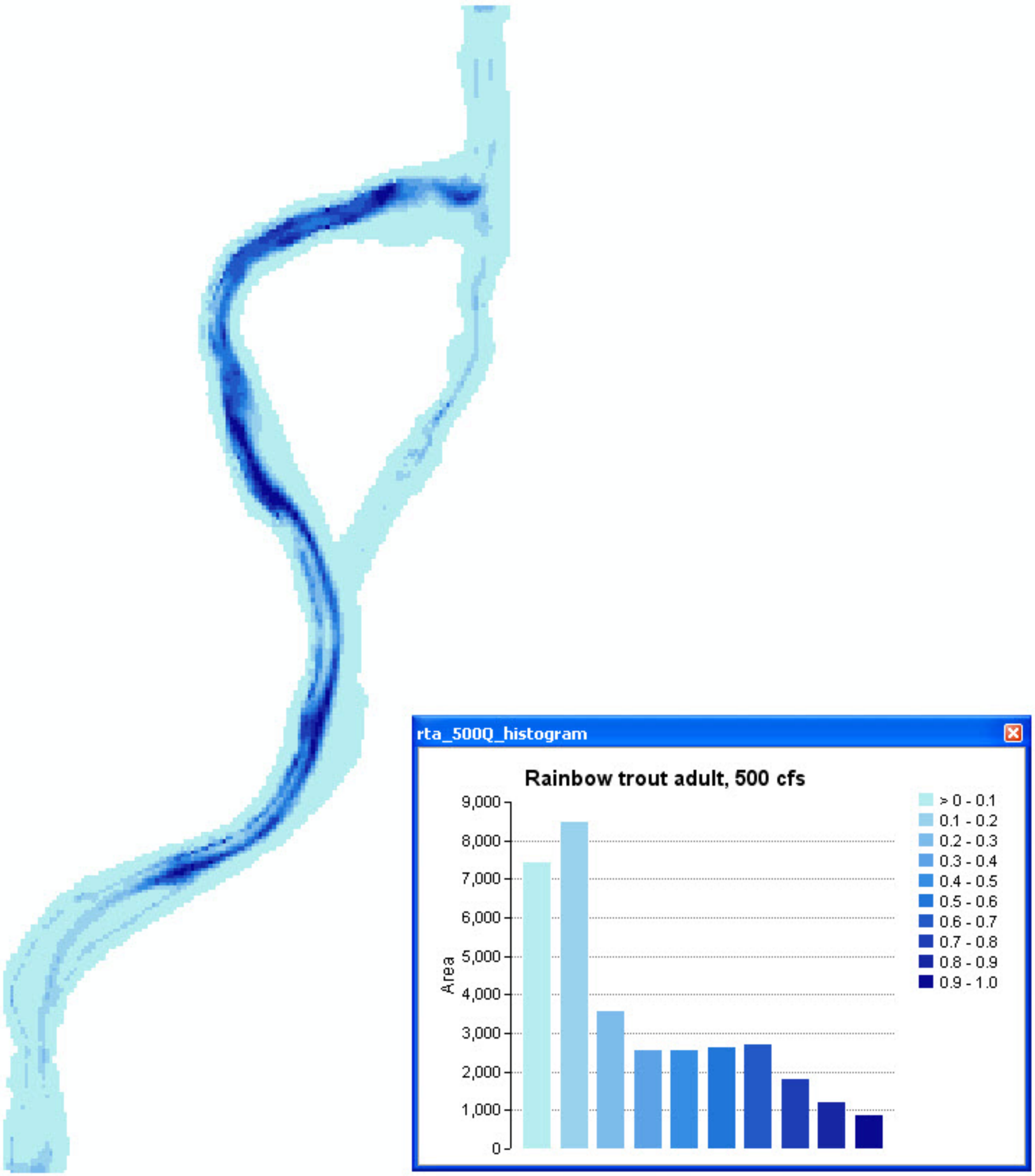


Figure A-36. Adult rainbow trout habitat map, Rancho del Rio site, 500 cfs.

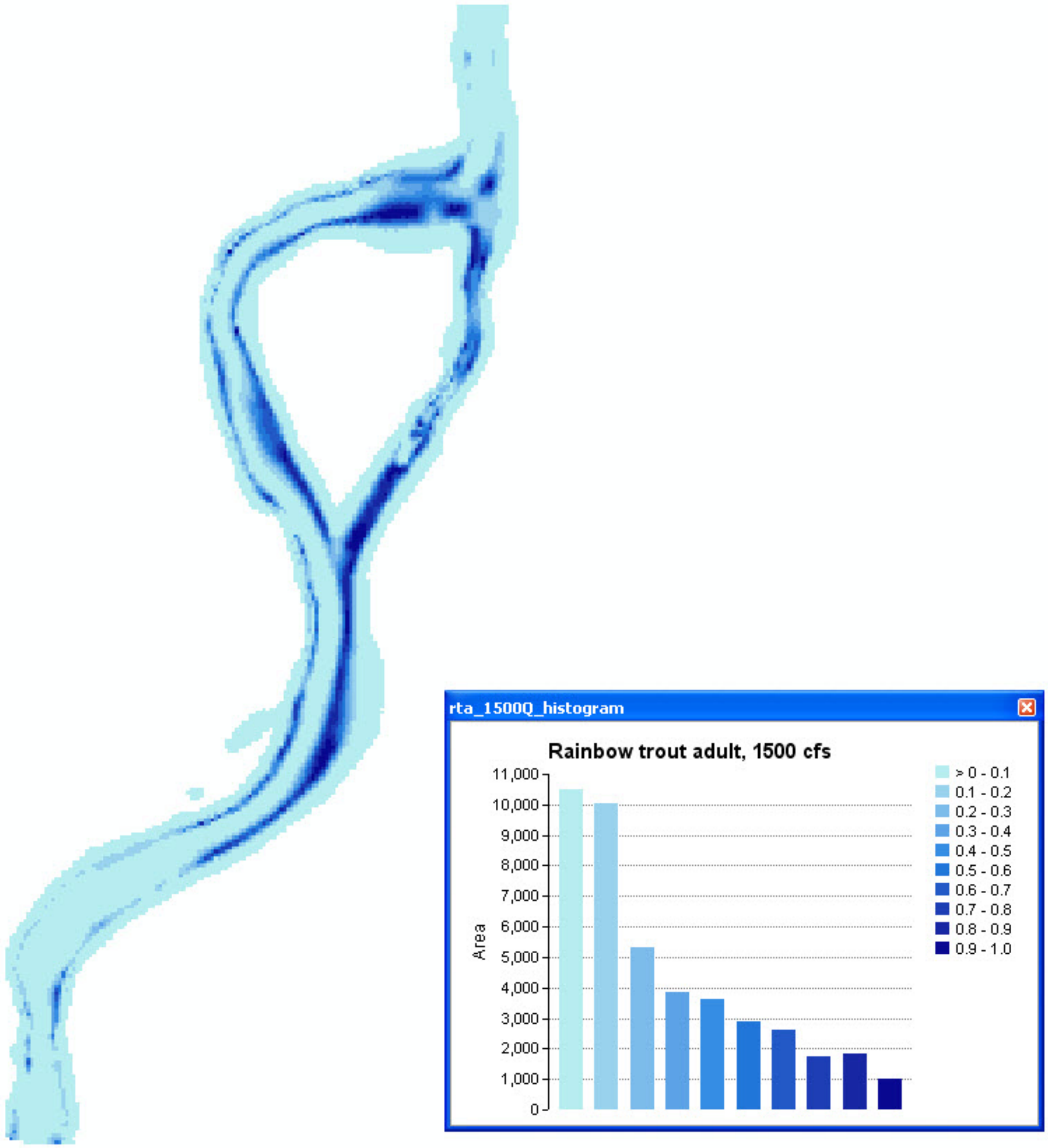
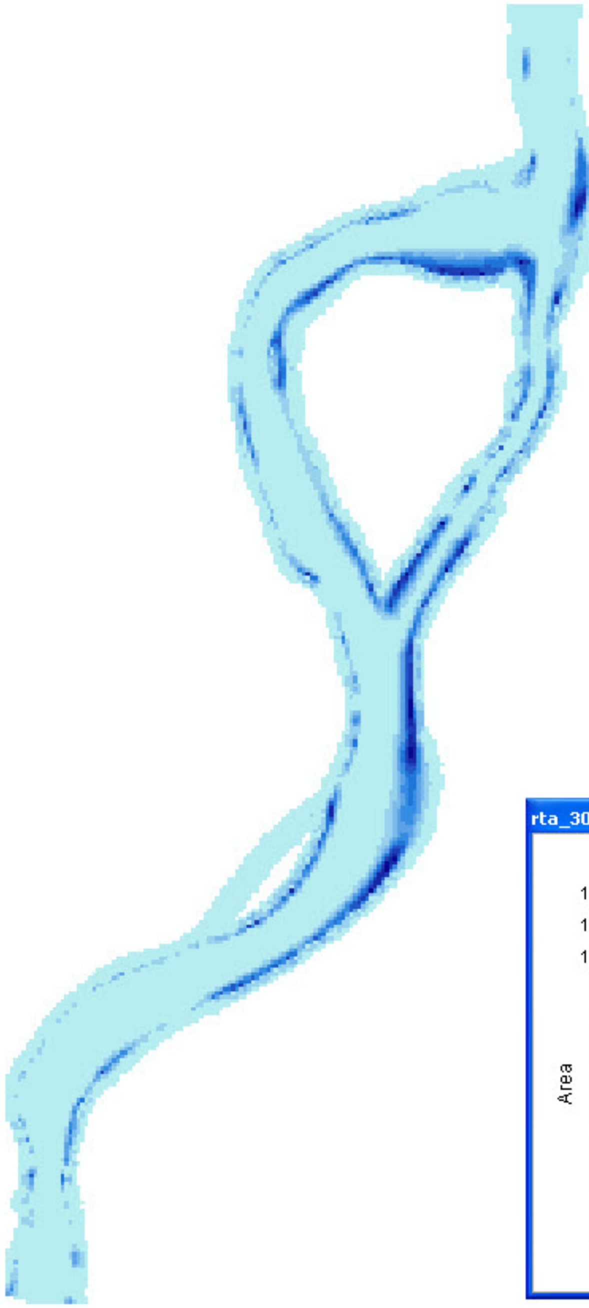


Figure A-37. Adult rainbow trout habitat map, Rancho del Rio site, 1500 cfs.



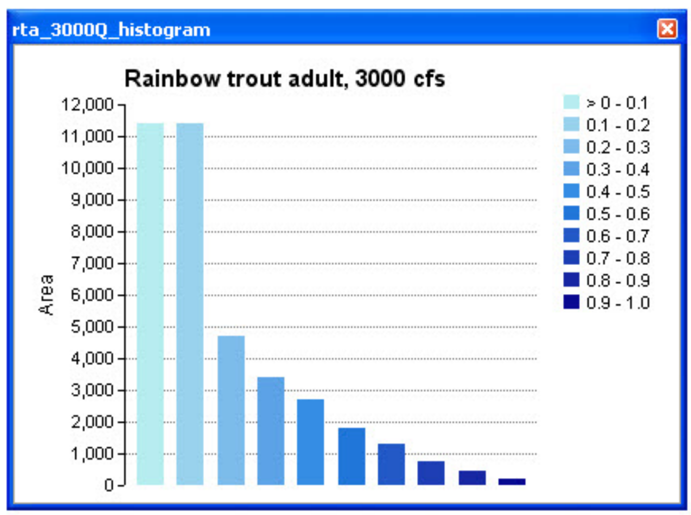


Figure A-38. Adult rainbow trout habitat map, Rancho del Rio site, 3000 cfs.

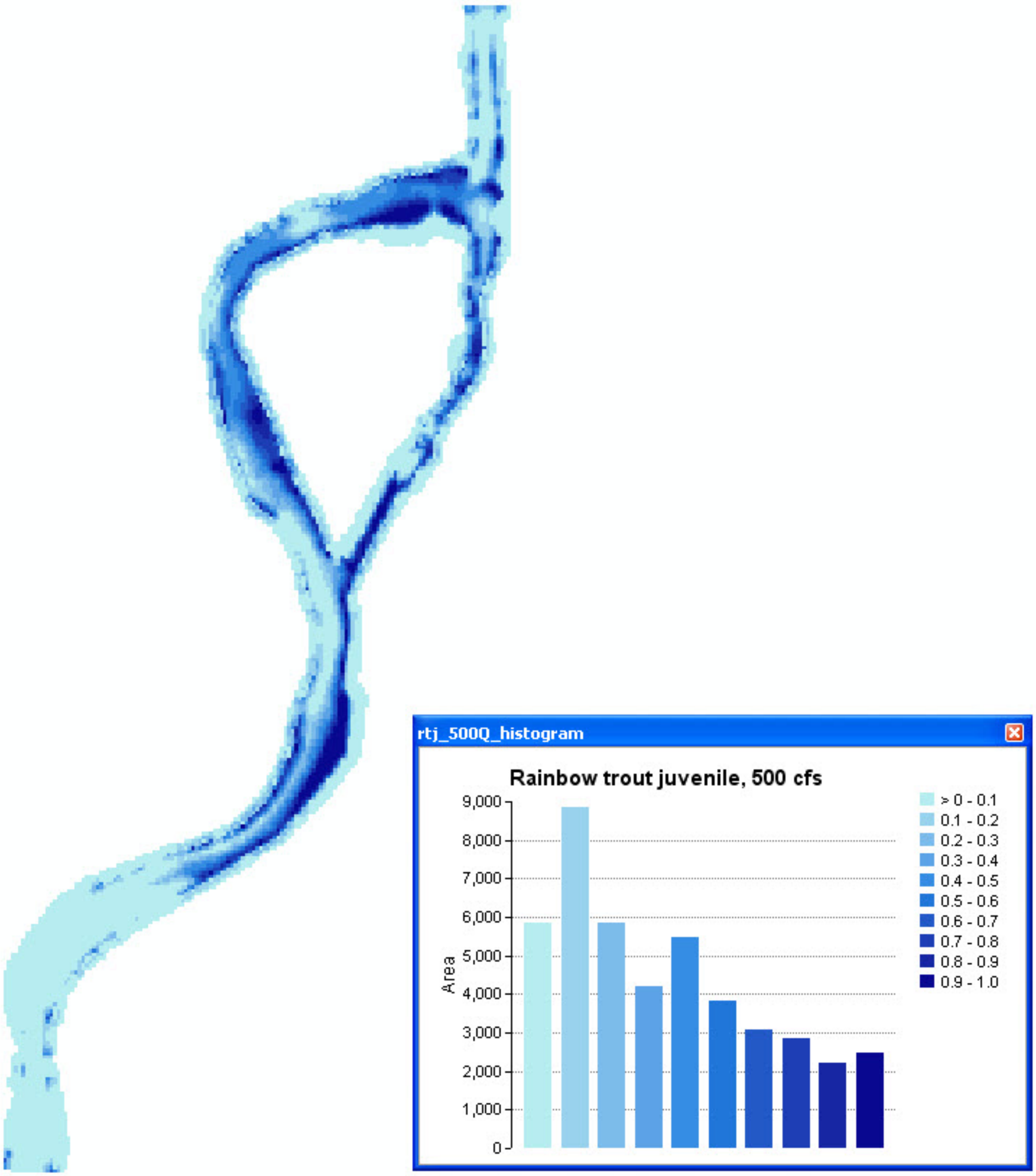


Figure A-39. Juvenile rainbow trout habitat map, Rancho del Rio site, 500 cfs.

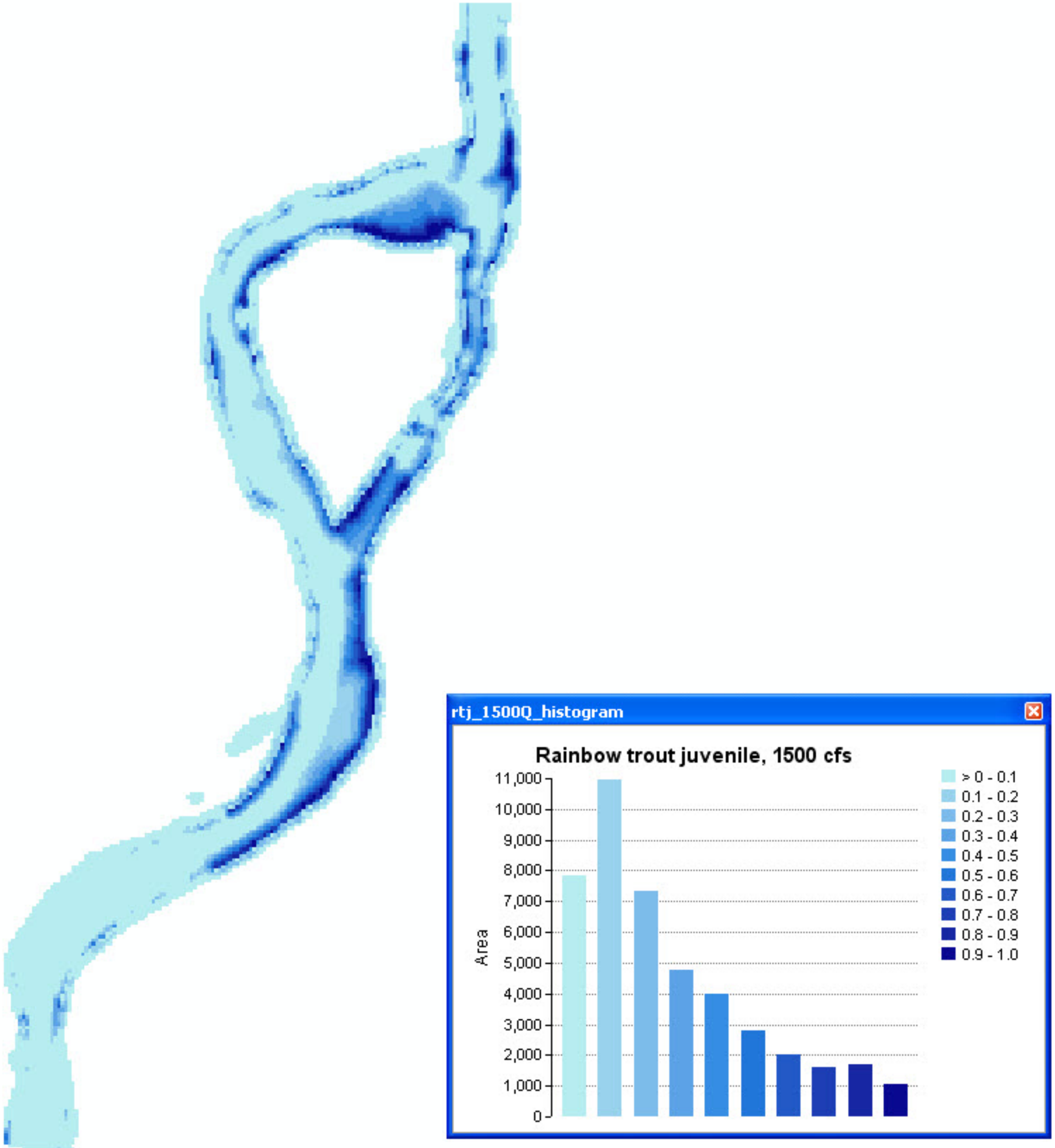


Figure A-40. Juvenile rainbow trout habitat map, Rancho del Rio site, 1500 cfs.

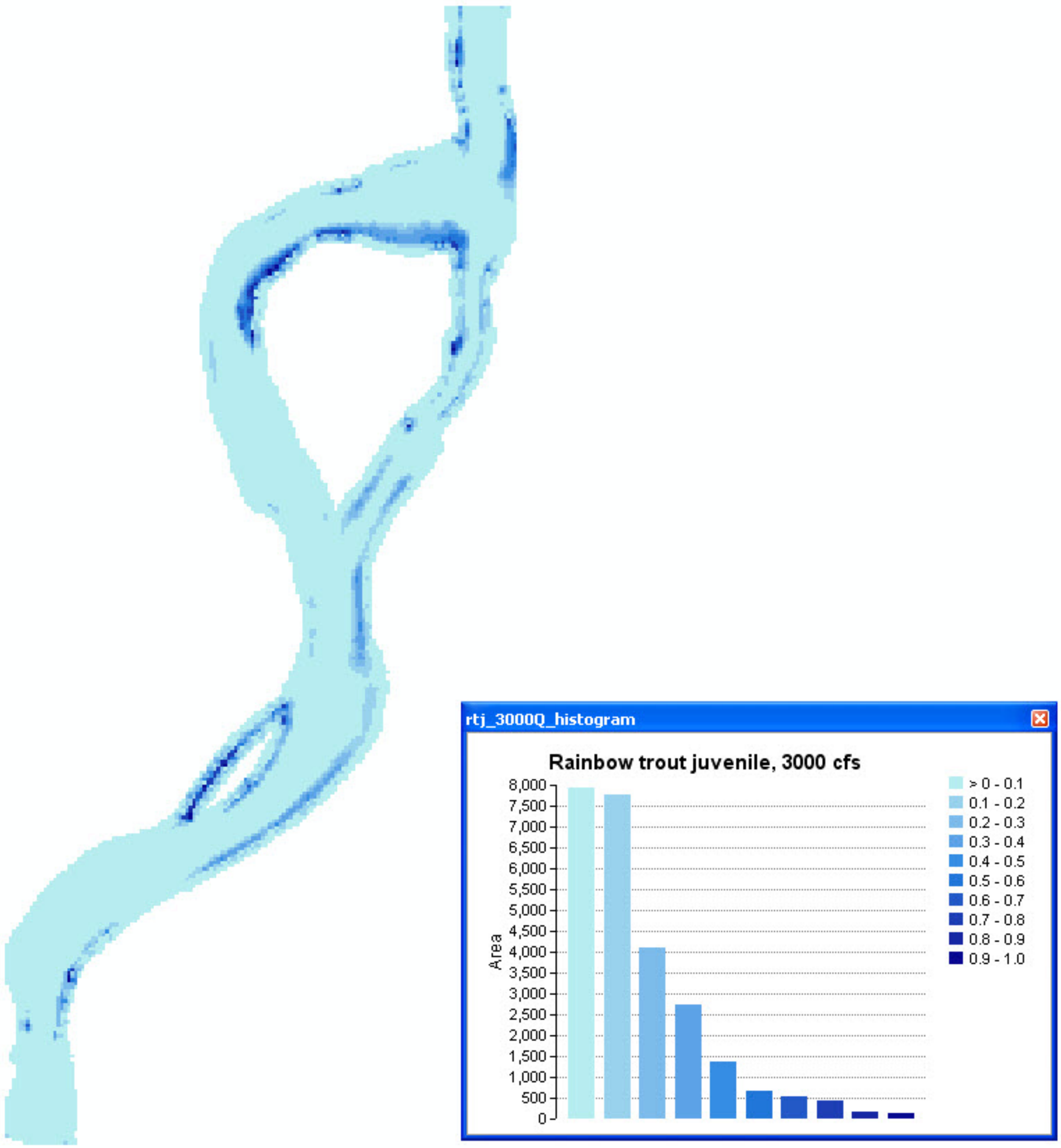


Figure A-41. Juvenile rainbow trout habitat map, Rancho del Rio site, 3000 cfs.

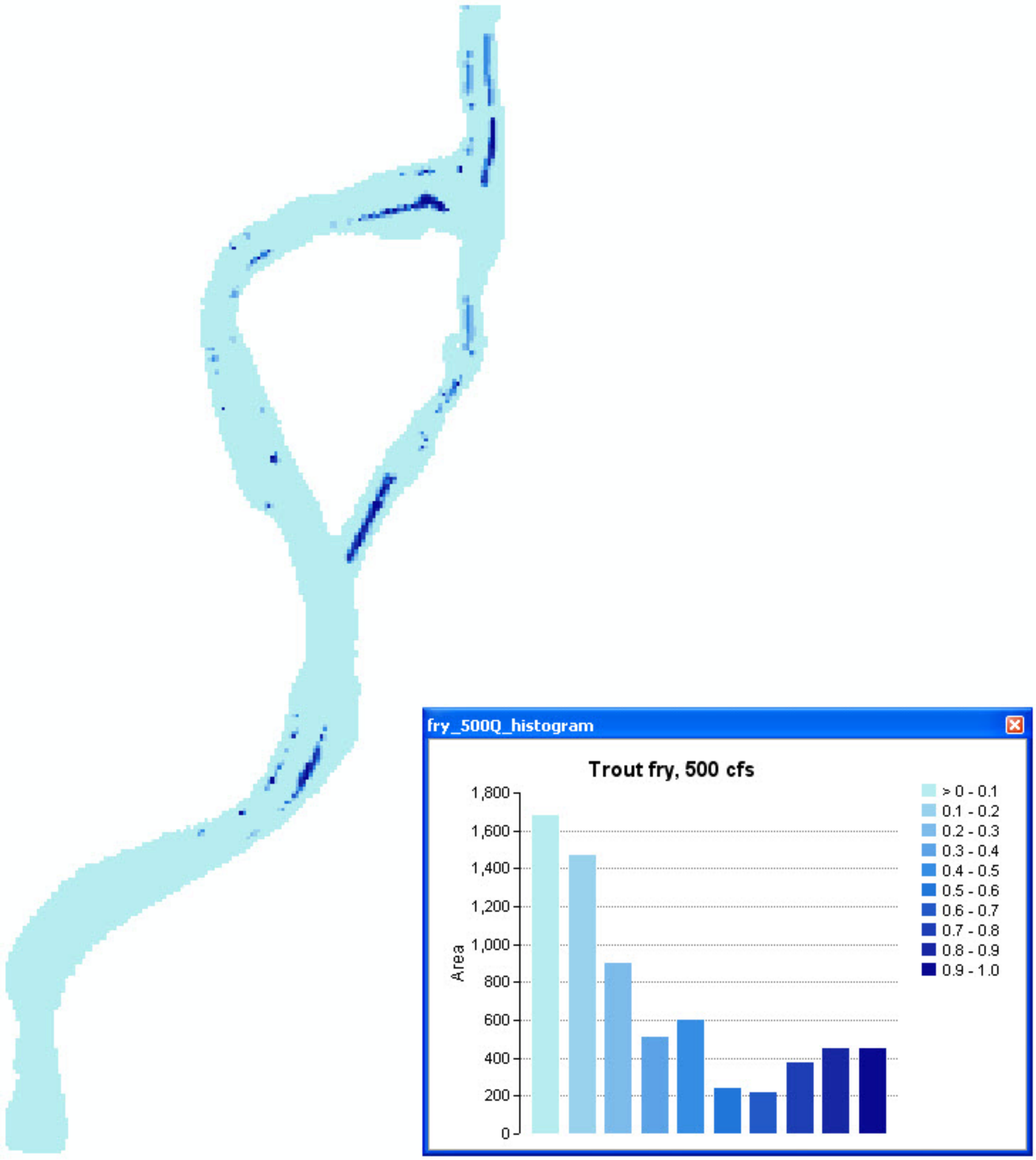


Figure A-42. Trout fry habitat map, Rancho del Rio site, 500 cfs.

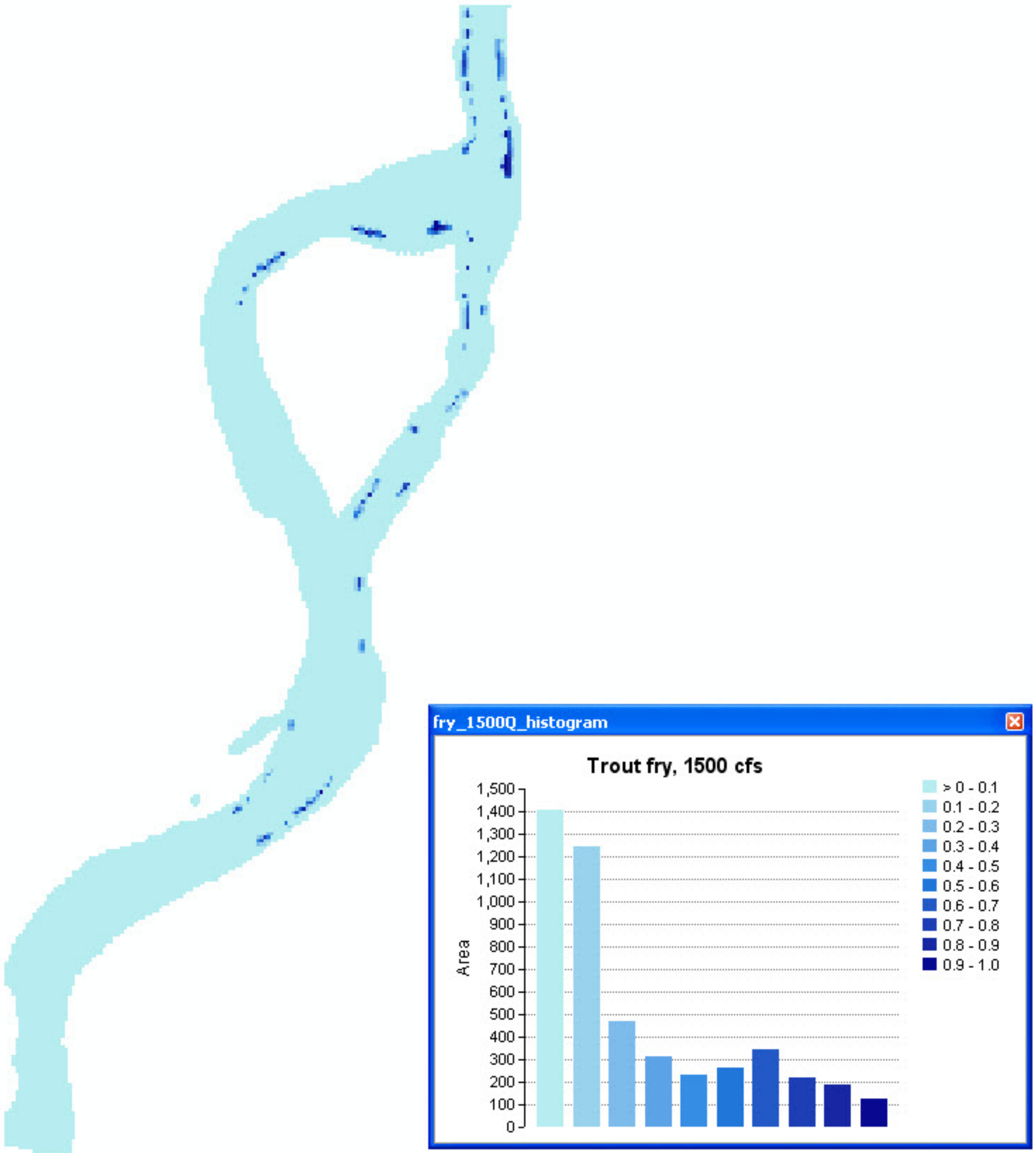


Figure A-43. Trout fry habitat map, Rancho del Rio site, 1500 cfs.

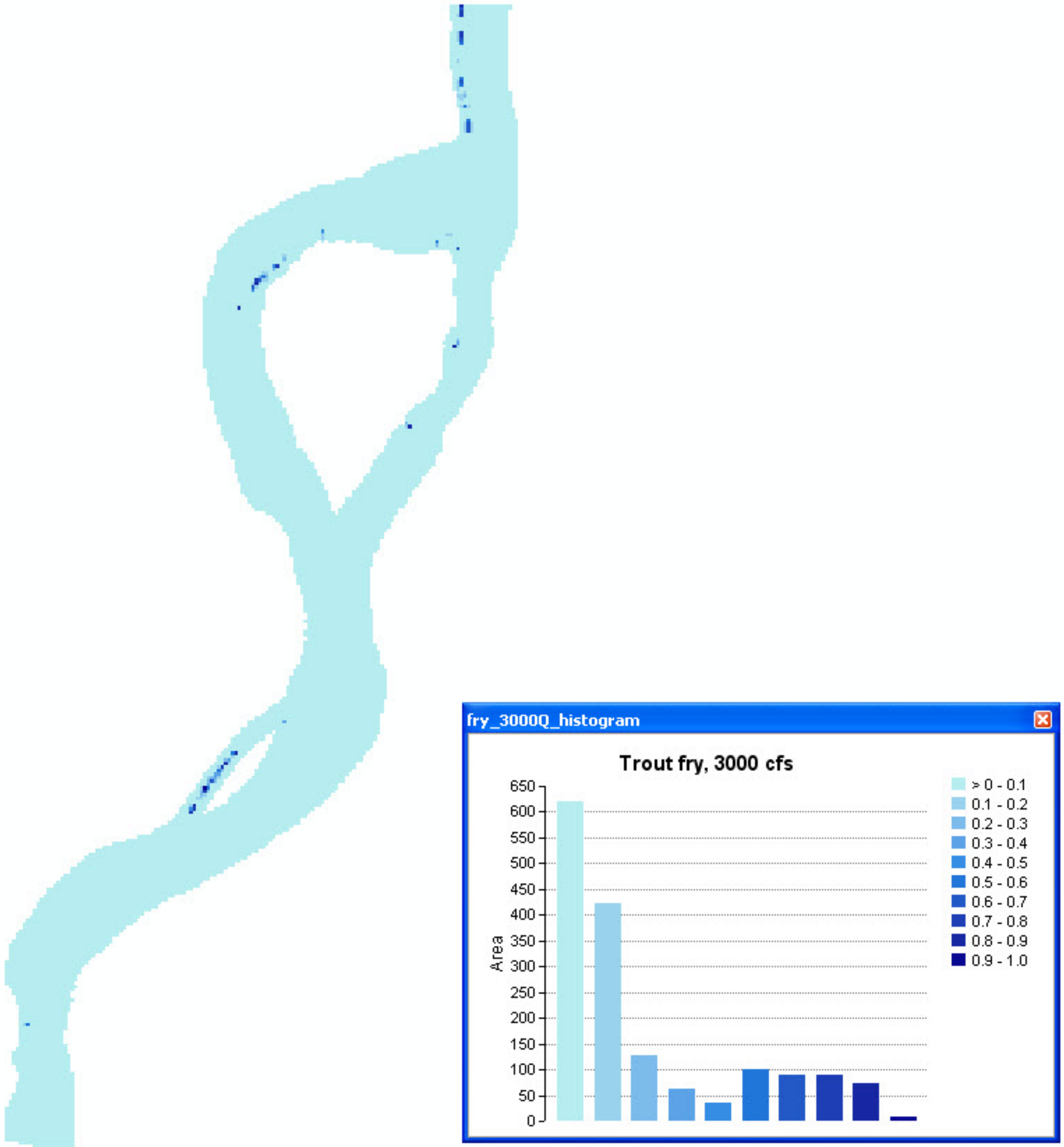
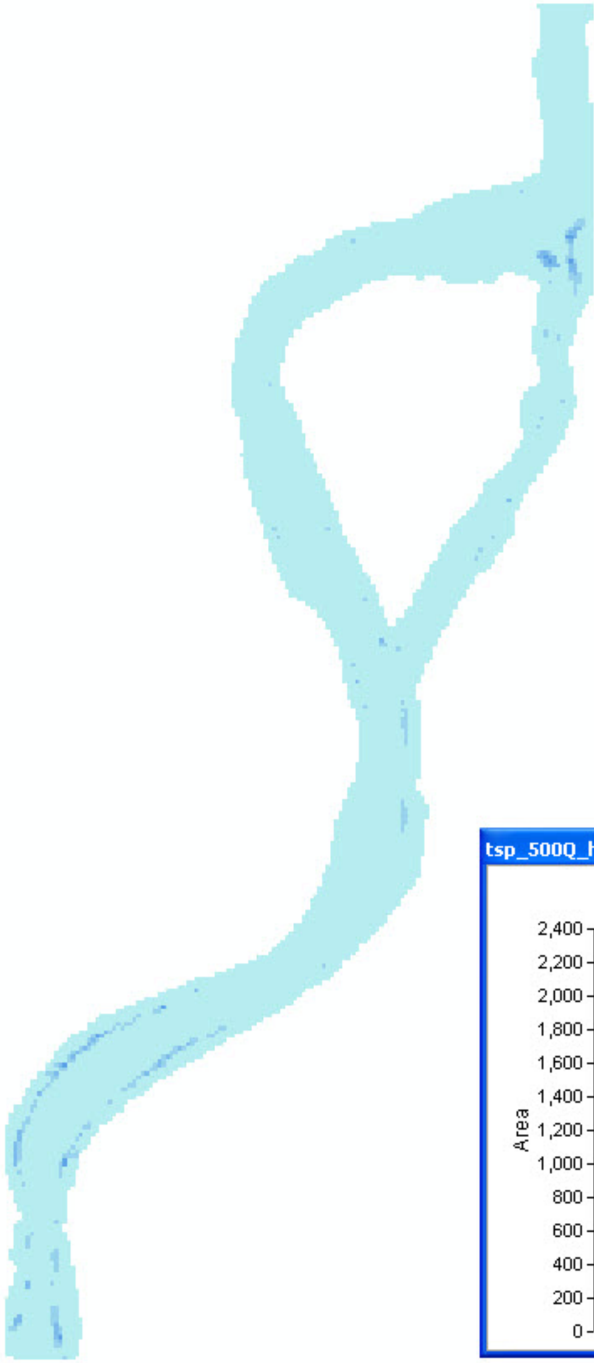


Figure A-44. Trout fry habitat map, Rancho del Rio site, 3000 cfs.



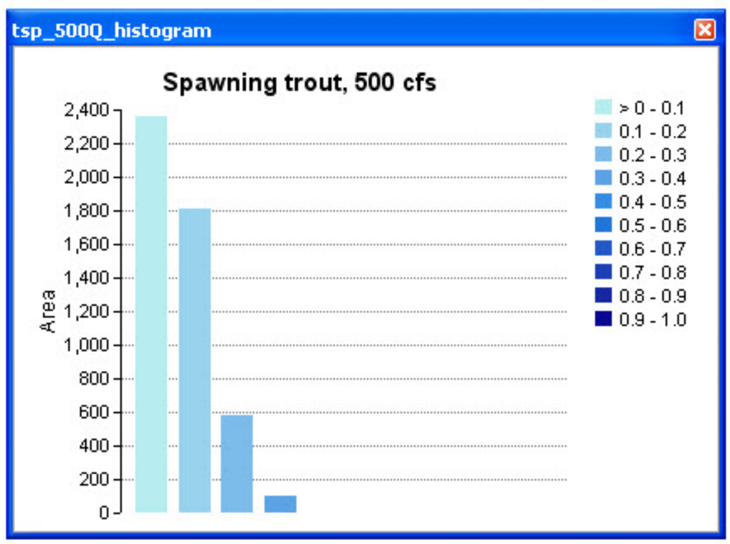


Figure A-45. Trout spawning habitat map, Rancho del Rio site, 500 cfs.

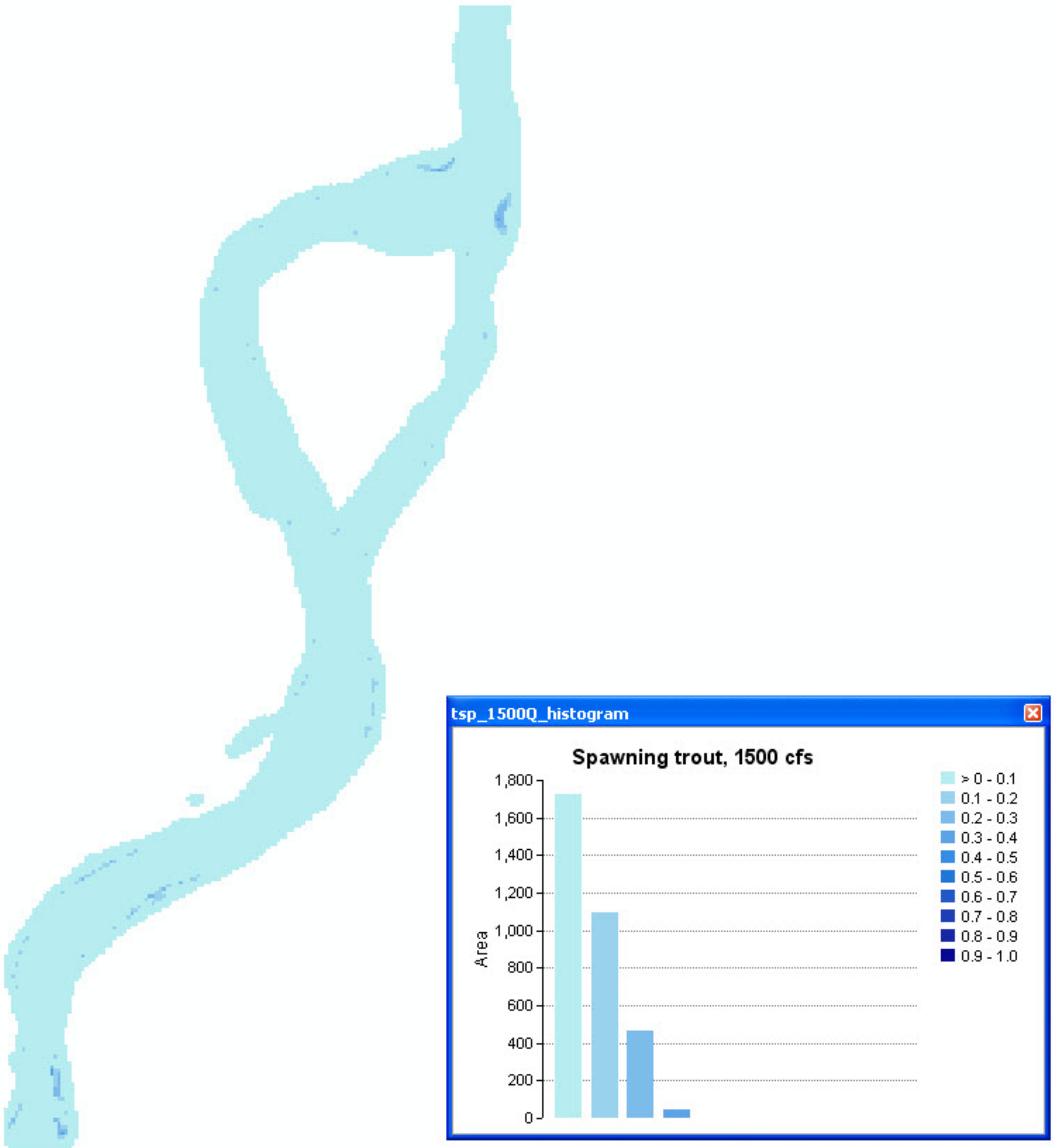
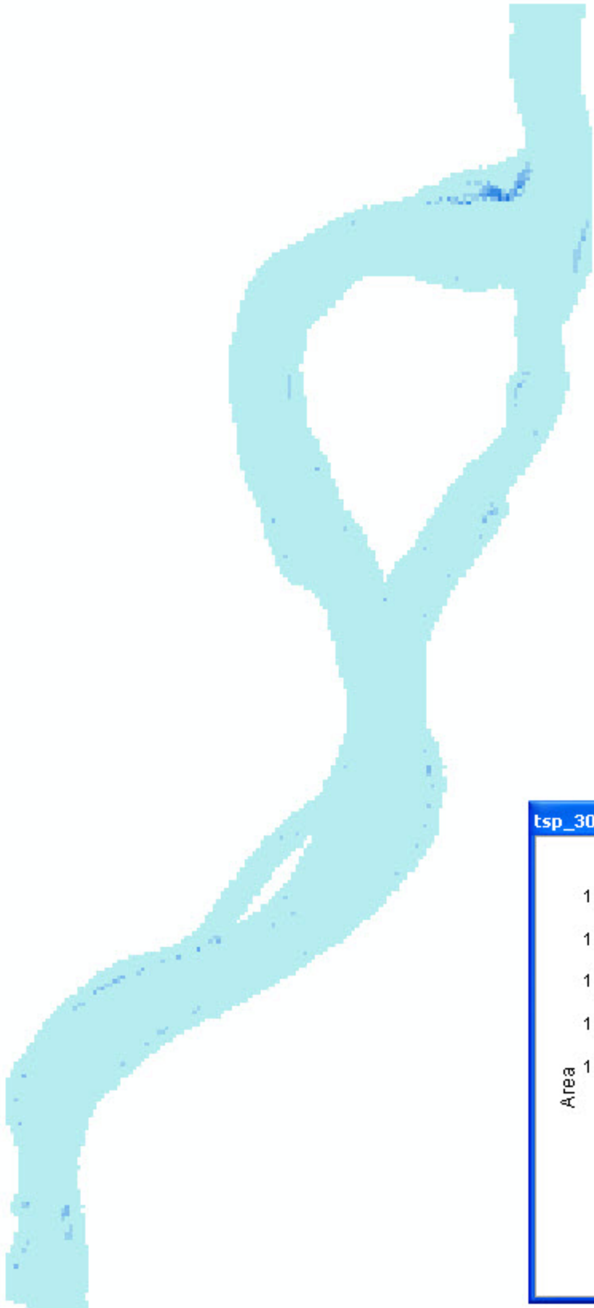


Figure A-46. Trout spawning habitat map, Rancho del Rio site, 1500 cfs.



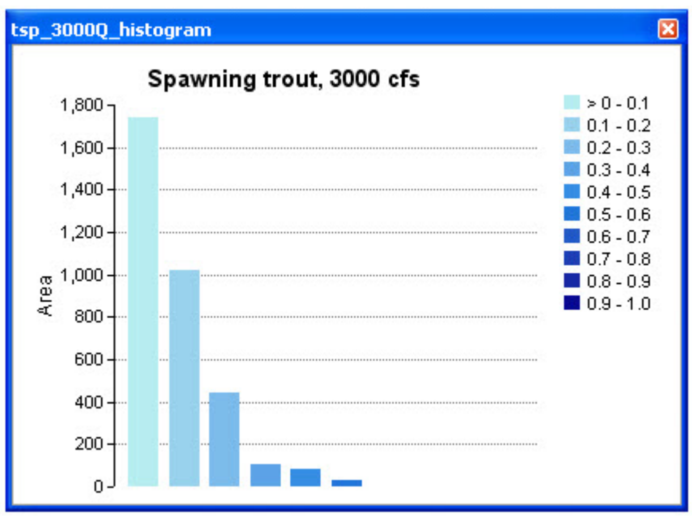


Figure A-47. Trout spawning habitat map, Rancho del Rio site, 3000 cfs.

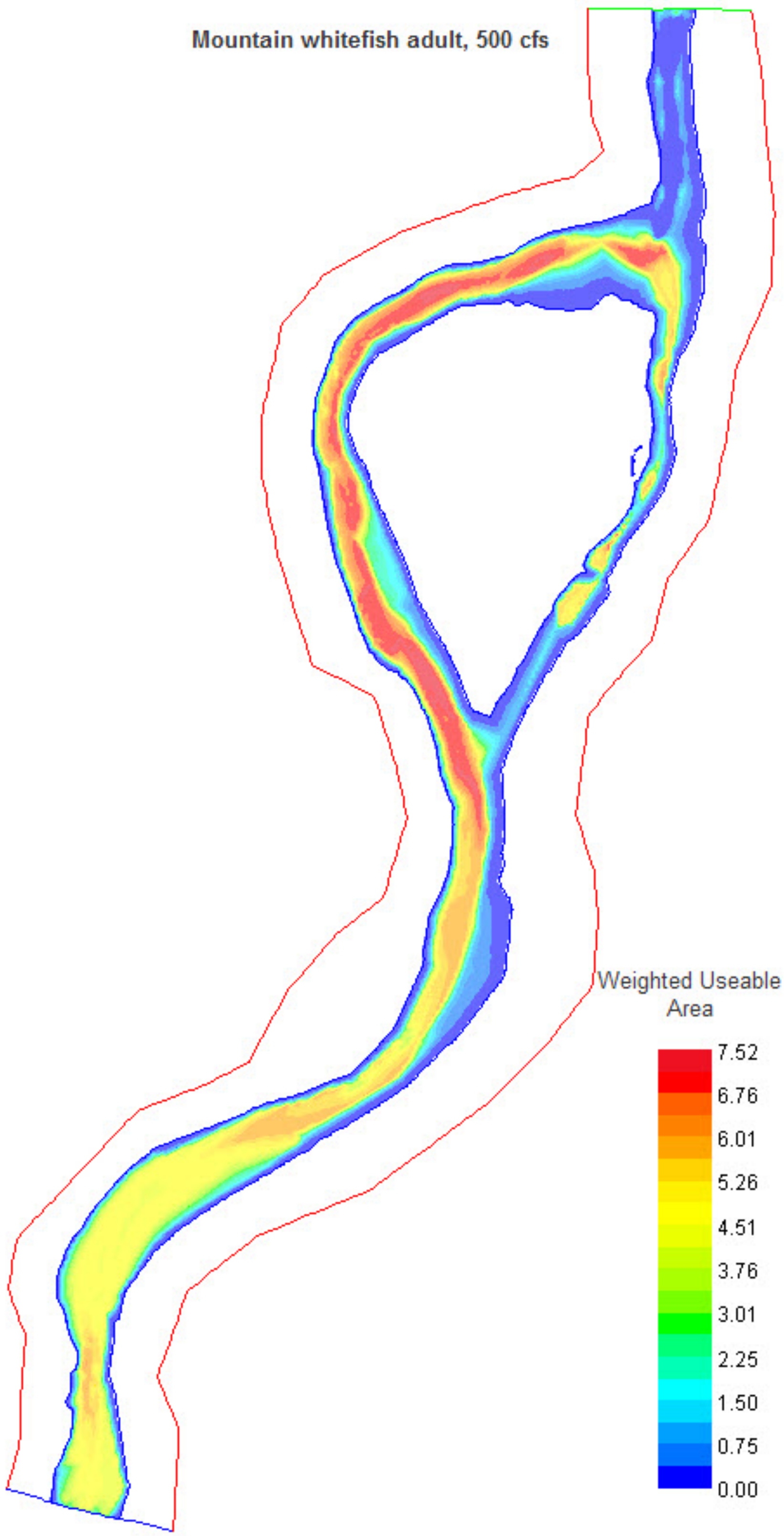


Figure A-48. Adult mountain whitefish habitat map, Rancho del Rio site, 500 cfs.

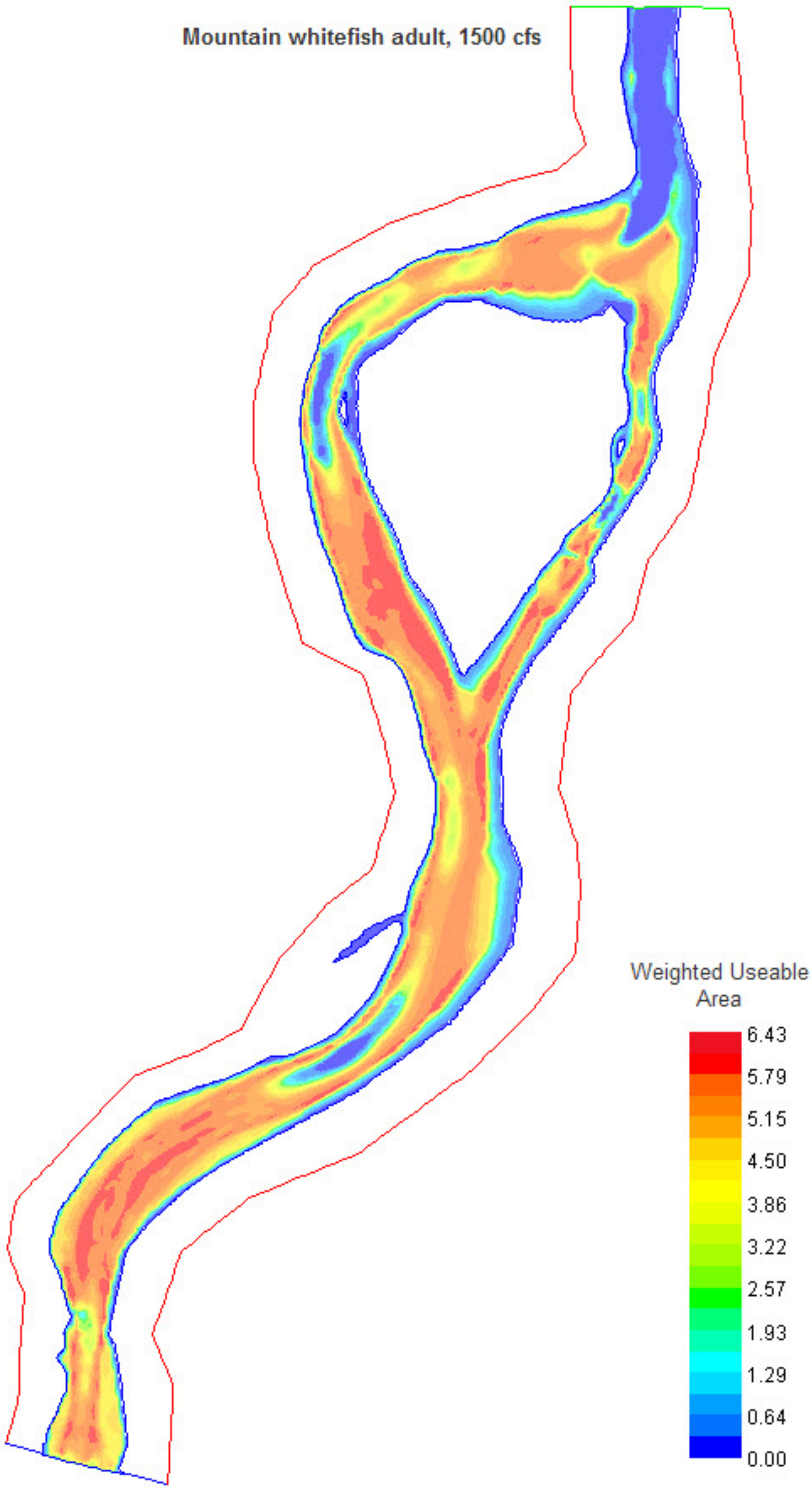


Figure A-49. Adult mountain whitefish habitat map, Rancho del Rio site, 1500 cfs.

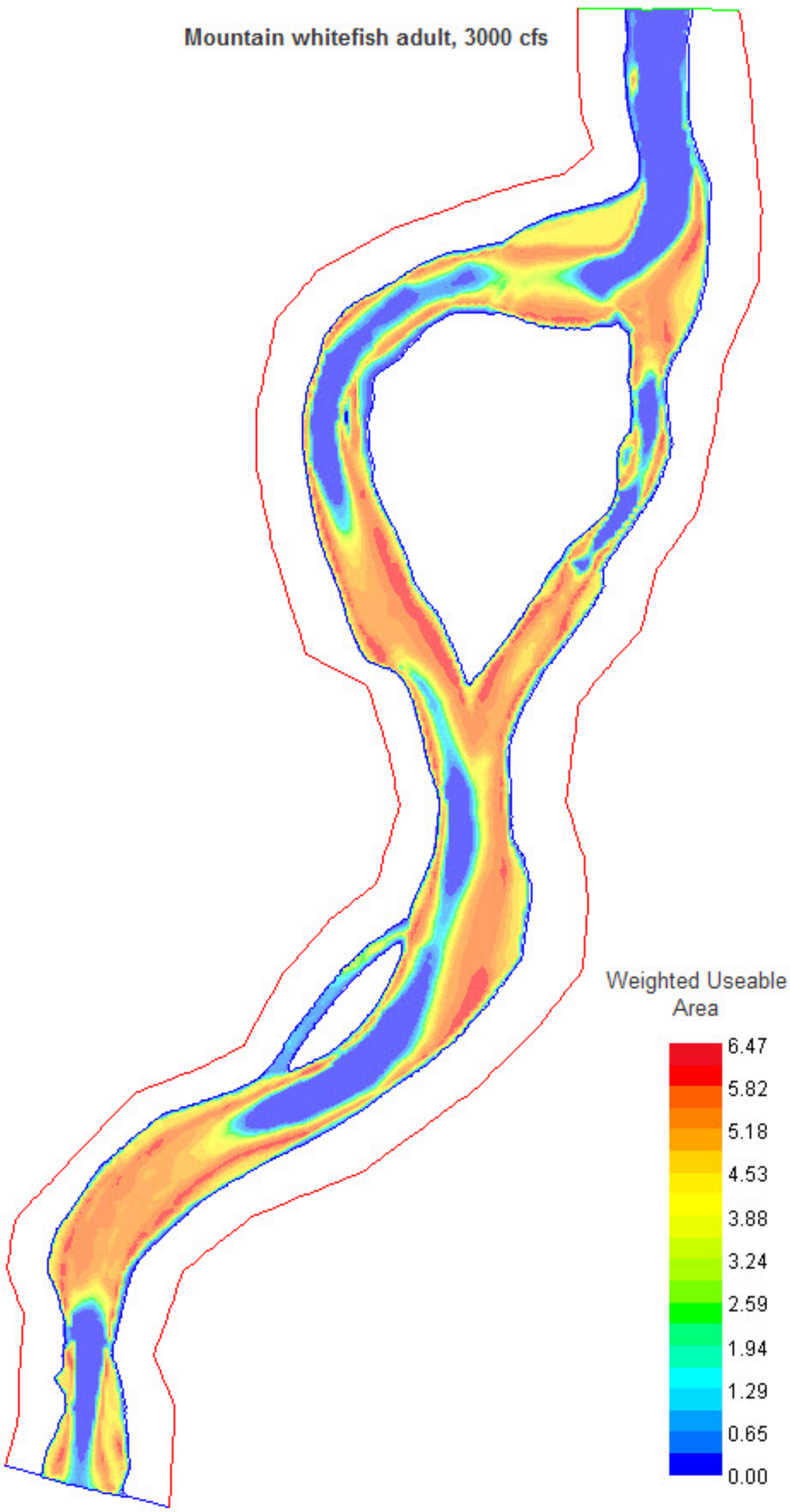


Figure A-50. Adult mountain whitefish habitat map, Rancho del Rio site, 3000 cfs.

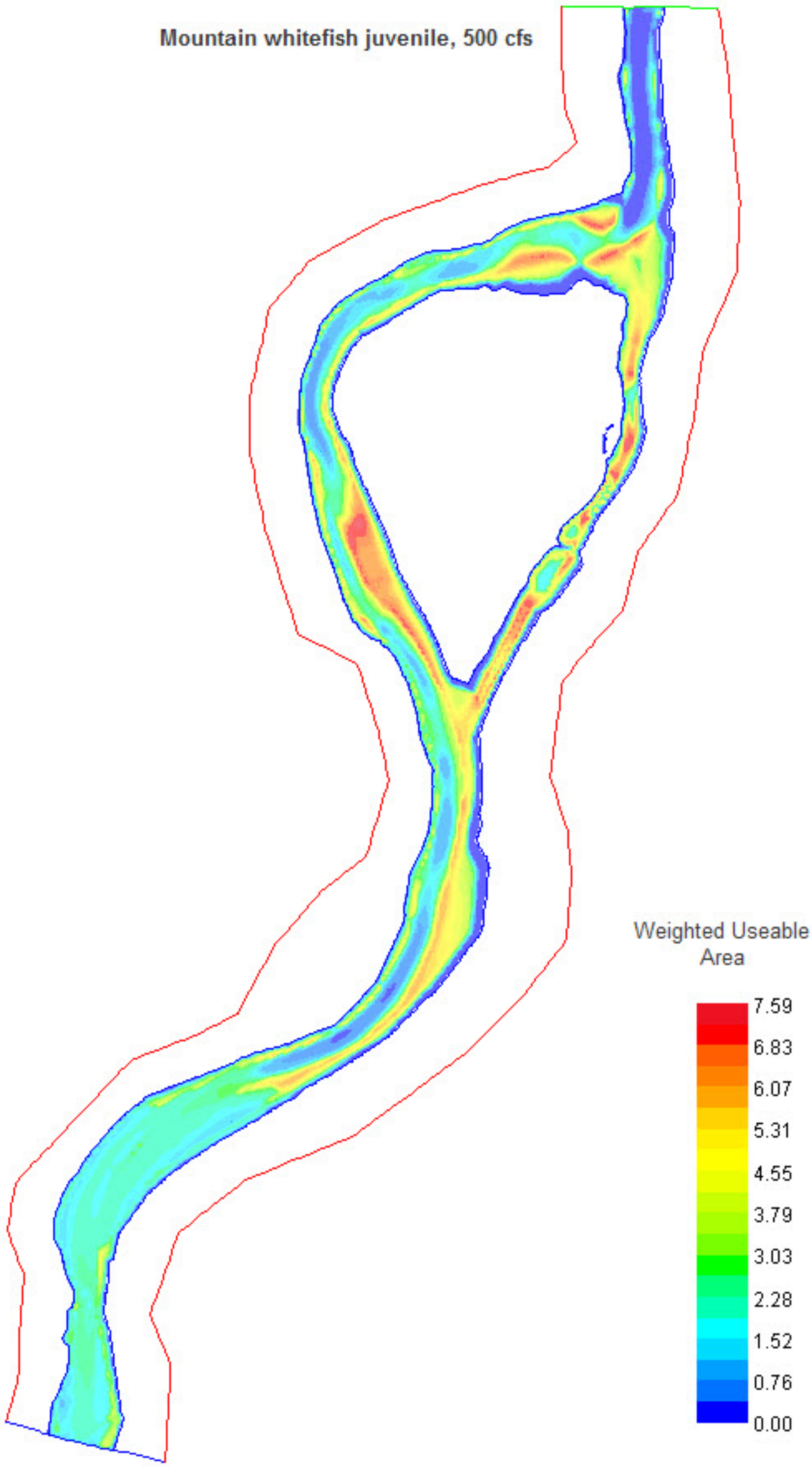


Figure A-51. Juvenile mountain whitefish habitat map, Rancho del Rio site, 500 cfs.

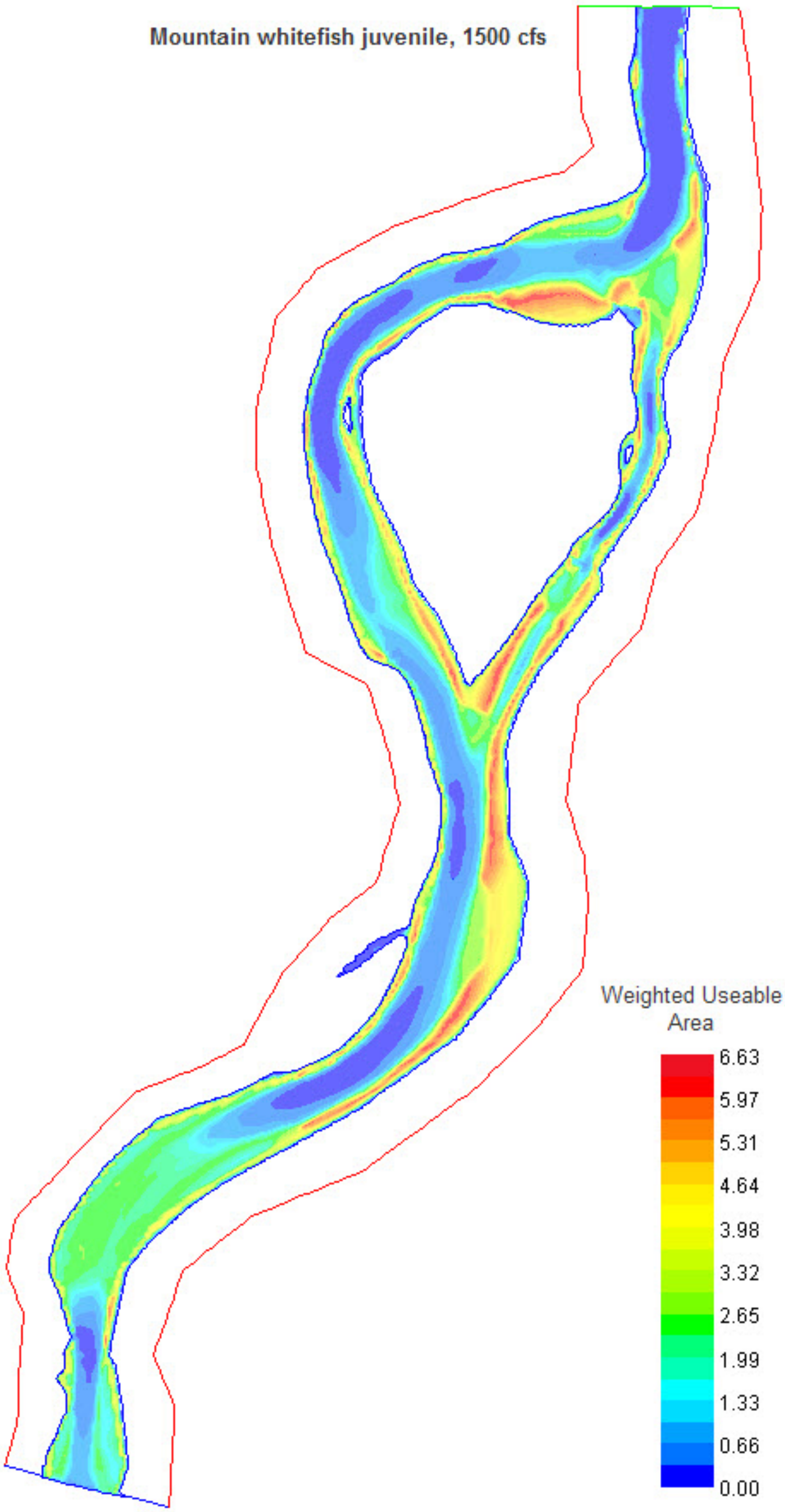


Figure A-52. Juvenile mountain whitefish habitat map, Rancho del Rio site, 1500 cfs.

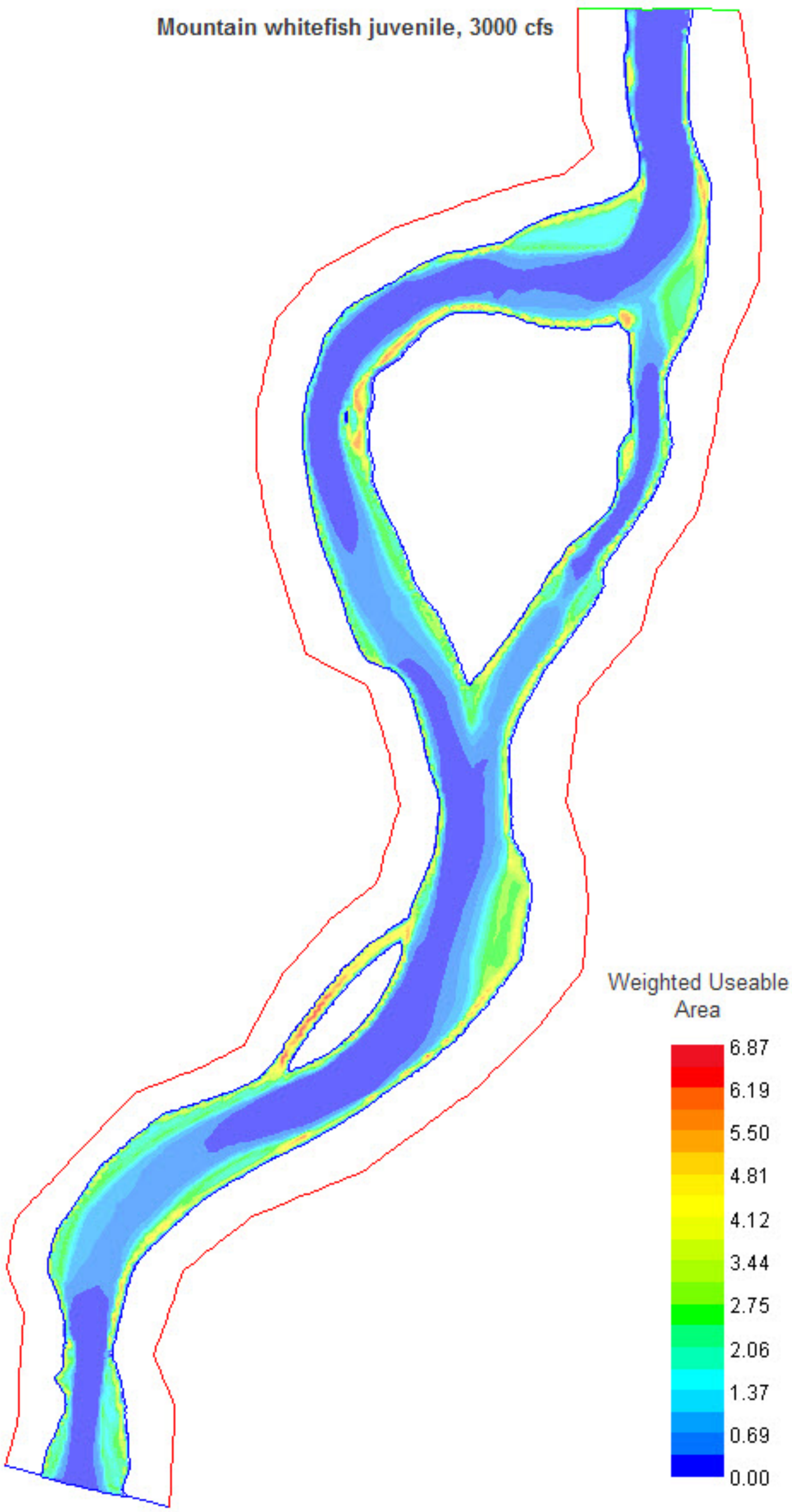


Figure A-53. Juvenile mountain whitefish habitat map, Rancho del Rio site, 3000 cfs.

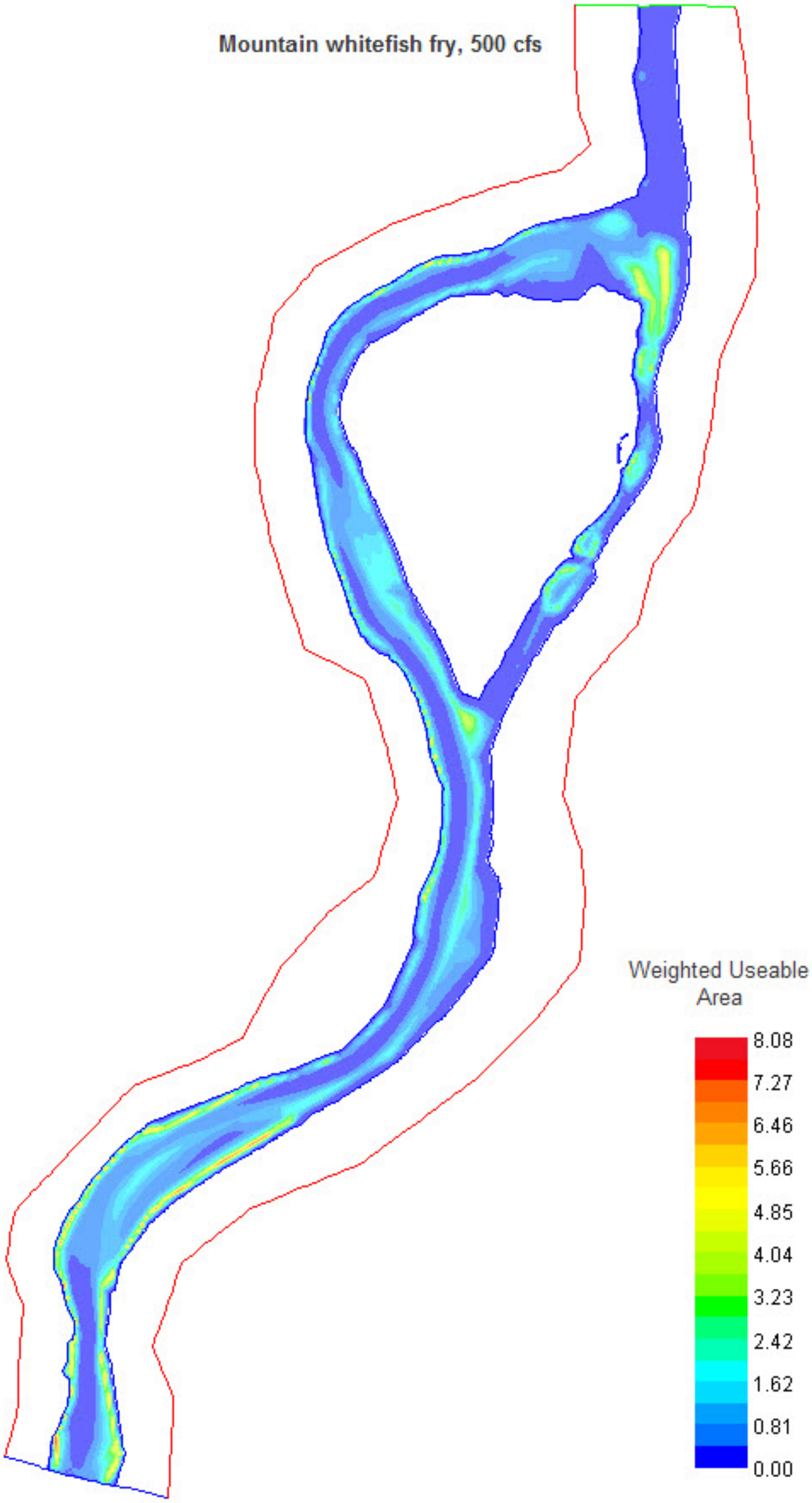


Figure A-54. Mountain whitefish fry habitat map, Rancho del Rio site, 500 cfs.

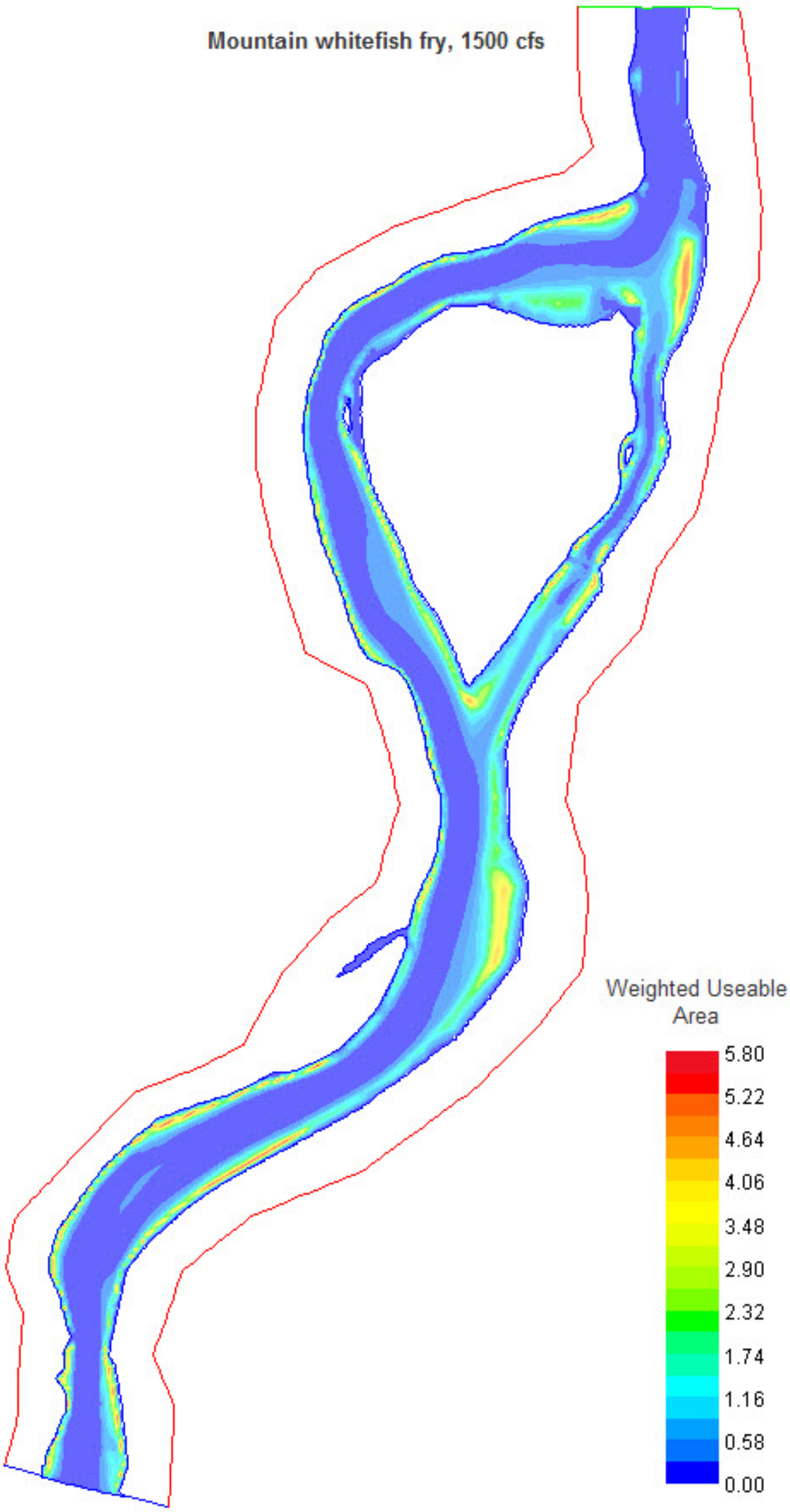


Figure A-55. Mountain whitefish fry habitat map, Rancho del Rio site, 1500 cfs.

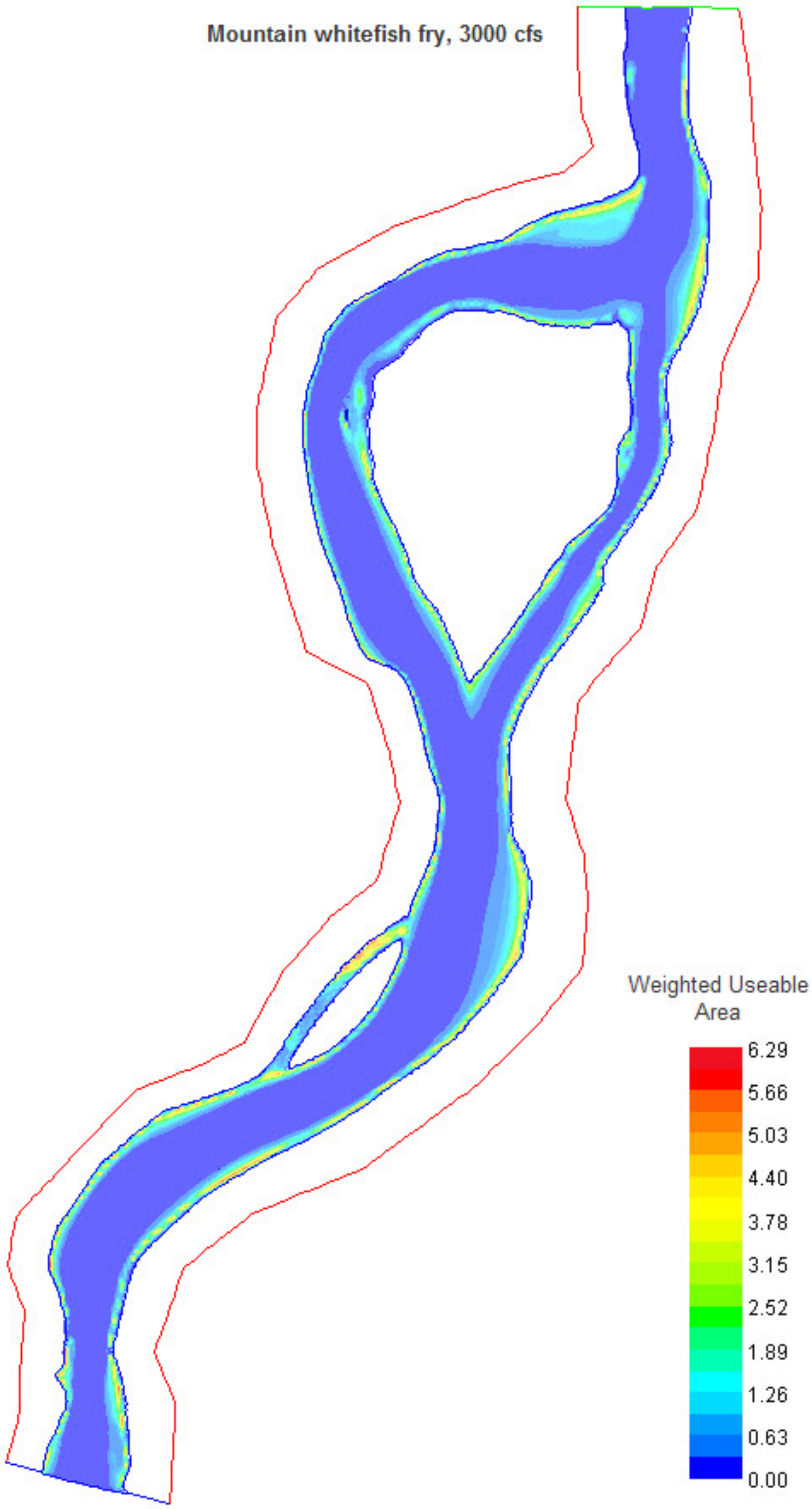


Figure A-56. Mountain whitefish fry habitat map, Rancho del Rio site, 3000 cfs.

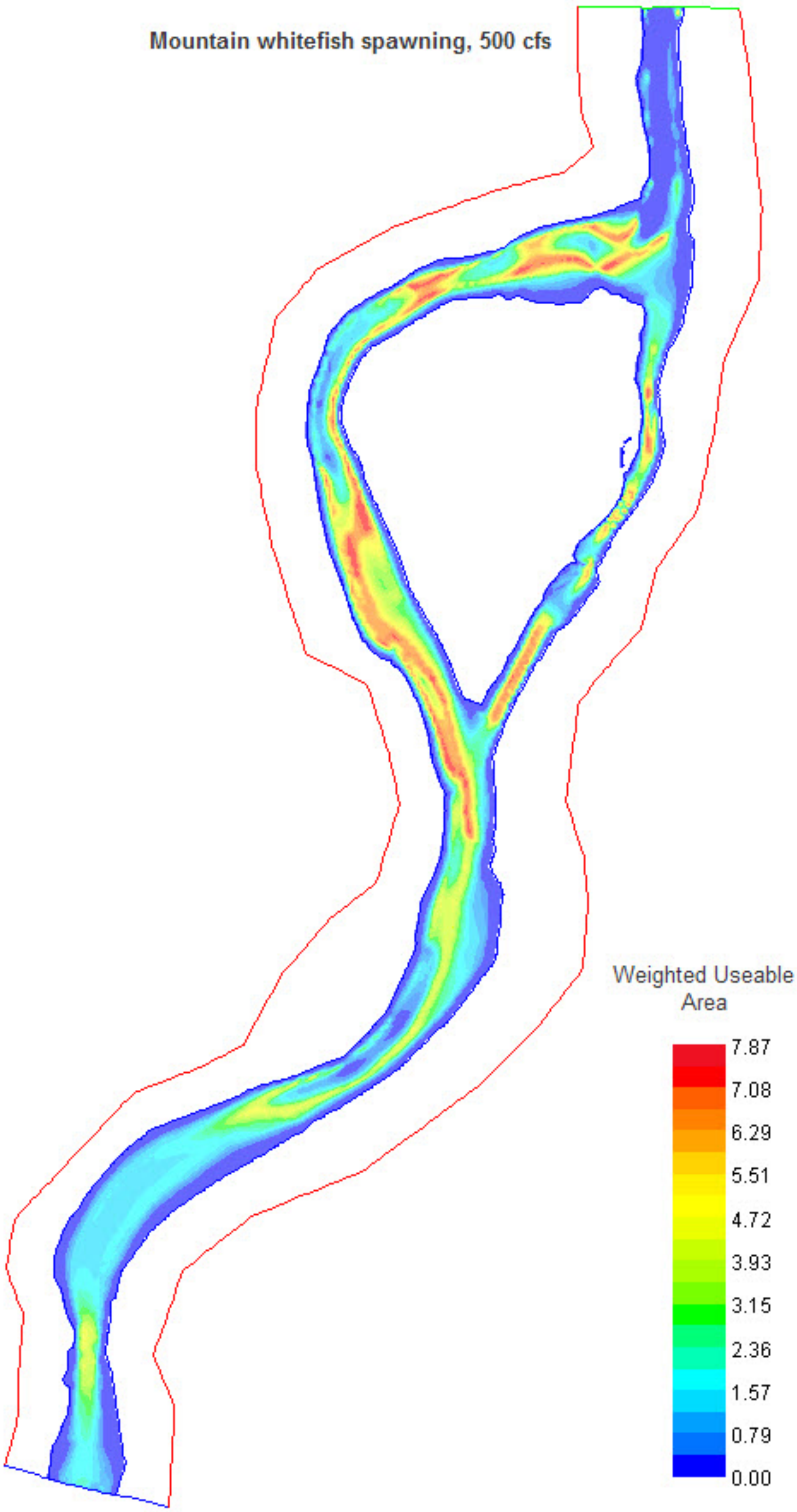


Figure A-57. Mountain whitefish spawning habitat map, Rancho del Rio site, 500 cfs.

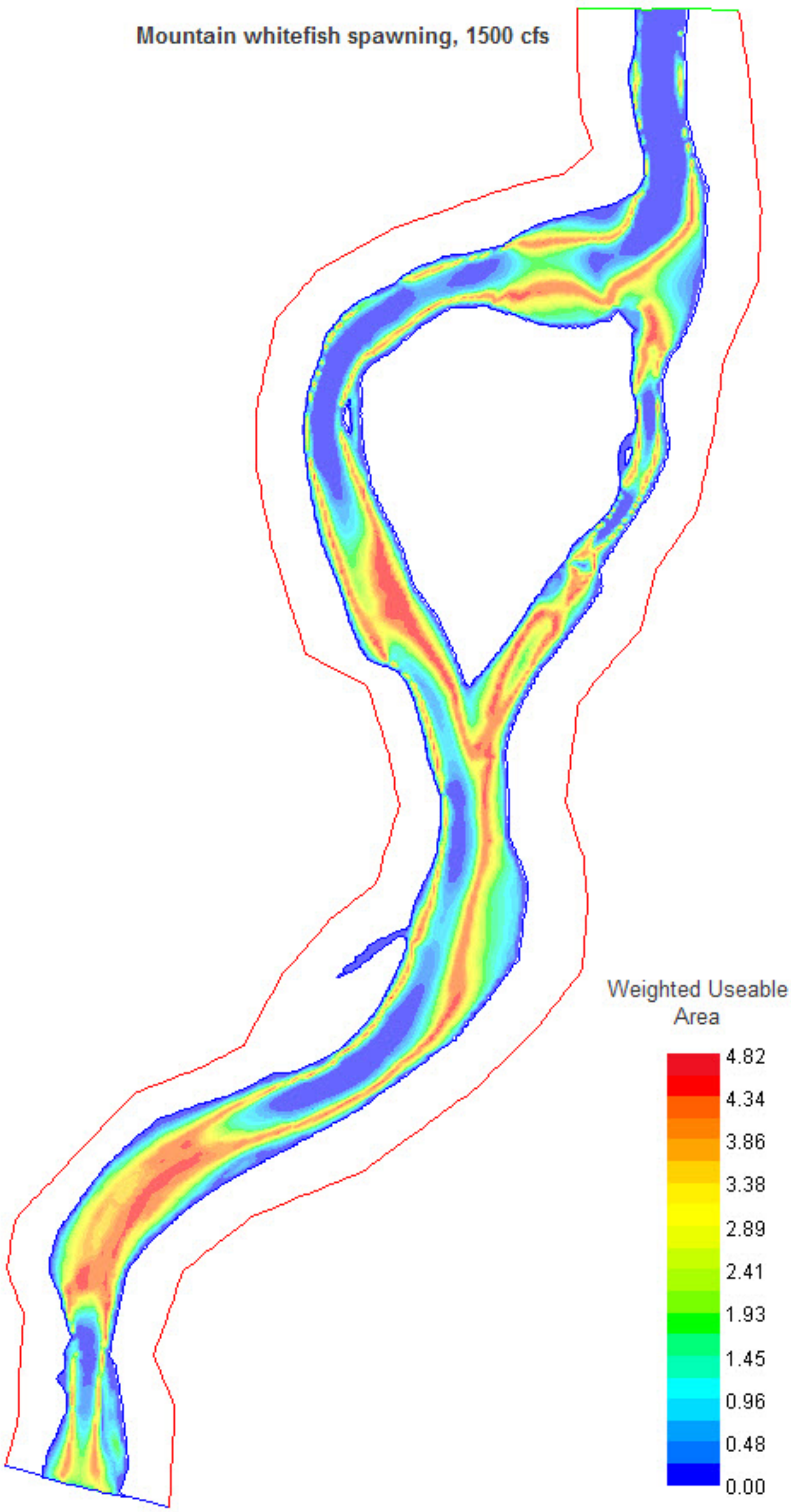


Figure A-58. Mountain whitefish spawning habitat map, Rancho del Rio site, 1500 cfs.

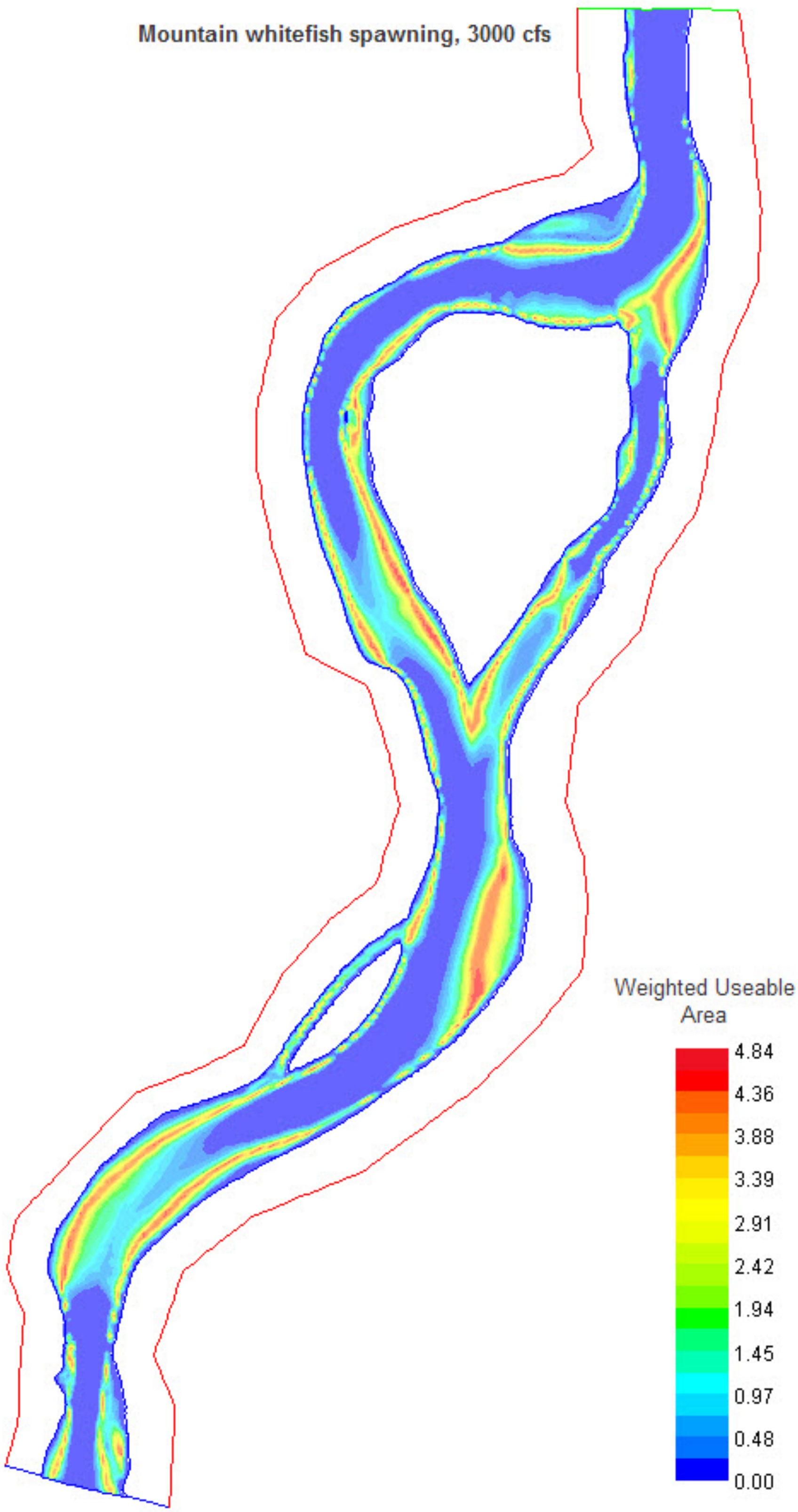


Figure A-59. Mountain whitefish spawning habitat map, Rancho del Rio site, 3000 cfs

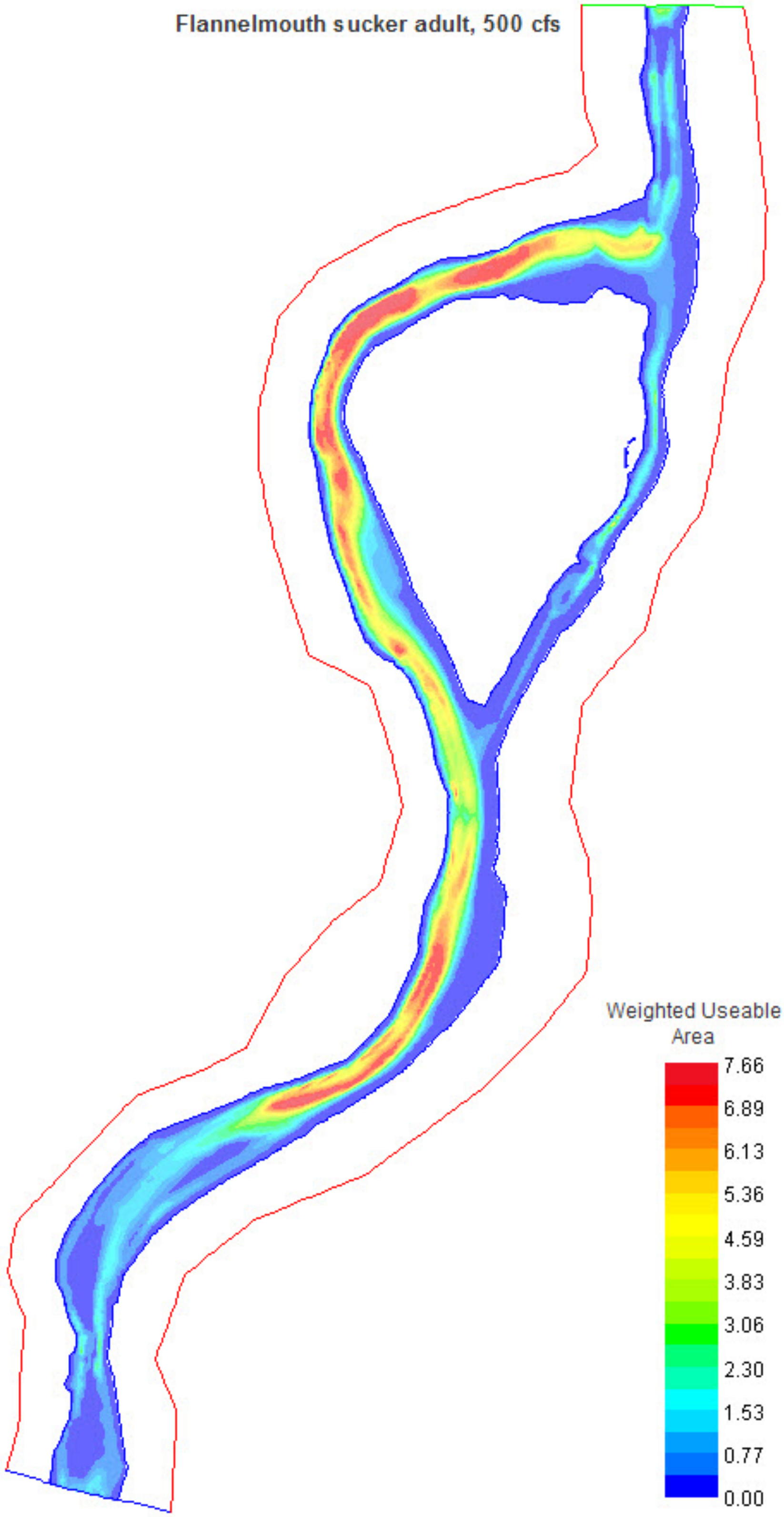


Figure A-60. Adult flannelmouth sucker habitat map, Rancho del Rio site, 500 cfs.

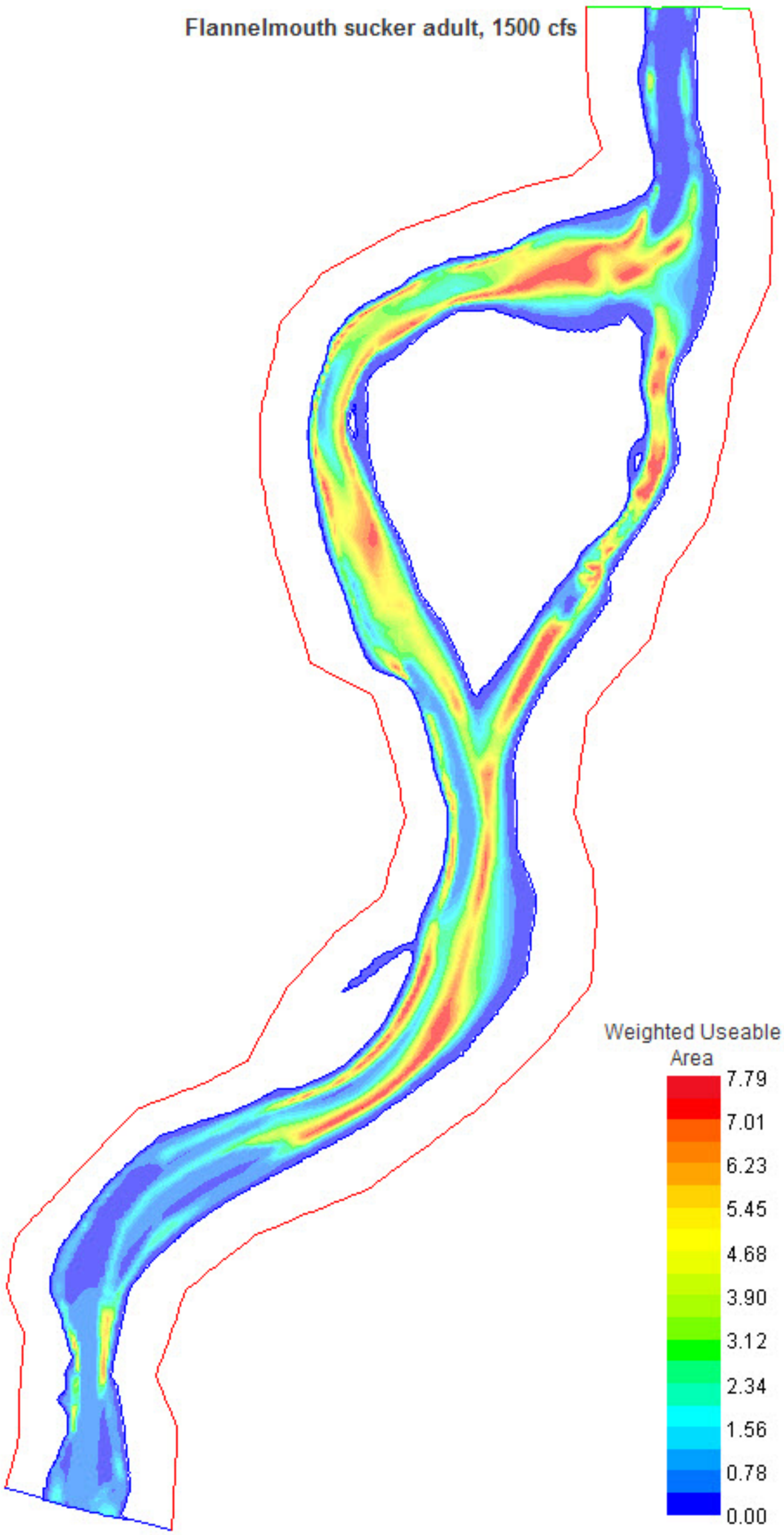


Figure A-61. Adult flannelmouth sucker habitat map, Rancho del Rio site, 1500 cfs.

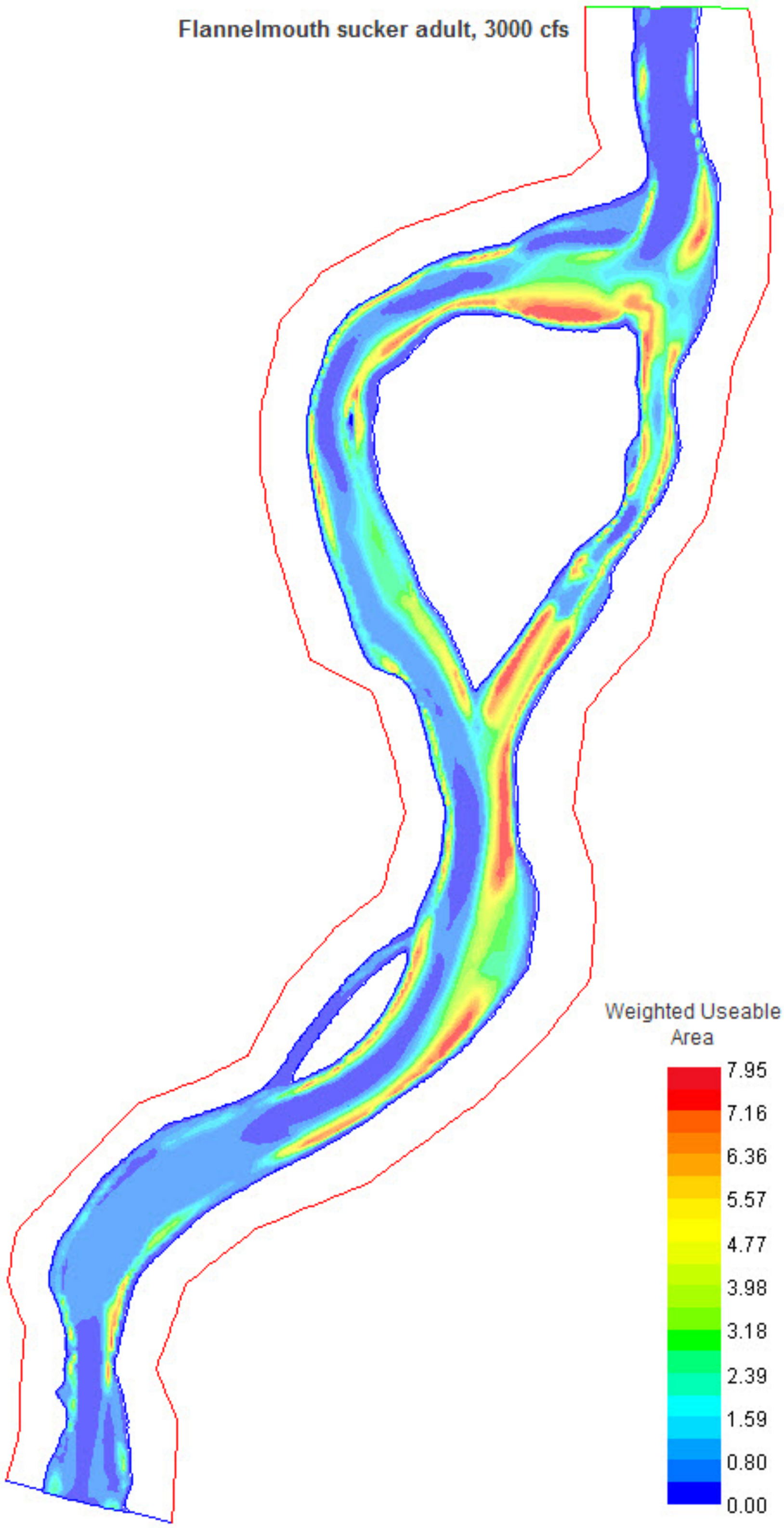


Figure A-62. Adult flannelmouth sucker habitat map, Rancho del Rio site, 3000 cfs.

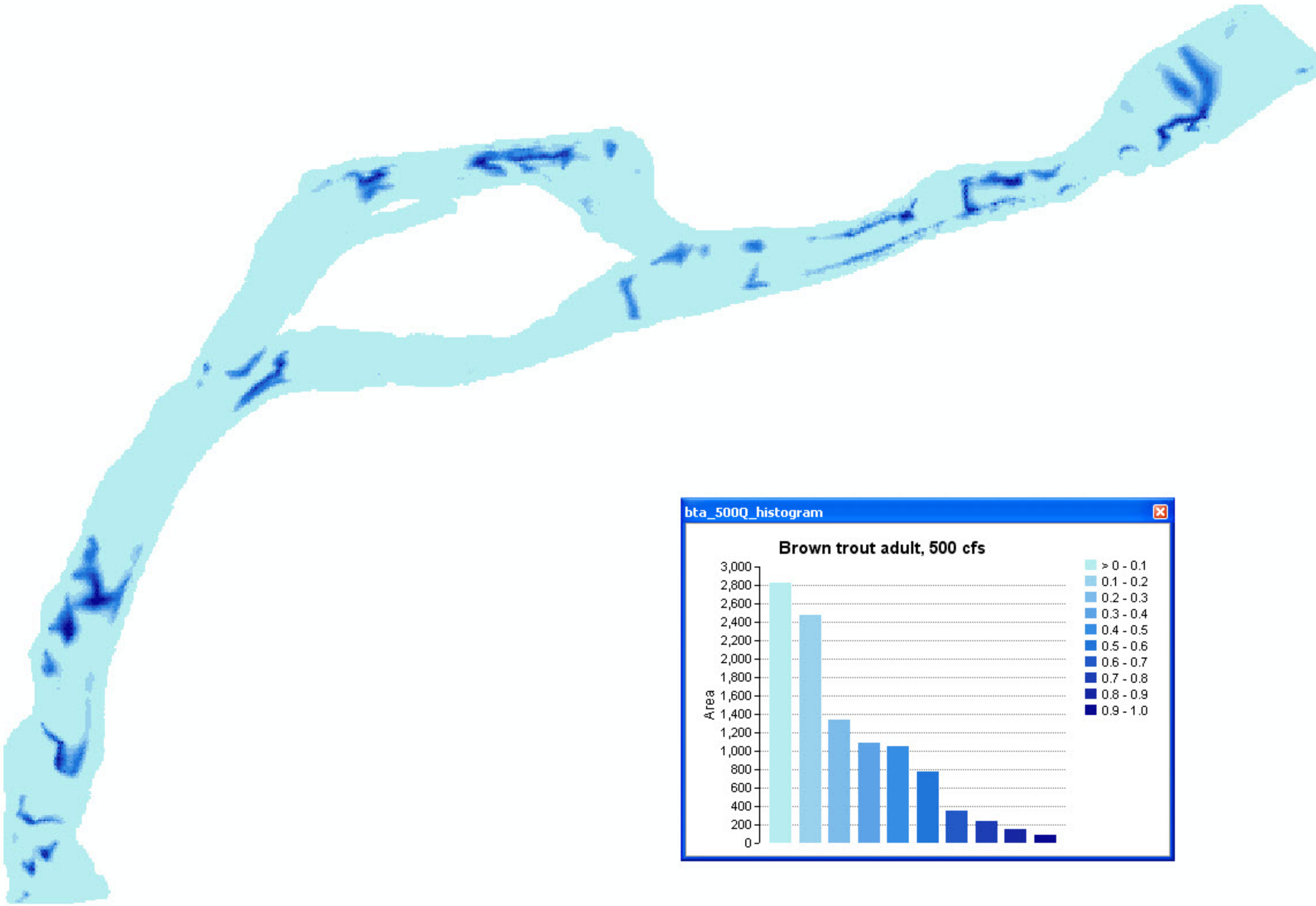


Figure A-63. Adult brown trout habitat map, Lyons Gulch site, 500 cfs.

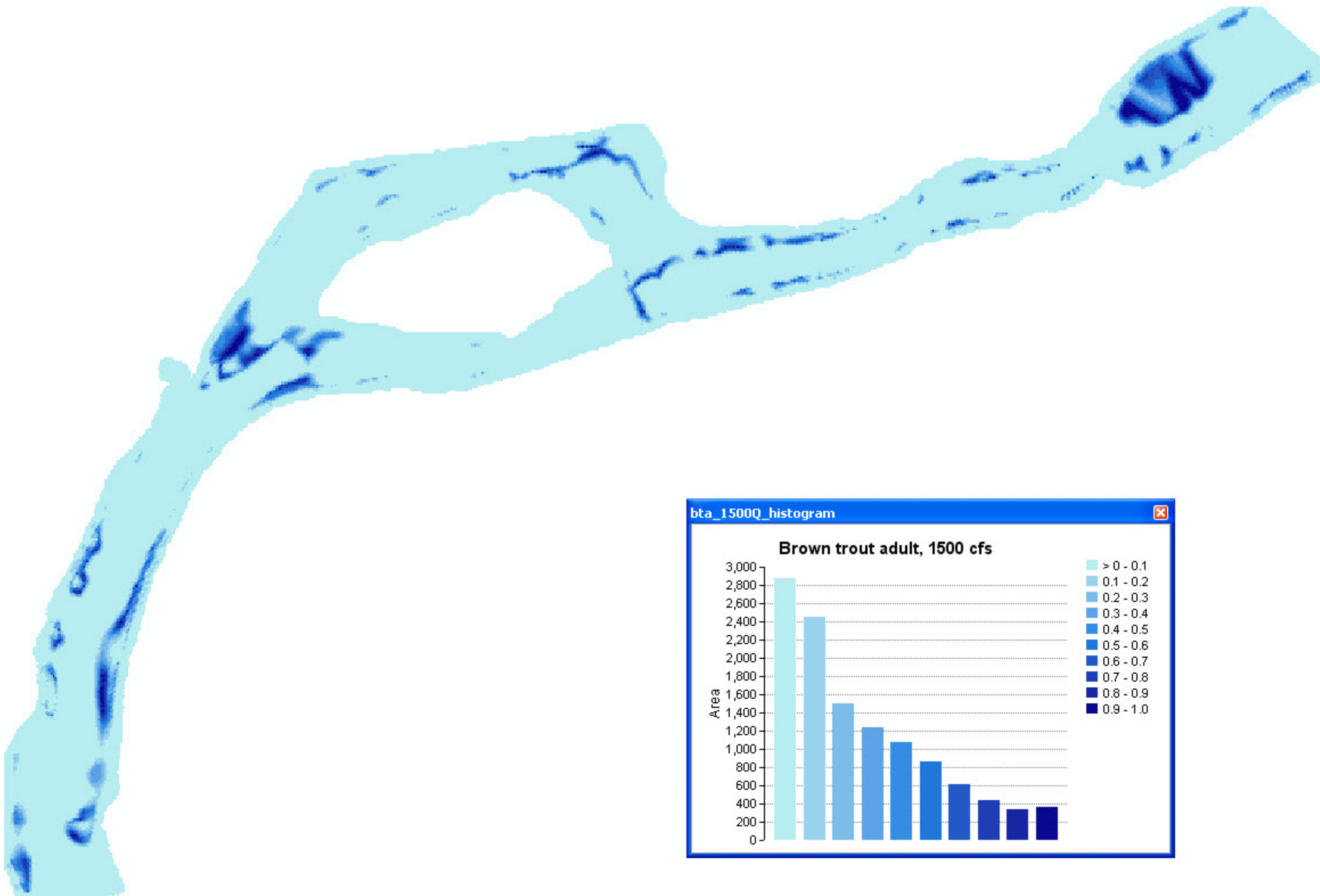


Figure A-64. Adult brown trout habitat map, Lyons Gulch site, 1500 cfs.

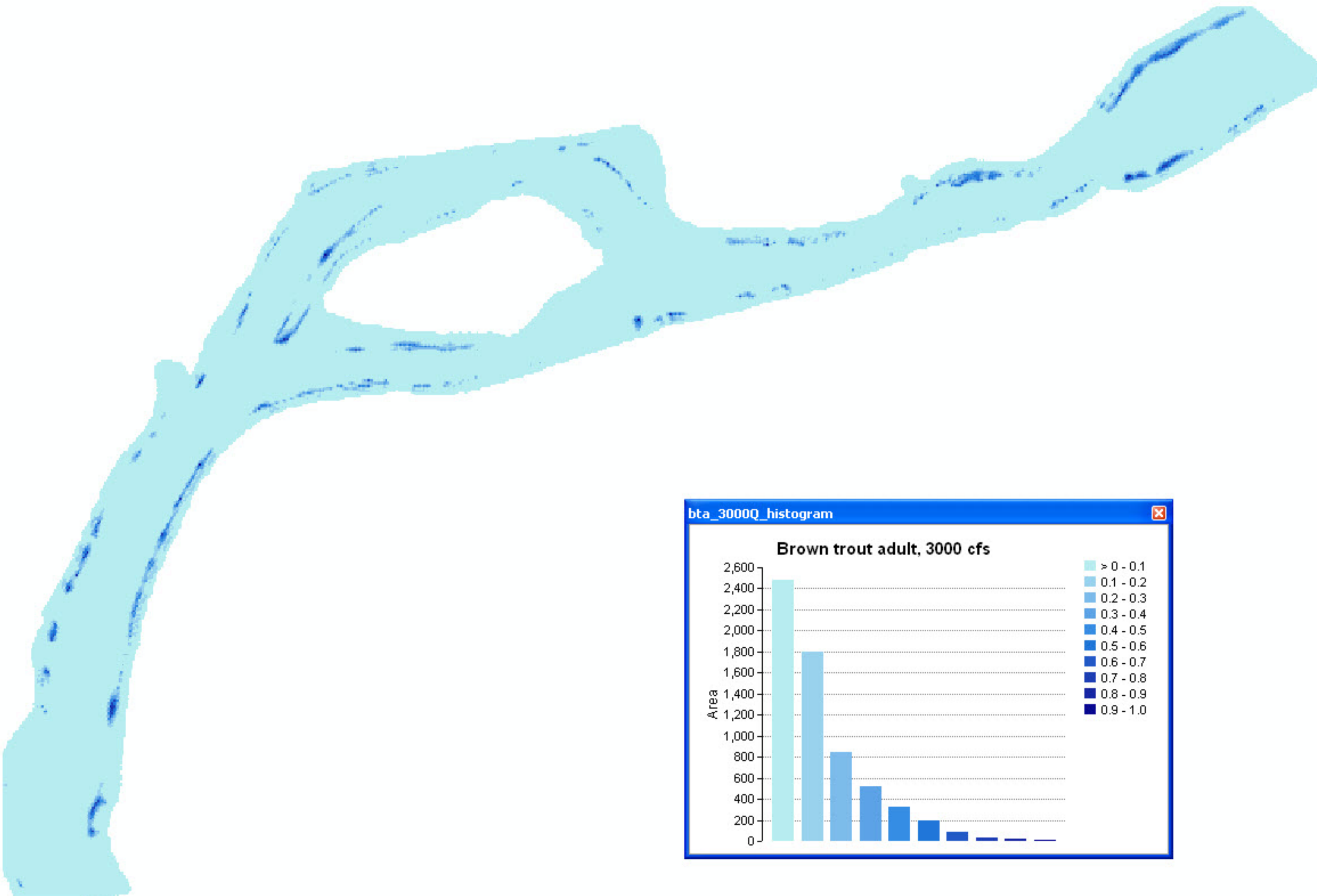


Figure A-65. Adult brown trout habitat map, Lyons Gulch site, 3000 cfs.

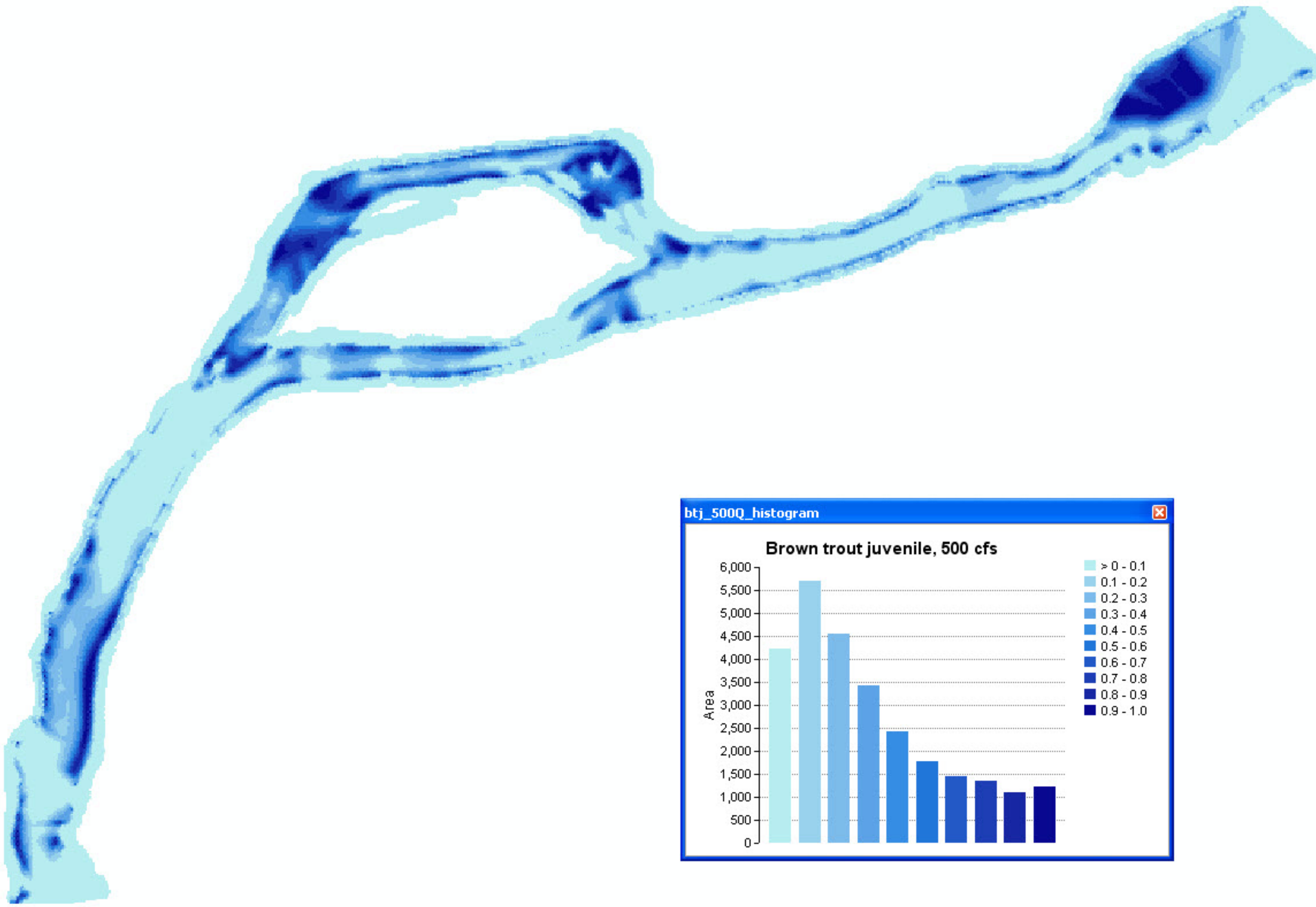


Figure A-66. Juvenile brown trout habitat map, Lyons Gulch site, 500 cfs.

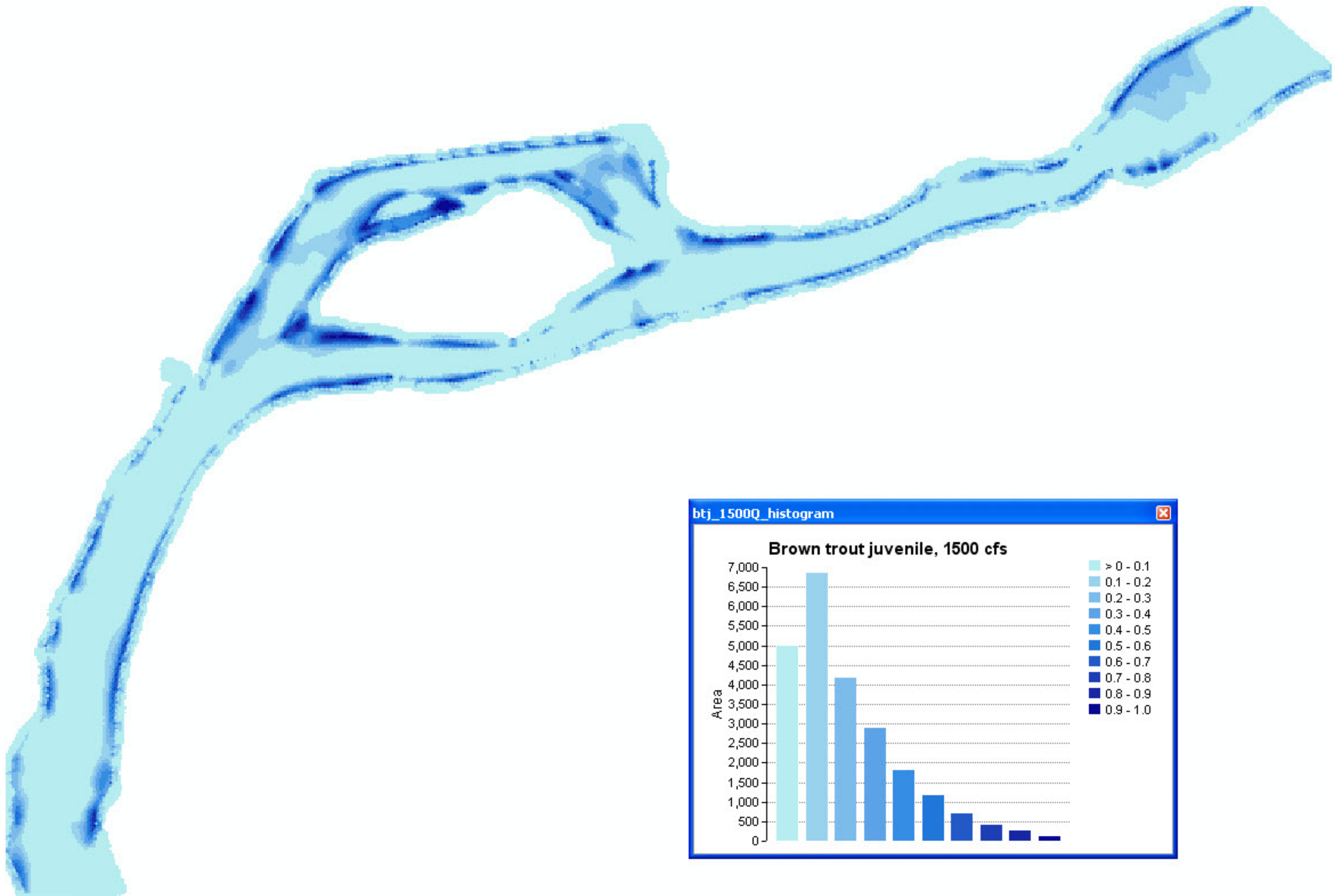


Figure A-67. Juvenile brown trout habitat map, Lyons Gulch site, 1500 cfs.

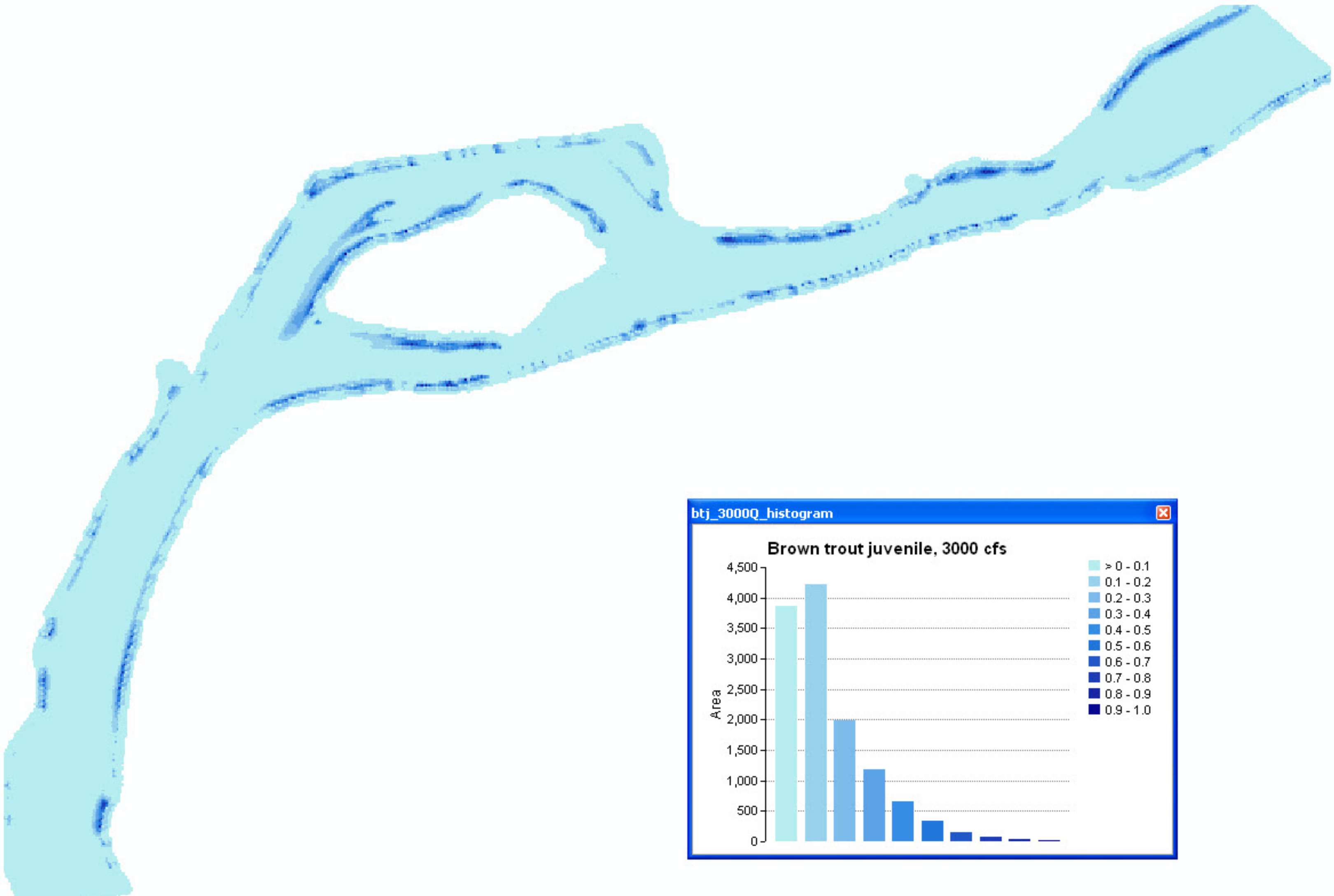


Figure A-68. Juvenile brown trout habitat map, Lyons Gulch site, 3000 cfs.

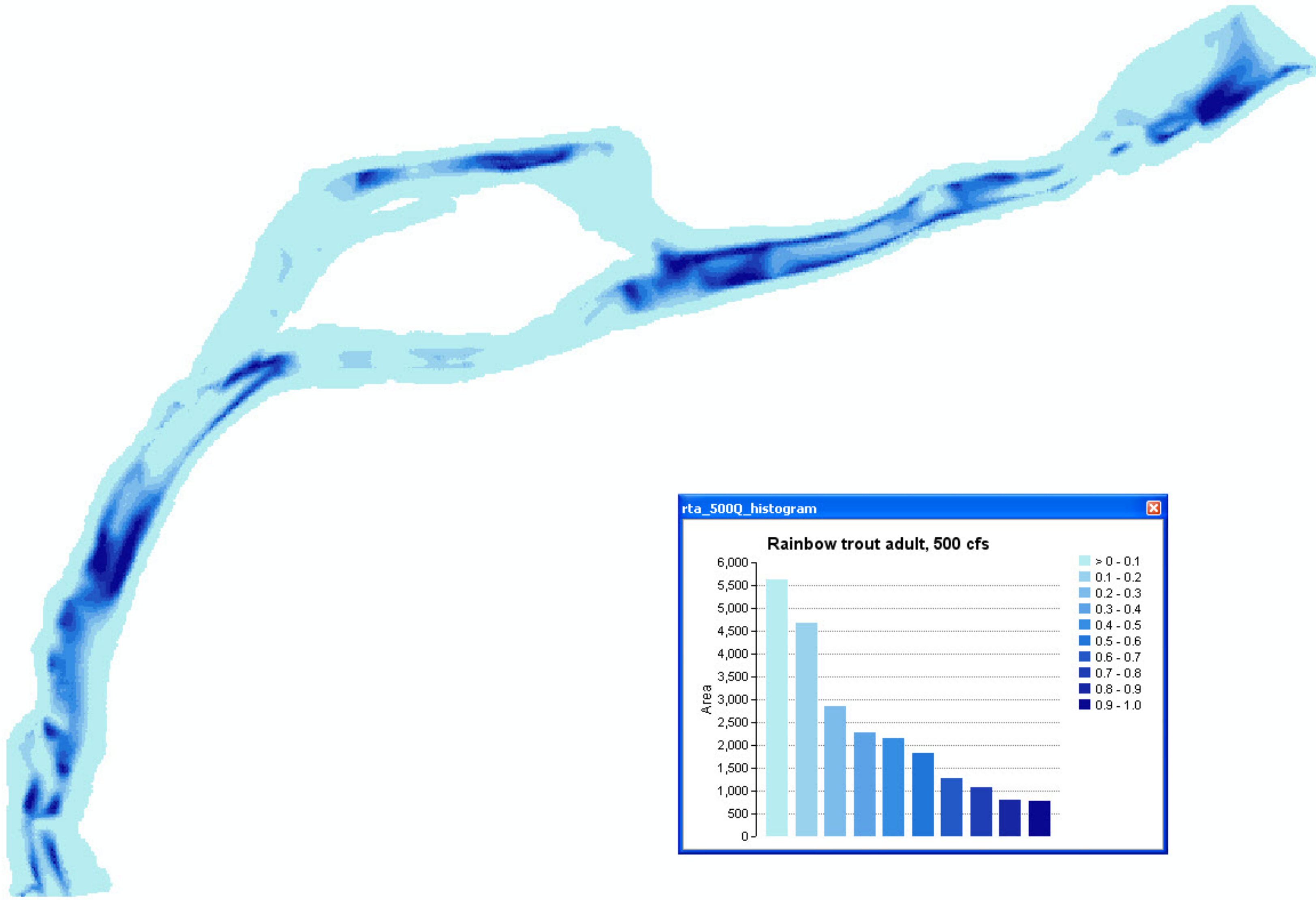


Figure A-69. Adult rainbow trout habitat map, Lyons Gulch site, 500 cfs.

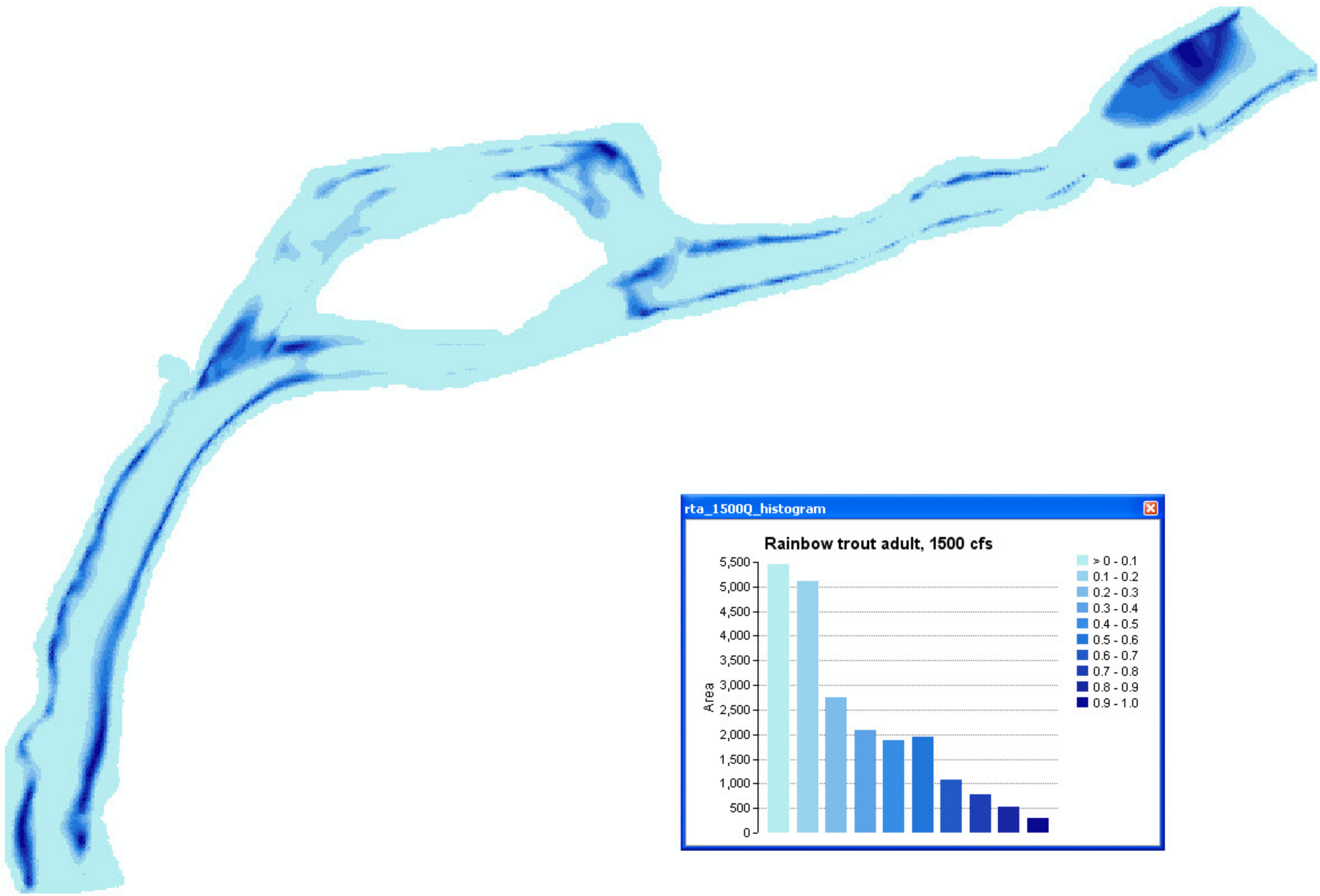


Figure A-70. Adult rainbow trout habitat map, Lyons Gulch site, 1500 cfs.

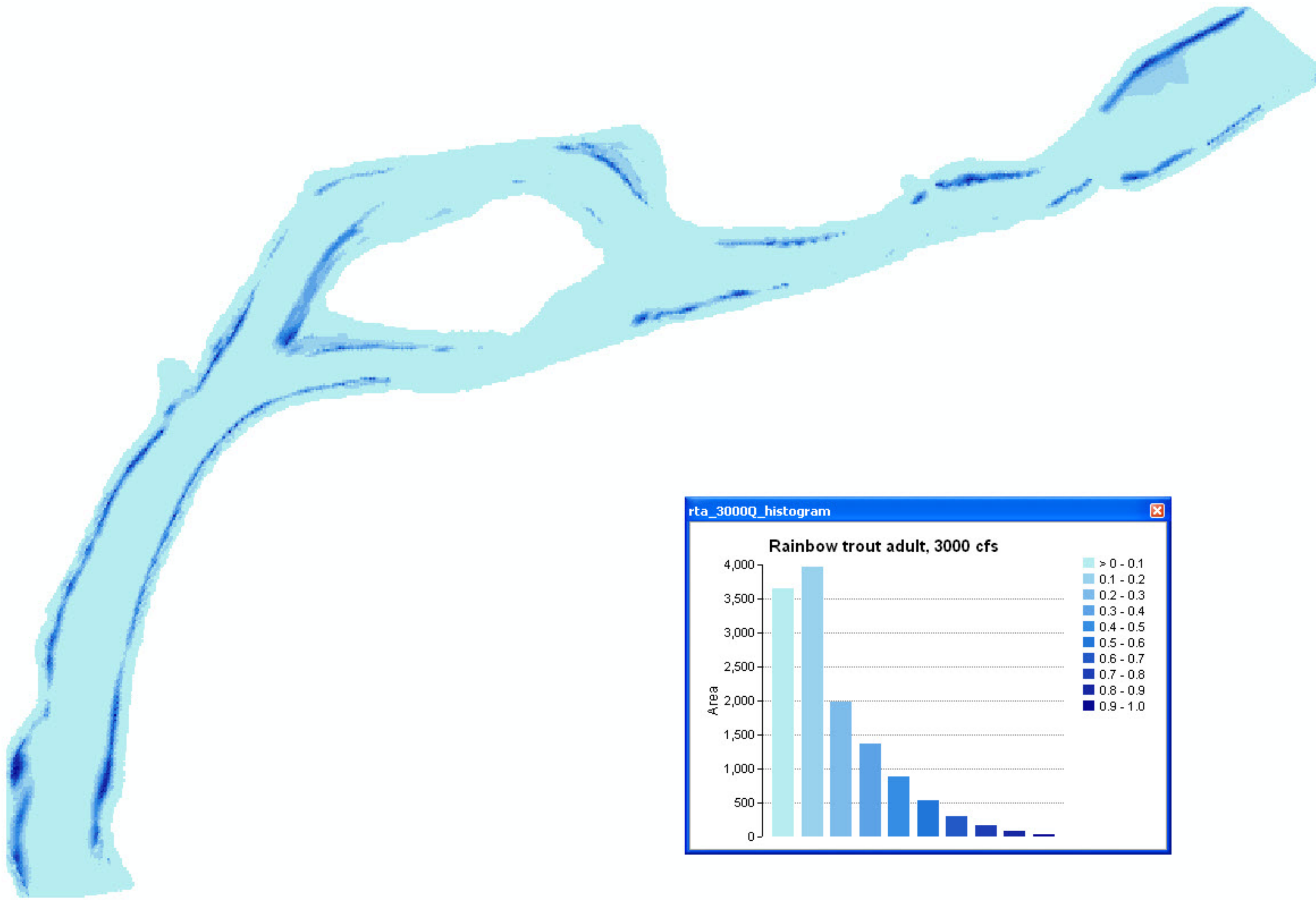


Figure A-71. Adult rainbow trout habitat map, Lyons Gulch site, 3000 cfs.

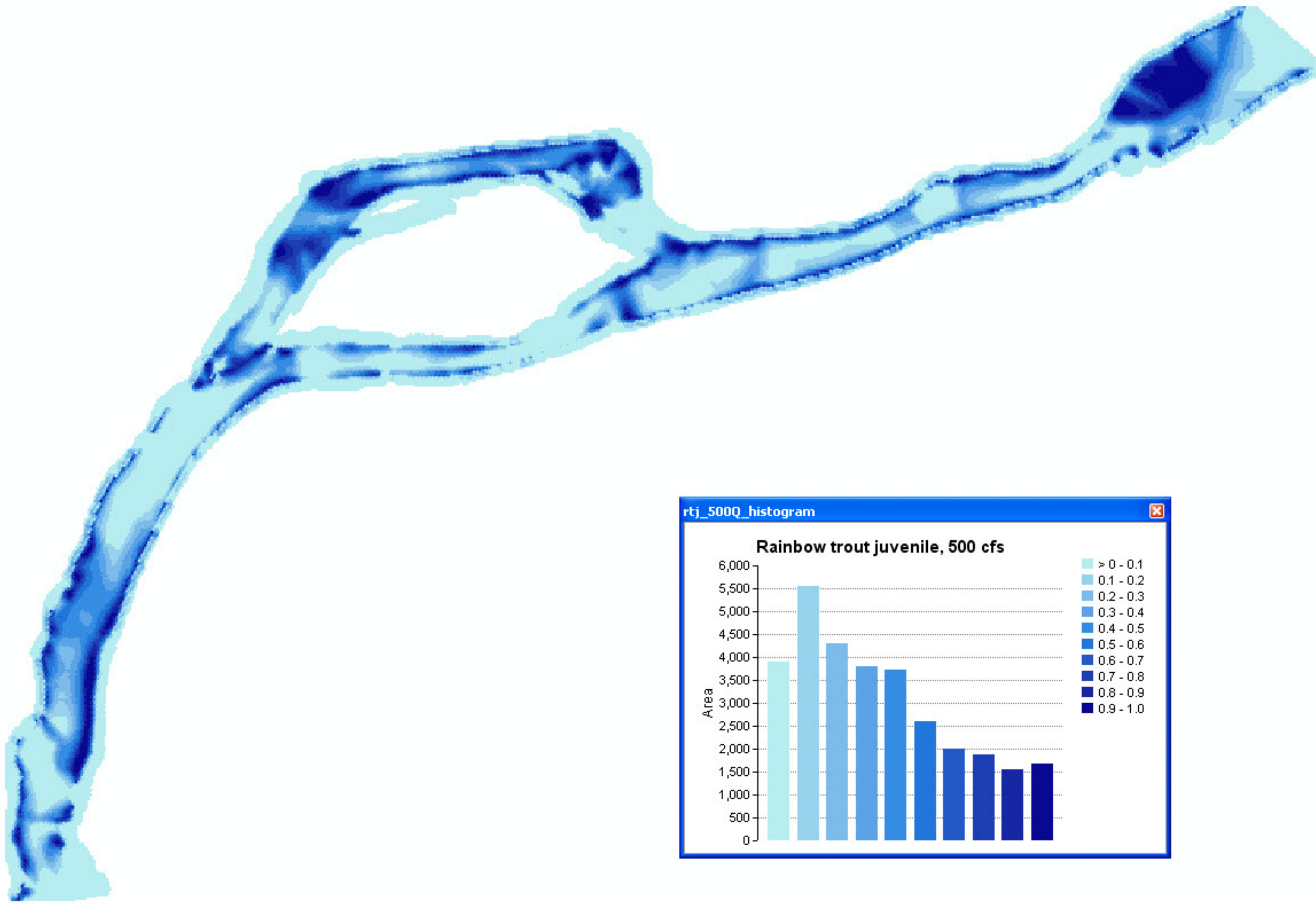


Figure A-72. Juvenile rainbow trout habitat map, Lyons Gulch site, 500 cfs.

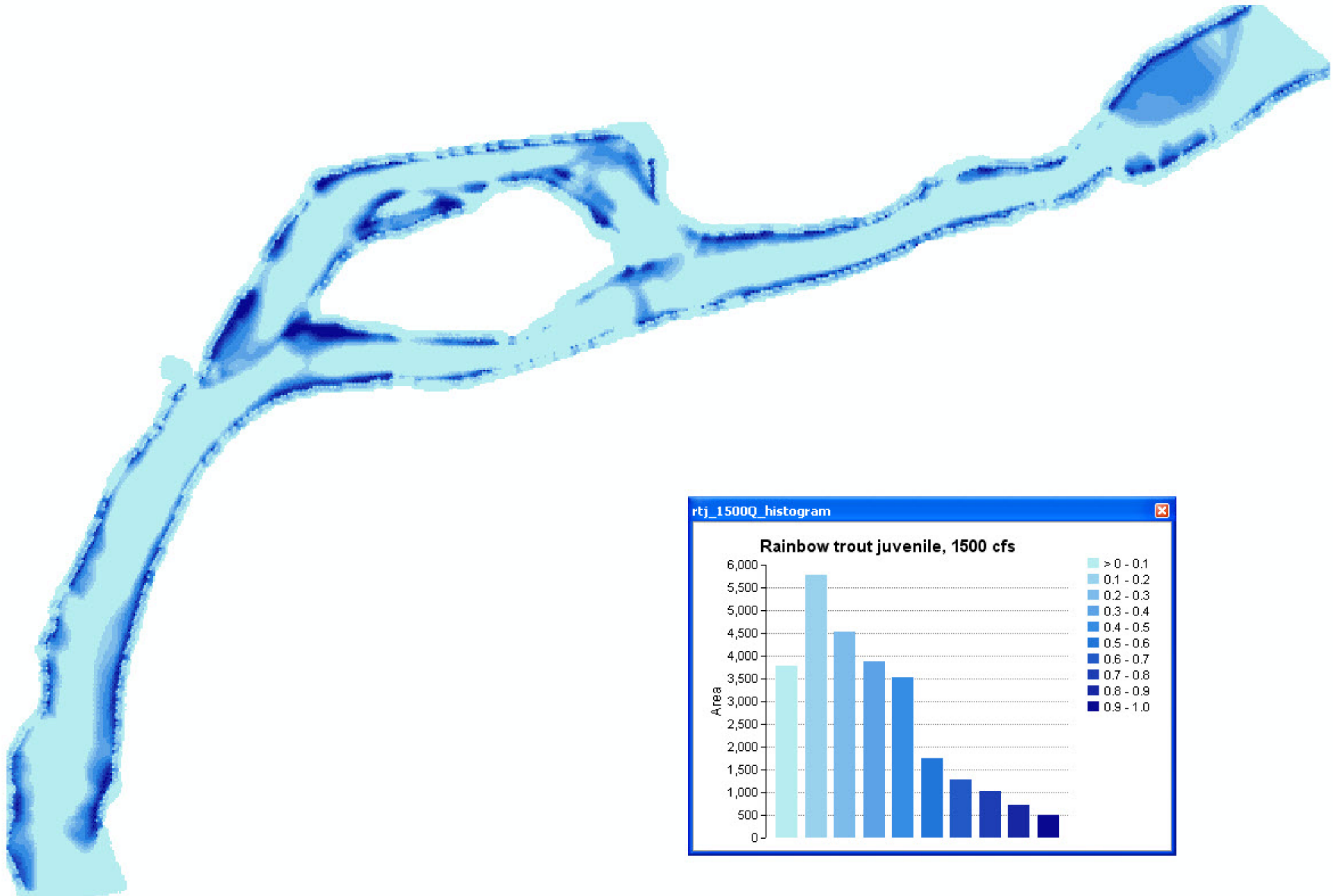


Figure A-73. Juvenile rainbow trout habitat map, Lyons Gulch site, 1500 cfs.

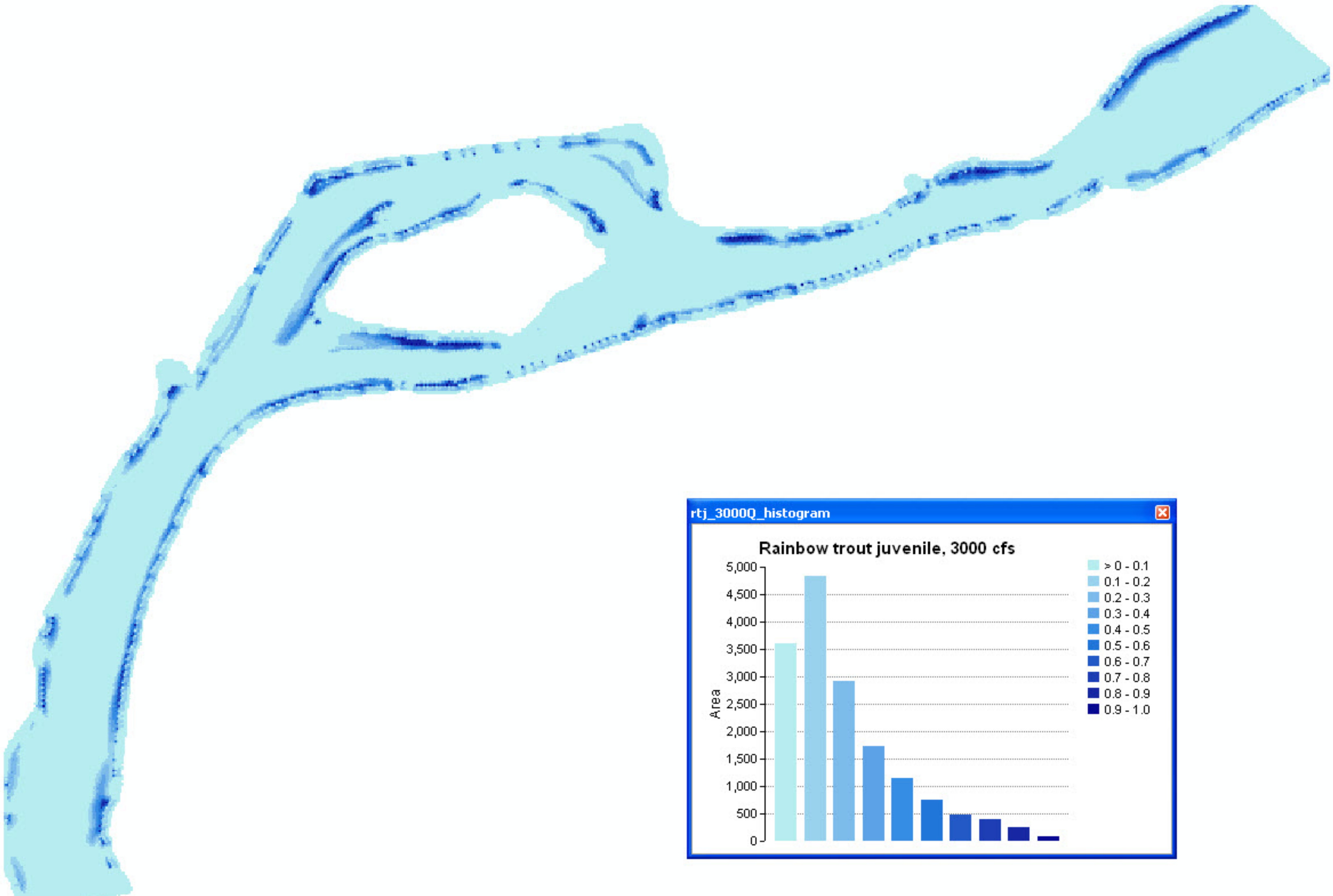


Figure A-74. Juvenile rainbow trout habitat map, Lyons Gulch site, 3000 cfs.

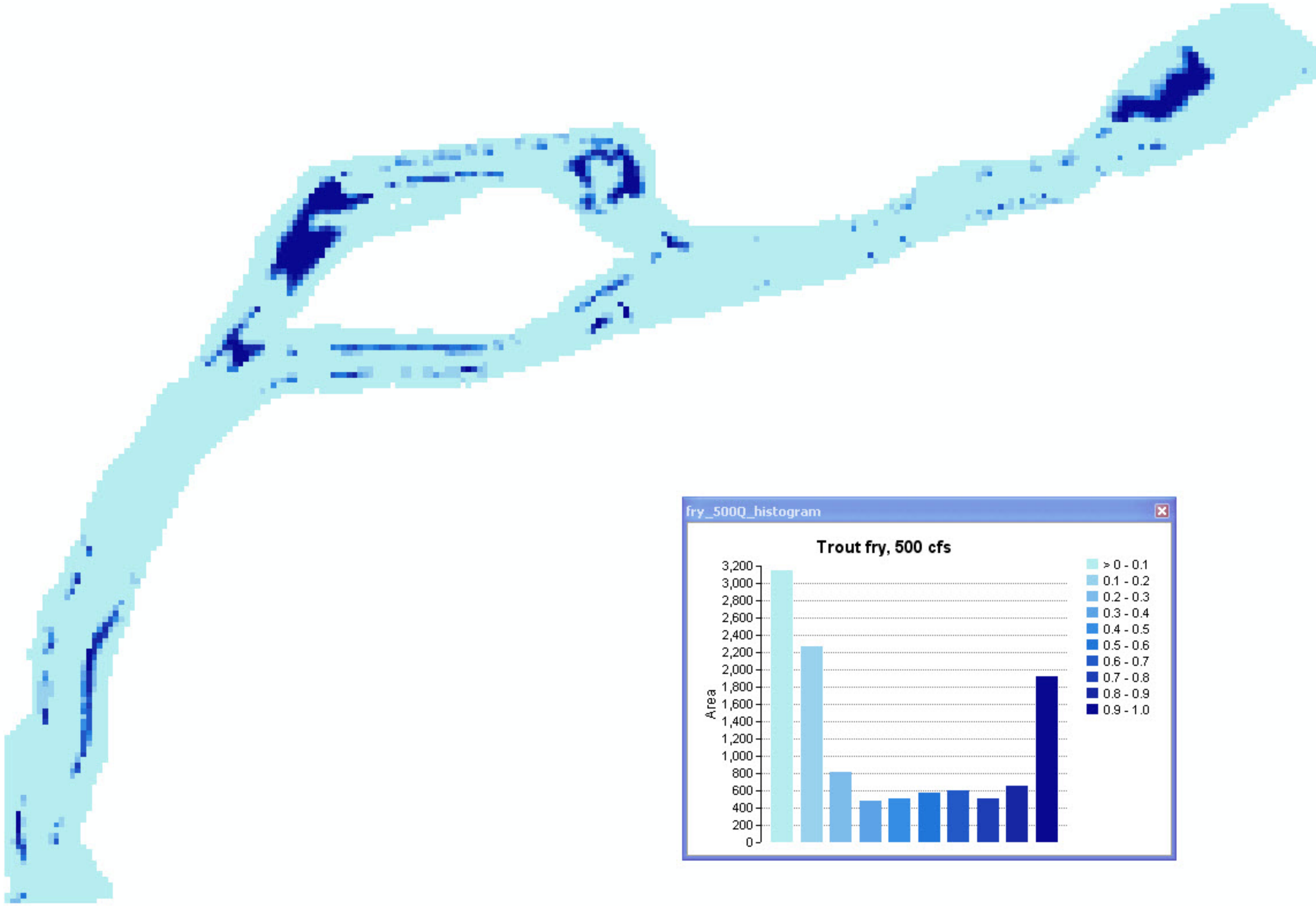


Figure A-75. Trout fry habitat map, Lyons Gulch site, 500 cfs.

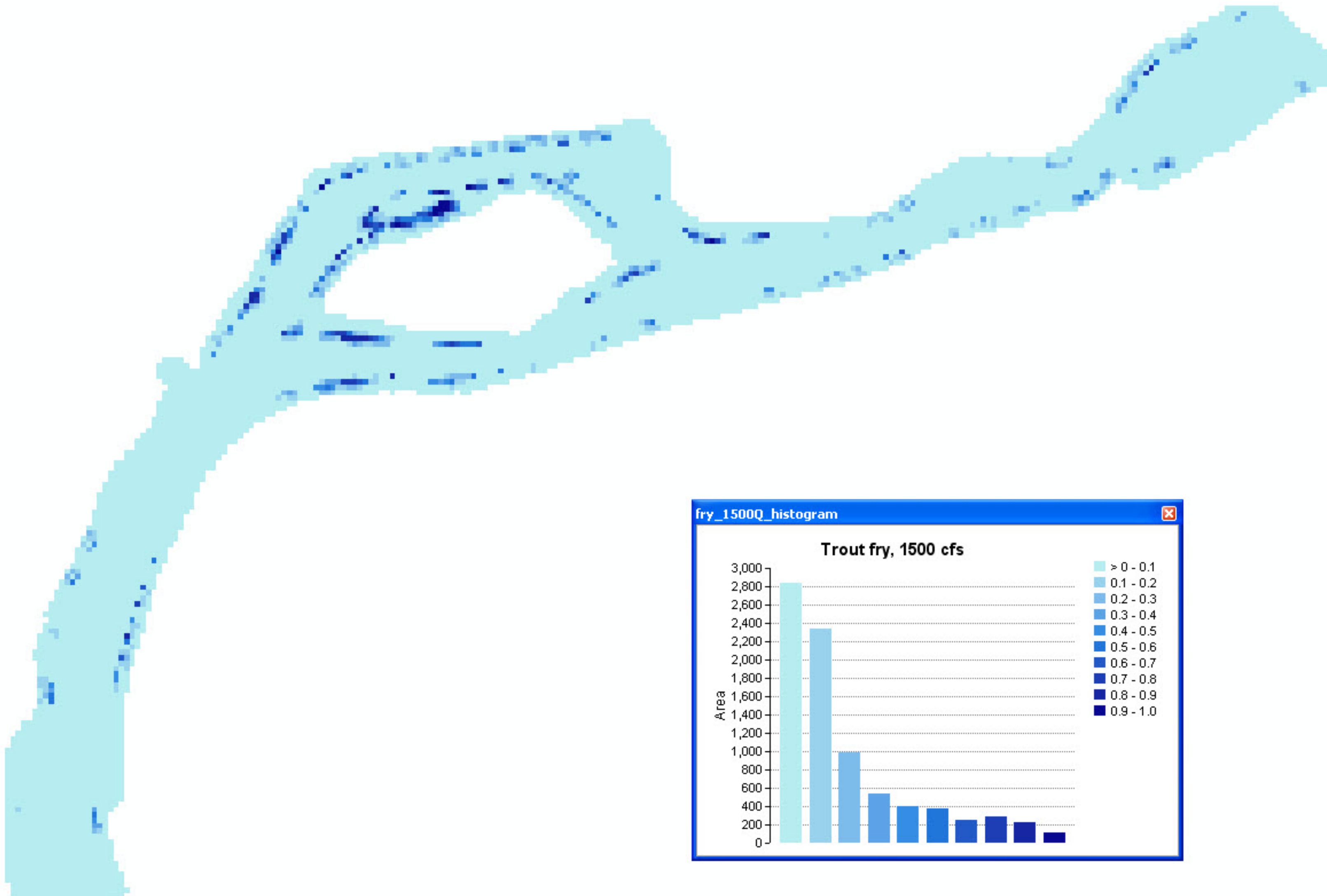


Figure A-76. Trout fry habitat map, Lyons Gulch site, 1500 cfs.

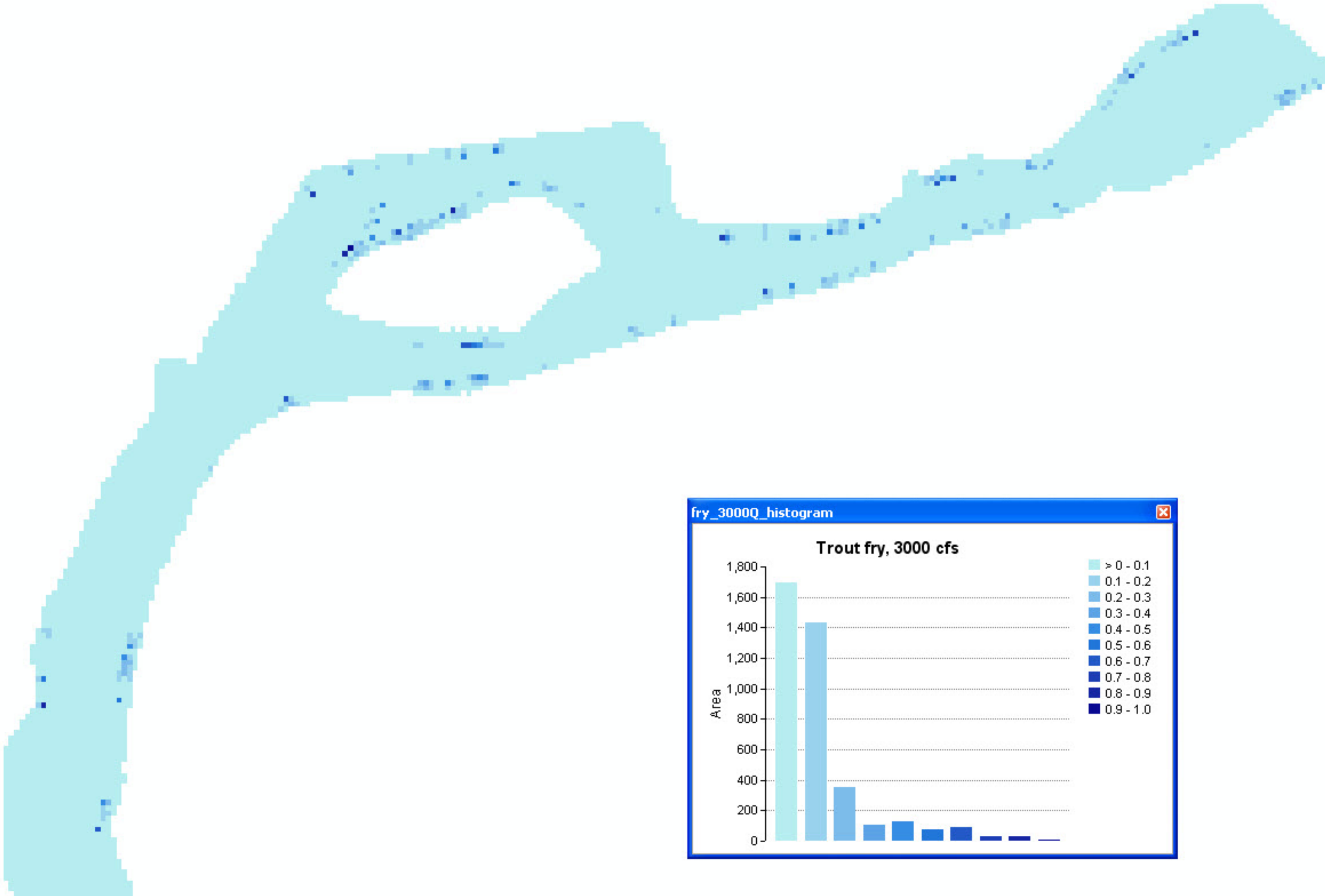


Figure A-77. Trout fry habitat map, Lyons Gulch site, 3000 cfs.

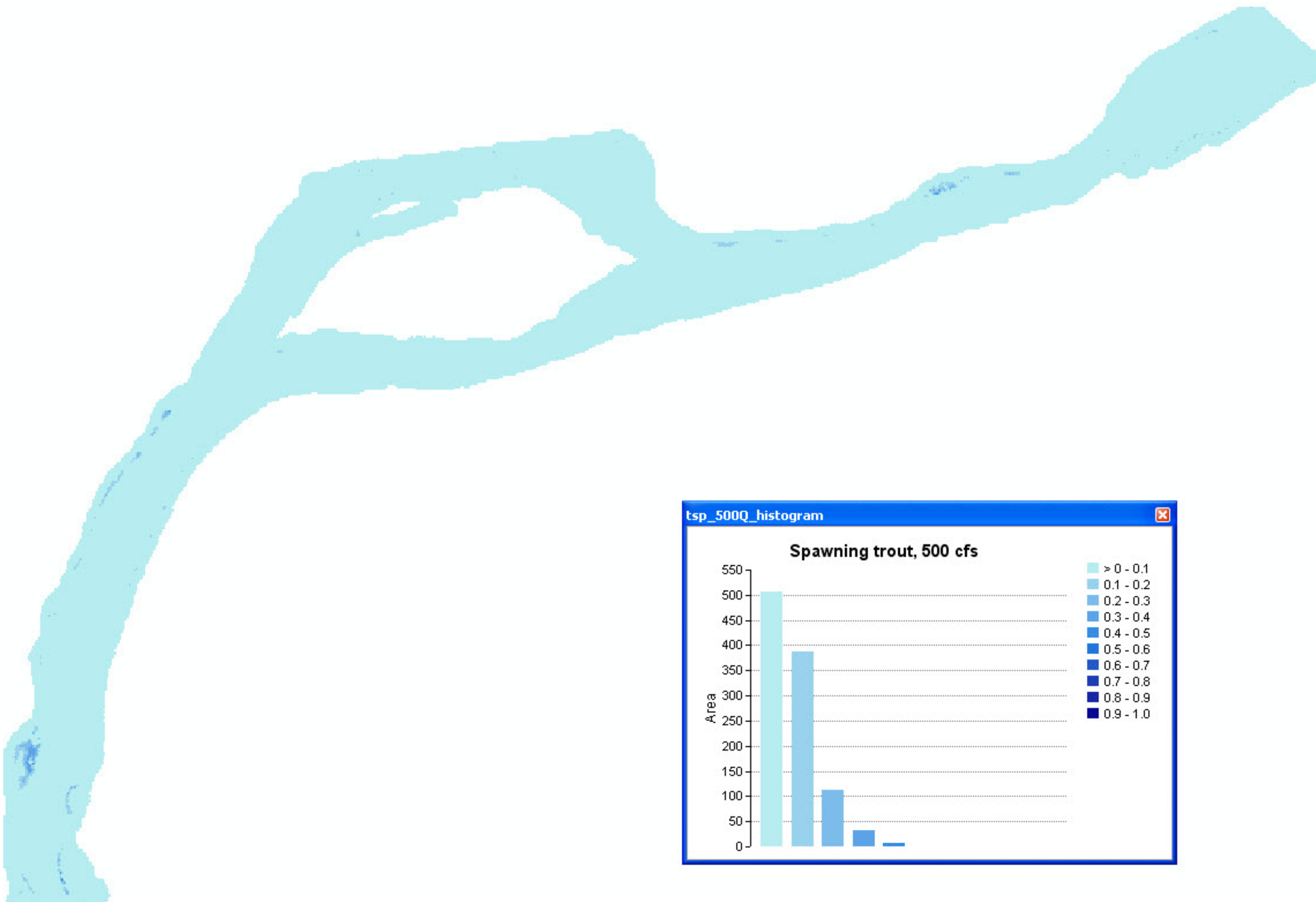


Figure A-78. Trout spawning habitat map, Lyons Gulch site, 500 cfs.

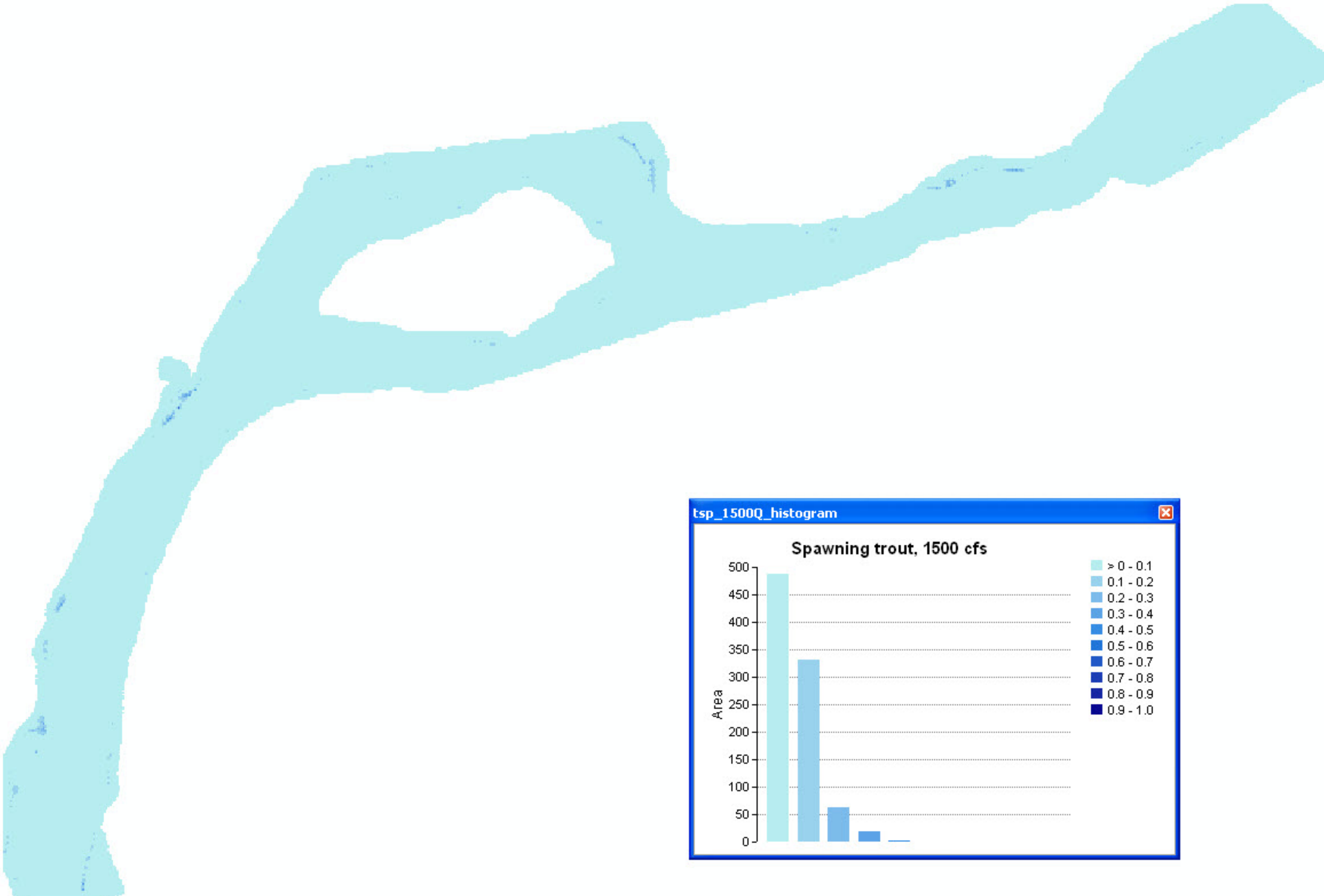


Figure A-79. Trout spawning habitat map, Lyons Gulch site, 1500 cfs.

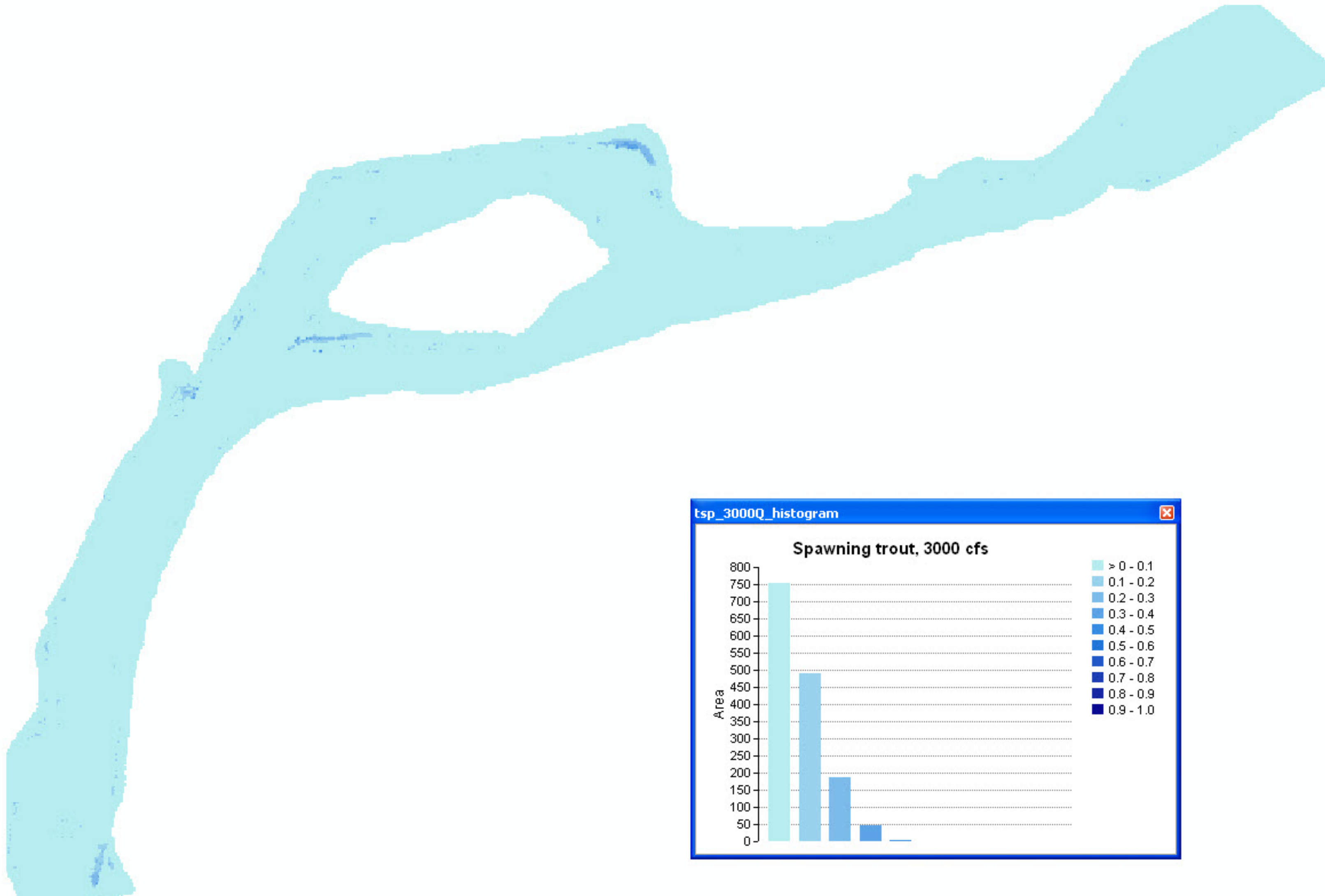


Figure A-80. Trout spawning habitat map, Lyons Gulch site, 3000 cfs.

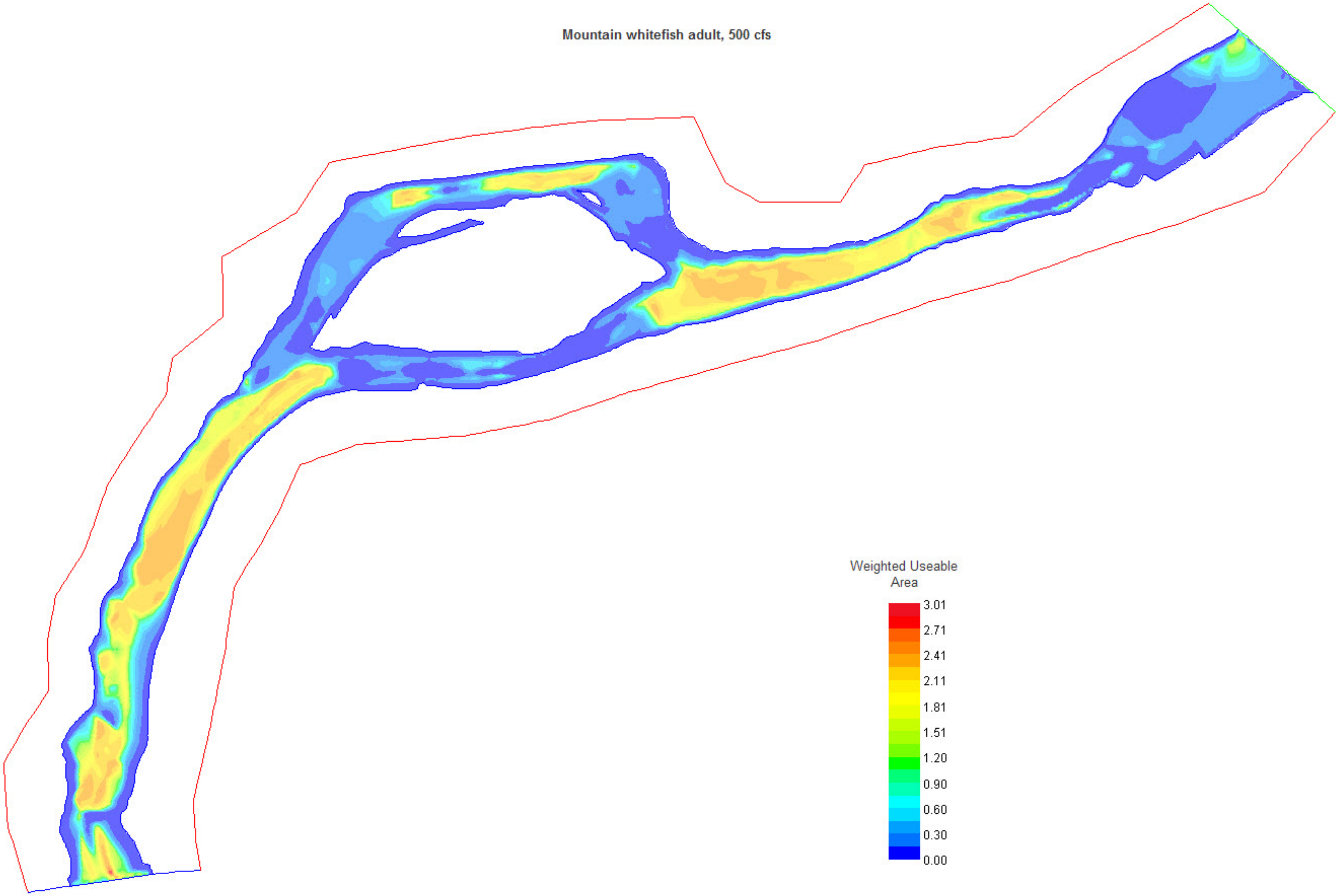


Figure A-81. Adult mountain whitefish habitat map, Lyons Gulch site, 500 cfs.

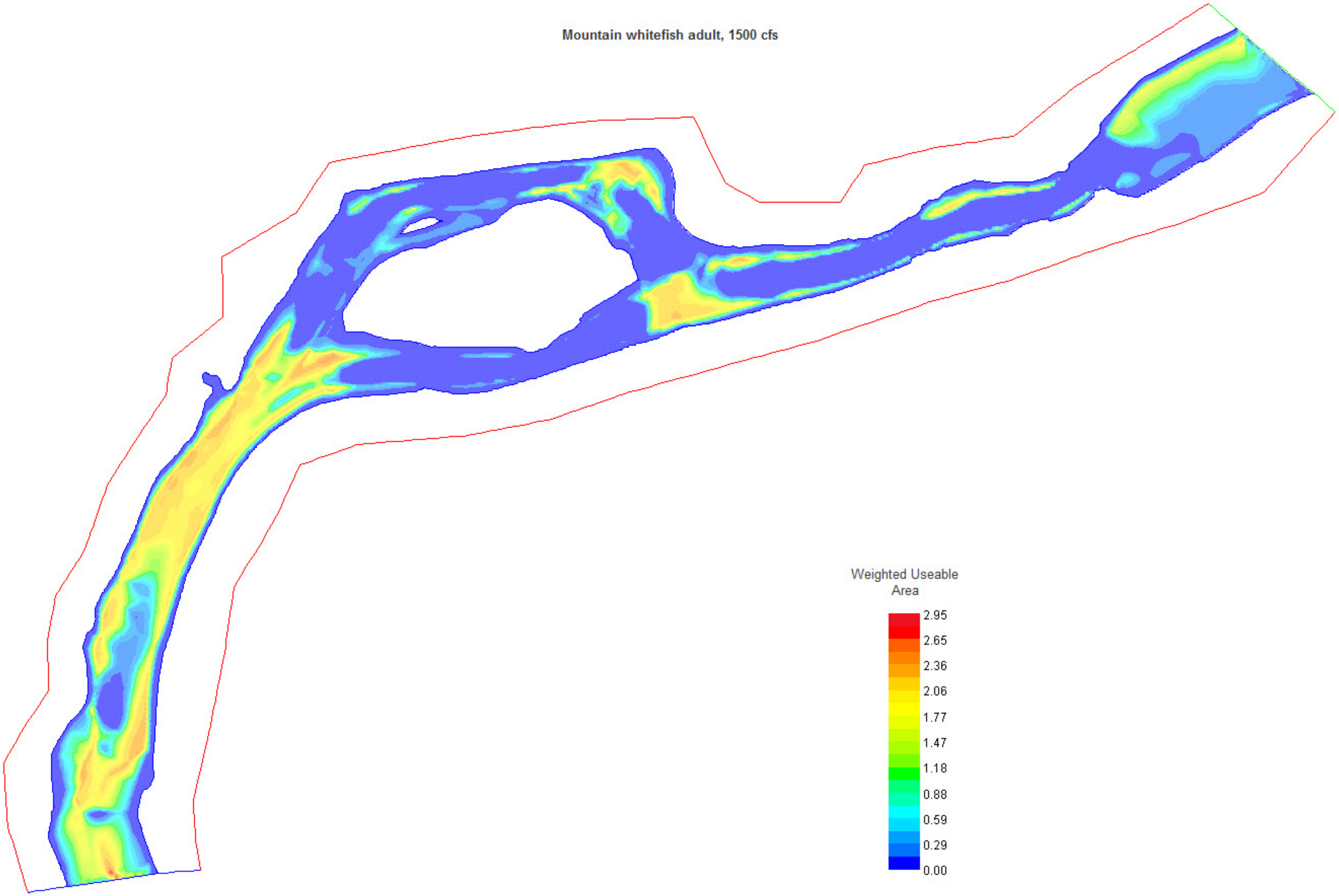


Figure A-82. Adult mountain whitefish habitat map, Lyons Gulch site, 1500 cfs.

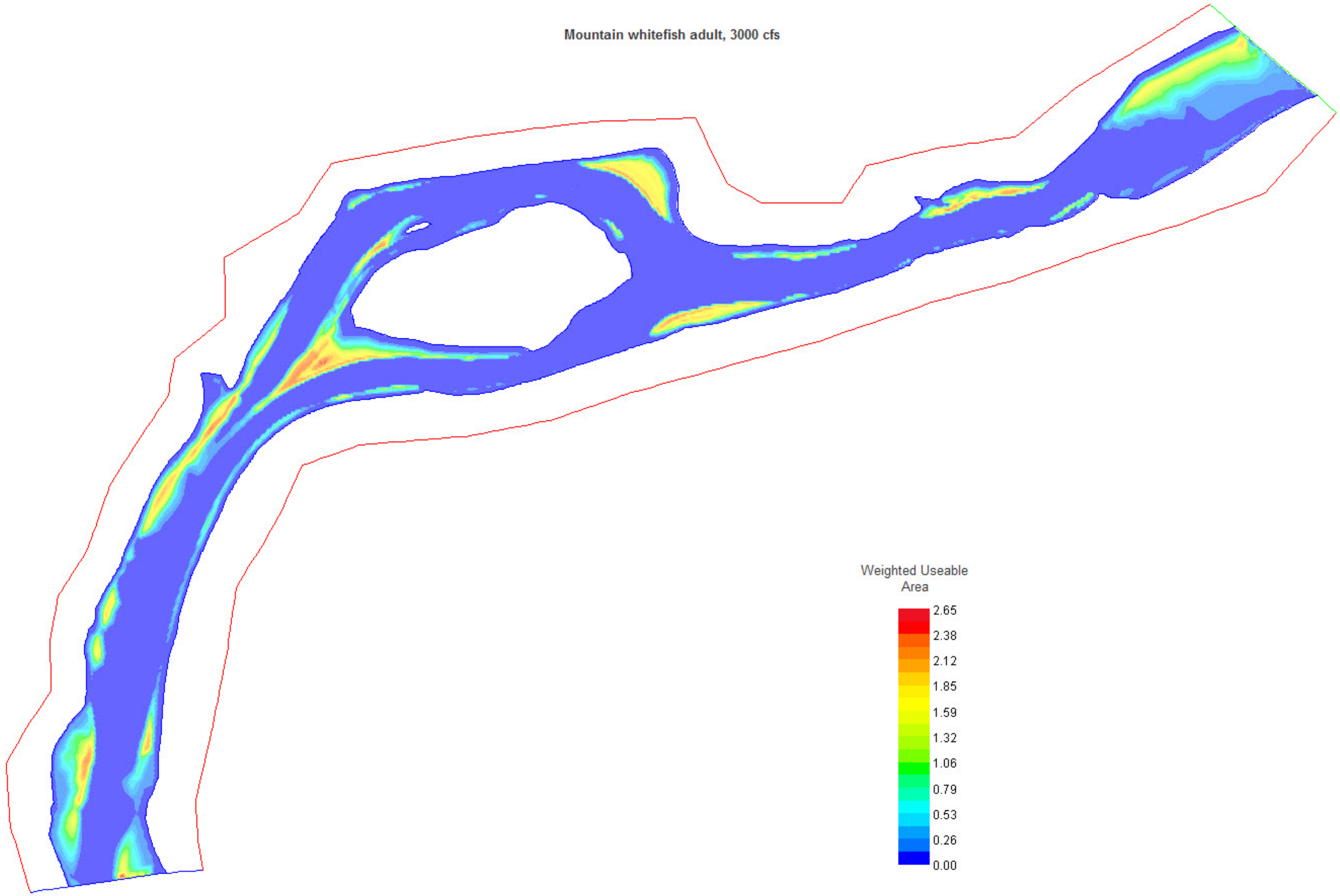


Figure A-83. Adult mountain whitefish habitat map, Lyons Gulch site, 3000 cfs.

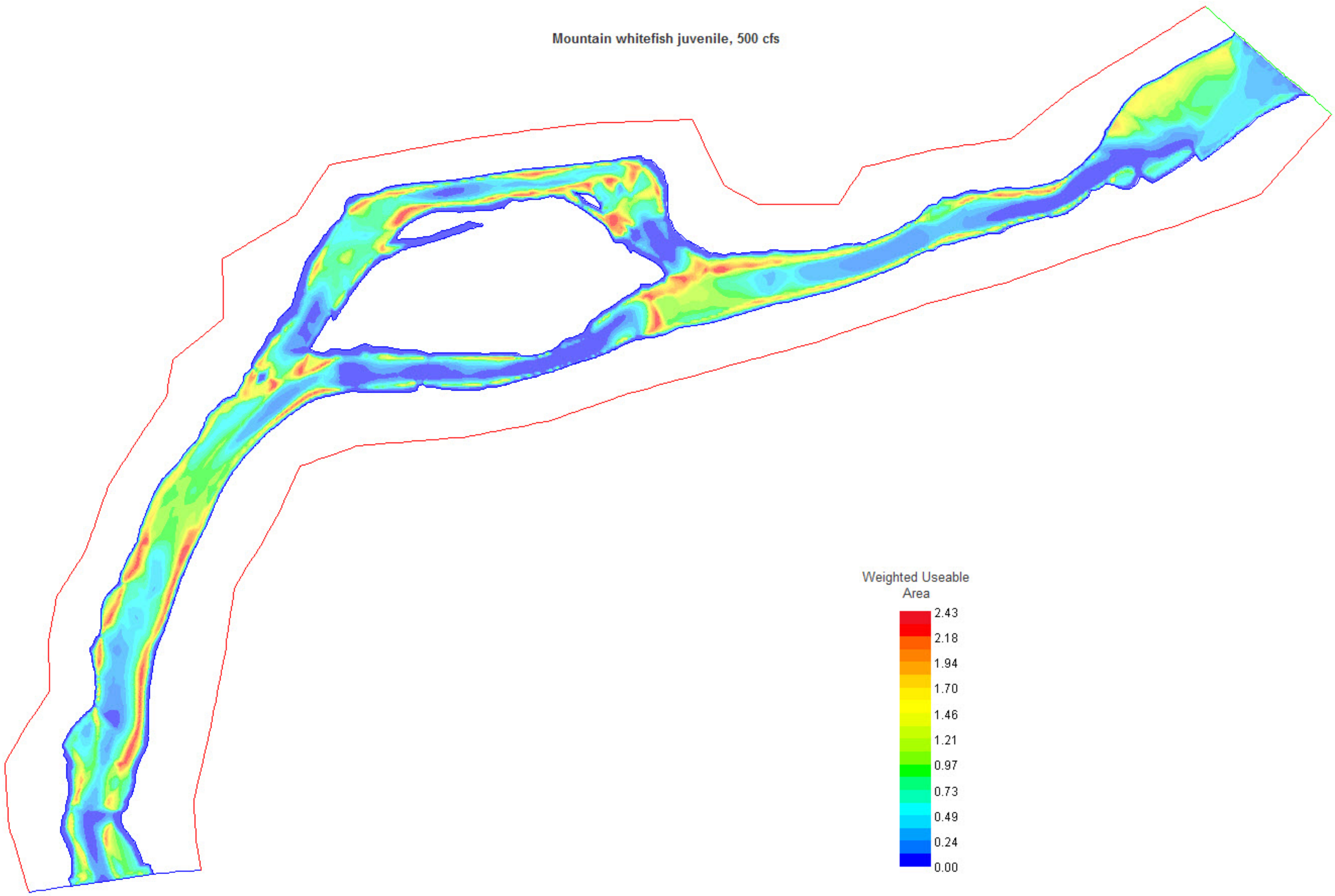


Figure A-84. Juvenile mountain whitefish habitat map, Lyons Gulch site, 500 cfs.

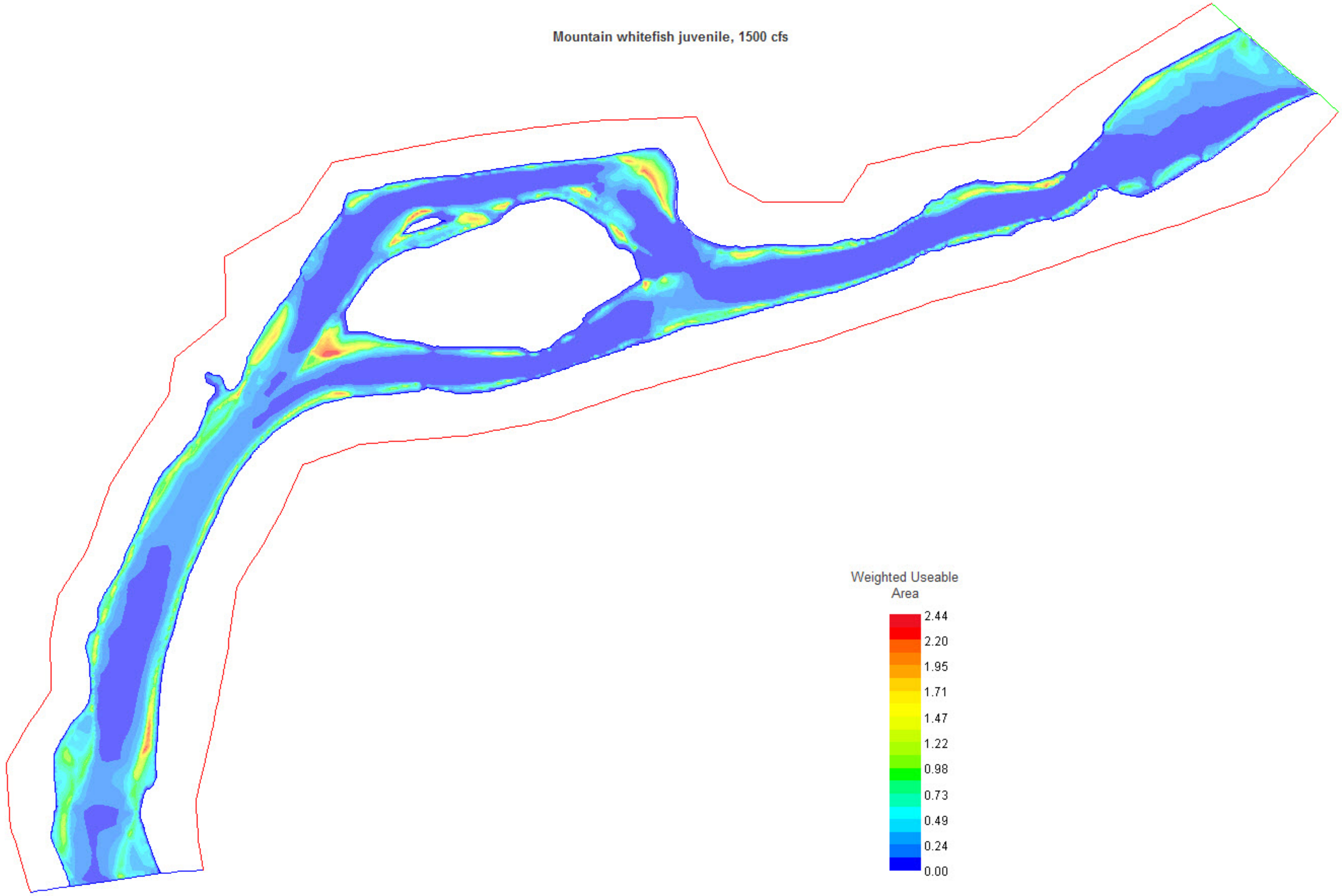


Figure A-85. Juvenile mountain whitefish habitat map, Lyons Gulch site, 1500 cfs.

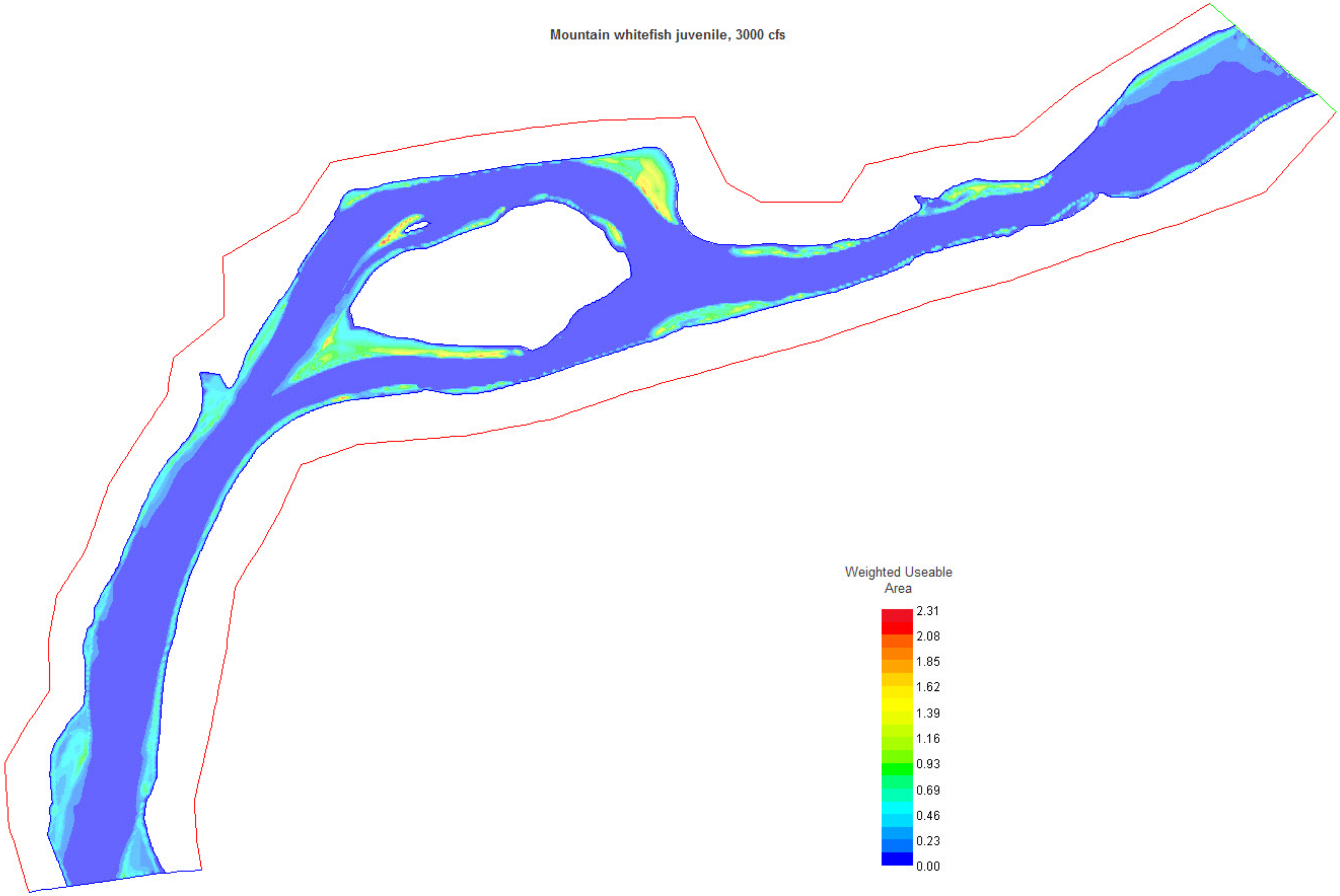


Figure A-86. Juvenile mountain whitefish habitat map, Lyons Gulch site, 3000 cfs.

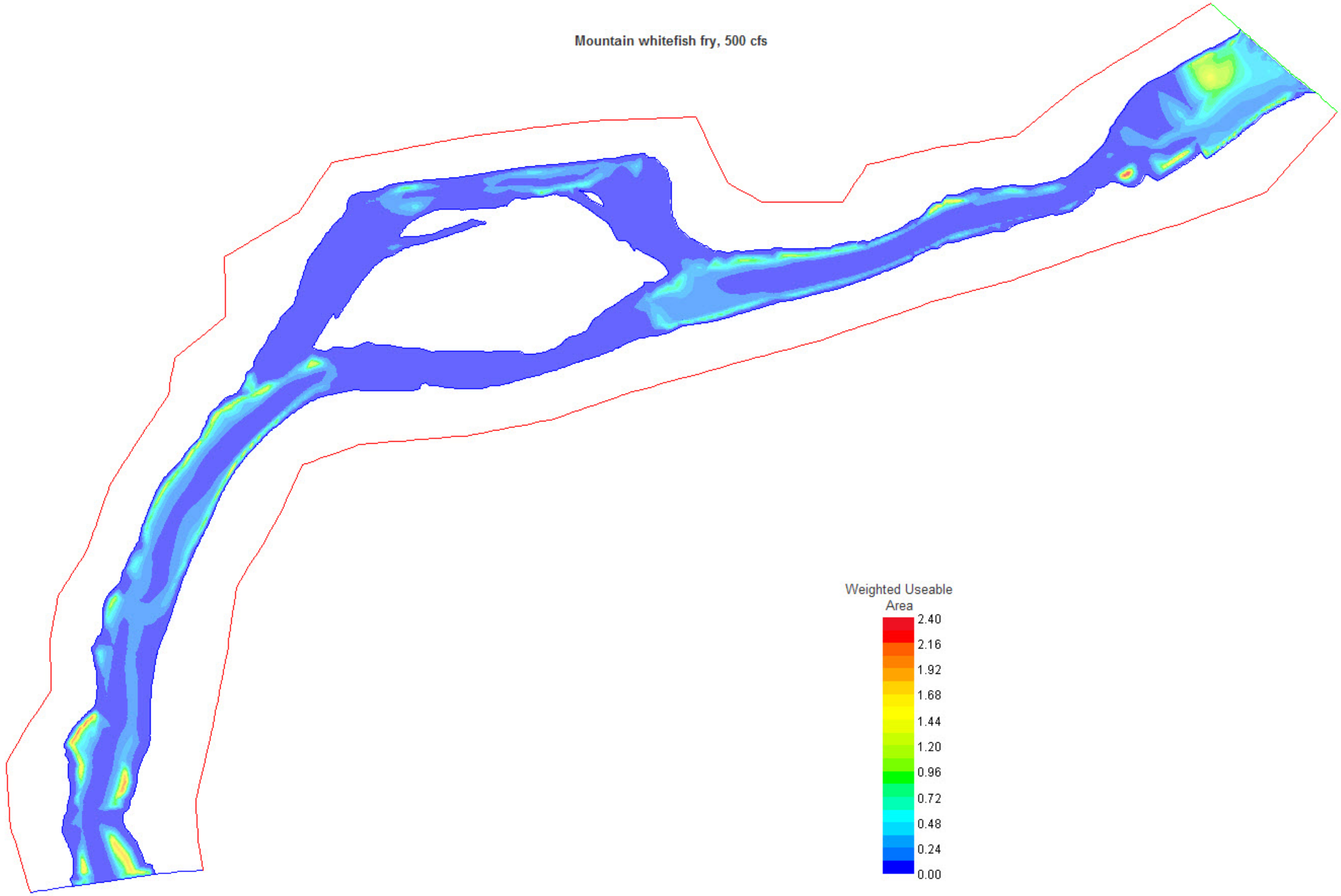


Figure A-87. Mountain whitefish fry habitat map, Lyons Gulch site, 500 cfs.

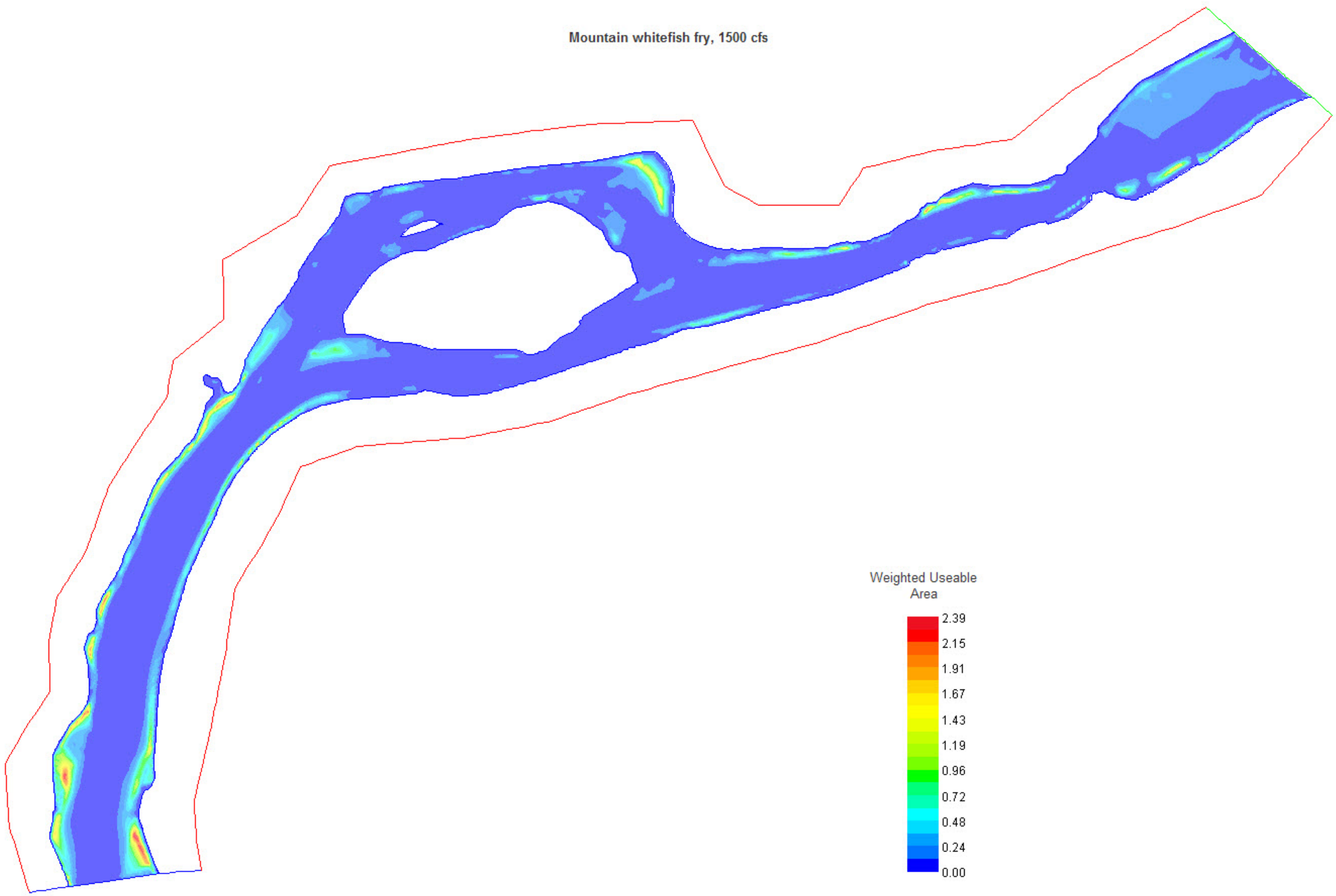


Figure A-88. Mountain whitefish fry habitat map, Lyons Gulch site, 1500 cfs.

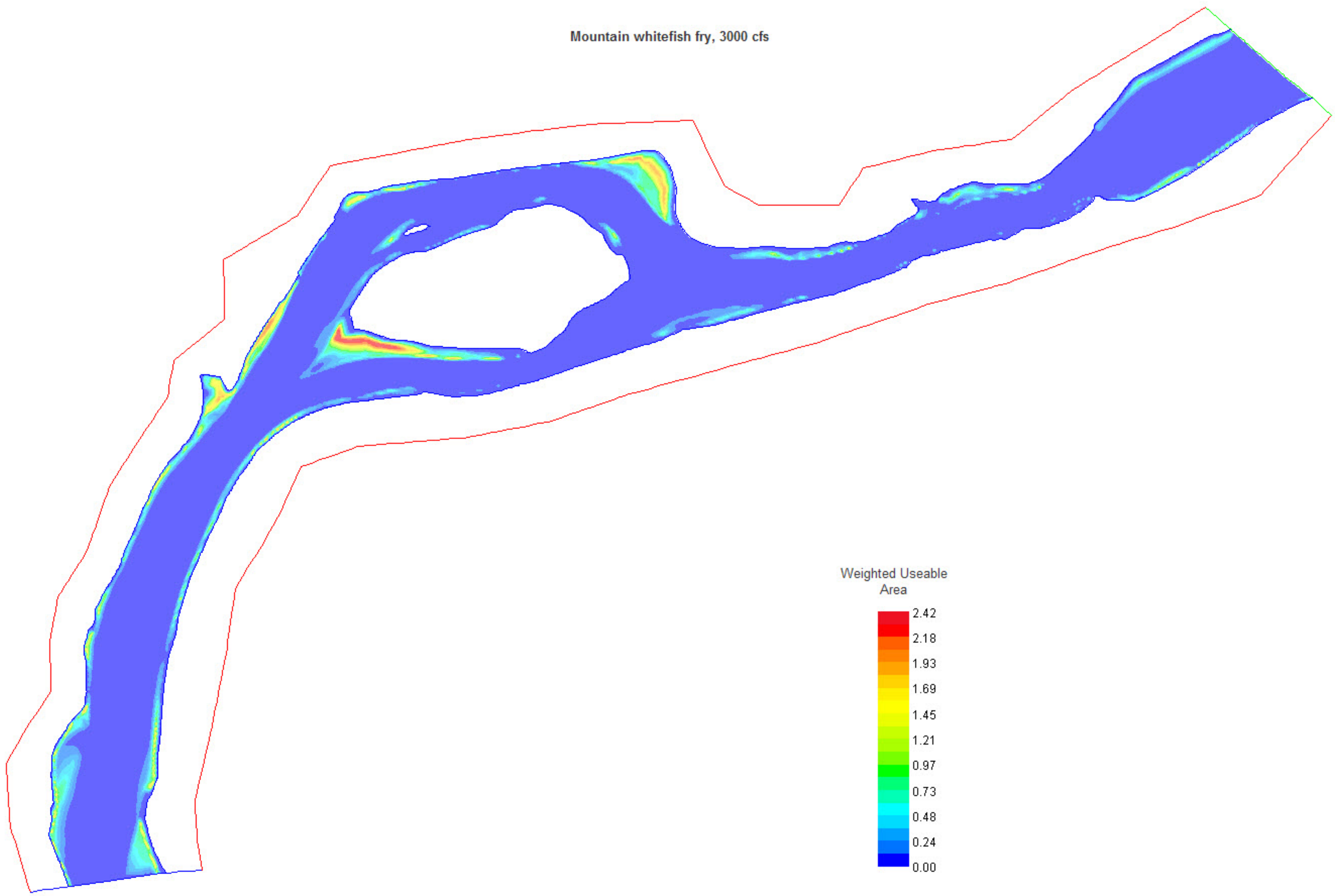


Figure A-89. Mountain whitefish fry habitat map, Lyons Gulch site, 3000 cfs.

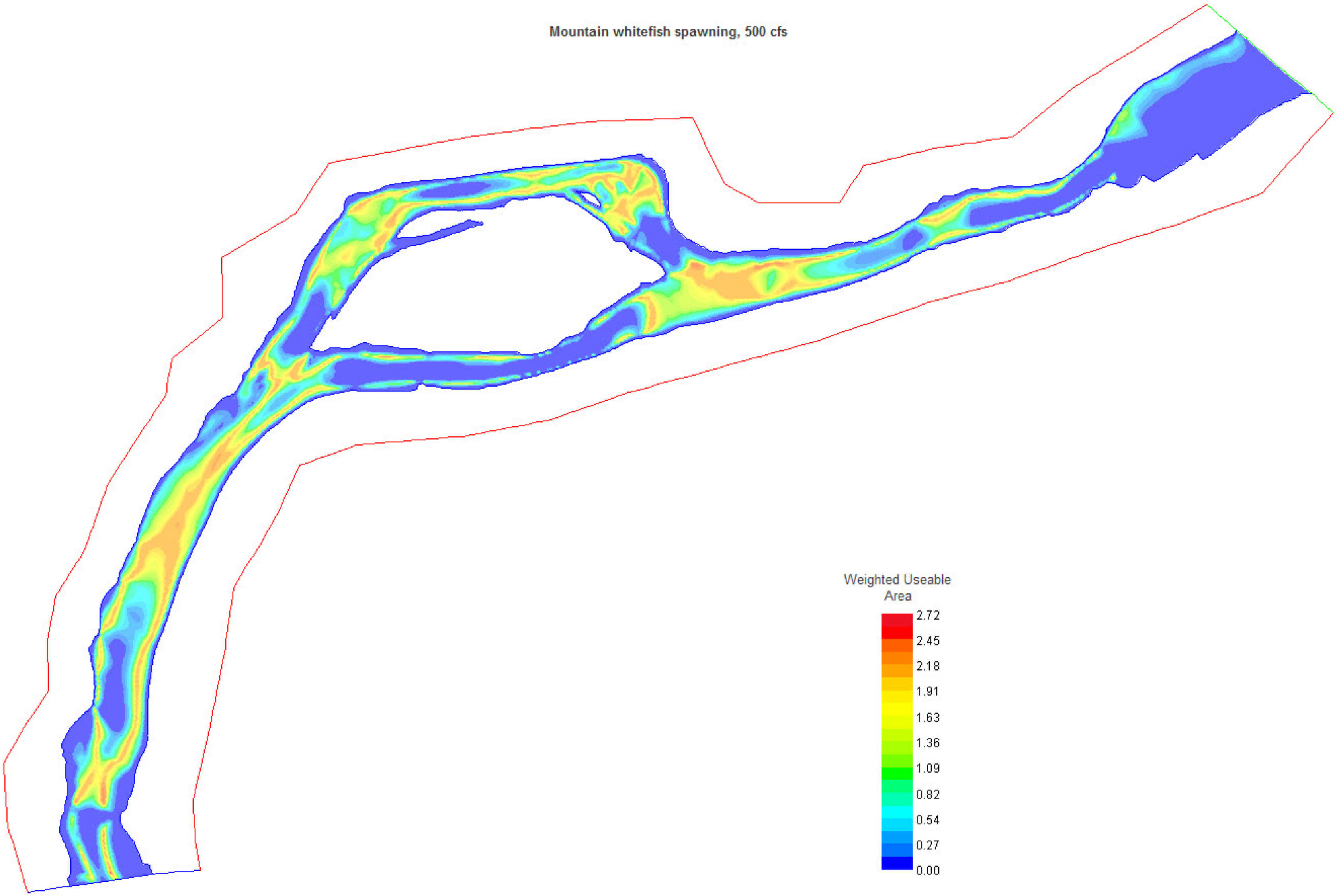


Figure A-90. Mountain whitefish spawning habitat map, Lyons Gulch site, 500 cfs.

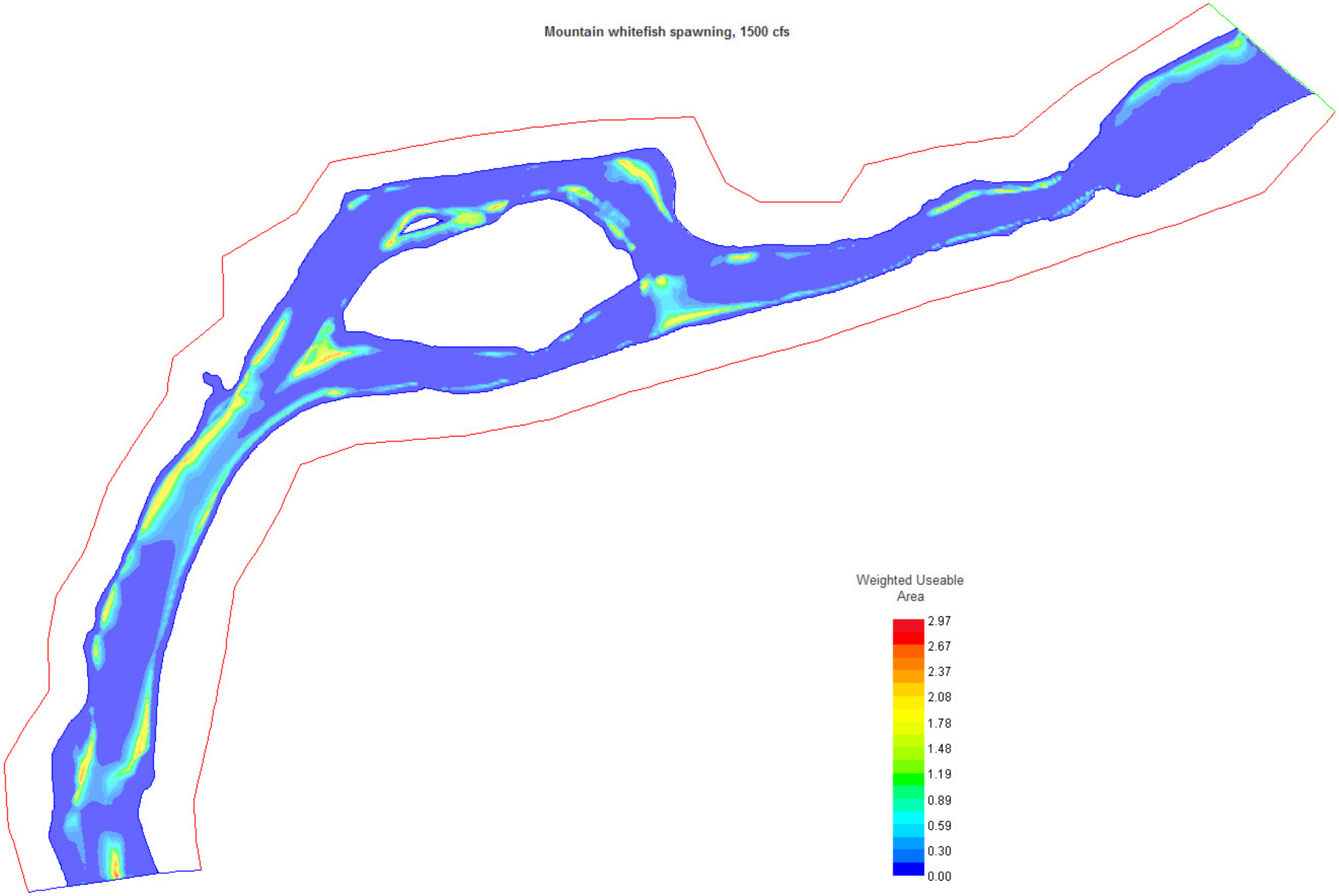


Figure A-91. Mountain whitefish spawning habitat map, Lyons Gulch site, 1500 cfs.

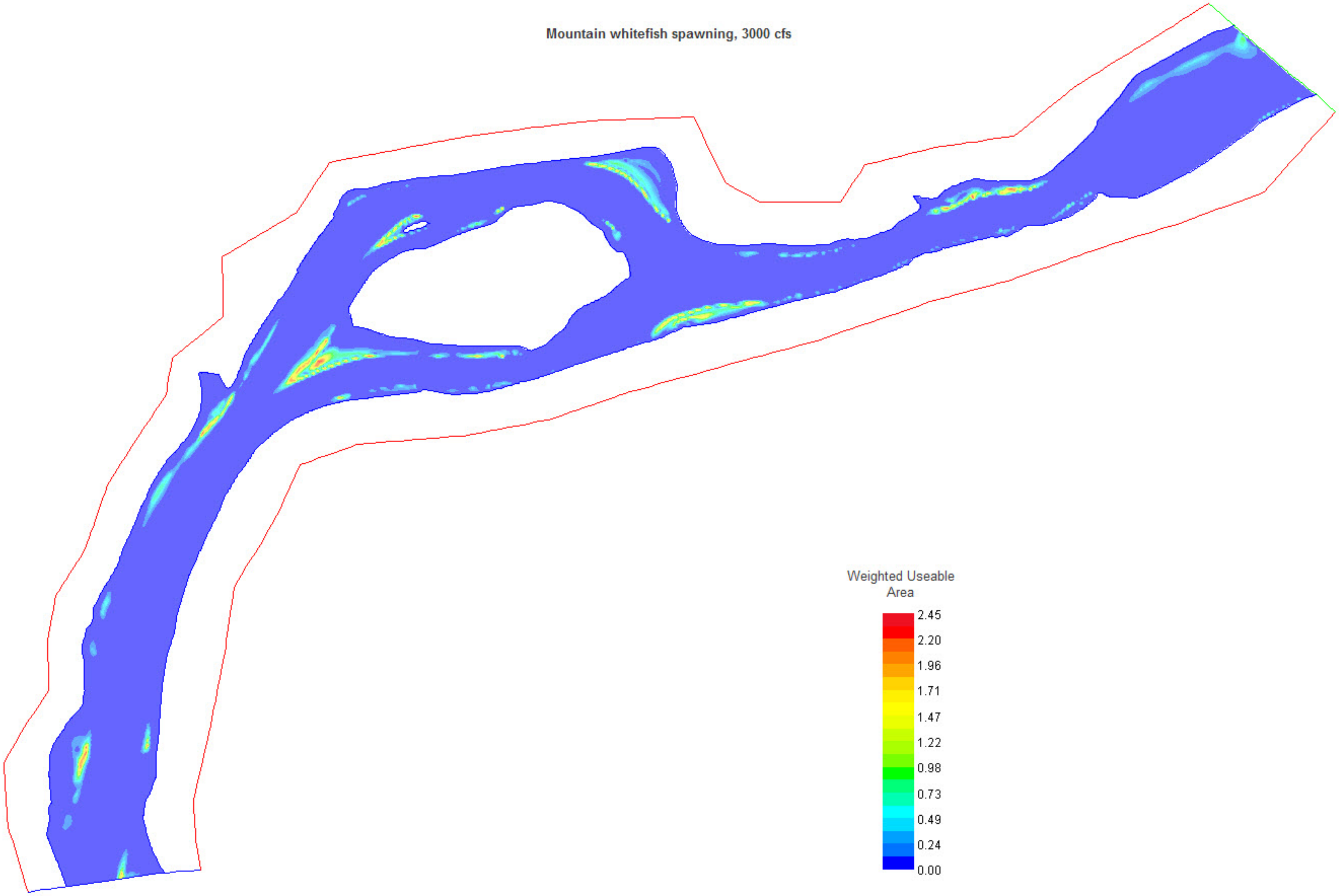


Figure A-92. Mountain whitefish spawning habitat map, Lyons Gulch site, 3000 cfs.

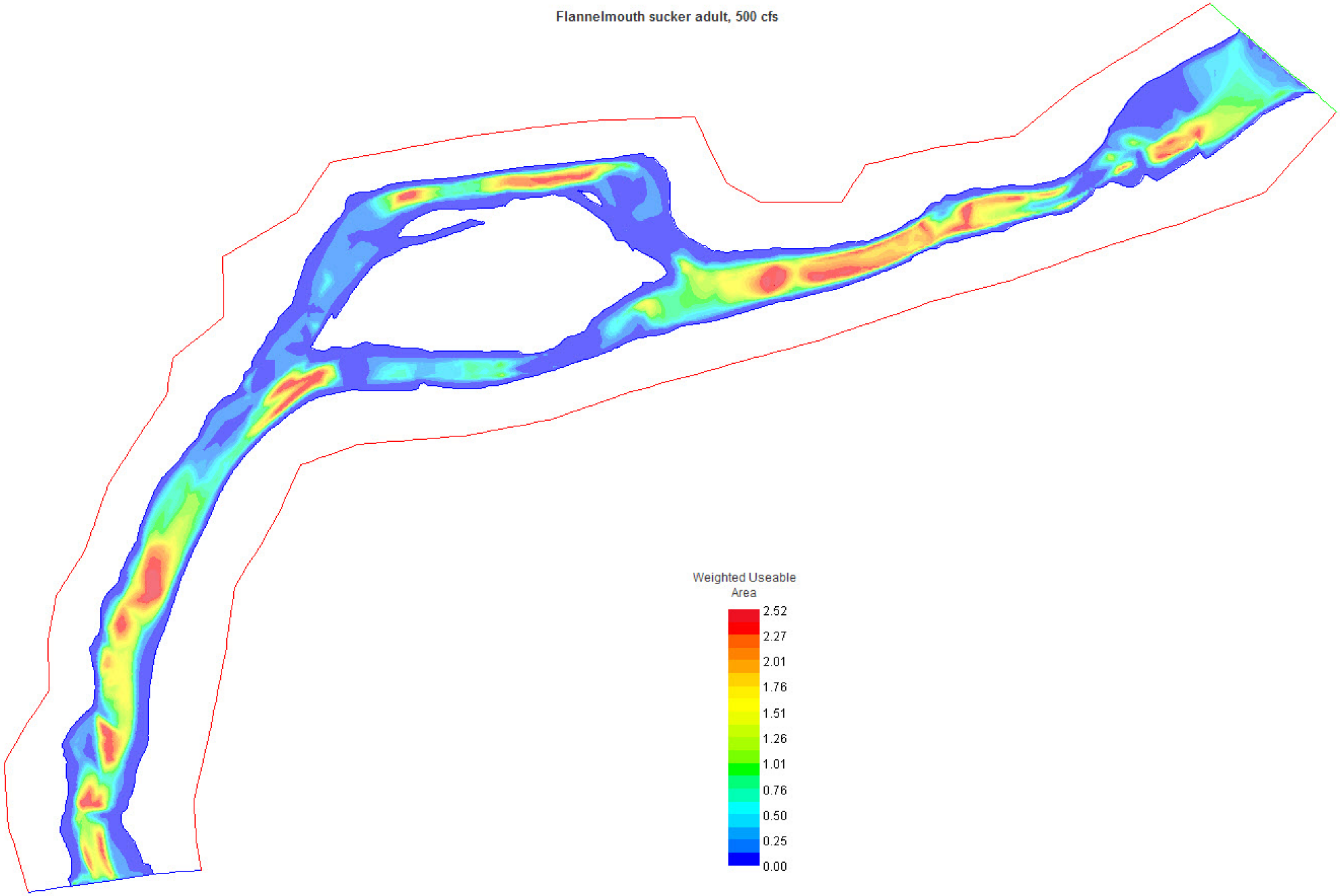


Figure A-93. Adult flannelmouth sucker habitat map, Lyons Gulch site, 500 cfs.

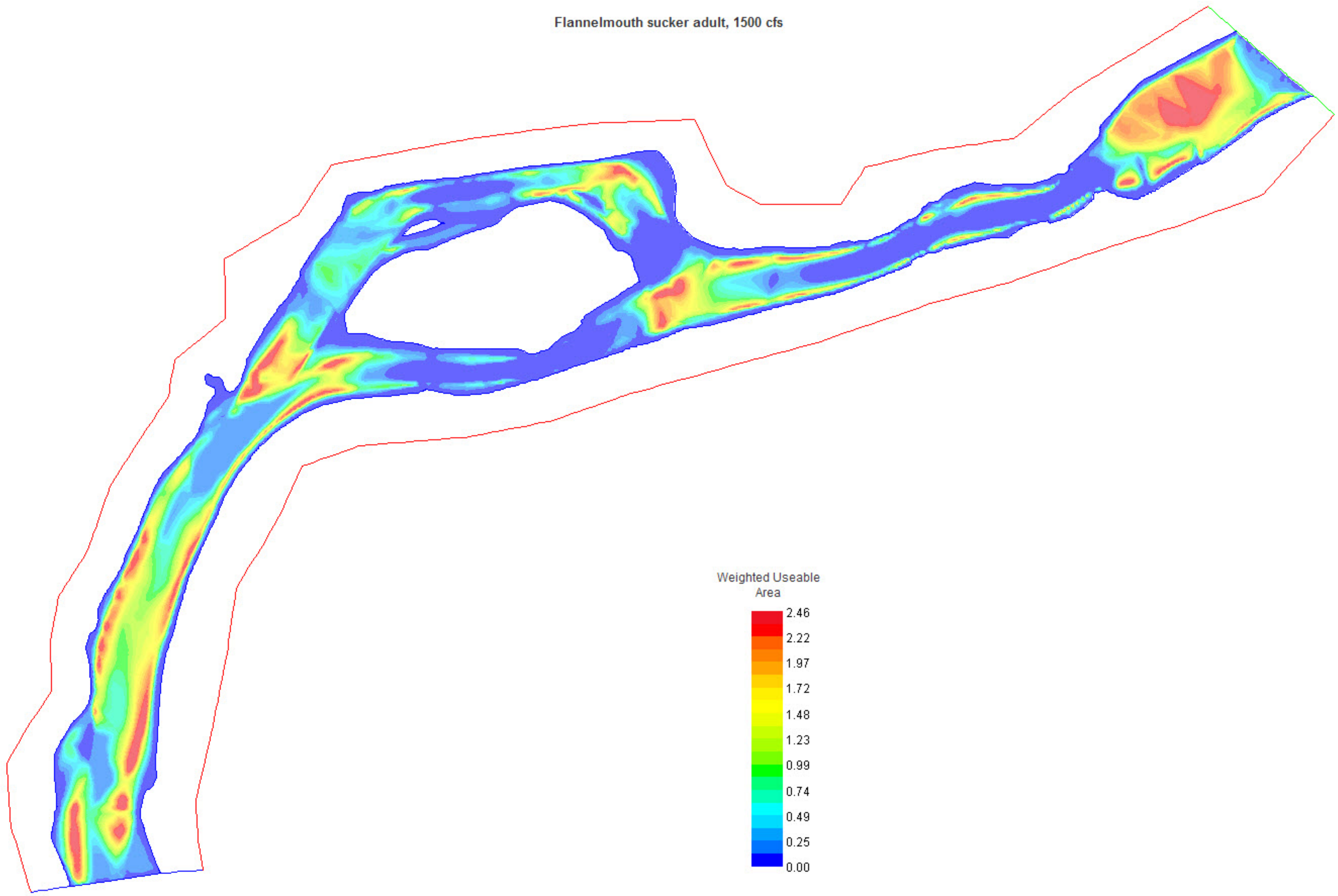


Figure A-94. Adult flannelmouth sucker habitat map, Lyons Gulch site, 1500 cfs.

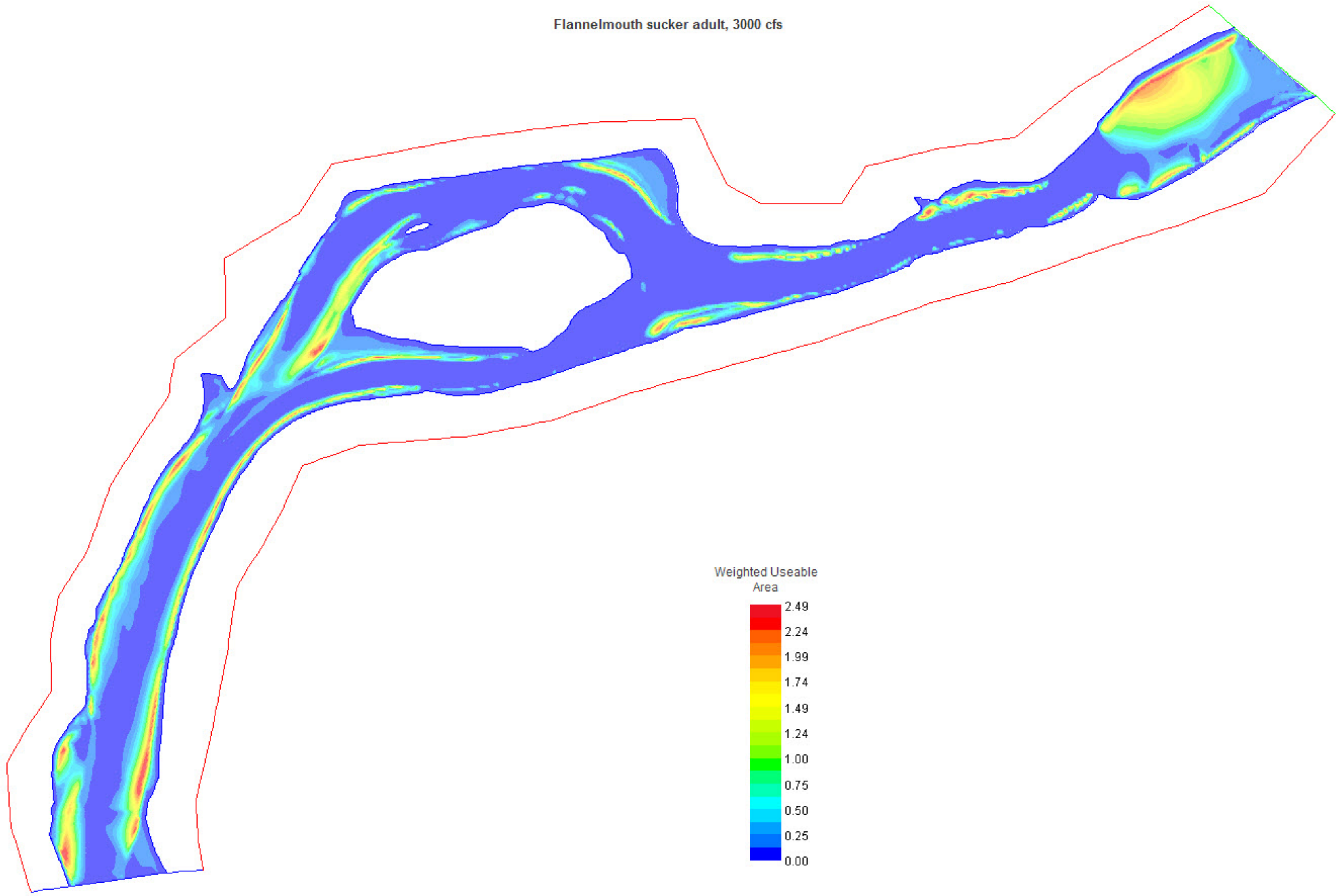


Figure A-95. Adult flannelmouth sucker habitat map, Lyons Gulch site, 3000 cfs.

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Appendix B – Habitat Time Series Graphs for Pumphouse, Rancho del Rio, and Lyons Gulch sites.

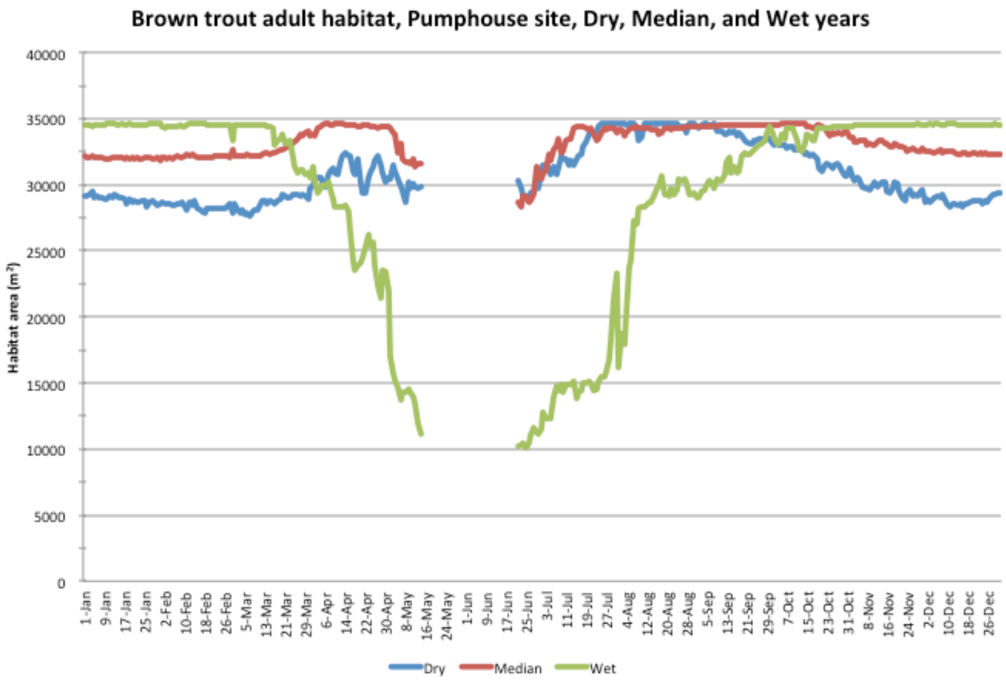

Figure B-1. Adult brown trout habitat time series, dry, median, and wet years, Pumphouse site.

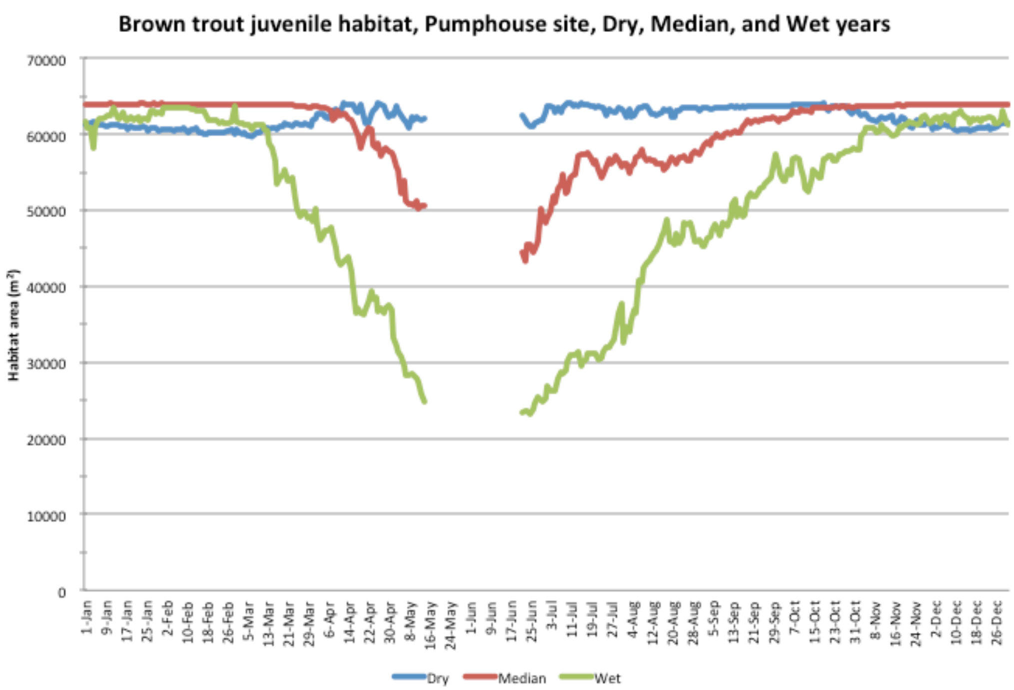

Figure B-2. Juvenile brown trout habitat time series, dry, median, and wet years, Pumphouse site.

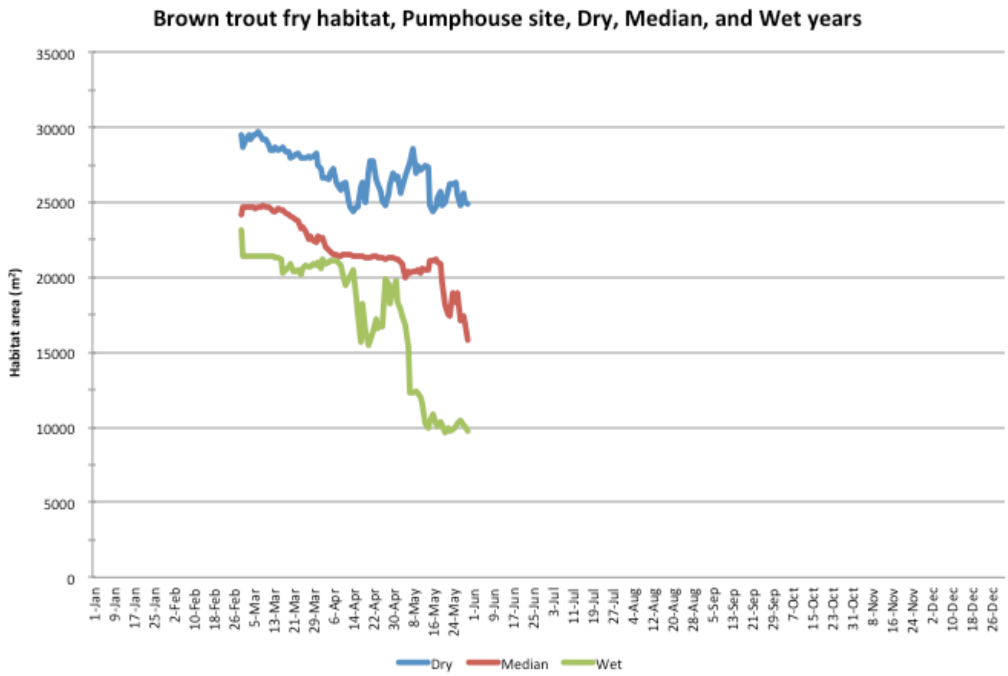

Figure B-3. Brown trout fry habitat time series, dry, median, and wet years, Pumphouse site.

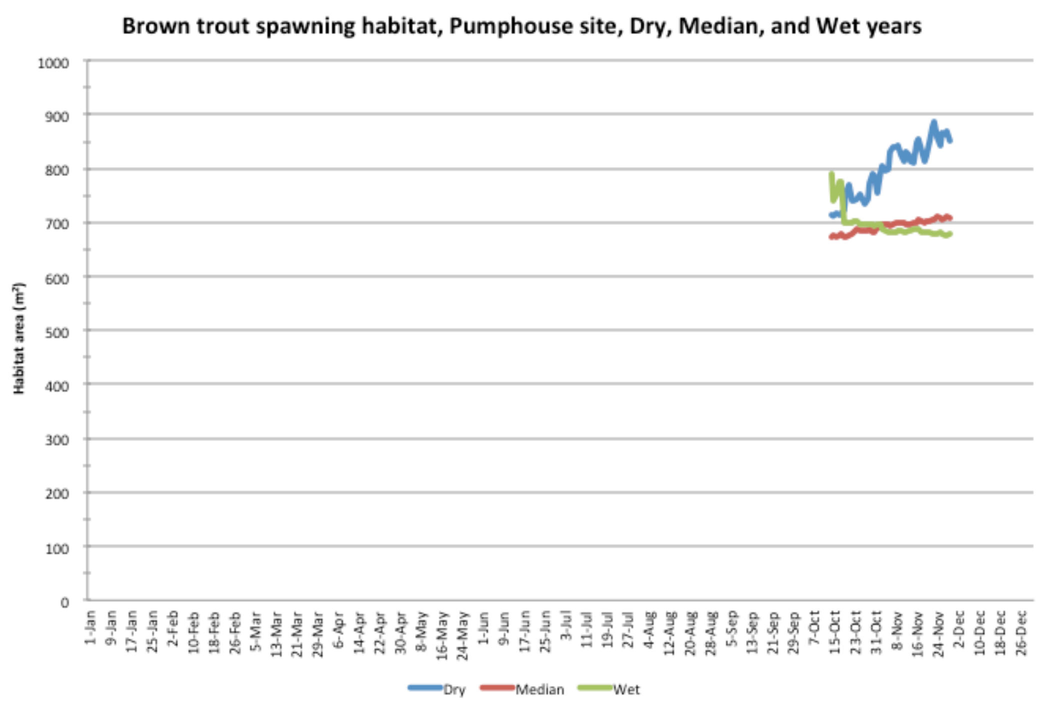

Figure B-4. Brown trout spawning habitat time series, dry, median, and wet years, Pumphouse site.

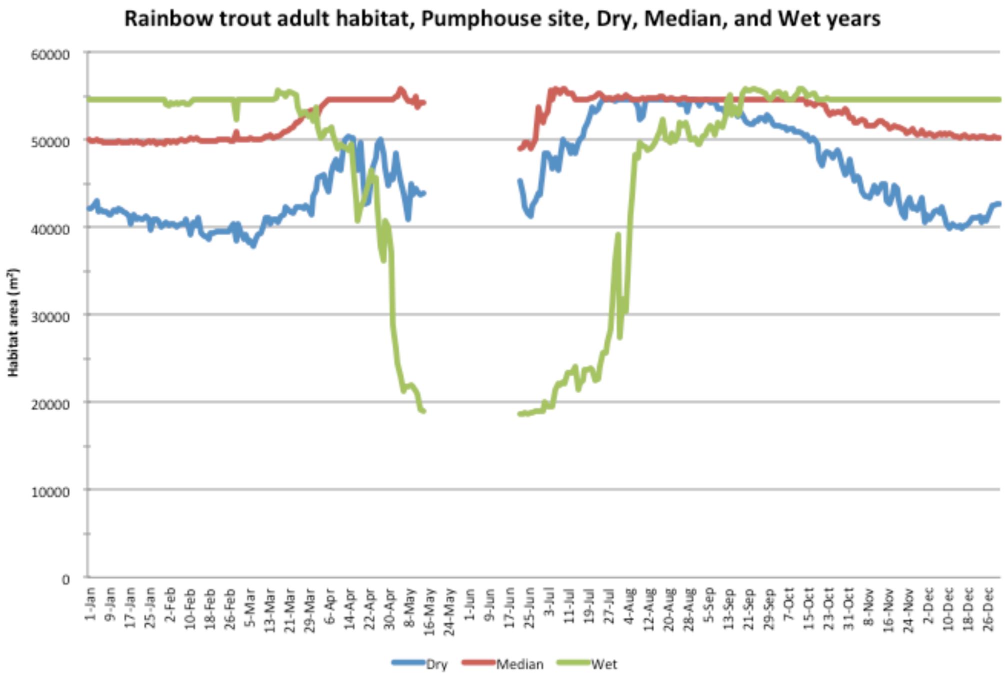

Figure B-5. Adult rainbow trout habitat time series, dry, median, and wet years, Pumphouse site.

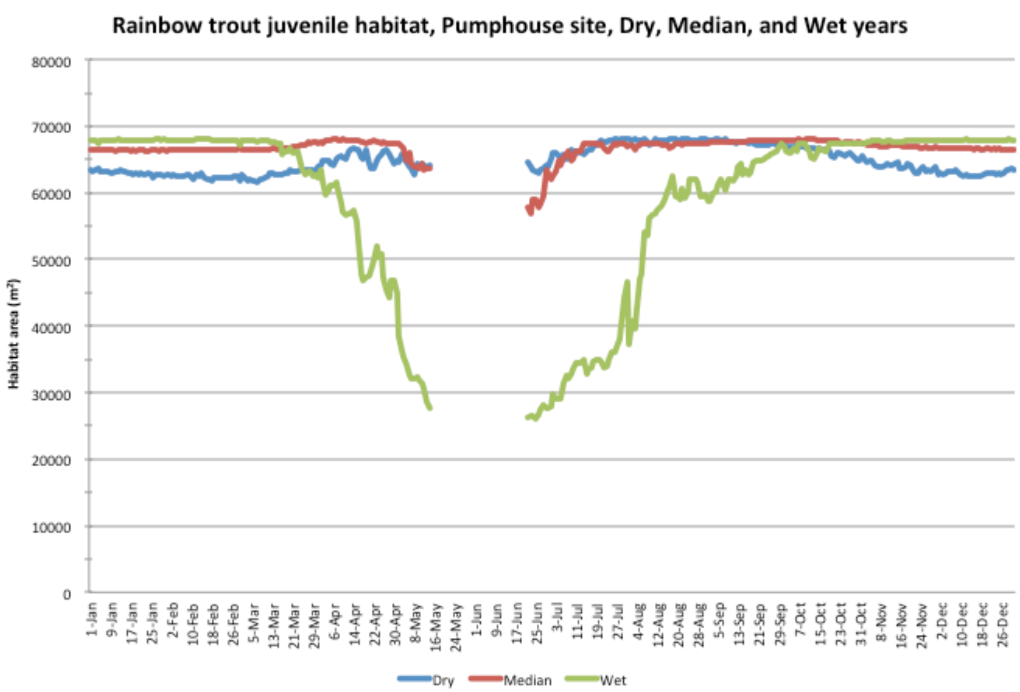

Figure B-6. Juvenile rainbow trout habitat time series, dry, median, and wet years, Pumphouse site.

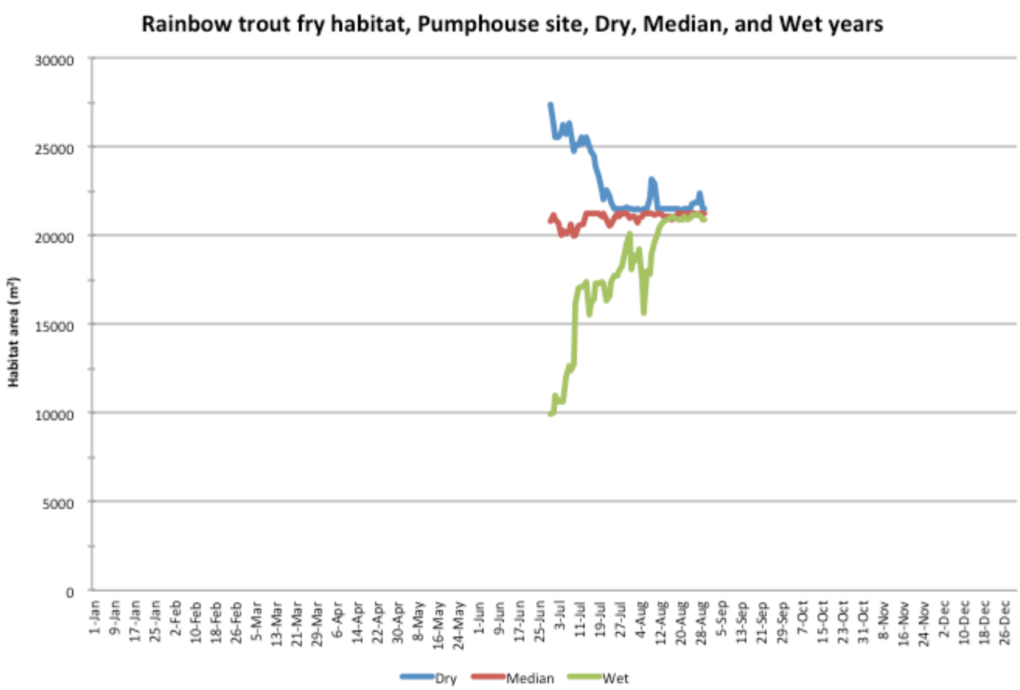

Figure B-7. Rainbow trout fry habitat time series, dry, median, and wet years, Pumphouse site.

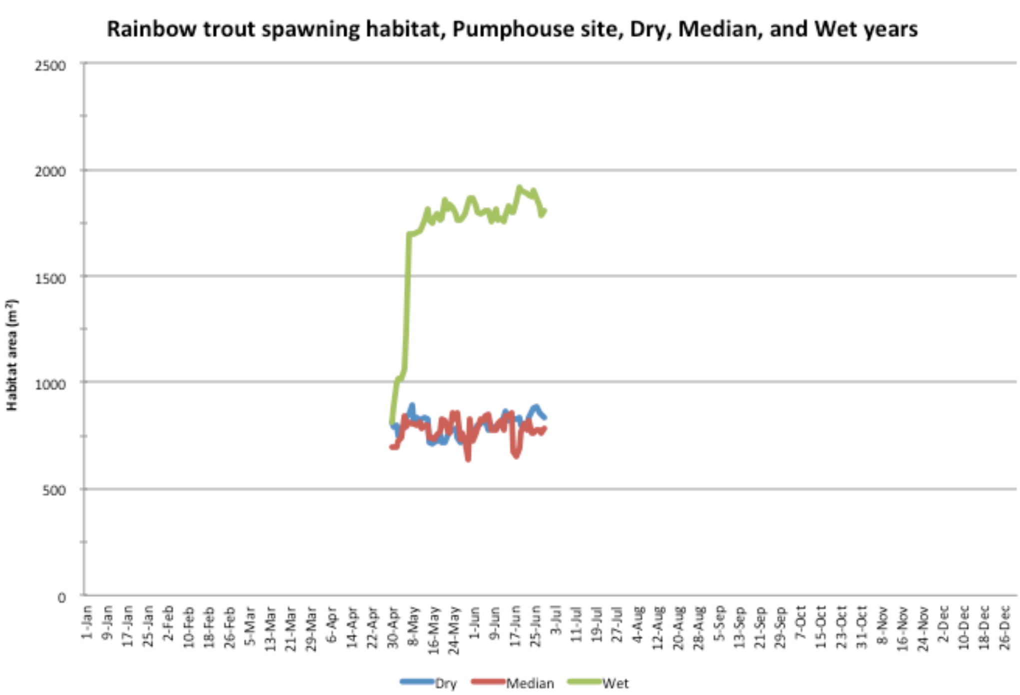

Figure B-8. Rainbow trout spawning habitat time series, dry, median, and wet years, Pumphouse site.

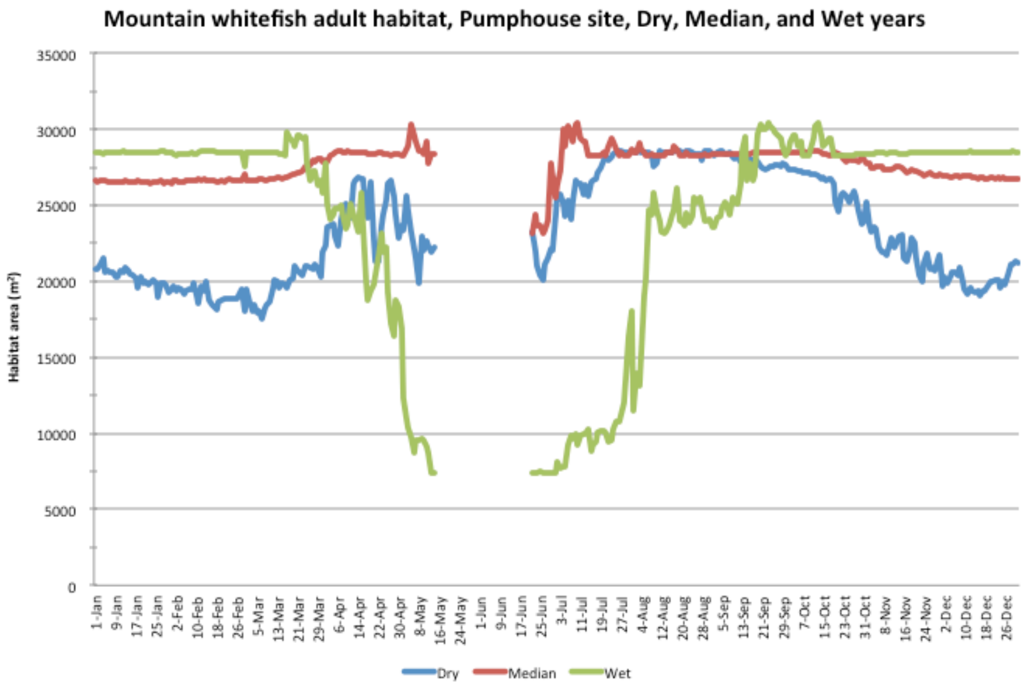

Figure B-9. Adult mountain whitefish habitat time series, dry, median, and wet years, Pumphouse site.

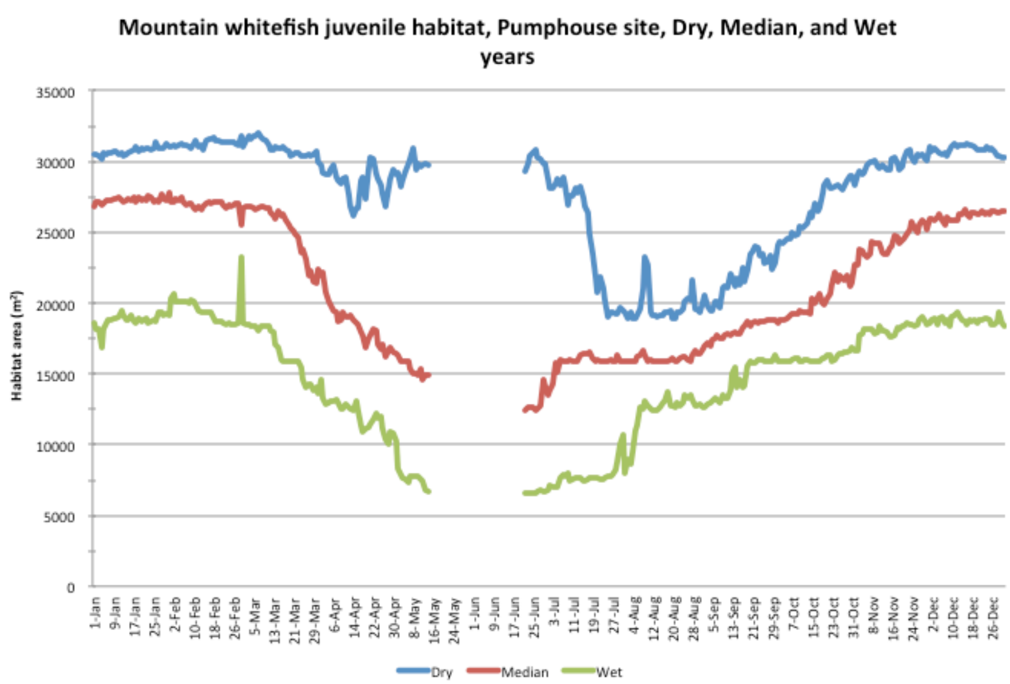

Figure B-10. Juvenile mountain whitefish habitat time series, dry, median, and wet years, Pumphouse site.

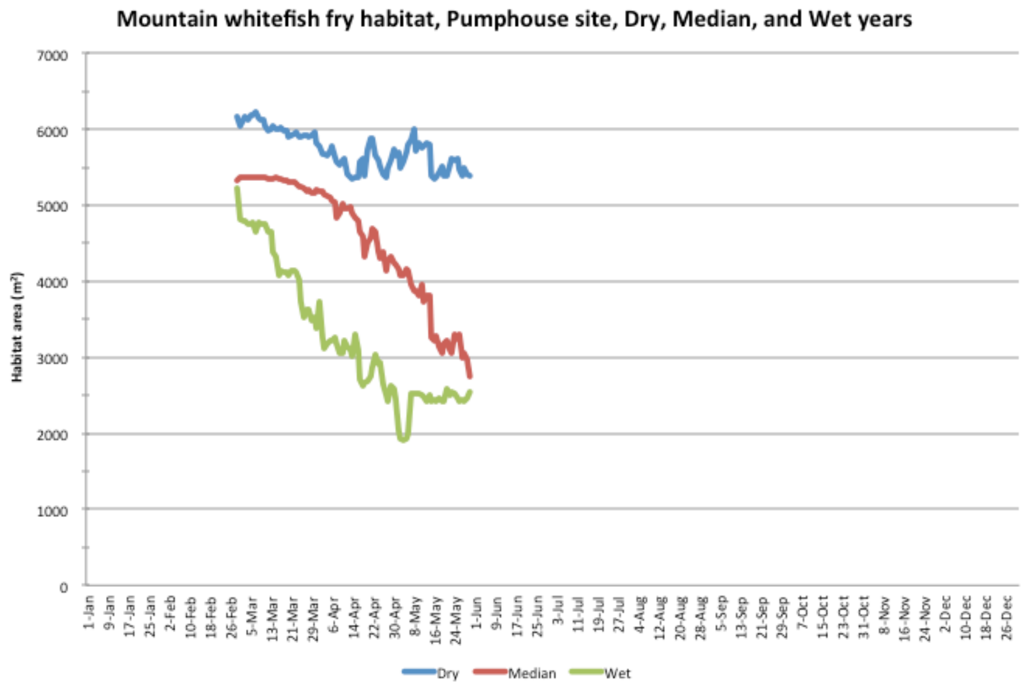

Figure B-11. Mountain whitefish fry habitat time series, dry, median, and wet years, Pumphouse site.

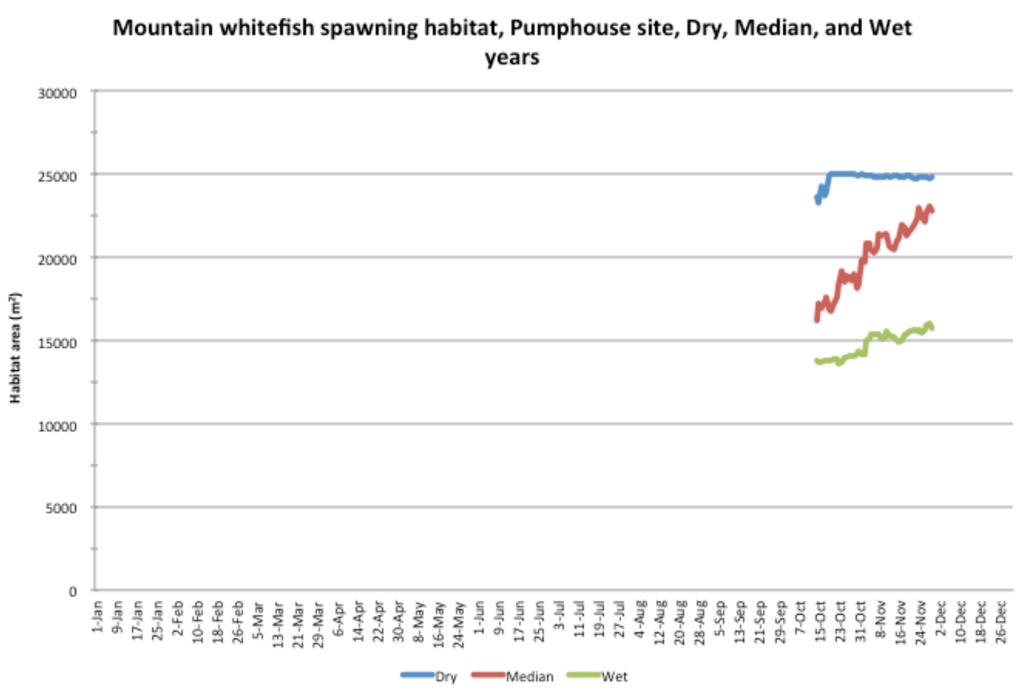

Figure B-12. Mountain whitefish spawning habitat time series, dry, median, and wet years, Pumphouse site.

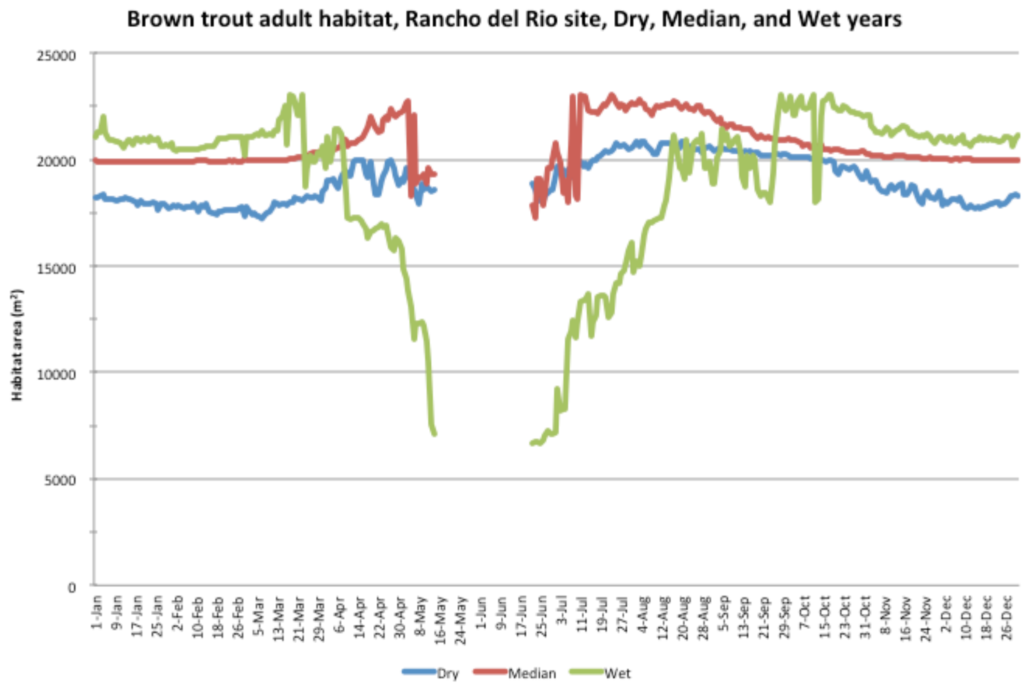

Figure B-13. Adult brown trout habitat time series, dry, median, and wet years, Rancho del Rio site.

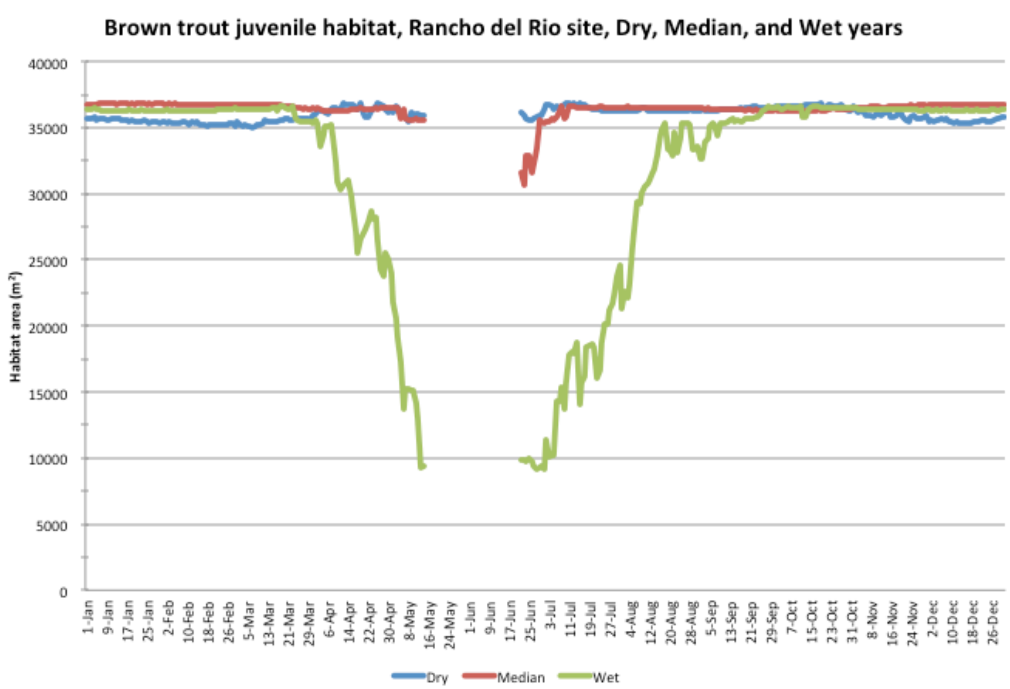

Figure B-14. Juvenile brown trout habitat time series, dry, median, and wet years, Rancho del Rio site.

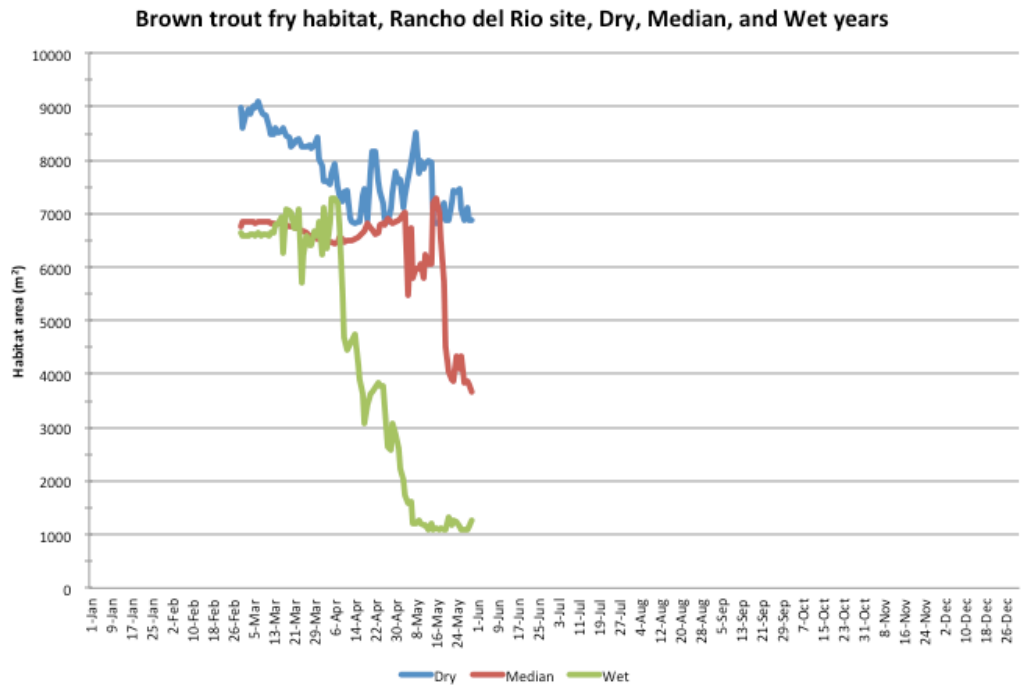

Figure B-15. Brown trout fry habitat time series, dry, median, and wet years, Rancho del Rio site.

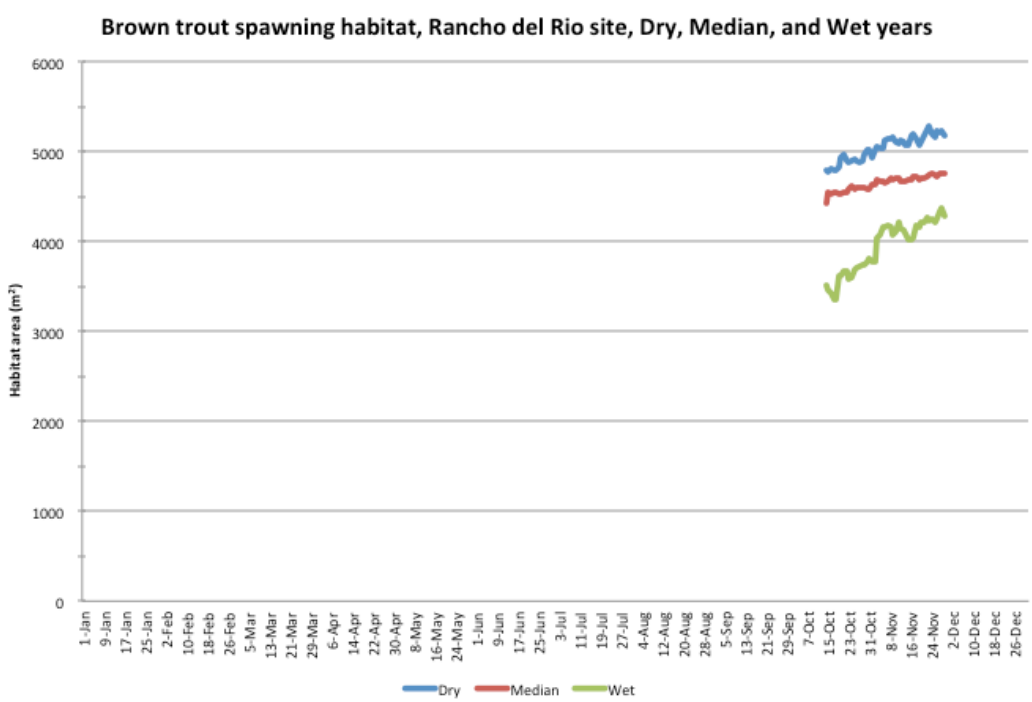

Figure B-16. Brown trout spawning habitat time series, dry, median, and wet years, Rancho del Rio site.

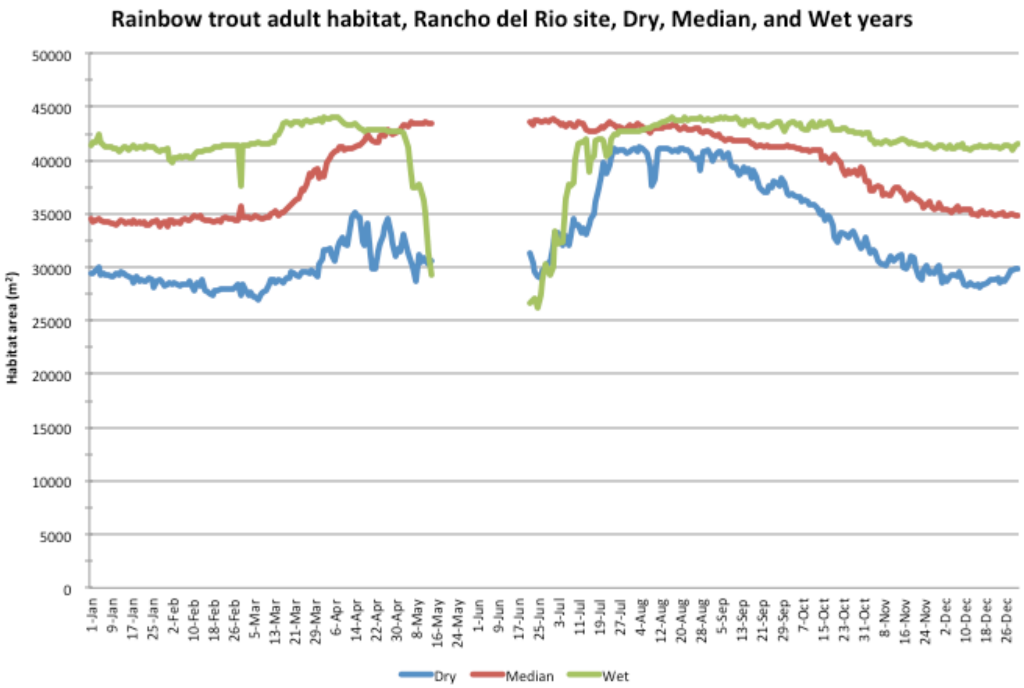

Figure B-17. Adult rainbow trout habitat time series, dry, median, and wet years, Rancho del Rio site.

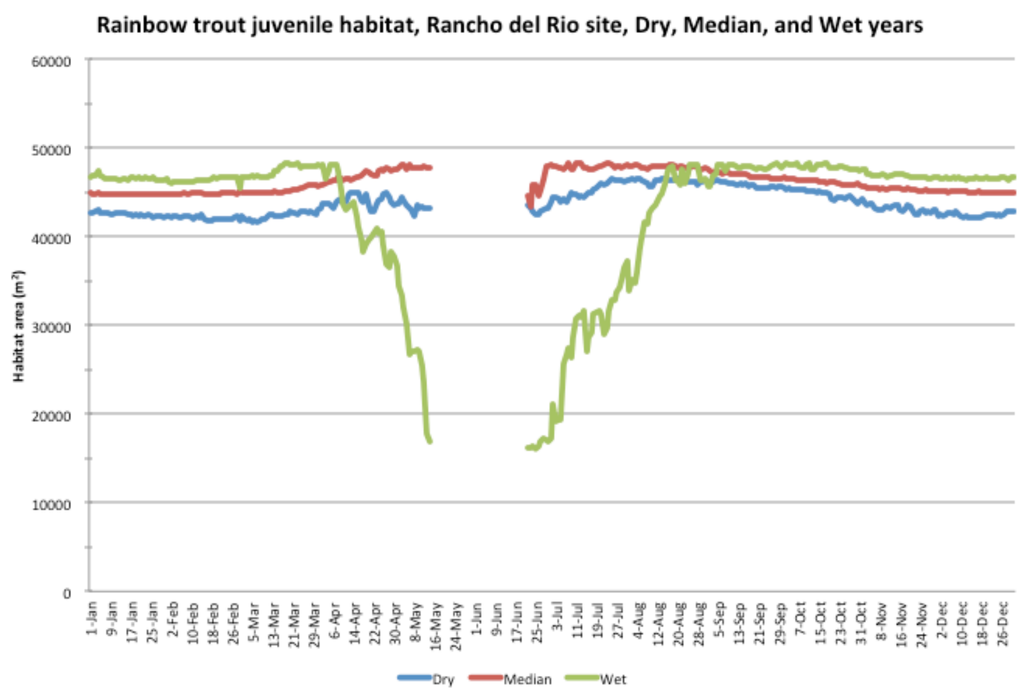

Figure B-18. Juvenile rainbow trout habitat time series, dry, median, and wet years, Rancho del Rio site.

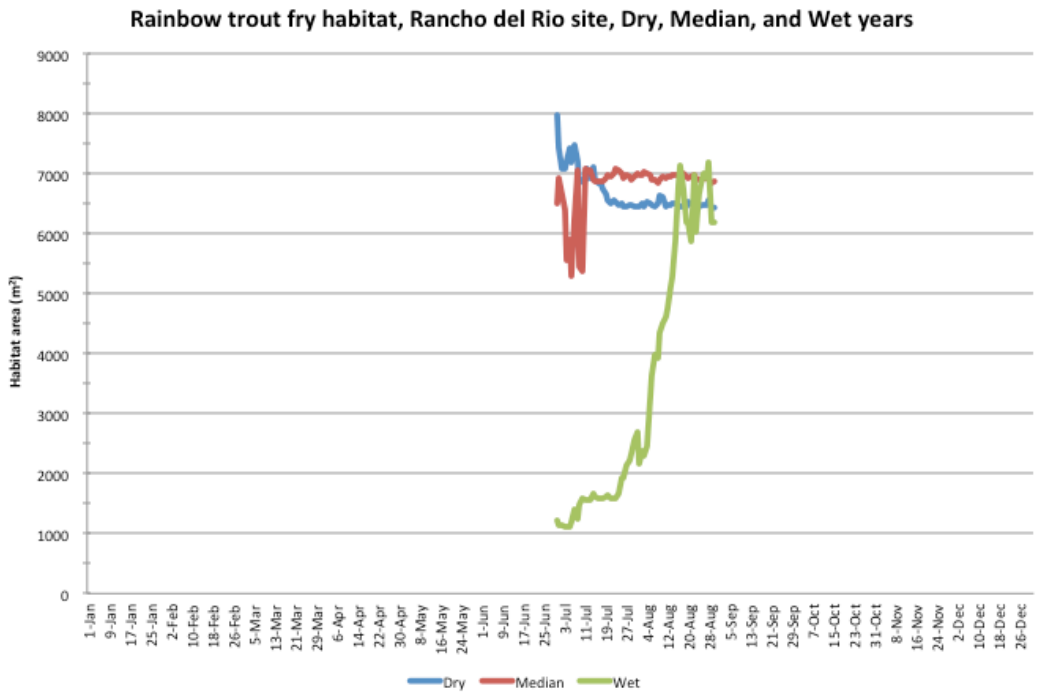

Figure B-19. Rainbow trout fry habitat time series, dry, median, and wet years, Rancho del Rio site.

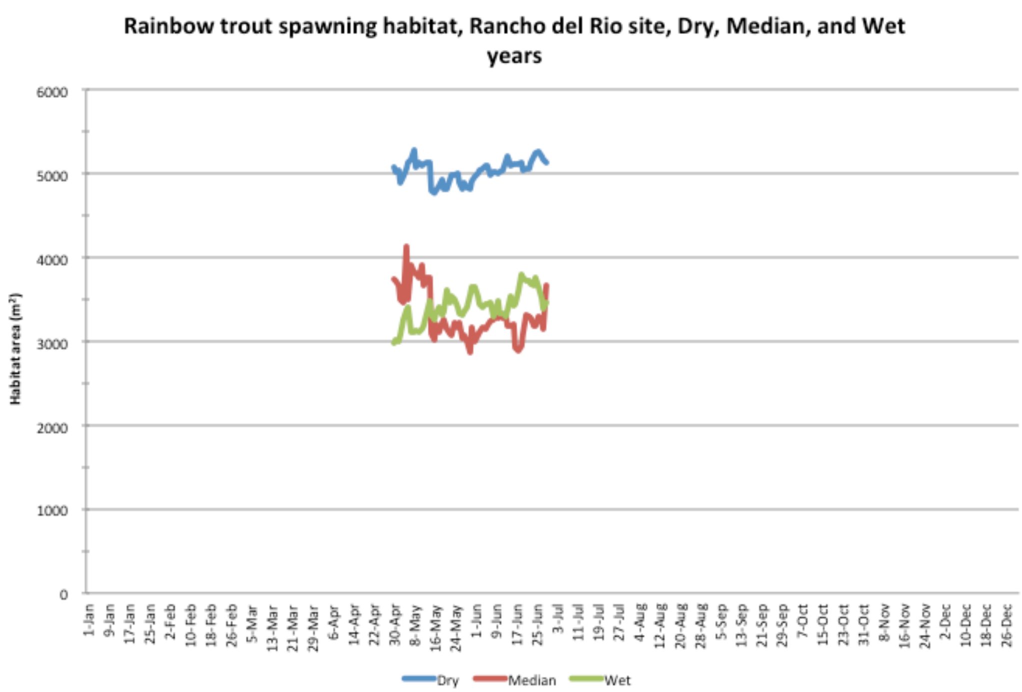

Figure B-20. Rainbow trout spawning habitat time series, dry, median, and wet years, Rancho del Rio site.

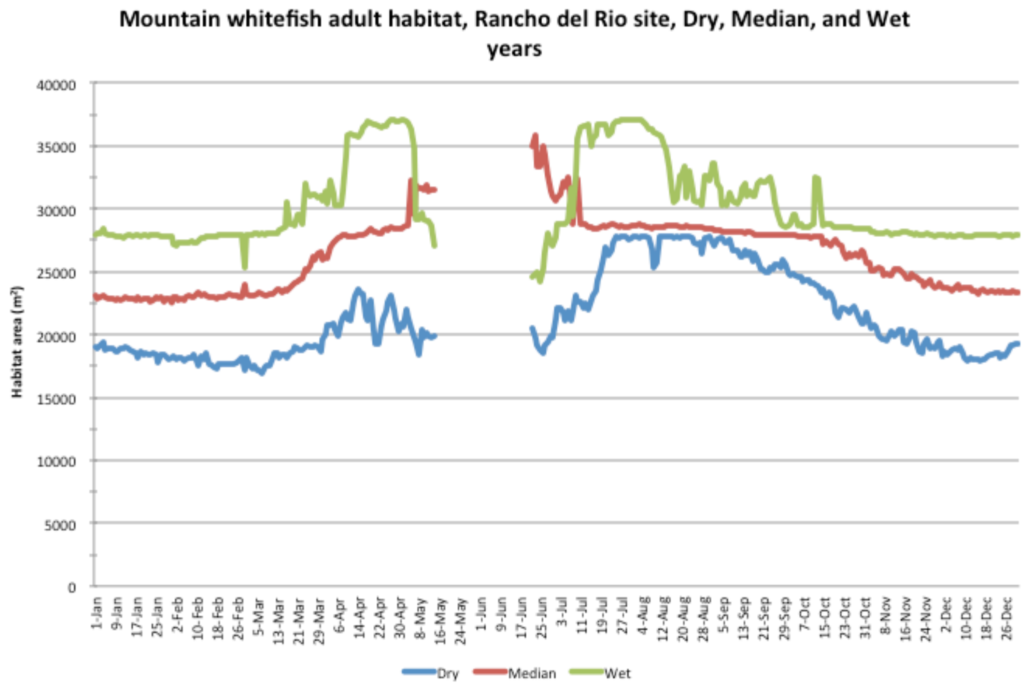

Figure B-21. Adult mountain whitefish habitat time series, dry, median, and wet years, Rancho del Rio site.

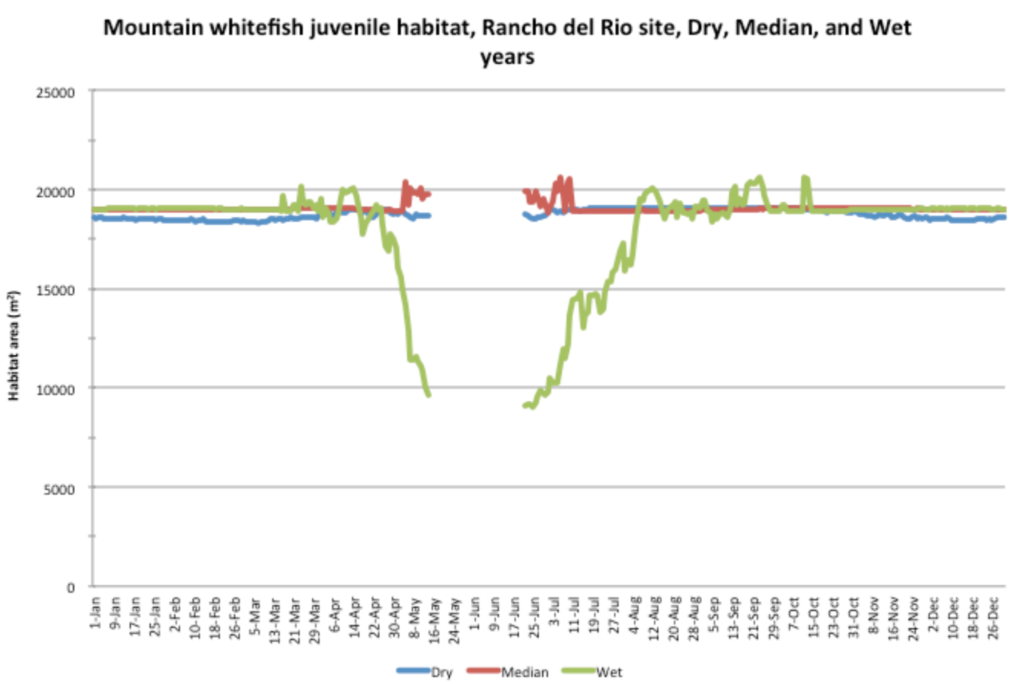

Figure B-22. Juvenile mountain whitefish habitat time series, dry, median, and wet years, Rancho del Rio site.

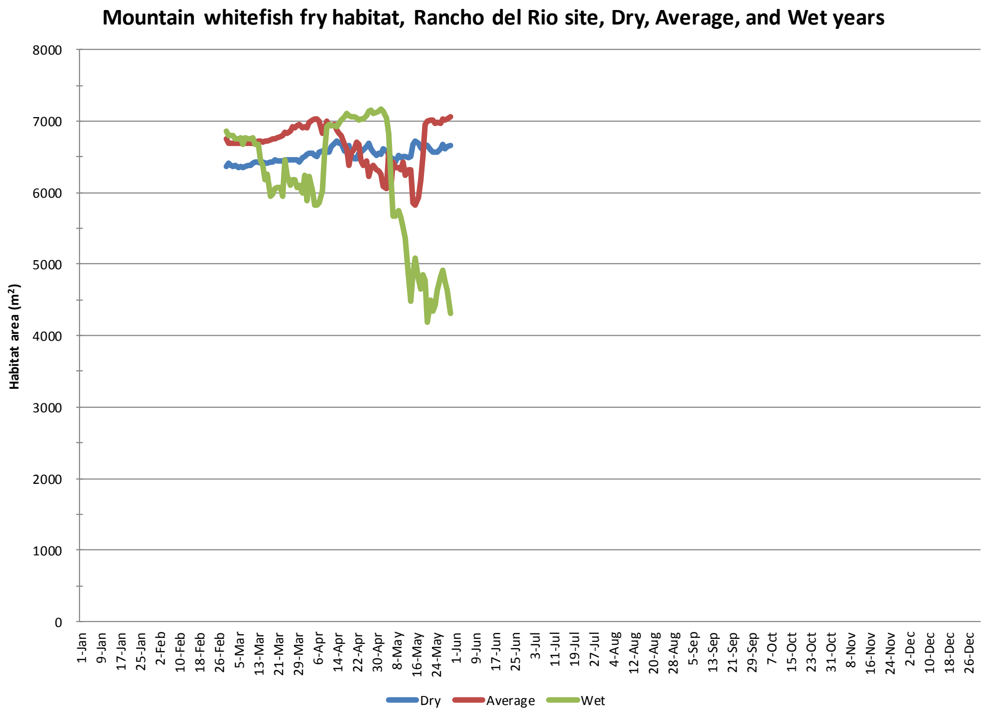

Figure B-23. Mountain whitefish fry habitat time series, dry, median, and wet years, Rancho del Rio site.

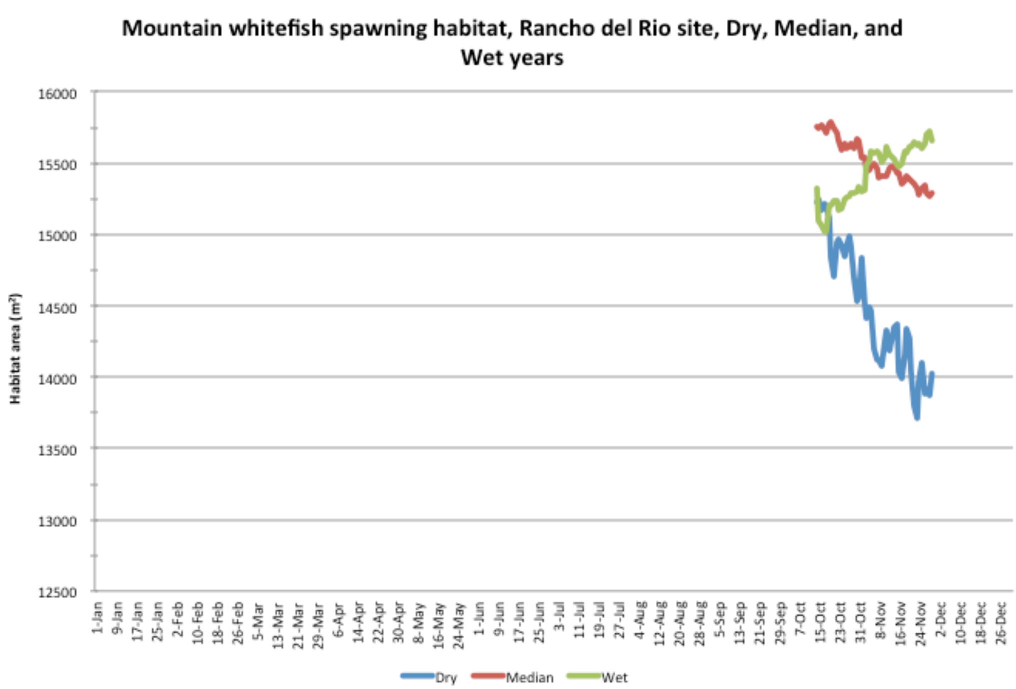

Figure B-24. Mountain whitefish spawning habitat time series, dry, median, and wet years, Rancho del Rio site.

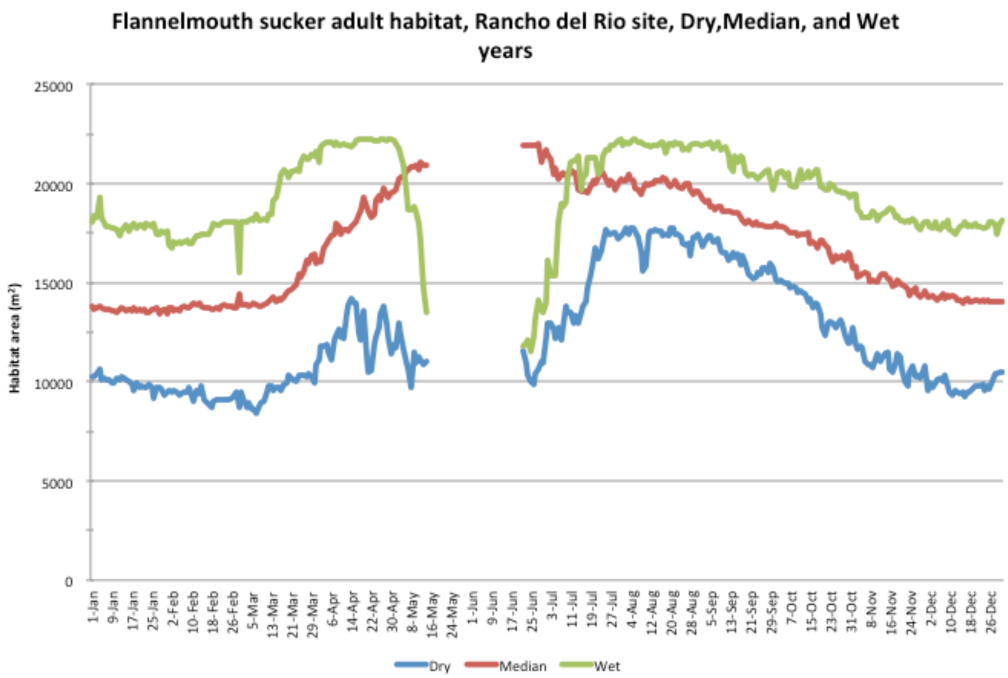

Figure B-25. Adult flannelmouth sucker habitat time series, dry, median, and wet years, Rancho del Rio site.

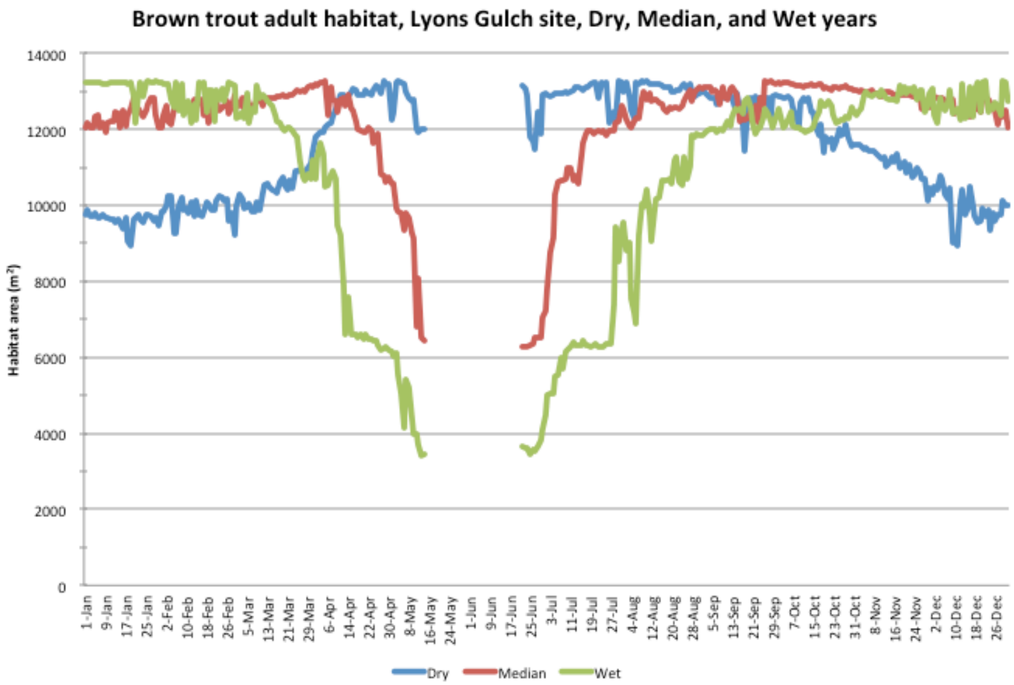

Figure B-26. Adult brown trout habitat time series, dry, median, and wet years, Lyons Gulch site.

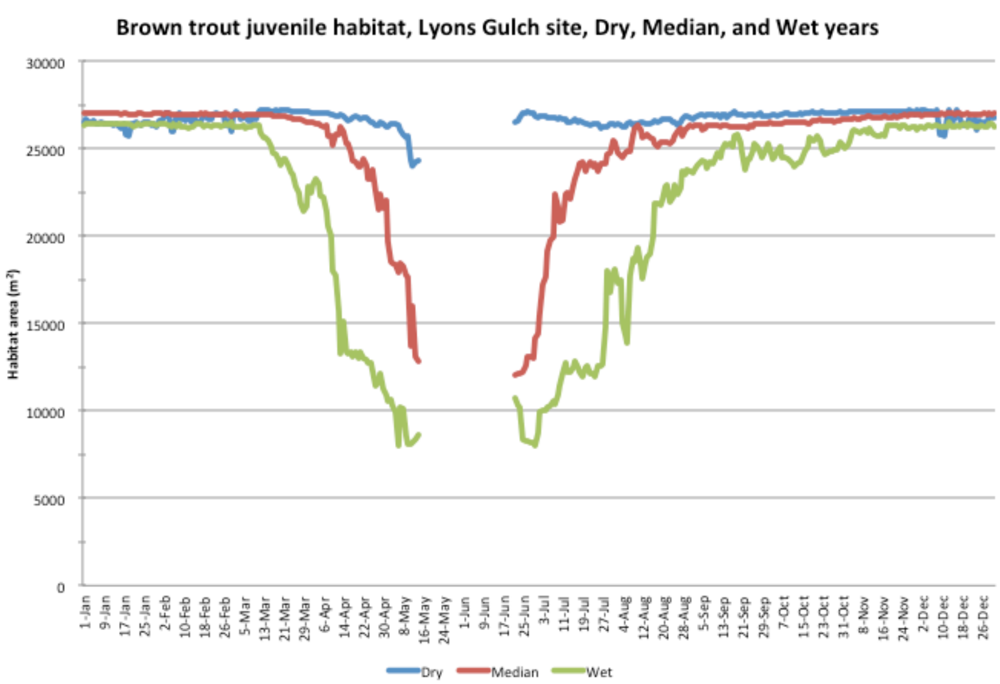

Figure B-27. Juvenile brown trout habitat time series, dry, median, and wet years, Lyons Gulch site.

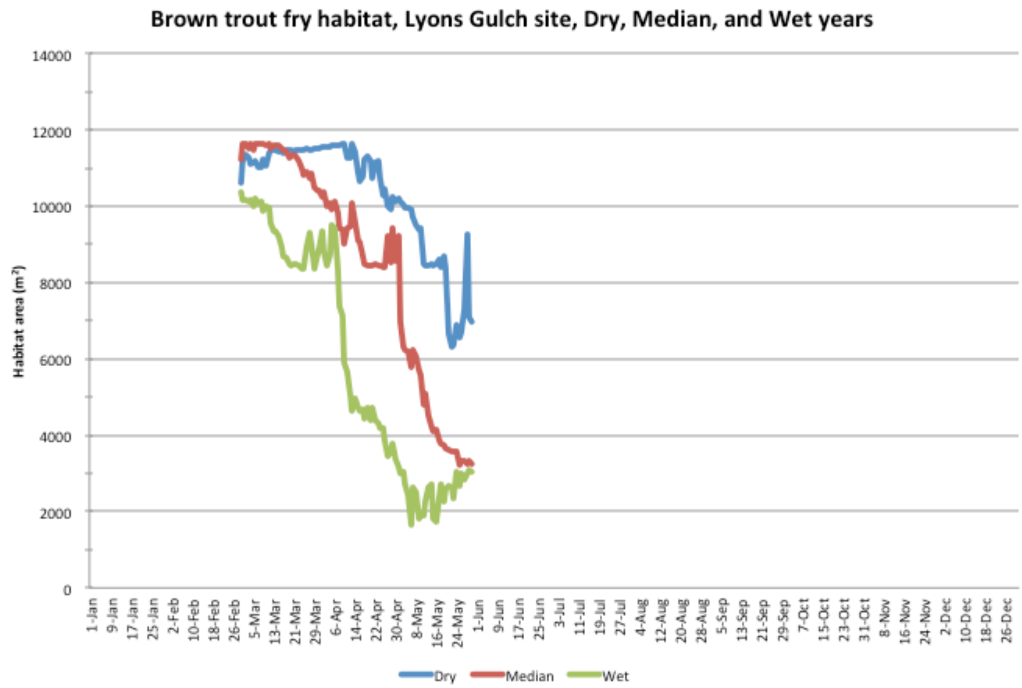

Figure B-28. Brown trout fry habitat time series, dry, median, and wet years, Lyons Gulch site.

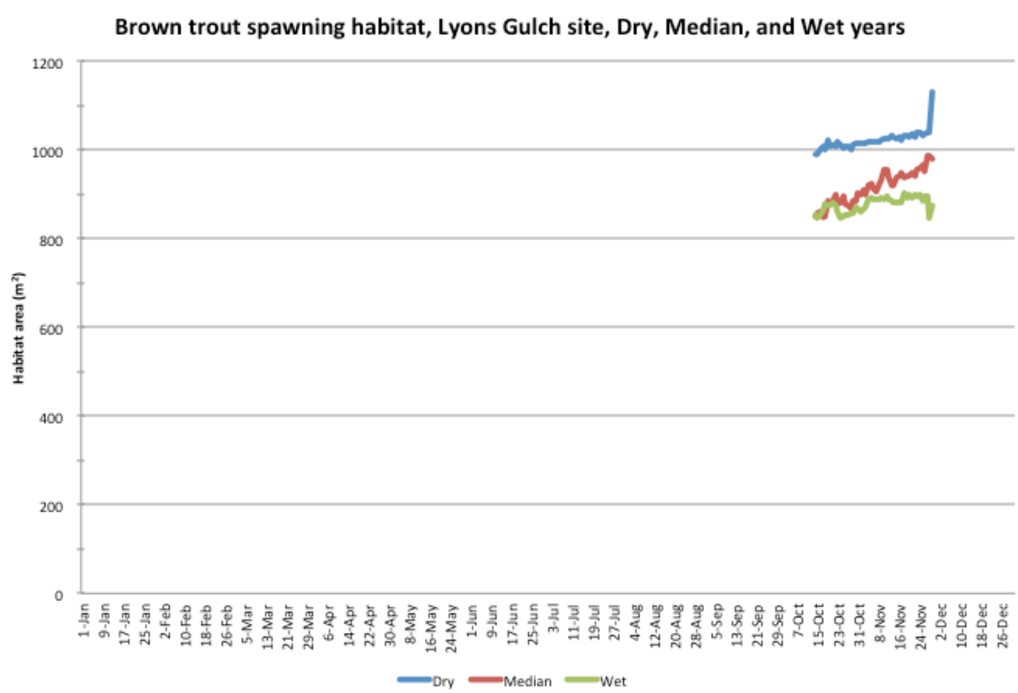

Figure B-29. Brown trout spawning habitat time series, dry, median, and wet years, Lyons Gulch site.

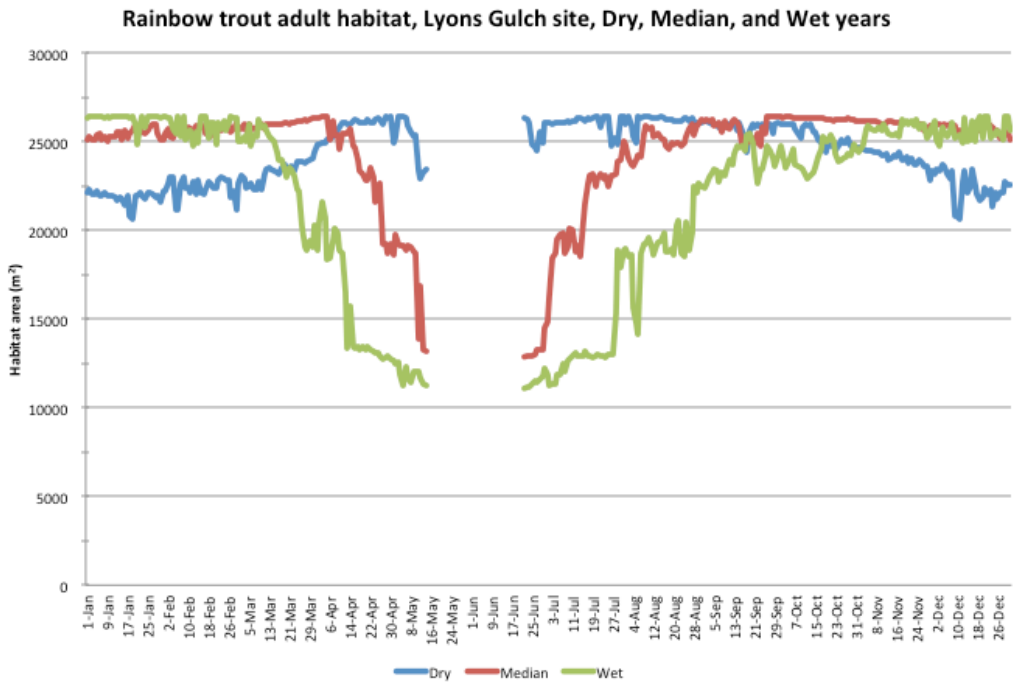

Figure B-30. Adult rainbow trout habitat time series, dry, median, and wet years, Lyons Gulch site.

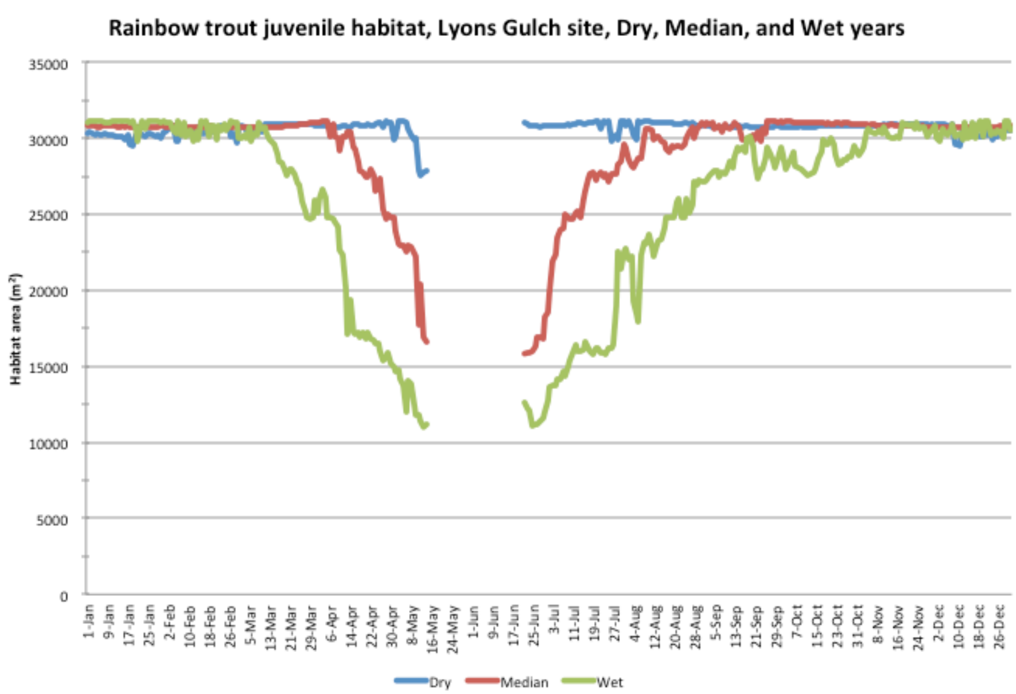

Figure B-31. Juvenile rainbow trout habitat time series, dry, median, and wet years, Lyons Gulch site.

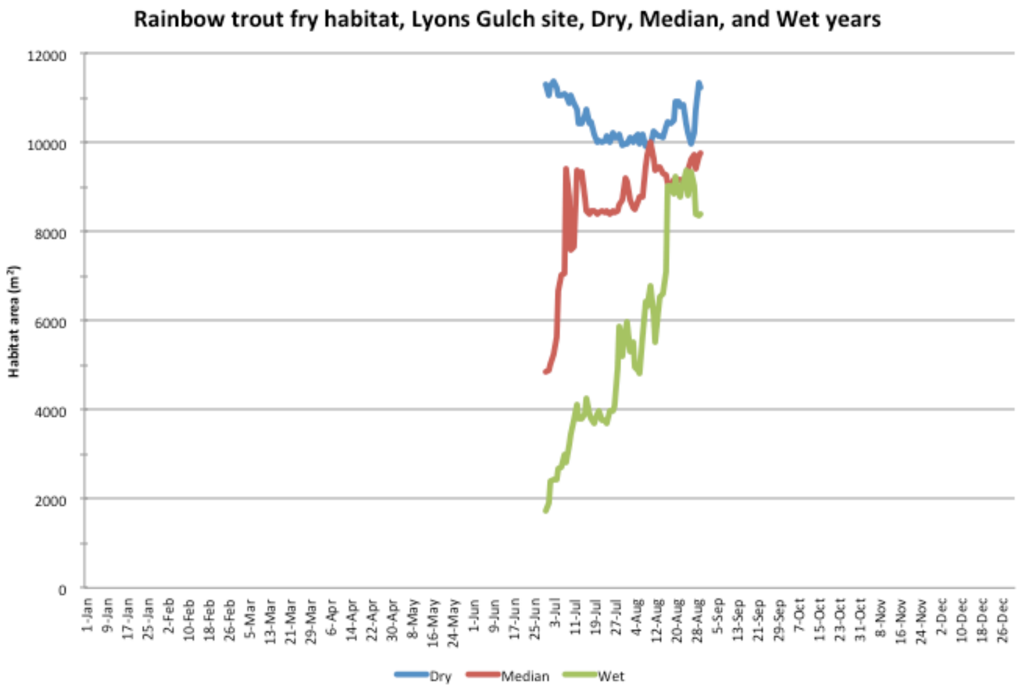

Figure B-32. Rainbow trout fry habitat time series, dry, median, and wet years, Lyons Gulch site.

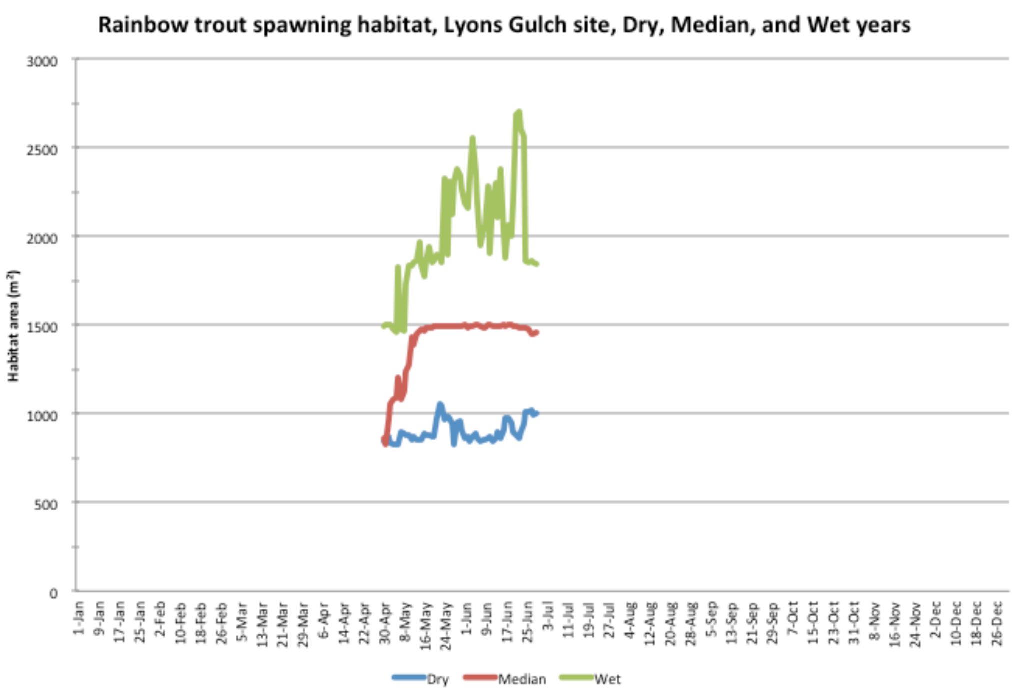

Figure B-33. Rainbow trout spawning habitat time series, dry, median, and wet years, Lyons Gulch site.

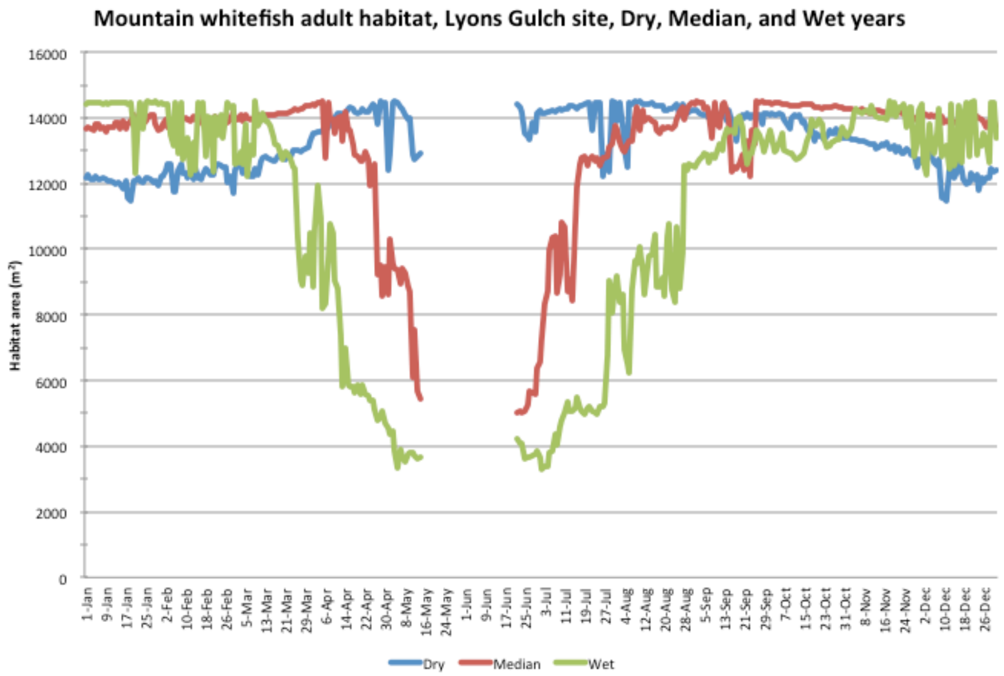

Figure B-34. Adult mountain whitefish habitat time series, dry, median, and wet years, Lyons Gulch site.

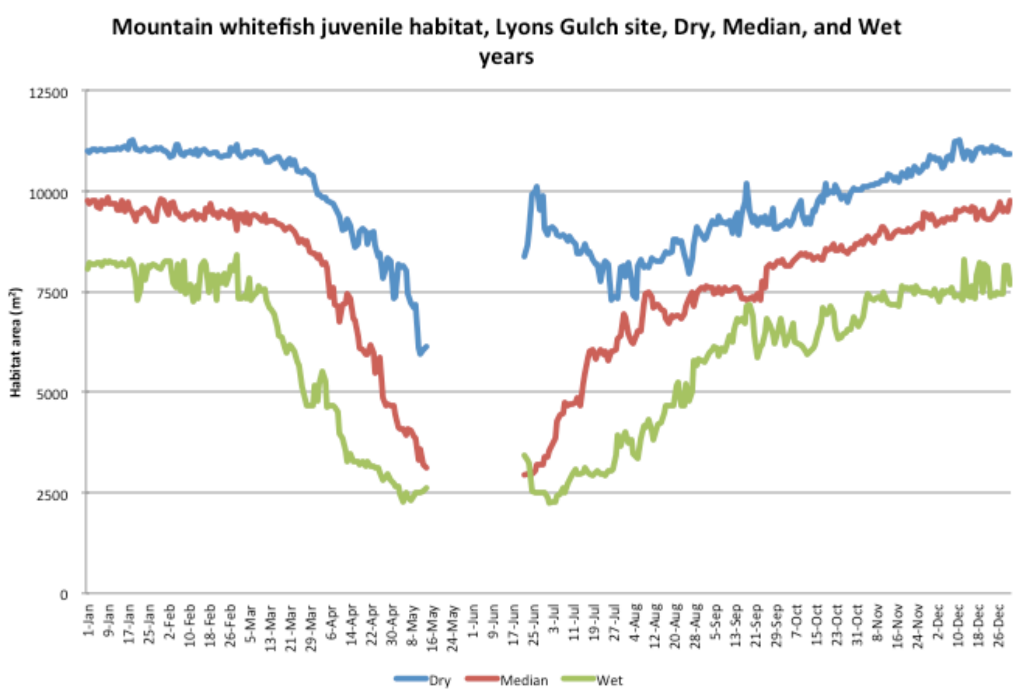

Figure B-35. Juvenile mountain whitefish habitat time series, dry, median, and wet years, Lyons Gulch site.

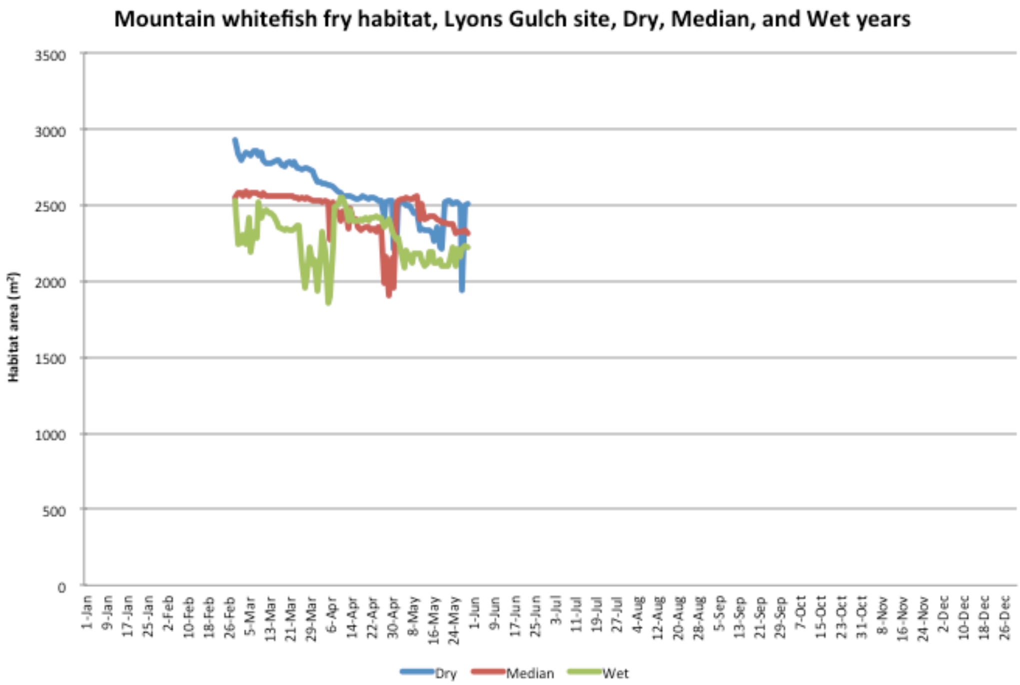

Figure B-36. Mountain whitefish fry habitat time series, dry, median, and wet years, Lyons Gulch site.

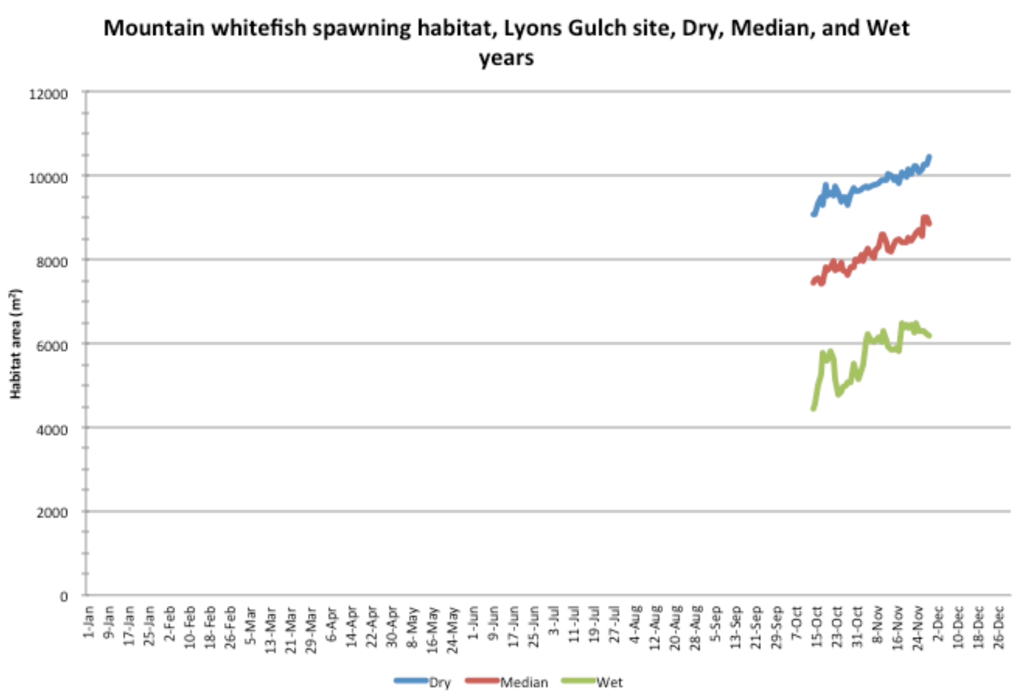

Figure B-37. Mountain whitefish spawning habitat time series, dry, median, and wet years, Lyons Gulch site.

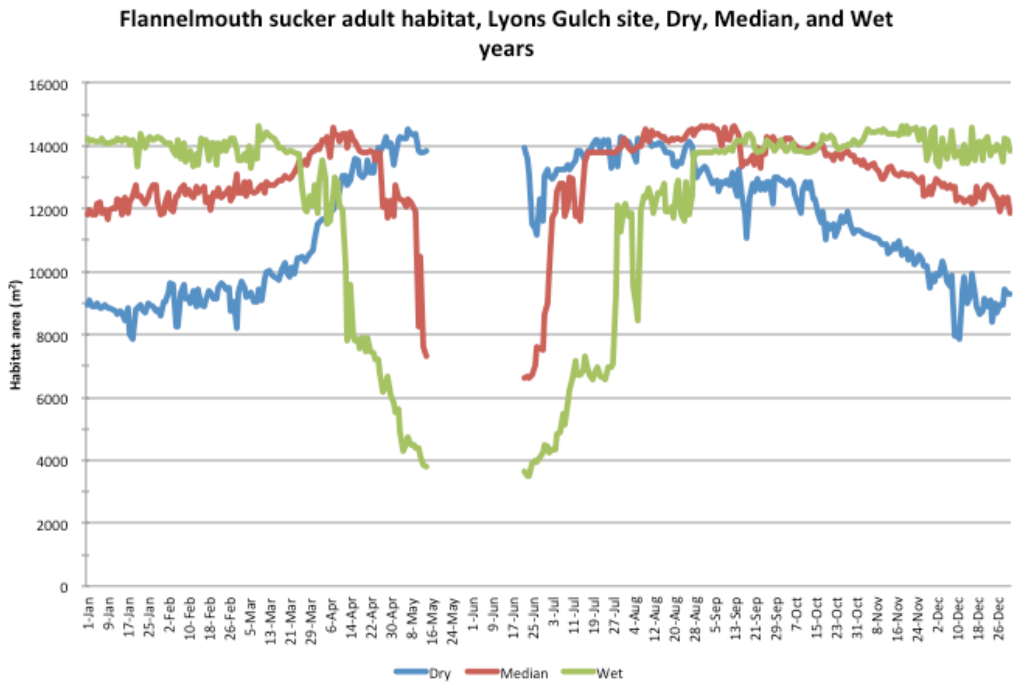

Figure B-38. Adult flannelmouth sucker habitat time series, dry, median, and wet years, Lyons Gulch site.

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