

Instream flow studies on Trail Ridge Creek, tributary of Beaver Creek

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ABSTRACT

Trail Ridge Creek has been identified as crucial habitat for Colorado River Cutthroat Trout (CRC; *Oncorhynchus clarkii pleuriticus*), a game fish and species of greatest conservation need in Wyoming. Though, historically, CRC were widespread throughout the Upper Green River drainage, relatively few populations remain in headwater streams and lakes. To help ensure the persistence of the Trail Ridge Creek CRC population, the Wyoming Game and Fish Department has selected the stream for instream flow water rights filing consideration. Securing an instream flow water right in Trail Ridge Creek is critical to ensuring that CRC remain in the creek by protecting existing base flow conditions against potential future consumptive water demands.

An instream flow investigation was conducted on Trail Ridge Creek in 2016 and the resulting flow recommendations are reported here. One 4.2-mile long stream segment was selected for the study. The segment was chosen considering land ownership, hydrology, and stream channel characteristics to maintain or improve the CRC population.

Several methods were employed to evaluate CRC habitat availability and develop flow recommendations for the study segment. Physical Habitat Simulation (PHABSIM) was used to calculate habitat availability for all life stages of CRC over a range of flow conditions. The Habitat Retention Method was used to examine riffle hydraulic characteristics needed to maintain fish passage (longitudinal connectivity) between habitat types and provide sufficient depth, velocity, and wetted area to ensure survival of fish prey (benthic invertebrates). The Habitat Quality Index (HQI) model was used to assess the relationship between streamflow and juvenile and adult trout habitat quality in the summer. For winter months, October through March, Habitat Retention Method results and natural flows represented by the 20% monthly exceedance values were evaluated for maintaining all life stages. Finally, a dynamic hydrograph model was used to quantify flow needs for maintenance of channel geomorphology.

Results of the instream flow investigation on Trail Ridge Creek show that flows ranging from 1.8 cubic feet per second (cfs) to 3.0 cfs throughout a year will provide critical habitat to maintain the CRC fishery in the proposed instream flow segment. If this instream flow application advances to permit status, approximately 4.2 miles of stream habitat in Trail Ridge Creek will be protected directly by allowing for CRC spawning, passage, and year-round survival.

INTRODUCTION

Rivers and streams and their associated fisheries are important to the residents of Wyoming, as evidenced by passage of Wyoming Statute 41-3-1001-1014 that allows protection of streamflows for fisheries through instream flow water rights. The Wyoming Game and Fish

Department (WGFD) works to protect fisheries throughout the State using various tools and strategies, including proposing instream flow water rights where appropriate and beneficial. Detailed background information on instream flows in Wyoming is presented in Appendix A. Guidance for selecting streams to evaluate for instream flow water right consideration is provided by WGFD's Water Management Plan and Stream Prioritization (Robertson and Annear 2011).

Some of the highest current priorities for new instream flow projects are streams containing Colorado River Cutthroat Trout (CRC; *Oncorhynchus clarkii pleuriticus*). Historically, this species occupied portions of the Colorado River drainage in Wyoming, Colorado, Utah, Arizona, and New Mexico. Widespread introductions of non-native salmonids over the last century have served to limit current distributions primarily to isolated headwater streams and lakes. Jespersen (1981) observed that a wide variety of land management practices as well as water depletion and diversion negatively affect CRC populations. A more recent assessment by Hirsch et al. (2005) indicates that CRC presently occupy about 14% of their historical range. Many of the streams that still contain populations of CRC have modified habitat conditions that restrict the CRC populations to isolated reaches relative to the watershed-wide distributions that the species once exhibited. These remaining isolated reaches are critical for conservation efforts, including maintaining sufficient streamflows to ensure long-term persistence to the extent allowed within the current interpretation of the instream flow statute.

Securing an instream flow water right on Trail Ridge Creek will help facilitate successful preservation and maintenance of CRC, which were re-introduced into this portion of their historical range. This creek is within a "crucial" habitat area as identified in the WGFD Strategic Habitat Plan (SHP) (WGFD 2015) and within an "aquatic conservation area" in the WGFD State Wildlife Action Plan (2017). According to the SHP, "Crucial Habitat Areas are based on significant biological and ecological values including habitats that support important life stages needed for maintaining game species, sensitive native non-game species, unique species assemblages and ecologically important species or communities." In addition, Trail Ridge Creek contains a core conservation population of CRC; this is a population that "... is greater than 99% pure, and representative of the historical genome of the native trout. Core populations contain cutthroat trout that have not been influenced by genetic alteration linked to human intervention" (CRCT Coordination Team 2006). Maintaining a core conservation population in Trail Ridge Creek is critical to protecting diversity of the CRC historical genome.

This report details the results of the Trail Ridge Creek instream flow study conducted in June through September 2016. Flow recommendations are based upon consideration of the five primary riverine components that influence the characteristics of a stream or river: hydrology, biology, geomorphology, water quality, and connectivity (Annear et al. 2004). Maintaining sufficient quantities of good quality water is essential for sustaining fish productivity in streams and rivers. When water resources are developed in Wyoming for out-of-stream, consumptive uses, there are corresponding changes in riverine components that alter the ability of a stream to support fisheries habitat. The five riverine components were evaluated using various models and data sources to generate the recommendations for how much flow, when naturally available, should remain in Trail Ridge Creek to provide sufficient habitat during critical time periods in the life stages of CRC.

The objective of this study was to quantify instream flow levels needed to maintain CRC habitat in Trail Ridge Creek during critical seasonal periods. The information can be used as supporting material for an instream flow water right application. In addition, a channel

maintenance flow regime is recommended to maintain long-term trout habitat and related physical and biological processes (Appendix B). The audience for this report includes the Wyoming State Engineer and staff, the Wyoming Water Development Office, aquatic habitat and fishery managers, and non-governmental organizations and individuals interested in instream flow water rights.

METHODS

Study Area

Trail Ridge Creek, located in Fremont County, Wyoming, is a tributary of Beaver Creek in the South Piney Creek drainage of the Upper Green River watershed (Figure 1). The stream is located within the WGFD Pinedale Region. The watershed (HUC12 140401010809) encompasses approximately 34.4 square miles. Land ownership includes 64% Bureau of Land Management (BLM), 18% Forest Service, 4% State, and 14% private ownership. All of the private land is downstream of the proposed Trail Ridge Creek instream flow segment.

The highest point in the Trail Ridge Creek watershed is approximately 9,770 ft and the elevation at the downstream end of the study segment, is approximately 7,585 ft. Annual precipitation averaged 14.5 inches in the area of the stream over the period 1895–2012, according to data retrieved from the Wyoming Water Resources Data System (WRDS 2017).

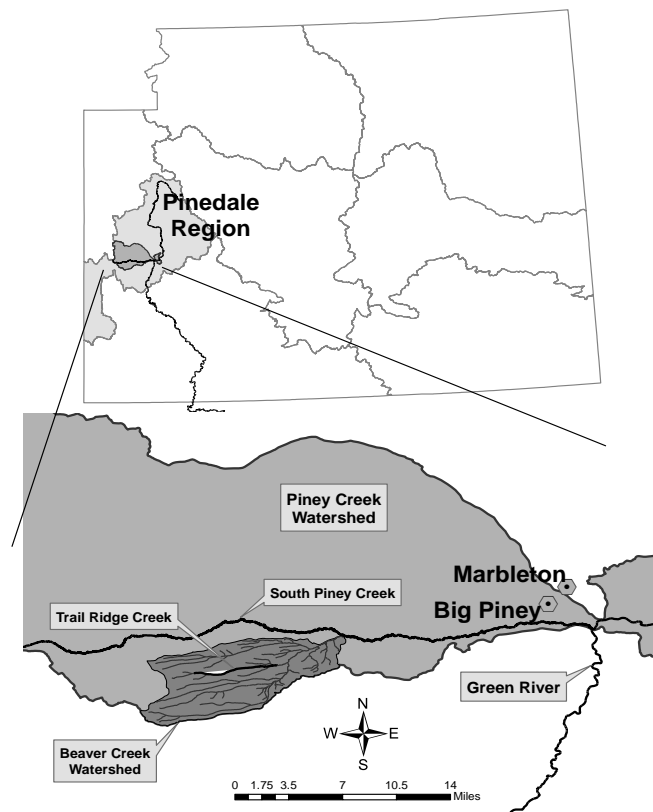


FIGURE 1. Location of Trail Ridge Creek, WY (HUC 140401010907).

The fish community in Trail Ridge Creek includes CRC and Mottled Sculpin (*Cottus bairdii*) within the proposed instream flow segment. The current management objective is to maintain a wild population of CRC in Trail Ridge Creek. Evaluation of flow conditions that are necessary to maintain or improve this fishery was conducted using the habitat and hydrological modeling efforts described below.

Instream Flow Segment and Study Site Selection

One stream segment is proposed for an instream flow water right filing in Trail Ridge Creek (Table 1; Figure 2). The boundaries for the segment were identified after considering land ownership, hydrology, and stream channel characteristics. The downstream end of the proposed instream flow segment is at the BLM boundary. The segment extends approximately 4.2 miles upstream to the boundary of the CRC population extent. The drainage area at the downstream end of the segment is 5.3 square miles. The instream flow segment on Trail Ridge Creek is located entirely on public land.

TABLE 1. Location, drainage area, length, and elevation at the downstream end of the proposed instream flow segment on Trail Ridge Creek.

Segment	Description	Drainage Area (mi ²)	Length (mi)	Elevation (ft)
Trail Ridge Creek	Begins at boundary between BLM and private property and extends upstream to the extent of the CRC conservation population.	5.3	4.2	7,585

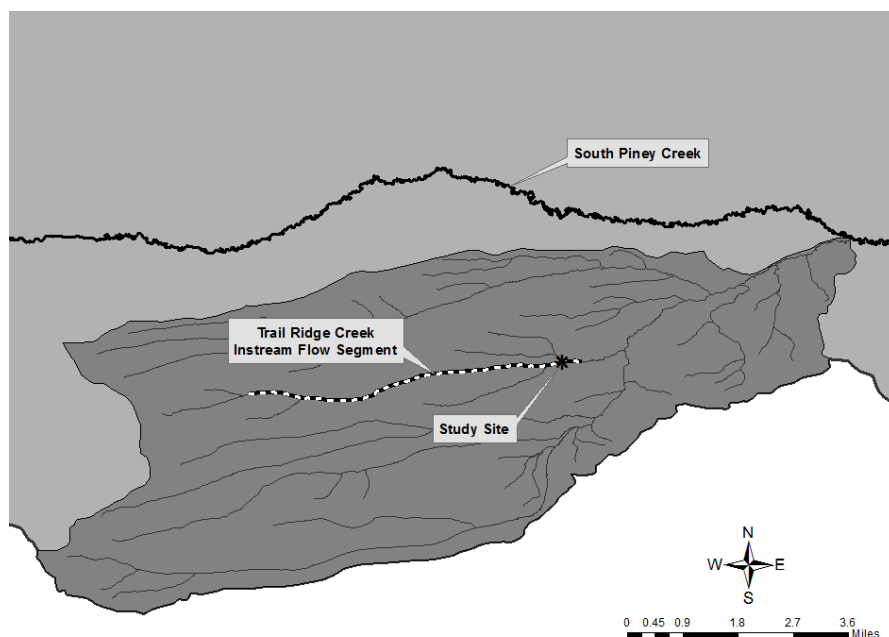


FIGURE 2. Location of Trail Ridge Creek instream flow segment and study site.

Within the instream flow segment, one study site of approximately 145 ft of stream was selected to represent habitat conditions in the segment. Because the bankfull width in this reach was approximately 8.3 ft, the study site length was equal to approximately 17 times the channel width; this is longer than the reach length recommended by Bovee (1982; 10-14 times the channel width).

The study site included three distinct sections (e.g., riffle-run-pool) characterized by eight cross-sections divided among the sections (Figure 3). The eight cross-sections included three riffles, three runs, and two pools. Each riffle transect created the downstream boundary of a section. Run and pool transects were placed in appropriate upstream locations to represent the range of conditions in each section. The complexity of this study site is representative of the range of habitat conditions available throughout the instream flow segment. All data collection was conducted in this study site and extrapolated to the entire proposed instream flow segment.



FIGURE 3. One of eight transects at the Trail Ridge Creek study site.

Hydrology

Development of flow recommendations for an instream flow study segment requires an understanding of hydrology within the study segment. There are no stream gage data available within the segment or stream, so flow variables were estimated from a regional reference gage (see Appendix C for details). The USGS gage on Fontenelle Creek near the Herschler Ranch (09210500) was selected as the reference gage for these analyses (USGS 2016; Figures 4, 5); the period of record used for analysis was water years 1952 to 2015. This gage was active during the study period and, based on proximity, it is assumed that precipitation and runoff patterns are similar between the reference gage and the study site.

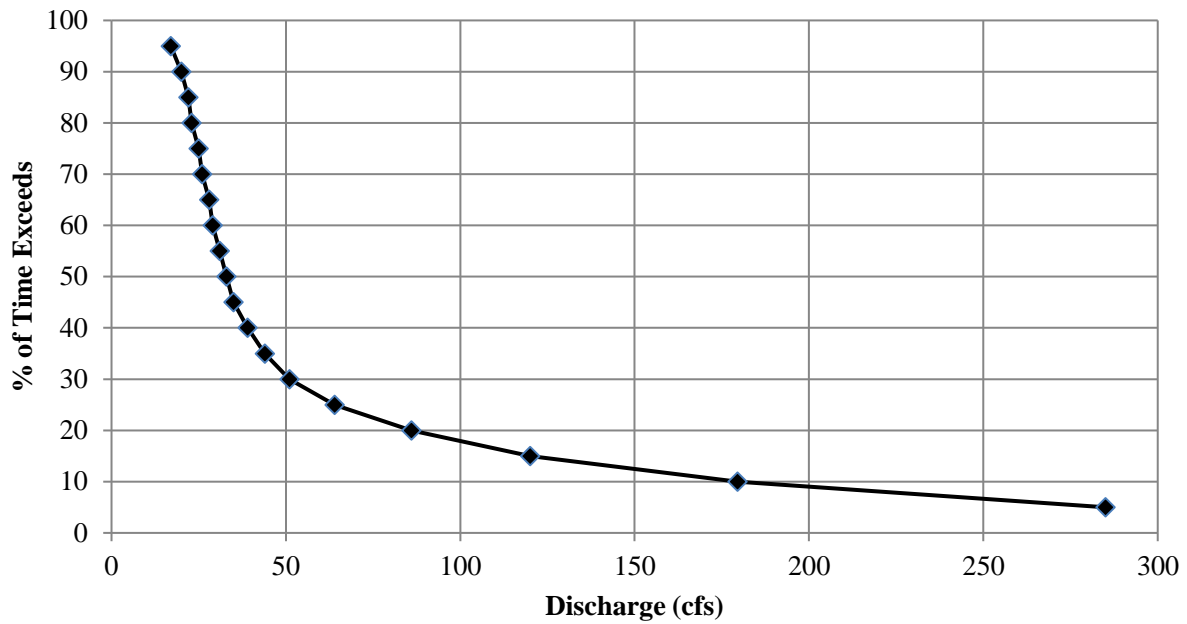


FIGURE 4. Annual flow exceedance curve for the reference stream gage (Fontenelle Creek; USGS gage 09210500) over the period of record (water years 1952-2015).

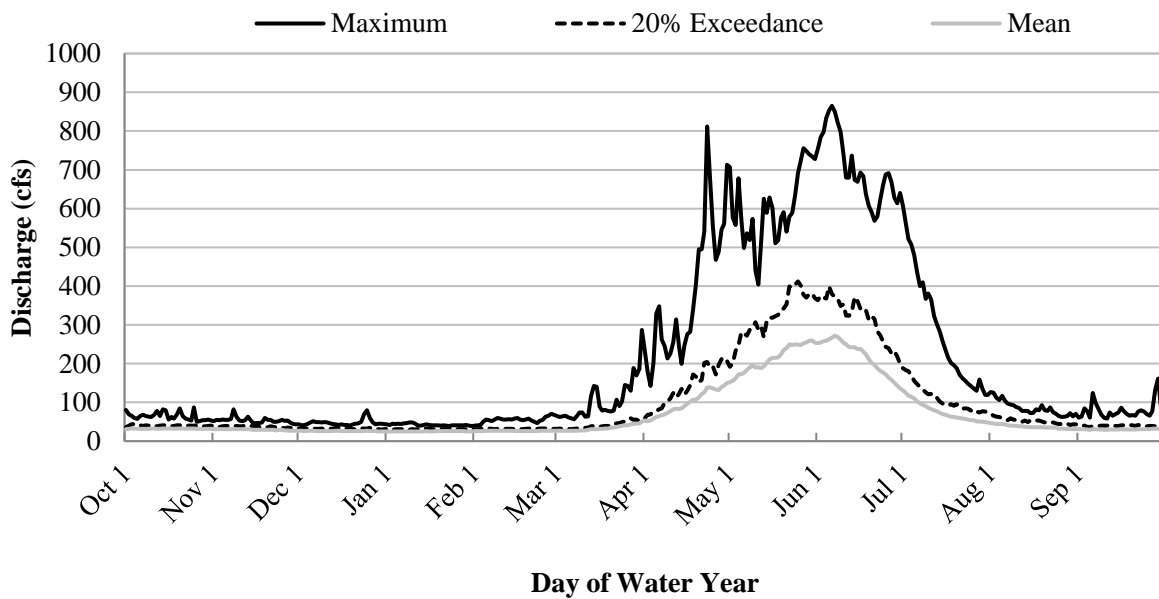


FIGURE 5. Hydrograph showing the maximum, 20% exceedance, and mean discharges for each day of the year over the period of record (water years 1952-2015) at the reference stream gage (Fontenelle Creek; USGS gage 09210500).

Dimensional analysis was used to estimate hydrologic characteristics of the instream flow segment (Appendix C). Average daily flow estimates were used in applying the Habitat Quality Index and Habitat Retention Method (described below). The 1.5-year return interval of the flood frequency series was used to estimate bankfull flow (Rosgen 1996) for use in the Habitat Retention Method and for developing channel maintenance flow recommendations (Appendix B). Channel maintenance flow calculations required the 25-year peak flow estimate from the flood frequency analysis. In addition, the monthly flow exceedance estimates were used in evaluating winter flow needs. Flow exceedance estimates indicate the percent of time that a given flow is equaled or exceeded. The 20% monthly exceedance flows were identified for the natural winter flow analysis. A 20% exceedance flow refers to the flow that, on average, would occur approximately one year out of every five years.

In addition to estimates of local hydrology based on the regional reference gage data, a temporary stream gage station was installed within the study site between June 21, 2016 and September 27, 2016. The temporary gage data provide a detailed look at the hydrologic variability during the study period and assist in selecting the appropriate regional reference gage (Appendix C). The gage was located upstream of a stable hydraulic control and a staff plate with 0.01 ft increments was placed in the stream in a location with minimal surface turbulence. The pressure transducer used for water level monitoring at 15-minute intervals was placed in a perforated PVC pipe that served as the stilling well. The pipe was anchored to a metal T-post and mounted vertically within the water column.

Discharge measurements in the stream reach were collected over a wide range of flow conditions, including relatively high flows after peak runoff and base flows near the end of the study period. The discharge measurements and corresponding readings on the staff plate were used to develop a local rating curve. The rating curve was used to convert the water level readings from the pressure transducer to discharge estimates for the study period.

Biology – Fish Habitat Modeling

Habitat preferences of target fish species, including each of their life stages, are important in instream flow studies because flow recommendations are based on maintaining sufficient habitat for target species to survive, grow, and reproduce. Growth of adult and juvenile CRC is most important during the summer and early fall periods. Habitat for these life stages is also critical during winter to allow overwinter survival. Species-specific habitat preferences are used to develop habitat suitability curves (HSCs) that are in turn used in habitat models.

Availability of fish habitat in the study site was evaluated using several different habitat models. “Habitat” in this report refers to the combination of physical conditions (width, depth, velocity, cover, and wetted substrate) in a given area. These physical conditions vary with discharge. It is important to note that these variables do not represent a complete account of all variables that constitute trout habitat. Habitat for trout also includes other environmental elements such as water temperature, dissolved oxygen, and turbidity. Although such other elements are important for maintaining trout populations, they are not included in models used for these analyses because they do not fluctuate with changes in the quantity of flow as predictably as physical habitat variables. Interpretation of model results, based on those physical habitat variables, assumes that this subset of trout habitat variables provides a reasonable indication of critical habitat availability at various streamflows and is an indirect expression of the ability of trout populations to persist at those flow levels, at least on a short-term basis.

Physical Habitat Simulation Model

The Physical Habitat Simulation (PHABSIM) model (Bovee et al. 1998) was used to estimate how much suitable habitat is available for individual life stages of CRC at different streamflow levels. The results of the model were evaluated to determine how much streamflow is needed to maintain sufficient habitat for these life stages during critical time periods.

The PHABSIM model calculated a relative suitability index for CRC based on depth, velocity, and substrate. Model calibration data were collected on all transects. Along each transect, depth and velocity were measured at multiple locations (cells); spacing was determined based on substrate characteristics and the cross-section depth profile. Measurements were taken in the same cells at three different discharge levels (5.6 cfs, 3.6 cfs, and 0.4 cfs). Calibrating the model involved hydraulic parameter adjustments to provide the best estimation of observed conditions at the different flows measured in the field (Bovee et al. 1998).

Simulations were conducted using a calibrated PHABSIM model over the flow range of 0.2 cfs to 20 cfs. Using the depth and velocity measurements in the cells along each transect at the calibration flow levels, the PHABSIM model predicted depth and velocity values in those cells for each simulated flow (Bovee and Milhous 1978, Milhous et al. 1984, Milhous et al. 1989). The predicted depths and velocities, along with substrate or cover information, were compared to HSCs of the target life stages to determine how much suitable habitat is present in the study site at each simulated flow.

The amount of suitable habitat, or weighted usable area (WUA), for each streamflow and life stage combination was calculated using the HSCs for depth, velocity, substrate, and cover. The HSCs range between “0” (no suitability) and “1” (maximum suitability) for each life stage. A suitability value was assigned to each cell for each HSC based on the simulation results for a given discharge. A combined suitability value was generated and multiplied by the surface area of each cell. The sum value of all cells yielded the WUA for the simulated discharge level. Data from the eight transects were grouped into three sections; each section was given equal weighting toward the total estimate of WUA for each flow.

Results were displayed by graphing WUA for a particular CRC life stage versus a range of simulated discharges (Bovee et al. 1998). The values were normalized to a percent of the maximum WUA value as recommended by Payne (2003).

Habitat Retention Method

The Habitat Retention Method (Nehring 1979, Annear and Conder 1984) was used to evaluate hydraulic characteristics that affect the survival and movement of all life stages throughout a range of discharges in the Trail Ridge Creek instream flow segment. The hydraulic model was used to identify the lowest flow that maintains specific hydraulic criteria in riffles (Table 2). These criteria represent conditions needed to maintain fish passage, or longitudinal connectivity, among habitat types. The criteria also reflect depths, velocities, and wetted areas needed for year-round survival of CRC and benthic invertebrates, many of which serve as fish prey (Nehring 1979). Flow recommendations derived from the Habitat Retention Method address portions of the connectivity and biology riverine components. The threshold flow identified by the Habitat Retention Method is important year-round, although greater flows are necessary to meet other behavioral or physiological requirements of the target life stages.

Simulation tools and calibration techniques used for hydraulic simulation in PHABSIM were also used with the Habitat Retention Method. The AVPERM model within the PHABSIM

methodology was used to simulate cross-section depth, wetted perimeter, and velocity within a range of flows. The flow that maintains two out of three criteria for all modeled transects was identified as the threshold flow sufficient to meet the needs of the fishery (Table 2). Because of the critical importance of depth for maintaining fish passage, the 0.2 ft threshold was required to be one of the criteria met for each transect. Trail Ridge Creek is less than 20 ft wide (8.3-ft mean bankfull width from the three transects) so the mean depth criterion was 0.2 ft.

TABLE 2. Hydraulic criteria for determining threshold flow using the Habitat Retention Method (Annear and Conder 1984).

Category	Criterion
Mean Depth (ft)	$\geq 0.20^a$
Mean Velocity (ft/s)	≥ 1.00
Wetted Perimeter ^b (%)	≥ 50

a – When transect bankfull width >20 ft, then $0.01 \times$ mean bankfull width.

b – Percent of bankfull wetted perimeter; calculated for each transect.

Habitat Quality Index Model

The Habitat Quality Index (HQI; Binns and Eiserman 1979, Binns 1982) was used to determine production potential of adult and juvenile CRC in the study site during late summer (July 16 through September) flow conditions. Most trout production (growth) in Wyoming streams occurs during summer, following peak runoff, when longer days and warmer water temperatures facilitate growth. Developed by the WGFD, the HQI model uses nine biological, chemical, and physical trout habitat attributes to estimate relative habitat suitability in a stream reach.

For this study, the HQI was used to estimate the number of CRC Habitat Units in the study site. Each Habitat Unit is expected to support about 1 lb of trout. Data were collected for HQI calculations at 5.6 cfs, 3.6 cfs, and 0.4 cfs between June 21 and September 27, 2016. Attribute ratings were interpolated between those measurements to characterize the relationship between discharge and trout habitat conditions at discharges other than those measured (Conder and Annear 1987).

Article 10, Section d of the Wyoming Instream Flow statute states that waters used for providing instream flow water rights, “. . . shall be the minimum flow necessary to maintain or improve existing fisheries.” To maintain a viable trout fishery, it is critical to maintain habitat available at normal late summer flows, which are represented by the September 20% exceedance flow. The HQI results were used to identify the number of Habitat Units that occur at that flow and the lowest flow that maintains that quantity of habitat.

Natural Winter Flow Analysis

Reduced living space (associated with naturally lower flow conditions), lack of food, and low water temperature, which reduces metabolic rates, are all factors that make winter a stressful period for fish in Rocky Mountain headwater streams (Locke and Paul 2011). Even relatively minor flow reductions at this time of year can change the frequency and severity of ice formation, force trout to move more frequently, affect distribution and retention of trout, and

reduce the holding capacity of the few large pools that often harbor a substantial proportion of the total trout population (Lindstrom and Hubert 2004).

The PHABSIM and HQI habitat modeling approaches may not be well suited to determine flow requirements during ice-prone times of year. These methods were developed for and apply primarily to open-water periods. Ice development during winter months can change the hydraulic properties of water flowing through some stream channels and compromise the utility of models developed for open-water conditions. The complexities of variable icing patterns make direct modeling of winter trout habitat over a range of flows difficult if not impossible. For example, frazil and surface ice may form and break up on multiple occasions during the winter over widely ranging spatial and temporal scales. Even cases that can be modeled, for example a stable ice cap over a simple pool, may not yield a result worthy of the considerable time and expense necessary to calibrate an ice model. There are no widely accepted aquatic habitat models for quantifying instream flow needs for fish in under-ice conditions (Annear et al. 2004). However, the Habitat Retention Method can be appropriate for winter flow recommendations.

For comparison with the Habitat Retention Method recommendation, the 20% monthly exceedance values for all winter months were averaged to develop a winter flow recommendation for maintaining the CRC fishery in Trail Ridge Creek. Whereas other flow values may be sufficient to support the fishery at other times of the year, the average of 20% monthly exceedance flows is most appropriate in winter. Hubert et al. (1997) observed that poor gage records often associated with the winter season requires use of a conservative value. Their studies showed that 50% monthly exceedance flow does not provide an appropriate estimate of naturally occurring winter flow. The average 20% exceedance flow approach ensures that even in cases where flow availability is underestimated due to poor gage records or other estimation errors, flow approximating the natural winter condition will be protected.

Geomorphology

Maintaining appropriate stream channel characteristics in a given stream segment is important for preventing loss of fish habitat throughout that stream over time. Reductions in flow quantity can affect the sediment load balance such that the sediment transport capacity of a stream decreases and excess fine sediment deposits in the channel (Bovee et al. 1998). This usually reduces habitat suitability for fish communities. Other physical changes in the stream caused by road building, culvert addition, riparian habitat reduction, and other activities also affect sediment transport dynamics. In streams compromised by excess sediment inputs from streambank instability, poor land management practices (such as over-grazing and inappropriate channel alterations) in the watershed, and road construction and maintenance activities, a reduction in natural flow conditions makes it even more difficult for the stream to move sediment sufficiently to prevent aggradation.

The geomorphology conditions of the proposed instream flow segment were evaluated by visual observation. Observations on channel form characteristics including Rosgen channel type, sinuosity, and riparian habitat conditions were noted. In addition, roads, culverts, and other changes to the watershed were identified along with areas of excessive erosion and any imbalances in sediment load conditions. This visual assessment also included observations on the influence of substrate sizes and large woody debris on pool development and habitat conditions for the fish community.

An evaluation of high flows, important for channel maintenance and necessary to maintain existing fisheries on a long-term basis, was not included in the main body of the report because the current interpretation of the instream flow statute does not allow issuance of water rights for high flows. Recommendations for flows sufficient to allow channel maintenance and to maintain fishery habitat in the segment are presented in Appendix B. However, should opportunities arise in the future to secure instream flow water rights for long-term maintenance of stream habitat conditions, this information will provide a valuable reference.

Water Quality

Water quality in late summer and fall has been found to be a limiting factor for many trout populations. Thus, water quality data are important to consider in development of an instream flow recommendation. Specifically, maximum summer water temperature and nitrate-nitrogen are used in the HQI model.

A data logger was used in the study site to collect water temperature data every 15 minutes between June 21 and September 27, 2016. These water temperature data were compared with NorWeST model results generated by the USFS Rocky Mountain Research station (<http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html>). That model is based on data collected at various points throughout the Yellowstone River watershed (HUC6 100800), including the Big Horn catchment, and estimates water temperature in all streams and tributaries throughout the watershed.

In addition, a Nitrate + Nitrite-N sample was collected and analyzed by the Wyoming Department of Agriculture Analytical Services Laboratory. Lastly, the Wyoming Department of Environmental Quality classification was noted.

Connectivity

River system connectivity functions along four dimensions: longitudinal, lateral, vertical, and temporal (Ward 1989). Flow levels for fish and many other aquatic organisms to move and migrate longitudinally within a stream are important to their survival and ability to meet their spawning, feeding, and temperature needs. Lateral connectivity is critical to the functioning of floodplain-based stream ecosystems due to the exchange of nutrients and organic matter between the floodplain and the stream during floods. This process is important in population dynamics of aquatic insects and ultimately affects fish productivity in streams. The seasonal flooding of unregulated streams creates and maintains diverse species of riparian vegetation (Nilsson et al. 1989), which increases stream channel stability and fosters diverse animal communities both within and adjacent to the stream channel. Vertical connectivity, the connections between groundwater and streamflow, is important for maintaining water table levels, streamflows, and water temperatures. Temporal connectivity refers to the seasonal timing of streamflow and biological interactions that fish and other aquatic organisms have evolved with and depend upon.

In developing instream flow recommendations for the Trail Ridge Creek segment, the presence of barriers was considered for physical, chemical, and biological conditions in all four dimensions of connectivity. The Habitat Retention Method was used to quantify the flow needed to maintain longitudinal hydrologic connectivity within the stream channel. A combination of methods was used to address the seasonal patterns of streamflow needs. However, no detailed assessment was conducted to quantify flows needed to maintain lateral or vertical connectivity because of the difficulty in evaluating these connections. Although the ability of the stream to

transport nutrients, energy, and sediments was beyond the scope of this study, such transport is also important in a properly functioning stream environment.

Instream Flow Recommendations

Results from all methods used in evaluation of all five riverine components were considered in determining instream flow needs for CRC in Trail Ridge Creek. The recommendations resulting from these analyses are expected to maintain short-term habitat for CRC in Trail Ridge Creek. However, the recommendations do not address changes in natural geomorphic characteristics and stream habitat-forming processes expected to occur over decades or longer. Consequently, the flow recommendations do not include channel maintenance flows and may not fulfill the statutory opportunity to maintain or improve the existing fishery on a long-term basis (perpetuity).

Wyoming statute 41-3-1001-1014, which declares that direct instream flows may be appropriated for maintaining or improving fisheries, has been interpreted by the Wyoming State Engineer's Office to include only hydrology and fisheries components of streams. This interpretation limits the ability to include the other riverine components (geomorphology, water quality, and some aspects of connectivity) as a basis for quantifying flow regime needs for maintaining fisheries. Though not specifically included in the flow recommendations, information on these other important riverine components on Trail Ridge Creek is presented in this report, including a detailed discussion of channel maintenance flows in Appendix B.

Instream flow recommendations were generated for three seasonal periods that are critical to the various life stages of CRC in Trail Ridge Creek. The timing and duration of each period is based on CRC biology and hydrology information from the reference gage (Table 3; Figure 6). Overwinter survival of adult and juvenile CRC from October 1 through March 31 was addressed with the results of the Habitat Retention Method and natural winter flow analysis. The estimated hydrograph (Figure 5) indicates that, on average, relatively low base flow conditions in winter persist through late March. Spawning and incubation habitat for CRC during April 1 to July 15 was quantified using PHABSIM habitat modeling results. Summer habitat for growth, production, and movement of adult and juvenile CRC during July 16 through September 30 was evaluated with results of the Habitat Quality Index, Habitat Retention Method, and PHABSIM modeling.

The models used for developing the recommendation for a given season were selected based on their appropriateness for the characteristics and flow needs at the study site (Table 3). Some models are more suited to certain life stages and time periods, so each was considered for the season(s) that was most appropriate. In some cases, the ecological characteristics and issues at the study site were unique and models used for developing flow recommendations in other studies were not necessarily appropriate in this situation. When two or more methods were appropriate for developing a flow recommendation, the one that yielded the higher flow requirement was chosen. Estimated monthly flow exceedances were also considered in comparing the appropriateness of methods.

TABLE 3. Methods used in developing instream flow recommendations for Colorado River Cutthroat Trout life stages, fishery functions, and seasons. Gray shading indicates the primary method used in each season. (NWF=Natural Winter Flow; HR=Habitat Retention Method; PHABSIM=Physical Habitat Simulation; HQ=Habitat Quality Index; CM=Channel Maintenance).

Life Stage and Fishery Function	Overwinter Oct 1 – Mar 31	Spring Apr 1 – Jul 15	Summer Jul 16 – Sep 30
Survival of all life stages	NWF or HR ^a		
Connectivity between habitats	HR	HR	HR
Adult and juvenile habitat availability	PHABSIM	PHABSIM	PHABSIM
Spawning habitat availability		PHABSIM	
Adult and juvenile growth			HQI
Habitat maintenance for all life stages		CM ^b	

a - Whichever is greater.

b - Channel maintenance flow recommendations are presented in Appendix B.

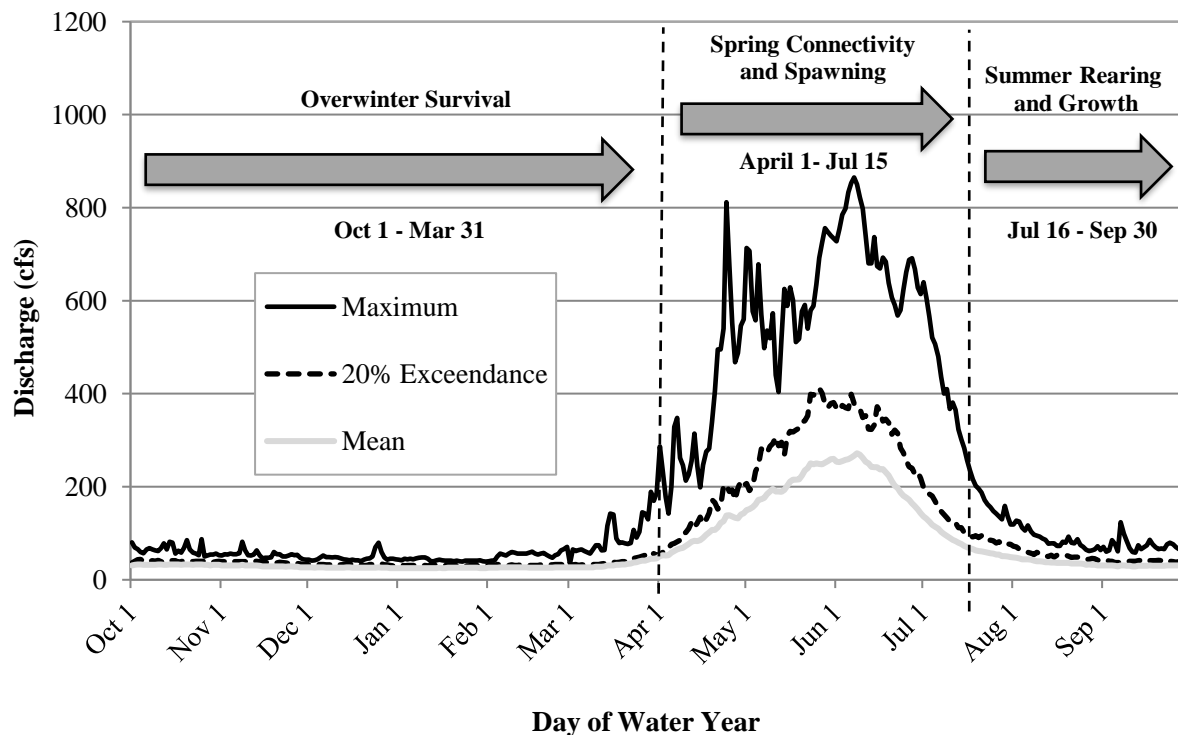


FIGURE 6. Historical daily maximum, 20% exceedance, and mean discharge values over the period of record at the reference gage, with critical time periods for CRC distinguished. Discharge data are from the USGS stream gage on Fontenelle Creek (9210500; water years 1952-2015).

RESULTS

Hydrology

Using drainage area of 5.3 square miles and the Lowham (1988) model based on drainage area and precipitation, mean annual flow was estimated to be 2.8 cfs in the Trail Ridge Creek instream flow segment (Table 4; Appendix C). Flood frequency analysis indicates that the 1.5-year peak flow is 13 cfs and the 25-year peak flow is 36 cfs. Monthly 50% and 20% exceedance values are displayed in Table 5. Discharge data collected during the study are presented in Table 6. In addition, a hydrograph was prepared that shows the daily maximum, 20% exceedance, and mean discharge estimates for the study segment during the reference gage period of record (Figure 7).

TABLE 4. Selected hydrologic statistics estimated for the Trail Ridge Creek instream flow segment.

Flow Parameter	Estimated Flow (cfs)
Mean Annual	2.8
1.5-year peak	13
25-year peak	36

TABLE 5. Estimated monthly exceedance flows for the Trail Ridge Creek instream flow segment.

Month	50% Exceedance (cfs)	20% Exceedance (cfs)
October	1.2	1.6
November	1.1	1.4
December	1.0	1.3
January	1.0	1.2
February	1.0	1.3
March	1.2	1.6
April	2.9	5.4
May	7.2	12.9
June	7.3	13.4
July	2.3	4.2
August	1.3	2.0
September	1.1	1.6

TABLE 6. Discharge measurements in the Trail Ridge Creek study site in 2016.

Date	Discharge (cfs)
6/23/16	5.59
7/6/16	3.62
9/27/16	0.39

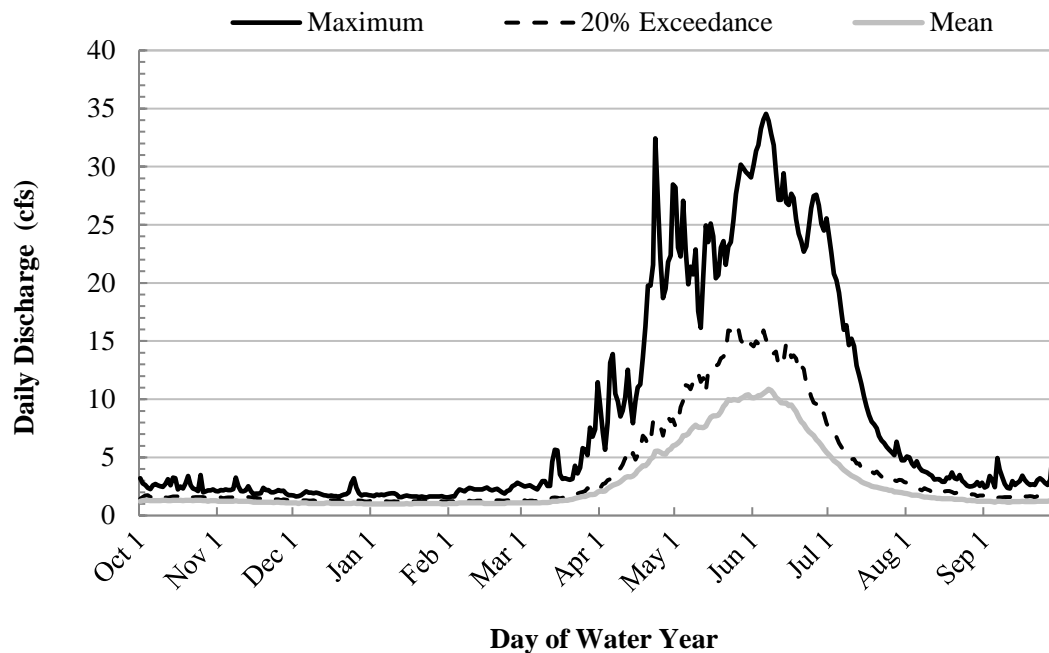


FIGURE 7. Hydrograph showing the estimated daily maximum, 20% exceedance, and mean discharge values for the Trail Ridge Creek instream flow segment over the reference gage period of record (Fontenelle Creek; USGS gage 09210500; water years 1952-2015).

Mean daily streamflow at the Fontenelle Creek reference gage was near average in 2016. At 65 cfs, mean discharge for the year was similar to the mean discharge over the period of record (71 cfs; water years 1952-2015; USGS 2016). For comparison with the reference gage data, the temporary stream gage in the Trail Ridge Creek study site allowed for estimation of daily discharge during the study period. Three stage and discharge pairs at 5.6 cfs, 3.6 cfs and 0.4 cfs were collected to create a rating curve (Figure 8). This rating curve ($y = 0.8614x^{0.2549}$) was applied to the water level data recorded from the pressure transducer to generate an estimate of instantaneous and daily discharge values (Figure 9).

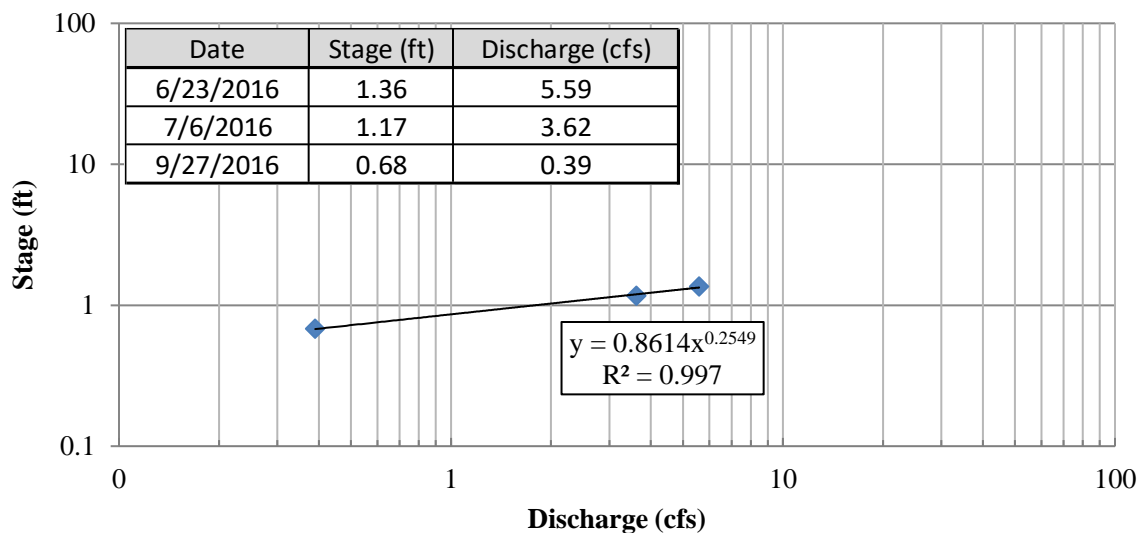


FIGURE 8. Rating curve data for the temporary gage established at the Trail Ridge Creek study site during 2016.

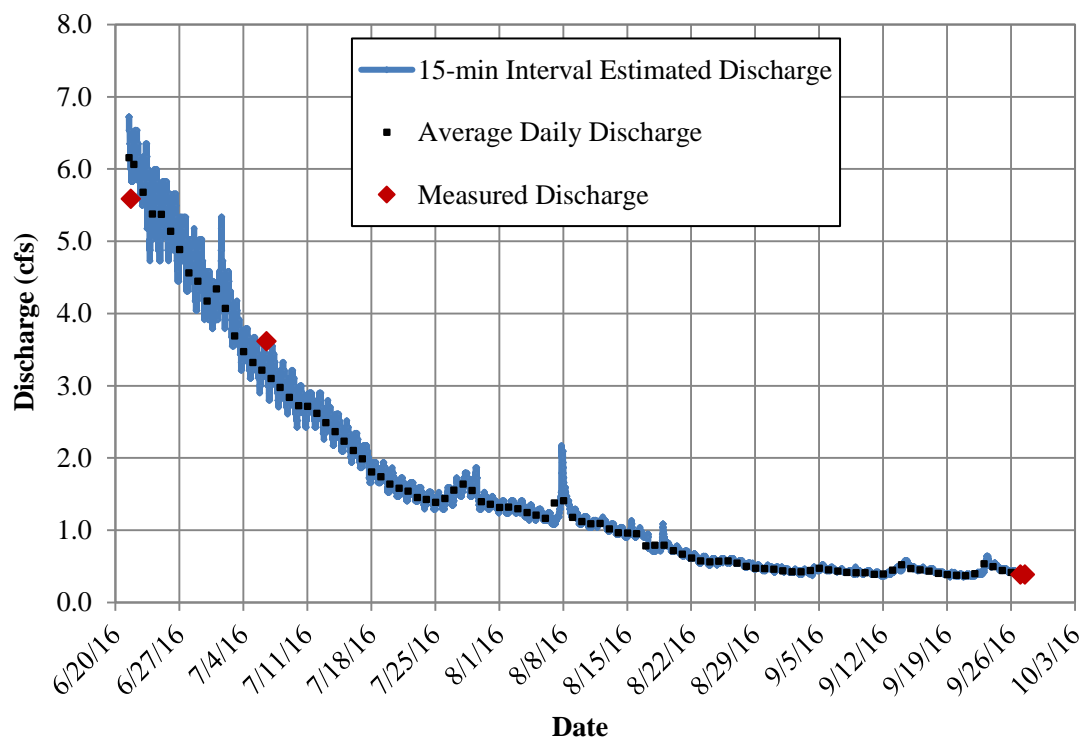


FIGURE 9. Hydrograph for Trail Ridge Creek study site during 2016.

Biology – Fish Habitat Modeling

Physical Habitat Simulation Model

The PHABSIM model was used to estimate weighted usable area (WUA) of habitat for adult, juvenile, and spawning life stages of CRC. The model results for the juvenile life stage indicate that WUA increases rapidly with increasing flow until it peaks at 1 cfs, decreases quickly with additional increases in flow up to 3 cfs, and then generally decreases more gradually at higher flows (Figure 10). Weighted Usable Area for the adult life stage shows a similar response to flow but peaks at 2 cfs. The lowest flow that maintained high percentages of WUA for both adult and juvenile life stages was 1.5 cfs. For the spawning life stage, WUA is very low up to 1 cfs, increases quickly to a peak at 3.6 cfs, and then declines rapidly as flow increases. The lowest flow that maintained more than 95% of spawning habitat WUA was 3.0 cfs, which is greater than the flows providing peak WUA for juvenile and adult life stages. Thus, 3.0 cfs is the recommended flow for spawning and connectivity in the spring.

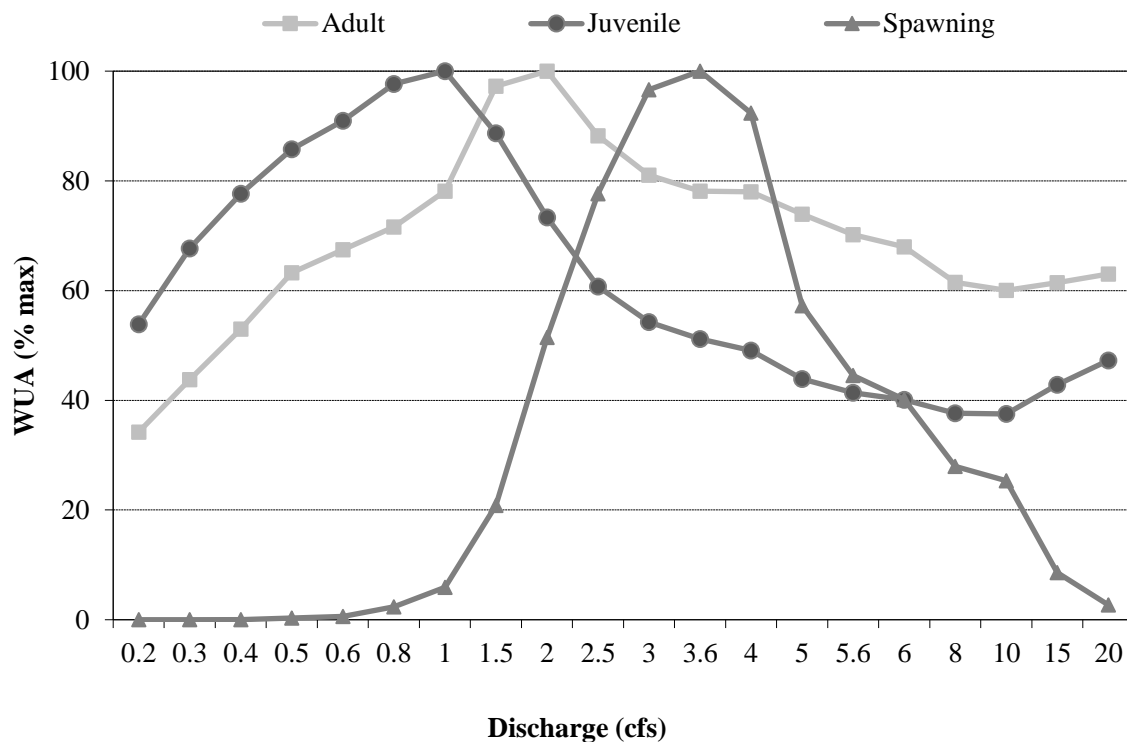


FIGURE 10. Relationship between WUA and discharge for CRC adult, juvenile, and spawning life stages in the Trail Ridge Creek study site. X-axis values are not to scale; the values were chosen to highlight important habitat conditions.

Habitat Retention Method

The Habitat Retention Method was used to evaluate hydraulic characteristics that affect the survival and movement of all life stages, through all seasons, over a range of discharges in the Trail Ridge Creek instream flow segment (Table 7). Three riffle cross-sections were modeled and the resulting discharge needed to maintain the necessary hydraulic criteria at all transects was 1.8 cfs. This threshold flow should maintain base level conditions for fish passage as well as provide overwinter survival habitat for CRC and habitat for benthic invertebrate populations on riffles with similar characteristics as the riffle cross-sections; though higher flows at some times of year may be needed for other fishery purposes.

TABLE 7. Estimated hydraulic conditions for three riffles at selected modeled discharges in the Trail Ridge Creek instream flow site. Bold indicates that the hydraulic criterion (shown in Table 2) was met at the associated discharge; the grayed-out values are the lowest discharges that meet two of the hydraulic criteria.

Riffle Transect Number	Discharge (cfs)	Mean Velocity (ft/sec)	Mean Depth (ft)	Wetted Perimeter (% of bankfull)
1	30	5.37	0.88	66
	3.0	1.34	0.44	50
	1.8	1.00	0.36	49
	0.4	0.42	0.20	46
	0.2	0.28	0.14	45
2	30	3.66	0.90	100
	3.0	1.30	0.41	58
	1.6	1.00	0.29	55
	0.8	0.76	0.20	52
	0.5	0.64	0.15	50
3	30	6.15	0.59	75
	3.0	1.33	0.34	59
	2.0	1.00	0.31	56
	0.5	0.41	0.20	52
	0.2	0.24	0.15	50

Habitat Quality Index Model

The HQI model was used to determine production potential of adult and juvenile CRC in the study site during late summer (July 16 through September 30) flow conditions. For this model, the 20% exceedance flow value for September (1.6 cfs; Table 5) was used as an estimate of existing, normal late summer flow levels. At 1.6 cfs, the Trail Ridge Creek study site provides 231 Habitat Units. The instream flow recommendation from the HQI model is the lowest streamflow value that provides as many Habitat Units as the September 20% exceedance value, which in this case is also 1.6 cfs (Figure 11). The model shows that long-term reductions of late summer flow to levels less than 1.6 cfs would reduce the productivity of the existing fishery by over 16%.

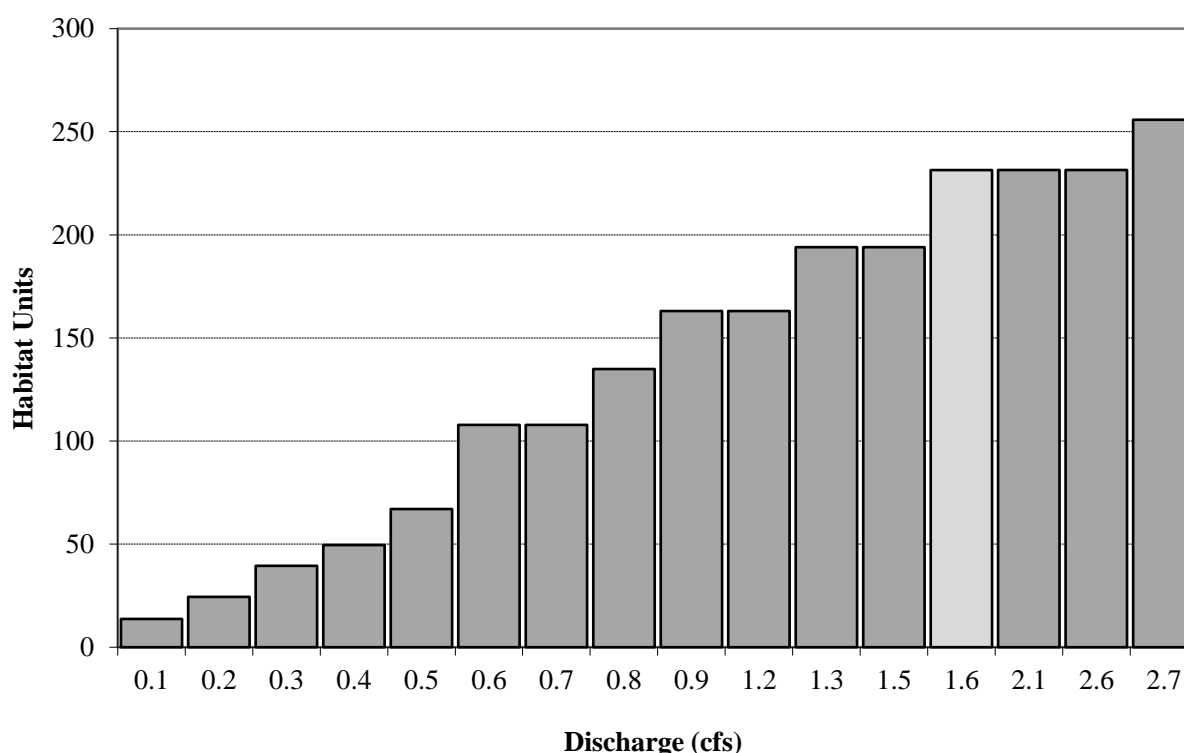


FIGURE 11. Habitat Quality Index vs. discharge in the Trail Ridge Creek instream flow site. X-axis is not to scale; the values were chosen to indicate where changes in Habitat Units occur. The recommended flow of 1.6 cfs (indicated by the lighter-shaded bar) is the lowest flow that provides the same amount of Habitat Units as the September 20% exceedance flow (also 1.6 cfs).

Natural Winter Flow Analysis

For October 1 through March 31, the estimated monthly 20% exceedance values in the proposed instream flow segment ranged from 1.2 cfs to 1.6 cfs (Table 5). According to this method, natural winter flows of up to 1.4 cfs (the mean of the 20% monthly exceedance flows for the winter period) are needed to maintain existing levels of overwinter survival of all life stages of CRC.

Geomorphology

The proposed instream flow segment in Trail Ridge Creek is predominantly a Rosgen E-type channel with a low slope and high sinuosity within and near the study site, with some sections forming more of a B-type with a steeper slope and lower sinuosity. The stream is stable throughout with dense riparian habitat stabilizing the banks and gravel substrates. Some large woody debris contributes to pool development. Hydraulic controls were formed primarily by gravel.

A detailed description of recommended channel maintenance flows to sustain the channel form and fisheries habitat in the proposed instream flow segment over the long term is presented in Appendix B.

Water Quality

Trail Ridge Creek is a moderate elevation stream located mostly on BLM lands and has some oil and gas development within its catchment. The limited efforts to evaluate water quality conditions in Trail Ridge Creek as part of this study indicated no impairment. A more detailed assessment of water quality may be warranted to evaluate whether flow reductions would have a detrimental impact on fish habitat.

The Wyoming Department of Environmental Quality rates Trail Ridge Creek as a “Class 2AB” water (WYDEQ 2013). According to their classification system, “Class 2AB waters are those known to support game fish populations or spawning and nursery areas at least seasonally and all their perennial tributaries and adjacent wetlands and where a game fishery and drinking water use is otherwise attainable. Class 2AB waters include all permanent and seasonal game fisheries and can be either ‘cold water’ or ‘warm water’ depending upon the predominance of cold water or warm water species present. All Class 2AB waters are designated as cold water game fisheries unless identified as a warm water game fishery by a ‘ww’ notation in the Wyoming Surface Water Classification List. Unless it is shown otherwise, these waters are presumed to have sufficient water quality and quantity to support drinking water supplies and are protected for that use. Class 2AB waters are also protected for nongame fisheries, fish consumption, aquatic life other than fish, recreation, wildlife, industry, agriculture and scenic value uses.”

The maximum recorded water temperature in Trail Ridge Creek was 64.7° F during the study period, with temperature exceeding 55° F approximately 31% of the time between June 21 and September 27, 2016. The mean August temperature recorded in 2016 was 53.5° F. The NorWeST model generated by the Rocky Mountain Research Station estimates the mean August temperature to be 55.4° F at the downstream end of the Trail Ridge Creek instream flow segment; the data collected in our study are close to the historical (1993-2011) average estimated in the NorWeST model. The NorWeST model also considers future changes in stream temperatures and predicts a mean August temperature of 57.7° F in 2040 in this reach. Isaak and Hubert (2004) found that cutthroat trout abundance peaked in Wyoming streams around 53.6° F. The water temperatures in Trail Ridge Creek favor CRC currently, but a moderate increase in temperatures could negatively affect CRC abundance.

The Nitrate + Nitrite – N sample, which was analyzed by the Wyoming Department of Agriculture Analytical Services Laboratory, had a result of <0.05 mg/L, which is a low value and further supports visual observations that water quality is good in this segment.

Flow recommendations in this report are expected to help maintain water quality within natural bounds; it is assumed that water quality characteristics will remain within existing limits of natural variability. If drastic long-term changes to watershed form or function occur, then flow recommendations may need to be revised.

Connectivity

There is one two-track crossing in the lower portion of Trail Ridge Creek where the stream banks are more unstable than the remainder of the creek, but this has little impact on connectivity in the reach. There are no known diversion structures in Trail Ridge Creek. The stream seems to have access to the floodplain throughout the watershed.

Flow recommendations in this report are expected to maintain good longitudinal connectivity conditions within the instream flow segment. If drastic long-term changes to watershed form or function occur, then flow recommendations may need to be revised.

Instream Flow Recommendations

The recommendations for specific seasonal fishery needs for the Trail Ridge Creek instream flow segment are (Table 8; Figure 12):

- Winter (October 1 – March 31) – Natural flow of up to 1.8 cfs is needed to maintain existing levels of overwinter survival of all life stages of CRC. This flow level is the result of the Habitat Retention Method.
- Spring (April 1 – July 15) – Natural flow up to 3.0 cfs is needed to provide sufficient habitat for spawning CRC (PHABSIM spawning results).
- Summer (July 16 – September 30) – Natural flow up to 1.8 cfs is needed, based on Habitat Retention Method results, to provide sufficient habitat conditions for passage, growth, and production of juvenile and adult CRC.

TABLE 8. Instream flow water right recommendations (cfs) for the proposed instream flow segment in Trail Ridge Creek.

Study Segment	Winter Oct 1 – Mar 31	Spring Apr 1 – Jul 15^a	Summer Jul 16 – Sep 30
Trail Ridge Creek	1.8	3.0	1.8

a - Channel maintenance flow recommendations for the spring runoff period are defined in Appendix B.

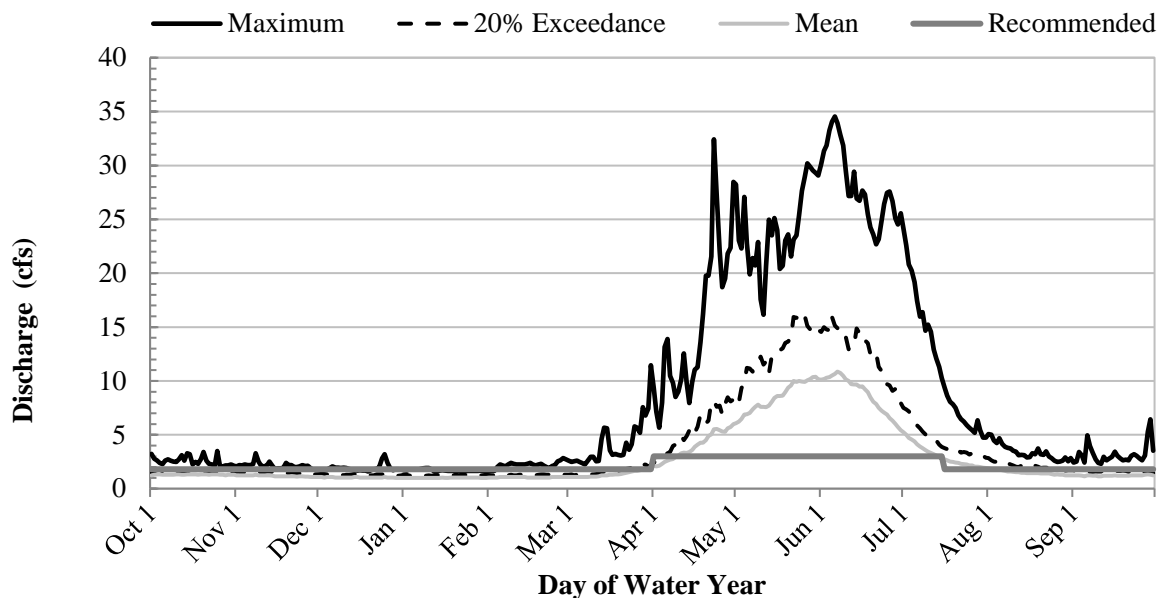


FIGURE 12. Recommended instream flow water right (when flow is naturally available) in the Trail Ridge Creek segment compared to daily maximum, 20% exceedance, and mean discharge estimates over the reference gage period of record (Fontenelle Creek; USGS gage 09210500; water years 1952-2015).

DISCUSSION

Trail Ridge Creek is within the historical range of CRC habitat, has a core conservation population of CRC, and is critical in the long-term management of the species. Protecting streamflows that provide sufficient habitat to support the CRC population will help ensure the long-term persistence of the species in the Upper Green River watershed. This action will also support the State's interests by adding to conservation actions needed to keep the species from being listed as threatened or endangered by the federal government. If approved by the State Engineer, the proposed instream flow water right filing on Trail Ridge Creek will maintain existing base flow conditions, when naturally available, up to the permitted amount. By protecting streamflows against potential future out-of-channel water use permits, approximately 4.2 miles of suitable habitat will be maintained directly for CRC in Trail Ridge Creek. If drastic long-term changes to watershed form or function occur, then flow recommendations may need to be revised to achieve the statutorily provided opportunity of maintaining or improving the existing fishery.

ACKNOWLEDGEMENTS

Data were collected by Wyoming Game and Fish Department fisheries biologist Mike Robertson and fisheries technician Betsy Morgan. Most of the data analysis and the draft report were completed in 2017 by Mike Robertson. Wyoming Game and Fish Department fisheries technician Hanna Foster reviewed the manuscript and provided constructive comments that greatly improved the quality and clarity of the report.

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Appendix A. Instream Flows in Wyoming

LEGAL AND INSTITUTIONAL BACKGROUND

The instream flow law, W.S. 41-3-1001-1014, was passed in 1986 and established that “. . . unappropriated water flowing in any stream or drainage in Wyoming may be appropriated for instream flows to maintain or improve existing fisheries and declared a beneficial use. . . .” The statute directs that the Wyoming Game and Fish Commission (WGFC) is responsible for determining direct streamflows that will “maintain or improve” important fisheries. The Wyoming Game and Fish Department (WGFD) fulfills this function under the general policy oversight of the WGFC. The WGFD conducts biological studies to determine the quantities of flow needed to maintain or improve fisheries. The Wyoming Water Development Office submits the instream flow water right applications and then conducts a feasibility study to determine the availability of flow to meet the WGFD recommendations. If approved by the State Engineer, instream flow water rights are held by the Wyoming Water Development Office on behalf of the State. The priority date for the instream flow water right is the day the application is received by the State Engineer. As with all other water rights in Wyoming, the doctrine of prior appropriation applies and instream flow water rights are junior to all pre-existing water rights in the stream. Permitted instream flow water rights will not affect the lawful use of water for senior rights.

BIOLOGICAL STUDIES

Stream segments that have critical need for instream flows are identified throughout the State of Wyoming and studies are conducted in each segment to determine how much flow is needed to maintain or improve the fisheries in those segments. A comprehensive instream flow study is designed to consider all five riverine ecosystem components (hydrology, biology, geomorphology, water quality and connectivity) and all aspects of each component (e.g., long-term habitat processes; Annear et al. 2004); however, the instream flow statute has been interpreted by the Wyoming State Engineer’s Office as applying only to direct fishery response to changes in flow. Other important components that influence stream conditions and fish populations, such as geomorphology, water quality, and some aspects of connectivity, are not addressed directly by the instream flow recommendations (though pertinent information, when available, is provided in biological study reports).

From a natural resource perspective, a fishery includes the habitat and associated natural processes that are required to support fish populations. The primary components that constitute physical habitat include, but are not limited to, the stream channel, riparian zone, and floodplain as well as the processes of sediment flux and riparian vegetation development that sustain those habitats (Annear et al. 2004). To maintain the existing dynamic character of an entire fishery, instream flow regimes must maintain the stream channel and its functional linkages to the riparian corridor and floodplain to perpetuate habitat structure and ecological function. Until the interpretation of State water law changes to include a full range of flows of a dynamic fishery, channel maintenance flow recommendations are not included on instream flow water right applications, but are presented in an appendix of the biological studies report.

GUIDING PRINCIPLES FOR INSTREAM FLOW RECOMMENDATIONS

The analyses and interpretation of data collected for instream flow studies include consideration of the important components of an aquatic ecosystem and their relationship to streamflow. Stream ecosystems are complex, and maintaining this complexity requires an appropriate flow regime. The recommendations of the Instream Flow Council (IFC), an organization of state and provincial fishery and wildlife management agencies, provide comprehensive guidance on conducting instream flow studies (Annear et al. 2004). The approach described by the IFC includes consideration of three policy components (legal, institutional, and public involvement) and five riverine components (hydrology, geomorphology, biology, water quality and connectivity). By using the eight components described by the IFC as a guide, WGFD strives to develop instream flow recommendations that work within Wyoming's legal and institutional environment to maintain or improve important aquatic resources for public benefit, while also employing a generally recognized flow quantification protocol.

PUBLIC PARTICIPATION

The public has several opportunities to be involved in the process of identifying instream flow segments or commenting on instream flow applications. Individuals or groups can inform WGFD of their interest in protecting the fisheries in specific streams or stream segments with instream flow filings. In addition, planning and selection of future instream flow study sites are detailed in the WGFD Water Management Unit's work plan (Robertson and Annear 2011).

The public is also able to comment on instream flow water rights that have been filed with the State Engineer through public hearings, which are required by statute and conducted by the State Engineer's Office for each proposed instream flow water right. The State Engineer uses these public hearings to gather information for consideration before issuing a decision on the instream flow water right application.

Instream flow segments are nearly always located on public land. However, landowners adjacent to a proposed segment are informed of WGFD instream flow study data collection, and have the opportunity to request that the State extend an instream flow segment onto the portion(s) of the stream crossing their property. Any such requests must be made in writing to WGFD. Instream flow segments are not located on private lands without such a request.

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Appendix B. Channel Maintenance Flows

BACKGROUND

Maintaining a dynamic flow regime within the natural range of variability and including occasional high flows is important for maintaining diverse fish habitat and riparian and floodplain vegetation in and along streams (Kuhnle et al. 1999). A managed flow regime should mimic natural dynamic hydrographs within and between years (Gordon 1995, Trush and McBain 2000, Schmidt and Potyondy 2004) and include high flows that maintain channel form and habitat conditions for fish over the long term (decades). High flows are needed in some years to scour the stream channel, prevent encroachment of stream banks, and deposit sediments on the floodplain to maintain a dynamic alternate bar morphology and a riparian community with diverse successional states (Carling 1995, Annear et al. 2004, Locke et al. 2008). Low flow years allow establishment of riparian seedlings on bars deposited in immediately preceding wet years (Trush and McBain 2000). When water is extracted from a stream, the natural dynamic flow patterns are changed. Larger extractions have greater impact on habitat conditions and the organisms associated with those habitats. If naturally occurring high flows are reduced substantially on a regular basis, it will have negative effects on the habitat, riparian assemblage of plants and animals, and ultimately the resident fishery (Stromberg and Patten 1990, Rood et al. 1995, Mahoney and Rood 1998).

The term “channel maintenance flows” refers to flows that maintain existing channel morphology, riparian vegetation and floodplain function (Schmidt and Potyondy 2004). The basis and approach used for defining channel maintenance flows applies to snowmelt-dominated gravel and cobble-bed (alluvial) streams and “. . . identifies the minimum essential regime of streamflows necessary for the channel and its floodplain to remain fully functioning with respect to sediment and flow conveyance.” These are streams with beds dominated by loose material with median sizes larger than 0.08 inches and with a pavement or armor layer of coarser materials overlaying the channel bed. In these streams, bedload transport processes determine the size and shape of the channel and the character of habitat for aquatic organisms (Andrews 1984, Hill et al. 1991, Leopold 1994).

Flow regimes that include sufficient flows for channel maintenance result in stream channels that are in approximate sediment equilibrium, where sediment export equals sediment import, on average, over a period of years (Leopold 1994, Carling 1995, Schmidt and Potyondy 2004). Thus, stream channel characteristics over space and time are a function of sediment input and flow (Schmidt and Potyondy 2004). When sediment-moving flows are removed or reduced over a period of years, some gravel-bed channels respond with changes in width and depth, rate of lateral migration, streambed elevation, streamside vegetation, water-carrying capacity, and bed material composition.

Channel maintenance flows must be sufficient to move the entire volume and all sizes of material supplied to the channel from the watershed over a long-term period (Carling 1995, Schmidt and Potyondy 2004). A range of flows, under the dynamic hydrograph paradigm, provides this function. Infrequent high flows move large bed elements, while the majority of the total volume of material is moved by more frequent but lower flows (Wolman and Miller 1960, Leopold 1994). In streams with a wide range of sediment sizes on the channel boundary, a range of flows may best represent the dominant discharge because different flow velocities are needed to mobilize different sizes of bedload and sediment. Kuhnle et al. (1999) noted, “A system

designed with one steady flow to transport the supplied mass of sediment would in all likelihood become unstable as the channel aggraded and could no longer convey the sediment and water supplied to it.”

BEDLOAD TRANSPORT

A bedload transport model (Figure B-1) shows the total amount of bedload sediment transported over time (during which a full range of stream discharge [Q] values occur). Smaller discharges, such as the substrate mobilization flow (Q_m) occur more frequently, but not much sediment is moved during those times. Over time, the effective discharge (Q_e) mobilizes the greatest volume of sediment. Transport of some larger sediment particles (gravels and small cobbles) is initiated by Q_e . The bankfull discharge (Q_{bf}), the flow that begins to inundate the floodplain and that has a return interval of approximately 1.5 years on average, typically occurs near the Q_e . The infrequent discharge corresponding to the 25-year return interval (Q_{25}) represents the upper limit of the required channel maintenance flow regime because the full range of mobile sediment materials move at flows up to this value. The more frequent discharges that occur between the Q_m and the Q_e move primarily smaller-sized particles (sand and small gravel) and prevent filling in of pools and other reductions in habitat complexity. Because these particles are deposited into the stream from the surrounding watershed with greater frequency, it is important to maintain a flow regime that provides sufficient conveyance properties (high frequency of moderate discharges) to move these particles through the system. However, alluvial streams, particularly those at higher elevations, also receive significant contributions of larger-sized particles from the surrounding watershed and restrictions to the flow regime that prevent or reduce the occurrence of flows greater than Q_e (which are critical for moving these coarser materials) would result in gradual bedload accumulation of these larger particles. The net effect would be an alteration of existing channel forming processes and habitat (Bohn and King 2001). For this reason, flows up to the Q_{25} flow are required to maintain existing channel form and critical habitat features for local fish populations.

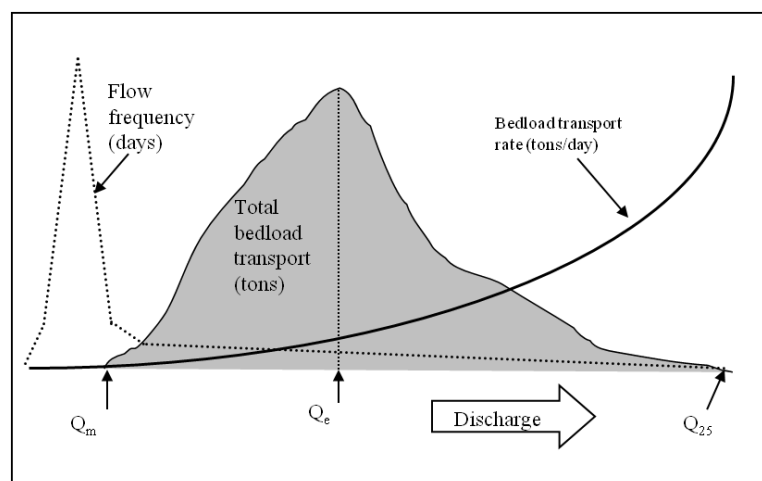


FIGURE B-1. Total bedload transport as a function of bedload transport rate and flow frequency (adapted from Schmidt and Potyondy 2004).

CHANNEL MAINTENANCE FLOWS MODEL

The model used to recommend flows to maintain the form and function of the stream channel is derived from bedload transport theory presented above. Based on these principles, the following channel maintenance flow model was developed by Dr. Luna Leopold (Gordon 1995):

$$Q \text{ Recommendation} = Q_f + \{(Q_s - Q_f) * [(Q_s - Q_m) / (Q_{bf} - Q_m)]^{0.1}\}$$

Where: Q_s = actual streamflow

Q_f = fish flow (required to maintain fish spawning habitat)

Q_m = sediment mobilization flow = $0.8 * Q_{bf}$

Q_{bf} = bankfull flow

The Leopold model can be used to calculate instream flow recommendations for selected increments of flow between the Q_m and Q_{bf} . However, such flow regulation is complex and could prove burdensome to water managers. To facilitate flow administration while still ensuring sufficient flows for channel maintenance, we modified this aspect of the approach to recommend a single instream flow for each of four quartiles between the Q_m and Q_{bf} .

Channel maintenance flow recommendations developed with the Leopold model require that only a portion of the flow remain instream for maintenance efforts (Figure B-2). When total discharge is less than Q_m , only fish flows are necessary; thus, discharge between the spawning habitat flow recommended in the main body of this report and Q_m is available for other uses. Similarly, all discharge greater than the Q_{25} flow is less critical for channel maintenance purposes and available for other uses (these higher flows do allow a connection to the floodplain and it is valuable for infrequent inundation of riparian habitat to occur, but not for the physical maintenance of the stream channel). Between the Q_m and Q_{bf} , the model is used to determine what proportion of flow should remain in channel for maintenance activities. For those relatively infrequent flows that occur in the range between Q_{bf} and the Q_{25} , all flow is recommended to remain in the channel for these critical channel maintenance purposes.

Using this “dynamic hydrograph” approach, the volume of water required for channel maintenance is variable from year to year. During low-flow years, less water is recommended for channel maintenance because flows may not reach the defined channel maintenance level. In those years, most water in excess of the fish habitat flow is available for other uses. The majority of flow for channel maintenance occurs during wet years. One benefit of this dynamic hydrograph approach is that the recommended flow is needed only when it is available in the channel and does not assert a claim for water that is not there as often happens with a threshold approach.

This channel maintenance flow model is the same as the one presented in Gordon (1995) and the Clark’s Fork River instream flow water right (C112.0F) filed by the U.S. Forest Service with the Wyoming State Engineer, with one exception. The model presented in those documents used the average annual flow to represent Q_m . Subsequent work by Schmidt and Potyondy (2004) identified Q_m as occurring at a discharge of 0.8 times Q_{bf} . Initial particle transport begins at flows somewhat greater than average annual flows but lower than Q_{bf} (Schmidt and Potyondy 2004). Ryan (1996) and Emmett (1975) found the flows that generally initiated transport were between 0.3 and 0.5 of Q_{bf} . Movement of coarser particles begins at flows of about 0.5 to 0.8 of Q_{bf} (Leopold 1994, Carling 1995). Schmidt and Potyondy (2004) discuss phases of bedload

movement and suggest that a flow trigger of 0.8 of the Q_{bf} “. . . provides a good first approximation for general application. . . .” in defining flows needed to maintain channels.

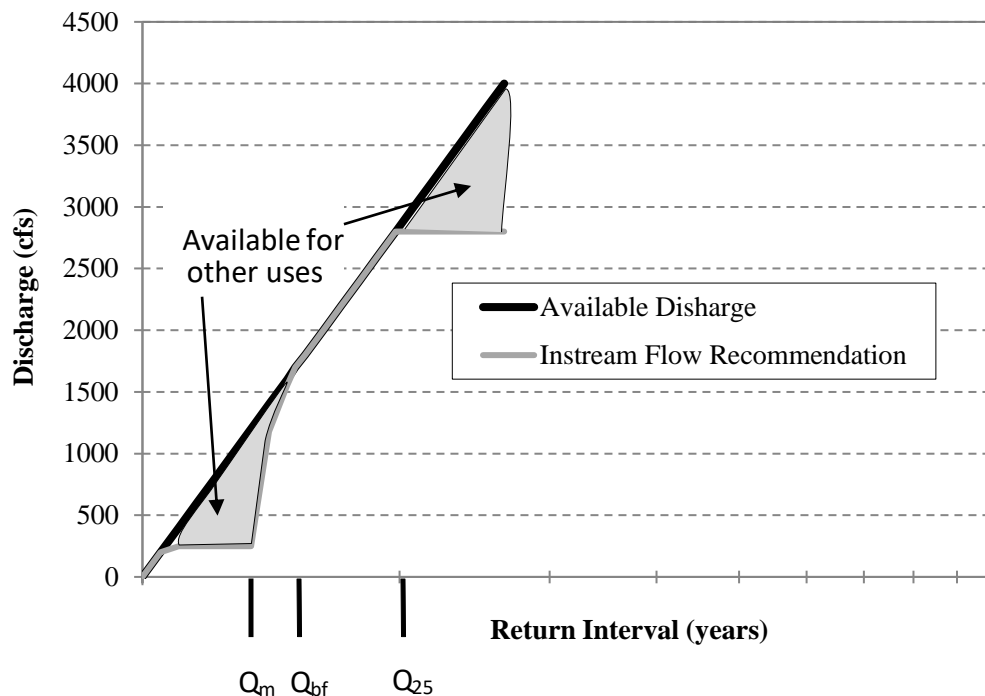


FIGURE B-2. Generalized dynamic hydrograph indicating recommended instream flow for fishery maintenance. Q_m is substrate mobilization flow, Q_{bf} is bankfull flow, and Q_{25} is the discharge with a 25-year return interval.

TRAIL RIDGE CREEK

Like all properly functioning rivers, Trail Ridge Creek has a hydraulically connected watershed, floodplain, riparian zone, and stream channel. Bankfull and overbank flow are essential hydrologic characteristics for maintaining the habitat in and along these river segments in their existing, dynamic forms. These high flows flush sediments from the gravels and maintain channel form (i.e., depth, width, and pool and riffle configuration) by periodically scouring encroaching vegetation. Overbank flow maintains recruitment of riparian vegetation, encourages lateral movement of the channel, and recharges groundwater tables. Instream flows that maintain the connectivity of these processes over time and space are needed to maintain the existing fishery (Annear et al. 2004).

The Leopold model, with modification to include a single recommendation for each of four quartiles from Q_m to Q_{bf} , was used to develop channel maintenance recommendations for the Trail Ridge Creek instream flow segment (Table B-1). The fish flow used in the analysis was the spring spawning flow (3.0 cfs). For naturally available flow levels less than the spawning flow, the channel maintenance instream flow recommendation is equal to natural flow. The spawning flow level is less than Q_m (10 cfs). For the flow range between the spawning flow and Q_m , the channel maintenance flow recommendation is equal to the spawning flow (Table B-1).

When naturally available flows range from Q_m to Q_{bf} (13 cfs), the Leopold formula is applied and results in incrementally greater amounts of water applied toward channel maintenance flow (Table B-1). At flows between Q_{bf} and Q_{25} (36 cfs), all streamflow is retained in the channel to perform maintenance functions. At flows greater than Q_{25} , only the Q_{25} flow is recommended for channel maintenance (Figure B-3).

TABLE B-1. Channel maintenance instream flow recommendations (May 1–July 15) to maintain existing channel forming processes and long-term aquatic habitat characteristics in the Trail Ridge Creek instream flow segment.

Flow Description	Available Flow (cfs)	Recommended Flow (cfs)
<Spawning Flow	<3.0	All available flow
Spawning Flow to Q_m	3.1-10.0	3.0
Q_m to Q_{bf} – Quartile 1	10.1-10.7	8.1
Q_m to Q_{bf} – Quartile 2	10.8-11.5	9.8
Q_m to Q_{bf} – Quartile 3	11.6-12.2	11.1
Q_m to Q_{bf} – Quartile 4	12.3-12.9	12.1
Q_{bf} to Q_{25}	13.0-36.0	All available flow
> Q_{25}	> 36	36

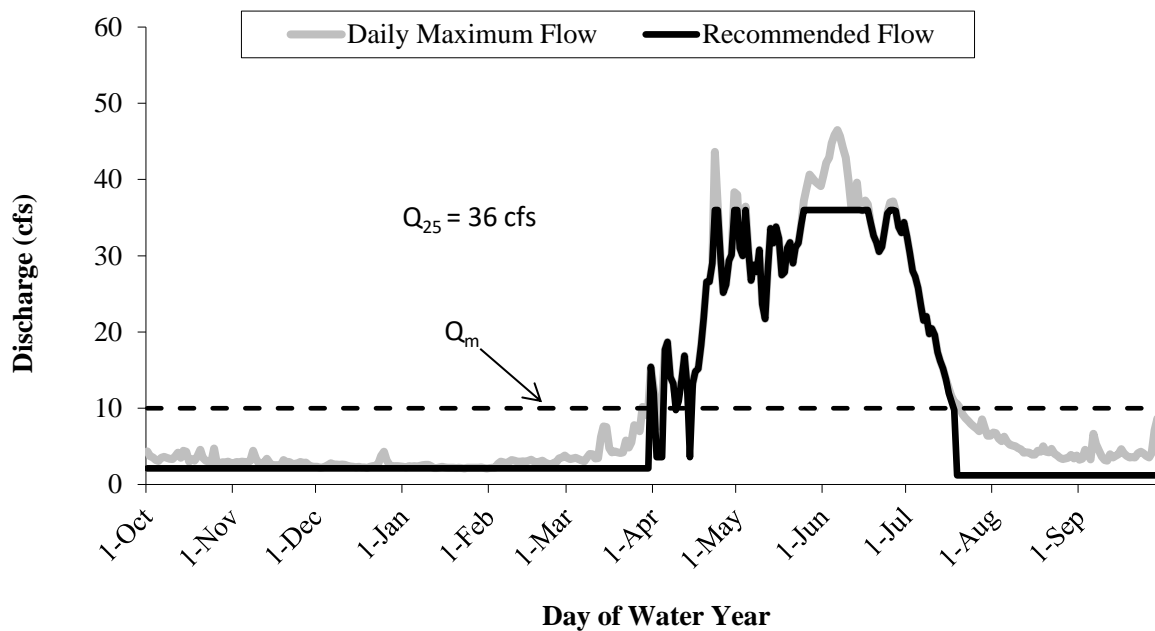


FIGURE B-3. Channel maintenance flow recommendations for the Trail Ridge Creek instream flow segment if the flows were at the daily maximum flow each day of the water year.

Implementing these channel maintenance flow recommendations would have to include moderating the abrupt changes that occur at threshold flows. Such moderation could be achieved with a ramping method that includes gradual changes similar to a natural hydrograph. Such sharp flow increases and decreases evident in Figure B-3 would cause habitat loss through excessive scour and potential trout mortality due to stranding. In addition, spawning redds may be disturbed and fish recruitment negatively affected without an appropriate ramping rate. The Index of Hydrologic Alteration (IHA; Richter et al. 1996) or other hydrologic summary models could provide a valuable reference to find suitable rates of change. Daily increases and decreases during runoff measured at the reference gage could serve as a guide for developing such ramping rate recommendations using the IHA.

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Appendix C. Hydrology Estimates for the Ungaged Study Segment

There are multiple methods for generating daily discharge estimates for ungaged stream segments. In this report, the method chosen for these estimates is based on watershed characteristics that typically can be calculated from maps and climatology data from the study area. These watershed characteristics models were developed using stream gage data both regionally and statewide. The results of these calculations and flow estimates for the study segment are compared with field data collected during the instream flow study. These results could be paired with a field hydrologic study (e.g., following the study design of Lowham 2009) to generate comprehensive flow estimates that have a higher probability of accuracy than either method used alone. An excellent example of how multiple flow estimation methods can be combined into a single set of daily discharge estimates is described in Parrett and Cartier (1990).

REFERENCE GAGE SELECTION

To estimate flows in an ungaged stream using a watershed characteristics model, a reference stream gage is first selected to provide baseline discharge data. The qualities of a good reference gage are that it: 1) be located close to the study segment, where possible (within the same eight-digit HUC drainage is preferred), 2) have at least 10 years of continuous records (preferably from a gage in current operation), and 3) be in a stream with similar watershed characteristics (mean elevation, drainage area, stream width, etc.). Due to the limited number of stream gages in Wyoming, this combination is difficult to find for most instream flow study segments. Once a reference gage is selected, the recorded flow estimates from that gage are adjusted through dimensional analysis intended to correct for differences between the reference gage stream and the ungaged study stream. After this adjustment factor is applied, the period of record at the reference gage can be used to estimate flows over the same period (including generating monthly and annual summary statistics) at the study segment.

In the area near the Trail Ridge Creek study segment, there are two active and one inactive USGS stream gaging stations that have more than 20 years of data and were considered as potential reference gages (Table C-1). Because there are good reference gage options that are active, the one inactive gage was excluded from consideration. One of the two active USGS gages was within the same watershed (HUC8 14040101 - Upper Green River) and the other is in a different watershed (HUC8 14040107 - Blacks Fork). The size of the drainage basins for the two active gages was 128 and 152 square miles. The Trail Ridge Creek drainage area is 5.3 square miles. From this perspective, both gages are equally well suited as a reference so the closer gage (Fontenelle Creek; 09210500) was selected as the reference gage for this study.

TABLE C-1. Selected information about potential USGS reference gages for Trail Ridge Creek.

Gage Name	Gage Number	Period of Record (Water Years)	Drainage Area	Elevation (ft)
Fontenelle Creek near Herschler Ranch, WY	09210500	1952-2015	152	6,950
Hams Fork below Pole Creek, WY	09223000	1953-2015	128	7,455
North Piney Creek near Mason, WY	09205500	1916-1972	58	7,510

TEMPORARY STREAM GAGE DATA

A temporary stream gage station was established upstream of the Trail Ridge Creek study site between June 21, 2016 and September 27, 2016. Discharge measurements collected during the study period were used with stage readings from the staff plate during the same day to establish a rating curve (Figure C-1). This rating curve was used to estimate daily discharges from water level readings at the study site (Figure C-2), and then those estimated values were compared to daily discharge values at the Fontenelle Creek reference gage (Figure C-3). The discharge estimates at the study site were highly correlated ($R^2 = 0.95$) with discharge estimates at the reference gage. The correlation is unknown for Trail Ridge Creek discharges less than about 0.4 cfs and greater than 5.6 cfs.

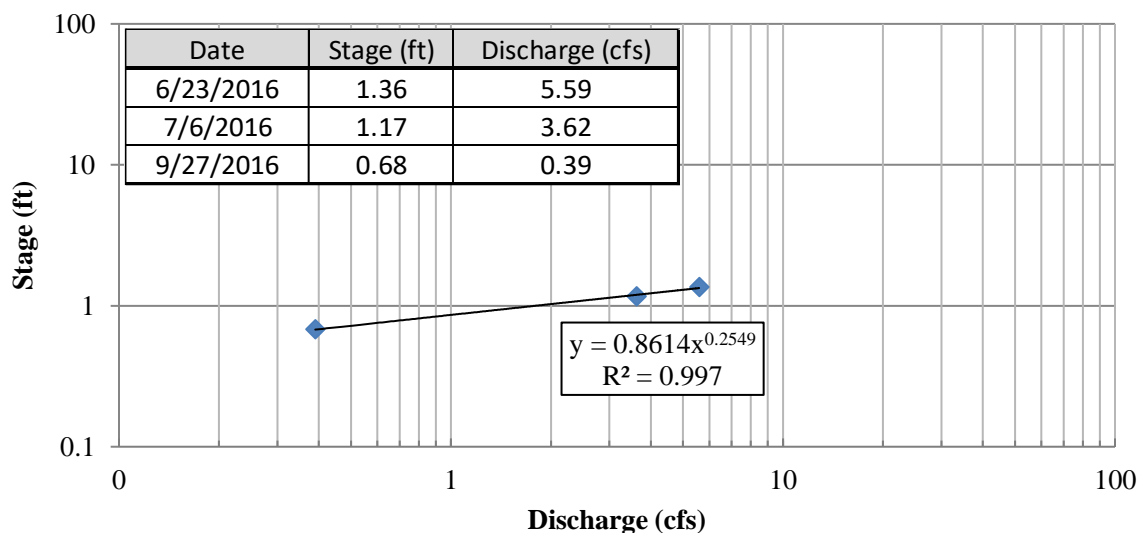


FIGURE C-1. Rating curve data for the temporary gage established at the Trail Ridge Creek study site during 2016.

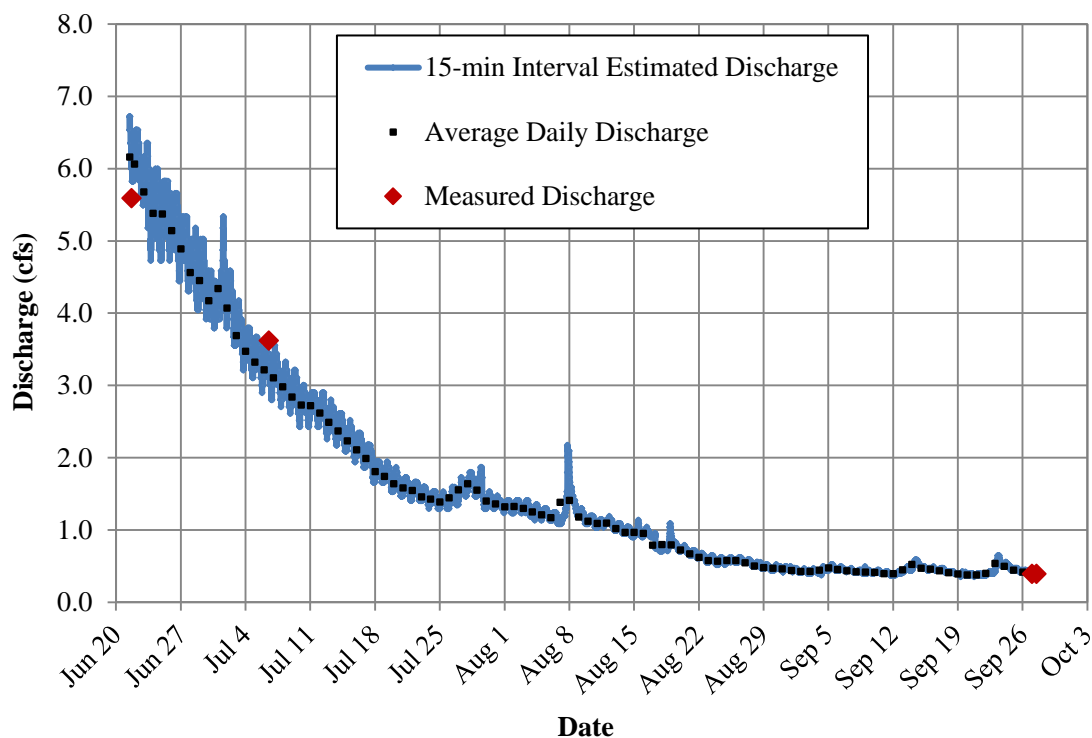


FIGURE C-2. Estimated hydrograph for Trail Ridge Creek study site during 2016.

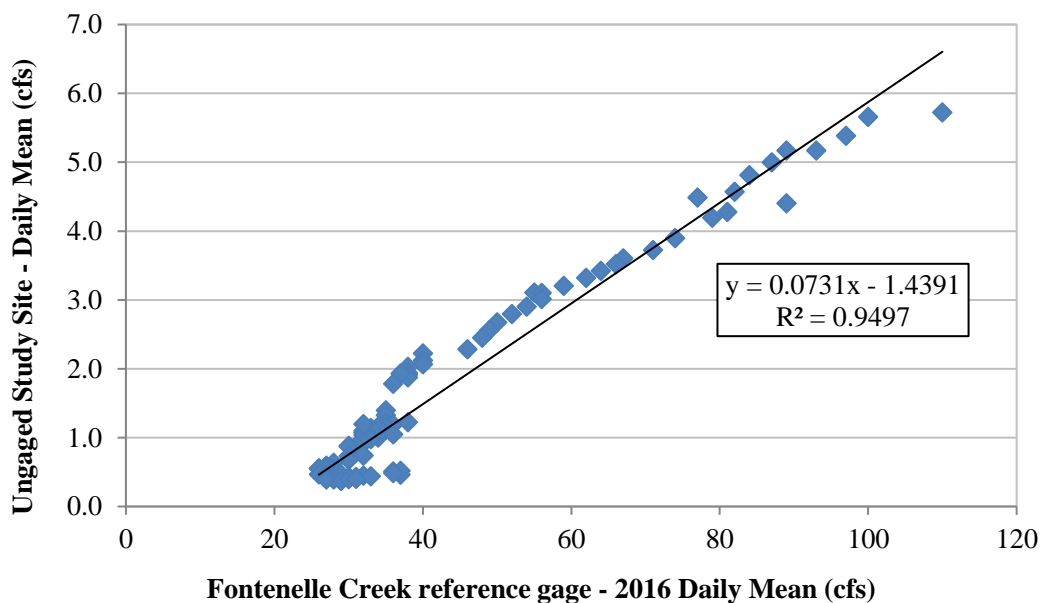


FIGURE C-3. Correlation between daily mean discharge estimates at the Trail Ridge Creek study site and daily mean discharge the Fontenelle Creek reference gage (USGS 09210500) during 2016.

WATERSHED MODEL SELECTION

After selecting a reference gage, models using various watershed characteristics were evaluated to determine which model is best suited to the study area. Potential models use variables that include mean elevation, drainage area, precipitation, stream length, and bankfull width to estimate mean annual flow (Q_{AA}). For Wyoming streams, mean annual flow models are found in two primary sources: Lowham (1988) and Miselis et al. (1999). The Lowham (1988) models are based on Wyoming streams in mountainous areas, statewide. Miselis et al. (1999) created separate models for each of eight specific mountain ranges in Wyoming. For this instream flow study, several models were used to estimate Q_{AA} at the reference gage and the results were compared to the Q_{AA} value calculated from gage records. The model that best predicts Q_{AA} at the reference gage is a good prospect for predicting Q_{AA} at the ungaged study segment, though sometimes a detailed evaluation may provide support for an alternate model. Local discharge measurements or temporary stream gaging data at the study site provide additional data sources, when available, to help guide model selection.

The Q_{AA} for the Fontenelle Creek reference gage (09210500) was 71 cfs for water years 1952-2015. Table C-2 shows Q_{AA} estimates from several models. The Lowham (1988) model using drainage area and precipitation produced an estimated Q_{AA} of 49 cfs, which was the estimate closest to the measured Q_{AA} .

TABLE C-2. Watershed model estimates of mean annual flow (Q_{AA}) for the Fontenelle Creek reference gage (USGS 09210500; water years 1952-2015). The model with the estimate closest to the reference gage period of record Q_{AA} of 71 cfs is shown in bold.

Model Description	Model ^a	Fontenelle Creek Q_{AA} (cfs)
Miselis et al (1999): Mountainous for WY, Drainage Area	1.20976 DA ^{0.894}	108
Miselis et al (1999): Wyoming Mountains, Drainage Area	3.25012 DA ^{0.72}	121
Miselis et al (1999): Wyoming Mountains, Stream Length	1.48902 SL ^{1.35}	231
Lowham (1988): Drainage area and Mean Elevation	0.0015DA ^{1.01} (Elev/1000) ^{2.88}	101
Lowham (1988): Drainage area and Precipitation	0.013DA^{0.93}P^{1.43}	49
Reference Gage Period of Record, Water Years 1952-2015		71

a - Basin characteristics include: DA – drainage area (5.33 square miles); P – annual precipitation (14.5 inches); SL – stream length (5.4 miles); Elev – mean basin elevation (8,430 feet).

DIMENSIONLESS ANALYSIS

After the watershed characteristics model was selected, a dimensionless analysis approach was used to develop estimates of daily flows, annual and monthly flow exceedance values, and flood frequencies for the proposed instream flow segment. As an example, to calculate daily discharge for the ungaged study segment, the Q_{AA} for the ungaged segment can be multiplied by a dimensionless adjustment factor, which is the reference gage daily discharge divided by reference gage Q_{AA} . The procedure is based on the following equation:

$$\frac{Q_1}{Q_{AA1}} = \frac{Q_2}{Q_{AA2}}$$

Where:

Q_1 = Daily discharge at the gage location

Q_{AA1} = Average annual discharge at the gage location

Q_2 = Daily discharge at the ungaged study segment

Q_{AA2} = Average annual discharge at the ungaged study segment

Daily discharge (Q_1) and Q_{AA1} are known for the reference gage location and are used to calculate a dimensionless adjustment factor (Q_1/Q_{AA1}). The watershed model provides the Q_{AA2} estimate for the ungaged study segment, so the formula can be rearranged to solve for Q_2 (estimated daily discharge at the ungaged location):

$$\left[\frac{Q_1}{Q_{AA1}} \right] * Q_{AA2} = Q_2$$

Similar equations can be used to estimate flood frequencies and annual and monthly flow exceedance values for the ungaged location.

FLOW ESTIMATES FOR THE TRAIL RIDGE CREEK STUDY SEGMENT

Using the Lowham (1988) model based on drainage area and precipitation (Table C-2), Q_{AA} at the Trail Ridge Creek study segment (drainage area 5.3 square miles) was estimated to be 2.8 cfs. Using the dimensionless analysis approach described above, daily flows were estimated for the study segment over the same period of record used for the reference gage (water years 1952-2015), and a graph of daily maximum, 20% exceedance, and mean discharges was prepared (Figure C-4). Dimensionless analyses were also used to calculate a flood frequency series (Table C-3; Log-Pearson Type III method) as well as annual (Table C-4) and monthly (Table C-5) flow exceedance values.

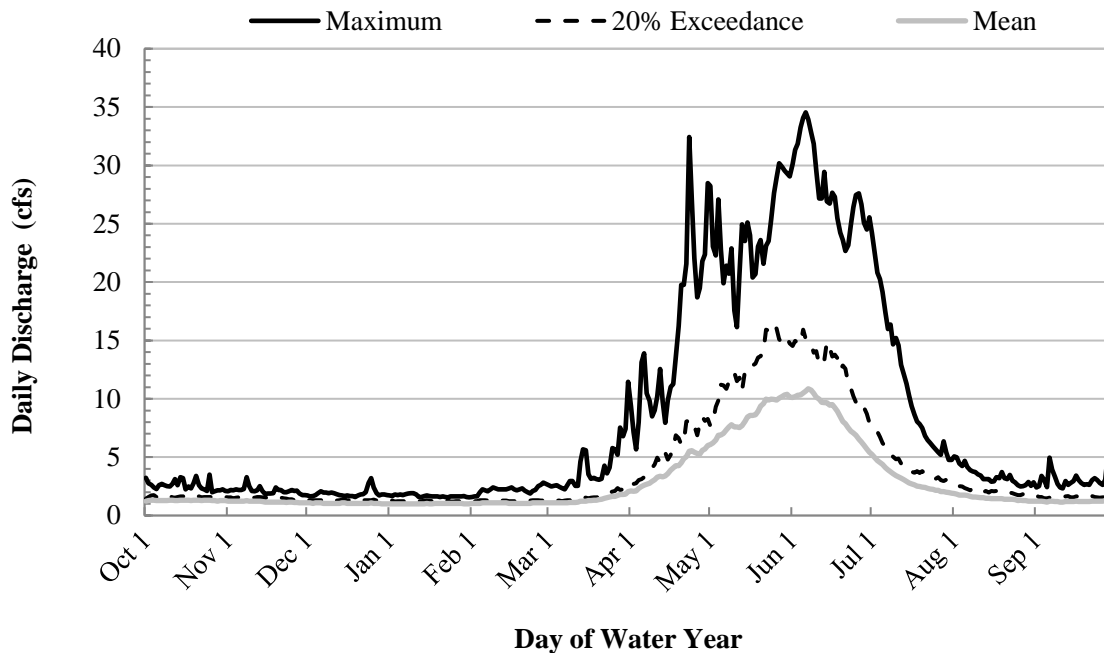


FIGURE C-4. Hydrograph showing the estimated daily maximum, 20% exceedance, and mean discharge values for the Trail Ridge Creek instream flow segment over the reference gage period of record (Fontenelle Creek; USGS gage 09210500; water years 1952-2015).

TABLE C-3. Flood frequency data for the Fontenelle Creek reference gage (USGS 09210500; water years 1952-2015) and estimated values for the Trail Ridge Creek study segment. (Values estimated with dimensional analysis; reference gage Q_{AA} is 70.9 cfs; estimated Q_{AA} for Trail Ridge Creek is 2.83 cfs.)

Return Period (years)	Fontenelle Creek (Water Years 1952-2015)	Dimensionless Adjustment Factor (Reference gage Q/Q_{AA})	Trail Ridge Creek (Q_{AA} * Adjustment Factor)
1.01	86	1.2125	3
1.05	144	2.0321	6
1.11	189	2.6679	8
1.25	254	3.5824	10
1.5	326	4.6050	13
2	416	5.8663	17
5	630	8.8890	25
10	761	10.7356	30
25	912	12.8644	36

TABLE C-4. Annual flow exceedance data for the Fontenelle Creek reference gage (USGS 09210500; water years 1952-2015) and estimated values for the Trail Ridge Creek study segment. (Values estimated with dimensional analysis; reference gage Q_{AA} is 70.9 cfs; estimated Q_{AA} for Trail Ridge Creek is 2.83 cfs.)

Duration Class (% Time Flow Equaled or Exceeded)	Annual Exceedance Flow Fontenelle Creek (Water Years 1952-2015)	Dimensionless Adjustment Factor (Reference gage Q/Q_{AA})	Predicted Annual Exceedance Flow Trail Ridge Creek ($Q_{AA} *$ Adjustment Factor)
95	17	0.2398	0.7
90	20	0.2821	0.8
85	22	0.3103	0.9
80	23	0.3244	0.9
75	25	0.3526	1.0
70	26	0.3667	1.0
65	28	0.3949	1.1
60	29	0.4090	1.2
55	31	0.4372	1.2
50	33	0.4654	1.3
45	35	0.4937	1.4
40	39	0.5501	1.6
35	44	0.6206	1.8
30	51	0.7193	2.0
25	64	0.9027	2.6
20	86	1.2130	3.4
15	120	1.6925	4.8
10	180	2.5317	7.2
5	285	4.0197	11.4

TABLE C-5. Monthly exceedance flow estimates for the Trail Ridge Creek study segment. Values were estimated through dimensionless analysis using exceedance data from the Fontenelle Creek reference gage (USGS 09210500; water years 1952-2015). Reference gage Q_{AA} is 70.9 cfs; estimated Q_{AA} for Trail Ridge Creek is 2.83 cfs.

Duration Class (% time flow equaled or exceeded)	Flow (cfs)											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep
95	0.8	0.7	0.6	0.6	0.6	0.8	1.2	2.3	1.4	0.8	0.5	0.6
90	0.9	0.8	0.7	0.6	0.7	0.8	1.4	3.1	2.2	1.0	0.7	0.7
85	0.9	0.8	0.8	0.7	0.8	0.8	1.6	3.6	2.9	1.2	0.8	0.8
80	1.0	0.9	0.8	0.8	0.8	0.9	1.7	3.9	3.4	1.4	0.9	0.8
75	1.0	1.0	0.8	0.8	0.9	1.0	1.8	4.3	4.0	1.5	1.0	0.9
70	1.0	1.0	0.9	0.8	0.9	1.0	2.0	4.8	4.6	1.7	1.1	0.9
65	1.1	1.0	0.9	0.9	0.9	1.0	2.2	5.2	5.2	1.8	1.1	1.0
60	1.2	1.0	1.0	1.0	1.0	1.1	2.4	5.7	5.9	2.0	1.2	1.0
55	1.2	1.1	1.0	1.0	1.0	1.1	2.6	6.4	6.6	2.1	1.2	1.0
50	1.2	1.1	1.0	1.0	1.0	1.2	2.9	7.2	7.3	2.3	1.3	1.1
45	1.2	1.2	1.0	1.0	1.1	1.2	3.2	7.9	8.1	2.6	1.4	1.2
40	1.3	1.2	1.1	1.1	1.1	1.2	3.4	8.6	9.0	2.8	1.5	1.2
35	1.3	1.3	1.1	1.1	1.2	1.3	3.8	9.6	9.9	3.1	1.6	1.3
30	1.4	1.3	1.2	1.2	1.2	1.4	4.3	10.6	10.9	3.4	1.8	1.4
25	1.4	1.4	1.2	1.2	1.2	1.5	4.8	11.7	12.2	3.8	1.9	1.5
20	1.6	1.4	1.3	1.2	1.3	1.6	5.4	12.9	13.4	4.2	2.0	1.6
15	1.7	1.6	1.4	1.3	1.3	1.8	6.3	14.3	15.0	4.9	2.3	1.7
10	1.8	1.6	1.4	1.4	1.4	2.0	7.7	16.3	17.7	5.8	2.5	1.9
5	2.0	1.8	1.6	1.5	1.5	2.7	10.0	18.9	22.4	7.8	2.9	2.2

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